A latest Cretaceous to earliest Paleogene dinoflagellate cyst zonation of Antarctica, and implications for phytoprovincialism in the high southern latitudes

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ABSTRACT

The thickest uppermost Cretaceous to lowermost Paleogene (Maastrichtian to Danian) sedimentary succession in the world is exposed on southern Seymour Island (65° South) in the James Ross Basin, Antarctic Peninsula. This fossiliferous shallow marine sequence, which spans the Cretaceous-Paleogene boundary, has allowed a high-resolution analysis of well-preserved marine palynomorphs. Previous correlation of Cretaceous-Paleogene marine palynomorph assemblages in the south polar region relied on dinoflagellate cyst biozonations from New Zealand and southern Australia. The age model of the southern Seymour Island succession is refined and and placed within the stratigraphical context of the mid to high southern palaeolatitudes. Quantitative palynological analysis of a new 1102 m continuous stratigraphical section comprising the uppermost Snow Hill Island Formation and the López de Bertodano Formation (Marambio Group) across southern Seymour Island was undertaken. We propose the first formal late Maastrichtian to

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early Danian dinoflagellate cyst zonation scheme for the Antarctic based on this exceptional succession. Two new late Maastrichtian zones, including three subzones, and one new early Danian zone are defined. The oldest beds correlate well with the late Maastrichtian of New Zealand. In a wider context, a new South Polar Province based on Maastrichtian to Danian dinoflagellate cysts is proposed, which excludes most southern South American marine palynofloras. This interpretation is supported by models of ocean currents around Antarctica and implies an unrestricted oceanic connection across Antarctica between southern South America and the Tasman Sea.

Keywords: Cretaceous; Paleogene; Seymour Island, Antarctica; dinoflagellate cysts, biostratigraphy; provincialism

1. Introduction

The shallow marine sedimentary succession exposed in the southern part of Seymour Island in the James Ross Basin, Antarctic Peninsula is an exceptional locality to investigate the nature of latest Cretaceous to earliest Paleogene (Maastrichtian-Danian) climates and sea levels in the high southern palaeolatitudes (Fig. 1; McArthur et al., 1998, 2000; Crame et al., 2004). The ~1100 m stratigraphical succession, located at a palaeolatitude of approximately 65° S (Lawver et al., 1992; Markwick and Valdes, 2004) is at a similar latitude today and has allowed a high-resolution analysis of linked marine and terrestrial palaeoenvironmental proxies during this important interval.

The Cretaceous-Paleogene (K-Pg) sequence on Seymour Island is highly fossiliferous and includes a well-preserved marine palynomorph record (Askin, 1988a; Thorn et al., 2009). Dinoflagellate cyst assemblages have been described from many Maastrichtian and K-Pg successions in the mid to high southern palaeolatitudes, but imprecise dating and endemism has hampered biostratigraphical correlation. Existing formal biozonations using dinoflagellate cysts for the K-Pg interval in the high southern palaeolatitudes are restricted to New Zealand and southern Australia (e.g. Roncaglia et al., 1999; Helby et al., 1987), with none proposed for Antarctica or southernmost South America. Consequently, until now there has been no framework for comparing Antarctic dinoflagellate cyst assemblages with those across the south polar region for this interval.

This study uses new data from Seymour Island to both refine the age model for this important succession and to address this regional biostratigraphical problem by providing the first formal dinoflagellate cyst zonation for the Antarctic Peninsula based on dinoflagellate cysts. To place the new Antarctic Peninsula biozonation into a wider stratigraphical context, Maastrichtian to Danian marine palynofloras are compared across the mid to high southern palaeolatitudes, and a new South Polar Province is proposed. The implications for Antarctic palaeogeography and south polar oceanic connections are discussed based on models of ocean circulation.

2. Geological Setting

The Maastrichtian-Danian succession in the James Ross Basin is part of the Coniacian to Danian Marambio Group, deposited in mid- and inner-shelf settings in a back-arc basin associated with the Antarctic Peninsula magmatic arc to the west, and open to the Weddell Sea to the east (Hathway, 2000; Crame et al., 2004). The James Ross Basin was bounded to the west by coastal plains on the flanks of the Antarctic Peninsula with a shoreline trending approximately north-northeast to south-southwest. Major rivers brought sediment sourced from the Antarctic Peninsula into deltaic systems that accumulated siliciclastic deposits offshore (Zinsmeister, 1982; Pirrie, 1989; Scasso et al., 1991; Olivero et al., 1992; Hathway, 2000; Crame et al., 2004; Olivero et al., 2008).

Maastrichtian sediments (ca. 1150 m thick; McArthur et al., 2000), comprising the majority of the Snow Hill Island Formation and the overlying López de Bertodano Formation crop out at Cape Lamb on Vega Island, the northeastern tip (the Spath Peninsula) of Snow Hill Island, and the southern half of neighbouring Seymour Island (Fig. 1; Pirrie et al., 1997; Crame et al., 2004). The López de Bertodano Formation on Seymour Island, studied here, crops out continuously over approximately 70 km^2 (Crame et al., 2004), striking on average 020° north-northeast, and dipping gently to the east-southeast by 9°. It is thick (1007 m, Fig. 2) and is bounded by unconformities with the Haslum Crag Member (uppermost Snow Hill Island Formation) beneath, and with the overlying Sobral Formation (Pirrie et al., 1997; Olivero et al., 2008). On the basis of several strontium isotope analyses, McArthur et al. (1998) suggested an average sediment accumulation rate of 27 cm ka^{-1} for the López de Bertodano Formation; this is consistent with the greatly expanded nature of the succession.

The relative homogeneity of the sediments suggests continuous sedimentation. The sediments are unconsolidated clayey silts and silty clays with rare, more indurated fine- to medium-grained sandstones and calcareous concretionary beds. Glauconitic layers increase in frequency up-section and are particularly prominent within the uppermost 100 m. The formation is fossiliferous throughout with macrofossils including fossil wood commonly exposed at the surface or within calcareous concretions. Various attempts have been made to subdivide this thick unit into coherent lithostratigraphical units, but this is difficult due to the remarkably homogeneous nature and significant lateral variation (Rinaldi et al., 1978; Macellari, 1988; Pirrie et al., 1997; Olivero, 1998; Crame et al., 2004; Olivero et al., 2007, 2008). For example, Macellari (1988) referred to the then lower half of the López de Bertodano Formation as the *Rotularia* units and subdivided this into six informal units. Pirrie et al. (1997) and Crame et al. (2004) proposed a lowermost member comprising Macellari's (1988) units Klb2 and 3, primarily on the basis of a finer grain size than the Haslum Crag Member beneath, and the upper part of the López de Bertodano Formation above. Macellari's (1988) Klb1 unit was reassigned to the Haslum Crag Member (Crame et al., 2004). The remaining upper part of the formation below the K-Pg boundary (including Macellari's [1988] "Molluscan" units, Klb7 to 9) has a more diverse macrofauna but remains difficult to subdivide. The uppermost López de Bertodano Formation above the K-Pg boundary can still be confidently identified as Macellari's (1988) unit Klb10, which is more distinctive due to its extinction recovery fauna (Crame et al., 2004). This led Crame et al. (2004) to suggest that the interval between the K-Pg boundary and the Sobral Formation should be given member status.

The López de Bertodano Formation contains an invertebrate and vertebrate macrofauna, a macroflora (calcified fossilised wood), a microfauna (including foraminifera and silicoflagellates) and a microflora (marine and terrestrial palynomorphs) (e.g. Askin, 1988a; Macellari, 1988; Zinsmeister and Macellari, 1988; Zinsmeister et al., 1989). The dinoflagellate cyst zonation scheme described here is based on a comprehensive palynological study throughout a 1102 m-thick sedimentary section measured across the southern part of Seymour Island and encompassing the uppermost Haslum Crag Member (Snow Hill Island Formation), the entire López de Bertodano Formation and the lowermost Sobral Formation (Figs. 1, 2).

3. Age of the succession studied

The K-Pg boundary on Seymour Island was identified by a small iridium anomaly within Zinsmeister's (1998) "Lower Glauconite" in the uppermost López de Bertodano Formation (Elliott et al., 1994). This was confirmed by the strontium isotope dating of a *Pycnodonte* bivalve (McArthur et al., 1998), and is coincident with noticeable changes in the fossil record, notably in the marine palynomorphs (e.g. Huber, 1985; Askin, 1988b; Zinsmeister et al., 1989; Elliott et al., 1994; Askin and Jacobsen, 1996; Zinsmeister, 1998; Thorn et al., 2007, 2009). Askin and Jacobsen (1996) stated that this iridium anomaly occurs near the base of a "20-30 cm K-T transitional interval" in the dinoflagellate cyst record.

