

Middle Palaeogene dinoflagellate cysts from Tierra del Fuego, Argentina: biostratigraphy and palaeoenvironments

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ABSTRACT – Palynological data from four surface sections in northern Tierra del Fuego, southern Argentina, provide a biostratigraphical and palaeoenvironmental framework for the lower member of the La Despedida Formation and the Cabo Peña Formation in their type areas. Selected dinoflagellate cyst (dinocyst) events indicate that the age of the lower member of the La Despedida Formation is Middle Eocene and that of the Cabo Peña Formation is Late Eocene–earliest Oligocene. The age assigned to the La Despedida Formation agrees with determinations based on calcareous microfossils, but there is a potential discrepancy regarding the Cabo Peña Formation. According to recent stratigraphic studies, the Cabo Domingo Group, which includes the Cabo Peña Formation, is Late Eocene–Miocene in age. The palynomorph assemblages from the lower member of the La Despedida Formation contain the endemic ‘Transantarctic Flora’, which reflects marginal marine conditions. The maximum abundance of *Enneadocysta* spp. reflects more open-sea conditions and a warming event during the late Middle Eocene. The lower part of the Cabo Peña Formation has a high ratio of dinocysts to sporomorphs and an abundance of *Nematosphaeropsis lemniscata*, *Reticulatosphaera actinocoronata* and *Impagidinium* spp., suggesting an oceanic to outer neritic environment. Abundant *Gelatinia inflata* and protoperidiniacean cysts indicate cool surface waters rich in dissolved nutrients. These cold-water markers may reflect the development of the Antarctic Circumpolar Current, an important event in the transition from a greenhouse to an icehouse climate mode. Toward the top of the sections, the lower ratios of dinocysts to sporomorphs, as well as the composition of the dinocyst assemblages, reflect a neritic rather than an oceanic setting. This palynological change may be due to eustatic sea-level lowering caused by cooling during the latest Eocene–earliest Oligocene. A new species, *Spiniferites scalenus*, is described and the new combination *Lingulodinium echinatum* proposed; an emendation for the latter species is also proposed. *J. Micropalaeontol.*, 27(1): 75–94, May 2008.

KEYWORDS: *Dinoflagellates, Palaeogene, biostratigraphy, palaeoenvironments, Argentina*

INTRODUCTION

Global cooling during the Palaeogene is demonstrated by the ¹⁸O record from benthic foraminifera (Zachos *et al.*, 2001). The record shows a gradual decline in global temperature from about 50 Ma (Early Eocene), with a significant cooling-glaciation event (Oi-1) at the Eocene–Oligocene boundary (33–34 Ma). This event was followed by a cold interval of about 12 million years, with the East Antarctica ice sheet growing during this time.

The mechanisms that led to the abrupt Eocene–Oligocene climate deterioration and the growth of extensive ice sheets in Antarctica is the subject of debate. Several authors (e.g. Kennett, 1977; Barker, 2001) considered that Palaeogene cooling was caused by thermal isolation of Antarctica, resulting from the opening of deep-water gateways (Tasman Gateway and Drake Passage) and subsequent development of the Antarctic Circumpolar Current (ACC). Other models are based on a decline in CO₂ (for example, DeConto & Pollard, 2003; Huber *et al.*, 2004; Pagani *et al.*, 2005), the closure of a circum-equatorial seaway (Lawver & Gahagan, 2003) and tectonic uplift (Raymo & Ruddiman, 1992). On the basis of marine geophysical data, Livermore *et al.* (2005) identified a major change in the relative motion of the South American and Antarctic plates at about 50 Ma. These authors considered that a connection between the Pacific and Atlantic oceans at Drake

Passage probably had a profound effect on global circulation and climate. Furthermore, they found a close correlation between crustal evolution and climatic events, reflected by the oxygen isotope record from benthic foraminifera.

The analysis of Palaeogene organic-walled, dinoflagellate cyst (dinocyst) assemblages provides a powerful biostratigraphic and palaeoclimatic tool (Sluijs *et al.*, 2005 and references therein). Data from dinocysts play an important role in evaluating different general circulation models when reconstructing Southern Ocean circulation (Huber *et al.*, 2004). Middle Palaeogene dinocyst information from Tierra del Fuego and Patagonia is potentially of great value but presently is scarce; moreover, most of the published papers are in Spanish (Menendez, 1965; Pöthe de Baldi, 1966; Archangelsky, 1969; Guerstein *et al.*, 2002).

Marine Palaeogene rocks, which crop out in northern Tierra del Fuego, southern Argentina, contain diverse dinocyst assemblages. Guerstein *et al.* (2002) published the results of a preliminary study of dinocysts from the Cabo Peñas and Cerro Águila sections (Fig. 1) of the Cabo Peña Formation (De Ferrariis, 1938). According to these authors the sediments are Late Eocene–Early Oligocene.

In this paper, a detailed biostratigraphical analysis of the dinocyst assemblages from the Cabo Peña Formation in the Cabo Peñas and Cerro Águila sections is presented, plus new

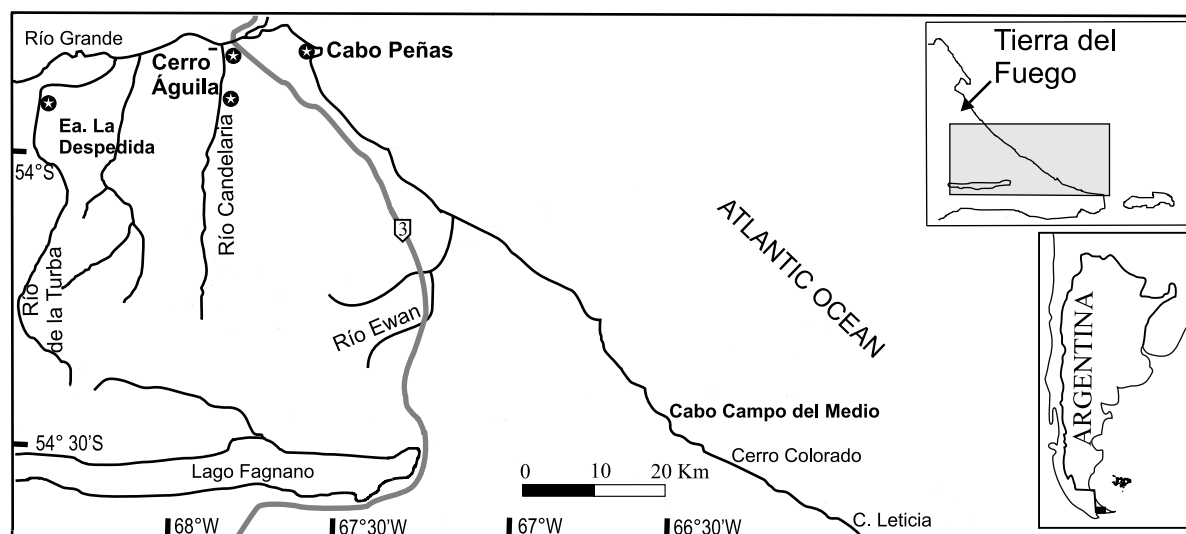


Fig. 1. Map of Tierra del Fuego showing studied localities.

data from the Río Candelaria section. Also included are results of analysis of the middle Eocene La Despedida Formation, which is exposed along the Río de la Turba (Fig. 1). Using this information, a reconstruction of palaeoclimatic trends for the middle Palaeogene of Tierra del Fuego is attempted. Observations from Tierra del Fuego are compared with coeval dinocyst datasets from other circum-Antarctic areas. The middle Palaeogene was a critical time in the evolution of Southern Ocean circulation and the transition from a greenhouse to an icehouse Earth.

GEOLOGICAL SETTING

The study area (Fig. 1) corresponds to the southernmost extra-andean Austral (or Magallanes) Basin, which evolved during the Late Cretaceous–Cenozoic as a foreland basin to the north of the Andes Fueguinos (Biddle *et al.*, 1986; Olivero & Malumíán, 1999). The tectonic history of the area during the Palaeogene is linked to the separation of South America from Antarctica and the opening of Drake Passage. According to Livermore *et al.* (2005), marine geophysical data reveal movement between the South American and Antarctic plates about 50 million years ago. These authors postulated that plate movements led to the formation of a gateway, about 1000 m deep, during the Middle Eocene. Although there were no significant changes near the Eocene–Oligocene boundary, continued extension developed a deep-water connection between 34 and 30 Ma.

Malumíán (1999) proposed five transgressive–regressive events for extra-andean Patagonia in the Cenozoic. In northern Tierra del Fuego, two marine Palaeogene units crop out in small sections: the La Despedida Formation (Doello-Jurado, 1922); and the Cabo Peña Formation. These units correspond to the second and third cycles of Malumíán (1999) and are of Middle Eocene and Late Eocene–Early Oligocene age respectively.

In a detailed stratigraphical and micropalaeontological study of northern Tierra del Fuego, Codignotto & Malumíán (1981) proposed that the Middle Eocene La Despedida Formation is overlain by the Cabo Peña Formation, although the contact is not exposed. Based on the presence of the foraminiferid

Elphidium saginatum, Codignotto & Malumíán (1981) and Malumíán (1988) determined that the lower of their two informal members of the La Despedida Formation is Middle Eocene. The upper member contains the *Cribrorotalia* cf. *C. tainuia* assemblage and was considered late Middle to Late Eocene.

In a study of the ‘Estratos de Leticia’ (Furque & Camacho, 1949), Olivero & Malumíán (1999) defined the La Despedida Group with three lithological units, from which the middle Leticia Formation middle unit, late Mid-Eocene in age, corresponds to the lower member of the La Despedida Formation outcropping along the Río de la Turba.

Codignotto & Malumíán (1981) and Malumíán & Caramés (1989) indicated a Late Eocene–Early Oligocene age for the Cabo Peña Formation at its type section. There the formation is overlain by the Cullen Formation (Petersen in Petersen & Methol, 1948). Because of the presence of the *Martinottiella–Spirosigmoinella* foraminiferid assemblage, the Cabo Peña was interpreted to be the same age in the Cerro Águila section, where it is overlain by the Cerro Águila Conglomerate (De Ferrariis, 1938).

Such was the state of knowledge until Malumíán & Olivero (2006) included the Cabo Peña Formation in the Cabo Domingo Group. They considered the age of the group to be Late Eocene–Middle Miocene. In a later paper, Olivero & Malumíán (2008, fig. 1) show an accompanying illustration, which implies that the age of the Cabo Peña is Late Chattian to Early Miocene. Unfortunately, the data substantiating this change are not given and the findings seem to be at odds with our age, based on the palynomorphs. Further studies are needed to resolve this issue.

