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Late Maastrichtian to Danian organic-walled dinoflagellate cysts and calcareous nannofossils from eastern Austral Basin, Patagonia, Argentina

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ABSTRACT

Late Maastrichtian to Danian dinoflagellate cyst and calcareous nannofossil biostratigraphy was analyzed at the Sur Río Chico borehole, Austral Basin, Argentina. Two stratigraphical intervals from the 965 to 1003 meters below ground surface of the drilled section were defined. The co-occurrence of *Manumiella bertodano*, *M. seelandica* and *M. conorata* in the 990-1000 to 1000-1003 mbgs interval, associated with the top of the nannofossil *Neprolithus frequens miniporus* Zone indicated a late (probably latest) Maastrichtian age. The acme of the presumed heterotrophic *Manumiella* spp. and the acme of the mesotrophic cool-water nannofossil *Prediscosphaera stoveri*, together with other cool-water taxa *Arkhangelskiella cymbiformis*, *Kamptnerius magnificus* and *Nephrolithus frequens* may indicate cool nutrient–rich waters in this interval. Finally, the co-occurrence of dinoflagellate cyst taxa *Carpatella cornuta*, *Cerodinium diebelii*, *Danea californica, Senoniasphaera inornata* and *Palaeoperidinium pyrophorum* linked to the nannofossil NP3 Zone, suggest a middle Danian age for the 965-970 to 985-990 mbgs interval. An acme of *P. pyrophorum* herein related to the Pp2 of New Zealand, might reflect an episode of cool temperature during the Danian in the Austral Basin. The sedimentary succession is represented by the Campo Bola Formation within which two discontinuities were recognized; the older is of early - late Maastrichtian,

and the younger the latest Maastrichtian to the earliest Danian. A third discontinuity

involving the middle to late Paleocene separates the Campo Bola Formation from the

overlain Eocene Man Aike Formation.

Keywords: Maastrichtian; Danian; dinoflagellate cysts; calcareous nannofossil;
biostratigraphy; Argentina

1. Introduction

The Austral Basin is located on the southwestern edge of South America and

constitutes one of the most important oil-producing basins of Argentina and Chile. It is

bounded by the Patagonian-Fuegian Andes to the west and by the Deseado Massif to the east.

It includes about 8000-m-thick deposits ranging from the Late Jurassic to the Cenozoic (e.g.,

Schwarz et al., 2011) and covers an area of approximately 230,000 km^2.

Organic-walled dinoflagellate cysts have proven to be particularly useful for

stratigraphy and paleoenvironmental interpretations. Numerous dinoflagellate cyst-based

biostratigraphic works gave rise to sequences of bioevents and zonal schemes that constitute

stratigraphic reference frameworks for the Upper Cretaceous and Paleogene sedimentary

successions of the Northern Hemisphere (e.g., Hansen, 1977; Slimani 2001; Williams et al.,

2004; Fensome et al., 2008; Slimani et al., 2016) and Southern Hemisphere (e.g., Helby et al.,

1987; Roncaglia et al., 1999; Bowman et al., 2012; Crouch et al., 2014). In the Southern

Hemisphere high-latitudes, the Upper Cretaceous - Paleocene dinoflagellate cyst

biostratigraphic information comes from the Antarctic Peninsula, Antártida Argentina (Askin,

1988a, b; Askin and Jacobson, 1996; Thorn et al., 2009; Bowman et al., 2012, 2016), New

Zealand (Wilson, 1984; Roncaglia et al., 1999); Australia (Helby et al., 1987; McMinn, 1988;

Marshall, 1990; Partridge, 2006); Southern Indian Ocean (Mao and Mohr, 1992) and the

Tasman Shelf (Brinkhuis et al., 2003). However, the southernmost part of South America –

the Austral Basin – lacks a continuous record of dinoflagellate cysts in the Late Cretaceous –

early Paleocene sedimentary succession, presumably due to the proximity to the Patagonian-Fuegian Andes (Fig. 1), areas subjected to the compression (e.g., high temperature, high pressure) associated with the early stages of the Andean orogeny (Ramos et al., 1982; Biddle et al., 1986; Fildani and Hessler, 2005). This compression process extended from the Late Cretaceous to the Neogene (Ramos et al., 1982; Biddle et al., 1986; Spalletti et al., 2007). Dinoflagellate cyst studies are confined to the southwest of the Santa Cruz Province and come from discontinuous outcrop sections (Pöthe de Baldis, 1986; Marenssi et al., 2004; Guler et al., 2005; Povilauskas and Guler, 2008; González Estebenet et al., 2017), which has so far hampered a biostratigraphical correlation, as well as the comparison of the Austral Basin assemblages with those from other coetaneous high-latitudes Southern Hemisphere successions.

Dinoflagellates are sensitive to changes in the sea surface physiochemical parameters (e.g., temperature, salinity, nutrient availability). High relative and/or high absolute abundances or acmes of taxa may reflect optimal environmental conditions (Sluijs and Brinkhuis, 2009), being useful in paleoenvironment and paleoclimatic reconstructions (e.g., Sluijs et al., 2005; Sluijs and Brinkhuis, 2009). Global, synchronous acmes have been identified in the Late Cretaceous to Early Paleogene in response to paleoenvironmental factors, mostly associated to paleotemperatures (e.g., Habib and Saaedi, 2007; Crouch et al., 2014; Sluijs and Brinkhuis, 2009; Slimani et al., 2010; Bowman et al., 2012; Acikalin et al., 2015; Woelders et al., 2017; Taylor et al., 2018). *Manumiella druggii*/*seelandica* spikes were related to climate changes episodes recognized globally during the latest Maastrichtian (e.g., Habib and Saaedi, 2007; Bowman et al., 2012; Woelders et al., 2017). Likewise, *Apectodinium* acmes were correlated with high temperatures associated to the Paleocene–Eocene Thermal Maximum (e.g., Crouch et al., 2001, 2003; Sluijs and Brinkhuis, 2009; Bijl et al., 2011, 2013; Crouch et al., 2014). In southern high latitudes, acmes of *Trithyrodinium*

evittii and *Palaeoperidinium pyrophorum* in the early Paleocene of Antarctica, New Zealand and Australia (e.g., Helby et al., 1987; Askin, 1988a; Willumsem 2011; Willumsen and Vajda, 2010; Bowman et al., 2012; 2016; Crouch et al., 2014) have been related to fluctuating periods of warm and cool sea surface temperatures (e.g., Willumsen and Vajda, 2010; Taylor et al., 2018). These acmes that are confidently dated (Willumsem, 2011; Crouch et al., 2014; Bowman et al., 2016) and linked to paleotemperatures data (e.g., Willumsen and Vajda, 2010; Taylor et al., 2018) allows chronostratigraphic correlation and become useful to elucidate the climatic evolution of the early Paleocene interval.

The aim of the present paper is to document the late Maastrichtian to Danian dinoflagellate cyst assemblages and re-examine the calcareous nannofossils from the Sur Río Chico (SRC) borehole in the eastern coastal margin of the Austral Basin (Fig. 1). We provide a refined biostratigraphical interpretation based on Highest Occurrences (HOs) and Highest Common Occurrences (HCO) or acme b events of diagnostic taxa. Moreover, based on the sea surface paleotemperatures implications of nannofossil and dinoflagellate cyst taxa acmes we infer paleoclimatic episodes that occurred during the latest Cretaceous to Early Paleogene in the Austral Basin. Comparison with the late Maastrichtian Antarctic Peninsula assemblages (Bowman et al., 2012) allowed paleobiogeographical and paleoceanographical interpretations for the southernmost tip of South America.

2. Geological setting

The Austral Basin extends over the southernmost end of Argentina and Chile from 45ºS to 54ºS latitudes and it is bounded by the Patagonian-Fuegian Andes to the west and by the Deseado Massif to the east. It includes about 8000-m-thick deposits ranging from the Late Jurassic to the Cenozoic (e.g., Schwarz et al., 2011) covering an area of approximately 230,000 km^2. It is one of the most important oil-producing basins of Argentina and Chile.

The marine Mesozoic deposits include several economically - very important hydrocarbon source and reservoir rocks (e.g., Peroni et al., 2002).

Three main tectonic stages have been identified in the Austral Basin (Biddle et al., 1986; Nullo et al., 1999; Ramos, 2002; Rodríguez and Miller, 2005; Richiano et al., 2012; Varela et al., 2012): (1) a rift stage associated with the breakup of Gondwana and the early opening of the South Atlantic Ocean during the Jurassic (e.g., Pankhurst et al., 2000; Peroni et al., 2002). (2) a thermal subsidence stage developed in the Early Cretaceous. (3) a foreland stage from the late Early Cretaceous to the Neogene (e.g., Biddle et al., 1986; Arbe, 1989, 2002). During the late Early Cretaceous, a change in the tectonic context took place due to the beginning of subduction along the western margin of South America, which generated the uplift of the Patagonian-Fuegian Andes and a retroforeland subsidence to the east (e.g., Biddle et al., 1986; Ramos, 1989; Fildani and Hessler, 2005; Spalletti et al., 2007; Varela et al., 2012).

