doi:10.1017/S0016756816000601

Dinoflagellate cyst zonation for the middle to upper Eocene in the Austral Basin, southwestern Atlantic Ocean: implications for regional and global correlation

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(*Received* 16 November 2015; *accepted* 26 May 2016)

Abstract – The well-exposed marine Eocene units from southwestern Patagonia, Argentina, contain useful information for reconstructing regional climate and oceanographic patterns in an area adjacent to the Drake Passage. The aim of this paper is to integrate dinoflagellate cyst data from three sections of the southwestern Austral Basin (Río Turbio Formation) to propose a zonation scheme, which can be applied to other southwestern Atlantic Ocean sites. Assemblages of organic walled dinoflagellate cysts have been analysed in different cropping-out sections and cores, showing the high potential of this fossil group as biostratigraphic markers. Comparison of dinoflagellate cyst events of the upper member of the Río Turbio Formation with calibrated biostratigraphic ranges in the Palaeogene South Pacific Ocean allowed us to date and correlate these sedimentary sections. The resulting zonation consists of four dinoflagellate cyst zones labelled RTF 1 to RTF 4, between the middle Lutetian and late Priabonian. As a final point, we applied dinoflagellate cyst species with importance as palaeoenvironmental markers to assess long-term climatic and oceanographic evolution for the area. This study shows that the endemic–Antarctic dinoflagellate cyst assemblage is dominant during the middle to late Eocene (RTF 1 to RTF 3), while a significant replacement of these taxa by cosmopolitan species characterizes the upper part of the upper member of the Río Turbio Formation (RTF 4). This turnover seems to be a consequence of changes in the ocean circulation patterns forced by deepening of the southern Atlantic gateways (the Drake Passage and the Tasman Gateway).

Keywords: dinoflagellate cyst, Eocene, biostratigraphy, palaeoenvironment, Austral Basin, Argentina.

1. Introduction

During the Palaeogene (*c.* 65–23 Ma), an important climatic transition took place from relatively warm early Cenozoic ‘greenhouse’ conditions to late Cenozoic ‘icehouse’ conditions with episodes of transient global warming (Bohaty & Zachos, 2003; Zachos, Dickens & Zeebe, 2008; Bijl *et al.* 2009, 2010; Bohaty *et al.* 2009). In the Southern Hemisphere, important palaeogeographic changes occurred, such as the deepening of the Drake Passage (Scher & Martin, 2006; Livermore *et al.* 2007; Lagabrielle *et al.* 2009; Eagles & Jokat, 2014) and the Tasmanian Gateway (Stickley *et al.* 2004*b*; Bijl *et al.* 2013*a*; Houben *et al.* 2013). These tectonic changes led to important modifications in the ocean circulation, to the onset of the the Antarctic Circumpolar Current (Stickley *et al.* 2004*b*; Houben *et al.* 2013), and the formation of relatively cold intermediate water (Bijl *et al.* 2013*a*).

In seeking evidence for changing surface oceanographic regimes in the Southern Ocean during this time of drastic climatic changes, much knowledge can be obtained from studies of marine surface microplankton assemblages, notably dinoflagellate cysts. Organic-walled dinoflagellate cysts are a valuable tool for studying past physical and chemical conditions of surface waters, and they complement the information provided by other groups of microfossils. Dinoflagellate cysts have proven especially useful in reconstructing Palaeogene marine palaeoenvironments (Sluijs, Pross & Brinkhuis, 2005 and references therein) and solving stratigraphic problems (Bijl, Sluijs & Brinkhuis, 2013*b*). Dinoflagellate cyst assemblages reflect changes in the surface-water temperature and in the ocean-circulation patterns during the Palaeogene. From the late–early Eocene (∼50 Ma) to the late Eocene, the dinoflagellate cyst assemblages were

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dominated by an endemic–Antarctic assemblage, which has been widely recognized at sites over 45° S latitude (e.g. Lentin & Williams, 1976; Wrenn & Hart, 1988; Brinkhuis *et al.* 2003*a*, *b*; Sluijs *et al.* 2003; Bijl *et al.* 2010, 2011, 2013*a*; Bijl, Sluijs & Brinkhuis, 2013*b*; Houben *et al.* 2013). Recently, Bijl, Sluijs & Brinkhuis (2013*b*) calibrated dinoflagellate cyst assemblages from sediment cores drilled in the Tasman Shelf using Vandenberghe, Speuer & Hilgen's (2012) geomagnetic polarity timescale (GPTS), and proposed a cyst zonation for the early Palaeogene South Pacific Ocean which provides a correlation tool that can be applied to sites around the Southern Ocean (Bijl, Sluijs & Brinkhuis, 2013*b*).

Regarding the areas close to the actual Drake Passage, Palaeogene sea-level changes caused major transgressions along the South American margin. In particular, the Austral Basin was almost completely flooded during the middle Eocene. This transgression deposited the upper member of the Río Turbio Formation and the Man Aike Formation in the southwestern part of Santa Cruz Province, Argentina (Malumián, 1999). Due to their proximity to the Drake Passage (Fig. 1), marine deposits in the basin are a valuable source of information for the assessment of palaeoenvironmental and palaeoclimatic changes during the Eocene in Patagonia.

This paper describes the middle to upper Eocene dinoflagellate cyst assemblages from the upper member of the Río Turbio Formation from three localities in southwestern Santa Cruz Province. Its aims are to: (1) provide a detailed biostratigraphic framework for the upper member of the Río Turbio Formation from three localities, based on the dinoflagellate cyst events and ranges determined by Brinkhuis *et al.* (2003*b*), Sluijs *et al.* (2003) and Bijl, Sluijs & Brinkhuis (2013*b*); (2) compare and correlate the three sections in order to integrate the stratigraphic records of the dinoflagellate cysts found in the Río Turbio Formation type area and define a dinoflagellate cyst zonation for the middle–late Eocene in the Austral Basin; and (3) interpret the palaeoenvironmental evolution of the southwestern Austral Basin during the middle to late Eocene.

2. Biostratigraphic significance of Palaeogene dinoflagellate cysts in the Southern Hemisphere

Dinoflagellate cyst assemblages in the Southern Ocean evidenced major modifications as a consequence of climatic and tectonic changes during the Palaeogene (Sluijs *et al.* 2003; Guerstein *et al.* 2010*a*; Bijl *et al.* 2013*a*; Bijl, Sluijs & Brinkhuis, 2013*b*). Bijl *et al.* (2011, 2013*a*) and Bijl, Sluijs & Brinkhuis (2013*b*) postulated that the Palaeocene and early Eocene circum-Antarctic assemblages were widely dominated by cosmopolitan early Palaeogene taxa, together with a few endemic species. By the late–early Eocene (∼50 Ma), dinoflagellate cyst assemblages began to change significantly, resulting in the dominance of an endemic–Antarctic assemblage to southern high latitudes (Wrenn & Beckman, 1982, as 'Transantarctic Flora'; Bijl *et al.* 2011; Bijl, Sluijs & Brinkhuis, 2013*b*). Huber *et al.* (2004), Warnaar (2006) and Bijl *et al.* (2011, p. 5, fig. 3) proposed that the spatial distribution of the endemic–Antarctic dinoflagellate cyst assemblage corresponded to an ocean-circulation regime with broad clockwise gyres that surrounded Antarctica. The endemic–Antarctic assemblage prevailed until the late Eocene, when the endemic species were replaced by Oligocene cosmopolitan taxa, mainly comprising heterotrophic species (Protoperidiniaceae) (Sluijs *et al.* 2003; Houben *et al.* 2013). The demise of the endemic assemblage may have resulted from the deepening of the Drake Passage and the Tasmanian Gateway (Sluijs *et al.* 2003; Stickley *et al.* 2004*b*; Guerstein *et al.* 2008; Houben *et al.* 2011, 2013). Such tectonically induced changes and the subsequent development of an unrestricted circumpolar water flow during the early Oligocene could have disrupted the subpolar gyres and altered the environmental conditions that favoured dinoflagellate endemism allowing the arrival and proliferation of cosmopolitan taxa (Huber *et al.* 2004; Guerstein *et al.* 2010*a*).

