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Research paper

Middle Eocene dinoflagellate cysts from Santa Cruz Province, Argentina: Biostratigraphy and paleoenvironment

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ABSTRACT

The upper member of the Río Turbio Formation is a well-exposed marine Eocene unit at high latitudes in Patagonia, Argentina. It holds important information helpful to reconstruct regional climate and oceanographic patterns in an area adjacent to the Drake Passage. Knowledge on the paleoenvironmental and paleoceanographic evolution of the southwestern Atlantic Ocean during the Paleogene is hindered by the lack of precise tools to date and correlate the sedimentary units. In this paper we present the dinoflagellate cyst assemblages from the upper member of the Río Turbio Formation and compare the stratigraphic distribution of their species with the ranges proposed in the Paleogene Southern Pacific Ocean dinoflagellate cyst zonation. The abundance of *Enneadocysta dictyostila*, the first occurrence of *Impagidinium parvireticulatum* and the presence of *Vozzhennikovia apertura* all allow us to propose a mid-Lutetian to mid-Priabonian age (44.6 to 34 Ma) for the upper member of the Río Turbio Formation. The study section is characterized by a middle Eocene endemic-Antarctic dinocyst assemblage. According to the dinocyst assemblages the analyzed section can be divided into four zones. Zone I is dominated by *E. dictyostila*, which points to a distal setting in an inner shelf environment. Zone II exhibits a high abundance of *V. apertura*, thus suggesting high trophic levels and cool waters in a shallow-marine, coastal environment. Zone III is dominated by *I. parvireticulatum* and a lower abundance of *E. dictyostila*, both species indicating a possible deepening of the depositional area with increasing influence of oceanic waters. Finally, Zone IV is dominated by *V. apertura*, indicating shallow marine waters. Our data suggest that *V. apertura* could have been produced by a stress-tolerant dinoflagellate species. Toward the top of the section, the samples are dominated exclusively by sporomorphs and zygospores of fresh-water green algae, which indicate a transition from a tide-dominated deltaic to a continental environment.

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1. Introduction

The Paleogene (~65–35 Ma) was a period of substantial climate change, involving the Earth's transformation from a greenhouse to an icehouse state, a transition which was not gradual, but was characterized by warming intervals, e.g. the Middle Eocene Climatic Optimum (Zachos et al., 2001, 2008; Bohaty and Zachos, 2003; Bohaty et al., 2009). During this period, there occurred significant tectonic changes, including the opening of deep Southern Ocean gateways (Tasman Gateway and Drake Passage), leading to the initiation of the Antarctic Circumpolar Current (Stickley et al., 2004a; Scher and Martin, 2006; Lagabrielle et al., 2009).

Paleoclimatic and paleogeographic data can be inferred from marine microfossil assemblages. Specifically, organic-walled dinoflagellate cysts (dinocysts) have been proven to be useful in reconstructing marine paleoenvironments for the Paleogene (Sluijs et al., 2005 and the references therein). These microfossils are found in large quantities in high-latitude shelf sediments, where carbonate is generally not well-preserved and less abundant. Dinoflagellates are susceptible to sea surface temperature and salinity fluctuations and depend on deep water fluctuations. They are also sensitive to slight changes in nutrient availability (e.g., Dale, 1996), and thus represent a valuable tool in determining surface-water productivity. The availability of nutrients in surface waters is directly related to upwelling and runoff, surface current patterns and water-mass mixing (e.g., Berger et al., 1989; Bertrand et al., 1996).

During the middle and late Eocene an endemic-Antarctic dinocyst assemblage, called “Transantarctic Flora” by Wrenn and Beckman (1982), has been recognized at sites with a paleolatitude south of 60°S (Sluijs et al., 2005). This assemblage is dominated by endemic and bipolar taxa that are clearly differentiated from assemblages rich in cosmopolitan and low-latitude species (Lentin and Williams, 1976; Wrenn

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and Hart, 1988; Brinkhuis et al., 2003a, 2003b; Sluijs et al., 2003; Bijl et al., 2011, 2013a, 2013b; Houben et al., 2013). Thus, our dinocyst assemblages, located off the southwestern Atlantic Ocean, can be biostratigraphically correlated with cores drilled in eastern Antarctica (Tasman Sea, Ross Sea) (Bijl et al., 2013a).

The middle Eocene in Patagonia is characterized by one of several Atlantic transgressions (Malumián, 1999). This transgression is represented by the upper member of the Río Turbio Formation in the westernmost part of the Austral Basin (Fig. 1). Due to the proximity of the Río Turbio Formation type area to the Drake Passage, whose opening leads to major ocean circulation and climate changes during the Paleogene, these marine deposits are a highly valuable source of information for the assessment of paleoenvironmental and paleoclimatic changes (Huber et al., 2004; Lagabrielle et al., 2009). However, paleoenvironmental reconstructions of the Paleogene in this area are prevented by the lack of biostratigraphic tools to date and correlate the sedimentary units. Earlier dinocyst studies of the Río Turbio Formation had been carried out by Archangelsky (1968, 1969) on cores drilled by the Argentine company Yacimientos Carboníferos Fiscales. Recently, Rodríguez Raising (2010) proposed a paleoenvironmental model based on sequence stratigraphy of sections outcropping in the Río Turbio Formation type area, which states that the processes responsible for transport and sedimentation during the deposition of the Rio Turbio Formation were generated by density flows with episodes of tidal diffusion processes. This model provides the stratigraphic framework for the present study.

This paper characterizes middle Eocene dinocyst assemblages from the upper member of the Río Turbio Formation in a composite section outcropping close to the Rio Turbio locality, southern Santa Cruz Province. Its aim is to provide a detailed biostratigraphic framework for the upper member of the Río Turbio Formation, taking as reference the dinocyst ranges determined by Brinkhuis et al. (2003b) and Bijl et al. (2013a) from cores drilled by the Ocean Drilling Program (ODP) on the East Tasman Plateau (Site 1172) and Integrated Ocean Drilling Program (IODP) at the Wilkes Land Antarctic Margin (Site U 1356). These records have magnetostratigraphically and biostratigraphically calibrated age models. We also reconstructed the paleogeographic and paleoceanographic conditions in the southwestern Austral Basin during the middle Eocene in order to critically assess and potentially improve the paleoenvironmental model proposed by Rodríguez Raising (2010).

