



A magneto- and chemostratigraphically calibrated dinoflagellate cyst zonation of the early Palaeogene South Pacific Ocean



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ABSTRACT

Investigation of the early Palaeogene palaeoecological and palaeoclimatological evolution of the Polar Regions is hindered by the absence of calcite microfossils in sedimentary archives, which are conventionally the main dating tool. To overcome this problem, we have generated large datasets of organic dinoflagellate cyst (dinocyst) assemblages from Southern Ocean shelf sediments over the past decade, and we here calibrate these to the Geomagnetic Polarity Time Scale (GPTS) using magnetostratigraphy and stable isotope stratigraphy. This now for the first time allows a high-resolution Southern Pacific Ocean dinocyst zonation for the late Palaeocene to late Eocene (58–36 million years ago; Ma). We compile published dinocyst chronologies from Ocean Drilling Program (ODP) Hole 1171D on the South Tasman Rise, Hole 1172A/D on the East Tasman Plateau and Integrated Ocean Drilling Program (IODP) Hole U1356A on the Wilkes Land margin. Correlation to dinocyst zonations from New Zealand lead to revisions of the magnetostratigraphic age model at Holes 1171D and 1172A/D. Stable carbon and oxygen isotope records reveal the stratigraphic location of the Palaeocene–Eocene Thermal Maximum (~56 Ma) and the Middle Eocene Climatic Optimum (~40 Ma), respectively. The resulting zonation consists of thirteen dinocyst zones, calibrated to the Geomagnetic Polarity Time Scale (GPTS) of Vandenberghe *et al.* (2012), which can likely be applied to the entire Southern Ocean. Finally, we apply the revised stratigraphy to all published TEX₈₆ data, a biomarker-based proxy for sea surface temperature (SST), from ODP Site 1172 to assess long-term climate evolution. This shows that Southwest Pacific SST trends mimic the global compilation of benthic foraminiferal oxygen isotopes even better than previously appreciated.

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1. Introduction

Throughout the past decades, interest has risen for high-latitude sediments from the early Palaeogene ‘greenhouse’ period (~65 to 35 Ma), particularly for palaeoclimate reconstructions (Wrenn and Beckman, 1982; Wrenn and Hart, 1988; Hannah, 1997; O’Brien et al., 1998, 2004; Brinkhuis et al., 2006; Moran et al., 2006; Sluijs et al., 2006, 2009a; Ivany et al., 2008; Bijl et al., 2009; Hollis et al., 2009, 2012; Pross et al., 2012; Houben et al., 2013). This is because atmospheric CO₂ levels during the early Palaeogene were likely analogous to those projected for the coming centuries should fossil fuel emissions continue unabated (Zachos et al., 2008), allowing documentation of the polar climatic end member in a greenhouse world.

A traditional problem in high latitude palaeoceanography is the precise dating of the sedimentary archives. Calcite fossil groups, such as foraminifera and calcareous nannoplankton, which are well calibrated to geomagnetic polarity time scales, are typically poorly or not preserved in high-latitude settings (Wilson et al., 1998; Florindo et al., 2003; Barker et al., 2007). In addition, siliceous microfossils such as diatoms and radiolaria dissolve when buried below a sub-surface diagenetic front (e.g., Rice et al., 1995). The only consistently available microfossils in high-latitude early Palaeogene sediments are organic dinoflagellate cysts (dinocysts), which are often abundant and well preserved in marginal marine sediments (Wrenn and Hart, 1988; Brinkhuis et al., 2003a,b). However, this group still lacks a well-calibrated biostratigraphic framework in both the Arctic and Antarctic regions. As a consequence, while several authors reported fossil and geochemical results that implied remarkable insight into the general warmth of the Polar Regions (e.g., Barron, 1987; Francis, 1988; Ehrmann, 1998; Ivany et al., 2008), detailed correlations to mid- and low latitude sites remained difficult.

The Southern Ocean is of particular interest to the palaeoclimate community, notably because the South Pacific Ocean was the region of intermediate-water formation during the early Palaeogene (Thomas et al., 2003; Huber and Caballero, 2011; Sijp et al., 2011). Through intermediate-water formation, the Southern Ocean has an important role in ocean circulation and global climate: palaeoclimatic changes in the Southern Ocean surface waters are effectively transported to other regions through deep convection. The oceanic surface circulation changed during the Eocene due to the tectonic evolution in the Southern Ocean, such as the opening of tectonic ‘gateways’ (Tasmanian Gateway, Drake Passage). This may have had a pivotal role in explaining the climatic evolution as interpreted from benthic foraminiferal oxygen isotopes, which reflect intermediate water temperatures and global ice volume. While the tectonic deepening of the Tasmanian Gateway in the late Eocene is well-documented through the study of sediment records from around Tasmania (Stickley et al., 2004a), the earlier history of opening has until recently been less well-constrained with sedimentary archives. Over the past 15 years, ocean drilling activities in the Southern Ocean have not only brought a wealth of palaeoclimate information, but also the potential of much improved age assessments through the integrated bio-magneto-chemostratigraphical approach. The Ocean Drilling Program (ODP) recovered early Palaeogene sedimentary successions around Tasmania during Leg 189 in 2000, e.g., at Sites 1171 and 1172 (Fig. 1; Exon et al., 2001). An initial bio-magnetostratigraphic age model (including dinocysts) was published based on shipboard and initial shore-based analyses (Stickley et al.,

2004b; Williams et al., 2004). Extensive research at Site 1172 over the past years lead to the identification of transient climate–carbon cycle perturbations such as the Palaeocene–Eocene Thermal Maximum (PETM; Sluijs et al., 2011) and the Middle Eocene Climatic Optimum (MECO; Bijl et al., 2010). These represent chrono-stratigraphic tie points, and allow for a significant improvement of the age model. In addition, the sedimentary succession at Site U1356 recovered in 2010 by the Integrated Ocean Drilling Program (IODP) offshore the Wilkes Land Margin, Antarctica (Fig. 1) provides additional age constraints for early–middle Eocene dinocyst stratigraphy through integration with magnetostratigraphy (Tauxe et al., 2012).

We here compile all existing dinocyst and magnetostratigraphic data at Holes 1171D, 1172A/D and U1356A, and subsequently compare these to dinocyst zonations from New Zealand (Wilson, 1988; Crouch, 2001; Crouch and Brinkhuis, 2005). Based on these correlations, we present a revised bio-magneto-chemostratigraphic age model for Holes 1171D and 1172A/D that allows for a South Pacific dinocyst zonation scheme. The dinocyst zonation proposed here allows high-resolution calibration of Southern Ocean sedimentary archives that are sampled previously and will be drilled in the future. To present the state-of-the-art palaeoclimatological evolution of the Southwest Pacific Ocean, we apply our proposed dinocyst zonation to a compilation of published records of a biomarker-based proxy for sea surface temperature (SST), TEX₈₆, which portrays the palaeoclimatic evolution of the Southwest Pacific Ocean.

2. Plate tectonics, oceanography and biogeography of the Southwest Pacific Ocean

2.1. Tectonic evolution of the South Pacific and South Indian Ocean

The breakup of supercontinent Gondwana around the Jurassic–Cretaceous boundary times (~145 Ma; Willcox and Stagg, 1990) resulted in rifting between Australia and Antarctica. Continental crustal stretching and thinning occurred pulse-wise, and formed the Australo-Antarctic Gulf. Continued rifting eventually resulted in the formation of oceanic crust in the Australo-Antarctic Gulf by the late Cretaceous (~83 Ma; Close et al., 2009). Sea floor spreading rates were slow initially (1.5–7.5 mm/year; Close et al., 2009), and Antarctica and Australia remained attached at the Tasmanian side. During the late Cretaceous, Australian and South American terrestrial mammal assemblages exchanged, via a land connection over the Tasmanian land bridge (Woodburne and Case, 1996). Diversifying mammal assemblages on Australia from 64 Ma onwards signify the formation of a marine barrier, the Tasmanian Gateway. Crustal anomaly studies have shown a distinct increase in sea floor spreading rates in the Australo-Antarctic Gulf from 48 Ma onwards (Fig. 2b, c; Close et al., 2009). Some continental blocks surrounding the Tasmanian Gateway slowly deepened, such as the East Tasman Plateau (Röhl et al., 2004a) while others, such as the South Tasman Rise (Cande and Stock, 2004; Exon et al., 2004a) show more rapid subsidence. The subsidence of particularly the South Tasman Rise allowed for the westward flow of southwest Pacific surface waters through a shallow southern opening of the Tasmanian gateway into the Australo-Antarctic Gulf from 49–50 Ma onwards (Bijl et al., in press). Continued drowning (Röhl et al., 2004a) ultimately evolved in rapid deepening of continental blocks surrounding Tasmania starting at ~35.5 Ma (Stickley et al.,