The onshore Sur Río Chico (SRC) borehole is located in the eastern part of the Austral Basin, in the southeastern Santa Cruz Province, near the coast (Fig. 1). In the east of the Santa Cruz Province the subsurface sedimentary rocks of the upper Campanian to Eocene are widely known as Magallanes inferior Formation (Robbiano et al., 1996; Malumián, 2002; Rodríguez and Miller, 2005; Rodríguez et al., 2008). Besides, Russo and Flores (1972) and Russo et al. (1980) formally defined Campo Bola Formation and Río Leona Formation for these rocks. The Campo Bola Formation was defined at SCS.CB X-3 (Campo Bola) borehole as a well-developed marine succession of fine to coarse, grey to grizzly glauconitic-sandstones with poor compaction and grey to grizzly claystones and siltstones, with low participation of sandstones in the upper part (Russo et al., 1980). The age of the Campo Bola Formation as defined by Russo et al. (1980) is equivalent to the Magallanes inferior Formation (Late Campanian – Eocene). Further works by Malumián (1990, 1999, 2002) and

Malumián and Náñez (2011) demonstrates that the upper part of the Campo Bola Formation, as defined by Russo et al. (1980), was equivalent to the Man Aike Formation (Furque, 1973) and proposed to restrict the unit to the Late Cretaceous – Paleocene subsurface rocks in the eastern Santa Cruz Province (see discussion in Pérez Panera, 2013). In this sense, the studied interval of the SRC borehole corresponds to Campo Bola Formation.

3. Material and methods

Samples from the Sur Río Chico (SRC) borehole were provided by Petrobras-Energía S.A. Figure 1 shows the general location of the SRC borehole in the Austral Basin (the exact geographic coordinates are held in confidence by the petroleum company). The palynological samples are identified with the number of meters below ground surface (mbgs). A total of fourteen samples were processed for palynological analysis using hydrochloric and hydrofluoric acids in order to remove carbonates and silicates, respectively. Organic residues were sieved through screens of 10 and 25 um and dehydrated with ethanol in order to prepared strew mounts using UV-curable acrylates (Trabasil ® NR2) as a mounting medium. The palynological samples were processed and the slides were stored at the Laboratorio de Palinología, Universidad Nacional del Sur, Bahía Blanca (LPUNS). Light microscopy was undertaken using a Leica DM 2500. The stratigraphical distribution and counting of the dinoflagellate taxa identified at the SRC borehole is presented in Table 1. The relative frequencies of the main dinoflagellate cyst taxa and the main morphological groups of taxa are shown in Figure 2. The Late Cretaceous part of the nannofossil distribution chart and counting of taxa is herein published for the first time, as well as a new Paleocene chart (initially reported in Pérez Panera, 2013), is provided in Table 2. The relative frequencies of selected nannofossil group of taxa are shown in Figure 3. The dinoflagellate cyst and calcareous nannofossil taxa mentioned in the text are listed in Tables 3 and 4, respectively.

The dinoflagellate cyst and the calcareous nannofossil nomenclature follow Williams et al. (2017) and Young et al. (2019), respectively. Selected specimens of dinoflagellate cysts and calcareous nannofossil were illustrated in Plates I and II.

4. Biostratigraphical analysis

The Sur Río Chico borehole spans from the Lower Cretaceous to the Oligocene between 220-230 mbgs and 1618-1620 mbgs (Pérez Panera, 2012, 2013). In this work, we analized the dinoflagellate cyst and calcareous nannofossil assemblages from the late Maastrichtian to Danian interval in a stratigrapical section from 1000-1003 to 965-970 mbgs. The biostratigraphy is generally based on the lowest occurrences (LOs) and highest occurrences (HOs) of dinoflagellate cyst and calcareous nannofossil taxa, as well as the lowest common occurrences (LCOs) and highest common occurrences (HCOs). We used the diagnostic HOs and HCOs events since the assemblages come from cutting samples and could be subject to downhole contamination (Table 1, 2).

The dinoflagellate cyst assemblages below the 1003-1005 mbgs exhibit high abundance of species of *Cribroperidinium*, especially *C. muderongense* (up to 82%), together with low proportions of *Alterbidinium acutulum*, *Andalusiella guersteiniae*, *Chatangiella tripartita*, *Xenascus ceratioides*, *Manumiella seymourensis*, *Nelsoniella aceras*, *Palaeohystrichophora infusorioides*, *Xenikoon australis* and species of *Andalusiella*, *Hystrichosphaeridium*, *Isabelidinium*, *Palaeocystodinium*, *Spiniferites*, among others. The HOs of the diagnostic dinoflagellate cyst events of *Andalusiella guersteiniae* (HO: early Maastrichtian; Ottone et al., 2018), *Chatangiella tripartita* (HO: early Maastrichtian, Fensome et al., 2008), *Cribroperidinium muderongense* (HO: late Campanian to early Maastrichtian; Mohr and Mao, 1997; Smith, 1992), *Nelsoniella aceras* (HO: middle

Campanian, Askin, 1988a; Askin et al., 1991; Duane et al., 1992; Roncaglia et al., 1999, and early Maastrichtian, Mao and Mohr, 1992; Mohr and Mao, 1997), *Palaeohystrichophora infusorioides* (HO: early Maastrichtian, Mao and Mohr, 1992; Mohr and Mao, 1997; Yepes, 2001; Williams et al., 2004), *Xenascus ceratioides* (HO: early Maastrichtian, Fensome et al. 2008) and *Xenikoon australis* (HO: early Campanian, Helby et al., 1987, and early Maastrichtian, Roncaglia et al., 1999) indicate an early Maastrichtian age or older for these assemblages. Sample 1003-1005 mbgf consists of dark bluish green glauconitic sandstone, and contains scarce dinoflagellate cysts (13 specimens, Table 1). According to the sedimentological interpretation from the well-log report, this sample is not a representative level due to the abundant cavings. Hence, we interpret that the Late Cretaceous dinoflagellate cyst specimens of *Manumiella seelandica*/*bertodano* are downhole contamination. Samples from this stratigraphic interval (1003-1005 and 1075-1080 m) are barren of calcareous nanofossils (Pérez Panera, 2012). Nevertheless, an agglutinated foraminifera assemblage characterized by *Haplophragmoides walteri* (Grzybowski) and "*Spiroplectammina – Textularia*" sp. Malumián, was recovered (Pérez Panera, 2012). This foraminifera assemblage has been recorded in other parts of the Austral Basin and dated Campanian – early Maastrichtian (Flores et al., 1973; Malumián and Masiuk, 1976, 1978; Malumián and Náñez, 1990, 1996; Náñez and Malumián, 2008).

Samples immediately above the 965-970 mbgs level show a strong turnover of taxa, with the record of a characteristic Eocene assemblage with abundance of *Deflandrea* spp. (e.g., *D. granulata*, *D. antartica*) together with *Hystrichosphaeridium truswelliae* (LO: Thanetian, Brinkhuis et al., 2003), *Spinidinium macmurdoense* (LO: early Ypresian; Bijl et al., 2013), among others. In agreement, an Eocene calcareous nannofossil assemblage (calcareous nannofossil NP10 Zone of Martini, 1971) was recorded in the same overlain bed. A re-examination of nannofossil slides of Pérez Panera (2013; Table 2) allowed

reinterpretation and better constrain of the nannofossil data. Eocene nannofossil markers found in 960-965 mbgs (without dinoflagellate data) and 955-960 mbgs (*Toweius callosus, T. eminens* and *Chiasmolithus solitus*), previously interpreted as downhole contaminants (Pérez Panera, 2013) are now interpreted to be *in situ*. The few Danian markers recovered up to sample 955-960 mbgs (*Cruciplacolithus primus* and *Prinsius dimorphosus*) were reinterpreted as reworked. This is also in agreement with the sedimentological data provided in the well-log report, where there is a change from light grey claystones up to 965-970 mbgs to dark blue to greeenish glauconitic sandstones from 960-965 mbgs and upward. This lithological change represents the contact between the Campo Bola and Man Aike formations (Fig 4).

4.1. Analyzed interval

The Late Maastrichtian to Danian biostratigraphy of the SRC borehole is based on dinoflagellate cyst and nannofossil assemblages from a ~38 m-thick interval, between 965 and 1003 mbgs. As the assemblages were recovered from cuttings samples, the order of the results is presented from top to bottom of the drilled section. The relative dating of the analyzed interval relies on age-diagnostic dinoflagellate cyst and nannofossil events, which allowed the definition of two intervals of Danian and late (probably latest) Maastrichtian ages.

4.1.1. Early Paleocene, middle Danian Interval (between 965-970 and 985-990 mbgs)

The early Paleocene dinoflagellate cyst assemblages contain mostly *Cordosphaeridium fibrospinosum, Danea californica, Glaphyrocysta* spp. (e.g., *G. texta*), *Hystrichosphaeridium* spp. (e.g., *H. tubiferum, H. tenuitubatum*), *Hystrichocolpoma* spp.

(e.g., *H. bulbosum*, *H. propium*), *Operculodinium* spp. (mostly *O. centrocarpum*),

Palaeoperidinium pyrophorum, Pervosphaeridium spp., *Riculacysta perforata*, *Spiniferites*

spp., and morphotypes intergrading between the taxa *Cordosphaeridium fibrospinosum* and

Danea californica. Representatives of *Cerodinium striatum*, *Cordosphaeridium gracile*,

Hafniasphaera delicate, *Senoniasphaera inornata, Spiniferella cornuta*, *Tanyosphaeridium*

spp. (e.g., *T. salpix*, *T. xanthiopyxides*) and *Turbiosphaera galatea* occur to a lesser extent

(Table 1; Fig. 2). The global index taxa *Carpatella cornuta*, *Cerodinium diebelii*, *Danea*

californica, *Senoniasphaera inornata* and *Palaeoperidinium pyrophorum* and the

identification of the nannofossil NP3 Zone, suggest a middle Danian age for the 965-970 to

985-990 mbgs interval (Fig. 4, 5).