Attempts to refine the dating of the lowermost strata on Seymour Island have been challenging. Crame et al. (2004) established the age of the base of the Maastrichtian Stage in the James Ross Basin at 71.3 Ma (see also Crame et al., 1999; McArthur et al., 2000), within the Snow Hill Island Formation on Snow Hill and Vega islands. Early biostratigraphical studies on the López de Bertodano Formation on Seymour Island concluded a late Campanian to early Danian age (Huber et al., 1983; Feldmann and Woodburne, 1988). However, despite the fossiliferous nature of this formation, microfossil analyses in particular have been problematical due to low numbers of individuals, low species diversity, taxa with long stratigraphical ranges, and a general paucity of age-diagnostic taxa (e.g. Huber et al., 1983; Askin, 1988a; Harwood, 1988; Huber, 1988). Later, a belemnite (*Dimitobelus (Dimitobelus) seymouriensis*) collected to the north of our section and approximately 600 m below the K-Pg boundary was dated as 67.5 Ma using strontium isotope stratigraphy (McArthur et al., 1998). In a regional stratigraphical synopsis, Crame et al. (2004) agreed that the lowermost beds on Seymour Island are probably early Maastrichtian. This study confirms that the oldest beds on Seymour Island are Maastrichtian in age.

4. Materials and Methods

Palynomorph assemblages from 81 sediment samples were studied and counted from the composite section D5.251 (Fig. 2). The samples were analysed approximately every 20 m in the lithologically homogeneous lower 680 m of the section, every 10 m in the glauconitic unit above and every 2-4 m across particularly glauconite-rich horizons and the K-Pg boundary. Bulk sediment was processed using standard quantitative techniques (Wood et al., 1996). Twenty-five grammes dry weight of each sample were sieved at 180 μm, the < 180 μm fraction treated with hydrochloric and hydrofluoric acids and oxidised for one or two minutes with nitric acid. Zinc chloride centrifugation and swirling completed the separation of the organic and inorganic matter. The organic residue was sieved with a 10 µm mesh cloth, and made up to 50 ml with distilled water. A standard aliquot of 1 ml (representing 0.5 g of the initial 25 g dry weight) was permanently mounting onto a microscope slide using polyvinyl alcohol as the dispersant and adhesive. All samples and microscope slides are curated and stored in the geological collections of the British Antarctic Survey, Cambridge, UK.

Palynomorphs were identified and counted within regularly spaced transects across the entire width of each cover slip until at least 300 specimens were recorded. The same technique was employed for each slide, which allowed the calculation of palynomorphs per gram of sediment. The un-counted transects comprising the remainder of each slide were also scanned to record the presence of any additional rare taxa. Abundant chorate dinoflagellate cysts (*Impletosphaeridium* spp.) commonly dominated each assemblage in samples from below ~ 830 m in the section so were counted to 100 specimens and then an estimate made of their overall percentage in the assemblage. These small spiny cysts were referred to in Thorn et al. (2009) as the acritarch *Micrhystridium* spp. Rare dinoflagellate cysts that were more thermally mature, comparatively torn or fragmented, or isolated beyond their common range were deemed to have been reworked.

To substantiate the biostratigraphic scheme described herein photomicrographs of selected marine palynomorph specimens are presented in Plates 1 and 2. All specimens were the best observed during this study for each illustrated taxa. Considerable effort has been made to produce the best images possible, especially for the very thick-walled, high relief or the very thin-walled fossils, which are difficult to photograph by any method. All images are taken using state-of-the-art Leica digital photomicrographic equipment at the University of Leeds, which allows stacking of a series of two-dimensional images into a single image encompassing all focal depths.

5. Marine palynology

The marine palynomorphs from the uppermost Snow Hill Island Formation and the López de Bertodano Formation comprise relatively well-preserved dinoflagellate cysts, acritarchs and marine algae, which have undergone minimal thermal maturation (Appendix A, Plates I and II). Count data for these marine palynomorphs are provided in the online Supplementary Information.

The ranges of selected marine palynomorphs are illustrated in Fig. 2. Other elements are sporomorphs (terrestrial pollen and spores, including the freshwater aquatic fern spores *Azolla* spp. and *Grapnelispora* sp.), fungi, freshwater algae (*Botryococcus braunii*, *Pediastrum* spp. and *Tetraporina* spp.), tracheid and cuticle fragments, amorphous organic matter, inertinite and rare scolecodonts. Foraminiferal linings were not observed. Terrestrial palynomorphs and their biostratigraphy are not discussed herein.

The total marine palynomorphs counted per slide (including estimates of *Impletosphaeridium* spp., see Methods) ranged from 29 to 4629. Quantitative processing allows standardisation of these counts, indicating that the total number of marine palynomorphs per gram of sediment ranged from 442 (at 890 m) to 141,175 (at 407 m). This accounts for up to 93% of the total marine and terrestrial palynomorph count per sample. Dinoflagellate cyst richness ranges from one to nine species per sample (not including specimens only identifiable to generic level) and is extremely low compared with other Late Cretaceous assemblages (Stover at al., 1996).

Several long-ranging taxa occur throughout the López de Bertodano Formation, notably the acritarchs *Nummus* spp. and *Paralecaniella indentata*. Dinoflagellate cyst taxa that occur throughout include *Impletosphaeridium* spp., *Palaeocystodinium granulatum*, *Spiniferites ramosus* and *Operculodinium* spp. There is a gradual turnover of marine palynomorph taxa throughout the formation, with an increase in the frequency of appearance of taxa above approximately 780 m (Fig. 2). This turnover in conjunction with abundance data allows the division of the López de Bertodano Formation into dinoflagellate cyst biozones and the identification of the K-Pg boundary, refining the preliminary schemes of Askin (1988 a,b) and Askin and Jacobsen (1996) (Figs. 2-4).

6. Zonation scheme

Species of *Manumiella* are relatively short-ranging and form the basis of Askin's (1988a) preliminary dinoflagellate cyst zonation scheme for Seymour Island (see also Thorn et al., 2009). Based on the stratigraphical ranges of key dinoflagellate cysts from this section, two new late Maastrichtian zones (including three subzones) and one new early Danian zone are defined. In addition, the latest Maastrichtian to earliest Danian *Manumiella druggii* Interval Zone is amended, and the top of the succession is marked by the *Trithryodinium evittii* Acme Zone (of Helby et al., 1987; Figs. 3,4). Where a zone or subzone boundary is based on the first or last appearance datum of a taxon, the zonal boundary is placed at that datum rather than halfway between neighbouring samples. The new zones are described below, and significant bioevents are illustrated in Fig. 3. The lowermost unit, Zone 1, remains informal because the base is stratigraphically below the Seymour Island succession.

Zone 1 of Askin (1988a)

Definition: The base of this zone was not observed herein; the top of the zone is defined by the first appearance datum (FAD) or range base of *Manumiella seymourensis*.

Type locality: Measured section D5.251 (zone base unseen, zone top 163 m, at least 163 m thick). Marambio Group, shallow marine facies, southern Seymour Island, Antarctic Peninsula.

Characteristic assemblage: Dinoflagellate cysts – *Batiacasphaera*? *reticulata, Impletosphaeridium* spp., *Isabelidinium* spp. (notably *Isabelidinium cretaceum* and *Isabelidinium pellucidum*), *Operculodinium* spp. and *Spiniferites ramosus*. Acritarchs - *Nummus* spp.

Correlation: Zone 1, Seymour Island, Antarctic Peninsula (Askin, 1988a); *Alterbidinium acutulum* Interval Zone, New Zealand (Wilson, 1984); *Palaeocystodinium granulatum* Interval Subzone, New Zealand (Roncaglia and Schiøler, 1997).

Age: ?late Maastrichtian

Remarks: This zone comprises abundant *Batiacasphaera*? *reticulata* and *Isabelidinium* spp., including the last appearance datum (LAD) or range top of *Isabelidinium cretaceum,* and the only occurrence in the entire section of *Isabelidinium pellucidum*. No representatives of *Odontochitina* were observed. Fensome and Williams (2004) transferred *Isabelidinium cretaceum* to *Manumiella*. It has been retained in *Isabelidinium* herein on the basis of its bicavate morphology (see also Appendix A). The lowermost 163 m of the Seymour Island section (i.e. 66 m of the Haslum Crag Member and the lower 97 m of the López de Bertodano Formation) correlates with preliminary Zone 1 of Askin (1988a), which also included the lowest record of *Alterbidinium acutulum* and the pollen *Tricolpites lilliei*. The base of this zone is unseen in this study and hence has yet to be formally defined.

Manumiella seymourensis Range Zone (new)

Definition: The interval between the FAD and the LAD of *in situ Manumiella seymourensis*.

Type locality: Measured section D5.251 (zone base 163 m, zone top 870 m, 707 m thick). Marambio Group, shallow marine facies, southern Seymour Island, Antarctic Peninsula.

Characteristic assemblage: Dinoflagellate cysts – *Batiacasphaera*? *reticulata, Impagidinium cristatum*, *Manumiella seymourensis*, *Palaeocystodinium granulatum* and *Spiniferites ramosus,* with consistent *Impletosphaeridium* spp., *Isabelidinium* spp., *Oligosphaeridium* spp., *Operculodinium* spp. and indeterminate peridiniacean cysts. Acritarchs - dinocyst n. gen. X of Askin (1988a), *Nummus* spp., *Paralecaniella indentata* and *Paucilobimorpha*? *apiculata*.