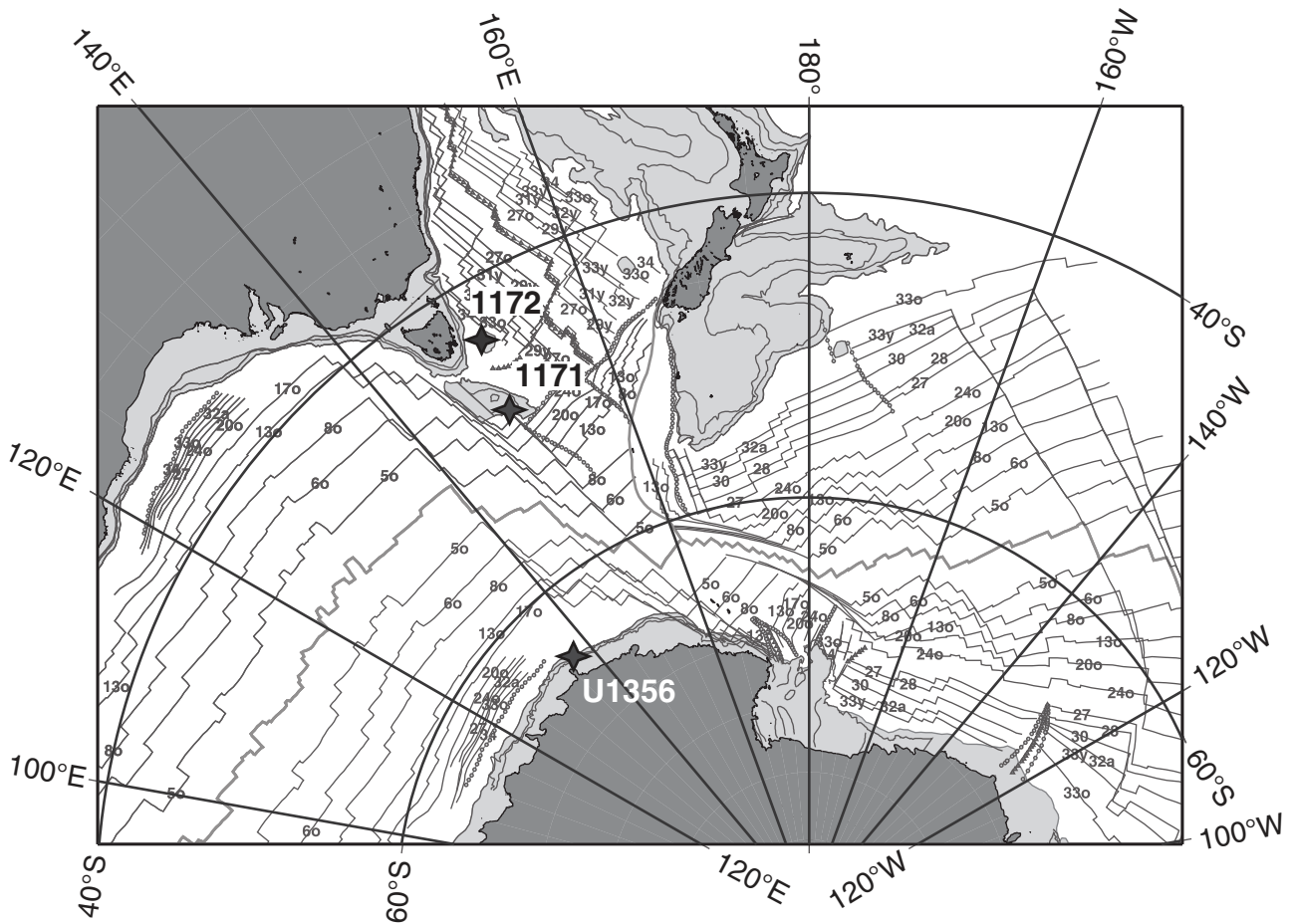


Fig. 1. Present-day site locations of Ocean Drilling Program Sites 1172 and 1171 on the East Tasman Plateau (ETP) and South Tasman Rise (STR) in the Southwest Pacific, and Integrated Ocean Drilling Program Site U1356 on the Wilkes Land Margin, Antarctica. Dark gray areas indicate present-day shorelines and light-gray areas are submerged continental blocks above 3000 m. White areas are below 3000 m. Map modified from Cande and Stock (2004).

2004a), when the northward drift of the Australian continent commenced (Fig. 2d). Thus, this tectonic evolution had a profound impact on regional surface ocean circulation.

2.2. Palaeogene Southern Ocean oceanography and dinoflagellate biogeography

Since the 1970s palaeoceanographers have investigated the consequences of the closed Southern Ocean Gateways on Palaeogene Southern Ocean oceanography (Kennett et al., 1974; Kennett, 1977, 1978; Lazarus and Caulet, 1993; Veevers, 2000; Lawver and Gahagan, 2003). Research focused on the presumed importance of the closed tectonic gateways in the Eocene Southern Ocean, i.e. the Tasmanian Gateway and the Drake Passage, which effectively blocked wind-driven clockwise circum-Antarctic surface current circulation: the Antarctic Circumpolar Current (ACC). In the absence of an ACC, it was thought that low-latitude currents could reach and warm the Antarctic coastline, and explaining the warmth of the Eocene Southern Ocean and Antarctica (Kennett, 1977, 1978). Subsequent opening of these gateways were found to be roughly time-equivalent with the onset of major glaciation on Antarctica, which lend further support to this theory (Lawver and Gahagan, 2003). However, with the application of sophisticated computer model simulations, the theory of thermal isolation was opposed in the 1990s (Sloan and Rea, 1995; Huber et al., 2004). Simulations of surface circulation with an Eocene tectonic configuration (i.e., with closed tectonic gateways) and modern-day

wind patterns suggested that instead of low-latitude-derived currents reaching Antarctic coasts, the Eocene Southern Ocean was characterized by circulating gyres, which prevented the low-latitude currents from reaching the Antarctic coastline. Furthermore, it was shown that the deepening of the Tasmanian Gateway was not time equivalent, but preceded the onset of major glaciation on Antarctica by ~2 million years (Stickley et al., 2004a).

The model output of clockwise gyral surface circulation in the Southern Ocean is supported by microfossil distributions in the Eocene Southern Ocean, notably by the regional dominance of a group of dinocyst taxa that are either endemic to the Southern Ocean south of 45°S, or are strictly bi-polar (Wrenn and Beckman, 1982; Huber et al., 2004; Bijl et al., 2011). Wrenn and Beckman (1982) termed the endemic dinocyst community the 'transantarctic flora'. Initially, the biogeographic distribution of this endemic community in the Weddell and Ross seas were thought to reflect a trans-Antarctic seaway (Wrenn and Beckman, 1982). However, recent reconstructions of the Eocene palaeotopography of Antarctica (Wilson and Luyendyk, 2009; Wilson et al., 2012) strongly oppose the possibility of a seaway connecting both Antarctic seas. Recent extensive analyses and reviews of the biogeographic distribution of the endemic dinocyst community in the Southern Ocean show an interesting pattern when compared to the Southern Ocean and comparison to the Southern Ocean surface current configuration as reconstructed through GCM experiments has shed new light on dinocyst biogeography in the Southern Ocean. Regions under influence of Antarctic-derived surface currents are dominated

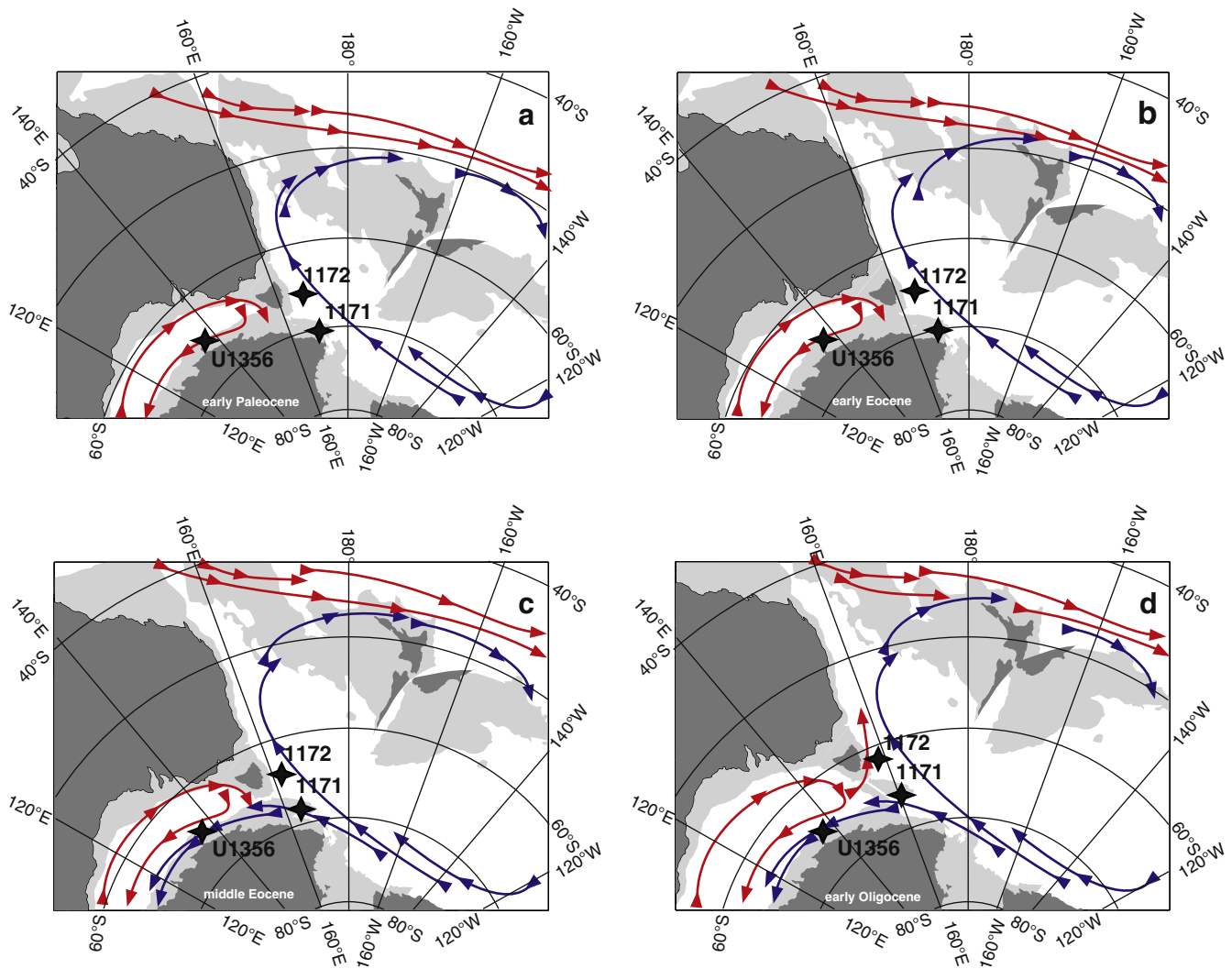


Fig. 2. Palaeogeographic reconstructions of the Australian Sector of the Southern Ocean, for (a) 62.4 Ma, (b) 53.9 Ma, (c) 43.4 Ma and (d) 33.7 Ma. Also plotted are the reconstructed locations of the sites mentioned in this study, and the reconstructed surface current configurations. Shadings as in Fig. 1. Maps modified from Cande and Stock (2004).

by endemic-Antarctic dinocysts, while regions under influence of low-latitude-derived currents are dominated by cosmopolitan- and low-latitude-derived dinocysts (Huber et al., 2004; Bijl et al., 2011, *in press*). A recent review of dinocyst biogeographic patterns has shown that the strong affinity of different dinocyst communities to surface currents has little relation to the surface water temperature, but is more likely related to other parameters, perhaps nutrients, that directly relate to specific water masses (Bijl et al., 2011).