The global Danian dinoflagellate marker *Danea californica* appears in samples from

965-970 to 985-990 mbgs in the SRC borehole, and its LO marks the base of the Danian in

both hemispheres. In the Northern Hemisphere *D. californica* has been largely used as a

Danian biostratigraphical marker in the Ivory Coast, Ghana (Masure et al., 1998; Oboh-

Ikuenobe et al., 1998; Sánchez-Pellicer et al., 2017), Senegal (Jan du Chêne, 1988), Morocco

(e.g., Rauscher and Doubinger, 1982; Slimani 2001; Slimani et al., 2010, 2016; Guédé et at.,

2014; Chakir et al., 2020; Ibaï et al., 2020), Tunisia (Brinkhuis and Zachariasse, 1988;

Brinkhuis et al., 1998; Khamdi et al., 2015; Vellekoop et al., 2015), Turkey (Vellekoop et

al., 2017a; Acıkalın et al., 2015), Israel (Eshet et al., 1992), United States (e.g., Firth, 1987,

1993; Moshkovitz and Habib, 1993) and Colombia-Venezuela (Yepes, 2001), among others.

In the Southern Hemisphere *D. californica* has been recorded in the north of Patagonia,

Argentina (Vellekoop et al., 2017b; Woelders et al., 2017; Guler et al., 2018, 2019), the

Seymour Island, Antártida Argentina (Elliot et al., 1994; Askin and Jacobson, 1996) and New

Zealand (Ferrow et al., 2011). Transitional morphotypes between *Cordosphaeridium*

fibrospinosum and *Danea californica* occur in samples 965-970 to 985-990 mbgs in the SRC

borehole. These morphotypes have been recorded in the early Danian of Tethyan realm

(Vellekoop et al., 2014, 2015; Açıkalın et al., 2015) and southernmost South America sites

(Vellekoop et al., 2017b; Woelders et al., 2017; Guler et al., 2018, 2019) and would have

been the predecessor of *D. californica* (Vellekoop et al., 2014, 2015, 2017a, b; Açıkalın et al.,

2015).

In the SRC borehole, the HO of *D. californica* coincides with the HO of *Cerodinium diebelii* in sample 965-970 mbgs. In the Northern Hemisphere mid-latitude, the HO of *Danea californica* coincides with the HO of *Cerodinium diebelii* at 61.05 Ma (early Selandian, Fensome et al., 2008). Nevertheless, the HO of *Cerodinium diebelii* is also recorded in the basal Danian of Australia, at the top of the *Manumiella druggii* Zone (Helby et al., 1987), and in the late Danian of New Zealand, within the *Palaeocystodinium golzowense* and the New Zealand Dinocyst Paleocene (NZDP) 4 zone of Crouch et al. (2014).

The global earliest Paleocene dinoflagellate marker *Carpatella cornuta* occurs only in sample 980-985 mbgs in the SRC borehole. In the Northern Hemisphere this species ranges from the Cretaceous–Paleogene (K–Pg) boundary to the latest Danian (e.g., Brinkhuis and Zachariasse, 1988; Fensome et al., 2008; Slimani et al., 2010, 2016; Açıkalın et al., 2015; M'Hamdi et al., 2015; Chakir et al., 2019; Jbari et al., 2020). Also, in the Southern Hemisphere, *C. cornuta* is recorded immediately above the K–Pg boundary in Seymour Island (Elliot et al., 1994; Askin and Jacobson, 1996) and New Zealand (Willumsen, 2011).

Senoniasphaera inornata occurs in samples from 965-970 to 985-990 in the SRC borehole. The biocron of this species is restricted to the early and middle Danian (64.95–62.60 Ma; e.g., Williams et al., 2004; Slimani et al., 2010, 2016; Crouch et al., 2014; Guédé et al., 2014; Vellekoop et al., 2015, 2017a; Açıkalın et al., 2015; Woelders et al., 2017; Soliman and Slimani, 2019; Chakir et al., 2020; Jbari et al., 2020). In New Zealand, the HO of *S. inornata* defined the top of the NZDP3 zone (Crouch et al., 2014) associated with the

uppermost part of calcareous nannofossil NP3 Zone. This species is also recorded in the

Danian of the Neuquén Basin, north of Patagonia (Palamarczuk and Habib, 2001; Woelders

et al., 2017).

Palaeoperidinium pyrophorum appears in samples from 965-970 to 985-990 mbgs in

the SRC borehole, and has its LO in the early Danian (e.g., Askin, 1988a, b; Brinkhuis et al.,

2003; Bowman et al., 2016) and the HO is mostly recorded associated with the Selandian-

Thanetian boundary, or in the basal Thanetian (e.g., Bujak and Brinkhuis, 1998; Crouch et

al., 2001; Williams et al., 2004; Schiøler et al., 1997; Bijl et al., 2013). However, the HO of

P. pyrophorum has been recorded at the top of the Danian NZDP4 zone in New Zealand

(Crouch et al., 2014), at the top of the early Paleocene zone 5 of Askin (1988a) in Antarctic

Peninsula, and at the top of the Danian *P. pyrophorum* Zone of Partridge (2006) in Australia,

associated with the calcareous nannofossil zones NP3 and part of the NP4 of Martini (1971).

In New Zealand, the HCO of *P. pyrophorum* is recorded in the Danian (~ 63.7 Ma),

near the top of the late early Paleocene dinoflagellate NZDP3 zone linked with the upper part

of the early Paleocene nannofossil NP3 Zone (~64.0 to ~63.4 Ma) (Willumsen, 2011; Crouch

et al., 2014). Likewise, Bowman et al., (2016) in Antarctic Peninsula correlated the HCO of

P. pyrophorum with the NZDP3–NZDP4 boundary. In the East Tasman Plateau, Brinkhuis et

al., (2003) documented the HCO of *Palaeoperidinium pyrophorum* at 63 Ma ("mid" Danian),

though Bijl et al., (2013) recorded the HCO of the species at the base of the Thanetian.

Vozzhennikovia angulata occurs only in sample 980-985 mbgs in the SRC borehole.

In New Zealand the LO and the HO of this species is recorded within NZDP3 and the upper

part of NZDP5 zones respectively, with peak abundance within the NZDP3 and NZDP4

zones (Crouch et al., 2014). *Cerodinium striatum* is present in sample 980-985 mbgs in the

SRC borehole, and its LO marks the boundary between the Danian NZDP1 and NZDP2 (~65

Ma) zones in New Zealand (Crouch et al., 2014) and in the Seymour Island (Bowman et al.,

2016). Nevertheless, there are references of the species in the late Maastrichtian of the Tasman Plateau (Brinkhuis et al., 2003) and Morocco (e.g., Chakir et al., 2019).

Spiniferella cornuta occurs in the interval between 965-970 and 985-990 mbgs in the SRC borehole and is represented through the early to middle Paleocene of New Zealand, with the LO near the top of the *Trithyrodinium evittii* Zone (Willumsen, 2011). However, there are references of the species from the late Maastrichtian to the Thanetian (Nøhr-Hansen and Dam, 1999; Fensome et al., 2008; Slimani et al., 2016; Woelders et al., 2017; Jbari et al., 2020). *S. cornuta* also occurs in the Maastrichtian and Danian in the north of Patagonia, Argentina (Heisecke, 1970 (as *Hystrichosphaera ramosa* cf. var. *granosa*); Woelders et al., 2017).

According to calcareous nannofossil assemblages (after Pérez Panera, 2013, and new data in this work (table 2) the analysed interval (between 965-970 and 985-990 mbgs) corresponds to the NP3 Zone of Martini (1971). This is based in the assumption that the Early Eocene taxa recorded at 955-960 and 960-965 mbgs considered as downhole contaminants in Pérez Panera (2013) are now interpreted *in situ,* and the HOs of *Cruciplacolithus primus* and *Prinsius dimorphosus* at 955-960 and 960-965 mbgs, respectively, are interpreted herein as reworking. This new interpretation seems to be more accurate in the light of sedimentological descriptions and dinoflagellate cyst data (Fig. 4). According to Pérez Panera (2013), the lowermost sample (985-990 mbgs) corresponds to the NP2 Zone, based on the presence of *Toweius africanus.* However, *T. africanus* is a synonym of *Prinsius tenuiculus* (see Table 2 and Table 4) which has a biochron within the NP2 to NP4 zones. In the same sample, *Chiasmolithus danicus* and *Hornibrookina teuriensis,* both with a LO in the NP3 Zone, constrain the age of the interval to the NP3 Zone at the base (Fig. 4). Sample 965-970 mbgs (top of interval) yields the LO of *Prinsius martini* (upper part of NP3 Zone) and the HO of

Cyclagelosphaera alta (within NP3 Zone). Based on these events, the entire interval is interpreted to correspond to the NP3 Zone (Fig. 4).

Conspicuous successive peak abundance events of *Palaeoperidinium pyrophorum* were recorded in the early Paleocene in high-latitudes Southern Hemisphere sedimentary successions (e.g., Askin, 1988a; Brinkhuis et al., 2003; Willumsen, 2000, 2011; Crouch et al., 2014; Bowman et al., 2016; Taylor et al., 2018). High relative abundances of *P. pyrophorum* (Pp1 and Pp2 of Taylor et al., 2018) were recorded through the Danian NZDP1 to NZDP3 zones of Crouch et al., (2014) in New Zealand (Fig. 5) (Willumsen, 2006, 2011; Crouch et al., 2014; Taylor et al., 2018). The younger acme interval of *P. pyrophorum* (Pp1) is recognized in the upper part of the NZDP1 and the lower part of the NZDP2, between two acme intervals of *Trithyrodinium evittii* (Te1 and Te2 of Taylor et al., 2018). The base of the second *P. pyrophorum* acme (Pp2) occurs above the second *T. evittii* acme (Te2) within the NZDP3 of Crouch et al. (2014) and is considered the HCO of the species in New Zealand. In the SRC borehole, in the analyzed 965-970 to 985-990 mbgs interval, we identified a peak abundance of *P. pyrophorum* (up to 35 %) with an abrupt decline in their relative proportions (3%) towards the top (Fig. 2). The high relative proportions of *P. pyrophorum* associated with the nannofossil NP3 Zone, together with the absence of the early Danian dinoflagellate *T. evittii* Acme Zone (Herby et al., 1987) and the nannofossil NP1 and NP2 zones, led us to assume that the acme of *P. pyrophorum* recorded in the SRC borehole correspond to the Pp2 within the NZDP3 zone of New Zealand (Fig. 4, 5). Our assemblages also include specimens of *Vozzhennikovia angulata, Cerodinium striatum* and *Spiniferella cornuta* (Table 1, Fig. 5) that reinforce the occurrence of the Pp2 in the Austral Basin. The LOs and HOs of *Vozzhennikovia angulata*, and the HO of *Cerodinium striatum* occur within the NZDP3 (Crouch et al., 2014), as well as Willumsen (2011) recorded *Spiniferella cornuta* associated to the Pp2.