Brinkhuis *et al.* (2003*b*), Sluijs *et al.* (2003) and Bijl, Sluijs & Brinkhuis (2013*b*) studied the dinoflagellate cyst assemblages from sediment cores drilled during Ocean Drilling Program (ODP) Leg 189 in the East Tasman Plateau (Site 1172). The dinoflagellate cyst events they recorded have been calibrated with magnetostratigraphic, biostratigraphic and isotope stratigraphic age models (Stickley *et al.* 2004*a*). The biostratigraphical ranges of dinoflagellate cyst species are based on the following data: the First Occurrence datum (FO), the First Common Occurrence datum (FCO, >25 % of total of dinoflagellate cysts), the Last Occurrence datum (LO) and the Last Common Occurrence datum (LCO, >25 % of total of dinoflagellate cysts) (Brinkhuis *et al.* 2003*b*; Sluijs *et al.* 2003; Bijl, Sluijs & Brinkhuis, 2013*b*). Based on records from ODP Leg 189, Sluijs *et al.* (2003) suggested three Dinocyst Associations from the middle Eocene (late Bartonian) to the early Oligocene. The authors stated that the replacement of the endemic species by a cosmopolitan association started about 35.5 Ma. Subsequently, Bijl, Sluijs & Brinkhuis (2013*b*) proposed 13 high-resolution dinoflagellate cyst zones for the South Pacific (South Pacific Dinocyst Zones, SPDZ), from the late Palaeocene to the late Eocene (58–36 Ma) and confirmed that the endemic–Antarctic dinoflagellate cyst assemblage was dominant from the middle to late Eocene (*c.* 45–35 Ma). Thus, the middle Palaeogene dinoflagellate cyst stratigraphic distribution provides a correlation tool that can be applied to other sites in and around the Southern Ocean.

3. Geological setting

3.a. Austral Basin

The Austral Basin is located in the southwestern part of the South American Plate between 45° S and 54° S

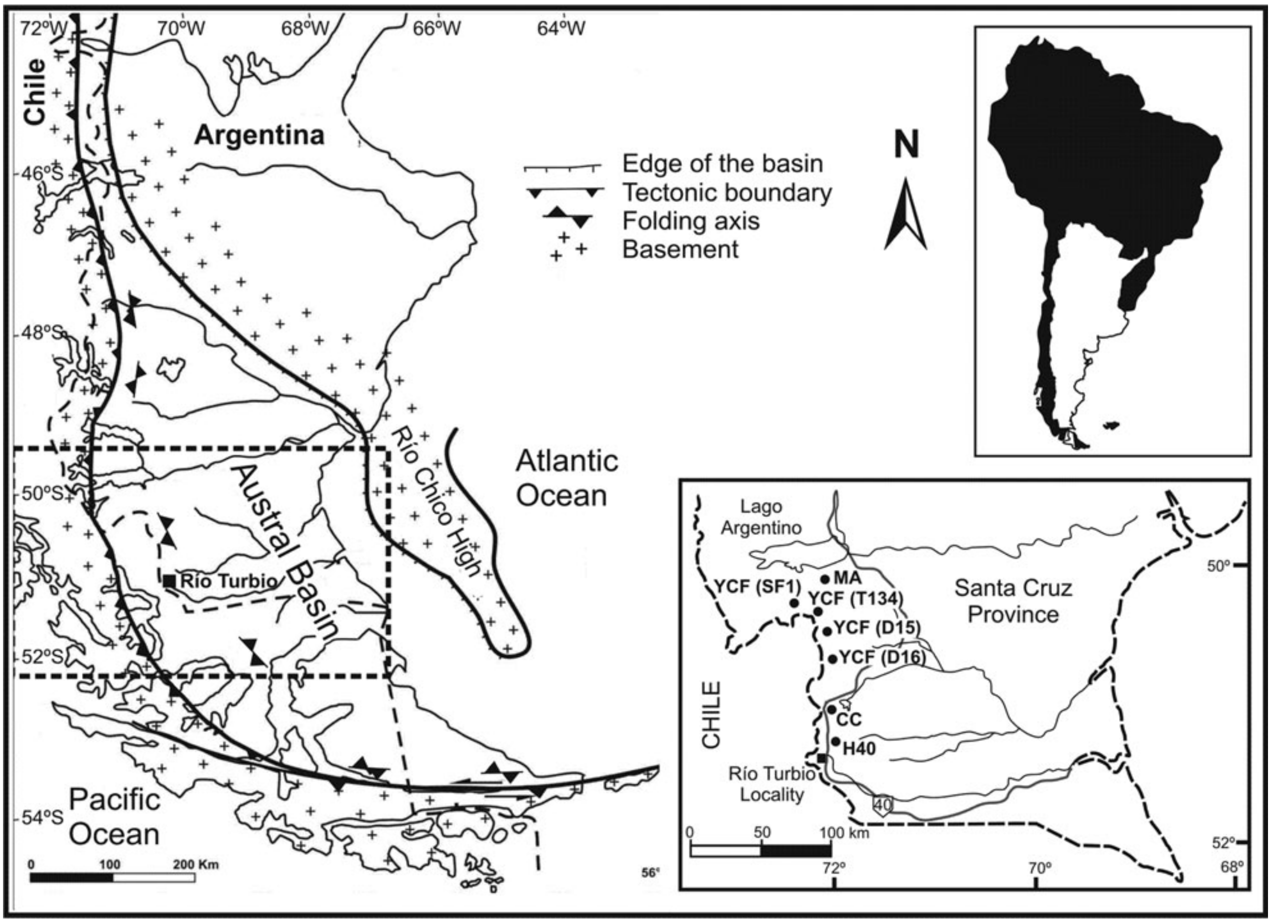

Figure 1. Map of southern Patagonia showing the extent of the Austral Basin. The inset map shows southern Santa Cruz Province and the location of the upper member of the Río Turbio Formation at: YCF Cores (cores, 50° 45′ 14″ S,72° 01′ 39″ W; 50° 56′ 21″ S,72° 02′ 08″ W; 50° 35′ 59″ S,72° 13′ 40″ W); the Cancha Carrera locality (CC) (outcrop sections, 51° 14′ 34″ S, 72° 15′ 26″ W); the Highway 40 locality (H40) (outcrop sections, 51° 31′ 13″ S, 72° 15′ 11″ W); and the outcrop section of the Man Aike Formation (50° 21′ 45″ S, 72° 14′ 30″ W). Modified from Nullo, Panza & Blasco (1999).

and underlies southern Patagonia, the island of Tierra del Fuego and the adjacent Argentine Continental Shelf (Malumián, 1999; Nullo, Panza & Blasco, 1999). This basin is elongated following a NNW–SSE axis and comprises about 160 000 km^2. It is bounded by the Andes mountains to the west, the Scotia Plate to the south, and the Deseado Massif and the Río Chico High to the northeast (Fig. 1).

During the Cenozoic, Patagonia was affected by several transgressions from the Atlantic Ocean (Malumián & Nañez, 2011), one of which resulted in the deposition of the upper member of the Río Turbio Formation during the middle to late Eocene in the westernmost part of the Austral Basin (Fig. 1).

3.b. Río Turbio Formation

The Río Turbio Formation (Leanza, 1972) is represented by a thick shallow-marine and estuarine succession, which reaches a thickness of 600 m in the type section (Furque & Caballé, 1993). The formation is divided into informal lower and upper members (Fig. 2). The lower member, assigned to an early to middle Eocene age (Malumián, 2002; Guerstein *et al.* 2010*b*), overlies a disconformity that erosionally truncates the shallow marine rocks of the Palaeocene Cerro Dorotea Formation. The upper member of the Rio Turbio Formation has been assigned a late–middle Eocene to early–late Eocene age (Malumián *et al.* 2000) and is unconformably overlain by the continental rocks of the late Eocene Río Guillermo Formation (Fig. 2) (Malumián & Caramés, 1997; Malumián *et al.* 2000; Ramos, 2005).