Correlation: Zone 2, Seymour Island, Antarctic Peninsula (Askin, 1988a); *Alterbidinium acutulum* Interval Zone, New Zealand (Wilson, 1984); *Palaeocystodinium granulatum* Interval Subzone, New Zealand (Roncaglia and Schiøler, 1997).

Age: ?late Maastrichtian

Remarks: The abundance of *Manumiella seymourensis* fluctuates throughout this zone, but is generally higher in the upper part (rare occurrences above 870 m are considered to be reworked, Fig. 2). The ranges of *Isabelidinium cretaceum* and *Manumiella seymourensis* do not overlap in this section, and no *Odontochitina* spp. were observed. Askin (1988a) defined the base of her preliminary Zone 2 using the FAD of *Manumiella seymourensis* and the top by the FAD of *Manumiella* n. sp. 1 (now *Manumiella conorata*, see Thorn et al., 2009) and the abundance of "*Manumiella*" n. sp. 2 (now *Manumiella bertodano,* see Thorn et al., 2009). The lower zonal boundary definition is retained, however the upper boundary is amended herein. *Manumiella conorata* is present only at 958 m, in the overlying *Manumiella bertodano* Interval Zone. A more coherent upper zonal boundary is considered to be the range top of *Manumiella seymourensis* (Askin, 1988a). The *Manumiella seymourensis* Range Zone is subdivided into three subzones, the *Batiacasphaera*? *reticulata* Interval Subzone, the *Operculodinium baculatum* Interval Subzone and the *Bosedinia laevigata* Interval Subzone.

Batiacasphaera? *reticulata* Interval Subzone (new)

Definition: The interval from the FAD of *Manumiella seymourensis* to the LAD of *Batiacasphaera*? *reticulata*.

Type locality: Measured section D5.251 (subzone base 163 m, subzone top 383 m, 220 m thick). Marambio Group, shallow marine facies, southern Seymour Island, Antarctic Peninsula.

Characteristic assemblage: Dinoflagellate cysts – *Batiacasphaera*? *reticulata, Cassidium fragile, Cribroperidinium* sp. A of Dettmann and Thomson (1987), *Impagidinium cristatum*, *Manumiella seymourensis*, *Operculodinium baculatum* and *Spiniferites ramosus*, in addition to consistent *Impletosphaeridium* spp. and indeterminate peridiniacean cysts. Acritarchs - dinocyst n. gen. X of Askin (1988a), *Nummus* spp. and *Paucilobimorpha*? *apiculata*.

Correlation: Zone 2, Seymour Island, Antarctic Peninsula (Askin, 1988a); *Alterbidinium acutulum* Interval Zone, New Zealand (Wilson, 1984); *Palaeocystodinium granulatum* Interval Subzone, New Zealand (Roncaglia and Schiøler, 1997).

Age: ?late Maastrichtian

Remarks: This subzone was not described specifically by Askin (1988a). It comprises the majority of the lower part of the López de Bertodano Formation referred to by Pirrie et al. (1997) as the “mudstone-dominated” lowermost unit. The unit spans the unconformity between the Haslum Crag Member and the López de Bertodano Formation at 66 m near the base of the section, with no dramatic change in the marine palynomorph assemblages. This implies either a narrow time gap at this unconformity, or a long time gap within a long period of stasis.

Operculodinium baculatum Interval Subzone (new)

Definition: The interval from the LAD of *Batiacasphaera*? *reticulata* to the FAD of *Manumiella bertodano*.

Type locality: Measured section D5.251 (subzone base 383 m, subzone top 826 m, 443 m thick). Marambio Group, shallow marine facies, southern Seymour Island, Antarctic Peninsula.

Characteristic assemblage: Dinoflagellate cysts – *Alterbidinium acutulum, Impagidinium cristatum*, *Manumiella seymourensis, Operculodinium baculatum, Palaeocystodinium granulatum* and *Spiniferites ramosus,* in addition to consistent *Impletosphaeridium* spp., *Isabelidinium* spp. and indeterminate peridiniacean cysts. Acritarchs - dinocyst n. gen. X of Askin (1988a), *Nummus* spp. and *Paucilobimorpha*? *apiculata*.

Correlation: Zone 2, Seymour Island, Antarctic Peninsula (Askin, 1988a); *Alterbidinium acutulum* Interval Zone, New Zealand (Wilson, 1984); *Palaeocystodinium granulatum* Interval Subzone, New Zealand (Roncaglia and Schiøler, 1997).

Age: ?late Maastrichtian

Remarks: At the base of this subzone, *Manumiella seymourensis* increases significantly in abundance and indeterminate peridiniaceans continue to be common (Thorn et al., 2009; Fig. 2). This relatively thick subzone comprises the majority of the López de Bertodano Formation (443 m) and displays little taxonomic change throughout.

Bosedinia laevigata Interval Subzone (new)

Definition: The interval from the FAD of *Manumiella bertodano* to the LAD of *Manumiella seymourensis*.

Type locality: Measured section D5.251 (subzone base 826 m, subzone top 870 m, 44 m thick). Marambio Group, shallow marine facies, southern Seymour Island, Antarctic Peninsula.

Characteristic assemblage: Dinoflagellate cysts – *Impletosphaeridium* spp., *Manumiella bertodano, Manumiella seymourensis, Operculodinium* spp., and *Spiniferites ramosus*, in addition to consistent *Isabelidinium* spp. and *Oligosphaeridium* spp. Acritarchs - dinocyst n. gen. X of Askin (1988a) and *Nummus* spp.

Correlation: Zone 2, Seymour Island, Antarctic Peninsula (Askin, 1988a); *Alterbidinium acutulum* Interval Zone, New Zealand (Wilson, 1984); *Palaeocystodinium granulatum* Interval Subzone, New Zealand (Roncaglia and Schiøler, 1997).

Age: ?late Maastrichtian

Remarks: This subzone includes the overlapping ranges of *Manumiella seymourensis* and *Manumiella bertodano* and correlates with preliminary upper subzone 2 of Askin (1988a) (Fig. 3). Although not a major component, the first occurrence of the small dinoflagellate cyst *Bosedinia laevigata* is coincident with the lower boundary. *Manumiella seymourensis* remains predominant over *Manumiella bertodano* until the uppermost part of the zone, where the latter becomes dominant with an acme at 866 m immediately below the boundary with the *Manumiella bertodano* Interval Zone (Thorn et al., 2009; Fig. 2). Rare specimens of *Manumiella seymourensis* in the overlying *Manumiella bertodano* Interval Zone are considered to have been reworked. Indeterminate peridiniacean cysts disappear from this subzone after an acme around the lower boundary. The oldest record of *Eisenackia reticulata* occurs in this subzone; this is slightly earlier than its first appearance in Zone 3 of Askin (1988a).

Manumiella bertodano Interval Zone (new)

Definition: The interval from the LAD of *Manumiella seymourensis* to the FAD of *Manumiella druggii.*

Type locality: Measured section D5.251 (zone base 870 m, zone top 974 m, 104 m thick). Marambio Group, shallow marine facies, southern Seymour Island, Antarctic Peninsula.

Characteristic assemblage: Manumiella bertodano, *Manumiella seymourensis* and *Spiniferites ramosus.*

Correlation: Zone 3, Seymour Island, Antarctic Peninsula (Askin, 1988a); *Alterbidinium acutulum* Interval Zone, New Zealand (Wilson, 1984); *Palaeocystodinium granulatum* Interval Subzone, New Zealand (Roncaglia and Schiøler, 1997).

Age: ?late Maastrichtian

Remarks: This zone is characterised by diverse *Manumiella* and relatively abundant *Manumiella bertodano*, which occurs throughout. In this section, the LAD of *Manumiella bertodano* is at the top of the zone.

Manumiella druggii Range Zone (amended)

Definition: The interval between the FAD and the LAD of *in situ Manumiella druggii.*

Type locality: Measured section D5.251 (zone base 974 m, zone top 1007 m, 33 m thick). Marambio Group, shallow marine facies, southern Seymour Island, Antarctic Peninsula.

Characteristic assemblage: Broomea spp.*, Eisenackia reticulata, Exochosphaeridium bifidum, Manumiella druggii*, *Manumiella seelandica* and *Phelodinium* sp. cf. *P. magnificum.*

Correlation: Zone 4, Seymour Island, Antarctic Peninsula (Askin, 1988a); *Manumiella druggii* Interval Zone, New Zealand (Wilson, 1984, 1987) and Australia (Helby et al., 1987).

Age: latest Maastrichtian to earliest Danian

Remarks: This zone encompasses the entire range of *Manumiella druggii*, coincident with *Exochosphaeridium bifidum.* In this section, the base of the zone is coincident with the LAD of *Manumiella bertodano* and the top with the LAD of *Manumiella seelandica*. Immediately prior to the K-Pg event on Seymour Island (i.e. above 974 m in the section), dinoflagellate cyst taxa begin to appear and disappear with a greater frequency than below. The amended *Manumiella druggii* Interval Zone is equivalent to Zone 4 of Askin (1988a) with the uppermost boundary approximately coincident with the K-Pg boundary.