4.1.2. Late Cretaceous, late (probably latest) Maastrichtian Interval (between 990-995 and 1000-1003 mbgs)

In the interval 990-995 to 1000-1003 mbgs of the SRC borehole the co-occurrence of the dinoflagellate cysts *Manumiella bertodano*, *M. seelandica*, and *M. conorata* associated with the top of the nannofossil *Neprolithus frequens miniporus* Zone indicates a late (probably latest) Maastrichtian age (Fig. 4, 5). This interval may be correlated with the ?late Maastrichtian *M. bertodano* Interval Zone of Bowman et al. (2012).

The dinoflagellate cyst assemblages are dominated by taxa of *Manumiella* (up to 45%), particularly represented by *Manumiella seelandica*, *Manumiella bertodano*, *Manumiella conorata* and transitional morphotypes between *Manumiella seelandica* and *Manumiella bertodano*. According to Thorn et al. (2009) the main feature which differentiates *M. seelandica* from *M. bertodano* is the prominence and symmetry of the two antapical horns, larger and strongly asymmetrical in *M. bertodano*. In SRC borehole, forms with moderately developed apical and antapical horns, showing intermediate features between both species were placed in *Manumiella seelandica/bertodano*. Other taxa frequently recorded belong to *Cordosphaeridium* (as *C. gracile*, *C. inodes*, among others) and *Spiniferites* (e.g., *Spiniferites ramosus*) (Table 2; Fig. 2).

The species of *Manumiella* are considered useful biostratigraphical markers for the late Maastrichtian of the Southern Hemisphere high-latitudes, as in Antarctic Peninsula, Antátida Argentina (e.g., Askin, 1988a, b; Thorn et al., 2009; Bowman et al., 2012; Scasso et al., 2020), New Zealand (Wilson, 1984, 1987, 1988; Wilson et al., 1989; Roncaglia and Schiøler, 1997; Roncaglia et al., 1999; Crampton et al., 2000, 2004), Australia (Helby et al., 1987) and South America (Marenssi et al., 2004). Bowman et al. (2012) proposed the first formal late Maastrichtian to early Danian dinoflagellate cyst zonation scheme for the

Antarctic Peninsula. These authors defined three ?late Maastrichtian zones: the still informal

lowermost unit, zone 1 of Askin (1988a), the *M. seymourensis* Range Zone (zone 2 of Askin,

1988a) and the *Manumiella bertodano* Interval Zone (zone 3 of Askin, 1988a). Bowman et al.

(2012) also described the latest Maastrichtian to earliest Danian *M. druggii* Range Zone

which correlated with zone 4 of Askin (1988a) and the *Manumiella druggii* Interval Zone of

New Zealand (Wilson, 1984, 1987) and Australia (Helby et al., 1987).

Manumiella bertodano Interval Zone is defined from the HO of *Manumiella*

seymourensis to the LO of *Manumiella druggii* (Bowman et al., 2012). This zone is

characterised by diverse *Manumiella* taxa and relatively abundant *Manumiella bertodano*,

together with some specimens of *Manumiella seelandica* and *Spiniferites ramosus*.

Manumiella bertodano occurs throughout and the HO of the species is at the top of the zone.

Furthermore, *Manumiella bertodano* co-occur with *Manumiella conorata* only within the *M.*

bertodano Interval Zone (sensu Thorn et al., 2009; Bowman et al., 2012) and *M. conorata*

have its LO within the base of the *M. bertodano* Interval Zone.

In the SRC, the *Manumiella* assemblages correlate with the acme of *Prediscosphaera*

stoveri (sample 995-1000) and an acme of *Micula* spp. (sample 995-1000), both events

identified whitin the top of the Maastrichtian nannofossil *Neprolithus frequens miniporus*

Zone. The acme of *P. stoveri* is used to define the base of the youngest Maastrichtian subzone

in the Watkins et al. (1996) scheme (*Prediscosphaera stoveri* Acme Subzone; *sensu*

Pospichal and Wise, 1990) (Fig. 4) and the youngest zone in the do Monte Guerra et al.

(2016) scheme (SAH1 Zone). The acme of *Micula* spp. has been also recorded in the Salado

(Pérez Panera et al., 2016), Colorado (Pérez Panera and Angelozzi, 2006; Pérez Panera,

2019) and Neuquén basins of Argentina (e.g., Scasso et al., 2005; Keller et al., 2007; Musso

et al., 2012), and proposed as a very reliable event for local correlation in the latest

Maastrichtian (Pérez Panera et al., 2016, 2019; Pérez Panera, 2019). This acme was calibrated at 67.3 Ma (Thibault et al., 2010) by correlation with the LO of *Micula murus* in southeastern Atlantic Ocean IODP sites 524, 525A, 527 and 530A (Pérez Panera, 2019). *Micula murus* is not expected to be present in the Austral Basin, as it is a tropical to subtropical species (Thibault et al., 2010). However, in other Southern Atlantic basins, this acme is evidenced by the most conspicuous *Micula staurophora* and *Micula concava*.

The typical *Manumiella druggii* acme globally recorded immediately prior to the K–Pg boundary is absent at the SRC borehole. This *M. druggii* acme is characteristic for the last tens of thousands of years of the Maastrichtian at mid and low latitudes (e.g., Habib and Saeedi, 2007; Slimani et al., 2010; Açıkalın et al., 2015; Woelders et al., 2017) and it is recorded within the top of the latest Maastrichtian to earliest Danian *M. druggii* Zone in high latitudes of the Southern Hemisphere (e.g., Heilv et al., 1987; Bowman et al., 2012; Scasso et al., 2020). Although this acme is not represented in the SRC borehole, it was recognized in the Calafate Formation in the southwest on the Austral Basin (Marenssi et al., 2004) (Fig. 5). Hence, we propose a late (probably latest) Maastrichtian age for 990-995 to 1000-1003 mbgs stratigraphical interval, even when the deposits close to the K–Pg boundary would not be represented.

4.2. Stratigraphical inferences

Based on integrated data from dinoflagellate cysts and calcareous nannofossils, we refined the time interval involved in the three discontinuities recognized through the sedimentary succession at the SRC borehole (Fig. 4, 5). These discontinuities have been previously identified by calcareous nannofossils in the SRC borehole (Pérez Panera, 2013) and discussed throughout the Austral Basin in Pérez Panera (2012, 2013). The youngest is placed at level 965 mbsf, between the Early Eocene and the early Paleocene (Danian).

Dinoflagellate cyst and nannofossil assemblages from 965-970 to 985-990 mbsf interval indicated a minimum Danian age, whereas assemblages above the 965-970 mbfs level show a strong turnover of species, with the record of conspicuous Eocene assemblages characterized by abundant *Deflandrea* spp. (e.g., *D. granulata*, *D. antartica*) together with *Hystrichosphaeridium truswelliae*, *Spinidinium macmurdoense*, among others (Fig. 4). In agreement, Pérez Panera (2009, 2013) recorded Danian calcareous nannofossil assemblages (NP3 and the basal NP4 zones) from the argillaceous silty-sandstones and glauconitic-sandstones at the 965-970 to 985-990 mbsf interval, of the the subsurface eastern Austral Basin Campo Bola Formation, overlain by the Eocene Man Aike Formation yielding a calcareous nannofossil assemblage (NP10 Zone). Thus, a discontinuity between the early Paleocene Campo Bola Formation and the Early to Middle Eocene Man Aike Formation seems to involve a middle to late Paleocene (Selandian to Thanetian) biostratigraphical hiatus (Fig. 4, 5).

A second discontinuity was interpreted at level 990 mbsf between the late Maastrichtian and the Danian sedimentary successions. The dinoflagellate cyst *M. bertodano* Interval Zone of Bowman et al. (2012) associated with the top of the nannofossil *Neprolithus frequens miniporus* Zone (Watkins et al., 1996) recognized in deposits between the 990-995 and 1000-1003 mbfs indicated a late (probably latest) Maastrichtian age. Overlying this interval, between the 965-970 and 985-990 mbsf, the assemblages show conspicuous Danian dinoflagellate cyst with a peak of *Palaeoperidinium pyrophorum* associated to the Pp2 sensu Taylor et al. (2018) and to the NZDP3 zone of Crouch et al. (2014). According to the high-latitudes Southern Hemisphere dinoflagellate cyst zonal schemes, this fact reflects that the earliest Danian *Trithyrodinium evittii* acme Zone and the NZDP1 and NZDP2 zones of Crouch et al. (2014), as well as the latest Maastrichtian *Manumiella druggii* Zone, are absent (Fig. 5). In agreement, new studies and reinterpretation of the calcareous nannofossil

assemblages from Pérez Panera (2013) indicated that the lowermost levels of the early

Paleocene interval (965-970 to 985-990 mbsf) correspond to the NP3, and the earliest Danian

nannofossil zones NP1 and NP2 are absent. Hence, this biostratigraphic hiatus interpreted as

a stratigraphic discontinuity would involve the latest Maastrichtian (presumable last tens

thousands of years) and the earliest Danian, including the K–Pg boundary. Partially

contemporaneous discontinuities were identified in the Lago Argentino area of the

southwestern Austral Basin (e.g., Malumián and Caramés, 1997; Marenssi et al., 2002, 2004),

where the Eocene Man Aike Formation unconformably overlies the latest Maastrichtian

Calafate Formation as well as in subsurface deposits of the eastern part of the Basin (Riggi,

1979).