The upper member of the Rio Turbio Formation is characterized by fine to coarse sandstones and conglomerates with interbedded clay horizons and abundant plant macrofossils that accumulated in coastal marine, wave- and tide-dominated shallow-water environments (Furque & Caballé, 1993; Rodríguez Raising, 2010; Pujana, Martínez & Brea, 2011) or in tide-dominated, outer-estuarine, coastal-plain environments (Pearson *et al.* 2012). According to Malumián (2002), the upper member of the Rio Turbio Formation contains sedimentation in subtidal environments corresponding to the middle–late Eocene Atlantic transgression, which is characterized by the presence of a glauconitic horizon widespread in the Austral Basin (Calegari, Baldi & Pioli, 1993). This

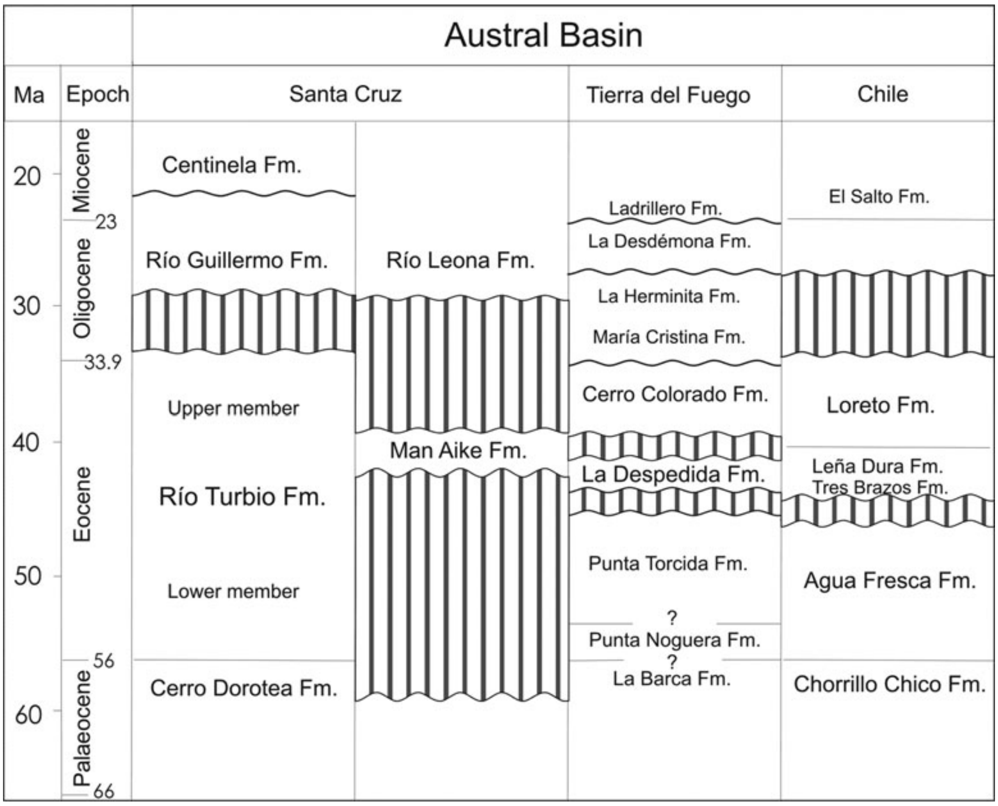

Figure 2. Chart showing correlation of late Palaeocene–Miocene marine formations in the Austral Basin. Correlations are based on foraminifera (Malumián, 1999; Malumián & Nañez, 2011) and dinoflagellate cysts (Guerstein *et al.* 2008, 2014*a*).

horizon can be correlated with the following units: the Man Aike Formation in Santa Cruz Province (Casadío *et al.* 2009; Guerstein *et al.* 2014*a*); the La Despedida Formation (Guerstein *et al.* 2008); the lower section of the Cerro Colorado Formation and the 'Glauconitico B' in Tierra del Fuego Province (Olivero & Malumián, 1999); and the Leña Dura Formation and Loreto Formation in Chile (Fasola, 1969; Archangelsky & Fasola, 1971) (Fig. 2). The first studies on dinoflagellate cysts of the Río Turbio Formation were carried out by Archangelsky (1968, 1969) and Archangesky & Fasola (1971) in samples recovered from Yacimientos Carboníferos Fiscales (YCF) Cores. Recently, Guerstein *et al.* (2014*a*), González Estebenet, Guerstein & Rodríguez Raising (2014) and González Estebenet, Guerstein & Casadío (2015) studied the dinoflagellate cyst assemblages from sections cropping out near the type area of the Río Turbio Formation.

The Río Turbio Formation is economically important because it contains the largest coal reserves in Argentina (Malumián, 2002). Furthermore, the proximity of the Austral Basin to the Drake Passage makes this marine deposit a valuable source of information in evaluating Eocene palaeoclimatic and palaeoenvironmental changes in southern South America. Despite the economic and geographical importance of the Austral Basin, correlations and palaeogeographic reconstructions of the Palaeogene are limited by the availability of biostratigraphic and isotopic data.

4. Materials and methods

4.a. Analysed sections

The studied samples were obtained from three localities: Ea. Cancha Carrera, Yacimientos Carboníferos Fiscales (YCF) Cores and Highway 40, close to Río Turbio town in the southwest of Santa Cruz Province (Fig. 1; Table 1). Twenty-three samples come from the Highway 40 locality, which involved two integrated outcropping sections; 20 samples were taken from the Ea. Cancha Carrera locality, which comprises four outcropping sections integrated into a composite profile; and 21 samples were collected from three YCF cores. Some of the samples from YCF cores were studied originally by Archangelsky (1968, 1969) and re-studied for this work. Following Guerstein *et al.* (2014*a*) we also include in the integrated section two samples from the uppermost part of the Man Aike Formation, an equivalent unit of the upper member of the Río Turbio Formation that crops out near the area where the cores were drilled (Fig. 1).

4.b. Palynological procedure and microscopical analysis

Samples from the Highway 40 and the Ea. Cancha Carrera localities were processed for palynological analysis using hydrochloric and hydrofluoric acids. The residues were sieved through 10 and 25 μm screens and stained with Bismarck C. Strew mounts were prepared using gelatin–glycerin as mounting medium. The

Table 1. List of samples showing sources and results. We indicate sterile (E) and fertile samples, containing dinoflagellate cysts (D), non-marine palynomorphs (P) and pollen and zygospores (PZ).

Locality	Metres	Sample No.	Result
Highway 40	2	RT 12/ 1-1	D
Highway 40	4	RT 12/1-2	D
Highway 40	6	RT 12/ 1-4	D
Highway 40	8	RT 12/ 1-5	D
Highway 40	10	RT 12/ 1-6	D
Highway 40	11	RT 12/ 1-9	D
Highway 40	32	RT 12/ 1-11	D
Highway 40	35	RT 13/ 1-1	D
Highway 40	37	RT 13/ 1-2	D
Highway 40	39	RT 13/ 1-3	D
Highway 40	47	RT 13/1-4	E
Highway 40	74	RT 14/ 1-1	D
Highway 40	75	RT 15/ 1-1	E
Highway 40	80	RT 14/ 1-4	D
Highway 40	81	RT 15/ 1-3	D
Highway 40	99	RT 15/ 1-4	D
Highway 40	102	RT 14/ 1-6	D
Highway 40	126	RT 15/1-5	D
Highway 40	135	RT 15/ 1-6	D
Highway 40	164	RT 15/1-7	D
Highway 40	183	RT 15/1-8	D
Highway 40	210	M. Cb A	P
Highway 40	214	RT 15/1-10	PZ
Ea. Cancha Carrera	286	CC 1	D
Ea. Cancha Carrera	290	CC 2	D
Ea. Cancha Carrera	352	CC 3	D
Ea. Cancha Carrera	354	CC 4	D
Ea. Cancha Carrera	360	CC 5	D
Ea. Cancha Carrera	452	CC 6	D
Ea. Cancha Carrera	493	CC 7	D
Ea. Cancha Carrera	511	CC8	P
Ea. Cancha Carrera	519	CC 9	D
Ea. Cancha Carrera	558	CC 10	D
Ea. Cancha Carrera	617	CC 11	D
Ea. Cancha Carrera	633	CC 12	PZ
Ea. Cancha Carrera	660	CC 13	D
Ea. Cancha Carrera	667	CC 14	D
Ea. Cancha Carrera	672	CC 15	E
Ea. Cancha Carrera	680	CC 16	E
Ea. Cancha Carrera	723	CC 17	E
Ea. Cancha Carrera	718	CC 18	E
Ea. Cancha Carrera	771	CC 19	E
Ea. Cancha Carrera	774	CC 20	E
YCF core	12	12	D
YCF core	20	20	D
YCF core	30	30	D
YCF core	33	33	D
YCF core	48	48	D
YCF core	51	51	D
YCF core	87	87	D
YCF core	130	130	D
YCF core	270	270	D
YCF core	280	280	D
YCF core	305	305	D
YCF core	308	308	D
YCF core	306	306	D
YCF core	312	312	D
YCF core	318	318	D
YCF core	325	325	D
YCF core	329	329	D
YCF core	334	334	D
YCF core	337	337	D
YCF core	346	346	D
YCF core	410	410	D

palynological samples were processed at the Museo Argentino de Ciencias Naturales, Bernardino Rivadavia, Buenos Aires (MACN), and the slides are stored at the Laboratorio de Palinología, Instituto Geológico del Sur, Bahía Blanca (LPUNS). Samples from the YCF