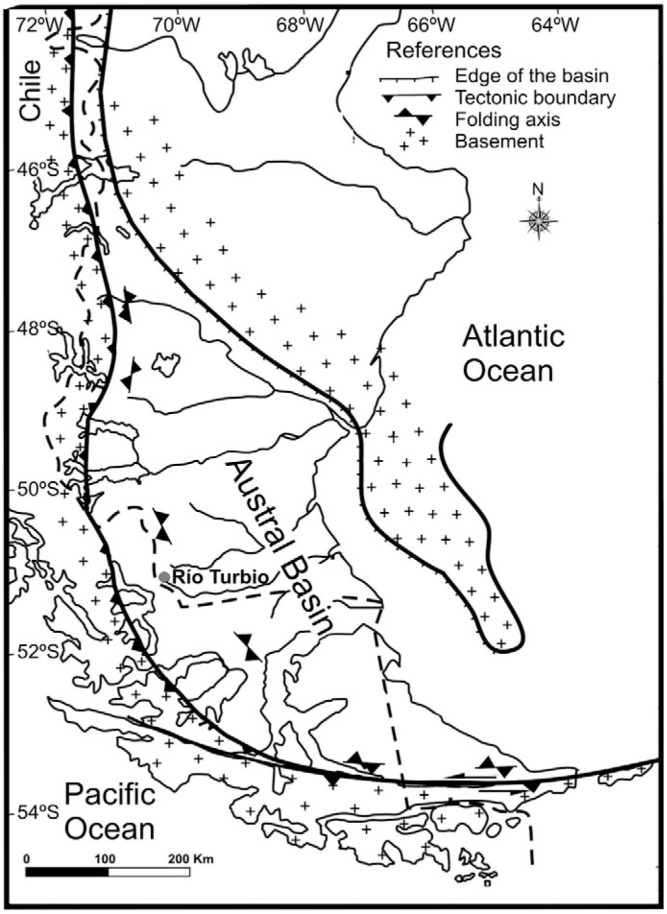

Fig. 1. Map of the south of Patagonia, Argentina with the Austral Basin and the Río Turbio study area identified.
Modified from Nullo et al. (1999).

2. Geological setting

The Austral Basin is located on the South American Plate south of 47°S and underlies the island of Tierra del Fuego, southern Patagonia, and the adjacent continental shelf of Argentina (Fig. 1). During the Late Cretaceous, a retro-foreland basin started to develop in response to the compression caused by the subduction of the Farallon, Aluk, Nazca and Antarctic plates beneath the South American Plate (Ramos, 2005; Somoza and Ghidella, 2005).

The upper member of the Río Turbio Formation is characterized by the presence of a glauconitic horizon widespread within the Austral Basin (Calegari et al., 1993) (Fig. 2). This horizon allows for the correlation with the Man Aike Fm. in Santa Cruz Province (Casadío et al., 2009), the Leticia Fm., the lower section of the Cerro Colorado Fm., the subsurfer Glauconítico B in Tierra del Fuego Province and the Ballena Fm. in Chile (Malumián, 2002; Olivero and Malumián, 2008).

Along the southwestern margin of the Austral Basin in Santa Cruz Province, outcrops of the upper member of the Río Turbio Formation have been assigned a late middle Eocene to early late Eocene age (Malumián et al., 2000). The lower member is separated from the underlying Paleocene Cerro Dorotea Formation by a disconformity. The upper member of the Rio Turbio Formation is separated from the overlying fluvial Río Guillermo Formation considered to be of late Eocene to early Oligocene age, by a gentle angular unconformity (Arguijo and Romero, 1981; Ramos, 2005). Based on a detailed ichnologic, sedimentologic and sequence stratigraphic study in the Río Turbio Formation type area, Pearson et al. (2012) interpreted the upper member as being deposited from multiple cycles of fall and rise of the relative sea-level forming a compound incised-valley system.

3. Materials and methods

The studied sections crop out in southwestern Santa Cruz Province along National Highway 40, south of the Rio Turbio locality (51°31′13″S, 72°15′11″O; Fig. 2). Two stratigraphic sections in the type area of the Rio Turbio Formation were measured using a Jacob's staff. The two sections belong to Sequences VI, VII and VIII of Rodríguez Raising (2010) (Fig. 3) and are up to 255 m thick (with 38 m of overlapping). The analysis of bed geometry, bounding surfaces, lithology, texture and sedimentary structures led to the distinction of three facies associations (FA) (Fig. 2). Sequence VI includes FA 1 and FA 2; Sequence VII constitutes FA 1 and Sequence VII includes FA 3. FA 1 is interpreted to represent deposits of distal zones of hyperpycnal lobe systems. FA 2 is explained as sediments accumulated in tidal plains, inter- to subtidal channels and abandoned channel systems. FA 3 is interpreted as intertidal alluvial deposits.

A total of 23 samples were processed for palynological analysis using hydrochloric and hydrofluoric acids. The residues were sieved through screens of 10, 25 and 180 μm and stained with Bismarck C. Strew mounts were prepared using gelatin–glycerin as a mounting medium. The palynological samples were processed at the Museo Argentino de Ciencias Naturales, Bernardino Rivadavia, Buenos Aires, and the slides are stored at the Laboratorio de Palinología, Instituto Geológico del Sur, Bahía Blanca. The field and laboratory numbers are shown in

Fig. 2. For each sample, a minimum of 200 dinocysts were counted and identified in terms of species level, except for the samples RT 12/1-9 and RT 13/1-1, for which only 150 specimens were identified due to the low yield of dinocysts. The percentage of peridinioid cysts (P-cysts) within the dinocyst assemblage was used to estimate the productivity (Brinkhuis et al., 1998; van Mourik and Brinkhuis, 2000; Crouch et al.,