 The third and oldest discontinuity was interpreted at level 1003 between the early

Maastrichtian and the late Maastrichtian deposits. The diagnostic dinoflagellate cyst taxa

(e.g., *Andalusiella guersteiniae*, *Chatangiella tripartita*, *Cribroperidinium muderongense*,

Nelsoniella aceras, *Palaeohystrichophora infusorioides*, *Xenascus ceratioides*, *Xenikoon

australis*) suggested an early Maastrichtian age or older, which correlate with an informal

zone of "*foraminíferos arenáceos*" (Malumián and Masiuk, 1976) dated Campanian – early

Maastrichtian (Flores et al., 1973; Malumián and Masiuk, 1976, 1978; Malumián and Náñez,

1996). Whereas the late Maastrichtian interval yielding the dinoflagellate cyst *M. bertodano*

Interval Zone and the top of the nannofossil *Neprolithus frequens miniporus* Zone, indicate at

least an early - late Maastrichtian biostratigraphic hiatus. Moreover, in the nearest Cerro

Redondo and Campo Bola wells, Danian sediments overlies the ?early Maastrichtian - late

Campanian nannofossil-barren succession, indicating that in this area, the hiatus also involves

the late Maastrichtian (Pérez Panera, 2009, 2012, 2013).

 In synthesis, the Campo Bola Formation would be restricted herein to the sedimentary

succession from the early Maastrichtian to the Danian, within which there were recognized

two discontinuities. The older is of the early - late Maastrichtian and, the younger the latest Maastrichtian to the earliest Danian (including the K–Pg boundary). In this regard, the Campo Bola Formation would be separated from the overlain Man Aike Formation by a discontinuity involving the middle to late Paleocene (Fig. 4, 5).

5. Paleoclimatical and paleogeographical implications

The organic walled cyst-producing dinoflagellates are highly sensitive to even small changes in the physiochemical parameters (e.g., temperature, salinity, nutrients) of the surface watermasses. The dinoflagellate cysts assemblages in the fossil record constitute an excellent tool for the environment reconstruction of ancient marine settings. Sea surface temperature (SST) is widely considered to be the most important parameter for describing environmental conditions of past oceans and is a crucial factor in paleoclimate modelling (e.g., Wefer et al., 1999). Dinoflagellates are particularly sensitive to temperature changes making them useful for SST reconstructions (e.g., de Vernal et al., 2001; Versteegh and Zonneveld, 1994; Rochon et al., 1998, Grøsfjeld et al., 1999; Devillers and de Vernal, 2000; Sluijs et al., 2005; Habib and Saeedi, 2007; Bijl et al., 2009, 2010; Vellekoop et al., 2014; Taylor et al., 2018).

Early Paleocene dinoflagellate cysts assemblages are in general characterized by high-dominance of taxa (like, e.g., acmes of *Palaeoperidinium pyrophorum*) presumably in response to global changes in climatic and environmental conditions (e.g., Brinkhuis et al., 2003). In New Zealand, the earliest Paleocene assemblages are distinguished by a succession of alternating abundance of *Trithyrodinium evittii* (Te1 and Te2 acmes) and *Palaeoperidinium pyrophorum* (Pp1 and Pp2 acmes) (e.g., Willumsen, 2011; Crouch et al., 2014; Taylor et al., 2018) as a signal of temperature variation. *Trithyrodinium evittii* is considered to be a warm-water species, it is recorded in the latest Cretaceous at low-latitudes

(e.g., Rauscher and Doubinger, 1982; Smit and Brinkhuis, 1996; Yepes, 2001; Slimani et al., 2010) and migrated to high latitudes in response to a global warming during the earliest Paleocene (Nøhr-Hansen and Dam, 1997, 1999; Brinkhuis et al., 1998; Vellekoop et al., 2015; Guler et al., 2019). On the other hand, *Palaeoperidinium pyrophorum* is inferred to be a cool-water species, being abundant in the early Paleocene of high latitudes of the Northern Hemisphere (e.g., Drugg, 1967; Thomsen and Heilmann-Clausen, 1985) and the Southern Hemisphere (Askin, 1988a; Brinkhuis et al., 2003; Willumsen 2006, 2011; Willumsen and Vajda 2010; Crouch et al., 2014). Recently, Taylor et al. (2018) reported a succession of *T. evittii* and *P. pyrophorum* acme events related to TEX86-derived SST in New Zealand. The Paleocene warm interval coincides with the warm-water *Eisthyrodinium evittii* acme and the cool intervals match with the cool-water *Palaeoperidinium pyrophorum* acme. In line with the recently exposed, the abundance of *P. pyrophorum* in SRC borehole herein related to the Pp2 of New Zealand (Taylor et al., 2018) might reflect an episode of cool temperature in the southernmost tip of South America during the Danian. Furthermore, the low abundance and diversity of the nannofossil assemblage might be related with corrosion associated with cold waters, which increase the carbonate dissolution.

Peak abundances of the genus *Manumiella* (particularly *M. druggii*) recognized in the late Maastrichtian worldwide hint toward biotic response to climate changes (specially related to temperature) (e.g., Helby et al., 1987; Yepes, 2001; Habib and Saeedi, 2007; Vellekoop et al., 2015) or marginal marine conditions (Askin and Jacobson, 1996; Nøhr-Hansen and Dam, 1997). Unfortunately, there are no studies (to our knowledge) that linked the peaks of the index *Manumiella* taxa of the *M. bertodano* Interval Zone with paleothermometry proxies. Nevertheless, in SRC borehole the peak abundance of *Manumiella* (composed by *M. bertodano*, *M. seelandica*, *M. seelandica*/*bertodano* and *M. conorata*) coincide with the acme of the nannofossil *Prediscosphaera stoveri* (Pérez Panera,

2012). The *P. stoveri* acme has been highligthed in the late Maastrichtian of the Austral

Ocean (Maud Rise and Broken Ridge: Pospichal, 1989; Northeast Georgia Rise: Crux, 1991;

Kerguelen Plateau: Watkins, 1992; Watkins et al., 1996) and South Atlantic Basins (Colorado

Basin: Pérez Panera and Angelozzi, 2006; Austral Basin: Pérez Panera, 2010, 2012).

According to do Monte Guerra et al. (2016), this nannoevent occurs within the Chron C31n

(~ 69 Ma), which roughly coincides with a global cooling episode and enhanced mixing of

intermediate and high latitude surface waters in the late Maastrichtian (Thibault et al., 2010).

In the SRC borehole, the acme of *P. stoveri* coincides with an increase of the relative

abundance of other high latitude, cool-water indicators like *Arkhangelskiella cymbiformis,*

Kamptnerius magnificus and *Nephrolithus frequens* (Worsley, 1974; Thierstein, 1976, 1981;

Roth, 1978; Wind, 1979; Shafik, 1990; Watkins et al., 1996; Lees, 2002; Thibault and

Gardin, 2006, 2007). Thus, the *M. bertodano* Interval Zone recognized in the SRC borehole

might be related to cool-water conditions in the Austral Basin. Futhermore, the high

proportions of the peridinioid (inferred heterotrophic; e.g., Powell et al., 1992) *Manumiella*

and the suggested mesotrophic *P. stoveri* (Lees, 2002; Thibault and Gardin, 2006, 2007) may

also indicate cool nutrient–rich waters.

Provincialism of dinoflagellate cyst assemblages (i.e., global spatial differentiation)

depends on physiochemical characteristics of the water masses and the surface water

circulation patterns (e.g., Lentin and Williams, 1980; Sluijs et al., 2005; Pross and Brinkhuis,

2005). Comparison of the Late Cretaceous-early Paleocene dinoflagellate cyst assemblages of

the Austral Basin with those coevals from other high-latitudes Southern Hemisphere

localities allowed inferring paleobiogeographical affinities and their implication in the

paleoceanographical circulation in the southernmost Atlantic Ocean. In general, the Late

Cretaceous dinoflagellate cyst assemblages from the Austral Basin (Pöthe de Baldis, 1986;

Marenssi et al., 2004; Guler et al., 2005; Povilauskas and Guler, 2008; González Estebenet et al., 2017, 2019, this study) show close similarity with those from the Antarctic region (e.g., Askin et al., 1988a; Thorn et al., 2009; Bowman et al., 2012; Scasso et al., 2020), New Zealand (e.g., Wilson, 1984; Roncaglia et al., 1999; Willumsen, 2006, 2011; Crouch et al., 2014), Australia (Helby et al., 1987; Marshall, 1990; Partridge, 2006), Southern Indian Ocean (Mao and Mohr, 1992) and the East Tasman Plateau (Brinkhuis et al., 2003; Williams et al., 2004), denoting marked austral affinities. Indeed, it is clear that the Late Cretaceous (Helby et al., 1987; Askin et al., 1988a; Roncaglia et al., 1999; Bowman et al., 2012) and the early Paleocene (e.g., Askin et al., 1988a; Partridge, 2006; Willumsen, 2011, 2016; Crouch et al., 2014; Bowman et al., 2016) dinoflagellate cysts zonal schemes defined for high-latitudes Southern Hemisphere sequences are applicable to the late Maastrichtian to Danian deposits of the Austral Basin (Fig. 5).