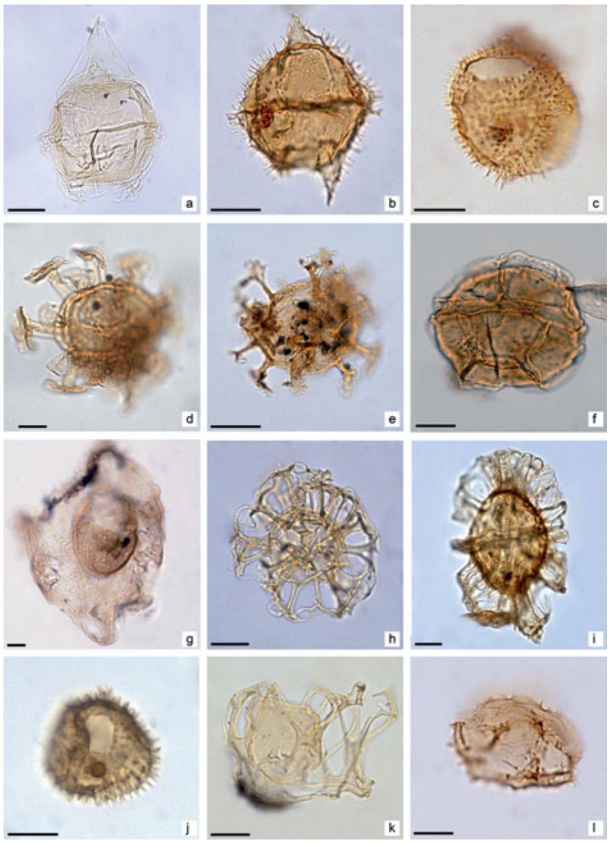

Figure 3. (Colour online) Dinoflagellate cysts from the upper member of the Río Turbio Formation. Specimens are identified by sample number/England Finder references. Scale bar is 20 µm. (a) *Deflandrea antarctica*; YCF 312/N21-3. (b) *Spinidinium macmurdoense*; YCF 48/P37-4. (c) *Vozzhennikovia apertura*; RT 14/1-1/P44-2. (d) *Hystrichosphaeridium truswelliae*; RT 13/1-1/G40-3. (e) *Enneadocysta dictyostila*; YCF 113/X39-2. (f) *Impagidinium parvireticulatum*; RT 15/1-6/R48-1. (g) *Thalassiphora pelagica*; CC 1/Y43. (h) *Nematosphaeropsis* sp. A; CC 14/M32-1. (i) *Turbiosphaera filosa*; YCF 12/Y21-1. (j) *Operculodinium* sp. CC 10/W24-0. (k) *Arachnodinium antarcticum* RT 12/1-4/R46-2. (l) *Selenopemphix* sp. CC 14/J39-1.

Cores locality were processed with hydrochloric acid and Schutze reagent for less than two hours (Archangelsky, 1968, 1969). Recently, some of the residues were sieved, and strew mounts were prepared using gelatin–glycerin as mounting medium. The slides are stored at LPUNS.

Light microscopy was undertaken using a Nikon Eclipse 600 microscope and an attached Micrometrics high-resolution digital camera. The sample number and slide number followed by the England Finder (EF) references are provided for each illustrated specimen in the caption to Figure 3. Dinoflagellate cyst nomenclature, unless otherwise indicated, is based on Fensome, MacRae & Williams (2008) and Sluijs *et al.* (2009). For each sample, a minimum of 200 dinoflagellate cysts were counted and identified at species level.

The quantitative results of each studied section are presented in a dissociated frequencies diagram indicating the percentages of the total number of dinoflagellate cysts counted (Fig. 4). The percentage of peridinoid

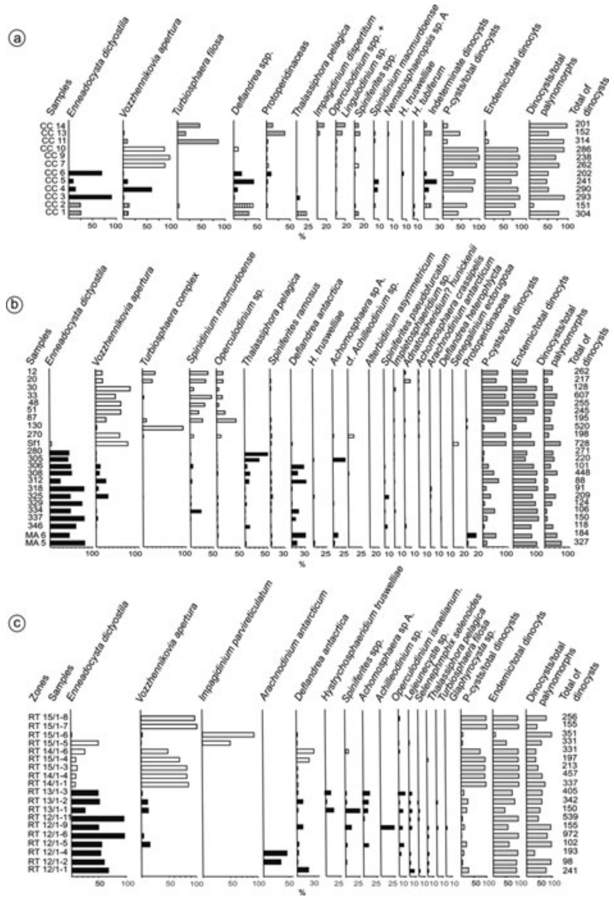

Figure 4. Quantitative distribution of dinoflagellate cysts within samples from the Río Turbio Formation at the sections outcropping at (a) Cancha Carrera; (b) YCF Cores and the Man Aike Formation (samples MA 5 and MA 6); and (c) Highway 40. P-cysts/total: percentages of peridinioid cysts (P-cysts) over total of dinoflagellate cysts; Endemic/total dinocyts: percentages of endemic dinoflagellate cysts over total of dinoflagellate cysts. The bars at the right show the percentages of dinoflagellate cysts over total of palynomorphs. Modified from González Estebenet, Guerstein & Alperin (2014), Guerstein *et al.* (2014*a*) and González Estebenet *et al.* (2015).

cysts (P-cysts) in the dinoflagellate cyst assemblage was used to estimate productivity (Brinkhuis *et al.* 1998; Crouch *et al.* 2003). Dinoflagellate cyst species were classified as endemic and cosmopolitan, based on Bijl *et al.* (2011), Bijl, Sluijs & Brinkhuis (2013*b*) and Houben *et al.* (2013). The percentage of endemic dinoflagellate cysts over the total number of dinoflagellate cysts was calculated in order to characterize the sea-surface temperature. The number of dinoflagellate cysts / total palynomorphs, expressed as percentage was calculated in order to estimate the proximity to the shoreline. We follow the geological timescale for the Palaeogene by Vandenberghe, Speuer & Hilgen (2012).

5. Sections

This work integrates 52 samples analysed from the upper member of the Río Turbio Formation and two samples from the upper part from the Man Aike Formation outcropping near the YCF Cores. All the samples bear assemblages rich in dinoflagellate cysts; four of them contain only non-marine palynomorphs (mainly pollen, spores and zygospores of fresh-water green algae), and eight were barren of palynomorphs (Table 1). Table 2 lists a total of 36 species recovered including their biogeographical distribution (endemic or cosmopolitan), most of which are illustrated in Figure 3. Figure 4a–c plots the quantitative composition of the dinoflagellate cyst assemblages through each studied section. The dinoflagellate cyst events recorded in our sections and their comparison with their biostratigraphical ranges based on calibrated data from the ODP Leg 189 cores are shown in Figure 5.

5.a. Cancha Carrera

The stratigraphic framework for the composed Cancha Carrera section is based on Rodríguez Raising (2010), and the dinoflagelate cysts assemblages were studied by González Estebenet, Guerstein & Casadío (2015).