MATERIALS AND METHODS

Processing of the samples for palynomorphs involved hydrochloric and hydrofluoric acids, followed by mild oxidation with nitric acid. The organic fraction was concentrated by separation in heavy liquids. The residues were sieved through screens of 10, 25 and 180 µm and stained with Bismarck C. Cabo Peña and Cerro Águila samples were processed at the Geological Survey

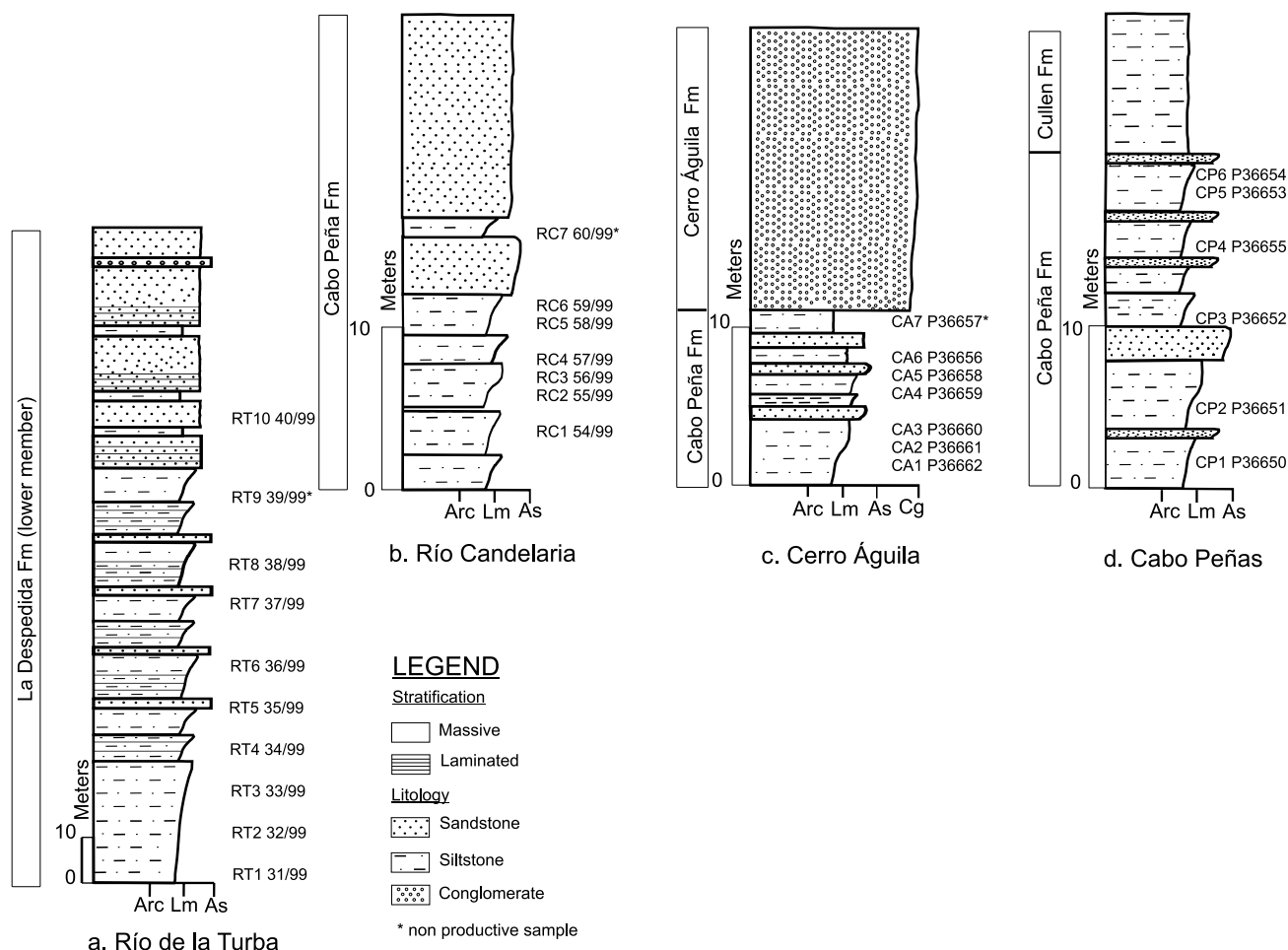


Fig. 2. Stratigraphical sections with field and laboratory sample numbers indicated.

of Canada (Atlantic) and the residues mounted in elvacite and cellosize substitute. The Río Candelaria and La Despedida samples were processed at the Museo de Ciencias Naturales, Bernardino Rivadavia, Buenos Aires and the material was mounted in glycerine jelly.

Light microscopy was undertaken using a Nikon Eclipse 600 microscope and an attached Nikon Coolpix 950 digital camera. Coordinates quoted are from the Vernier scale of microscope serial n° 772751, and follow the sample and slide number for each illustrated specimen. England Finder (EF) references are provided in the explanations of plates. The type and figured specimens are housed in the collection of the Laboratorio de Palinología, Universidad Nacional del Sur, Bahía Blanca, Argentina. The ElectroScan E3 environmental scanning electron microscope (SEM) at the Geological Survey of Canada (Atlantic) was used under a partial pressure of water vapour. All the specimens were coated with gold prior to scanning. The geological time-scale of Gradstein *et al.* (2004) and – except where indicated – the dinoflagellate cyst nomenclature of Fensome & Williams (2004) is followed.

The type section of La Despedida Formation is 550 m thick, with a mainly grey, pelitic lower member and a sandy upper member (Malumián, 1988). Ten samples were processed from the lower member for palynological analysis (Fig. 2a).

The Cabo Peña Formation consists mainly of siltstones grading upwards into silty sandstones. These are overlain by siltstones (Cullen Formation) at Cabo Peñas, by coarse-grained sandstones at Río Candelaria and by conglomeratic sandstones at Cerro Águila. The eighteen palynological samples that were productive were from the lower silty levels (Figs 2b–d).

SYSTEMATIC PALYNOLOGY

Division **Dinoflagellata** (Bütschli, 1885) Fensome *et al.*, 1993

Subdivision **Dinokaryota** Fensome *et al.*, 1993

Class **Dinophyceae** Pascher, 1914

Subclass **Peridiniphyceae** Fensome *et al.*, 1993

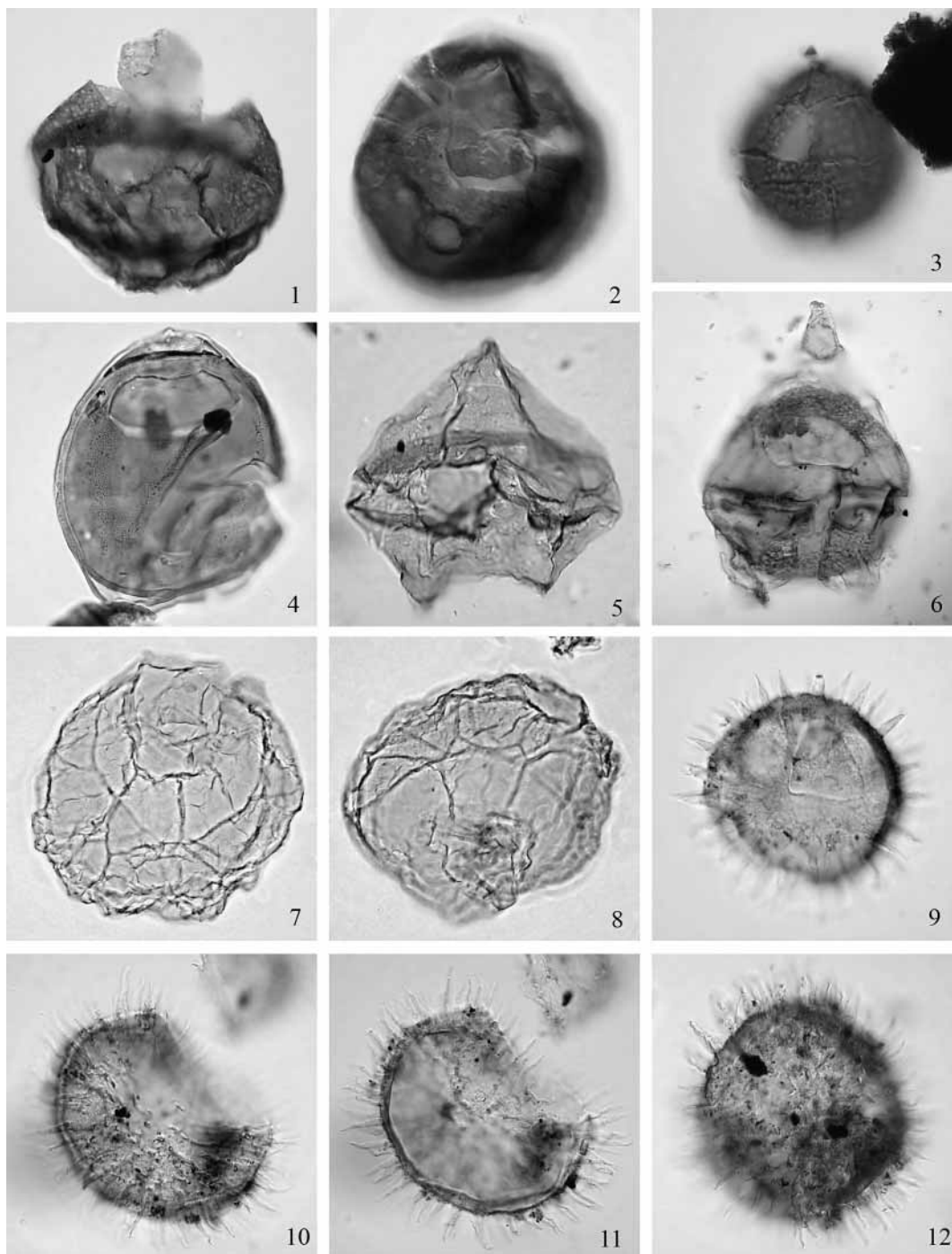
Genus *Brigantedinium* Reid, 1977 ex Lentin & Williams, 1993

Brigantedinium ? spp.

(Pl. 1, fig. 2)

Occurrence. Río Candelaria section, RC1–RC5.

Remarks. This group includes round-brown forms, which are generally poorly preserved and have a single, usually wrinkled wall. All the specimens have a thinner wall than modern representatives of *Brigantedinium*. This could be due to preservation, since a thin wall has also been observed in some species



Explanation of Plate 1.

In Plates 1, 2, 4 and 5, the Laboratorio de Palinología, Universidad Nacional del Sur collection number is followed by slide numbers and England Finder references. A Nikon Eclipse 600 microscope fitted with Nomarski differential interference contrast (DIC) was used except where indicated.

fig. 1. *Batiacasphaera compti*: LPUNS-RC4; 57/99 (1); 31/102.5; N31/3; width 60 µm; ventral view, intermediate focus. **fig. 2.** *Brigantedinium* sp.: LPUNS-RC4; 57/99 (1); 27/103.8; N28/1; width 56 µm; dorsal view, high focus. **fig. 3.** *Corrudinium incompositum*: LPUNS-RC4; 57/99 (1); 36.3/107.3; J37/3; length 47 µm, width 43 µm; right lateral dorsal view, high focus. **fig. 4.** *Deflandrea convexa*: LPUNS-CP3; P36652 (1); 43.2/100.7; Q44/3; central body width 75 µm; dorsal view, intermediate focus. **fig. 5.** *Lejeunecysta* sp.: LPUNS-RC5; 58/99 (1); 39.5/103.4; N40/3; width 65 µm; ventral view, intermediate focus. **fig. 6.** *Deflandrea scabrata*: LPUNS-RC3; 56/99 (2); 52.2/103.2; O53/4; central body width 67 µm; ventral view, low focus. **fig. 7.** *Gelatia inflata*: LPUNS-CP3; P36652 (1); 42.6/95.8; V43/1; diameter 82 µm; apical view, intermediate focus; phase contrast. **fig. 8.** *Gelatia inflata*: LPUNS-CP3; P36652 (1); 38/105; L38/4; diameter 86 µm; antapical view, intermediate focus; phase contrast. **fig. 9.** *Lingulodinium machaerophorum*: LPUNS-RC5; 58/99 (1); 37.3/111; E37/2; central body width 52 µm; ventral view, low focus showing the archaeopyle. **figs 10–11.** *Lingulodinium echinatum*: LPUNS-RC6; 59/99 (1); 48/97; T49/3; central body width 95 µm; left lateral view – **10**, high focus, **11**, intermediate focus. **fig. 12.** *Lingulodinium echinatum*: LPUNS-RC6; 59/99 (1); 29.2/100; Q29/4; central body width 64 µm; ventral view, high focus.

of *Brigantedinium* from Middle to Upper Miocene deposits in the Colorado Basin, eastern Argentina (Guler, 2003). The shape of the archaeopyle cannot be determined in most of the specimens.

Genus *Lingulodinium* Wall, 1967 emend. Dodge, 1989

Lingulodinium echinatum Menéndez, 1965 n. comb., emend.
(Pl. 1, figs 10–12)

Basionym. *Hystriospheraidium?* *echinatum* Menéndez, 1965: 12–13; pl. 2, fig. 9.

Neotype. Plate 1, figs 10–11. Río Candelaria section, 11 m above the base. UNS RC 59/99- 48/97 EF: T 49/3. Designated here.

Emended description. Chorale cysts with a subspherical central body, covered with numerous nontabular processes. Processes relatively thin, flexuous, flattened, with acuminate tips and with a length about one quarter of the cyst diameter. The wall is two-layered, with a thick endophragm and a thin, densely granular periphragm. Granules are distributed evenly along the processes. Archaeopyle precingular, type P or 2P.