Bowman et al. (2012) decribed a shallow oceanic connection among the Peninsula Antarctica, southern Australia, the East Tasman Plateau, Southern India Ocean (Kerguelen Plateau), New Zealand and the western tip of Southern South America and defined a late Maastrichtian to earliest Paleocene dinoflagellate cyst South Polar Province. This shallow oceanic connection with the southernmost part of South America – the Austral Basin – was based by Bowman et al. (2012) on the biogeographical affinity between the latest Maastrichtian dinoflagellate cyst assemblages (belonging to the *Manumiella druggii* Range Zone) from the Calafate Formation (Marenssi et al., 2004; Guler et al., 2005) and coeval assemblages from the Southern Hemisphere high-latitudes sites. The identification of the *M. bertodano* Interval Zone of Bowman et al. (2012) in the Austral Basin (this study) reinforces this oceanic connection between the southernmost tip of South America and the Antarctic Peninsula, also integrating the Maastricthian to earliest Paleocene South Polar Province.

6. Conclusions

The biostratigraphical analysis of latest Cretaceous to Paleocene dinoflagellate cyst and nannofossil assemblages from the Sur Rio Chico borehole allowed defining two stratigraphical intervals: (1) a late (probably latest) Maastrichtian interval (990-995 to 1000-1003 mbsf) correlated with the Antarctic *Manumiella bertodano* Interval Zone of Bowman et al. (2012) associated with the calcareous nannofossil *N. frequens* Zone and with nannofossils *Prediscosphaera stoveri* and *Micula* spp. acmes, and (2) a middle Danian interval (965-970 to 985-990 mbsf) correlated with New Zealand NZDP3 zone of Crouch et al. (2014) associated with the calcareous nannofosil NP3 Zone (Martini, 1971).

Three sedimentary hiatuses were identified in the subsurface Campo Bola Formation in the SRC borehole, eastern Austral Basin. One discontinuity comprises a late Paleocene (Selandian to Thanetian) biostratigraphical hiatus that separate the Campo Bola Formation from the overlying Eocene Man Aike Formation. The other two discontinuities were recognized within the Campo Bola Formation; the younger is from the end of the late Maastrichtian to the earliest Danian (including the K–Pg boundary) and the older the early - late Maastrichtian.

From the paleoclimatical point of view, the high abundances of the dinoflagellate cysts *Manumiella* spp. (*M. bertodano*, *M. seelandica/bertodano*, *M. seelandica* and *M. conorata*) and the nannofossils *Prediscosphaera stoveri* acmes indicated cool nutrient–rich waters conditions during the late Maastrichtian in the Austral Basin. Besides, a *Palaeoperidinium pyrophorum* acme allows inferring a Danian cool temperature interval in the southernmost tip of South America.

Finally, considering the paleogeographical implications, the identification of the *Manumiella bertodano* Interval Zone at the SRC borehole supports the inclusion of the south

of Patagonia as part of the Maastrichtian to earliest Paleocene South Polar Province of
Bowman et al. (2012).

Acknowledgments

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Fig. 1. Map of southern of Patagonia (Argentina) showing the extent of the Austral Basin and the location of the Sur Río Chico (SRC) borehole and other sites mentioned in the text: Calafate Formation (Marenssi et al., 2004), Campo Bola (CB) borehole and Cerro Redondo (CR) borehole (Pérez Panera 2009, 2012, 2013). Modified from Nullo et al. (1999).

Fig. 2. Relative frequencies of selected dinoflagellate cyst species and groups of morphologically related species recorded at the SRC borehole, Austral Basin. *Cordosphaeridium*/*Damassadinium* group includes *C. fibrospinosum*, *D. californica* and transitional morphotypes between both taxa. *Spiniferites* complex is mainly dominated by species of *Spiniferites* and the morphologically relatives genera *Achomosphaera*, *Hafniasphaera* and *Impagidinium*. *Glaphyrocysta* complex includes species of *Glaphyrocysta*

(as *G. texta*), *Riculacysta* (as *R. perforata*) and *Senoniasphaera inornata*. *Manumiella* spp. comprises *M. seelandica*, *M. bertodano*, *M. conorata* and transitional morphotypes between *M. seelandica* and *M. bertodano*. (*) non representative sample.

Fig. 3. Relative frequencies of selected calcareous nanofossils species and groups of taxa recorded at the SRC borehole, Austral Basin. Other new Cenozoic taxa includes *Coccolithus pelagicus*, *Markalius apertus*, *Cyclagelosphaera alta*, *Prinsius martini*, *P. dimorphosu*, *P. tenuiculus*, *Hornibrookina teuriensis*, *Chiasmolithus consuetus*, *Holodiscolithus solidus*, *Cruciplacolithus primus*, *C. tenuis*, *C. edwardsii*, *Neochia tozygus concinnus*. Others K–Pg boundary survivors comprise *Cervisiella saxea*, *Placozygus sigmoides*, *Thoracosphaera heimii*, *Braarudosphaera bigelowi*, *Markalius inversus*. Cretaceous cold-water taxa includes *Prediscosphaera stoveri*, *Nephrolithus frequens*, *Arkhangelskiella cymbiformis*, *Ahmuellerella octoradiata*, *Repagulum parvidentatum*, *Gartnerago segmentatum*, *Kamptnerius magnificus* and *Biscutum coronum*.

Plate I. Dinoflagellate cysts recovered from the Sur Río Chico borehole, Austral Basin. The sample number is followed by the England Finder (EF) references. (1) *Manumiella conorata*, 1000-1003 mbsf, M45-2. (2) *Manumiella seelandica*, 1000-1003 mbsf, L55. (3) *Manumiella seelandica/bertodano*, 990-1000 mbsf, Q51-1. (4) *Manumiella seelandica/bertodano*, 1000-1003, T42-4. (5) *Manumiella bertodano*, 1000-1003 mbsf, D49-2. (6) *Manumiella bertodano*, 990-1000 mbsf, N30-3. (7) *Cribroperidinium muderongense*, 1010-1015 mbsf, G42-3. (8) *Membranilarnacia* sp. cf. *M. picena*, 980-985 mbsf, S41-1. (9) *Carpatella cornuta*, 980-985 mbsf, Q49-1. (10) *Alisocysta circumtabulata*, 1000-1003 mbsf, X25-3. (11) *Phelodinium magnificum*, 990-1000 mbsf, L55. (12) *Cordosphaeridium* sp., 990-1000 mbsf, D44-1. (13) *Cordosphaeridium-Danea* complex, 965-970 mbsf, P43. (14) *Riculacysta perforata*, 980-985

mbsf, E43-3. (15) *Palaeoperidinium pyrophorum*, 975-980 mbsf, E28-2. (16)

Palaeoperidinium pyrophorum, 975-980 mbsf, S32-1. (17) *Cerodinium diebelii*, 965-970

mbsf, O52. (18) *Xenascus ceratioides*, 1015-1020 mbsf, L44. (19) *Spiniferella cornuta*, 980-

985 mbsf, J43-1. (20) *Andalusiella guersteiniae*, 1015-1020 mbsf, B24-3. Scale bar = 10 μm.

Plate II. Calcareous nannofossils from Sur Río Chico (SRC) borehole. (1) *Arkhangelskiella*

cymbiformis, 995-1000 mbsf. (2) *Ahmuellerella octoradiata*, 995-1000 mbsf. (3)

Kamptnerius magnificus, 995-1000 mbsf. (4) *Gartnerago segmentatum*, 995-1000 mbsf. (5)

Chiastozygus litterarius, 995-1000 mbsf. (6) *Cribrosphaerella ehrenbergi*, 995-1000 mbsf.

(7) *Nephrolithus frequens,* 995-1000 mbsf. (8) *Prediscosphaera spinosa*, 995-1000 mbsf. (9)

Prediscosphaera stoveri, 995-1000 mbsf. (10) *Prediscosphaera stoveri*, 995-1000 mbsf. (11)

Micula staurophora, 995-1000 mbsf. (12) *Cruciplacolithus primus*, 980-985 mbsf. (13)

Chiasmolithus danicus, 985-990 mbsf. (14) *Chiasmolithus danicus*, 980-985 mbsf. (15)

Prinsius martinii, 985-990 mbsf. (16) *Prinsius dimorphosus*, 965-970 mbsf. (17) *Prinsius*

tenuiculus, 985-990 mbsf. (18) *Hornibrookina teuriensis*, 980-985 mbsf. (19) *Cervisiella*

operculata fragments, 985-990 mbsf. (20) *Cervisiella operculata* fragments, 985-990 mbsf.

Scale bar = 10 μm.

Fig. 4. Dinoflagellate cysts and nannofossil events and zones recorded in the Sur Río Chico

borehole, Austral Basin. Lithologic column according to well log. Maastrichtian and Danian

dinoflagellate cyst zones follow Bowman et al. (2012) and Crouch et al. (2014), respectively.

Maastrichtian and Danian calcareous nannofossil zones follow Watkins et al. (1996) (sensu

do Monte Guerra, 2016 and de Pospichal and Wise, 1996) and Martini (1971), respectively.

Lowest Occurrences of taxa marked by grey arrows do not represent significant biostratigraphical data since microfossil assemblages come from cutting samples.

Fig. 5. Diagnostic dinoflagellate cyst taxa and zones for the Maastrichtian and Danian at the Sur Río Chico borehole, Austral Basin. Asterisk (*) of *Manumiella druggii* indicate that the Lowest Occurrences data come from the Calafate Formation, Austral Basin (Marenssi et al., 2004). Comparison of the dinoflagellate cysts event sequences from Southern South America with others dinoflagellate cyst biostratigraphical frameworks from Antarctic Peninsula, New Zealand and Australia.