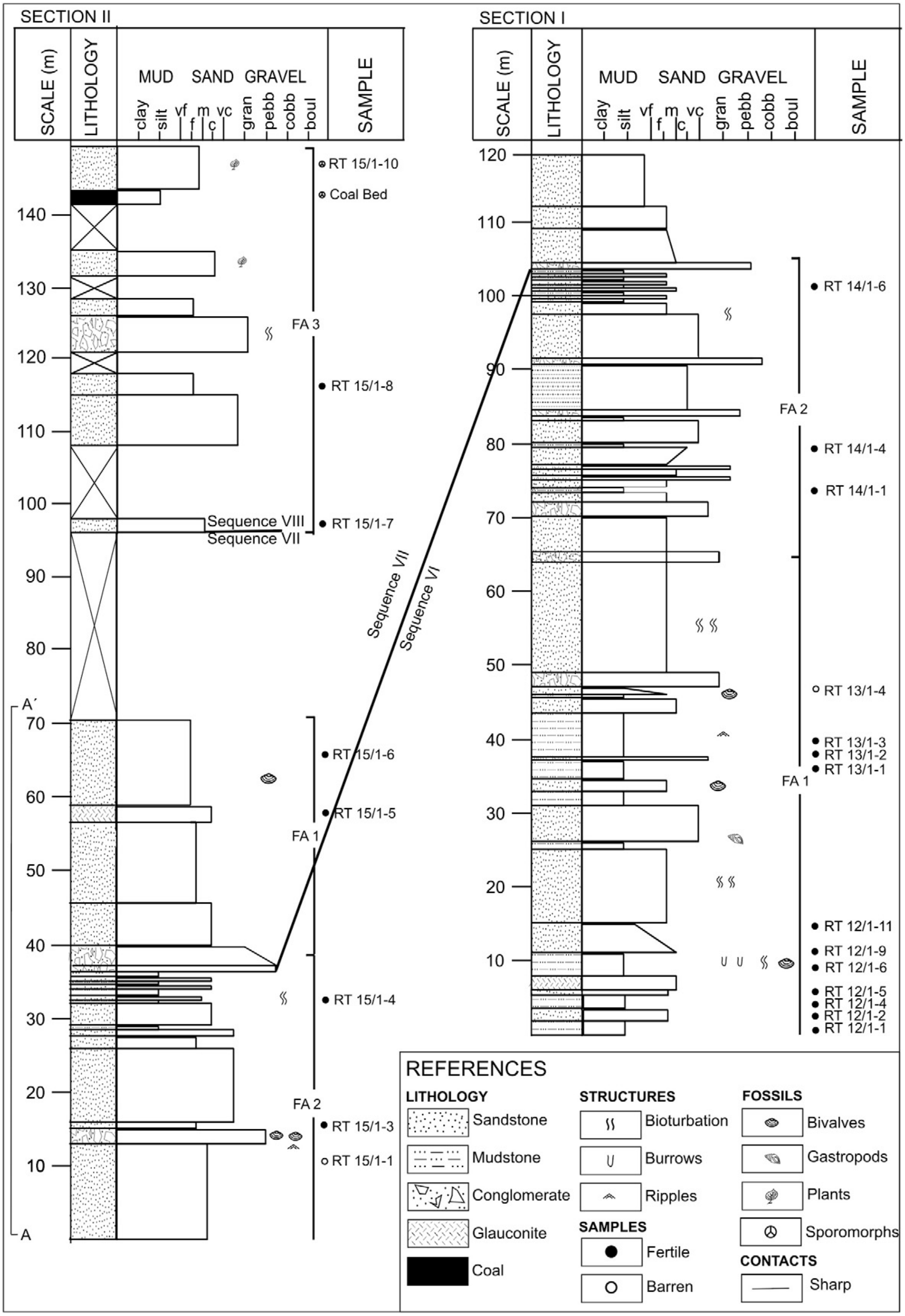

Fig. 2. Stratigraphical sections of the Río Turbio Formation indicating field/laboratory sample numbers, sequences and the facies associations (FA). FA 1: deposits of distal zones of hyperpycnal lobe systems; FA 2: deposits of tidal plains, inter- to subtidal channels and abandoned channel systems. FA 3: inter-tidal alluvial deposits. A–A′: part of Section II shown in Fig. 3.

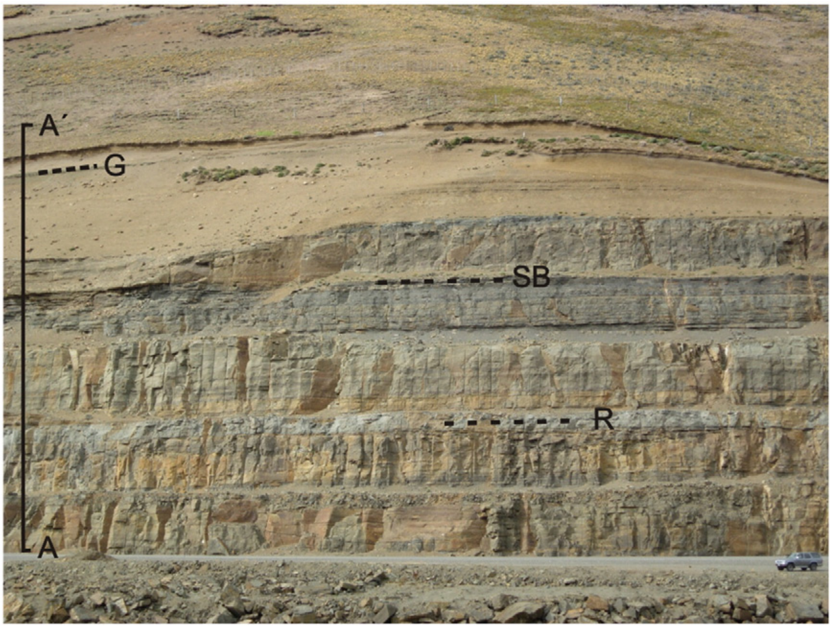

Fig. 3. Detail of Section II (A–A′). R: *Ostrea* sp. reef. SB: VI - VII sequence boundary. G: glauconitic layer.

2003). It was also possible to calculate the percentage of endemic and bipolar dinocysts over the total dinocysts in order to characterize the sea-surface temperature, and the dinocysts/total palynomorphs ratio, expressed as percentage, in order to estimate the proximity to the shoreline. Light microscopy was undertaken using a Nikon Eclipse 600 microscope and an attached Micrometrics high-resolution digital camera. In the explanations for the plates, sample and slide number with England Finder (EF) references are provided for each illustrated specimen. Dinocyst nomenclature, unless otherwise indicated, is based on Fensome et al. (2008) and Sluijs et al. (2009). Dinocyst species were classified as endemic, bipolar and cosmopolitan, based on Bijl et al. (2011, 2013a) and Houben et al. (2013). The geological time scale is from Vandenberghe et al. (2012).

4. Results

Nineteen of the 23 samples analyzed from the upper member of the Río Turbio Formation are rich in dinocysts, 2 samples only contain non-marine palynomorphs (mainly pollen, spores and zygospores of freshwater green algae) and 2 samples were barren. Table 1 lists a total of 19 species recovered including their biogeographical distribution (endemic or cosmopolitan), most of them are illustrated in Plates I and II. Quantitative changes in the composition of dinocyst assemblages through the studied sections have allowed us to define the following four local dinocyst zones (Fig. 4):

Zone I. It comprises the lowermost 40 m of stratigraphic section I and includes 10 samples (RT 12/1-1, RT 12/1-2, RT 12/1-4, RT 12/1-5, RT 12/1-6, RT 12/1-9, RT 12/1-11, RT 13/1-1, RT 13/1-2 and RT 13/1-3). Assemblages are dominated by *Enneadocysta*, mainly *Enneadocysta dictyostila* (48–97%) and only a few *Enneadocysta brevistila*. As a result, the presence of P-cysts is relatively low (0.3–28.5%) and the percentage of endemic forms is high (58–98%). Only sample RT 13/1-1 presents a lower quantity of *E. dictyostila* (25%) and endemic elements (42.6%). The dinocyst spectrum is completed by a lower abundance of *Vozzhennikovia apertura*, *Deflandrea antarctica*, *Hystrichosphaeridium truswelliae*, *Spiniferites scalenus*, *Spiniferites ramosus*, *Operculodinium israelianum*, *Lejeunecysta* sp., *Selenophemphix selenoides*, *Thalassiphora pelagica* and *Turbiosphaera filosa*. Samples RT 12/1-2 and RT 12/1-4 both show high abundance of *Arachnodinium antarticum*, and sample RT 12/1-9 yields a few *Glaphyrocysta* sp. and *Achilleodinium* sp. Despite being largely dominated by *E. dictyostila*, the samples in this zone present the highest number of taxa of the whole section. The dinocysts/total palynomorphs ratio ranges from 30 to 96%.