From the base to 286 m high correspond to the lower member of the Río Turbio Formation (Rodriguez Raising *et al.* 2008). The interval from 286 m to the top of the section (774 m) represents the upper member of the formation.The dinoflagellate cyst assemblages from 286 to 290 m high, measured from the base of the section, (samples CC 1 to CC 2) show different dinoflagellate cysts typical of the endemic–Antarctic association (*Deflandrea antarctica*, *Enneadocysta dictyostila* and *Vozzhennikovia apertura*) (Fig. 4a). The base of this interval is defined by the FO of *Enneadocysta dictyostila*, which has not been recorded in the lower member of the Río Turbio Formation (Guerstein *et al.* 2010*b*), and the presence of *Hystrichosphaeridium tubiferum*, with its LO recorded in the sample CC 2. In research conducted in the South Pacific Ocean, Brinkhuis *et al.* (2003*b*) and Bijl, Sluijs & Brinkhuis (2013*b*) established the FO of *Enneadocysta dictyostila* at the Magnetochron C20r (*c.* 45.5 Ma). Williams *et al.* (2004) recorded the LO of *Hystrichosphaeridium tubiferum* at the top of Magnetochron C21n, at about 45.6 Ma according to Vandenberghe, Speuer & Hilgen (2012). The coexistence of both species constrains the age of this part of the section to the middle Lutetian. Sample CC3 (at 352 m from the base of the section) shows the FCO of *Enneadocysta dictyostila* dated at 45.2 Ma (middle Lutetian) by Bijl, Sluijs & Brinkhuis (2013*b*). In sample CC 6, at 452 m from the base of the section, the presence of *Hystrichosphaeridium truswelliae* allows us to propose a minimum age of this stratigraphic part of the Cancha Carrera section of the middle Bartonian (or early Priabonian). Brinkhuis *et al.* (2003*b*) recorded the LO of this species at the Magnetochron C18n1n, at *c.* 38.6 Ma.

In the middle part of the section (493–558 m from the base; samples CC 7 to CC 10) the abundance of *Enneadocysta dictyostila* is replaced by *Vozzhennikovia apertura* with maximum abundances throughout this

Table 2. List of species of dinoflagellate cysts cited in the text.

Species	Or	LD	CC	YCF	HN
Achomosphaera crassipellis (Deflandre & Cookson 1955) Stover & Evitt 1978	G	C		*	
Achomosphaera sp. A	G	?	*	*	*
*Adnatosphaeridium? hunickenii*Archangelsky 1969	G	?		*	
Alterbidinium asymmetricum (Wilson 1967) Sluijs *et al.* 2009	P	E?		*	
Arachnodinium antarcticum Wilson & Clowes 1982	G	E	*	*	*
Cordosphaeridium sp.	G	?		*	
Deflandrea antarctica Wilson 1967a	P	E	*	*	*
Deflandrea granulata Menéndez 1965	P	E	*		*
Deflandrea heterophlycta Deflandre & Cookson 1955	P	C	*	*	*
Enneadocysta brevistila Fensome *et al.* 2006	G	E	*	*	*
Enneadocysta dictyostila (Menéndez 1965) Fensome *et al.* 2006	G	E	*	*	*
Glaphyrocysta retiintexta (Cookson, 1965) Stover & Evitt 1978	G	C		*	*
*Hystrichosphaeridium truswelliae*Wrenn & Hart 1988	G	C	*	*	*
Hystrichosphaeridium sp. cf. *H. truswelliae*Wrenn & Hart 1988	G	C?	*	*	*
Hystrichosphaeridium tubiferum (Ehrenberg 1838) Emend. Davey & Williams 1966	G	C	*		
Impagidinium dispertitum (Cookson & Eisenack, 1965) Stover & Evitt 1978	G	C	*	?	?
Impagidinium parvireticulatum Wilson 1988	G	C		*	*
Impagidinium sp.	G	C	*	*	
*Impletosphaeridium clavus*Wrenn & Hart 1988	G	E	*	*	*
Lejeunecysta spp.	P	C	*	*	*
Lingulodinium machaerophorum (Deflandre & Cookson 1955) Wall 1967	G	C	*	?	
Nematosphaeropsis cf. *rigida*Wrenn 1988	G	C	*		
Nematosphaeropsis sp. A	G	C?	*	*	?
Operculodinium centrocarpum/ israelianum	G	C	*	*	*
Phthanoperidinium echinatum Eaton 1976	P	C	*	*	
?*Rhombodinium* sp.	P	C	*		
Selenopemphix crenata Matsuoka & Bujak 1988	P	C	*		*
Selenopemphix nephroides Benedek 1972	P	C	*	*	*
Selenopemphix spp.	P	C	*	*	*
Spinidinium macmurdoense (Wilson 1967) Lentin & Williams 1976	P	E	*	*	*
Spiniferites pseudofurcatus (Klumpp 1953) Sarjeant 1981	G	C	*	*	
Spiniferites ramosus/ membranaceus	G	C	*	*	*
*Spiniferites scalenus*Guerstein *et al.* 2008	G	E?	*	*	*
Thalassiphora pelagica (Eisenack 1954) Eisenack & Gocht 1960	G	C			*
Turbiosphaera filosa (Wilson 1967) Archangelsky 1969	G	C	*	*	*
Vozzhennikovia apertura (Wilson 1967) Lentin & Williams 1976	P	E	*	*	*

The latitudinal distribution is based on Bijl *et al.* (2011), Bijl, Sluis & Brinkhuis, (2013*b*) and Houben *et al.* (2013). The localities where the species are present are indicated with asterisk (*).Or: orden; G: Gonyaulacales; P: Peridiniales; LD: latitudinal distribution; C: cosmopolitan distribution; E: endemic–Antarctic distribution; CC: Ea. Cancha Carrera locality; YCF: Yacimientos Carboníferos Fiscales Cores locality; HN: Highway 40 locality.

stratigraphic interval. Acmes of this species in the South Pacific Ocean were recognized as part of a complex of species, *Vozzhennikovia* spp., between 50 Ma and 33.5 Ma (Bijl, Sluijs & Brinkhuis, 2013*b*).

Towards the top of the section (617–670 m above the base; samples CC 11 to CC 14) the endemic–Antarctic assemblages are replaced by species with cosmopolitan distribution such as *Turbiosphaera filosa*, Protoperidiniaceae (species of *Selenopemphix* and *Lejeunecysta*) together with *Impagidinium dispertitum*, *Operculodinium* spp., *Spiniferites* spp. (mostly *S. pseudofurcatum*) and *Nematosphaeropsis* sp. A. Sluijs *et al*. (2003), Stickley *et al*. (2004*b*) and Houben *et al.* (2013) related the replacement of cosmopolitan species by endemic taxa with the beginning of the deepening of the Tasmanian Gateway, dated through magnetostratigraphy at *c*. 35.5 Ma (Priabonian). The maximum age proposed agrees with the FCO of *Turbiosphaera filosa* at the base of the uppermost stratigraphic interval, recorded by Sluijs *et al.* (2003) at 35.5 Ma. *Turbiosphaera filosa* is abundant throughout the interval, with its LO in sample CC 14 (667 m). This event was recorded at Magnetochron C13r, at *c.* 34 Ma in the South Pacific Ocean (Brinkhuis *et al*. 2003*b*).

5.b. YCF Cores

Guerstein *et al.* (2014*a*) compared the samples of YCF Cores and some samples from the Highwat 40 section with those assigned to the Man Aike Formation outcropping in the same area. These authors determined the equivalence of the dinoflagellate cyst assemblages from the uppermost part of the Man Aike Formation with those from the lower part of the YCF Cores and the lower part of Highway 40. Figure 4b shows the dinoflagellate cyst quantitative distribution data from the YCF Cores and the Man Aike Formation in an integrated section.