Table 1. Stratigraphical distribution of the dinoflagellate cyst taxa identified in the Sur Río Chico borehole, ordered following the highest occurrences. Taxa interpreted as downhole contaminants (c).

Table 2. Stratigraphical distribution of the nannofossil taxa identified in the Sur Río Chico borehole, ordered following the highest occurrences. Taxa interpreted as downhole contaminants (c).

Table 3. Taxonomic list of dinoflagellate cysts contained in the SRC borehole, Austral Basin. References follow Williams et al. (2017).

Table 4. Taxonomic list of nannofossils contained in the SRC borehole, Austral Basin.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Table 1.

Age	Depth (mbsf) - samples	Dinoflagellate indet	Deflandrea spp.	Hystrichokolpoma spp.	Hystrichosphaeridium tubiferum	Hystrichosphaeridium tenuitubatum	Lejeunecysta spp.	Operculodinium spp.	Spiniferites spp.	H. tenuitubatum/truswelliae	Hystrichosphaeridium truswelliae	Selenopemphix nephroides	Spinidinium macmurdoense	Vozzhennikovia spp.	Glaphyrocysta spp.	Cerodinium diebelii	Cordosphaeridium fibrospinosum	Cordosphaeridium/Danea complex	Cordosphaeridium spp.	Danea californica	Dapsilidinium pastielsii	Hystrichokolpoma proprium	Impagidinium sp. cf. I. cristatum	Membranilarnacia sp. cf. M. ?picena	Pervosphaeridium	Riculacysta perforata	Palaeoperidinium pyrophorum	Senoniasphaera inornata	Sepispinula ancorifera	Spiniferella cornuta	Tanyosphaeridium indet	Alisocysta margarita	Glaphyrocysta texta	Hystrichokolpoma bulbosum	Pierceites pentagonus	Riculacysta spp.	Tanyosphaeridium salpinx
Eocene	950-955	3	58	8	5	6	6		19	32	7	2	2	2																							
Eocene	955-960	7	28		1	2	1	6	10	3	1	1	1		4																						
Danian	965-970	24	7	1	26	1	1	19	46						4	3	11	25	21	6	1*	3	4	3	2		3	1	3	1	1						
Danian	975-980	34	1	1	10	12	14	12	40						1		12	1	3						1	4	110	1		6		1	15	1	1	1	1
Danian	980-985	25	2	3	6	21	3	29	37						18	2	5	5	4	4					2	53	44	3		15	5		2	2	4		5
Danian	985-990	2	3	3	13			8	34						7	2		7	7	1			2	2	17	1	17	1		10	5		2				2
Late Maastr	990-1000	38		4	6			13	41								5		64						4									1			3
Late Maastr	1000-1003	45			9				56						1	1	3		26	1c					2	6									2		2
Early Maastrich.	1003-1005	3c						1c	3																											1	
Early Maastrich.	1005-1010	6			6				12											1														1			
Early Maastrich.	1010-1015	10						1	3																												
Early Maastrich.	1015-1020	45			3			3	2						1																						

Table 1. Continuation

Age	Depth (mbsf) - samples	Tanyosphaeridium salpinx	Tanyosphaeridium xantiopyxides	Turbiosphaera galatea	Andalusiella/Palaeocystodinium	Cannosphaeropsis utinensis	Cassidella cornuta	Cerodinium striatum	Hafniasphaera delicata	Heteraulacacysta	Hystrichosphaeridium tubiferum brevispinum	Nematosphaeropsis rigida	Pterodinium cf. cretaceum	Spinidinium spp.	Vozzhennikovia angulata	Alisocysta circumtabulata	Manumiella bertodano	Manumiella conorata	Manumiella seelandica	Manumiella seelandica/bertodano	Phelodinium magnificum	Diconodinium lurense	Cerodinium medcalfii	Deflandrea galeata	Fibrocysta bipolaris	Isabelidinium spp.	Lacinadinium sp.	Membranilarnacia ?tenella	Alterbidinium acutulum	Cribroperidinium spp.	Isabelidinium cretaceum	Andalusiella guersteinae	Chatangiella tripartita	Manumiella seymourensis	Palaeocystodinium pilosum	Xenascus ceratioides	Total
Eocene	950-955																																				153
Eocene	955-960																																				65
Danian	965-970																																				235
Danian	975-980	1	1	15																																	298
Danian	980-985	5	3	6	3	1	1	2	2	1	1	1c	1	1																							340
Danian	985-990														3	2			2																		152
Late Maastr	990-1000														3					1		2	3	1	43	64	13	1									310
Late Maastr	1000-1003	2	1																			6	17	7	35	83	1	1	1	3	1	2	1	1			313
Early Maastr.	1003-1005						1c															1c	4c														13
?Early Maastr.	1005-1010				4																								1								31
?Early Maastr.	1010-1015				1																							3		4	131	6					159
?Early Maastr.	1015-1020				3																							1		13	105	3	2	30	1	2 45	259

Table 2.

Age	Depth (mbsf) - samples	Chiasmolithus bidens	Coccolithus pelagicus	Pontosphaera multipora	Pontosphaera obliquipons	Pontosphaera pulchra	Reticulofenestra bisecta	Reticulofenestra dictyoda	Reticulofenestra filewiczii	Reticulofenestra minuta	Toweius eminens	Toweius callosus	Toweius occultatus	Zygrhablithus bijugatus	Chiasmolithus consuetus	Cruciplacolithus latipons	Cruciplacolithus primus	Markalius apertus	R. hampdenensis	Toweius serotinus	Cyclagelosphaera alta	Neococcolithes protenus	Prinsius martinii	Toweius rotundus	Cervisiella operculata	Chiasmolithus danicus	Hornibrookina teuriensis	Markalius apertus	Prinsius dimorphosus	Prinsius martinii	Cervisiella saxea	Holodiscolithus solidus	Placozygus sigmoides	Thoracosphaera heimii	Braarudosphaera bigelowi	Cruciplacolithus edwardsii
Ypresian	950-955	14	8	1	1	1	1	18	13	9	20	3	57	1																						
	955-960	5	10	3		8		14	4	17	15	15	47		1	1	1	1	1	1																
	960-965	3	10		2			18	15	2	2	2	16		1		1					1	1	3	1	4	2									
Danian	965-970		3					12c	5c	1c			3c		2		2						2	1	16	5	1	2	5	1						
	970-975		7		1c			7c	6c	1c			5c												32	3		3		3	1	1				
	975-980							2c	1c								2								8	2				2			1			
	980-985		2				8c	23c	6c	4c							2								12	1	2	10					1	1	1	
	985-990		2				4c	11c	3c								1								35	2	3	10					1	1	1	4
	990-995																																			
L. Maast.	995-1000																																			
	1000-1003																																			
	1003-1005																																			
E. Maast.	1005-1010																																			
	1010-1015																																			
	1015-1020																																			

Table 2. Continuation.

Age	Depth (mbsf) - samples	Cruciplacolithus tenuis	Markalius inversus	Reticulofenestra bisecta	Neochiastozygus concinnus	Prinsius tenuiculus	Ahmuellerella octoradiata	Arkhangelskiella cymbiformis	A. maastrichtiana	...scutum melaniae	B. jinscaia signata	Cribrosphaerella ehrenbergi	Eiffellithus turriseiffelii	Gartnerago segmentum	Helicolithus trabeculatus	Kamptnerius magnificus	Micula concava	Micula staurophora	Nephrolithus frequens	Prediscosphaera spinosa	Prediscosphaera stoveri	Repagulum parvidentatum	Retecapsa crenulata	Amphizygus brooksii	Biscutum coronum	Chiastozygus garrisonii	Cretarhabdus conicus	Microrhabdulus belgicus	Prediscosphaera cretacea	P. microrhabdulina	Rhagodiscus splendens	Staurolithites crux	C. synquadriperforatus	Cyclagelosphaera reinhardtii	Total
Ypresian	950-955																																		181
	955-960																																		184
	960-965																																		176
Danian	965-970																																		30
	970-975																																		43
	975-980																																		13
	980-985	1	3	8c	1																														33
	985-990			4c		2																													59
	990-995						2	2	8	2	1	3	5	1	2	3	41	38	1	4	4	1	2												130
L. Maast.	995-1000						4	12	18			2	6		2	26	8	7	24	5	23		4	1	4	1	1	2	4	2	1	6			165
	1000-1003	1					4	2				4	4	2		10	2	9	10	10	8						2						1	2	76
	1003-1005																																		
E. Maast.	1005-1010																																		
	1010-1015																																		
	1015-1020																																		

Alisocysta circumtabulata (Drugg, 1967) Stover and Evitt, 1978

Alisocysta margarita Harland, 1979a

Alterbidinium acutulum (Wilson, 1967b) Lentin and Williams, 1985

Andalusiella guersteiniae Ottone *et al.*, 2018

*Cannosphaeropsis utinensis (*Wetzel, 1933b) emend. May, 1980; Duxbury, 1980; Sarjeant, 1985*b*; Marheinecke, 1992

*Carpatella cornuta (*Grigorovich, 1969a) emend. Fechner and Mohr, 1986; Damassa, 1988

Cerodinium diebelii (Alberti, 1959b) Lentin and Williams, 1987

Cerodinium medcalfii (Stover, 1974) Lentin and Williams, 1987

Cerodinium striatum (Drugg, 1967) Lentin and Williams, 1987

Chatangiella tripartita (Cookson and Eisenack, 1960a) Lentin and Williams, 1976 emend. Cookson and Manum, 1964

Cordosphaeridium fibrospinosum Davey and Williams, 1966b emend. Davey, 1969c

Cordosphaeridium spp.

Cordosphaeriium/*Damassadinium* complex

Cribroperidinium spp.