Zone II. It includes 5 samples (RT 14/1-1, RT 14/1-4, RT 14/1-6, RT 15/1-3 and RT 15/1-4), which were obtained from 65 to 105 m from the base of section I and the first 38 m of section II. It is dominated by *V. apertura* (46–94%), and thus exhibits a high percentage of P-cysts (73.7–94.9%) and endemic taxa (95–100%). *Enneadocysta dictyostila* is present in all samples, but it is less abundant than in Zone I. *Deflandrea antarctica* (although still with low percentages) is more abundant than in Zone I. Assemblages from this zone exhibit a low number of species except for sample RT 14/1-6, which contains a few species of *Spiniferites* and *Operculodinium*. Sample RT 15/1-4 contains a small proportion of *T. pelagica* (2%). The dinocysts/total palynomorphs ratio ranges between 34 and 67%.

Zone III. It comprises two samples (RT 15/1-5 and RT 15/1-6) located at 38–70 m above the base of section II. RT 15/1-5 is composed of *E. dictyostila* (48.6%) and *Impagidinium parvireticulatum* (48.9%), and contains a few specimens belonging to *Operculodinium*, *Lejeunecysta*, *Spinidinium* and *Selenopemphix*. Hence the percentage for P-cysts is 1.2% and endemic taxa is 48.6%. RT 15/1-6 is dominated almost exclusively by *I. parvireticulatum* (92%) and has only a few specimens of *V. apertura*, *E. dictyostila* and *D. antarctica*. As a result, the percentages for P-cysts (7%) and endemic taxa (7%) are low. The dinocysts/total palynomorphs ratio represents the 56 and 95%.

Zone IV. It includes the uppermost part of section II (between 97 and 150 m from the base of the section) and includes two samples dominated by dinocysts (RT 15/1-7, RT 15/1-8) and two samples with exclusively non-marine palynomorphs (Coal Mantle A and RT 15/1-10). The dinocyst assemblages are extensively dominated by *V. apertura* (98–100%), only sample RT 15/1-8 has a few specimens of *Operculodinium* (1.6%) and *E. dictyostila* (0.4%). Thus, both samples exhibit a high percentage of P-cysts (98–100%) and endemic taxa (98.6–100%). The samples exclusively dominated by non-marine palynomorphs (mainly pollen, spores and zygospores of fresh-water green algae) are located in the upper part of section II. The dinocysts/total palynomorphs ratio ranges between 37 and 70%.

5. Discussion

5.1. Biostratigraphy

The biostratigraphic ranges of the dinocyst species recorded in the upper member of the Río Turbio Formation are taken from the dinocyst distribution in the sites of the ODP Leg 189, Tasman Gateway (Brinkhuis et al., 2003a, 2003b), where the records are magnetostratigraphically and chemostratigraphically calibrated (Stickley et al., 2004b). The ages of the zones proposed in the present work are based on the first and last occurrences of diagnostic dinocyst species considering the dinoflagellate cyst zonation of the early Paleogene South Pacific Ocean published by Bijl et al. (2013a) (Fig. 5).

Zone I. It is dominated by *E. dictyostila*, whose first occurrence is recorded at Site 1172 in the C20r magnetochron at 44.6 Ma. This dinocyst event constrains the age of the section to the mid-Lutetian or to an even younger age. This zone can be correlated with the base of Zone SPDZ 11 (45.2 Ma to 44 Ma) proposed by Bijl et al. (2013a). Other dinocyst markers present in this zone are *H. truswelliae* and *Arachnodinium antarcticum*. According to Brinkhuis et al. (2003a, 2003b), these species have their last occurrences in the magnetochron C18n1n, at 38.8 Ma, suggesting an age no younger than late Bartonian.

Zone II. The ranges of species found in this zone (*V. apertura*, *E. dictyostila*, *D. antarctica*, *S. scalenus*, and *O. israelianum*) do not allow us to closely constrain the age of this interval. However, their stratigraphic ranges are compatible with the ages proposed for the lower part and the upper part of the section.

Zone III. It is dominated by *I. parvireticulatum*, whose first and last occurrences are 43.7 Ma (mid-Lutetian) and 35.5 Ma (mid-Priabonian). This zone can be correlated with Zone SPDZ 12 of Bijl et al. (2013a) mid-Lutetian to early Bartonian (44 Ma to 40 Ma).

Zone IV. The dominance of *V. apertura* in this zone could be correlated with Zone SPDZ 13 (40 Ma to 35 Ma) of Bijl et al. (2013a) where this species is characteristic. However, abundant records of *V. apertura* are not exclusive of Zone SPDZ 13. The lack of biostratigraphic diagnostic taxa markers does not allow us to confirm this biostratigraphic correlation and constrain the age of this zone.

In summary, the age of the upper member of the Río Turbio Formation in the studied section ranges from mid-Lutetian to mid-Priabonian.

5.2. Paleoenvironment

Paleogene dinocysts are useful in the reconstruction of marine paleoenvironments because most of the dinoflagellates producing cysts respond to sea surface temperature, salinity fluctuations and deep water changes. They are also sensitive to the availability of nutrients and thus can be used to measure surface-water productivity (Sluijs et al., 2005 and the references therein). In dinocyst-based paleoecological reconstructions, surface-water productivity can be estimated using the ratio of peridinioid (P) versus gonyaulacoid (G) cysts, based on the modern heterotrophic lifestyle of *Protoperidinium*, P-cysts are interpreted as remains of heterotrophic dinoflagellates, whereas G-cysts correspond to autotrophic–mixotrophic dinoflagellates (Powell et al., 1992; Dale, 1996; Sluijs et al., 2005; Esper and Zonneveld, 2007). Thus, high relative abundances of peridinioid cysts could indicate an elevated supply of nutrients (e.g., Goodman and Ford, 1983; Wrenn and Hart, 1988; Mao and Mohr, 1995; Brinkhuis et al., 2003b; Sluijs et al., 2003) and offer information about trophic levels of ancient surface-water masses. The quantitative dinocyst data, together with the sedimentological analysis of the upper member of the Río Turbio Formation, allows characterization of the surface-water conditions during the middle Eocene in the study area.

Zone I. The palynological samples exhibit a high abundance of *E. dictyostila*. Röhl et al. (2004) connected high abundances of *Enneadocysta* spp. with neritic sediments rich in $CaCO_3$, suggesting warm waters and offshore conditions. Sedimentological results show that this stratigraphic interval represents the most distal part of a system dominated by density flows (FA 1; Rodríguez Raising, 2010). For this reason, the dominance of *E. dictyostila* is consistent with the most distal settings in an inner shelf environment.

Zone II. It includes dinocyst assemblages dominated by *V. apertura* and lower percentages of *D. antarctica*. Both species are related to cold circum-Antarctic shallow marine waters (Wilson, 1967; Mohr, 1990; Hannah, 1997; MacPhail and Truswell, 2004; Röhl et al., 2004; Warnaar et al., 2009). *V. apertura* and *D. antarctica* could indicate high trophic levels because they were presumably formed by

Table 1
List of species of dinocysts cited in the text. The latitudinal distribution is based on Bijl et al. (2013a) and Houben et al. (2013).