Askin (1988a) defined the lower boundary of her Zone 4 using the FADs of *Manumiella druggii* and *Exochosphaeridium bifidum*, although in this study the latter datum appears to be earlier, but the zone is still defined by the co-occurrence of these two taxa. *Cerodinium medcalfii* and *Eisenackia circumtabulata* were both noted by Askin (1988a) in this zone, but were not observed herein until the overlying *Hystrichosphaeridium tubiferum* Interval Zone. The top of this zone, as defined herein, is marked by a change within 1 m from the uppermost Maastrichtian assemblage dominated by *Manumiella* spp. (at 1007 m) to an acme of the small dinoflagellate cyst *Senegalinium obscurum* (at 1008 m), followed by a varied Paleocene assemblage (Askin, 1988a,b; Elliott et al., 1994; Askin and Jacobsen, 1996; Thorn et al., 2009). Although palynomorph counts at high resolution across the K-Pg boundary were not the focus of this study, presence/absence scans were done at 1 m resolution between the counted samples at 1004 and 1008 m. These scans determined the last in place *Manumiella* spp. to be at 1007 m before the *Senegalinium obscurum* acme at 1008 m. Abundant *Senegalinium obscurum* occur 0.1-1 m above an iridium anomaly on Seymour Island (Elliott et al., 1994) and mark the K-Pg boundary at this locality. Askin (1988a) noted a 1 m overlap between the ranges of *Manumiella druggii* and *Senegalinium obscurum,* but this was not observed herein possibly due to a coarser sampling resolution. Detailed analyses of dinoflagellate cyst assemblages across the K-Pg boundary on Seymour Island were discussed by Askin (1984, 1988a,b), Elliott et al. (1994) and Askin and Jacobsen (1996).

Hystrichosphaeridium tubiferum Acme Zone (new)

Definition: The interval from the LADs of *Manumiella druggii* to the FAD of abundant *Trithryodinium evittii*.

Type locality: Measured section D5.251 (zone base 1008 m, zone top 1074 m, 66 m thick). Marambio Group, shallow marine facies, southern Seymour Island, Antarctic Peninsula.

Characteristic assemblage: Eisenackia circumtabulata, Hystrichosphaeridium tubiferum, Palaeoperidinium pyrophorum, Senegalinium obscurum and *Spinidinium* spp.

Correlation: The lower part of Zone 5, Seymour Island, Antarctic Peninsula (Askin, 1988a); upper *Manumiella druggii* Interval Zone to lowermost *Trithyrodinium evittii* Acme Zone, New

Zealand (Wilson, 1984, 1987); upper *Manumiella druggii* Interval Zone, Australia (Helby et al., 1987).

Age: early Danian

Remarks: This zone is characterised by successive dinoflagellate cyst acmes of varying magnitudes and a gradual but significant influx of new taxa. The acmes include those of *Senegalinium obscurum* (at 1008 m), *Hystrichosphaeridium tubiferum* (at 1014 m), *Palaeoperidinium pyrophorum* (at 1024 m) and *Spinidinium* spp. (predominantly *Spinidinium* sp. 1 of Askin (1988a) at 1034-1044 m). *Spinidinium* spp. are prominent throughout this zone. In this section, the zone base is coincident with the LAD of *Manumiella seelandica.* Many of the long-ranging dinoflagellate cyst and acritarch taxa, for example, *Spiniferites ramosus* and *Nummus* spp., span the K-Pg boundary and occur throughout this zone. Isolated occurrences of several taxa above the K-Pg boundary are probably reworked; these include *Isabelidinium* spp., *Eisenackia reticulata* and *Exochosphaeridium bifidum.*

Trithryodinium evittii Acme Zone (of Helby et al., 1987)

Definition: The top of this zone was not observed herein; the base of the zone is defined by the FAD of abundant *Trithryodinium evittii.*

Type locality: Measured section D5.251 (zone base 1074 m, zone top unseen, at least 28 m thick). Marambio Group, shallow marine facies, southern Seymour Island, Antarctic Peninsula.

Characteristic assemblage: Cerodinium medcalfii, Trithryodinium evittii and *Senegalinium*? *dilwynense.*

Correlation: Zone 5, Seymour Island, Antarctic Peninsula (Askin, 1988a); *Trithyrodinium evittii* Acme Zone, New Zealand (Wilson, 1987, 1988; Wilson et al., 1989) and Australia (Helby et al., 1987).

Age: early Danian

Remarks: This zone is characterised by the relative abundances of *Cerodinium medcalfii* and *Trithryodinium evittii.* This zone was defined in New Zealand on the FAD and the LAD of *Trithryodinium evittii* (Wilson, 1987; 1988). In Australia, the base of the *Trithryodinium evittii* Zone was defined at the FAD of consistent and abundant *Trithryodinium evittii* by Helby et al. (1987).

7. Dinoflagellate cyst biostratigraphy

7.1. ?Late Maastrichtian

The new late Maastrichtian to early Danian dinoflagellate cyst biozonation scheme for the Antarctic Peninsula begins with the assignment of the majority of the oldest strata on southern Seymour Island to three zones. These are the informal Zone 1 of Askin (1988a) and the new *Manumiella seymourensis* Range Zone and *Manumiella bertodano* Interval Zone (up to 974 m). These zones correlate well with the late Haumurian (late Maastrichtian) *Palaeocystodinium granulatum* Interval Subzone of the *Alterbidinium acutulum* Interval Zone of New Zealand, and with an unzoned biostratigraphical interval in the southern Australian scheme (Figs. 3, 4; Wilson, 1984; Helby et al., 1987; Roncaglia and Schiøler, 1997; Roncaglia et al., 1999; Crampton et al., 2004). In New Zealand, the maximum thickness of the *Palaeocystodinium granulatum* Interval Subzone is 124 m in the Waipara South Branch section (Roncaglia et al., 1999), compared with a minimum of 972 m on Seymour Island. This correlation emphasises the exceptionally expanded nature of the latest Cretaceous succession of the James Ross Basin.

In New Zealand, the base of the late Maastrichtian *Alterbidinium acutulum* Interval Zone is defined by the LAD of *Odontochitina porifera*, and the top by the FAD of *Manumiella druggii* (see Wilson, 1984), with *Odontochitina* disappearing within the zone. *Odontochitina* spp. were not seen on Seymour Island, and the FAD of *Manumiella druggii* is at 974 m in the current section, implying a correlation with the upper part of the *Alterbidinium acutulum* Interval Zone. *Odontochitina* spp. and *Xenascus* spp. have LADs in the underlying *Cerodinium diebelii* Interval Subzone in New Zealand (Roncaglia and Schiøler, 1997). Fragments of *Xenascus* spp. were seen in the lowermost two samples of the Seymour Island section, within the Snow Hill Island Formation, but their poor preservation suggests that they are reworked.

The base of the *Palaeocystodinium granulatum* Interval Subzone in New Zealand is defined by the LAD of *Odontochitina operculata*, which was not seen on Seymour Island. The *Palaeocystodinium granulatum* Interval Subzone is characterised in New Zealand by common *Manumiella seymourensis* with *Palaeocystodinium granulatum* occurring throughout (Roncaglia and Schiøler, 1997; Roncaglia et al., 1999), which compares well to Zone 1 and the *Manumiella seymourensis* Range Zone assemblages from Seymour Island. Askin (1988a) noted the similarity between *Manumiella seymourensis* and *Satyrodinium haumuriense* from the type Haumurian in New Zealand, although the latter is more elongate and bicavate with a more stenoform archeopyle (Wilson, 1984). In New Zealand, the last appearance of *Cribroperidinum*? *muderongense* also occurs within the *Palaeocystodinium granulatum* Interval Subzone, consistent with observations from Seymour Island, although *Isabelidinium pellucidum* was last seen below the base of the *Manumiella seymourensis* Range Zone herein.

The dinoflagellate cyst zonation for the Late Cretaceous of southern Australia unfortunately contains an unzoned interval due to a lack of diagnostic taxa between the *Isabelidinium korojonense* Range Zone (mid Campanian to early Maastrichtian) and the *Manumiella druggii* Interval Zone (late Maastrichtian to early Danian) (Helby et al., 1987; Fig. 4). Dinoflagellate cyst biozones for northwest Australia (McMinn, 1988) do not compare well with taxa from Seymour Island, precluding the use of this zonal scheme for the Antarctic Peninsula.

The southern Australian index species *Isabelidinium korojonense* does not occur in Seymour Island. However, *Isabelidinium pellucidum* is a significant accessory form in southeast Australia and *Isabelidinium cretaceum* has its LAD at the top of the zone. Although *Isabelidinium cretaceum* occurs within the lowermost 100 m of the Seymour Island section, there is no further evidence to confidently correlate with this Australian biozone. The assemblages from Zone 1, the *Manumiella seymourensis* Range Zone and the *Manumiella bertodano* Interval Zone on Seymour Island appear to correlate with the unzoned interval in southern Australia prior to the FAD of *Manumiella druggii*, precluding any refinement of the substage biostratigraphy within the Maastrichtian of the Antarctic Peninsula (Fig. 4).