3. Sites

Our proposed dinocyst zonation scheme is obtained from high-resolution dinocyst analyses on four Ocean Drilling Holes: ODP Hole 1172A/D, ODP Hole 1171D and IODP Hole U1356A. Before we propose our dinocyst zonation, background information on the drill sites, lithology and the initial age model is provided.

3.1. Site 1172

3.1.1. Site and lithology description of Hole 1172A/D

Site 1172 is located on the submerged flat western side of the East Tasman Plateau (ETP), at 45°S, at a water depth of 2620 m (Fig. 1;

Exon et al., 2004b). Four holes were drilled in total, of which Hole 1172A extends down to the mid-Lutetian at ~504 m below sea floor (mbsf). Below an additional copy of the Eocene–Oligocene transition, Hole 1172D recovered sediments from mid-Lutetian to upper Maastrichtian age, with sufficient overlap to correlate to Hole A (Exon et al., 2001; Stickley et al., 2004b). Sediments used in this study are from ~358 to 630 mbsf. Palaeocene–lower Eocene sediments are olive gray, with some variations to grayish brown and to greenish gray, with abundant bioturbation (Exon et al., 2001). Sediments are virtually barren of any calcareous and siliceous microfossil groups, hampering conventional biostratigraphic dating (Stickley et al., 2004b). Middle–upper Eocene sediments contain increasing abundances of other microfossil groups, upsection, such as calcareous nannofossils, radiolarians and diatoms and eventually planktonic foraminifera (Stickley et al., 2004b). Prior to 35.5 Ma, lateral tectonic motion of the ETP was limited to slight eastward rift, away from Australia (Fig. 2). Gradual subsidence of the East Tasman Plateau provided accommodation space for continuous (although minor (~100 kyr) unconformities occur; Röhl et al., 2004a) shallow marine deposition. Middle Eocene strata are characterized by slightly deeper facies, increased carbonate content of the sediments and rapid shifts in dinocyst assemblages and elemental counts, all of which reflect third-order sea level cycles (Röhl et al., 2004a).

3.1.2. Age model of Hole 1172A/D

Age control in the pre-Oligocene part of the succession relies on dinocysts, and occasionally on diatom and calcareous nannofossil stratigraphy, combined with magnetostratigraphy (Stickley et al., 2004b). Inclination data for Hole 1172A/D were published in the “Initial Reports” volume (Exon et al., 2001) available from the ODP website (www.odp.tamu.edu), and magnetic reversals were identified from the palaeomagnetic data as published by Fuller and Touchard (2004). We note that the interpretation of the inclination data is complicated due to the strong normal overprint (Fuller and Touchard, 2004). Because of this overprint, Fuller and Touchard (2004) used an unconventional approach of correlating inclination data with the z-intensities to distinguish normal from reversed polarities (Fuller and Touchard, 2004). A first inventory of dinocyst species found during ODP Leg 189 is published in the Scientific Results section of the Ocean Drilling Program (Brinkhuis et al., 2003a,b; Sluijs et al., 2003). The upper Palaeocene and Eocene successions can be correlated to sections from New Zealand, which are calibrated to nanoplankton stratigraphy (which is unfortunately based on poorly preserved nannofossils), because many key dinocyst events were recognized at both locations (Brinkhuis et al., 2003a,b; Sluijs et al., 2003; Crouch and Brinkhuis, 2005). In addition, high-resolution analyses have added stratigraphic tie points and independent age constraints for Holes 1172A and D. For example, the identification of an ~3‰ negative excursion in the stable carbon isotopic composition ($\delta^{13}\text{C}$) of total organic carbon in Section 1172D-15R-4, along with dominance of dinocyst *Apectodinium* spp. and a transient 5–8 °C sea surface temperature rise reveals the position of the Palaeocene–Eocene Thermal Maximum (PETM) (Sluijs et al., 2011). Moreover, bulk carbonate oxygen isotope analyses combined with nanoplankton and radiolarian bio-events revealed the Middle Eocene Climatic Optimum (MECO) in Core 1172A-46X to -42X (Bijl et al., 2010). These independent age constraints generally support the magnetostratigraphic inferences of Fuller and Touchard (2004), although they implied slight changes (Bijl et al., 2010). We incorporated the new chemo-stratigraphic insights into a revised magnetostratigraphic interpretation of the palaeomagnetic data from ODP Site 1172 in the range chart of selected dinocyst species (Fig. 3). The palaeomagnetic interpretation follows that in Bijl et al. (2010).

3.2. Site 1171

3.2.1. Site and lithology description of Hole 1171D

Site 1171 is located in lower bathyal water depths of about 2150 m on a gently south-westerly slope on the southern part of the South Tasman Rise (STR), at 48°S (Fig. 1; Stickley et al., 2004b). The age model for this site indicates the presence of strata deposited during the early Eocene, mid-Subchron C24n (Röhl et al., 2004b) to early Oligocene times. The middle Eocene section does contain occasional calcareous nannofossils, but the lithology is predominantly carbonate-low, dark greenish gray to olive gray claystone, with increasing abundance of calcareous nannofossils going upsection. Notably, the entire succession is rich in dinocysts. High sedimentation rates of >12 cm/kyr evidence steady subsidence of the sub-basins that were formed during faulting of the STR. Continental stretching resulted in a NW oriented movement of the STR until around 51 Ma, when directions rotated to N–S (Hill and Exon, 2004).

3.2.2. Age model of Hole 1171D

In contrast to shipboard interpretations (Exon et al., 2001, 2004b) Palaeocene strata were not recovered at Site 1171: oldest recovered sediments are correlated to upper Subchron C24n (Röhl et al., 2004b). Many and large core gaps in the mid-middle Eocene interval of ODP Site 1171 compromise proper investigations of the expression of the MECO at this site. An integrated magneto-biostratigraphic age

model for 1171 was published in the Scientific Results Volume (Stickley et al., 2004b), combining dinocyst and few calcareous nanoplankton events with magnetostratigraphy. Higher resolution dinocyst analyses since then have increased confidence in the chronology at this site (Fig. 4). Sedimentation rates in the Eocene are much higher (12 cm/kyr) compared to Site 1172. Particularly around the end of the early Eocene, sedimentation rates vastly increase (Stickley et al., 2004b). Importantly, the record at Site 1171 covers the interval from mid-Subchron C24n to mid Subchron C23n, an interval truncated in an unconformity at Site 1172 (Bijl et al., 2009, 2010).

3.3. Site U1356

3.3.1. Site and lithology description of Hole U1356A

Site U1356 is located on the Wilkes Land Margin at the transition between the continental rise and the abyssal plain at 4003 m below sea level (Escutia et al., 2010). Eocene sediments were recovered between 890 and 1000 mbsf, and consist of dark green bioturbated claystone that is faintly stratified (millimeter to meter scale) as defined by color variations, overlain by interbedded stratified and massive sandstones, diamictites, silty claystones, and siltstones with graded bedding and parallel lamination (Escutia et al., 2010). While the drill site is now at abyssal depths, it was located on the Antarctic continental shelf in the Eocene, when the Wilkes Land shelf was much broader than at present (Close et al., 2009). The outer shelf submerged during the late Eocene–early Oligocene when rapid spreading widened the Australo-Antarctic Gulf (Close et al., 2009).

3.3.2. Age model of Hole U1356A

Shore-based high-resolution dinocyst analyses (Fig. 5; Tauxe et al., 2012; Pross et al., 2012; Houben et al., 2013; Bijl et al., in press) have increased confidence in the shipboard integrated dinocyst- and magneto-stratigraphic age model for the Eocene section at Site U1356 (Escutia et al., 2011). An integrated bio-magnetostratigraphic framework was published by Tauxe et al. (2012). The lowermost 60 m of the succession dates back to the mid-early Eocene (Subchrons C24n to C23n), followed by 50 m of strata that straddle the early–middle Eocene boundary (Magnetochron C22/C21).

4. Methods for palynology

Sediments were processed for palynology using standard palynological processing techniques at the Laboratory of Palaeobotany and Palynology (LPP) of Utrecht University, as described in the original papers (Brinkhuis et al., 2003a; Sluijs et al., 2003; Bijl et al., 2011, in press). All material is stored in the collection of the Laboratory of Palaeobotany and Palynology of Utrecht University. Dinocyst taxonomy follows that cited in Fensome and Williams (2004), unless stated otherwise, such as in case of recently described or emended taxa. A complete list of encountered taxa is given in Appendix 1.