Dinocyst species	Order	Latitudinal distribution
Achomosphaera sp. A	Gonyaulacales	Cosmopolitan?
Arachnodinium antarcticum Wilson and Clowes, 1982	Gonyaulacales	Endemic-Antarctic
Deflandrea antarctica Wilson, 1967a	Peridiniales	Endemic-Antarctic
Deflandrea heterophlycta Deflandre and Cookson, 1955	Peridiniales	Cosmopolitan
Enneadocysta brevistila Fensome et al., 2006	Gonyaulacales	Endemic-Antarctic
Enneadocysta dictyostila (Menéndez) Fensome et al., 2006	Gonyaulacales	Endemic-Antarctic
Achilleodinium sp.	Gonyaulacales	Cosmopolitan
Glaphyrocysta sp.	Gonyaulacales	Cosmopolitan
Hystrichosphaeridium truswelliae Wrenn and Hart, 1988	Gonyaulacales	Cosmopolitan
Impagidinium parvireticulatum Wilson, 1988	Gonyaulacales	Cosmopolitan
Lejeunecysta spp.	Peridiniales	Cosmopolitan
Operculodinium israelianum (Rossignol) Wall, 1967	Gonyaulacales	Cosmopolitan
Selenopemphix crenata Matsuoka and Bujak, 1988	Peridiniales	Cosmopolitan
Selenopemphix nephroides Benedek, 1972	Peridiniales	Cosmopolitan
Spiniferites scalenus Guerstein et al., 2008b	Gonyaulacales	Endemic-Antarctic?
Spiniferites ramosus (Ehrenberg) Mantell, 1854	Gonyaulacales	Cosmopolitan
Thalassiphora pelagica (Eisenack,) Eisenack and Gocht, 1960	Gonyaulacales	Cosmopolitan
Turbiosphaera filosa (Wilson) Archangelsky, 1969a	Gonyaulacales	Cosmopolitan
Vozzhennikovia apertura (Wilson) Lentin and Williams, 1976	Peridiniales	Endemic-Antarctic

heterotrophic dinoflagellates (P-cysts) (Brinkhuis et al., 2003a, 2003b; Sluijs et al., 2003; Warnaar et al., 2009). This stratigraphic interval is represented by a facies association interpreted as an intertidal deltaic plain (FA 2; Rodríguez Raising, 2010) and is characterized by a monospecific *Ostrea* sp. reef with taphonomic features, which reflect fluctuations in the rate of salinity. Such variations, probably originated by freshwater input changes, would have established a factor of environmental stress (Pearson et al., 2012). It is possible that the freshwater discharge had increased nutrient inputs, thus promoting the dominance of heterotrophic species (P-cysts). It is important to note that the increasing number of non-marine palynomorphs reinforces the reconstruction of an environment close to the paleoshoreline (Fig. 4). Goodman (1979) indicated that low diversity–high dominance dinoflagellate cyst assemblages have been associated with stressed conditions. *V. apertura* has been recorded in assemblages of La Meseta Formation of Seymour Island which reflect a stressed, shallow water environment (Cocozza and Clarke, 1992). The high percentages of *V. apertura* and the low dinocyst diversity in Zone II allow us to regard this dinocyst as produced by an extinct stress-tolerant dinoflagellate species.

Zone III. The dinocyst assemblages are dominated by the marine open water species *I. parvireticulatum* and *E. dictyostila*. Currently, most of the species of *Impagidinium* are taxa thriving in neritic to oceanic waters (Marret and Zonneveld, 2003; Dale et al., 2006). Assuming that the ecological preferences of these species have been the same since the Eocene, an actuo-paleontological approach suggests that this *Impagidinium* dominance could indicate a deepening of the depositional area and an increasing influence of oceanic waters. This interpretation is consistent with the sequence stratigraphic analysis, which indicates a maximum flooding surface with low tidal influence and an increase in the marine connection within the FA 1 (Fig. 2).

Zone IV. In the first portion of this zone, *V. apertura* is extremely abundant, but further up in the section, dinocyst percentages decrease and palynological assemblages are almost exclusively dominated by sporomorphs. This zone corresponds to the facies association (FA 3) deposited in an intertidal deltaic plain with plant remains (e.g. leaves) reflecting coastal areas with important freshwater input. In addition, trace fossils indicate environmental stress conditions (Pearson et al., 2012), consistently with the almost exclusive dominance of *V. apertura* (see above). In the uppermost part of the section, the presence of coal beds coincides with the abundance of non-marine palynomorphs, indicating the transition from a coastal to a continental paleoenvironment.

5.3. Paleobiogeography

The endemic dinocyst assemblage associated with peaks of *E. dictyostila*, *D. antarctica*, *Vozzhennikovia*–*Spinidinium* complex and *A. antarcticum* has been recorded mainly in middle Eocene sections from Southern Hemisphere high latitudes. Such quantitative and semi-quantitative records include the lower part of the Rio Turbio Formation recovered from boreholes drilled in southwestern Santa Cruz Province (Archangelsky, 1968, 1969); the upper part of the Man Aike Formation, in southwestern Lago Argentino area, Santa Cruz Province (Guerstein et al., 2014); lateral equivalents of Leticia Formation in the north of Tierra del Fuego (Guerstein et al., 2008b); DSDP Leg 29, off southeastern Australia and western New Zealand (Haskell and Wilson, 1975); the upper part of La Meseta Formation in northern Seymour Island (Cocozza and Clarke, 1992); a core from Brunce Bank in the Scotia Sea, off Antarctica (Mao and Mohr, 1995) and the already mentioned records from ODP Leg 189, off Tasmania (Brinkhuis et al., 2003a, 2003b; Sluijs et al., 2003) and from IODP Site U1356, across the Wilkes Land margin of Antarctica (Escutia et al., 2011).

Bijl et al. (2011, 2013a, 2013b) noted that during the Paleocene and early Eocene dinocyst assemblages from the Southern Ocean were dominated by cosmopolitan taxa and around the early-middle Eocene boundary (~50 Ma), the trend shifted to endemic-dominated assemblages. The geographical distribution and dominance of this endemic-Antarctic assemblage accord with the surface water circulation pattern reconstructed using general circulation models for the Eocene (Huber et al., 2004). The cause of this endemism is widely discussed by Bijl et al. (2011), who considered that the expansion of the endemic-Antarctic assemblage was not linked to regional sea surface temperature records but possibly to large-scale changes in the availability of surface-ocean nutrients.

The latest information on the South Pacific Ocean suggests that around 50 Ma a connection developed between the Australo-Antarctic Gulf and the Pacific Ocean, resulting in a southern shallow-water opening of the Tasmanian Gateway (Escutia et al., 2011). Dinoflagellate

Plate I. Specimens are identified by sample number/England Finder references. Scale bar 20 μm.