Dimensions. Range of five specimens-central body 54–68 µm; length of processes 14–17 µm.

Occurrence. Río de la Turba section, RT7, RT9; Río Candelaria section, RC1–RC3, RC5–RC6.

Remarks. In the protologue, Menéndez (1965) described this species as having processes that are acuminate or truncate, or that have tips with a small expansion that appears bifurcate. However, the specimens here have processes with thin, flexuous and strongly acuminate tips; bifurcate or capitate tips were not observed. The apparently truncate ends and small bifurcations described by Menéndez (1965) possibly reflect the flexuous structure of the processes. His specimens are smaller than those described from the Cabo Peña Formation. Because of poor preservation of the slides, the holotype or any topotype material could not be located. Thus, a neotype is designated. *Lingulodinium echinatum* closely resembles *Lingulodinium pycnospinosum* but is considerably larger and has granulate processes that are not perforated by pores.

Genus *Spiniferites* Mantell, 1850 emend. Sarjeant, 1970

Spiniferites scalenus sp. nov.
(Pl. 2, figs 3–8; Pl. 3, figs 6–12)

Derivation of name. From the Latin ‘scalenus’, meaning ‘unequal’, in reference to the uneven height of the sutural crests.

Diagnosis. A species of *Spiniferites* with an elongate central body, bearing relatively short, trifurcate gonol processes, joined at their base by sutural crests of variable height. The crests vary even within a single specimen, from simple, sutural low ridges to

high, membranous septa, almost reaching the distal expansion of the processes.

Holotype. Plate 2, figs 3–4. Cerro Águila section, 0.5 m above the base. UNS CA1-P34662-1: 48/108 EF: H 49/3.

Locality and horizon. Cerro Águila Section, northeast Tierra del Fuego, Argentina. Lower part of the Cabo Peña Formation; Upper Eocene.

Description. Chorale cysts with an elongate central body bearing trifurcate gonol processes. Most of the processes are short, membranous, subtriangular in cross-section, with a central solid stem. Terminations are usually trifurcate with bifurcate ends. Generally, the processes are connected at their bases by high membranous septa of variable height. Specimens with the highest crests do not have stems but simply a trifurcate expansion at the gonol junctions of septa (Pl. 3, figs 6, 8). Septa margins are irregularly undulate to denticulate (Pl. 3, figs 5–12). The endophragm is smooth and the periphragm is microgranular to granular. The archaeopyle is precingular, type P, resulting from the loss of the 3" plate, and with a free operculum. Paratabulation gonyaulacoidean, defined by membranous septa and/or low sutural ridges and by the gonol processes. Plates 1' and 4' are generally fused (Pl. 3, figs 6, 8).

Dimensions. Holotype – central body width 38 µm; central body length 47 µm; height of sutural septa 5 µm. Range of ten specimens – central body width 28–45 µm; central body length 35–47 µm; height of sutural septa 1–7 µm.

Occurrence. Río de la Turba section, RT6, RT10; Cabo Peñas section, CP1–CP2; Cerro Águila section, CA1–CA6; Río Candelaria section, R1–R2, R4–R5.

Remarks. The new species differs from other species of *Spiniferites* by having crests of variable height. Several of the observed specimens have septa rising up to the base of the furcate process terminations. In such cases they resemble species of the genus *Impagidinium* (Pl. 2, figs 3–4; Pl. 3, figs 6, 8). Because of the presence of some processes in all specimens observed, this species has been included in *Spiniferites*.

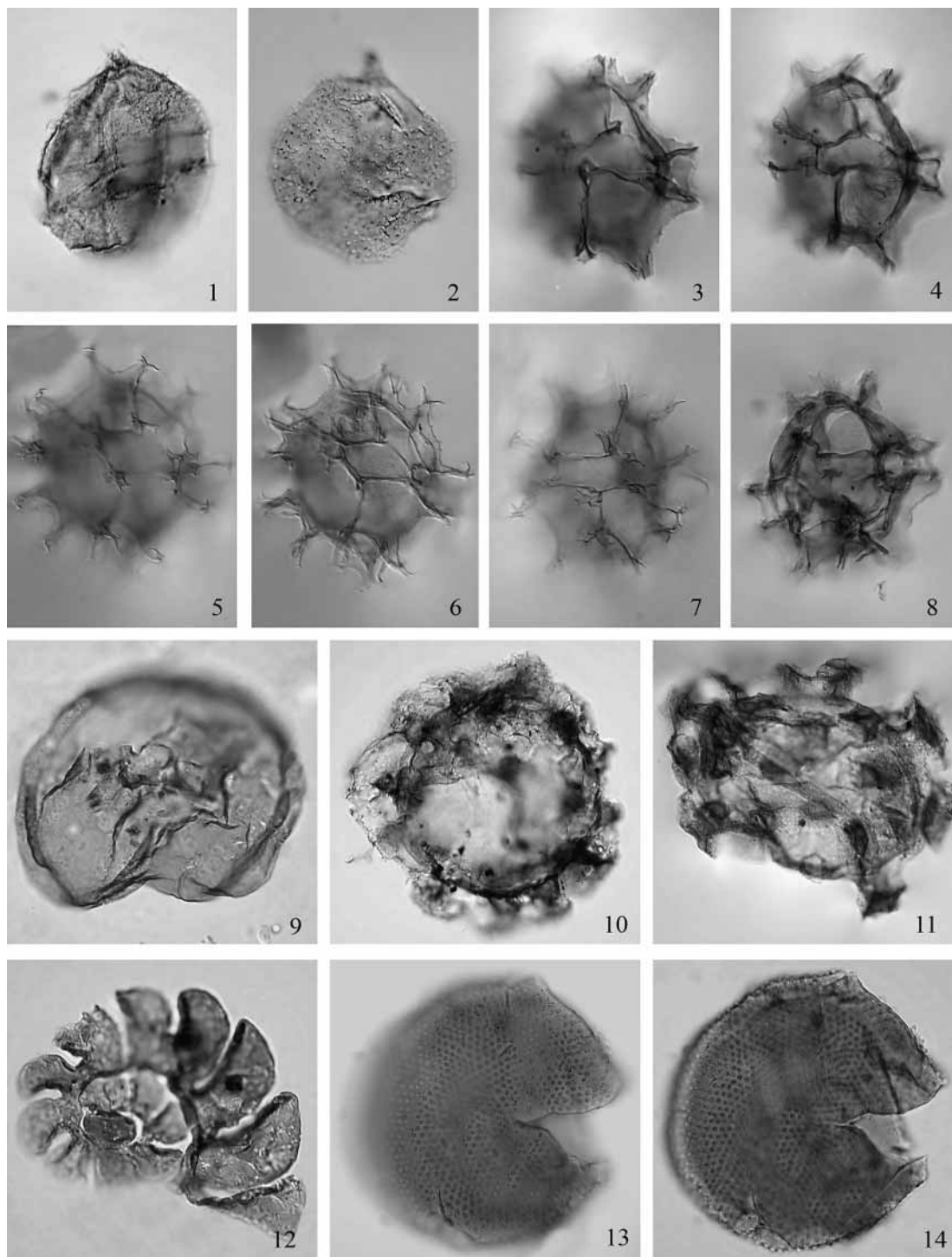
Genus *Tuberculodinium* Wall, 1967

Tuberculodinium sp.
(Pl. 2, figs 10–11)

Dimensions. Range of eight specimens – central body diameter 75–90 µm; length of processes: up to 15 µm.

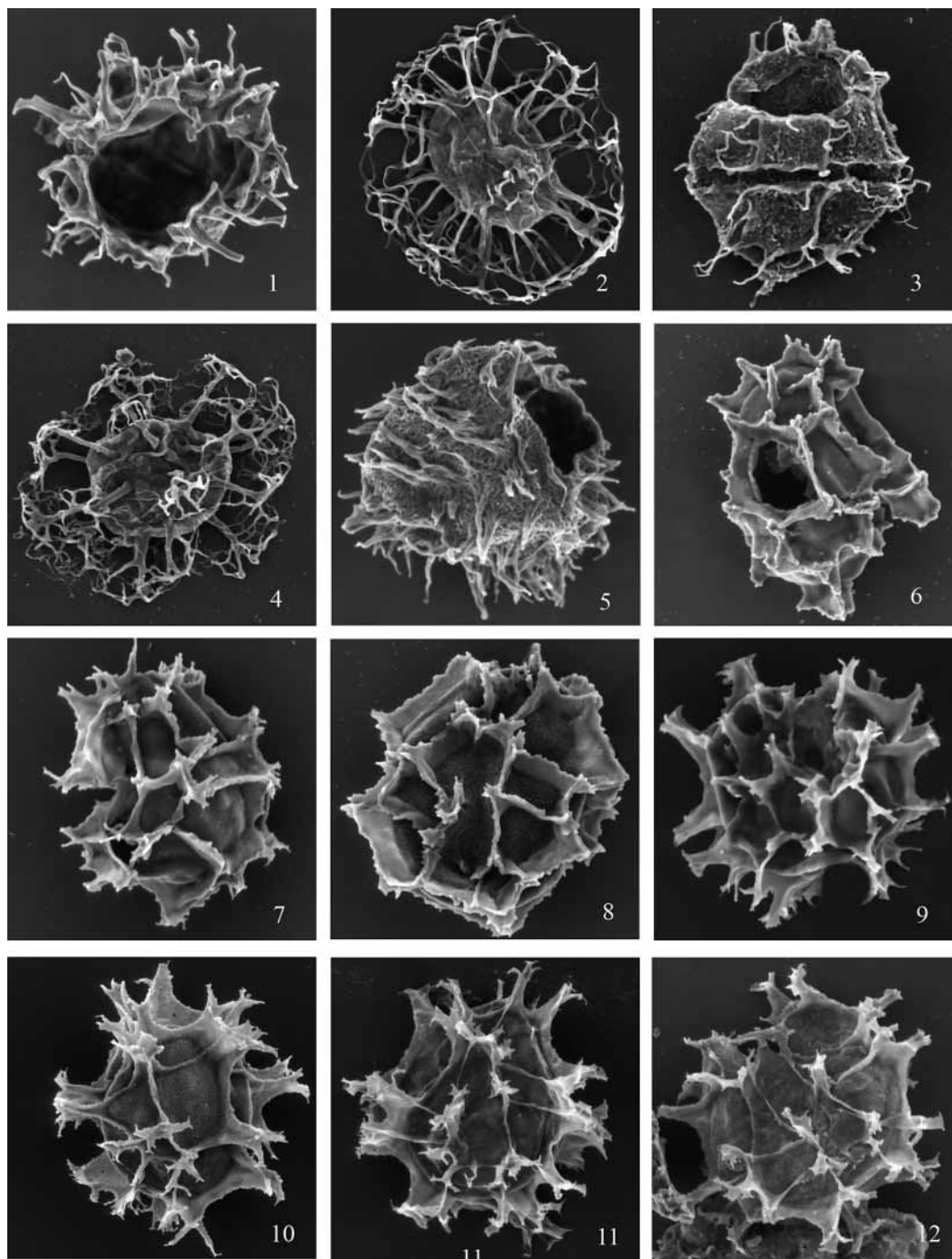
Occurrence. Cerro Águila section, CA1–CA3; Río Candelaria section, RC2–RC5.

Remarks. *Tuberculodinium* sp. differs from described species of the genus in that most of its processes have a quadrangular cross-section and support a fibroid ectophragm. Though it was not possible to assess the number and distribution of processes, some appear to be pre- and postcingular, and some appear to be cingular and apical.