The assemblages from the lower and middle parts of the integrated section (including 11 samples between 346 and 280 m depth and the two samples from the Man Aike Formation) are dominated by *Enneadocysta dictyostila*, indicating an age for this stratigraphic interval younger than 45.2 Ma, based on Bijl, Sluijs & Brinkhuis (2013*b*). The dinoflagellate cyst events recognized in this part of the integrated section are the LOs of *Arachnodinium antarcticum* and *Hystrychosphaeridium truswelliae*. Both events restrict the maximum age of this stratigraphic interval to the

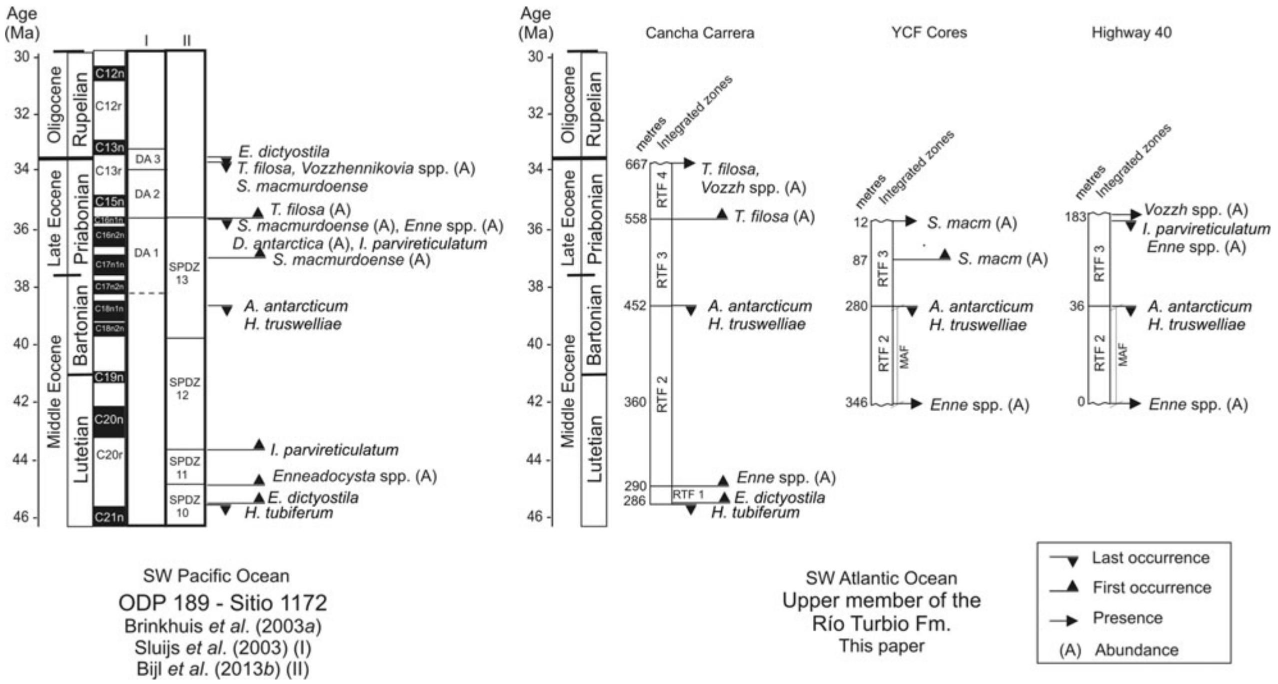

Figure 5. Dinoflagellate cyst events and zones recorded in the upper member of the Río Turbio Formation compared and correlated with those recorded in ODP cores from South Pacific Ocean. DA: Dinocyst Association (Sluijs *et al.* 2003); SPDZ: South Pacific Dinocyst Zones (Bijl, Sluijs & Brinkhuis,. 2013*b*); MAF: Man Aike Formation (Guerstein *et al.* 2014*a*); RTF: dinoflagellate cyst zones of the upper member of the Río Turbio Formation; *Enne*: *Enneadocysta*; *Vozzh*: *Vozzhennikovia*; *S. macm*: *Spinidinium macmurdoense*.

middle Bartonian (Fig. 5). Moreover, dinoflagellate cysts together with calcareous microfossil biostratigraphy, mollusc affinities and the $^{87}Sr/^{86}Sr$ data constrain the age of the Man Aike Formation and the lower part of the YCF Cores section to *c.* 42 to 39 Ma (Guerstein *et al.* 2014*a*).

A significant dinoflagellate cyst replacement is observed in the assemblages between 270 and 12 m depth, including nine samples. The dinoflagellate cyst assemblages are dominated by *Vozzhennikovia apertura* and *Spinidinium macmurdoense*, both members of the endemic–Antarctic assemblage, together with species included in the *Operculodinium* spp. and *Turbiosphaera* complex (Fig. 4). The FCO of *Spinidinium macmurdoense* is recorded in the South Pacific Ocean at *c.* 37 Ma, suggesting that this part of the integrated core section cannot be older than Priabonian. The LCO of *Spinidinium macmurdoense* determined at 33.5 Ma by Brinkhuis *et al.* (2003*b*) allows us to propose an age no younger than late Priabonian for the entire analysed section. It is noticeable that the uppermost stratigraphic interval has no record of *Enneadocysta dictyostila*, *Deflandrea antarctica* or *Thalassiphora pelagica.*

5.c. Highway 40

The stratigraphic framework for the study of this section is based on Rodríguez Raising (2010) and Rodríguez Raising *et al.* (2014). The results of the dinoflagellate cyst analysis from two integrated sections were presented in González Estebenet, Guerstein & Rodríguez Raising (2014) and are summarized in Figure 4c. Almost the complete section from the base to 135 m high, represented by 17 productive palynological samples (from RT 12/1-1 to RT 15/1-6), shows an alternation of assemblages dominated by *Enneadocysta dictyostila* and those with high abundances of *Vozzhennikovia apertura*. *Enneadocysta dictyostila* is abundant from the base of the section, where the FCO is determined at 45.2 Ma by Bijl, Sluijs & Brinkhuis (2013*b*). Moreover, as mentioned for YCF Cores, the base of the Highway 40 section can be defined at 42 Ma due to its correlation with the Man Aike Formation (Guerstein *et al.* 2014*a*). The most significant dinoflagellate cyst events recognized in the samples RT 13/1-1 to RT 13/1-3 (35– 39 m from the base of the section) are the LOs of *Arachnodinium antarcticum* and *Hystrychosphaeridium truswelliae.* According to Brinkhuis *et al.* (2003*b*), both species presented their LOs at 38.6 Ma. These events allow us to establish a late Bartonian age for the middle part of the Highway 40 section. The RT 15/1-5 sample contains the uppermost assemblage with a high proportion of *Enneadocysta dictyostila*. *Impagidinium parvireticulatum* is dominant in the RT 15/1-5 and RT 15/1-6 samples. The FO of *Impagidinium parvireticulatum* is defined at 44 Ma by Bijl, Sluijs & Brinkhuis (2013*b*). These authors defined the LO of *Impagidinium parvireticulatum* and the LCO of *Enneadocysta dictyostila* at 35.5 Ma. Towards the top of the section (RT-15-1-7 and RT 15-1-8) the dinoflagellate cyst assemblages are characterized by *Vozzhennikovia apertura* as the unique species.

6. Zonation

The stratigraphic sections are placed along a N–S transect *c.* 120 km long. Therefore, bearing in mind the size of the basin, we can asume that the dinoflagellate cyst events are nearly synchronic among the three localities. Considering the dinoflagellate cyst quantitative distribution and their biostratigraphic events we are able to correlate the three analysed sections and propose four Dinoflagellate Cyst Zones, labelled RTF 1 to RTF 4, for the middle to upper Eocene in the Austral Basin (Fig. 5). We determine the top of each zone by dinoflagellate cyst events that also state the base of the overlying zone. A type section with a base and top samples is assigned for each dinoflagellate cyst zone. Where possible, we correlate these events and assemblage shifts with those in other sections from the Austral Basin. Finally, we compare our dinoflagellate cyst zones with the middle–late Eocene South Pacific Dinocyst Zones (Bijl, Sluijs & Brinkhuis, 2013*b*) and the middle–late Eocene to late Eocene dinoflagellate cyst associations described by Sluijs *et al*. (2003).

6.a. Zone RTF 1

Definition. The base of this zone is marked by the FO of *Enneadocysta dictyostila* and the LO of *Hystrichosphaeridium tubiferum*; the top of the zone is defined by the FCO of *Enneadocysta dictyostila.*

Type locality. Cancha Carrera section. Base sample: CC 1 (286 m from the base of the section). Top sample: CC 2 (290 m from the base of the section).

Characteristic species. *Deflandrea antarctica*, *Deflandrea granulata*, *Enneadocysta dictyostila*, *Vozzhennikovia apertura*, *Thalassiphora pelagica*, *Hystrichosphaeridium tubiferum*, *Spiniferites ramosus*.

Age. Middle Lutetian (*c.* 46 Ma).