1–2	*Enneadocysta dictyostila* (Menéndez) Fensome et al., 2006; fig. 1. RT 12/1-6/K52-0; oblique-ventral view, focus on plates 5″ and 6″; fig. 2. RT 13/1-1/ Q59-1; lateral view, low focus.
3	*Thalassiphora pelagica* (Eisenack) Eisenack and Gocht, 1960. RT 12/1-9/T53-0; ventral view, dorsal surface, see operculo inside.
4–5	*Hystrichosphaeridium truswelliae* Wrenn and Hart, 1988. RT 13/1-3/S43-3; fig. 4. Lateral right view, lower focus; fig. 5. Lateral right view, upper focus.
7–8	*Operculodinium israelianum* (Rossignol) Wall, 1967. RT 13/1-3/G55-4; dorsal view, dorsal focus.
7–8	*Achomosphaera* sp. A. RT 13/1-3/P48-0; fig. 7. Lateral-left view, upper focus; fig. 8. Lateral-left view, lower focus.
9	*Spiniferites scalenus* Guerstein et al., 2008b. RT 13/1-1/N51-3; dorsal view, dorsal surface.
10–11	*Impagidinium parvireticulatum* Wilson, 1988. RT 15/1-6/M50-0; fig. 10. Apical view, apical surface; fig. 11. Apical view, antapical surface.
12	*Spiniferites ramosus* (Ehrenberg) Mantell, 1854. RT 13/1-1/V54-1; dorsal view, dorsal focus.

Plate II. Specimens are identified by sample number/microscope coordinates/England Finder references. Scale bar 20 μm. (see on page 62)

1	*Lejeunecysta* sp. RT 12/1-4/T32-4; ventral view, ventral surface.
2	*Selenopemphix nephroides* Benedek, 1972. RT 13/1-2/W44-4; intermediate surface.
3	*Selenopemphix crenata* Matsuoka and Bujak, 1988. RT 13/1-1/T33-3; antapical view, intermediate surface.
4–5	*Deflandrea antárctica* Wilson, 1967a. RT 12/1-9/K48-3; fig. 4. Dorsal view, ventral surface; fig. 5. Dorsal view, dorsal surface.
6	*Deflandrea heterophlycta* Deflandre and Cookson, 1955. RT 12/1-6/B37-0; ventral view, dorsal surface.
7	*Vozzhennikovia apertura* (Wilson, 1967a) Lentin and Williams, 1976. RT 14/1-4/C43-0; dorsal view, dorsal surface.
8	*Turbiosphaera filosa* (Wilson, 1967a) Archangelsky, 1969a. RT 12/1-9/J42-2; ventral view, dorsal surface.
9	*Achilleodinium* sp. RT 12/1-4/K32-3; dorsal view, dorsal surface.
10–11	*Arachnodinium antarticum* Wilson and Clowes, 1982. RT 12/1-4/K32-3; indet orientation.
12	*Glaphyrocysta* sp. RT 12/1-9/ P46-0; lateral right view, intermediate surface.