Explanation of Plate 2.

fig. 1. *Phthanoperidinium echinatum*: LPUNS-CP4; P36655 (1); 48.3/101.2; P49/3; width 38 μ m; high focus. **fig. 2.** *Vozzhennikovia cearaichia*: LPUNS-CP3; P36652 (1); 37.5/106.6; J38/4; width 37 μ m; right lateral view, high focus. **figs 3–4.** *Spiniferites scalenus*: LPUNS-CA1; P36662 (1); 48/108; H49/3; central body width 38 μ m; left lateral dorsal view – 3, high focus, 4, intermediate focus. **figs 5–6.** *Spiniferites scalenus*: LPUNS-CA3; P36660 (1); 43.5/104.5; M44/1; central body width 37 μ m; oblique left lateral view – 5, high focus on the crests and processes, 6, low focus showing the archaeopyle. **fig. 7.** *Spiniferites scalenus*: LPUNS-CA1; P36662 (1); 49.5/109.5; G50/4; central body width 35 μ m; lateral view, high focus. **fig. 8.** *Spiniferites scalenus*: LPUNS-CA1; P36662 (1); 505/94.5; $\times 51/2$; central body width 35 μ m; dorsal view, high focus. **fig. 9.** *Selenopemphix nephroides*: LPUNS-RC5; 58/99 (1); 36.1/105.7; K37/3; width 75 μ m; apical view, intermediate focus. **fig. 10.** *Tuberculodinium* sp.: LPUNS-RC4; 57/99 (1); 28.3/98.7; S28/0; width 75 μ m; antapical view, high focus. **fig. 11.** *Tuberculodinium* sp.: LPUNS-CA1; P36662 (1); 39.6/113.5; C40/1; width 80 μ m; lateral view, high focus. **fig. 12.** Foraminiferal lining: LPUNS-RC4; 57/99 (1); 27/97.3; T27/3; total width 78 μ m. **figs 13–14.** Prasinophycean algae: LPUNS-RC6; 59/99 (1); 25.5/96.8; U25/2; diameter 100 μ m – 13, high focus, 14, intermediate focus.



Explanation of Plate 3.

Scanning electron photomicrographs. The specimens illustrated here are curated in the National Collection of Type Invertebrate and Plant Fossils, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A 0E8 (at the time of writing on long-term loan to the GSC Atlantic, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada B2Y 4A2). The species name is followed by the section designation, the sample number and then the National Collection ('GSC') number; further supplemental information follows that. **fig. 1.** *Cleistosphaeridium diversispinosum*: CA3; P36660; GSC 34680; central body width 48 µm; apical view. **fig. 2.** *Nematosphaeropsis lemniscata*: CA4; P36659; GSC 34681; central body width 37 µm. **fig. 3.** *Phthanoperidinium comatum*: CA3; P36660; GSC 34682; central body width 55 µm; dorsal view. **fig. 4.** *Reticulosphaera actinocoronata*: CA3; P36660; GSC 34683; central body width 33 µm. **fig. 5.** *Operculodinium centrocarpum*: CA3; P36660; GSC 34684; central body width 40 µm; left lateral view. **fig. 6.** *Spiniferites scalenus*: CA3; P36660; GSC 34685; central body width 35 µm; oblique dorsal view. **fig. 7.** *Spiniferites scalenus*: CA4; P36659; GSC 34686; central body width 35 µm; lateral view. **fig. 8.** *Spiniferites scalenus*: CA4; P36659; GSC 34687; central body width 38 µm; ventral view. **fig. 9.** *Spiniferites scalenus*: CA4; P36659; GSC 34688; central body width 40 µm. **fig. 10.** *Spiniferites scalenus*: CA4; P136659; GSC 34689; central body width 36 µm. **fig. 11.** *Spiniferites scalenus*: CA3; P136660; GSC 34690; central body width 35 µm; ventral view. **fig. 12.** *Spiniferites scalenus*: CA3; P136660; GSC 34691; central body width 38 µm; ventral view. figs 6–12 show specimens with crests of variable height.

Genus *Vozzhennikovia* Lentin & Williams, 1976

Vozzhennikovia sp.
(Pl. 4, figs 10–11)

Occurrence. Río de la Turba section, R1–R6, R10.

Remarks. This species of *Vozzhennikovia* closely resembles *V. apertura*. However, in most of the specimens here, the archaeopyle involves not only the 2a plate but also the 1a and 3a plates.

PALYNOSTRATIGRAPHY

La Despedida Formation

Figure 3 shows the distribution of dinocyst species in the lower member of the La Despedida Formation in the Río de la Turba section. In this section, the La Despedida Formation cannot be older than Middle Eocene (Lutetian–Bartonian) because of the consistent and common occurrence of *Enneadocysta dictyostila* throughout the section. *Enneadocysta dictyostila* was first described by Menéndez (1965) from Eocene–Oligocene deposits of Tierra del Fuego. Other authors mistakenly assigned specimens of this species to *Areosphaeridium diktyoplokum*, a species described by Klumpp (1953) from the Eocene of Germany (Fensome *et al.*, 2007). *Areosphaeridium diktyoplokum* has one process on the single antapical plate, whereas *Enneadocysta* has two. Stover & Williams (1995) erected *Enneadocysta partridgei* to include those specimens from the Southern Hemisphere, which had been mistakenly assigned to *Areosphaeridium diktyoplokum* and gave its first occurrence as Bartonian. Fensome *et al.* (2007) considered *Enneadocysta dictyostila* to be the taxonomic senior synonym of *Enneadocysta partridgei*. Brinkhuis *et al.* (2003a), based on calibrated information from ODP site 1172 (East Tasman Plateau), assigned an age of 48.8 Ma to the first common occurrence of *Enneadocysta dictyostila*.

Constraints to allow delineation of the minimum age of the lower member of the La Despedida Formation are more difficult to find. Because of the presence of *Hystriochsphaeridium tubiferum*, the lower part of the section (RT1 to RT5) is considered to have a minimum middle Lutetian age. According to Williams *et al.* (2004), this species has its LO in Northern Hemisphere mid-latitudes at 47 Ma (based on Bujak & Mudge, 1994). *Arachnodinium antarcticum* (Pl. 5, figs 1–2; first occurrence, FO: 51.4 Ma; last occurrence, LO: 38.8 Ma; Williams *et al.*, 2004) occurs in most of the samples up to RT7, confirming a Middle Eocene (Lutetian–Bartonian) age for most of the section. *Hystriochsphaeridium truswelliae*, which is present throughout the section, has its LO at 39 Ma, according to Brinkhuis *et al.* (2003a). It would appear to be a useful index species but occurs consistently in all three of the Cabo Peña sections. These sections also contain *Reticulatosphaera actinocoronata*, *Nematosphaeropsis lemniscata* and *Phthanoperidinium echinatum*. Since *Reticulatosphaera actinocoronata* has a first occurrence of 33.5 Ma in high latitudes and 35.3 Ma in mid latitudes (Brinkhuis *et al.*, 2003a, b), it is assumed that the true LO of *H. truswelliae* is within the Priabonian, indicating a Bartonian minimum age. The presence of *Turbiosphaera filosa* (FO: 71.3 Ma; LO: 37 Ma; Williams *et al.*, 1998) and *Pyxidinopsis delicata* (Early to Middle Eocene, according to Wilson, 1988) are

supporting evidence for a Lutetian–Bartonian age. However, a more definitive age for the upper part of the Río de la Turba section cannot be determined, except to conclude that it is within the Eocene. One possible clue is the presence of *Glaphyrocysta* spp., which is relatively uncommon in post-Middle Eocene rocks from offshore eastern Canada. However, that is too tenuous to be definitive.

A few specimens of *Odontochitina* sp., *Manumiella* sp., *Isabelidinium* sp., *Oligosphaeridium complex*, *Sepispinula ancorifera* and *Xenascus* sp. were recorded in this section. These species represent reworked material from Upper Cretaceous deposits.

Cabo Peña Formation

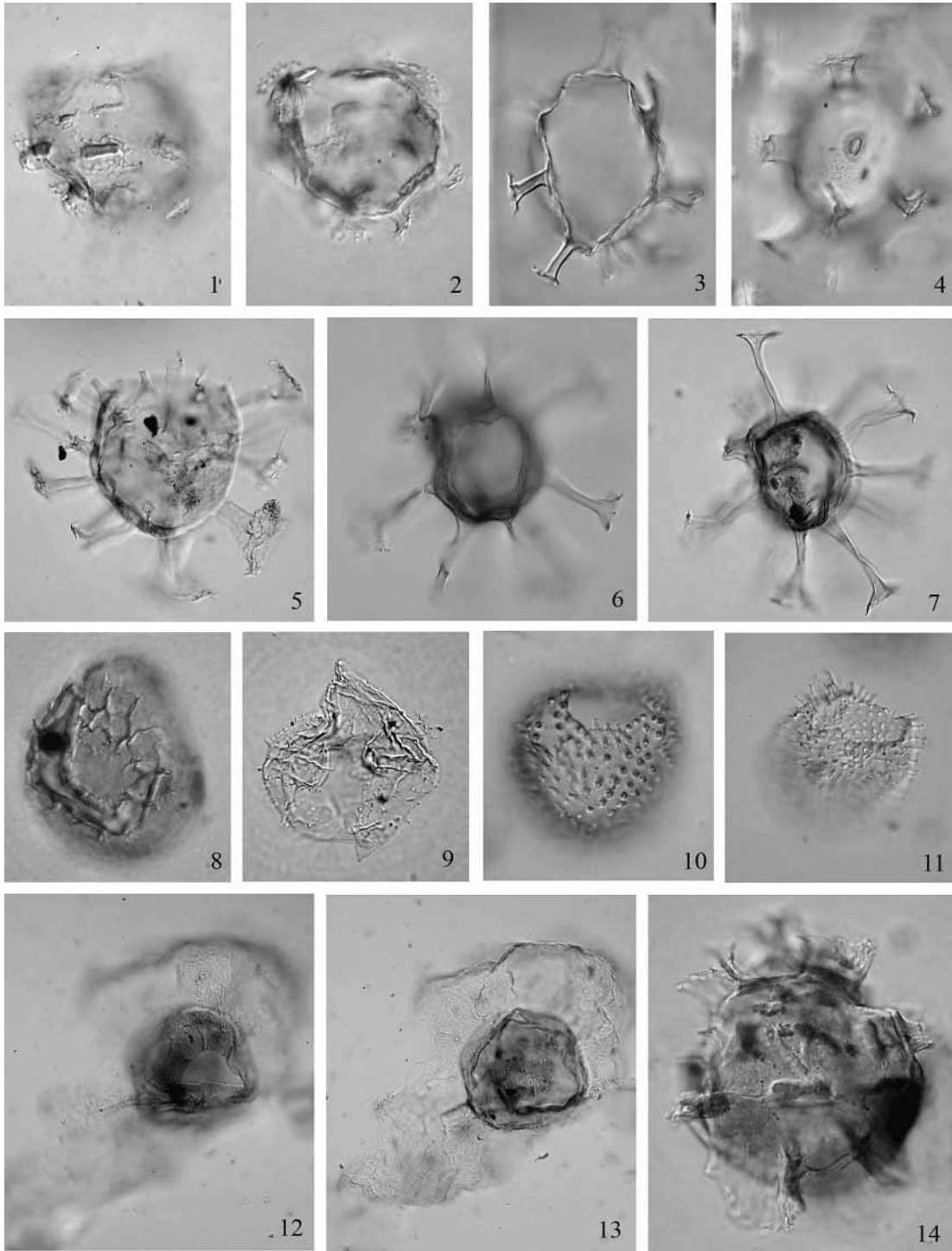
Figure 4 shows the distribution of dinocyst species in the Cabo Peñas section. Most of the species are long ranging and are common in Palaeogene deposits world-wide. The presence of *Reticulatosphaera actinocoronata*, *Gelatia inflata* and *Nematosphaeropsis lemniscata* at the base indicates an age no older than Priabonian (Late Eocene). As noted above, *Reticulatosphaera actinocoronata* has a first occurrence of 33.5 Ma in high latitudes and 35.3 Ma in mid latitudes (Brinkhuis *et al.*, 2003a, b, respectively). Brinkhuis *et al.* (2003a) and Sluijs *et al.* (2003) suggested a Magnetochron C16 base for this species, which would place it at about 36 Ma. Brinkhuis *et al.* (2003a) indicated that *Gelatia inflata* had its first occurrence at the same horizon in ODP Leg 189 sites off Tasmania.

Brinkhuis *et al.* (2003b) gave a LO for *Deflandrea convexa* at 35.8 Ma, within the Priabonian. The presence of a few specimens of this species in samples CP3 and CP4 might constrain the age of the middle part of the section to the early Priabonian.