5. South Pacific dinocyst zonation

We recognized 12 key dinocyst events that allow for detailed correlation between Hole 1172A/D and Hole 1171D, and are consistent with magnetostratigraphic correlation (Fig. 6; Table 1). In addition, these dinocyst events correlate well to the lower Eocene succession of the Wilkes Land Margin (Fig. 6). This allows for solid correlations between the Tasman and Wilkes Land Region. In addition, for the upper Palaeocene–lower Eocene succession in Holes 1172A/D and 1171D, key dinocyst events were recognized that allow correlation to the dinocyst stratigraphy of New Zealand (Crouch and Brinkhuis, 2005). Younger sediments in New Zealand are not independently calibrated. However, we recognize several dinocyst events in the Tasmanian sector that are consistent with an uncalibrated New Zealand

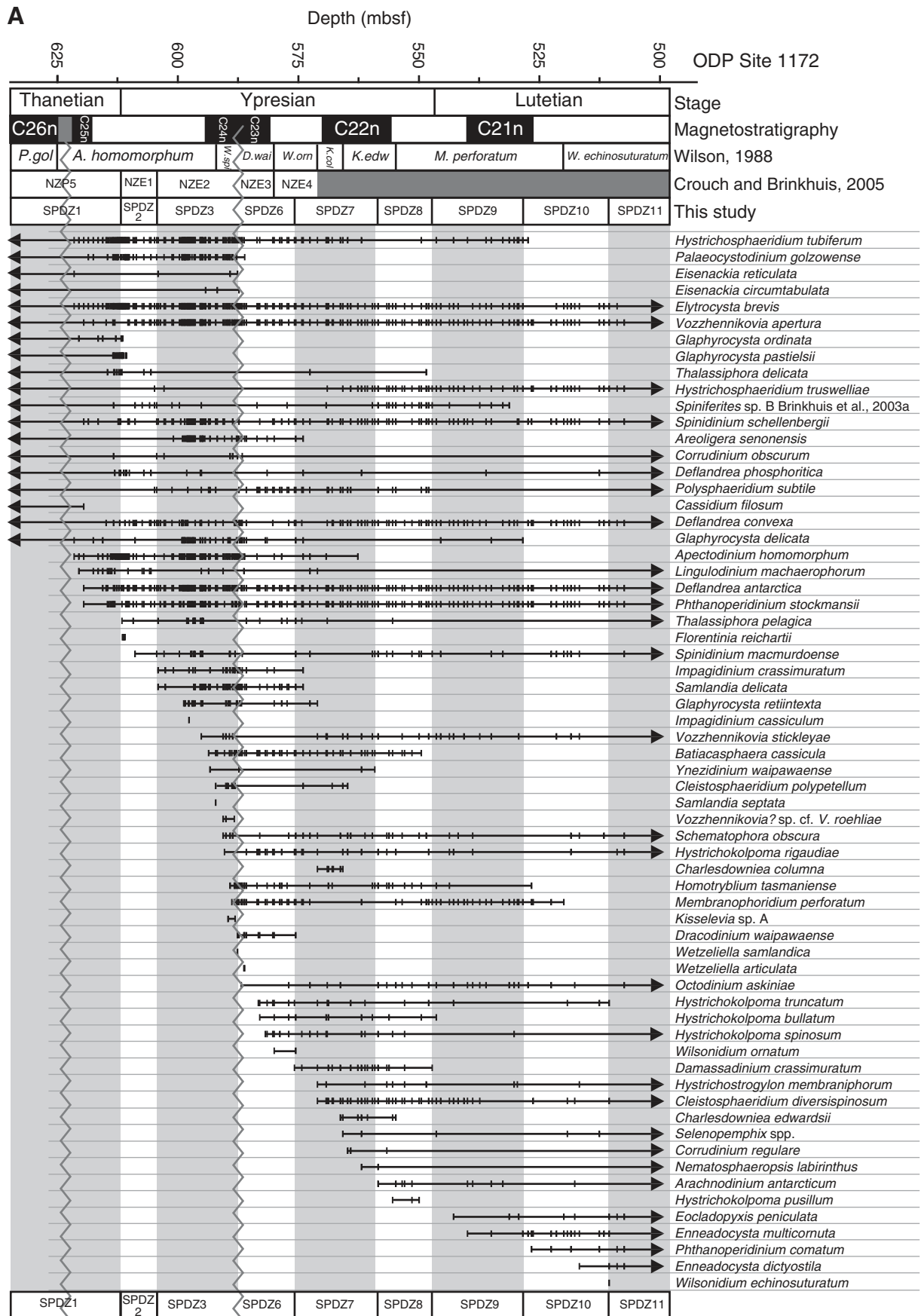


Fig. 3. Ranges of dinocyst taxa for ODP Site 1172. A: Thanetian–Lutetian strata. B: Lutetian–Priabonian strata. Also plotted are the magnetostratigraphic interpretation, and other dinocyst zonations such as those from Wilson (1988) and Crouch and Brinkhuis (2005).



Fig. 3 (continued).

dinocyst zonal scheme (Wilson, 1988). The combined information allows for the recognition of inter-regional dinocyst index-events that correlate well despite differences in dinocyst biogeography.

We use the first occurrences (FO), last occurrences (LO), first common (~25%) occurrences (FCO) and last common (~25%) occurrences (LCO) of dinocyst taxa to define boundaries between thirteen formal dinocyst zones for the late Palaeocene–late Eocene South Pacific Ocean (Figs. 6 and 7; Table 1). Where possible, we use the events that mark zones in New Zealand. The top of each zone is defined by a dinocyst event that also defines the base of the overlying zone. We assign a type locality for each dinocyst zone and a base- and top sample for that zone is assigned at the type locality. In addition, the

base and top samples in the paratype locality are assigned where applicable. The age calibration of the top of each zone is given to the Geomagnetic Polarity Time Scale of Vandenberghe et al. (2012), including the associated magneto (sub-)chron. The dinocyst zonation is correlated to stages, with ages according to Vandenberghe et al. (2012). A comparison of our dinocyst zonation to those from previous studies is presented in Fig. 7.

- (1) South Pacific Dinocyst Zone (SPDZ) 1
 Base definition: LCO *Palaeoperidinium pyrophorum*
 Top definition: FCO *Apteodinium homomorphum*
 Type locality: ODP Site 1172

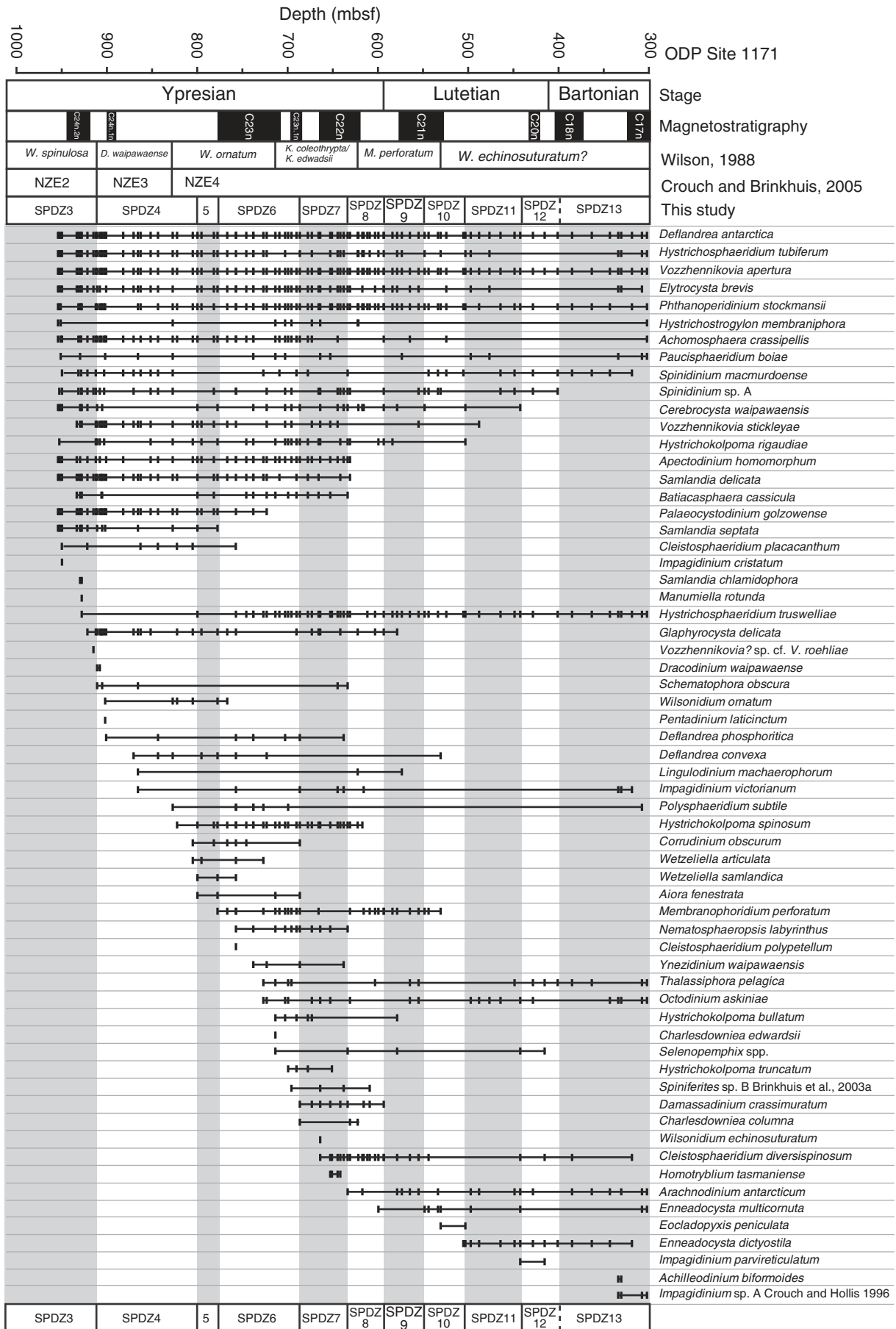


Fig. 4. Ranges of dinocyst taxa for ODP Site 1171, with magnetostratigraphic interpretation and other dinocyst zonations such as those from Wilson (1988) and Crouch and Brinkhuis (2005).