The best south polar correlation for the lower part of the succession is therefore with the late Haumurian *Palaeocystodinium granulatum* Interval Subzone of New Zealand, which suggests an entirely late Maastrichtian age for the oldest strata on southern Seymour Island. However, the Maastrichtian has yet to be formally divided globally into early and late substages, and regional solutions are commonly applied when placing the early/late Maastrichtian boundary (Crame et al., 2004). For the James Ross Basin, Crame et al. (2004) placed this boundary within the lower part of the López de Bertodano Formation on Seymour Island (636 m below the K-Pg boundary) using a strontium isotope-derived date (67.5 Ma) from a belemnite (McArthur et al., 1998; Fig. 2). This does not agree with the dinoflagellate cyst biostratigraphy herein. However, the probable heterochroneity of dinoflagellate cyst taxa across the south polar region, influenced by palaeogeography, ocean circulation patterns and facies differences (Askin, 1989), further complicate substage refinement of the Maastrichtian of the Antarctic Peninsula. For example, Roncaglia et al. (1999) tabulated the ranges of eleven Late Cretaceous dinoflagellate cyst species across the high southern palaeolatitudes including *Isabelidinium pellucidum*, which has a FAD that ranges from the mid Campanian to the early Maastrichtian between Australia and the Antarctic Peninsula. It is important to note therefore, that although we use the terms FAD and LAD herein, there is no intended implication of species inception and extinction (respectively). Evidence highlighted by Roncaglia et al. (1999) of heterochroneity across the south polar region implies that confidently placing the oldest strata on Seymour Island within the early or late Maastrichtian using dinoflagellate cyst biostratigraphy is not possible without further independent dating. Consequently, placement of a regionally-relevant early/late Maastrichtian boundary remains problematical in the James Ross Basin succession.

7.2 Latest Maastrichtian – early Danian

7.2.1. The Manumiella druggii *Range Zone*

Across the south polar region, the top of the *Manumiella druggii* Interval Zone defines the K-Pg transition. In New Zealand, Wilson (1984, 1987) defined the *Manumiella druggii* Zone using the ranges of *Manumiella druggii* and *Manumiella seelandica.* Roncaglia et al. (1999) subsequently defined the base of the zone at the first appearance of *Manumiella druggii* and the top at the first appearance of *Trithyrodinium evittii.* Several taxa have their FADs in this zone, of which those common to the López de Bertodano Formation are *Manumiella conorata*, *Tanyosphaeridium xanthiopyxides* and *Senegalinium*? *dilwynense* (see Roncaglia et al., 1999). However, the latter two species both have their FADs below and above this zone in Seymour Island respectively. Correlating the FAD of *Manumiella druggii* with worldwide foraminiferal zones, Roncaglia et al. (1999) argued that this event occurs in the early Maastrichtian in New Zealand. However, subsequent refinement of the New Zealand Cretaceous timescale places this zone within the late Maastrichtian (Crampton et al., 2000; 2004). In Australia, Helby et al. (1987) also placed the lower boundary of the zone at the first appearance of *Manumiella druggii*, but their upper boundary definition is slightly different, suggesting it should be placed at the first consistent and abundant appearance of *Trithyrodinium evittii*. Wilson in Strong et al. (1995) stated that the first appearance of *Trithyrodinium evittii* in New Zealand is within the earliest Paleocene.

The definition of the *Manumiella druggii* zone by Roncaglia et al. (1999) encompasses an interval in the Seymour Island succession section 33 m below to 66 m above the K-Pg boundary. This interval comprises marine palynomorph assemblages that are highly variable and change significantly across the K-Pg horizon. Although there appears to be no dramatic extinction in the marine palynoflora, ocean conditions probably changed instantaneously in a geological sense, which is reflected in the sudden occurrence of successive acmes of different taxa during the earliest Danian. The expanded nature of the succession on Seymour Island indicates a significant time gap between the LAD of *Manumiella druggii* and the FAD of consistent and abundant *Trithyrodinium evittii*. This study suggests that it would be appropriate to restrict the *Manumiella druggii* Zone to the range of this species, with an upper limit approximately at the K-Pg boundary, as inthe original definition by Wilson (1984, 1987), and to insert a new zone (the *Hystrichosphaeridium tubiferum* Interval Zone) between the top of the *Manumiella druggii* Range Zone and the overlying *Trithyrodinium evittii* Acme Zone. The *Manumiella druggii* Range Zone is therefore amended herein as the total range of *Manumiella druggii*.

Manumiella druggii and *Manumiella seelandica* disappear at the K-Pg horizon on Seymour Island (Fig. 2). Brinkhuis et al. (2003) also recognised the K-Pg boundary at Ocean Drilling Program ODP) Site 1172 in the East Tasman Plateau by the disappearance of *Manumiella* spp., particularly the prominent *Manumiella druggii*. However, in a previous study on Seymour Island, *Manumiella druggii* was observed in the earliest Danian (Askin, 1988a) and *Manumiella druggii* and *Manumiella seelandica* also range through the K-Pg boundary in the type Danian Fish Clay at Stevns Klint in Denmark (Lange, 1969; Hultberg, 1986). Similarly, *Manumiella druggii* commonly ranges into the earliest Danian in New Zealand (Willumsen, 2003, 2006, 2011; Willumsen et al., 2004a,b). To enhance the applicability of the new zonation scheme beyond the Antarctic Peninsula, and to account for the fact that these taxa are present in the earliest Danian (Askin, 1988a), the age of the amended *Manumiella druggii* Range Zone includes the earliest Danian.

7.2.2. The Hystrichosphaeridium tubiferum *Interval Zone*

The newly defined *Hystrichosphaeridium tubiferum* Interval Zone, between the *Manumiella druggii* Range Zone and the *Trithyrodinium evittii* Acme Zone, correlates with the lower part of Zone 5 of Askin (1988a). This continues into the overlying Sobral Formation and is Danian in age based on palynomorph, foraminiferal and silicoflagellate biostratigraphy (Askin, 1998a).

An acme of *Senegalinium obscurum* marks the base of this zone, and occurs immediately after the K-Pg boundary. Abundance spikes characterise the early Danian of Seymour Island, and continued into the overlying *Trithyrodinium evittii* Acme Zone. These have also been observed in the Early to Mid Paleocene (Teurian) of New Zealand (Willumsen, 2011; Willumsen and Vajda, 2010) and in the Late Paleocene, following a K-Pg boundary hiatus, on the East Tasman Plateau (Brinkhuis et al., 2003). *Eisenackia circumtabulata* appears immediately after the K-Pg boundary, which correlates with a FAD at the K-Pg boundary in equatorial and Northern Hemisphere mid-latitudes (Williams et al., 2004).

The newly defined *Hystrichosphaeridium tubiferum* Interval Zone between the LAD of *Manumiella druggii* and the FAD of consistent and abundant *Trithyrodinium evittii* may not always be recognisable in more condensed sections. In the Gippsland Basin of Australia, Partridge (1976) also recognised an interval between the *Manumiella druggii* and *Trithyrodinium evittii* zones, but noted that it consisted of undiagnostic dinoflagellate cysts. Although not specifically discussed, Willumsen (2011) included this interval within the early Danian (early Teurian) *Trithyrodinium evittii* Zone.

7.2.3. The Trithyrodinium evittii *Acme Zone*

The Early Paleocene (Teurian) *Trithyrodinium evittii* Zone lies immediately above the *Manumiella druggii* Zone in New Zealand (Wilson, 1987, 1988; Wilson et al., 1989), and is correlated with Zone 5 of Askin (1988a) on Seymour Island and the top of the current section. The associated taxa *Eisenackia reticulata* and *Palaeoperidinium pyrophorum* from New Zealand (Wilson, 1987, 1988) have their LADs below the lower boundary of this zone on Seymour Island. This suggests some heterochroneity between the Antarctic Peninsula and New Zealand, although *Eisenackia reticulata* occurs rarely herein. Brinkhuis et al. (2003), using correlations with the geomagnetic timescale, noted that *Eisenackia reticulata* ranges between 68.5 and 57 Ma at ODP Site 1172, East Tasman Plateau, which broadly agrees with the New Zealand occurrences associated with the *Trithyrodinium evittii* Zone. Brinkhuis et al. (2003) also dated the FAD of *Trithyrodinium evittii*, as 64.7 to 65.5 Ma from the East Tasman Plateau. In the absence of independent dating, these dates cannot be compared directly with the ranges of these taxa in the Seymour Island section, however, knowing the stratigraphical position of the K-Pg boundary and taking into account the estimated sedimentation rate based on strontium isotope stratigraphy by McArthur et al. (1998), it is likely that they are comparable.

8. Provincialism and palaeogeographical implications for Antarctica

As a consequence of this biostratigraphical study, and in the context of south polar palaeogeography and models of ocean currents, a new South Polar Province based on the distribution of Maastrichtian to Danian dinoflagellate cysts in the mid-high southern palaeolatitudes is proposed (Table 1, Fig. 5).