Nematosphaeropsis lemniscata has not been recorded below the Eocene–Oligocene boundary in the Northern Hemisphere (Williams *et al.*, 1998). However, this species occurs at the base of the Cabo Peñas section, with other dinocysts that have their LOs within the Late Eocene. Thus, it is reasonable to conclude that the FO of *Nematosphaeropsis lemniscata* might be within the Priabonian in the Southern Hemisphere.

Stover & Williams (1995) and Williams *et al.* (2004) considered *Enneadocysta dictyostila* (as *Enneadocysta partridgei*) to have a LO in the Rupelian (about 31 Ma). However, Sluijs *et al.* (2003) noted that the consistent LO of *E. partridgei* at different sites from ODP Leg 189, offshore Tasmania, does not extend into the Early Oligocene. They suggested that the rare occurrence of *E. partridgei* in the Early Oligocene represents reworking. Archangelsky (1969) believed *E. dictyostila* (as *Cordosphaeridium diktyoplokum*) was probably reworked in the upper part of the Río Turbio Formation of southwest Santa Cruz Province, Argentina. Malumián (2002, chart 1), regarded the upper part of the Río Turbio Formation as early Rupelian. Stickley *et al.* (2004) indicated a last (abundant) occurrence for *Enneadocysta* spp. in ODP 1172A core at the top of Magnetochron C13n (about 33.5 Ma), extending this event into the earliest Oligocene. Based on the above, the age of the Cabo Peña Formation at its type locality is interpreted as being no younger than earliest Oligocene.

Dinocyst distribution in the Cerro Águila section is shown in Figure 5. The presence of *Reticulatosphaera actinocoronata* and *Gelatia inflata* at the base indicates a maximum Priabonian age. Based on the above discussion on *Enneadocysta dictyostila*, the



Explanation of Plate 4.

figs 1–2. *Enneadocysta brevistila*: LPUNS-RT4; 34/99 (1); 46/105; L46/4; central body width 50 μ m; orientation unknown – 1, high focus, 2, low focus. **figs 3–4.** *Homotryblum abbreviatum*: LPUNS-RT9; 39/99 (1); 39.7/105; L39/3; central body width 40 μ m; apical view – 3, high focus, 4, low focus. **fig. 5.** *Hystrichosphaeridium truswelliae*: LPUNS-RT3; 33/99 (1); 39.5/104; N40/1; central body width 45 μ m; intermediate focus. **figs 6–7.** *Hystrichosphaeridium tubiferum*: LPUNS-RT1; 31/99 (1); 42.2/112; D43/3; central body width 40 μ m; apical view – 6, high focus, 7, intermediate focus. **fig. 8.** *Pyxidiniopsis delicata*: LPUNS-RT2; 32/99 (1); 41.5/109; G42/3; central body width 37 μ m; intermediate focus. **fig. 9.** *Spinidinium* sp.: LPUNS-RT4; 34/99 (1); 37/95; V37/3-4; central body width 50 μ m; high focus. **fig. 10.** *Vozzhennikovia* sp.: LPUNS-RT6; 36/99 (1); 37/94; \times 37/0; central body width 35 μ m; dorsal view, high focus on process and archaeopyle. **fig. 11.** *Vozzhennikovia* sp.: LPUNS-RT3; 33/99 (1); 44/108.5; H44/2; central body width 42 μ m; lateral view, high focus showing the 3I archaeopyle. **figs 12–13.** *Thalassiphora pelagica*: LPUNS-RT4; 34/99 (2); 24.2/104.9; M24/1; central body width 75 μ m; dorsal view – 12, high focus showing the archaeopyle, 13, intermediate focus. **fig. 14.** *Turbiosphaera filosa*: LPUNS-RT3; 33/99 (1); 35.8/101.3; R33/3; central body width 60 μ m; right lateral view, intermediate focus.

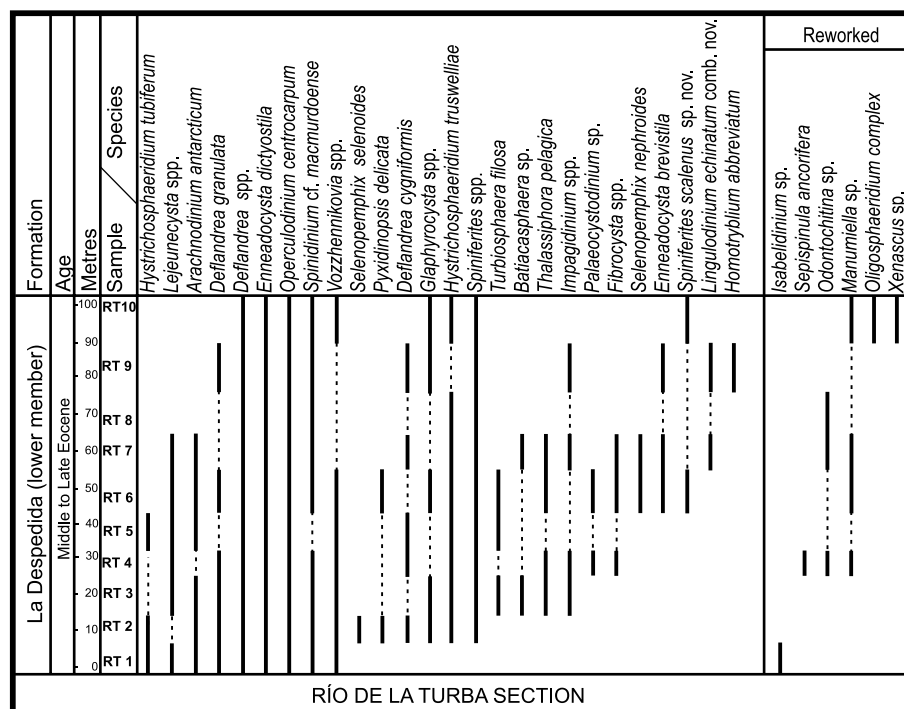


Fig. 3. Stratigraphical distribution of dinocyst species from the lower member of the La Despedida Formation at the Río de la Turba section.

uppermost part of the Cabo Peña Formation is interpreted to be close to the Eocene/Oligocene transition. The stratigraphical ranges of *Batiacasphaera compta* (FO: 38 Ma; LO: 33.7 Ma; Williams *et al.*, 1998) and *Phthanoperidinium comatum* (FO: 45.7 Ma; LO: 30.7 Ma; Williams *et al.*, 1998) are consistent with this age.

The biostratigraphy of the Río Candelaria section is derived solely from dinocyst assemblages (Fig. 6). As discussed previously, the presence of *Reticulosphaera actinocoronata* and *Gelatia inflata* at the base, and *Deflandrea convexa* (with a LO at 35 Ma) in sample RC2, indicates a maximum Priabonian age. The upper part of the Cabo Peña Formation at Río Candelaria may extend into the Rupelian, based on the presence of *Corrudinium incompositum*, *Deflandrea antarctica* and *Phthanoperidinium comatum*, which have LOs at 28.5 Ma, 29.4 Ma and 30.7 Ma respectively (Williams *et al.*, 1998, 2004). Based on the presence of *Enneadocysta dictyostila*, however, the minimum age of the section is considered to be earliest Oligocene. As in the Cabo Peñas and Cerro Águila sections, *Reticulosphaera actinocoronata*, *Gelatia inflata* and *Nematosphaeropsis lemniscata* co-exist with species whose LOs are close to the base of the Rupelian. This is taken to indicate an age close to the Eocene–Oligocene boundary for the Cabo Peña Formation in its type area. However, the resolution of these data does not allow precise correlation of the sections studied with the boundary.

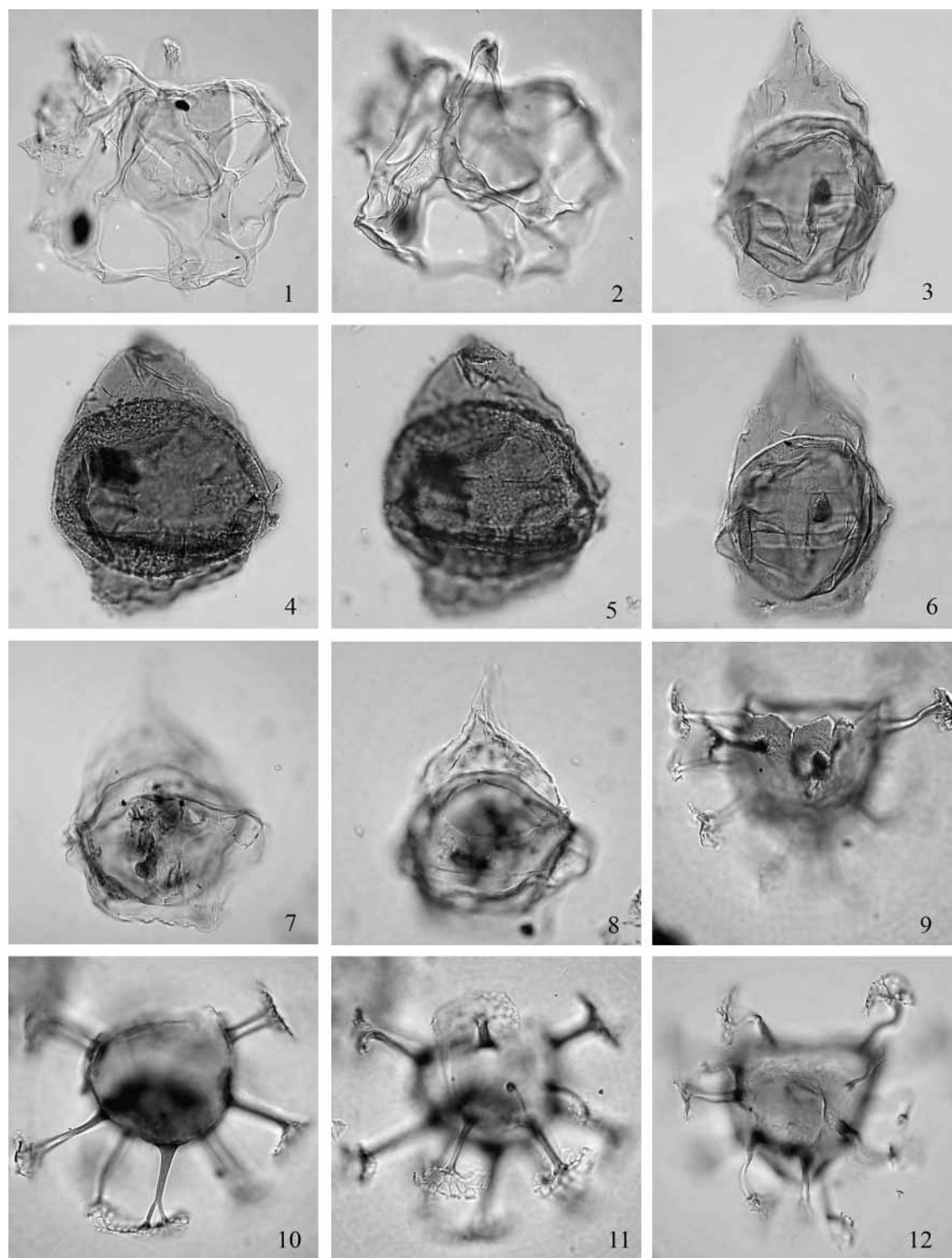
The few specimens of *Arachnodinium antarcticum* in the Cerro Águila and Río Candelaria sections are interpreted as reworked, since its LO has been placed at 38.8 Ma (Brinkhuis *et al.*, 2003a). Specimens of this species are probably derived from the lower member of the La Despedida Formation. The dinocyst assemblages from the Cabo Peñas section contain a few specimens of *Glaphyrocysta retiintexta*, *Alisocysta margarita*,

Oligosphaeridium complex and *Hafniasphaera* sp., which are probably from lower Palaeogene deposits. Likewise, specimens of *Odontochitina costata* and *Manumiella* sp. at Cerro Águila and *Odontochitina* sp. and *Nelsoniella aceras* at Río Candelaria are considered to be reworked from Upper Cretaceous rocks.