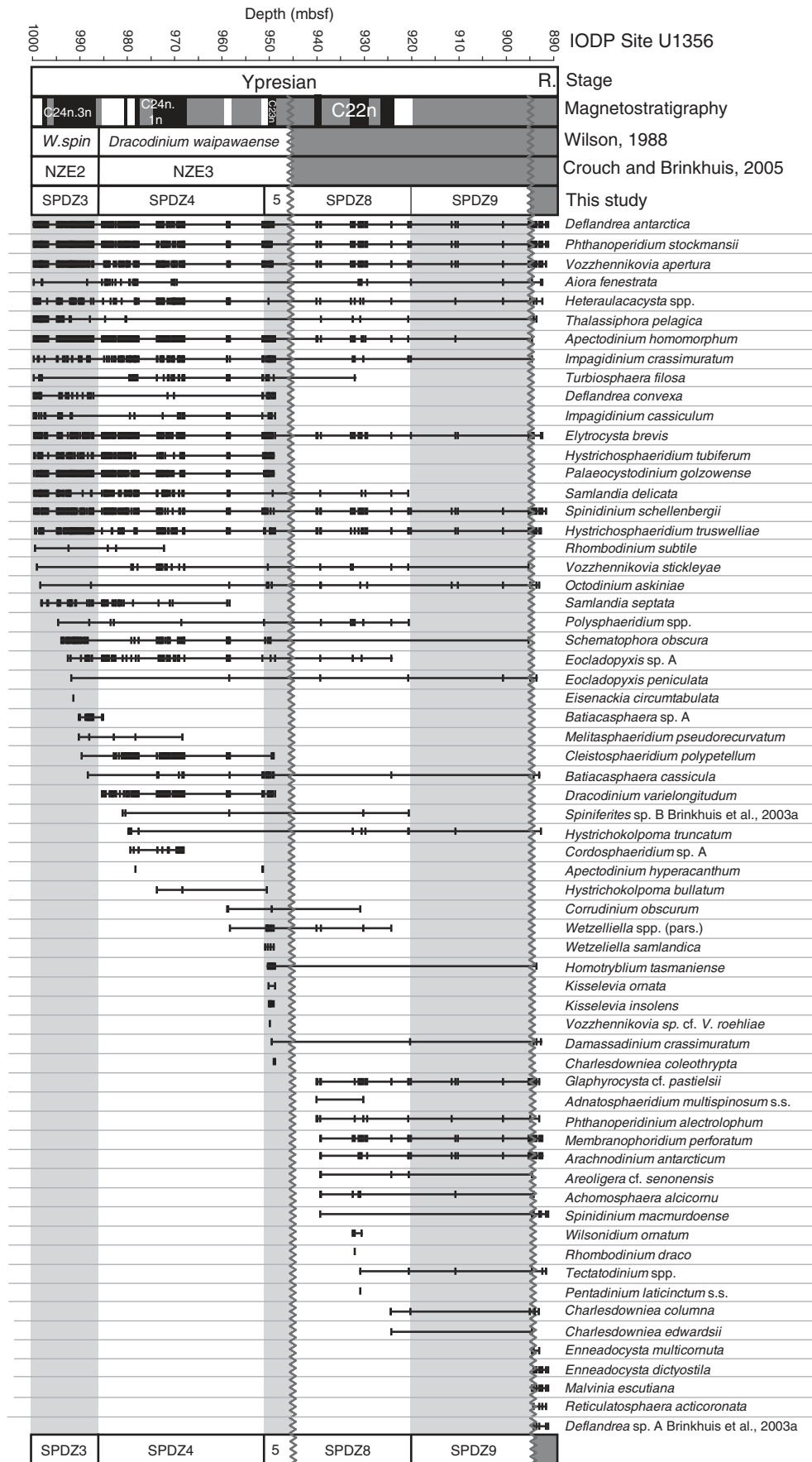


Fig. 5. Ranges of dinocyst taxa for Site U1356. The stages are indicated, where R. stands for Rupelian. The shipboard magnetostratigraphy is plotted, with gray areas indicating intervals with no magnetostratigraphic information due to disturbed core or core gaps. Dinocyst zonations are shown from Wilson (1988) and Crouch and Brinkhuis (2005).

- Base sample: 1172D-18R-1W, 40–42 cm (634.98 mbsf)
 Top sample: 1172D-15R-5W, 120–122 cm (612.7 mbsf)
 Calibration: The base is correlated to the base of Subchron C26n. The top of this zone is correlated to just prior to the Palaeocene–Eocene boundary, Subchron C24r.
 Age: late Thanetian; 59.2 Ma–55.6 Ma
 Characteristic species: *Elytrocysta brevis*, *Senegalinium* cpx. and *Cerebrocysta bartonensis*
 Significant bioevents: LO *Eisenackia reticulata*, FO *Cleistosphaeridium placacanthum*, FO *Deflandrea antarctica*, FO *Glapyrocysta delicata* and FO *Phthanoperidinium stockmansii*
 Remarks: This zone equates to New Zealand Palaeocene Zone 5 of Crouch and Brinkhuis (2005).
- (2) Zone SPDZ2
 Base definition: FCO *Apectodinium homomorphum*
 Top definition: FO *Samlandia delicata*
 Type locality: ODP Site 1172
 Base sample: 1172D-15R-5W, 100–102 cm (612.5 mbsf)
 Top sample: 1172D-14R-6W, 40–42 cm (604.44 mbsf)
 Calibration: At the type locality (ODP Site 1172), bulk organic carbon isotope analyses have revealed the stratigraphic position of the Palaeocene–Eocene boundary within this dinocyst zone (at 611.8 mbsf). This calibrates the oldest strata within this dinocyst zone to the latest Thanetian. The top of this zone is correlated to the top of Subchron C24r
 Age: latest Thanetian–early Ypresian, 55.6 Ma–55.2 Ma
 Characteristic species: *Apectodinium homomorphum*, *Senegalinium* cpx., *Cordosphaeridium fibrospinosum*, *Elytrocysta brevis*, *Deflandrea antarctica*, *Glaphyrocysta retiintexta*, *Deflandrea convexa* and *Hystriochosphaeridium truswelliae*
 Significant bioevents: ACME *Apectodinium homomorphum* and FO *Spinidinium macmurdoense*
 Remarks: This dinocyst zone includes the quasi-globally recorded dominance of the genus *Apectodinium* associated with the PETM. It is calibrated with high accuracy (error <20 kyr) using the negative excursion in the stable carbon isotopic composition ($\delta^{13}\text{C}$) of the exogenic carbon pool (Crouch et al., 2001; Sluijs et al., 2007a), as recorded in total organic carbon at the type locality (Sluijs et al., 2011). Regionally, this zone is equivalent to Zone New Zealand Eocene zone 1 (NZE1) of Crouch and Brinkhuis (2005). Centimeter-scale dinocyst and stable carbon isotope studies of expanded PETM sections have revealed that the *Apectodinium* acme precedes the carbon isotope excursion by <10 kyr in New Jersey, in the North Sea and perhaps at Tawanui, New Zealand (Sluijs et al., 2007b), and in Spitsbergen, Arctic Ocean (Harding et al., 2011). Also at Site 1172, the type section of this dinocyst zone, the acme of *Apectodinium* precedes the negative carbon isotope excursion of the PETM, but it remains unclear how well this correlates to the precursors elsewhere (Sluijs et al., 2011). The resulting maximum uncertainty is in the order of 10^3 or 10^4 years, much smaller than the uncertainty related to the other zones described here. An acme of *Deflandrea* spp. in sample 1172D-15R-1, 10–12 cm (605.6 mbsf) likely correlates to a subzone proposed for New Zealand.
- (3) Zone SPDZ3
 Base definition: FO *Samlandia delicata*
 Top definition: FO *Dracodinium waipawaense*
 Type locality: ODP Site 1172
 Base sample: 1172D-14R-6W, 10–12 cm (604.14 mbsf)
 Top sample: 1172D-13R-2W, 60–62 cm (587.85 mbsf) and 1171D-71R-4W, 30–32 cm (915.3 mbsf)
 Calibration: The top of this zone is truncated by a hiatus at ODP Site 1172; ODP Site 1171 indicates a tentative correlation to the top of Subchron C24n for this zone. At the Wilkes Land Margin, the top of this dinocyst zone is correlated to the top of Subchron C24n.3n
 Age: mid-Ypresian, 55.2 Ma–53.4 Ma
 Characteristic species: *Apectodinium homomorphum*, *Areoligera* spp., *Deflandrea antarctica*, *Membranosphaera* spp., *Thalassiphora pelagica*, *Cordosphaeridium fibrospinosum* and *Palaeocystodinium golzowense*
 Significant bioevents: FO *Cleistosphaeridium polypetellum* and LO *Eisenackia circumtabulata*
 Remarks: This zone equates to dinocyst zone NZE2 of Crouch and Brinkhuis (2005), indicating the supra-regional stratigraphic significance of the dinocyst species that define the zone. These species have also been recognized in the Australo-Antarctic Gulf. However, on that side of the Tasmanian Gateway, *Dracodinium varielongitudum*, a taxon characteristic for the Northern Hemisphere, has been identified rather than *D. waipawaense*. The differences between the two species are subtle at most, and the stratigraphic ranges are identical. Hence it can be debated whether these should be considered different species. We consider these species as interchangeable with respect to the zonation.
- (4) Zone SPDZ4
 Base definition: FO *Dracodinium waipawaense*
 Top definition: FO *Wetzeliiella samlandica*
 Type locality: ODP Site 1171
 Base sample: 1171D-71R-2W, 60–62 cm (912.6 mbsf) and 1172D-13R-2W, 60–62 cm (587.85 mbsf)
 Top sample: 1171D-59R-CCW, 10–12 cm (805.32 mbsf) and 1172D-13R-2W, 40–42 cm (587.65 mbsf)
 Calibration: At ODP Site 1171 and IODP Site U1356 the top of this zone correlates to the onset of Subchron C23n. This zone is within a core gap at ODP Site 1172
 Age: mid-Ypresian, 53.4 Ma–52.0 Ma
 Characteristic species: *Senegalinium* cpx., *Phthanoperidinium stockmansii*, *Deflandrea antarctica*, *Palaeocystodinium golzowense* and *Spinidinium/Vozzhennikovia* cpx.
 Significant bioevents: FO *Polysphaeridium subtile* and FO *Corrudinium obscurum*
 Remarks: The base of this dinocyst zone equates to the base of NZE3 of Crouch and Brinkhuis (2005), of which the FO of *Wilsonidium ornatum* defines the top. While this species is recognized at both Site 1171 and 1172, our magnetostratigraphic calibration shows that the FO of this species is diachronous in the region. We prefer *Wetzeliiella samlandica* as a zonal boundary definition because its FO is synchronous, also at Wilkes Land. Unfortunately, *W. samlandica* has not been reported from New Zealand thus far.