8.1 Dinoflagellate cyst distributions

Analysis of Maastrichtian to early Danian dinoflagellate cyst assemblages throughout the mid to high southern palaeolatitudes (Table 1) confirms a general similarity in marine palynofloras throughout the Antarctic region extending to the New Zealand subcontinent and southern Australia. The assemblages throughout this region contain taxa in common with the López de Bertodano Formation of the Antarctic Peninsula (for example, *Manumiella* spp., *Batiacasphaera reticulata* and *Tanyosphaeridium xanthiopyxides*), in addition to the long-ranging more cosmopolitan taxa (for example, *Spiniferites ramosus* and *Hystrichosphaerida tubiferum*) seen further north in southern South America and on the Falkland Plateau. On the opposite side of the Antarctic continent to the James Ross Basin, Maastrichtian to Paleocene marine palynofloras from ODP site 1172 on the East Tasman Plateau are "virtually identical to those known from Seymour Island" (Brinkhuis et al., 2003). Marine palynofloras of this age from Campbell Island and ODP Leg 120 (Site 748) do not compare well to those from Seymour Island, but this is probably due to the sampling of shallow water facies, perhaps even above sea level (Wilson, 1967; Mao and Mohr, 1992).

The closest palaeogeographical region to the James Ross Basin is southernmost South America, but interestingly, there is general lack of similarity in Maastrichtian to early Danian dinoflagellate cyst assemblages (e.g. Troncoso and Doubinger, 1980; Gamerro and Archangelsky, 1981; Papú et al., 1999; Guerstein and Junciel, 2001; Prámparo and Papú, 2006). The only records from southern South America that resemble the Seymour Island marine palynofloras are those from the ?late Maastrichtian Calafate Formation in the Austral Basin, southern Patagonia (Marenssi et al., 2004; Guler et al. 2005). In the South Atlantic, Late Cretaceous and Early Paleogene marine palynofloras from the Falkland Plateau show little commonality with those from Seymour Island (Harris, 1977), despite a strong resemblance in the foraminiferal record (Huber, 1988). However, despite the slightly older age, early Maastrichtian marine sequences from the South Georgia Basin (ODP site 698) and Maud Rise (ODP site 689 and 690) compare well (Mohr and Mao, 1997).

8.2. Provincialism

Zinsmeister (1979, 1982) originally divided the high southern palaeolatitudes into three Late Cretaceous biogeographical provinces based on the regional distribution of molluscs; these are the

Antarctic, Weddellian and Austral provinces. The James Ross Basin lies within the Antarctic Province (Askin, 1989), which approximately follows the Antarctic continental shelf margin (Fig. 5).

Lentin and Williams (1980) also proposed North and South Atlantic Provinces based on Campanian peridiniacean dinoflagellate cysts, which were characterised by a warm temperate "Williams Suite" of taxa (dominated by *Isabelidinium* with *Alterbidinium*, *Chatangiella, Spinidinium* and *Trithyrodinium;* Lentin, 1976). Despite some regional taxonomic differences, Lentin and Williams (1980) noted that this suite occurs in Argentina and Australasia, and is broadly comparable to the Late Cretaceous dinoflagellate cyst assemblages of the James Ross Basin (e.g. Askin, 1988a; Pirrie et al., 1991; this study). Mao and Mohr (1992) supplemented this scheme by adding a Campanian to Maastrichtian South Indian Province populated by a "Helby Suite" considered to reflect cool temperate conditions in the Southern Hemisphere during this time. However, until now it was unclear whether these biogeographical provinces reflected Maastrichtian to Paleocene marine plankton distribution in the south polar region.

This study suggests the existence of a Maastrichtian to earliest Paleocene dinoflagellate cyst province that includes the entire Antarctic margin extending to southern Australia, the East Tasman Plateau, New Zealand and up the western tip of southern South America in what is here termed the South Polar Province (Fig. 5). This province approximately incorporates the geographical extent of the Late Cretaceous Antarctic and Weddellian provinces previously defined by Zinsmeister (1979, 1982) based on mollusc distributions in the mid to high southern palaeolatitudes and discussed by Case (1988) and Askin (1989). Zinsmeister (1979, 1982) included the Falkland Plateau and southern South America approximately up to the Austral Basin within his Weddellian Province (Askin, 1989). However this study agrees with Harris (1977) that dinoflagellate cyst assemblages from these regions are different from those of the James Ross Basin/New Zealand/southeastern Australian regions (except the southwest coast of southern South America; Marenssi et al., 2004). The characteristic taxa of Mao and Mohr's (1992) Campanian to Maastrichtian Helby Suite (*Isabelidinium*, *Chatangiella*, *Nelsoniella*, *Amphidiadema* and *Xenikoon*) are all found within the James Ross Basin suggesting that their South Indian Province is also part of the newly defined South Polar Province. The validity of a Late Cretaceous Austral Province *sensu* Zinsmeister (1979, 1982) with respect to dinoflagellate cyst distribution awaits additional work on successions from southern South America and South Africa, and a review of Australian Late Cretaceous palynology beyond the southern sedimentary basins.

8.3. Antarctic Ocean circulation and palaeogeographical implications

During the Maastrichtian, palaeogeographic reconstructions for Antarctica suggest only a shallow water connection through an archipelago that linked the Scotia Arc with the tip of southern South America (Markwick and Valdes, 2004; Markwick, 2007). A Pacific-Atlantic deep-water connection through the modern Drake Passage began opening during the Eocene (Eagles, 2010). Similarly, only a narrow shallow water passage separated East Antarctica from modern Tasmania (the proto-Tasman Gateway), which deepened during the Mid-Late Eocene ca. 35.5 Ma ago (Brinkhuis et al., 2003). More broadly, the palaeogeographical reconstruction of the Southern Hemisphere during the Maastrichtian by Markwick and Valdes (2004) agrees with Zinsmeister's (1979, 1982) reconstructions allowing oceanic contact between all the Weddellian regions, but there is no strong evidence for a deep circumpolar flow until the earliest Oligocene (Katz et al., 2011).

Models of ocean circulation help explain the distribution of Maastrichtian dinoflagellate cyst assemblages throughout the mid to high southern palaeolatitudes, and have implications for the refinement of Antarctic palaeogeography at this time. Maastrichtian palaeoenvironments have been modeled using the HADC3ML fully-coupled atmosphere-ocean global climate model using a reconstructed Maastrichtian palaeogeography and bathymetry at different levels of atmospheric carbon dioxide (CO_2) (Markwick and Valdes, 2004; Hunter, 2009). A relatively coarse model grid resolution for the land-sea mask, based on the reconstructed palaeogeography, allows a shallow water Pacific-Atlantic connection through the Drake Passage, but no oceanic connection between Tasmania and East Antarctica. For all levels of CO_2, surface ocean currents (at 5 m depth, annual average) around the Antarctic margin are relatively slow (0-50 mms^{-1}) compared with modern circumpolar flow (ca.100-200 mms^{-1}) (Hunter, 2009). With increasing CO_2 levels, current intensity increases, but there is little change in the mode of circulation, which would probably be more sensitive to changes in bathymetry and palaeogeography (Hunter, 2009). This surface circulation pattern translates to at least 450 m below sea level, decreasing in intensity with depth (Hunter, 2009) and encompassing the shelf habitats of most dinoflagellate cyst taxa (Fig. 5).

Models of surface ocean currents indicate flow along the Antarctic margin from the southwestern corner of Australia into a gyre within the Weddell Sea; this helps to explain the similarities in marine palynofloras from the Kerguelen Plateau, Maud Rise, the James Ross Basin and the South Georgia Basin. Currents then passing further north across the southern Atlantic from the Weddell Sea may have carried dinoflagellate cysts as far as the tip of South Africa (Davey, 1969; Fig. 5).

The surface ocean current gyre that is modelled flowing down the west of the Antarctic Peninsula, to New Zealand, back up to the western side of southern South America and through the proto Drake Passage, suggests a direct oceanic link and provides a route for dinoflagellate cyst transport on the Pacific side of Antarctica (Fig. 5). However for taxa to freely circulate between the James Ross Basin on the eastern side of the Scotia Arc and the Tasman Sea between New Zealand and Australia, there is a requirement for an unrestricted oceanic connection across the west Antarctic rift. Huber (1988) also noted the need for at least a surface oceanic connection between West and East Antarctica on the basis of the circum-Antarctic distribution of foraminifera.

This hypothesis does not therefore support the presence of a continuous geographical landmass through South America, the Antarctic Peninsula and West Antarctica to Australasia (e.g. Woodburne and Zinsmeister, 1984; Case et al., 1987; Case, 1988; Cantrill and Poole, 2002). However, this does not preclude the presence of a closely-spaced archipelago through this region to account for the dispersion of *Nothofagus* spp. and marsupials across Antarctica from South America (Schuster, 1976; Case, 1988).

9. Conclusions

This palynostratigraphical study, based on the shallow marine sedimentary succession exposed on Seymour Island, proposes the first formal late Maastrichtian to early Danian dinoflagellate cyst zonation scheme for the Antarctic continent. This fills a biostratigraphical gap where previous correlations based on marine palynology relied on remote schemes from New Zealand and southern Australia. This new biozonation has refined the age model for the southern Seymour Island succession, confirming the oldest exposed beds are of Maastrichtian, probably late Maastrichtian, age. To improve the age model further for the base of this key stratigraphical succession requires detailed analysis of the palynofloras within older Late Cretaceous sediments on Vega Island to the north of the James Ross Basin.