PALAEOENVIRONMENT

In the Río de la Turba section, the dinocyst assemblages include most of the species in the Antarctic-endemic ‘Transantarctic flora’ of Wrenn & Beckman (1982): these are *Arachnodinium antarcticum*, *Deflandrea antarctica*, *D. granulata*, *D. cygniformis* and species of *Spinidinium* and *Vozzhennikovia*. Well-represented taxa include *Hystrichosphaeridium tubiferum*, *H. truswelliae*, species of *Lejeunecysta*, and *Fibrocysta* sp. *Enneadocysta dictyostila* was regarded as another component of the ‘Transantarctic flora’ by Truswell (1997) but has been recorded also from mid-latitudes – in the Punta del Este and Colorado Basins (Guerstein *et al.*, 2003).

The lowermost palynological assemblage from the Río de la Turba section is characterized by low palynomorph abundances, with 26% of the palynomorphs being dinocysts. This percentage increases upwards to sample LT 5, then decreases to sample LT10. Even in samples where the dinocyst percentage is greater than 50%, palynomorphs are sparse and species richness is low (Table 1; Fig. 7). The presence of several specimens of *Deflandrea* and other peridiniacean cysts (P-cysts) may reflect near-shore marine conditions (Brinkhuis, 1994; Pross & Brinkhuis, 2005). Sluijs *et al.* (2005) suggested that high abundances of P-cysts of supposed heterotrophic habits (even though most of them have no living relatives), may indicate nutrient-rich waters, probably derived from terrigenous input. However, RT5 to RT7 assemblages (Fig. 7) are dominated mainly by



Explanation of Plate 5.

figs 1–2. *Arachnodinium antarcticum*: LPUNS-RT6; 1546 (2); 30.7/105.5; L31-1; orientation unknown; central body width 45 μ m, central body length 50 μ m – 1, high focus, 2, low focus. **figs 3, 6.** *Deflandrea antarctica*: LPUNS-RT6; 36/99 (1); 35.1/94; \times 35/0; central body width 60 μ m; dorsal view – 3, dorsal surface, 6, ventral surface. **figs 4–5.** *Deflandrea granulata*: LPUNS-RT3; 33/99 (1); 33.4/98; S33/4; central body width 85 μ m; ventral view – 4, intermediate focus, 5, dorsal surface. **figs 7–8.** *Deflandrea cygniformis*: LPUNS-RT4; 34/99 (1); 38/106.3; K38/0; central body width 70 μ m; ventral view – 7, ventral surface, 8, dorsal surface. **figs 9, 12.** *Enneadocysta dictyostila*: LPUNS-RT4; 34/99 (1); 41.6/95.5; V42/0; central body width 53 μ m; ventral view – 9, ventral surface showing the sulcal notch, 12, dorsal surface. **figs 10–11.** *Enneadocysta dictyostila*: LPUNS-RT9; 39/99 (1); 35/104.5; M35/0; central body width 44 μ m; bright field – 10, intermediate focus, 11, low focus.

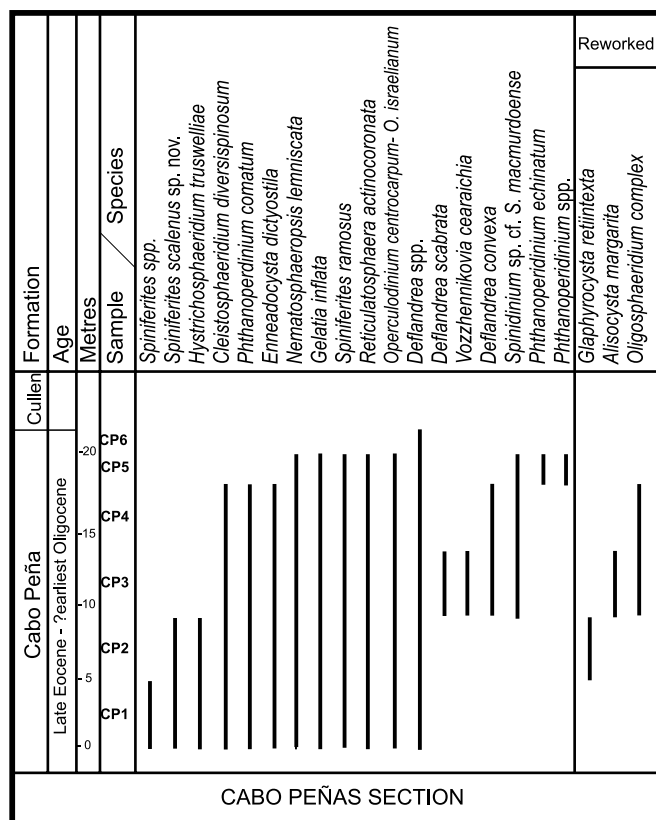


Fig. 4. Stratigraphical distribution of dinocyst species from the Cabo Peña Formation at the Cabo Peñas section.

Enneadocysta dictyostila. In dinocyst assemblages from ODP Leg 189, Site 1170, the *Enneadocysta* spp. maxima correlate with high CaCO_3 content in sediments, possibly reflecting more offshore, less eutrophic marine conditions (Röhl *et al.*, 2004).

A general transgressive–regressive event was observed in the Late Eocene–earliest Oligocene Cabo Peña Formation. This is based on the decrease in dinocyst percentages of the total palynomorphs toward the top of the three sections. Common occurrences of outer neritic to oceanic markers throughout the Cabo Peñas section, however, suggest open-water conditions (Table 2; Fig. 8). The authors agree with Pross & Brinkhuis (2005) and Sluijs *et al.* (2005) that *Nematosphaeropsis lemniscata*, *Reticulatosphaera actinocoronata* and *Impagidinium* spp. are offshore taxa. However, in the Cerro Águila section the regressive trend is steeper than in Cabo Peñas, with the best representation of outer neritic and oceanic species in the lower part of the section (Table 3; Fig. 9). In the upper part of the Cerro Águila section, *Cleistosphaeridium diversispinosum*, *Deflandrea* spp., *Enneadocysta* spp. and protoperidiniaceans have their maximum frequencies. All these taxa are considered to have inhabited coastal palaeoenvironments (Brinkhuis, 1994; Pross & Brinkhuis, 2005; Sluijs *et al.*, 2005).

The Río Candelaria dinocyst assemblages indicate a change from inner neritic at the bottom to coastal marine conditions in the middle part of the section (Table 4; Fig. 10). Common protoperidiniaceans (*Brigantedinium?* spp., *Selenopemphix nephroides* and *Lejeunecysta* spp.) are characteristic of cold, nutrient-rich waters, related to inner neritic environments (e.g.

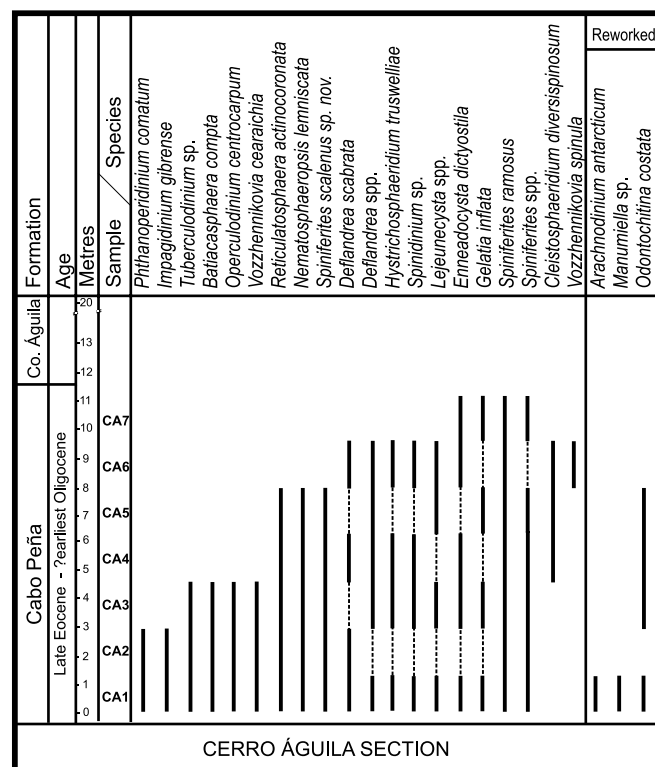


Fig. 5. Stratigraphical distribution of dinocyst species from the Cabo Peña Formation at the Cerro Águila section.

Head *et al.*, 1989a, b; Edwards & Andrie, 1992; Head & Westphal, 1999). Species of *Deflandrea*, *Enneadocysta*, *Operculodinium* and *Tuberculodinium* are considered restricted marine to coastal taxa according to Pross & Brinkhuis (2005). Assemblages from the upper part of the section are dominated by *Operculodinium* spp. and *Spiniferites* spp., and have high percentages of sporomorphs and green algae (hydrodictyaceans and prasinophyceans), reflecting marginal marine conditions.

Several of the dinocyst species are viable palaeoclimatic markers. For example, *Gelatia inflata* indicates cool water and high latitudes, based on its common occurrences in the North Pacific Ocean, in the Bering Sea and over the Tasman Plateau (Bujak, 1984; Head & Norris, 1989; Brinkhuis *et al.*, 2003a, respectively). Based on observations from central Italy, Brinkhuis & Biffi (1993) considered the migration of this species into lower latitudes at the Eocene–Oligocene transgression to reflect cooling episodes.

Comparison of the La Desperido assemblages at Río de la Turba (Fig. 7) with those from three Cabo Peña assemblages (Figs 8–10) shows that neither the high dominance of the typical ‘Transantarctic flora’ (*sensu* Wrenn & Beckman, 1982) nor the *Enneadocysta* spp. peaks occur in the latter. The Cabo Peña assemblages contain common protoperidiniacean cysts, supposedly produced by heterotrophic dinoflagellates that inhabited cool surface waters rich in dissolved nutrients. These components may indicate increasing terrestrial input, or may reflect the development of an upwelling system related to the incipient Antarctic Circumpolar Current.

Codignotto & Malumián (1981) suggested an outer shelf depositional environment for the lower part of the Cabo Peña

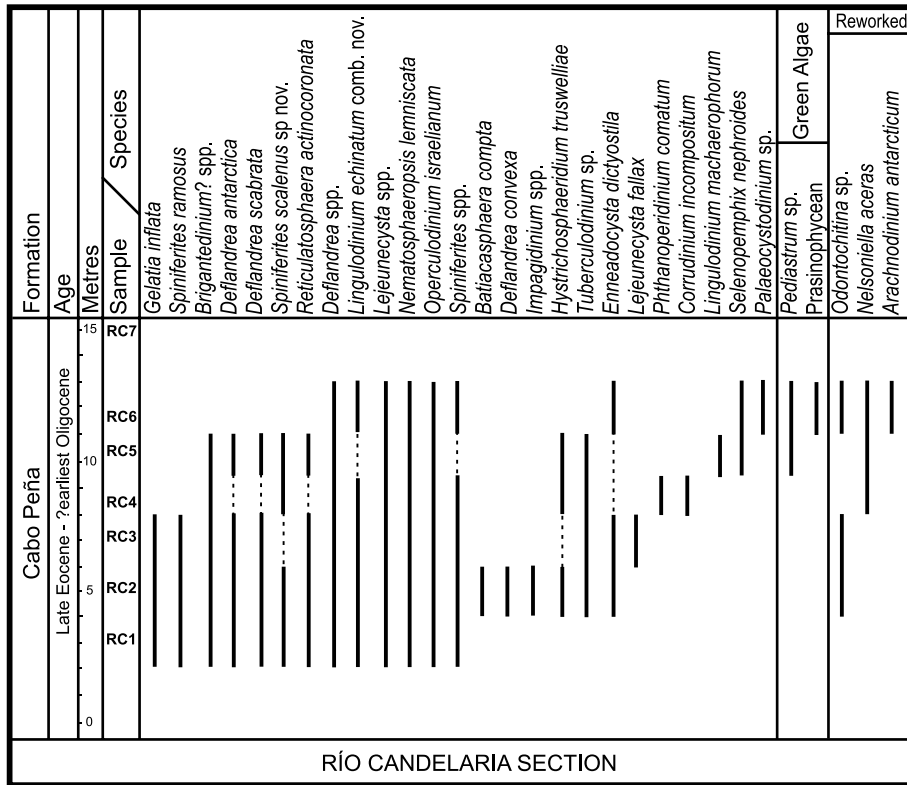


Fig. 6. Stratigraphical distribution of dinocyst species from the Cabo Peña Formation at the Río Candelaria section.