Fig. 6. Correlation of Eocene dinocyst events between ODP Holes 1171D and 1172A/D, and IODP Hole U1356A, and their magnetostratigraphies. In red the dinocyst bioevents are indicated: First Occurrence (FO) of *Samlandia delicata* (*S.del*), *Dracodinium waipawaense/varielongitudum* (*D.wai*), *Wetzeliiella samlandica* (*W.sam*), *Damassadinium crassimuratum* (*D.cra*), *Arachnodinium antarcticum* (*A.ant*), *Impagidinium parvireticulatum* (*I.par*), *Dracodinium rhoiboideum* (*D.rho*) and *Alterbidinium distinctum* (*A.dis*); Last Common Occurrence (LCO) of *Palaeocystodinium golzowense* (*P.gol*); Last Occurrence (LO) of *Damassadinium crassimuratum* (*D.cra*); and First Common Occurrence (FCO) of *Enneadocysta multicornuta* (*E.mul*) and *Enneadocysta dictyostila* (*E.dic*). Gray bars indicate intervals with normal magnetic polarity; white indicates reversed polarity. Magnetochrons are correlated between the sites based on the dinocyst events in red. Identification of the K–Pg boundary (Schellenberg et al., 2004) and chemostratigraphic correlations to the Palaeocene–Eocene Thermal Maximum (PETM; Sluijs et al., 2011), and Middle Eocene Climatic Optimum (MECO; Bijl et al., 2010) further ties ODP Site 1172 to the Geomagnetic Polarity Time Scale of Vandenberghe et al. (2012).

(5) Zone SPDZ5

Base definition: FO *Wetzeliella samlandica*

Top definition: LCO *Palaeocystodinium golzowense*

Type locality: ODP Site 1171

Base sample: 1171D-59R-4W, 10–12 cm (800.1 mbsf) and 1172D-13R-2W, 60–62 cm (587.85 mbsf)

Top sample: 1171D-55R-1W, 10–12 cm (757.3 mbsf) and 1172D-13R-2W, 40–42 cm (587.65 mbsf)

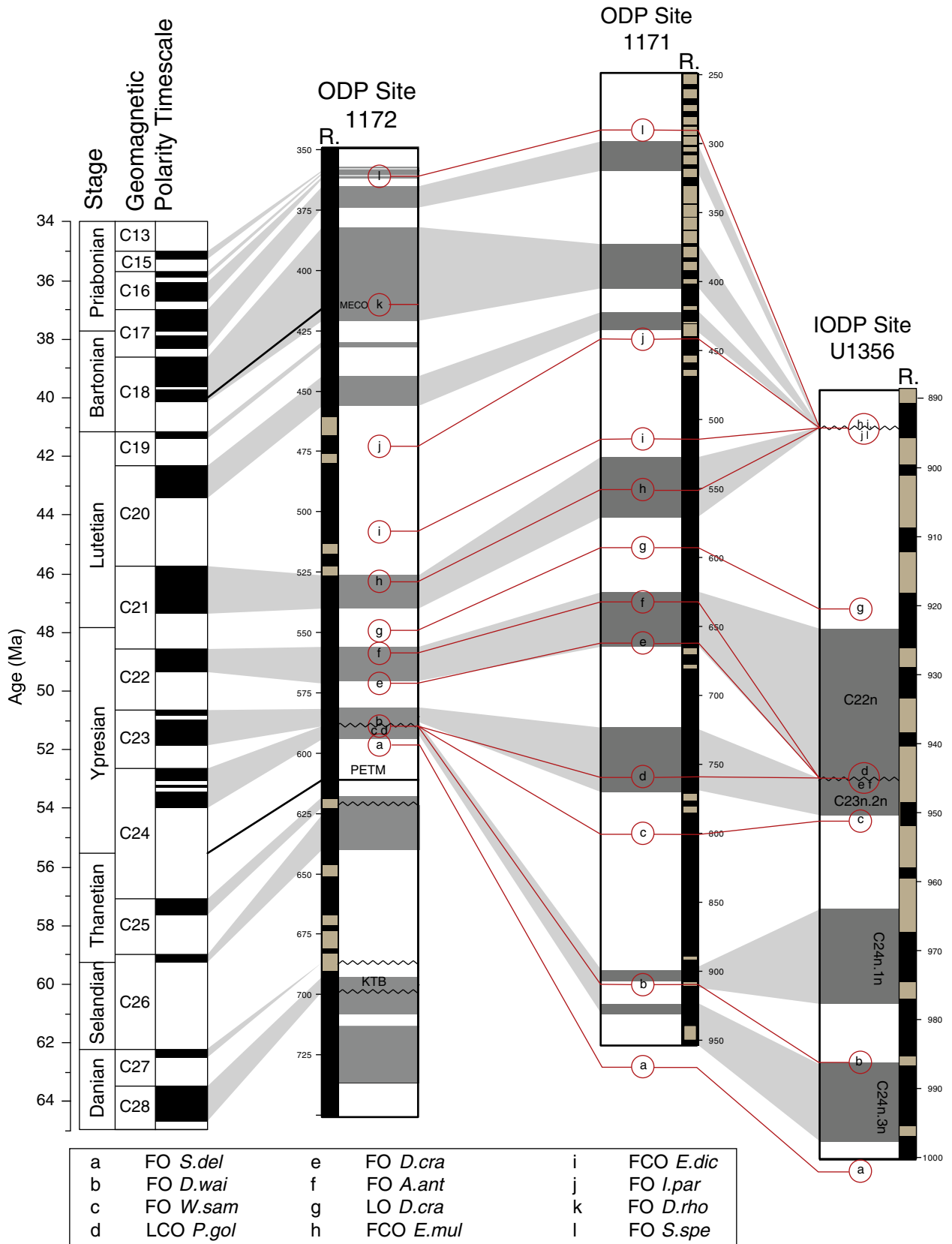


Table 1
Samples and depths for the zone boundaries in the type locality of the proposed dinocyst zone. SPDZ = South Pacific Dinocyst Zone. The top and bottom depths are in meters below sea floor (mbsf); uncertainties indicate the depth uncertainty (\pm) in meters.

Dinocyst zone	Type section	Bottom sample	Top sample	Bottom depth	Top depth	Bottom uncertainty	Top uncertainty
SPDZ1	1172D	17R-6W, 70–72 cm	15R-5W, 120–122 cm	633.17	612.7	0.895	0.1
SPDZ2	1172D	15R-5W, 100–102 cm	14R-6W, 40–42 cm	612.5	604.44	0.1	0.15
SPDZ3	1172D	14R-6W, 10–12 cm	13R-2W, 60–62 cm	604.14	587.85	0.15	0.1
SPDZ4	1171D	71R-2W, 630–62 cm	59R-CCW, 10–12 cm	912.6	805.32	1.35	2.61
SPDZ5	1171D	59R-4W, 10–12 cm	55R-1W, 10–12 cm	800.1	757.3	2.61	0.025
SPDZ6	1171D	54R-CCW, 9–11 cm	47R-CCW, 17–19 cm	757.25	690.24	0.025	1.865
SPDZ7	1172D	12R-2W, 40–42 cm	10R-3W, 110–112 cm	575.84	559.2	0.61	0.35
SPDZ8	1172D	10R-3W, 40–42 cm	9R-2W, 40–42 cm	558.5	547.3	0.35	0.4
SPDZ9	1172D	9R-1W, 105–107 cm	6R-4W, 135–137 cm	546.5	522.55	0.4	0.535
SPDZ10	1172D	6R-4W, 38–40 cm	5R-3W, 54–56 cm	521.48	510.5	0.535	1.62
SPDZ11	1172A/D	5R-2W, 38–40 cm	51X-4W, 85–87 cm	508.88	475.15	1.62	0.75
SPDZ12	1172A	51X-3W, 85–87 cm	45X-2W, 32–34 cm	473.65	414.02	0.75	0.4
SPDZ13	1172A	45X-1W, 102–104 cm	39R-5W, 105–107 cm	413.22	361.46	0.4	0.07

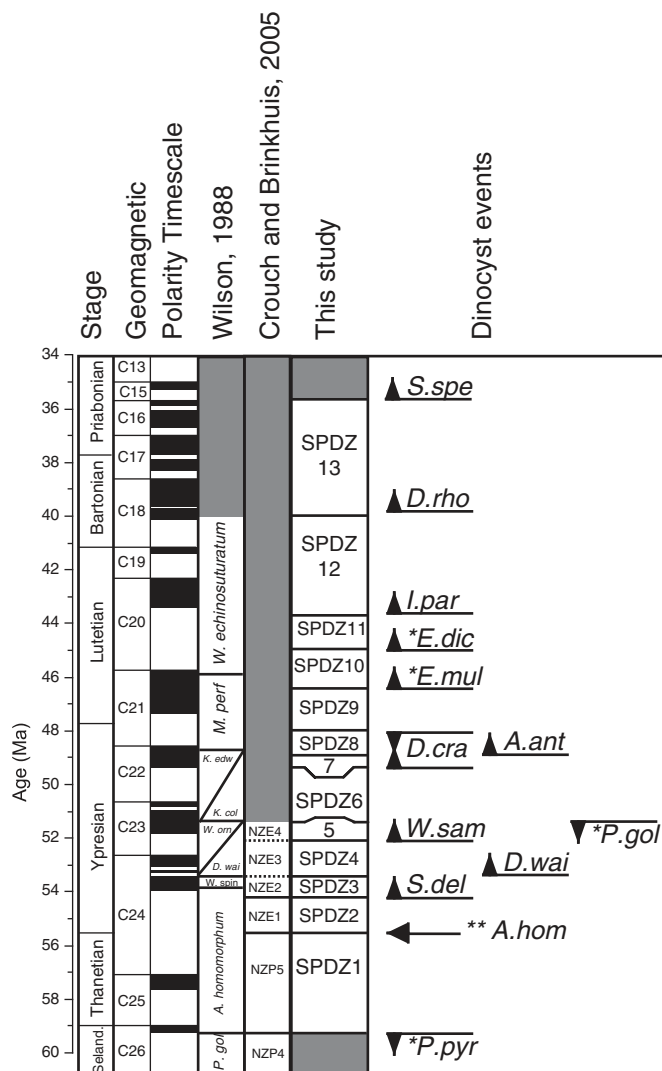


Fig. 7. South Pacific dinocyst zonation scheme, with zonal definitions and Southern Ocean dinocyst events. Also indicated are dinocyst zonations from Wilson (1988) and Crouch and Brinkhuis (2005). Abbreviations: *Palaeoperidinium pyrophorum* (*P.pyr*), *Apertodinium homomorphum* (*A.hom*; ** indicates acme), *Samlandia delicata* (*S.del*), *Dracodinium waipawaense/varielongitutum* (*D.wai*), *Wetzelia samlandica* (*W.sam*), *Palaeocystodinium golzowense* (*P.gol*), *Damassadinium crassimuratum* (*D.cra*), *Arachnodinium antarcticum* (*A.ant*), *Enneadocysta multicornuta* (*E.mul*), *Enneadocysta dictyostila* (*E.dic*), *Impagidinium parvireticulatum* (*I.par*), *Dracodinium rhomboideum* (*D.rho*) and *Schematophora speciosa* (*S.spe*).