Correlation. Zone RTF 1 was not recognized in the sections along Highway 40 or in the YCF Cores. This zone can be correlated with the base of La Despedida Fm., Tierra del Fuego Province (Guerstein *et al*. 2008), and with the Leña Dura Formation in Chile (Cookson & Cranwell, 1967). Both formations, and likewise Zone RTF 1, show the co-dominance of *Deflandrea antarctica* and *Enneadocysta dictyostila*. Within the Austral Ocean realm, Zone RTF 1 can be correlated with the Zone SPDZ10 (middle Lutetian, 46.2– 45.2 Ma) proposed by Bijl, Sluijs & Brinkhuis (2013*b*). The authors defined the Zone SPDZ10 by dinoflagellate cyst assemblages alternating between *Deflandrea antarctica*, *Enneadocysta multicornuta* and *Enneadocysta dictyostila*, and with the FO of *Enneadocysta dictyostila* as a significative event.

6.b. Zone RTF 2

Definition. The base of this zone is marked by the FCO of *Enneadocysta dictyostila*; the top of the zone is defined by the LOs of *Arachnodinium antarcticum* and *Hystrichosphaeridium truswelliae.*

Type locality. Cancha Carrera section. Base sample: CC 2 (290 m from the base of the integrated section); top sample: CC 6 (452 m from the base of the integrated section).

Characteristic species. *Enneadocysta dictyostila*, *Vozzhennikovia apertura*, *Deflandrea antarctica*, *Arachnodinium antarcticum*, *Hystrichosphaeridium truswelliae*, *Achomosphaera* sp. A.

Age. Middle Lutetian (46 Ma) to late Bartonian (39 Ma).

Correlation. Zone RTF 2 is recognized along the Highway 40 section, from the base up to 42 m from the base of the section, and in the YCF Cores, from 346 to 280 m depth. This zone is characterized by the dominance of *Enneadocysta dictyostila* in most of the dinoflagellate cyst assemblages. Guerstein *et al*. (2014*a*) proposed an age between 42 and 39 Ma for the Man Aike Formation and the equivalent parts of the Río Turbio Formation that represent only the upper part of Zone RTF 2 (Fig. 5). Thus, the lower part of Zone RTF 2 is merely represented in the type section (Cancha Carrera locality), as shown in Figure 5. The age of this stratigraphic interval cannot be precisely determined. The high abundances of *Enneadocysta dictyostila* allow us to correlate this zone with the upper part of La Despedida Formation in Tierra del Fuego Province (Guerstein *et al.* 2008). The base of Zone RTF 2 can be considered equivalent to the base of Zone SPDZ11 (Bijl, Sluijs & Brinkhuis, 2013*b*), both defined by the FCO of *Enneadocysta dictyostila*. Considering the age range and the characteristic species included in the upper part of the RTF 2 it can be correlated with the SPDZ12 of Bijl, Sluijs & Brinkhuis (2013*b*).

Remarks. Bijl *et al.* (2010) studied a sedimentary record spanning the Middle Eocene Climate Optimum (MECO) recovered from ODP Site 1172. Subsequently, Bijl, Sluijs & Brinkhuis (2013*b*) considered that the MECO was found at the top of the SPDZ12. Thus, this global hyperthermal episode lasting *c.* 500 000-years-, and dated at *c.* 40 Ma (Bohaty & Zachos, 2003; Bohaty *et al*. 2009), may be included in the upper part of the RTF 2 recognized in the three sections analysed in this study.

6.c. Zone RTF 3

Definition. The base of this zone is defined by the LOs of *Arachnodinium antarcticum* and *Hystrichosphaeridium truswelliae.* The top corresponds to the FCO of *Turbiosphaera filosa* and the LCO of the species of the endemic–Antarctic assemblage.

Type locality. Cancha Carrera section. Base sample: CC 6 (452 m from the base of the integrated section); top sample: CC 10 (558 m from the base of the integrated section).

Characteristic species. In the type section the assemblages are highly dominated by *Vozzhennikovia apertura.* The palynological recovery and the dinoflagellate cyst event in this zone are hampered by the scarcity of fine clastic horizons.

Age. Late Bartonian (39 Ma) to middle Priabonian (36 Ma).

Correlation. Zone RTF 3 has been recognized in Highway 40 (74–183 m from the base of the integrated section) and in the YCF Cores (12–270 m depth). In the Highway 40 section the LO of *Impagidinium parvireticulatum* and the LCO of *Enneadocysta dictyostila* are two significant events dated at the middle Priabonian (Bijl, Sluijs & Brinkhuis, 2013*b*). In the YCF Cores two significant events are the FCO and the LCO of *Spinidinium macmurdoense.* The FCO of *Spinidinium macmurdoense* allows us to correlate with SPDZ 13 of Bijl, Sluijs & Brinkhuis (2013*b*), and its LCO is a remarkable event recorded in the South Pacific Ocean at *c.* 36 Ma (Sluijs *et al.* 2003). Abundance of *Vozzhennikovia apertura* and the FCO of *Spinidinium macmurdoense* are significant bioevents of the dinoflagellate cyst Zone DA 1 of Sluijs *et al.* (2003). This composition is also observed in the dinoflagellate cyst assemblages of the Loreto Formation in Chile (Archangelsky & Fasola, 1971).

Remarks. The upper part of Zone RTF 3 in the three sections is characterized by the presence of a coal seam recorded both by Archangelsky (1969) and Rodríguez Raising (2010).

6.d. Zone RTF 4

Definition. The base of this zone is defined by the FCO of *Turbiosphaera filosa* and the LCO of the species of the endemic–Antarctic assemblage. The top is determined by the LO of *Turbiosphaera filosa*.

Type locality. Cancha Carrera section. Base sample: CC 10 (558 m from the base of the integrated section); top sample: CC 14 (667 m from the base of the section).

Characteristic species. *Turbiosphaera filosa*, species of *Selenopemphix* and *Lejeunecysta*, *Operculodinium centrocarpum / israelianum* spp., *Impagidinium dispertitum*, *Spiniferites* spp. and *Lingulodinium machaerophorum.* The assemblages from the base of this zone have only a few specimens of the endemic species *Vozzhennikovia apertura.*

Age. Middle to late Priabonian (*c.* 35.5–33.5 Ma).

Correlation. The RTF 4 has not been recognized along the Highway 40 sections or YCF Cores. The FCO of *Turbiosphaera filosa* is one of the events delimiting the base of Zone DA 2 (*c.* 35.5–33.5 Ma) in the South Pacific Ocean (Sluijs *et al.* 2003). According to Sluijs *et al.* (2003), Zone DA 2 is a transition from assemblages dominated by endemic–Antarctic species to assemblages dominated by protoperidiniaceae and other cosmopolitan taxa.

Remarks. Sluijs *et al.* (2003), Stickley *et al.* (2004*b*) and Houben *et al.* (2013) related the replacement of endemic taxa by cosmopolitan species to the beginning of the deepening of the Tasmanian Gateway, dated through magneto-stratigraphy at *c.* 35.5 Ma (Priabonian).

7. Palaeoenvironmental evolution during the middle and late Eocene

In the biostratigraphic scheme defined above for the upper member of the Río Turbio Formation, palaeoenvironmental changes can be recognized based on the palaeoecological preferences of several dinoflagellate cyst taxa (Table 3).

Zones RTF 1 to RTF 3 show the dominance of species of the endemic–Antarctic assemblage. The changes in the abundance of *Enneadocysta dictyostila* versus *Vozzhennikovia apertura – Spinidinium macmurdoense – Deflandrea antarctica* have been mentioned by Röhl *et al.* (2004) and Sluijs, Pross & Brinkhuis (2005) as a characteristic alternation of the middle to late Eocene at high latitudes of the Southern Hemisphere. The high percentages of *Enneadocysta dictyostila* related to neritic sediments rich in $CaCO_3$ suggest the presence of warm surface waters and offshore settings (Röhl *et al.* 2004; Sluijs, Pross & Brinkhuis, 2005; Guerstein *et al.* 2010*a*). On the other hand, species of *Deflandrea*, *Vozzhennikovia* and *Spinidinium*, corresponding to more $CaCO_3$-depleted sediments, indicate coastal environments characterized by surface temperate waters with high dissolved nutrient availability (Röhl *et al.* 2004; Pross & Brinkhuis, 2005; Sluijs, Pross & Brinkhuis, 2005; Warnaar *et al.* 2009), possibly related to continental freshwater inputs (González Estebenet, Guerstein & Rodríguez Raising 2014; Rodríguez Raising *et al.* 2014).