Samples	<div></div>																															
RT 10	<div></div>																															
RT 9	<div></div>																															
RT 8	<div></div>																															
RT 7	2	1		1	18	178	2	3			6		1	3	1	1			2		1	1	3	1			5	55	72	74	201	27
RT 6	4		5		2	92	304	2	2	2		10	4		1	4	1	1	1			1	1	2	1	1	27	462	56	73	591	78
RT 5	2			1	74	132						1	1		1	3						3		1	3	222	12	8	242	92		
RT 4		2		5	2	71	96		3			11			4	2	1				1		2	3			32	235	33	55	323	73
RT 3	5	2		3	68	84		2	2			10		2	2	5					2	6	1	1	1	5	200	110	25	335	60	
RT 2	3			3	5	50	94			1		6	3			10		1		1	1	3				19	200	108	10	318	63	
RT 1	2				6	10	2					8		6		10					6					9	59	141	23	213	26	

Table 1. Dinocyst distribution within samples from the lower member of the La Despedida Formation at Río de la Turba section (raw data)

Formation type section. Towards the upper part of the formation, they found a decrease in deep-water benthic foraminifera. Malumián & Caramés (1989) recognized cool water assemblages including some of the same species that inhabit present-day subantarctic waters.

DISCUSSION

The 'Transantarctic flora' associated with *Enneadocysta dictyostila* peaks (usually recorded as *Areosphaeridium diktyoplokum* or *E. partridgei*) has been recorded mainly in Middle Eocene sections from Southern Hemisphere high latitudes. Such records

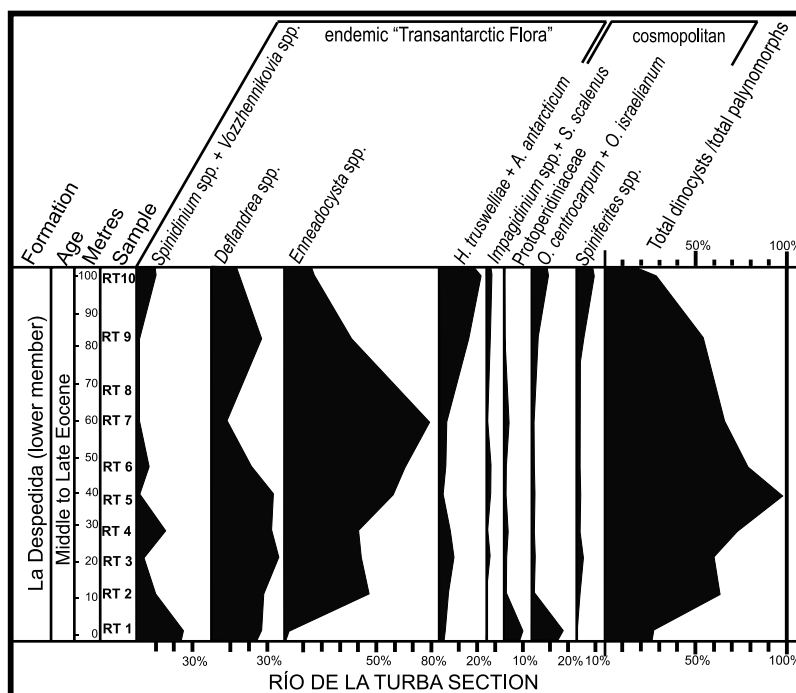


Fig. 7. Quantitative distribution of selected dinocyst groups within samples from the lower member of the La Despedida Formation at Río de la Turba section. The graph at the right shows ratio of dinocysts/total of palynomorphs.

Samples	<i>Cleistostraphaeridium diversispinosum</i>	<i>Cordosphaeridium</i> sp.	<i>Deflandrea convexa</i>	<i>Deflandrea scabrata</i>	<i>Deflandrea</i> spp.	<i>Enneadocysta dictyostyla</i>	<i>Gelatia inflata</i>	<i>Hystriosphraeridium truswelliae</i>	<i>Impagidinium</i> spp.	<i>Nematosphaeropsis lemniscata</i>	<i>O. centrocarpum</i> + <i>O. israelianum</i>	<i>Phthalanoperidinium conatum</i>	<i>Phthalanoperidinium echinatum</i>	<i>Reticulatosphaera actinocoronata</i>	<i>Spinidinium</i> cf. <i>macmurdoense</i>	<i>Spiniferites ramosus</i>	<i>Spiniferites scalenus</i> sp. nov.	<i>Spiniferites</i> spp.	<i>Vozzhennikovia cearaichia</i>	Total dinoflagellates	Pollen	Spores	Total palynomorphs	% dinocysts/total palynomorphs	<i>Alisocysta margarita</i> (R)	<i>Glaphyrocysta retintexta</i> (R)	<i>Oligosphaeridium complex</i> (R)
CP 6					4															nc			nc	nc			
CP 5					38	37				8	35		3	18	17	35				173	135	86	394	44			
CP 4	32	2	5		8	17	35			15	57	4		8		17				200	95	48	343	58			
CP 3	35	2	3	8	37	6	32			15	43			15	6	7			3	202	72	35	309	65	2		1
CP 2	32	1			35	15	50	12	5	18	17			9		18	8			230	58	42	330	70		2	
CP 1	18				8	4	45	25	2	30	29	2		35		15	8	7		228	20	25	273	83			

Table 2. Dinocyst distribution within samples from the Cabo Peña Formation at the Cabo Peñas section (raw data)

include: Archangelsky (1969), in the lower part of the Río Turbio Formation, southern Argentina; Haskell & Wilson (1975) in the DSDP Leg 29, off southeastern Australia and western New Zealand; Coccozza & Clarke (1992) from the upper part of La Meseta Formation in northern Seymour Island; Mao & Mohr (1995) in a core from Bruncie Bank in the Scotia Sea, off Antarctica; and the already mentioned records from ODP Leg 189, off Tasmania (Brinkhuis *et al.*, 2003a, b; Sluijs *et al.*, 2003). Using fully coupled, climate model simulations, Huber *et al.* (2004) demonstrated that clockwise system gyres were

responsible for cooling the atmosphere; they proposed a 'cold trap' mechanism that would have removed the cold-intolerant taxa in the Southern Ocean during the Mid-Eocene.

Fensome *et al.* (2007) interpreted *Enneadocysta* as an areolig-eracean (gonypylacinean) rather than a cladopyxiinean dinocyst. Thus, it seems reasonable to conclude that the motile stage of *Enneadocysta* was autotrophic and that species of this genus preferred relatively warmer waters. On this basis, a relationship is suggested between the *Enneadocysta* peaks observed in the Río de la Turba section and the three other sites mentioned

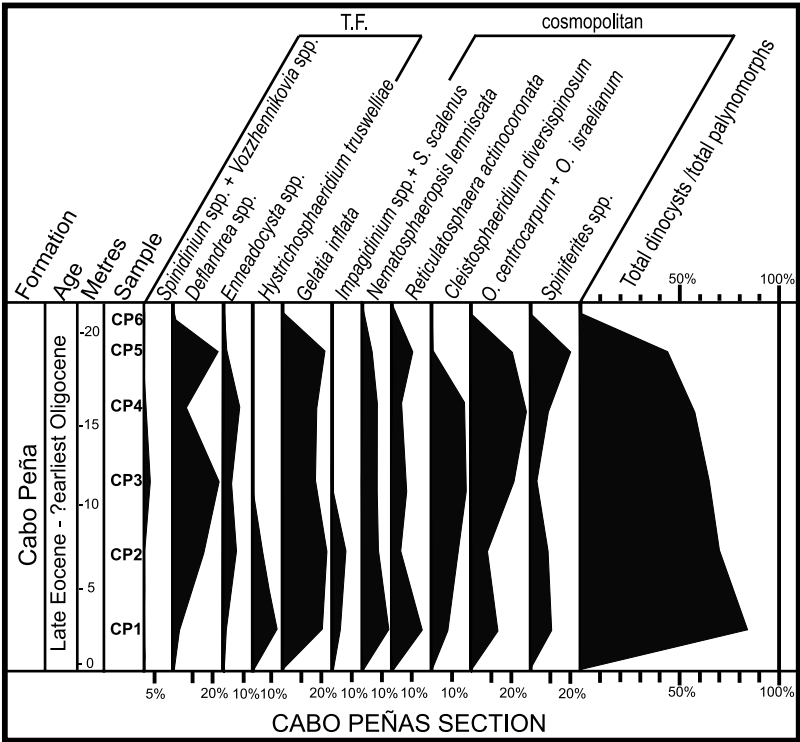


Fig. 8. Quantitative distribution of selected dinocyst groups within samples from the Cabo Peña Formation at the Cabo Peñas section. The graph at the right shows ratio of dinocysts to total of palynomorphs. T.F., endemic ‘Transantarctic Flora’.

Samples	<i>Batiacasphaera compta</i>	<i>Cleistosphaeridium diversispinosum</i>	<i>Cordosphaeridium</i> sp.	<i>Deflandrea scabrata</i>	<i>Deflandrea</i> spp.	<i>Enneadocysta dictyostila</i>	<i>Gelatia inflata</i>	<i>Hystriochsphaeridium truswelliae</i>	<i>Impagidinium gibrense</i>	<i>Lejeunecysta</i> spp.	<i>Nematosphaeropsis lemniscata</i>	<i>O. centrocarpum</i> + <i>O. israelianum</i>	<i>Phthanoperidinium comatum</i>	<i>Reticulatosphaera actinocoronata</i>	<i>Spinidinium</i> cf. <i>macmurdoense</i>	<i>Spiniferites ramosus</i>	<i>Spiniferites scalenus</i> sp. nov.	<i>Spiniferites</i> spp.	<i>Tuberculodinium</i> sp.	<i>Vozzhemikovia cearaichia</i>	<i>Vozzhemikovia spinula</i>	Total dinoflagellates	Pollen	Spores	Total palynomorphs	% dinocysts/total palynomorphs	<i>Arachnodinium antarcticum</i> (R)	<i>Manumiella</i> sp. (R)	<i>Odontochitina costata</i> (R)
CA 7						4	6											12				nc	nc	nc	nc				
CA 6		16	1			18	13	13		16					7	8	7			1	100	152	135	287	35				
CA 5		12				8	8			7	8			36		38	17	53				187	124	98	409	46			2
CA 4		15		8		9	17	6			18			45	8	36	34	7				203	105	68	376	54			1
CA 3	4					7	8	16	3		7	34	15	48	12	32	17	8	6	5		222	85	67	374	59			1
CA 2			5	6					5		36	18	2	38		17	37	9	7	3		185	69	72	326	57			
CA 1	3			12	38	14	35	1	3	17	45	8	1	12	15	46	52	8	5	3		318	38	45	401	79	1	1	1

Table 3. Dinocyst distribution within samples from the Cabo Peña Formation at the Cerro Águila section (raw data)

above and warming events during the generally cool late Middle Eocene.

Mohr (1990) interpreted the decrease in dinocyst diversity in ODP Leg 113 samples from the Weddell Sea as reflecting cooling water masses in the Late Eocene. Sluijs *et al.* (2003) and Stickley *et al.* (2004) recognized that in the Priabonian, at about 35.5 Ma, the association dominated by the endemic Antarctic flora was replaced by more cosmopolitan and open marine

assemblages, with abundant protoperidinioids. This change, which reflects different oceanographical and environmental conditions, was related to the deepening of the Tasmanian Gateway.