Calibration: At ODP Site 1171 the top of this zone correlates to the top of Subchron C23n. This zone is within a hiatus at ODP Site 1172
Age: mid-Ypresian, 52.0 Ma–51.5 Ma

Characteristic species: *Senegalinium* cpx., *Phthanoperidinium stockmansii*, *Deflandrea antarctica*, *Palaeocystodinium golzowense*, *Wetzelia samlandica* and *W. articulata*

Significant bioevents: FO *Polysphaeridium subtile*, FO *Membranophoridium perforatum*, LO *Samlandia septata* and FO *Ynezidinium waipawaense*

Remarks: Although the last common occurrence of *Palaeocystodinium golzowense* might be expected to strongly depend on local ecology, it correlates well within the Tasmanian sector, uncalibrated records from New Zealand sections and tentatively to Wilkes Land.

(6) Zone SPDZ6

Base definition: LCO *Palaeocystodinium golzowense*
Top definition: FO *Damassadinium crassimuratum*

Type locality: ODP Site 1171

Base sample: 1171D-54R-CCW, 9–11 cm (757.25 mbsf) and 1172D-13R-2W, 40–42 cm (587.65 mbsf)

Top sample: 1171D-47R-CCW, 17–19 cm (690.24 mbsf) and 1172D-12R-3W, 10–12 cm (577.06 mbsf)

Calibration: The base of this zone is truncated by an unconformity at ODP Site 1172. At ODP Sites 1171 and 1172 the top of this zone is correlated to the onset of Subchron C22n

Characteristic species: *Polysphaeridium subtile*, *Wetzelia samlandica*, *Wilsonidium ornatum*, *Membranophoridium perforatum* and *Hystrichokolpoma* spp.

Age: late Ypresian, 51.5 Ma–49.3 Ma

Significant bioevents: FO *Selenopemphix* spp. and FO *Hystrichokolpoma truncatum*

Remarks: The base of the youngest dinocyst zone of Crouch and Brinkhuis is defined by the FO of *Wilsonidium ornatum*. The FO of this species is, however, diachronous between ODP Sites 1171 and 1172. The FO of other key species for the late Ypresian of New Zealand, such as *Charlesdowniea coleothrypta* (as *Kisselovia coleothrypta*, but this might be *C. columna*, based on the rounded outline and limited number of processes supporting the ectophragm on the dorsal side; see Appendix 1) and *Charlesdowniea edwardsii* (as *Kisselovia edwardsii*; Wilson, 1988) were recognized at ODP Sites 1171 and 1172 and U1356, but are also diachronous. The FO of *Damassadinium crassimuratum*, however, correlates well between 1171 and 1172 is also reported from the uncalibrated sections in

- New Zealand (as *Danea crassimurata*; Wilson, 1988). We hence consider this the best dinocyst event to employ for our zonation.
- (7) Zone SPDZ7
 Base definition: FO *Damassadinium crassimuratum*
 Top definition: FO *Arachnodinium antarcticum*
 Type locality: ODP Site 1172
 Base sample: 1172D-12R-2W, 40–42 cm (575.84 mbsf) and 1171D-47R-6W, 10–12 cm (686.51 mbsf)
 Top sample: 1172D-10R-3W, 40–42 cm (558.5 mbsf) and 1171D-42R-5W, 10–12 cm (638.1 mbsf)
 Calibration: The top of this zone is correlated to the top of Subchron C22n
 Age: late Ypresian, 49.3 Ma–48.7 Ma
 Characteristic species: *Cleistosphaeridium diversispinosum*, *Deflandrea antarctica*, *Deflandrea convexa* and *Damassadinium crassimuratum*
 Significant bioevents: LO *A. homomorphum*, FO *Charlesdowniea columna*, FO *C. edwardsii* and LO *S. delicata*
 Remarks: *Arachnodinium antarcticum* is a distinct dinocyst species that is found as a characteristic element of the “transantarctic flora” (Wrenn and Beckman, 1982) from basal middle Eocene sediments upwards on the Antarctic shelf (Wrenn and Hart, 1988). As a consequence of its Antarctic-endemic biogeography, this species has not been found in New Zealand. One dinocyst event that roughly coincides with the FO of *Arachnodinium antarcticum* and that does allow for correlation to New Zealand is the LO of *Apectodinium homomorphum* (Hollis et al., 2009). We however do not consider this dinocyst event to be a useful zone definition, because this species reaches high abundances in the lower Eocene and hence is very likely to be found reworked in younger sediments.
- (8) Zone SPDZ8
 Base definition: FO *Arachnodinium antarcticum*
 Top definition: LO *Damassadinium crassimuratum*
 Type locality: ODP Site 1172
 Base sample: 1172D-10R-3W, 40–42 cm (558.5 mbsf) and 1171D-42R-2W, 10–12 cm (633.6 mbsf)
 Top sample: 1172D-9R-2W, 40–42 cm (547.3 mbsf) and 1171D-38R-1W, 10–12 cm (593.7 mbsf)
 Calibration: The top of this zone is correlated to mid-Subchron C21r
 Age: early Lutetian, 48.7 Ma–48.0 Ma
 Characteristic species: *Arachnodinium antarcticum*, *Damassadinium crassimuratum*, *Deflandrea antarctica*, *Vozzhennikovia/Spinidinium* cpx. and *Phthanoperidinium* spp.
 Significant bioevents: LO *Batiacasphaera cassicula*, LO *Polysphaeridium subtile*, FCO *Octodinium askinae* and LO *Charlesdowniea edwardsii*
 Remarks: Also the LO of *Damassadinium crassimuratum* correlates well between ODP Sites 1171 and 1172. Because the range of this species is relatively short, the likelihood of reworking is small. Therefore, this LO is a robust zonal boundary criterion.
- (9) Zone SPDZ9
 Base definition: LO *Damassadinium crassimuratum*
 Top definition: FCO *Enneadocysta multicornuta*
 Type locality: ODP Site 1172
 Base sample: 1172D-9R-1W, 105–107 cm (547.3 mbsf) and 1171D-37R-CCW, 17–19 cm (593.56 mbsf)
 Top sample: 1172D-6R-4W, 135–137 cm (522.55 mbsf) and 1171D-33R-CCW, 0–2 cm (555.02 mbsf)
 Calibration: The top of this zone is correlated to mid-to top Subchron C21n
 Age: early Lutetian, 48.0 Ma–46.2 Ma
 Characteristic species: *Arachnodinium antarcticum*, *Deflandrea antarctica*, *Membranophoridium perforatum* and *Vozzhennikovia apertura*
 Significant bioevents: FO *Enneadocysta multicornuta*
 Remarks: The FO of *Enneadocysta multicornuta* is near the top of zone SPDZ8, and subsequently increases in abundance. We prefer to use the FCO of this species as a zone definition rather than its first occurrence because that is more robust compared to the FO.
- (10) Zone SPDZ10
 Base definition: FCO *Enneadocysta multicornuta*
 Top definition: FCO *Enneadocysta dictyostila*
 Type locality: ODP Site 1172
 Base sample: 1172D-6R-4W, 38–40 cm (521.48 mbsf) and 1171D-33R-3W, 10–12 cm (548.6 mbsf)
 Top sample: 1172D-5R-3W, 54–56 cm (510.5 mbsf) and 1171D-30R-CCW, 12–14 cm (524.58 mbsf)
 Calibration: The top of this zone is correlated to early Subchron C20r
 Age: mid-Lutetian, 46.2 Ma–45.2 Ma
 Characteristic species: *Enneadocysta multicornuta* and *Deflandrea convexa*
 Significant bioevents: FO *Enneadocysta dictyostila* and LO *Membranophoridium perforatum*
 Remarks: This zone is characterized by near-monotypic assemblages of dinocysts, alternating between *Deflandrea antarctica*, *Enneadocysta multicornuta* and *E. dictyostila*. Because of the low diversity of the samples, few dinocyst events are recognized.
- (11) Zone SPDZ11
 Base definition: FCO *Enneadocysta dictyostila*
 Top definition: FO *Impagidinium parvireticulatum*
 Type locality: ODP Site 1172
 Base sample: 1172D-5R-2W, 38–40 cm (508.88 mbsf) and 1171D-28R-CCW, 5–7 cm (505.73 mbsf)
 Top sample: 1172A-51X-4W, 85–87 cm (475.15 mbsf) and 1171D-22R-CCW, 12–14 cm (448.84 mbsf)
 Calibration: The top of this zone is correlated to the top of Subchron C20r
 Age: mid-Lutetian, 45.2 Ma–44.0 Ma
 Characteristic species: *Enneadocysta dictyostila*, *Deflandrea antarctica*, *Eocladopyxis peniculata* and *Thalassiphora pelagica*
 Significant bioevents: LCO *Deflandrea convexa*
 Remarks: Similar to *Enneadocysta multicornuta*, the FO of *E. dictyostila* is within the underlying Zone SPDZ10, and it subsequently rapidly increases in abundance. We prefer to use the FCO of *E. dictyostila* rather than its FO.
- (12) Zone SPDZ12
 Base definition: FO *Impagidinium parvireticulatum*
 Top definition: FO *Dracodinium rhomboideum*
 Type locality: ODP Site 1172
 Base sample: 1172A-51X-3W, 85–87 cm (473.65 mbsf) and 1171D-22R-3W, 10–12 cm (442.7 mbsf)
 Top sample: 1172A-45X-2W, 32–34 cm (414.02 mbsf) and 1171D: not found
 Calibration: The top of this zone is calibrated to the onset of Subchron C18n, also with use of isotope stratigraphy around the Middle Eocene Climatic Optimum
 Age: mid-Lutetian to early Bartonian, 44.0 Ma–40.0 Ma
 Characteristic species: *Thalassiphora pelagica*, *Arachnodinium antarcticum*, *Deflandrea antarctica*, *Enneadocysta dictyostila* and *Enneadocysta multicornuta*

Significant bioevents: LO *Cleistosphaeridium diversispinosum*
 Remarks: The LO of *Dracodinium rhomboideum* is also calibrated to the onset of Magnetochron C18n in Northern Hemisphere sites (Eldrett and Harding, 2009). This allows for correlation of the top of this zone to global dinocyst stratigraphies.