The lower part of the section on southern Seymour Island is characterised by long-ranging marine palynomorph taxa with little taxonomic turnover, after which the rate of speciation increases into the early Danian. Below the K-Pg boundary, Askin’s (1988a) preliminary Zone 1 has been retained for the lowermost 163 m of the section, which is overlain by two new biozones based on the stratigraphically useful dinoflagellate cyst genus *Manumiella*. These are the *Manumiella* *seymourensis* Range Zone (707 m) and the *Manumiella bertodano* Interval Zone (104 m). Zone 1, the *Manumiella seymourensis* Range Zone and the *Manumiella bertodano* Interval Zone correlate well with the late Maastrichtian (late Haumurian) *Palaeocystodinium granulatum* Interval Subzone of the *Alterbidinium acutulum* Interval Zone in New Zealand.

The *Manumiella druggii* Interval Zone, which spans the latest Maastrichtian to earliest Danian interval in New Zealand and southern Australia, has been amended and subdivided to account for a significant change in the marine palynological assemblages across the K-Pg horizon on Seymour Island. *Manumiella* spp. dominate in the latest Maastrichtian, followed by a succession of acmes of different taxa, starting with *Senegalinium obscurum* in the earliest Danian, although no dramatic extinction event is evident. Due to the expanded succession on Seymour Island a new early Danian *Hystrichosphaeridium tubiferum* Acme Zone (70 m) has been defined between a modified latest Maastrichtian to earliest Danian *Manumiella druggii* Range Zone and the early Danian *Trithryodinium evittii* Acme Zone (of Helby et al., 1987).

Comparing Maastrichtian to Danian dinoflagellate cyst assemblages across the mid to high southern palaeolatitudes confirms the overall commonality of New Zealand and southern Australian marine palynofloras with those from the Antarctic Peninsula. We propose a new wide-ranging South Polar Province that encompasses this entire region, but precludes most of southern South America, except for the southwestern coast. This analysis is supported by models of ocean currents around Antarctica and implies an unrestricted oceanic connection across Antarctica between southern South America and the Tasman Sea at this time.

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Captions for the display materials:

Figure 1. The location of Seymour Island and the measured section. (a) The location of Seymour Island within the James Ross Basin, off the northeastern tip of the Trinity Peninsula (northern Antarctic Peninsula). CL - Cape Lamb. The grey shading indicates the outcrop of the Marambio Group, which includes the López de Bertodano Formation (LDBF). (b) Landscape of the southern part of Seymour Island showing the continuous surface exposure of the LDBF (looking east). The field camp provides scale. The inset map shows Seymour and the immediately adjacent islands; SP - Spath Peninsula. (c) A geological map of southern Seymour Island showing the location of the measured sub-section lines, which comprise the composite section D5.251. The K-Pg boundary occurs within a distinctive glauconitic interval that is traceable along strike.

Figure 2. A summary lithological log of measured section D5.251 on Seymour Island and a range chart illustrating the stratigraphical occurrences of selected marine palynomorphs (dinoflagellate cysts and other marine algae). Since the publication of Thorn et al (2009), the original field logs have been reviewed, resulting in a re-drafting of the composite lithological log. All sample heights and stratigraphical information remain the same, the only change is an adjustment to the composite stratigraphical height scale. Taxa are plotted in stratigraphical order of their First Appearance Datums (FADs) and include questionable occurrences. Acmes are defined as maxima of a particular taxon within a single sample that comprise greater than 50% of the marine palynomorph assemblage. The K-Pg boundary is dated at 65.5 Ma (Walker and Geismann, 1998). The

Maastrichtian substage boundary (67.5 Ma, McArthur et al., 1998) was placed by Crame et al. (2004) at ca. 600 m below the K-Pg boundary in a separate stratigraphical section 4 km to the north on Seymour Island. SHI - Snow Hill Island Formation (i.e. the Haslum Crag Member); S - Sobral Formation; c - clay; si - silt; fs - fine sand; ms - medium sand; D and T (1987) – Dettmann and Thomson (1987).

Figure 3. The new dinoflagellate cyst zonation for southern Seymour Island showing the key bioevents (First Appearance Datums (FADs) and Last Appearance Datums (LADs)). Zone 1, lowermost zone after Askin's (1988a) preliminary scheme; base unseen. New zones proposed: *Manumiella seymourensis* Range Zone, *Manumiella bertodano* Interval Zone and *Hystrichosphaeridium tubiferum* Acme Zone. Revised zone: *Manumiella druggii* Range Zone: *Trithyrodinium evittii* Acme Zone (of Helby et al., 1987); top unseen.

Figure 4. Biostratigraphical correlations between the new dinoflagellate cyst zonation for southern Seymour Island and other zonal schemes in high southern latitude locations. Seymour Island lithostratigraphy, and correlation with the preliminary biozone scheme of Askin (1988a) is shown for reference. The age interpretation for the entire Seymour Island section pre-K-Pg event is based on comparison with well-dated New Zealand K-Pg sections after Wilson (1984, 1987, 1988), Wilson et al. (1989), Wilson in Strong et al. (1995), Roncaglia and Schiøler (1997), Roncaglia et al. (1999) and Crampton et al. (2000, 2004). The Australian scheme is based on Helby et al. (1987) and is only applicable from the base of the *Manumiella druggii* Interval Zone. SHI, Snow Hill Island Formation (here the Haslum Crag Member); S, Sobral Formation; RZ, Range Zone; IZ, Interval Zone; ISZ, Interval Subzone; AZ, Acme Zone. Grey shading highlights the present study.

Figure 5. Palaeogeographical maps of the south polar region during the Maastrichtian (base map with overlain modern coastlines courtesy of Paul Markwick, personal communication). (a) Maastrichtian to early Danian dinoflagellate cyst assemblages from localities throughout the region (see also Table 1). The symbols indicate which assemblages have some similarity (star), or little similarity (square), to those from the López de Bertodano Formation on Seymour Island. 1, James Ross Basin, Antarctic Peninsula; 2, Magallanes region, Chile; 3, offshore Colorado Basin, Argentina; 4, Neuquén Basin, Argentina; 5, Austral Basin, Argentina; 6, Southern Argentine Basin; 7, South Georgia Basin; 8, Maud Rise; 9, Zululand, South Africa; 10, ODP site 738, Kerguelen Plateau; 11, ODP site 748, Kerguelen Plateau; 12, Otway, Bass and Gippsland Basins, Australia; 13, East Tasman Plateau; 14, North and South Islands, New Zealand; 15, Campbell Island. Ocean

circulation based on HADC3ML modeled currents (Hunter, 2009). (b) The biogeographical provinces discussed in the text, including the new South Polar Province for dinoflagellate cysts.

Appendix A

List of marine palynomorphs from the Maastrichtian to Danian López de Bertodano Formation of Seymour Island. *Reworked. The references for the author citations pertaining to all the dinoflagellate cysts mentioned in this paper described before 2004 are given in Fensome and Williams (2004).

Dinoflagellate cysts:

Achomosphaera ramulifera (Deflandre 1973) Evitt 1963

Alterbidinium acutulum (Wilson 1967) Lentin & Williams 1985

Batiacasphaera? *reticulata* (Davey 1969) Davey 1979

Batiacasphaera spp.

Bosedinia laevigata (Jiabo 1978 ex He Chengquan & Qian Zeshu 1979) He Chengquan 1984

Brigantedinium sp.

Broomea spp.

Cassidium fragile (Harris 1965) Drugg 1967

Cerodinium medcalfii (Stover 1974) Lentin & Williams 1987

Cerodinium striatum (Drugg 1967) Lentin & Williams 1987

Cerodinium spp.

Cordosphaeridium spp.

Cribroperidinium? *muderongense* (Cookson & Eisenack 1958) Davey 1969

Cribroperidinium sp. A of Dettmann & Thomson (1987)

Cribroperidinium sp. of Askin (1988a)

Cribroperidinium spp.

**Diconodinium cristatum* Cookson & Eisenack 1974

Eisenackia circumtabulata Drugg 1967

Eisenackia reticulata (Damassa 1979) Quattrocchio & Sarjeant 2003

Eisenackia spp.

Elytrocysta sp. of Askin (1988a)

Exochosphaeridium bifidum (Clarke & Verdier 1967) Clarke et al., 1968

Hystrichosphaeridium tubiferum (Ehrenberg 1838) Deflandre 1937

Hystrichosphaeridium tubiferum (Ehrenberg 1838) Deflandre 1937 subsp. *brevispinum* (Davey & Williams 1966) Lentin & Williams 1973

Impagidinium cristatum (May 1980) Lentin & Williams 1981

Impagidinium spp.