Cribroperidinium muderongense (Cookson and Eisenack, 1958) Davey, 1969a

Danea californica (Drugg, 1967) Stover and Evitt (1978)

Dapsilidinium pastielsii (Davey and Williams, 1966b) Bujak et al., 1980

Deflandrea antarctica Wilson, 1967a

Deflandrea galeata (Lejeune-Carpentier, 1942) Lentin and Williams, 1973 emend. Lejeune-Carpentier and Sarjeant, 1981

Deflandrea granulata Menéndez, 1965

Deflandrea spp.

Diconodinium lurense Guerstein *et al.*, 2005

Fibrocysta bipolaris (Cookson and Eisenack, 1965b) Stover and Evitt, 1978

Glaphyrocysta spp.

Glaphyrocysta texta (Bujak, 1976) Stover and Evitt, 1978

Hafniasphaera delicata Fensome *et al.* 2009

Heteraulacacysta

Hystrichokolpoma bulbosum (Ehrenberg, 1837b) Morgenroth, 1968 emend. Morgenroth, 1968

Hystrichokolpoma proprium (Marheinecke, 1992) Foucher in Fauconnier and Masure, 2004

Hystrichokolpoma spp.

Hystrichosphaeridium tenuitubatum Marheinecke, 1992

Hystrichosphaeridium truswelliae Wrenn and Hart, 1988

Hystrichosphaeridium tubiferum (Ehrenberg, 1837b) Deflandre, 1937b emend. Davey and Williams, 1966b

Hystrichosphaeridium tubiferum subsp. brevispinum (Davey and Williams, 1966b) Lentin and Williams, 1973 emend. Marheinecke, 1992

Impagidinium sp. cf. *I. cristatum* (May, 1980) Lentin and Williams, 1981

Isabelidinium cretaceum (Cookson, 1956) Lentin and Williams, 1977a

Isabelidinium spp.

Lacinadinium

Lejeunecysta spp.

Manumiella bertodano Thorn et al. 2009

Manumiella conorata (Stover, 1974) Bujak and Davies, 1983

Manumiella seelandica (Lange, 1969) Bujak and Davies, 1983 emend. Firth, 1987

Manumiella seelandica/*bertodano*

Manumiella seymourensis Askin, 1999

Membranilarnacia sp. cf. *M. picena* Biffi and Manum, 1988 emend. Zevenboom and Santarelli in Zevenboom, 1995

Membranilarnacia sp. cf. *M. tenella* Morgenroth, 1968

Operculodinium spp.

Palaeocystodinium pilosum Guler *et al.* 2005

Palaeoperidinium pyrophorum (Ehrenberg 1837b) Sarjeant, 1967b emend. Sarjeant, 1967b; Gocht and Netzel, 1976; Evitt et al., 1998

Pervorsphaeridium spp.

Phelodinium magnificum (Stanley, 1965) Stover and Evitt, 1978

Pierceites pentagonus (May, 1980) Habib and Drugg, 1987

Pterodinium cf. *cretaceum* Slimani et al. 2008

Riculacysta perforata Stover, 1977

Riculacysta spp.

Selenopemphix nephroides Benedek, 1972

Senoniasphaera inornata (Drugg, 1970b) Stover and Evitt, 1978

Sepispinula ancorifera (Cookson and Eisenack, 1960a) Islam, 1993 emend. Cookson and Eisenack, 1968

Spinidinium macmurdoense (Wilson, 1967a) Lentin and Williams, 1976

Spinidinium spp.

Spiniferella cornuta (Gerlach, 1961) Stover and Hardenbol, 1994

Spiniferites spp.

Tanyosphaeridium spp.

Tanyosphaeridium salpinx Norvick, 1976

Tanyosphaeridium xanthiopyxides (Wetzel, 1933b) Stover and Evitt, 1978 emend. Morgenroth, 1968; Sarjeant, 1985

Turbiosphaera galatea Eaton, 1976

Vozzhennikovia angulata Wilson, 1988

*Vozzhennikovia apertura (*Wilson, 1967a) Lentin and Williams, 1976

Vozzhennikovia spp.

Xenascus ceratioides (Deflandre, 1937b) Lentin and Williams, 1973

Ahmuellerella octoradiata (Górka, 1957) Reinhardt and Górka, 1967

Amphizygus brooksii Bukry, 1969

Arkhangelskiella cymbiformis Vekshina, 1959

Arkhangelskiella maastrichtiana Burnett, 1998b

Biscutum coronum Wind and Wise in Wise and Wind, 1977

Biscutum melaniae (Górka, 1957) Reinhardt, 1969

Braarudosphaera bigelowii (Gran and Braarud, 1935) Deflandre, 1947

Broinsonia signata (Noël, 1969) Noël, 1970

Cervisiella operculata (Bramlette and Martini 1964) Streng, Hildebrand-Habel and Williams 2004

Cervisiella saxea (Stradner 1961) Hildebrand-Habel, Willems, and Versteegh 1999

Chiasmolithus consuetus (Bramlette and Sullivan, 1961) Hay and Mohler, 1967

Chiasmolithus bidens (Bramlette and Sullivan, 1961) Hay and Mohler, 1967

Chiasmolithus danicus (Brotzen, 1959) Hay and Mohler, 1967

Chiastozygus garrisonii Bukry, 1969

Chiastozygus synquadriperforatus Bukry, 1969

Coccolithus pelagicus (Wallich, 1871) Schiller, 1930

Cretarhabdus conicus Bramlette and Martini, 1964

Cribrosphaerella ehrenbergii (Arkhangelsky, 1912) Deflandre in Piveteau, 1952

Cruciplacolithus edwardsii Romein, 1979

Cruciplacolithus latipons Romein, 1979

Cruciplacolithus primus Perch-Nielsen, 1977

Cruciplacolithus tenuis (Stradner, 1961) Hay and Mohler in Hay et al. 1967

Cyclagelosphaera alta Perch-Nielsen (1979)

Cyclagelosphaera reinhardtii (Perch-Nielsen, 1968) Romein, 1977

Eiffellithus turriseiffelii (Deflandre in Deflandre and Fert, 1954) Reinhardt, 1965

Gartnerago segmentatum (Stover, 1966) Thierstein, 1974

Helicolithus trabeculatus (Górka, 1957) Verbeek, 1977

Holodiscolithus solidus (Deflandre in Deflandre and Fert, 1954) Roth, 1970

Hornibrookina teuriensis Edwards, 1973

Kamptnerius magnificus Deflandre, 1959

Markalius apertus Perch-Nielsen 1979

Markalius inversus (Deflandre in Deflandre and Fert, 1954) Bramlette and Martini, 1964

Microrhabdulus Belgicus Hay and Towe, 1963

Micula concava (Stradner in Martini and Stradner, 1960) Verbeek, 1976

Micula staurophora (Gardet 1955), Thierstein, 1974

Neochiastozygus concinnus (Martini, 1961) Perch-Nielsen, 1971

Neococcolithes protenus (Bramlette and Sullivan, 1961) Hay and Molher, 1967

Nephrolithus frequens Górka 1957

Placozygus sigmoides (Bramlette and Sullivan, 1961) Romein 1979

Pontosphaera multipora (Kamptner, 1948 ex Deflandre in Deflandre and Fert, 1954) Roth, 1970

Pontosphaera obliquipons (Deflandre in Deflandre and Fert, 1954) Romein, 1979

Pontosphaera pulchra (Deflandre in Deflandre and Fert, 1954) Romein, 1979

Prediscosphaera cretacea (Arkhangelsky, 1912) Gartner, 1968

Prediscosphaera microrhabdulina Perch-Nielsen, 1973

Prediscosphaera spinosa (Bramlette and Martini, 1964) Gartner, 1968

Prediscosphaera stoveri (Perch-Nielsen 1968) Shafik and Stradner, 1971

Prinsius dimorphosus (Perch-Nielsen, 1969) Perch-Nielsen, 1977

Prinsius martinii (Perch-Nielsen, 1969) Haq 1971

Prinsius tenuiculus (Okada and Thierstein, 1979) Perch-Nielsen, 1984

Repagulum parvidentatum (Deflandre and Fert, 1954) Forchheimer, 1972

Retecapsa crenulata (Bramlette and Martini, 1964) Grün in Grün and Allemann, 1975

Reticulofenestra bisecta (Hay, Mohler and Wade, 1966) Roth, 1970

Reticulofenestra dictyoda (Deflandre in Deflandre and Fert, 1954) Stradner in Stradner and Edwards, 1968

Reticulofenestra filewiczii (Wise and Wiegard in Wise, 1983) Dunkley et al., 2009

Reticulofenestra hampdenensis Edwards, 1973

Reticulofenestra minuta Roth, 1970

Rhagodiscus splendens (Deflandre, 1953) Verbeek, 1977

Staurolithites crux (Deflandre and Fert, 1954) Caratini, 1963

Thoracosphaera heimii (Lohmann, 1920) Kamptner, 1944

Toweius callosus Perch-Nielsen, 1971

Toweius eminens (Bramlette and Sullivan, 1961) Perch-Nielsen, 1971

Toweius occultatus (Locker, 1967) Perch-Nielsen, 1971

Toweius rotundus Perch-Nielsen in Perch-Nielsen et al., 1978

Toweius serotinus Bybell and Self-Trail, 1995

Zygrhablithus bijugatus (Deflandre in Deflandre and Fert, 1954) Deflandre, 1959

Maastrichtian to Danian dinoflagellate cyst and nannofossil biostratigraphy

Late Maastrichtian and middle Danian assemblages were recognized

Manumiella acme and the nannofossils assemblages reflected cool nutrient–rich waters

Palaeoperidinium pyrophorum acme indicated cool water episode in Patagonia