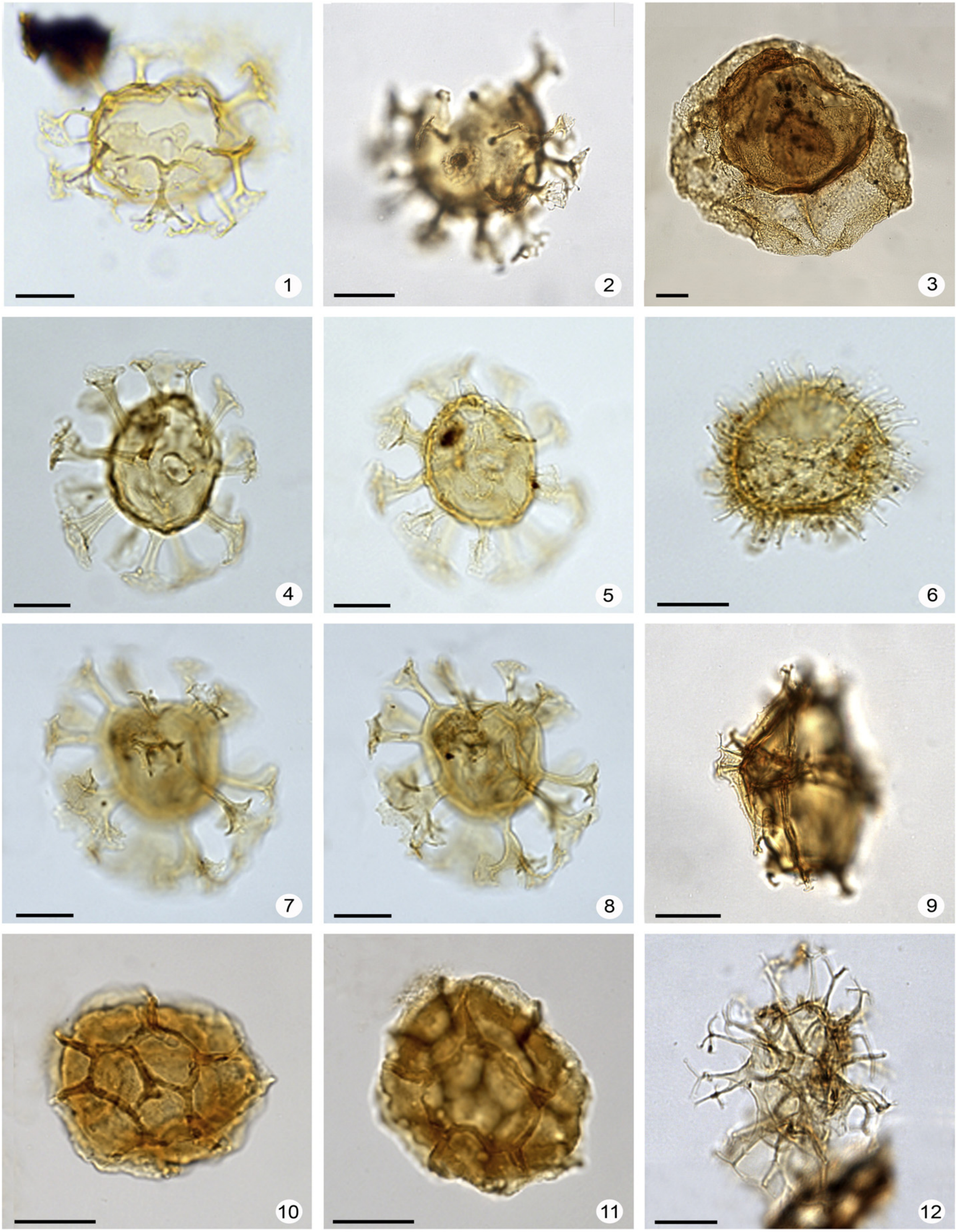

Plate I

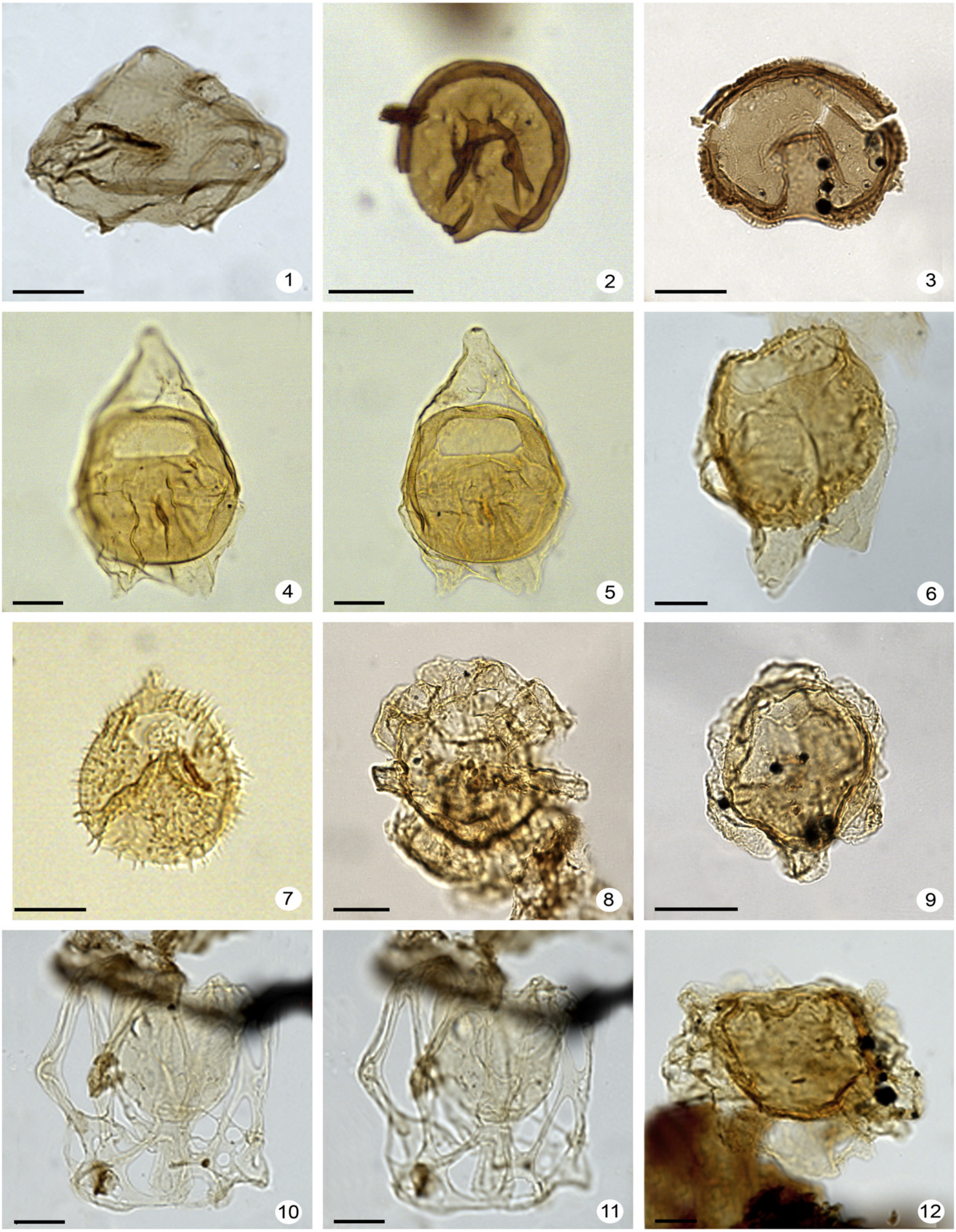

Plate II. (*caption on page 60*).

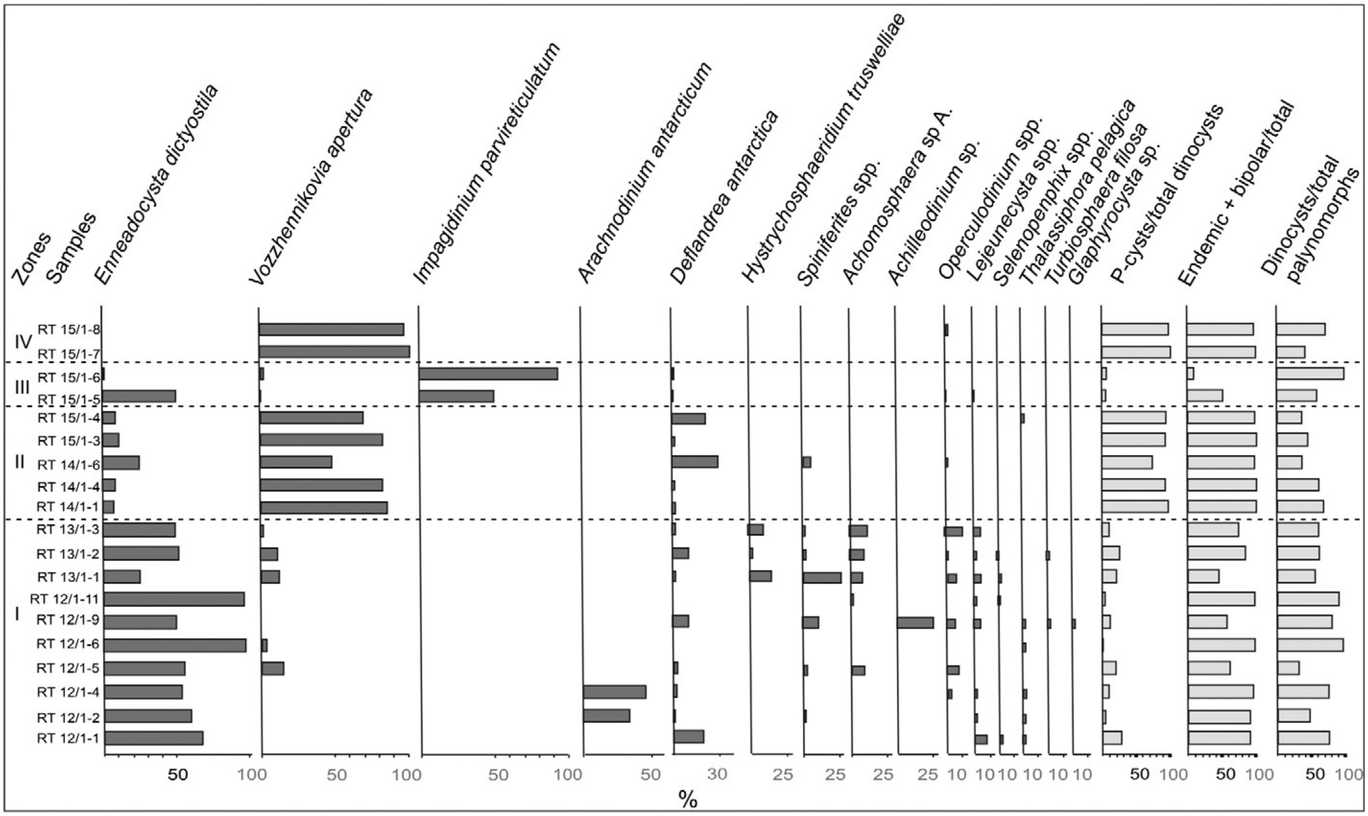

Fig. 4. Zones and quantitative distribution of dinocysts within samples from the Río Turbio Formation at the sections cropping out along Highway Number 40. P-cysts/total: percentages of peridinioid cysts (P-cysts) over total of dinocysts; Endemic + bipolar/total: percentages of endemic and bipolar dinocysts over total of dinocysts. The bars at the right show the percentages of dinocysts over total of palynomorphs.

biogeography and sea surface temperature paleothermometry reveal that the earliest through flow of a westbound Antarctic Counter Current began ~49–50 Ma through a southern opening of the Tasmanian Gateway (Bijl et al., 2013b). These authors interpret that this westbound flowing current resulted in the middle Eocene cooling of Antarctic surface waters, which was transferred to global intermediate waters through strengthened deep convection in southern high latitudes.