The age determined for the upper part of Zone RTF 2 (~42 and 39 Ma) suggests that it encompasses the Middle Eocene Climate Optimum (MECO). Zone RTF 2 is characterized by an increase of *Enneadocysta dictyostila*, a warm-water-tolerant species. This assumption is consistent with a significant representation of *Enneadocysta dictyostila* in samples from the Colorado (~38° S), Punta del Este (~36° S) and Pelotas basins (Guerstein & Daners, 2010; Premaor *et al.* 2013; Guerstein *et al.* 2014*b*). However, higher-resolution studies are required in order to more closely constrain the part of the upper member of the Río Turbio Formation containing the MECO.

In Zone RTF 4, the endemic middle Eocene dinoflagellate cyst taxa are largely replaced by cosmopolitan species. There are species of *Turbiosphaera filosa* characterized by well-developed processes, suggesting normal marine conditions (González Estebenet, Guerstein & Casadío, 2015; Table 3). This zone also shows higher proportions of protoperidiniaceans associated

Table 3. List of distinctive species of the upper member of the Río Turbio Formation and its significance as palaeoenvironmental indicators.

Species	Environmental conditions
Vozzhennikovia apertura (M)	Inner neritic environment (Sluijs, Pross & Brinkhuis, 2005; Sluijs *et al*. 2009) subjected to freshwater discharges that generate environmental stress (González Estebenet, Guerstein & Rodríguez Raising, 2014; González Estebenet, Guerstein & Casadío, 2015).
Vozzhennikovia apertura, *Spinidinium macmurdoense*, *Deflandrea antárctica* (A)	Inner neritic environment associated with high trophic levels (Röhl *et al.* 2004; Sluijs, Pross & Brinkhuis, 2005; Sluijs *et al.* 2009), influenced by freshwater discharge that increased nutrient inputs (González Estebenet, Guerstein & Rodríguez Raising, 2014*a*; González Estebenet, Guerstein & Casadío, 2015).
Enneadocysta dictyostila (A)	Outer neritic conditions, warm waters and oligotrophic settings (Röhl *et al.* 2004; Sluijs, Pross & Brinkhuis, 2005; Guerstein *et al.* 2010*a*; González Estebenet, Guerstein & Rodríguez Raising, 2014).
Spiniferites, Operculodinium, Lingulodinium (P)	Inner–outer neritic waters. Reflect open marine neritic conditions when they are dominant (Brinkhuis, 1994; Pross & Brinkhuis, 2005; Sluijs, Pross & Brinkhuis, 2005)
Thalassiphora pelagica with periphragm showing an early stage of cyst development (M)	*T. pelagica* relates to episodes of freshwater infux responsible for environmental perturbations (Pross, 2001; Pross & Schmiedl, 2002).
Turbiosphaera filosa with early process development (M)	*T. filosa* seems to respond to the same environmental and physicochemical water conditions as *T. pelagica* (González Estebenet *et al.* 2015).
Thalassiphora pelagica strongly developed of the periphragm (P). *Turbiosphaera filosa* with early process development (P).	Normal environmental conditions in outer neritic to oceanic settings (Pross, 2001; Pross & Schmiedl, 2002; Pross & Brinkhuis, 2005; González Estebenet, Guerstein & Casadío, 2015).
Impagidinium and *Nemathosphaeropsis* (P)	Outer neritic to oceanic environment (Brinkhuis, 1994; Dale, 1996; Pross & Brinkhuis, 2005; Sluijs, Pross & Brinkhuis, 2005). In samples of Highway 40 the dominance of *I. parvireticulatum* was related to an episode of maximum flooding (González Estebenet, Guerstein & Rodríguez Raising, 2014).
Protoperidiniaceae (A)	Coastal environment waters with dissolved nutrient inputs due to freshwater discharges or neritic environments subjected to upwelling processes (Brinkhuis, 1994; Pross & Brinkhuis, 2005; Sluijs, Pross & Brinkhuis, 2005).

M: monospecific; A: abundant; P: presence.

with nutrient-rich surface waters (Pross & Brinkhuis, 2005; Zonneveld, Susek & Fischer, 2010; Zonneveld *et al*. 2013), and the number of endemic peridinoids is considerably reduced. Gonyaulacoids such as *Impagidinium* and *Nematosphaeropsis*, which are typical of outer neritic and oceanic environments (Dale, 1996; Marret & Zonneveld, 2003), occur together with *Operculodinium* spp., and *Lingulodinium machaerophorum*, which today are distributed in inner to outer neritic environments (Pross & Brinkhuis, 2005). Hence, the top of the upper member of the Río Turbio Formation (Zone RTF 4) could have been deposited in an outer-shelf setting that was subject to upwelling processes, leading to high nutrient concentrations in surface waters. Upwelling episodes in subsurface waters on the modern continental shelf off Argentina associated with the northward-flowing Malvinas Current on the continental slope have been described by numerical ocean-circulation modelling of the southwestern Atlantic Ocean (Matano & Palma, 2008; Palma, Matano & Piola, 2008; Combes & Matano, 2014) and hydrographic observations (Piola *et al.* 2010).

The decrease in endemic species in high southern latitudes and the advance and evolution of modern cosmopolitan taxa could be a consequence of the deepening of the Tasman Gateway and the Drake Passage (Sluijs *et al.* 2003; Stickley *et al.* 2004*b*; Guerstein *et al.* 2008; Houben *et al.* 2011, 2013). These changes would have led to the development of an unconstrained current (the proto- Circum Antarctic Current) around Antarctica in the earliest Oligocene. In turn, such modifications in the surface oceanic circulation patterns would have disrupted the subpolar gyres that originated during the middle Eocene, leading to the extinction of endemic species and the arrival and installation of cosmopolitan taxa (Huber *et al.* 2004; Guerstein *et al.* 2010*a*).

8. Conclusions

The dinoflagellate cyst events that we recorded in the upper member of the Río Turbio Formation were compared with the biostratigraphic ranges published by Brinkhuis *et al.* (2003*b*), Sluijs *et al.* (2003) and Bijl, Sluijs & Brinkhuis (2013*b*) for the South Pacific Ocean. Based on these comparisons it is possible to determine an age ranging from 46 Ma (mid-Lutetian) to 33.5 Ma (late Priabonian) for the upper member of the Rio Turbio Fm.

We have recognized four dinoflagellate cyst zones, RTF 1 to RTF 4 dated as middle Lutetian (ca. 46 Ma); middle Lutetian (~45.2 Ma) to late Bartonian (39 Ma); late Bartonian (39 Ma) to middle Priabonian (36 Ma); and middle to late Priabonian (*c.* 35.5–33.5 Ma), respectively. The dinoflagellate cyst zones recorded in the upper member of the Río Turbio Formation can be correlated with Zone SPDZ 10 to Zone SPDZ 13 as determined by Bijl, Sluijs & Brinkhuis (2013*b*), and with DA 1 to DA 2 as defined by Sluijs *et al.* (2003).

Alternating abundances of the gonyaulacoid *Enneadocysta dictyostila* and the extinct peridinioids *Deflandrea Antarctica*, *Vozzhennikovia apertura* and *Spinidinium macmurdoense* in Zones RTF 1 to RTF 3 indicate changes within an inner–outer neritic palaeoenvironment. High abundances of *Enneadocysta dictyostila* characterize offshore settings and low nutrient availability, whereas high proportions of the extinct peridinioids can be related to shallow marine palaeoenvironments and enhanced nutrient availability, likely related to fluvial discharges.

The endemic–Antarctic species are abundant in the assemblages from zones RTF 1 to RTF 3, while Zone RTF 4 shows a marked replacement of endemic species by cosmopolitan taxa. These assemblages are dominated by *T. filosa*, protoperidinaceans, and species of *Impagidinium* and *Nematosphaeropsis*, possibly related to an oceanic environment influenced by upwelling. This turnover in the dinoflagellate cyst assemblages seems to have been forced by the deepening of the Drake Passage and the Tasman Gateway, and changes in the global ocean circulation patterns (Sluijs *et al.* 2003; Stickley *et al.* 2004*b*; Guerstein *et al.* 2008; Houben *et al.* 2011, 2013; González Estebenet, Guerstein & Alperin, 2014).

Acknowledgements. The authors thank O. Cárdenas for palynological technical assistance, and J. Cornago for improving the language of the manuscript before submission. Rob Fensome and Peter Bijl are thanked for useful comments and suggestions that led to significant improvements to the new version of the manuscript. This study was funded by grants from the Agencia Nacional de Promoción Científica y Tecnológica (PICT 89/09), from Consejo Nacional de Investigaciones Científicas y Técnicas (PIP: 112-201101-00566) and from Universidad Nacional del Sur (PGI 24/H125).

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