The same differences were observed between the La Despedida and Cabo Peña formations in Tierra del Fuego, although there appears to be a stratigraphical gap between the late Middle Eocene and the latest Eocene. It is believed that this

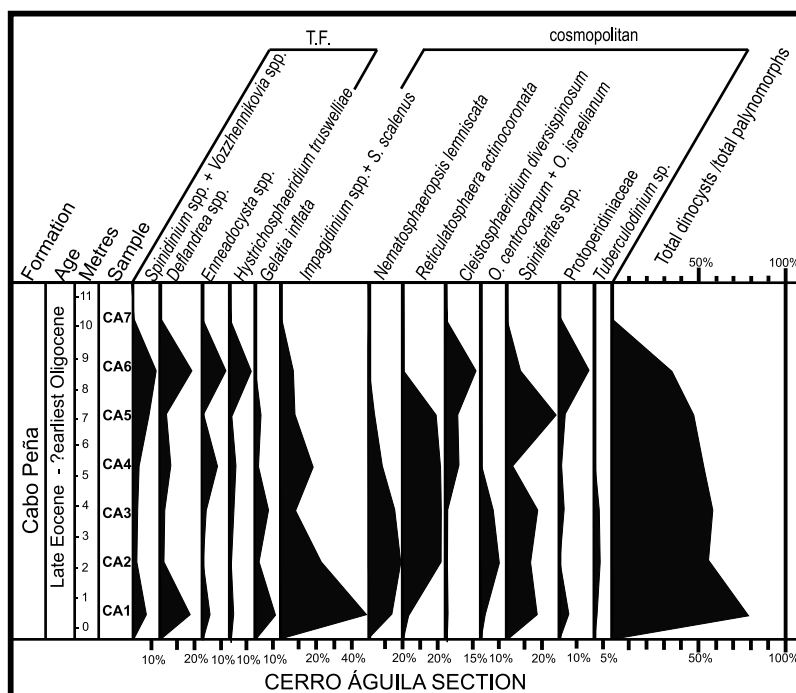


Fig. 9. Quantitative distribution of selected dinocyst groups within samples from the Cabo Peña Formation at the Cerro Águila section. The graph at the right shows ratio of dinocysts to total of palynomorphs. T.F., endemic 'Transantarctic Flora'.

Samples	<i>Batiacasphaera compta</i>	<i>Brigantedinium</i> ? spp.	<i>Corrudinium incompositum</i>	<i>Deflandrea antarctica</i>	<i>Deflandrea convexa</i>	<i>Deflandrea scabrata</i>	<i>Deflandrea</i> spp.	<i>Emneadocysta dictyostila</i>	<i>Gelatia inflata</i>	<i>Hysitrichosphaeridium truswelliae</i>	<i>Impagidinium</i> spp.	<i>Lejeunecysta fallax</i>	<i>Lejeunecysta</i> spp.	<i>Lingulodinium echinatum</i> comb. nov.	<i>Lingulodinium machaerophorum</i>	<i>Nematosphaeropsis lemniscata</i>	<i>O. centrocarpum</i> + <i>O. israelianum</i>	<i>Palaeocystodinium</i> sp.	<i>Phthanoperidinium comatum</i>	<i>Reticulatosphaera actinocoronata</i>	<i>Selenopemphix nephroides</i>	<i>Spiniferites ramosus</i>	<i>Spiniferites scalenus</i> sp. nov.	<i>Spiniferites</i> spp.	<i>Tuberculodinium</i> sp.	Total dinoflagellates	Pollen	Spores	Total palynomorphs	% dinocysts/total palynomorphs	<i>Pediastrum</i> sp.	<i>Prasinophyceae</i>	<i>Arachnoidinium antarcticum</i> (R)	<i>Nelsoniella aceras</i> (R)	<i>Odontochitina</i> sp. (R)	
RC 7								9	6				4	7	2	38	3									nd	116	84	200	nd						
RC 6																				3				10	82	96	106	284	29	2	1	1	1	2		
RC 5	35		7		9	10			4			6	16	7	5	8			10	2		7		8	134	137	89	360	37	3			1			
RC 4	17	4				7			6		8				5	36		2				8	7	6	106	90	119	315	34				2			
RC 3	39		8		9	9	8	7			6	8	9		8	38				9	7		20	8	191	196	128	505	38					1		
RC 2	3	18	6	2	8	8	4	5	6	5		6	7		9	18			18	8	6	17	7	161	94	61	316	51						2		
RC 1	15		7		8	7		8				9	8		7	17			5		7	9	8	115	65	55	235	49								

Table 4. Dinocyst distribution within samples from the Cabo Peña Formation at the Río Candelaria section (raw data)

represents two different second-order depositional cycles. The endemic Antarctic flora is well represented in the Middle Eocene lower member of the La Despedida Formation. Also, deep-marine conditions are clearly reflected in the lower part of the Cabo Peña Formation. In the upper part of the three sections of the Cabo Peña Formation, the increasing continental influence and regressive trends might be related to eustatic lowering of sea-level by the growth of Antarctic ice sheets towards the latest

Eocene–earliest Oligocene. In a re-interpretation of geophysical data, related to the rifting history of basins in the Scotia Sea, Livermore *et al.* (2007) suggested that an ocean gateway may have developed during the Middle Eocene. This new plate tectonic model suggests that even a shallow Drake Passage could have caused the climatic changes in Southern Ocean circulation, which were responsible for Eocene cooling and development of Antarctic ice sheets.

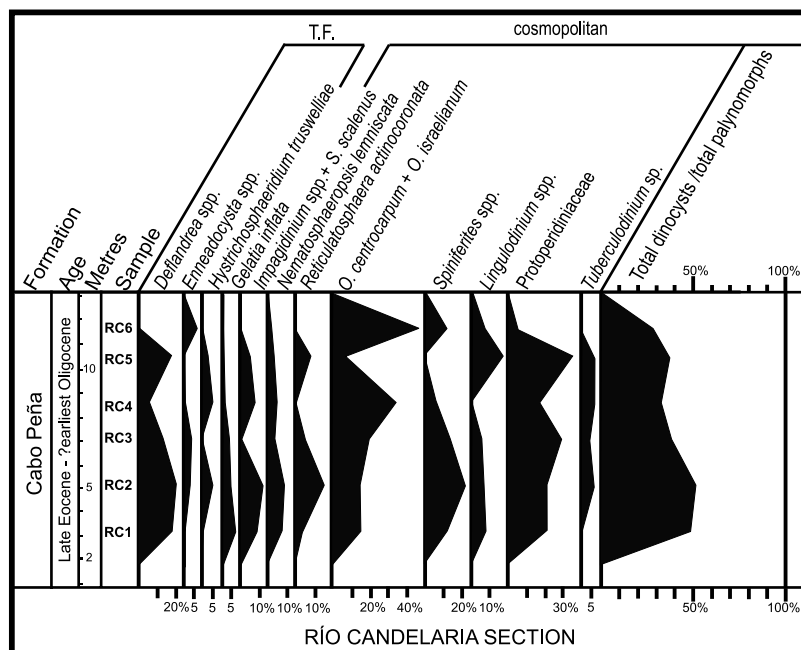


Fig. 10. Quantitative distribution of selected dinocyst groups within samples from the Cabo Peña Formation at the Río Candelaria section. The graph at the right shows ratio of dinocysts to total of palynomorphs. T.F., endemic 'Transantarctic Flora'.

CONCLUSIONS

Based on dinocyst assemblages, the lower member of the La Despedida Formation is considered to be Middle to Late Eocene in age. This agrees with calcareous microfossil data, mainly benthic and planktonic foraminifera (Codignotto & Malumián, 1981; Malumián, 1988).

The endemic 'Transantarctic flora' reflects marginal marine conditions, with a restricted connection to the open sea during the Middle Eocene. The *Enneadocysta* peak may be related to relatively more open conditions and slightly warmer coastal waters.

The Cabo Peña Formation, in its type area, is no older than Late Eocene and the uppermost deposits may extend into the earliest Oligocene.

All three sections of the Cabo Peña Formation contain cool water, heterotrophic dinocysts, plus increasing numbers of cosmopolitan, open-marine species. Regressive trends can be identified in the upper parts of the sections.

Thus, these data are consistent with other palaeoclimatic records from the Southern Hemisphere that suggest a temperature decrease during the earliest Oligocene (Zachos *et al.*, 2001). Furthermore, the presence of cold-water dinocysts reflects the incipient development of the Antarctic Circumpolar Current during the Eocene–Oligocene transition. This oceanographical change is considered a key event in climatic change from a greenhouse to an icehouse Earth.

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List of dinocyst species cited in the text

Full references can be found in Fensome & Williams (2004). "(R)" denotes those species considered to be reworked.

- Alisocysta margarita* Harland, 1979 (R)
- Arachnodinium antarcticum* Wilson & Clowes, 1982
- Areosphaeridium diktyoplokum* (Klumpp, 1953), emend. Eaton, 1971. Stover & Williams, 1995.
- Batiacasphaera compta* Drugg, 1970
- Cleistosphaeridium diversispinosum* Davey *et al.*, 1966
- Corrudinium incompositum* (Drugg, 1970) Stover & Evitt, 1978
- Deflandrea antarctica* Wilson, 1967
- Deflandrea convexa* Wilson, 1988
- Deflandrea cygniformis* Pöthe de Baldis, 1966
- Deflandrea granulata* Menéndez, 1965
- Deflandrea scabrata* Wilson, 1988
- Enneadocysta dictyostila* (Menéndez) Stover & Williams, emend. Fensome *et al.*, 2007
- Enneadocysta brevistila* Fensome *et al.*, 2007
- Enneadocysta partridgei* Stover & Williams, 1995
- Gelatia inflata* Bujak, 1984
- Glaphrocysta retintexta* (Cookson, 1965) Stover & Evitt, 1978 (R)
- Homotryblium abbreviatum* Eaton, 1976
- Hystrichosphaeridium? echinatum* Menéndez, 1965
- Hystrichosphaeridium truswelliae* Wrenn & Hart, 1988

- Hystriospheraidium tubiferum* (Ehrenberg, 1938) Deflandre, 1937, emend. Davey & Williams, 1966
- Impagidinium gibrense* Michoux, 1985
- Lejeunecysta fallax* (Morgenroth, 1966) Artzner & Dörhöfer, 1978, emend. Biffi & Grignani, 1983.
- Lingulodinium echinatum* Menéndez, 1965 comb. nov.
- Lingulodinium machaerophorum* (Deflandre & Cookson, 1955) Wall, 1967
- Lingulodinium pycnospinosum* (Benedek, 1972) Stover & Evitt, 1978, emend. Benedek & Sarjeant, 1981
- Nelsoniella aceras* Cookson & Eisenack, 1960 (R)
- Nematosphaeropsis lemniscata* (Bujak, 1984) Wrenn, 1988
- Odontochitina costata* (Alberti, 1961, emend) Clarke & Verdier, 1967 (R)
- Oligosphaeridium complex* (White, 1842) Davey & Williams, 1966 (R)
- Operculodinium centrocarpum* (Deflandre & Cookson, 1955) Wall, 1967
- Operculodinium israelianum* (Rossignol, 1962) Wall, 1967
- Phthanoperidinium comatum* (Morgenroth, 1966) Eisenack & Kjellström, 1972
- Phthanoperidinium echinatum* Eaton, 1976
- Pyxidinosia delicata* Wilson, 1988
- Reticulosphaera actinocoronata* (Benedek, 1972) Bujak & Matsuoka, 1986
- Selenopemphix nephroides* Benedek, 1972, emend. Bujak in Bujak *et al.*, 1980
- Selenopemphix selenoides* Benedek, 1972, emend. Bujak in Bujak *et al.*, 1980
- Sepispinula ancorifera* (Cookson & Eisenack, 1960) Islam, 1993, emend. Cookson & Eisenack, 1968 (R)
- Spinidinium* sp. cf. *S. macmurdoense* (Wilson, 1967) Lentin & Williams, 1976
- Spiniferites ramosus* (Ehrenberg, 1838) Mantell, 1854
- Spiniferites scalenus* sp. nov.
- Thalassiphora pelagica* (Eisenack, 1954) Eisenack & Gocht, 1960, emend. Benedek & Gocht, 1981
- Turbiosphaera filosa* (Wilson, 1967) Archangelsky, 1969
- Vozzhennikovia apertura* (Wilson, 1967) Lentin & Williams, 1976
- Vozzhennikovia cearaichia* Stover & Hardenbol, 1994
- Vozzhennikovia spinula* Stover & Hardenbol, 1994
- Brinkhuis, H. 1994. Late Eocene to Early Oligocene dinoflagellate cysts from the Priabonian type-area (northeast Italy); biostratigraphy and paleoenvironmental interpretation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **107**: 121–163.
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