The opening history of the Drake Passage had been viewed as an event associated with changes in global circulation and climate taking place at or near the Eocene–Oligocene boundary. However, Livermore et al. (2007) suggest that an efficient ocean gateway may have developed during the middle Eocene, characterized by several current pathways which evolved across the subsiding continental shelves. According to González Estebenet et al. (in press) these shallow openings may have caused a scenario similar to that described for the initial opening of the Tasman Gateway causing significant changes in Southern Ocean circulation and contributing to the development of the endemic-Antarctic dinocyst assemblage in the southwestern Atlantic Ocean basins.

During the Eocene–Oligocene Transition, endemic middle Eocene dinocyst taxa were largely replaced by cosmopolitan assemblages, consisting mainly of heterotrophic taxa (protoperidinacean) with modern analogues living today in sea-ice systems (Houben et al., 2013). This turnover seems to be forced by the deepening of the Tasman Gateway and the Drake Passage (Sluijs et al., 2003; Stickley et al., 2004a; Guerstein et al., 2008a; Houben et al., 2011, 2013). The aforesaid tectonic changes disrupted the subpolar gyres originated during the Eocene, with the subsequent development of the Circum Antarctic Current in the earliest Oligocene. In turn, such a condition could have caused the extinction of endemic species and the arrival and installation of cosmopolitan taxa (Huber et al., 2004; Guerstein et al., 2008b). The maximum of the oceanic-cosmopolitan *Impagidinium*, recorded in the upper part of the studied sections (Zone III), can be associated with tectonic regional factors instead of major tectonic changes leading to water-circulation pattern modifications. This interpretation is reinforced by the subsequent blooms of the endemic *V. apertura* at the uppermost part of the section (Zone IV).

To summarize, the highly dominant endemic-Antarctic dinocyst assemblages of the Río Turbio Formation in its type area may be linked to an early opening of the Drake Passage, with shallow-water connections between the Pacific and Atlantic oceans before the emplacement of the Antarctic Circumpolar Current and the development of Antarctic ice-sheets.

6. Conclusions

The dinocyst events recorded in the upper member of the Río Turbio Formation were compared with the stratigraphic ranges published by Brinkhuis et al. (2003b) and Bijl et al. (2013a) for the South Pacific Ocean. The dinocyst assemblages correspond to Zone SPDZ 11 to Zone SPDZ 13 of Bijl et al. (2013a).

The upper member of the Río Turbio Formation is considered to be mid-Lutetian to mid-Priabonian in age. The lowermost part of the section cannot be considered younger than late Bartonian.

Four dinocyst zones were recognized. Particularly, the dominance of *E. dictyostila* in Zone I suggests distal settings in an inner shelf environment. Peaks of *V. apertura* in Zone II indicate shallow marine waters associated with coastal areas and high trophic levels, as a result of freshwater input. Zone III is characterized by *I. parvireticulatum* and reflects a deepening of the depositional area with influence of oceanic waters, coinciding with a maximum flooding surface. Finally, Zone IV corresponds to the transition from a tide-dominated deltaic system to a continental environment as evidenced by the replacement of a *V. apertura* assemblage with a non-marine palynomorph association.

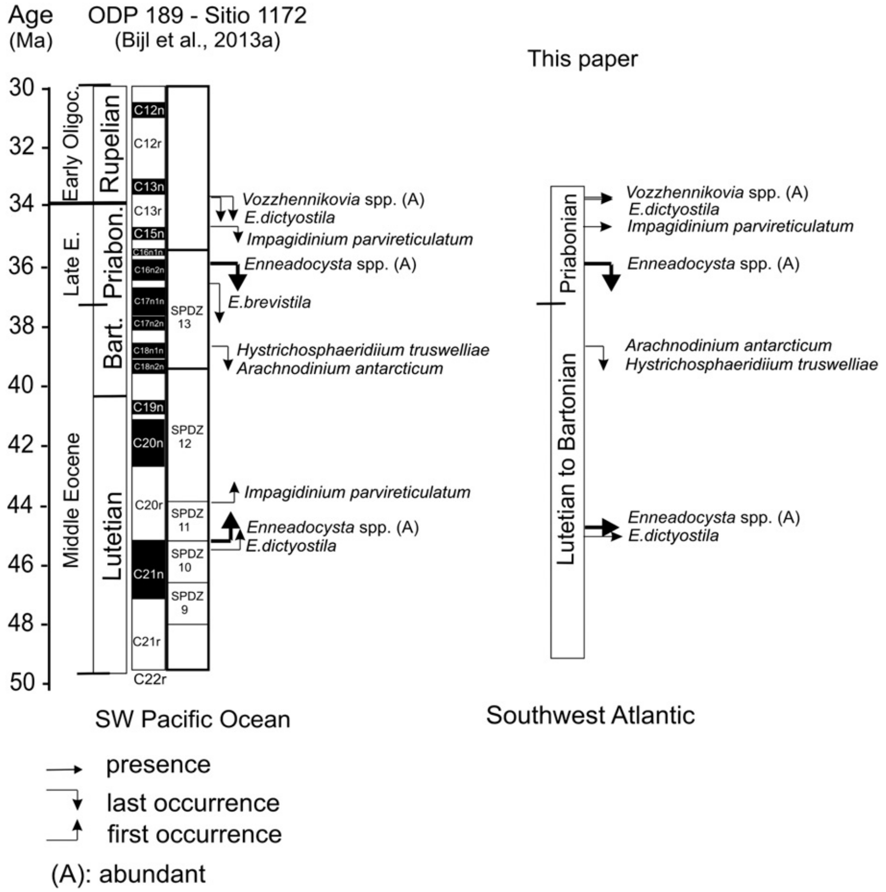

Fig. 5. Dinocyst events recorded in Río Turbio Formation compared with the South Pacific Ocean Zonation (Bijl et al., 2013a).

Assimilation of palynologic and sedimentologic data supports that the upper member of the Río Turbio Formation represents sediment accumulation in inner shelf and intertidal coastal-plain environments.

Sedimentological and paleontological data from Zones II and IV reflect stressed environmental conditions. *V. apertura* is highly dominant in both zones, indicating that it is a dinocyst probably developed by an extinct stress-tolerant dinoflagellate.

The middle Eocene endemic-Antarctic dinocyst assemblage is well documented in the southwestern Atlantic Ocean basins and in western and eastern Antarctic areas. The presence of the endemic dinocyst assemblages throughout the Río Turbio Formation in its type area suggests that this unit was deposited during the early opening of the Drake Passage before the emplacement of the Antarctic Circumpolar Current.

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