Impletosphaeridium clavus Wrenn & Hart 1988

Impletosphaeridium spp.

indeterminate dinoflagellate cysts

indeterminate peridiniacean dinoflagellate cysts

Isabelidinium cretaceum (Cookson 1956) Lentin & Williams 1977

Remarks: Bujak and Davies (1983) questionably reassigned this species to *Manumiella*. However, they stated that a distinguishing feature between these two genera is that *Isabelidinium* has bicavate pericoels and *Manumiella* is circumcavate. The specimen of *Manumiella*? *cretacea* illustrated in Bujak and Davies (1983, Plate 7, fig. 11) is bicavate. Specimens of this species from the current study of the López de Bertodano Formation are also bicavate, so this taxon is herein retained as *Isabelidinium cretaceum*.

Isabelidinium pellucidum (Deflandre & Cookson, 1955) Lentin & Williams 1977

Isabelidinium spp.

Lingulodinium bergmannii (Archangelsky 1969) Quattrocchio & Sarjeant 2003

Magallanesium densispinatum (Stanley 1965) Quattrocchio & Sarjeant 2003

Manumiella bertodano Thorn et al., 2009

Manumiella conorata (Stover 1974) Bujak & Davies 1983

Manumiella druggii (Stover 1974) Bujak & Davies 1983

Manumiella seelandica (Lange 1969) Bujak & Davies 1983

Manumiella seymourensis Askin 1999

Manumiella spp.

Microdinium sp.

Oligosphaeridium complex (White 1842) Davey & Williams 1966

Oligosphaeridium spp.

Operculodinium baculatum Yu Jingxian & Zhang Wangping 1980

Operculodinium spp.

Remarks: Specimens assigned to *Operculodinium* spp. are similar to *Operculodinium flucturum* Smith 1992 and *Operculodinium radiculatum* Smith 1992, having capitate processes covering a spherical cyst body. The majority of specimens are torn with the processes lying flattened against the cyst body so that the form of the process bases could not be determined. The preservation of surface sculpture was not clear enough to decide whether it is coarsely scabrate or was once reticulate. Therefore, all of these specimens were grouped into *Operculodinium* spp.

Palaeocystodinium granulatum (Wilson 1967) Lentin & Williams 1976

Palaeocystodinium lidiae (Górka 1963) Davey 1969

Palaeocystodinium spp.

Palaeoperidinium pyrophorum (Ehrenberg 1838 ex Wetzel 1933) Sarjeant 1967

Peridinium sp. of Drugg (1967)

Phelodinium exilicornutum Smith 1992

Phelodinium sp. cf. *P. magnificum* (Stanley 1965) Stover & Evitt 1978

Remarks: Rare specimens of this morphotype are compared to *Phelodinium magnificum* because the dimensions are smaller (75µm, 80µm wide; n=2) than in the original diagnosis (100-115 µm, Stanley, 1965).

Phelodinium spp.

Senegalinium obscurum (Drugg 1967) Stover & Evitt 1978

Senegalinium? *dilwynense* (Cookson & Eisenack 1965) Stover & Evitt 1978

Senegalinium spp.

Spinidinium sp. 1 of Askin (1988a)

Spinidinium spp.

Spiniferites ramosus (Ehrenberg 1838) Mantell 1854

Spiniferites spp.

Tanyosphaeridium xanthiopyxides (Wetzel 1933 ex Deflandre 1937) Stover & Evitt 1978

Trithyrodinium evittii Drugg 1967

Xenascus spp.

Acritarchs:

Baltisphaeridium sp.

Dinocyst n. gen. X of Askin (1988a)

Remarks: Askin (1988a) noted an apical archeopyle for this morphotype, but this was not unequivocally identified in the specimens observed during this study. Cingular and sulcal folds were consistently observed, but no other tabulation was discerned. Due to the lack of a clear archeopyle and significant evidence of tabulation, this morphotype is herein classified as an acritarch.

Fromea spp.

Nummus spp.

Paralecaniella indentata (Deflandre & Cookson 1955) Cookson & Eisenack 1970

Paucilobimorpha? *apiculata* (Cookson & Eisenack 1962) Prössl 1994

Miscellaneous microplankton:

indeterminate microplankton

Palamblages spp.

Pterospermella australiensis (Deflandre & Cookson 1955) Eisenack et al. 1973

Tasmanites spp.

Online Supplementary Information caption:

Dinoflagellate cyst, acritarch and other microplankton count data from composite section D5.251, southern Seymour Island, James Ross Basin, Antarctic Peninsula. x, presence beyond formal count; italic font, questionable occurrence; bold font, compared with (cf.); R, presumed reworked; D and T (1987), Dettmann and Thomson (1987). All samples counted on a Leitz Ortholux binocular microscope, except D5.601.1A and D5.621.1A, which were counted on a Leica DM750P binocular microscope.

Plate captions:

Plate I. Selected dinoflagellate cysts from the Snow Hill Island Formation (Haslum Crag Member, HCM) and the López de Bertodano Formation (LDBF) of Seymour Island. The images are stacked to show the entire focal depth of each specimen. The unique British Antarctic Survey (BAS) collection numbers are in the format D5.****.1 for the bulk sediment samples, with the suffix A (e.g. D5.1247.1A) referring to palynomorph slide A. The England Finder coordinate (e.g. A54-2) and the stratigraphical height within composite section D5.251 are quoted for each specimen. The images of *Manumiella* are of the best specimens illustrated by Thorn et al. (2009).

1 - *Isabelidinium pellucidum* (Deflandre & Cookson, 1955) Lentin & Williams 1977, D5.621.1A (HCM, 20 m), N63-4.

2 - *Isabelidinium cretaceum* (Cookson 1956) Lentin & Williams 1977, D5.621.1A (HCM, 20 m), R63-2.

3 - *Batiacasphaera*? *reticulata* (Davey 1969) Davey 1979, D5.525.1A (LDBF, 203 m), X49-1.

4 - *Operculodinium baculatum* Yu Jingxian & Zhang Wangping 1980, D5.525.1A (LDBF, 203 m), V49-0.

5 - *Impletosphaeridium clavus* Wrenn & Hart 1988, D5.466.1A (LDBF, 143 m), V52-2. Phase contrast image.

6 - *Tanyosphaeridium xanthiopyxides* (Wetzel 1933 ex Deflandre 1937) Stover & Evitt 1978, D5.905.1A (LDBF, 383 m), N67-0.

7 - Indeterminate peridiniacean dinoflagellate cyst, D5.525.1A (LDBF, 203 m), W69-0.

8 - *Palaeocystodinium granulatum* (Wilson 1967) Lentin & Williams 1976, D5.1268.1A (LDBF, 984 m), S52-4.

9 - *Impagidinium cristatum* (May 1980) Lentin & Williams 1981, D5.905.1A (LDBF, 383 m), N72-1.

10 - *Spiniferites ramosus* (Ehrenberg 1838) Mantell 1854, D5.621.1A (HCM, 20 m), S50-2.

11 - *Manumiella seymourensis* Askin 1999, D5.1121.1A (LDBF, 746 m), O63-1.

12 - *Manumiella bertodano* Thorn et al. 2009, D5.1184.1A (LDBF, 866 m), D40-2.

13 - *Bosedinia laevigata* (Jiabo 1978 ex He Chengquan & Qian Zeshu 1979) He Chengquan 1984, D5.1184.1A (LDBF, 866 m), K49-4.

14 - *Exochosphaeridium bifidum* (Clarke & Verdier 1967) Clarke et al. 1968, D5.1268.1A (LDBF, 984 m), M51-3.

15 - *Senegalinium obscurum* (Drugg 1967) Stover & Evitt 1978, D5.1293.1A (LDBF, 1008 m), L49-2.

16 - *Eisenackia circumtabulata* Drugg 1967, D5.1309.1A (LDBF, 1024 m), B56-0.

17 - *Manumiella seelandica* (Lange 1969) Bujak & Davies 1983, D5.1237.1A (LDBF, 958 m), T41-4.

18 - *Manumiella druggii* (Stover 1974) Bujak & Davies 1983, D5.1253.1A (LDBF, 988 m), F43-2.

Plate II

Selected dinoflagellate cysts from the López de Bertodano Formation (LDBF) of Seymour Island. The images are stacked to show the entire focal depth of each specimen. The unique British Antarctic Survey (BAS) collection numbers are in the format D5.****.1 for the bulk sediment samples, with the suffix A (e.g. D5.1247.1A) referring to palynomorph slide A. The England Finder coordinate (e.g. A54-2) and stratigraphical height within composite section D5.251 are also quoted for each specimen.

1 - *Phelodinium* sp. cf. *P. magnificum* (Stanley 1965) Stover & Evitt 1978, D5.1279.1A, 994 m, R38-2.

2 - *Broomea* sp., D5.1253.1A, 988 m, X39-0.

3 - *Hystrichosphaeridium tubiferum* (Ehrenberg 1838) Deflandre 1937, D5.1309.1A, 1024 m, W60-0.

4 - *Palaeoperidinium pyrophorum* (Ehrenberg 1838 ex Wetzel 1933) Sarjeant 1967, D5.1309.1A, 1024 m, C41-4.

5 - *Cerodinium medcalfii* (Stover 1974) Lentin & Williams 1987, D5.1387.1A, 1084 m, O70-0.

6 - *Trithyrodinium evittii* Drugg 1967, D5.1379.1A, 1074 m, T58-3.

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