(13) Zone SPDZ13

Base definition: FO *Dracodinium rhomboideum*

Top definition: FO *Schematophora speciosa*

Type locality: ODP Site 1172

Base sample: 1172A-45X-1W, 102–104 cm (413.22 mbsf) and 1171D: not found

Top sample: 1172A-39X-5W, 105–107 cm (361.61 mbsf)

Calibration: The top of this zone is correlated to mid-C16n.1r

Age: Bartonian–Priabonian, 40.0 Ma–35.95 Ma

Characteristic species: *Spinidinium macmurdoense*, *Phthanoperidinium stockmansii*, *Vozzhennikovia apertura*, *Enneadocysta* spp. and *Glaphyrocysta semitecta*

Significant bioevents: FO *Deflandrea cygniformis* and FCO *Spinidinium macmurdoense*

Remarks: This zone is characterized by the first occurrence of several transantarctic floral elements with short ranges such as *Deflandrea cygniformis*.

6. Applications

6.1. Previous reports

The dinocyst zonation scheme proposed here can be applied to Southern Ocean sediments where other stratigraphic tools are lacking. For instance, outcrops on the Antarctic Peninsula, such as Seymour Island (Wrenn and Hart, 1988; Ivany et al., 2008), Tierra del Fuego (Quattrocchio and Sarjeant, 2003; Guerstein et al., 2003, 2004, 2008; Quattrocchio, 2009), outcrops along the South Australian and Tasmanian Margin (e.g., Cookson and Eisenack, 1961, 1965a,b; Cookson, 1965a,b; Cookson and Eisenack, 1967; Partridge, 1976; Truswell, 1997), ODP Leg 182 on the Australian Bight (Feary et al., 2000) and ODP Sites 274, 277 and 280–283 (Kennett and Houtz, 1975), 511 and 512 (Goodman and Ford, 1983), 696 (Mao and Mohr, 1995), 739, 742 and 748 (Mohr, 1990; Wei and Thierstein, 1991;

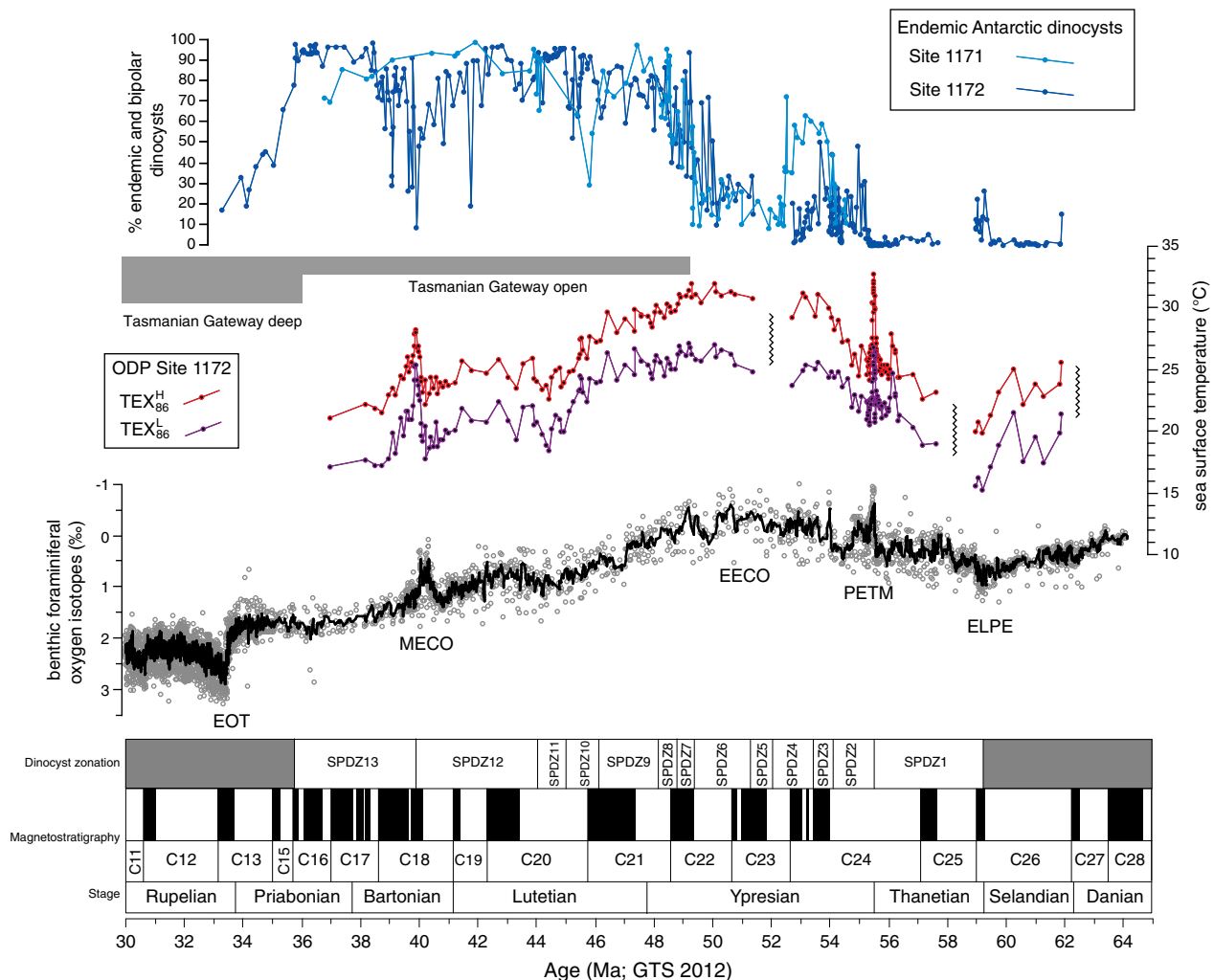


Fig. 8. A summary of the palaeoclimatic evolution of the South Pacific Ocean. a. Relative abundance of endemic Antarctic and bipolar dinocysts from ODP Site 1171 and 1172, modified from Bijl et al. (2011) plotted in the new calibrated biostratigraphic age model presented in this paper. b. Sea surface temperature evolution of the southwest Pacific Ocean from TEX₈₆ analyses on sediments from ODP Site 1172. The TEX₈₆ data is a compilation of data from ODP Site 1172 from Bijl et al. (2009, 2010) and Sluijs et al. (2011), recalibrated to biostratigraphic age model presented here, with the most recent calibrations: TEX₈₆^H and TEX₈₆^L (Kim et al., 2010). c. A compilation of benthic foraminiferal oxygen isotope records from sites spread around the world's oceans. Data is obtained from Zachos et al. (2008). Additional benthic foraminiferal oxygen isotope data is included for intervals that were represented with low-resolution data, such as the mid-Eocene (Sexton et al., 2006) and the Palaeocene (Westerhold et al., 2011). All data is calibrated to the GTS 2012 time scale (Vandenberghe et al., 2012).

Truswell, 1991; Roberts et al., 2003), and 1090 (Latimer and Filippelli, 2002) and the erratic boulders from coastal moraines at the McMurdo Sound Station, Antarctica (Levy and Harwood, 2000) await further analysis for chronostratigraphic calibration. Furthermore, dredge samples from the Southern Ocean floor (e.g., Truswell, 1982) can now be calibrated chronostratigraphically with the zonation scheme proposed here. This provides a major improvement for planning future ocean drilling of Palaeocene–Eocene strata in the Southern Ocean.

6.2. Environmental and climatological evolution of the Southwest Pacific Ocean

The dinocyst zonation scheme proposed here allows for chronostratigraphic calibration of many sediment records from the Southern Ocean, which were previously poorly calibrated. However, the lack of carbonate in marine sediments from the high southern latitudes has not only precluded detailed biostratigraphic analyses, but also the application of conventional calcite-based tools to reconstruct past temperatures of

Table 2

Magnetostratigraphically calibrated ages of key dinocyst species in the Southern Ocean, compared to calibrations from other sections in the world. Ages in italics refer to first or last common occurrences. The errors refer to age uncertainty caused by correlation error, core recovery issues and/or sample spacing. Ages are calibrated to the geomagnetic polarity time scale of Vandenberghe et al. (2012).

Dinocyst species	South Pacific Ocean				Other oceans				References
	FO	Error	LO	Error	FO	Error	LO	Error	
<i>Apectodinium homomorphum</i>	58.20	0.65	48.80	0.20					
<i>Arachnodinium antarcticum</i>	48.70	0.20	36.00	0.30	Transantarctic flora				
<i>Charlesdowniea coleothrypta</i>	51.70	0.30							
<i>Charlesdowniea columna</i>	49.70	0.10	49.10	0.10	51.80	0.20	49.00	0.40	Bujak and Mudge (1994)
<i>Charlesdowniea edwardsii</i>	49.30	0.10	48.40	0.10	51.50	0.20	47.30	0.20	Bujak and Mudge (1994)
<i>Cleistosphaeridium diversispinosum</i>	49.30	0.20	38.30	0.30					
<i>Cleistosphaeridium polypetellum</i>	53.20	0.10	51.80	0.10					
<i>Corrudinium regulare</i>	49.20	0.20			Transantarctic flora				
<i>Damassadinium crassimuratum</i>	49.30	0.10	48.00	0.10					
<i>Deflandrea antarctica</i>	58.20	0.30			Transantarctic flora				
<i>Deflandrea convexa</i>	58.20	0.30			Transantarctic flora				
<i>Dracodinium rhomboideum</i>	40.00	0.10			40.00	0.10			Eldrett and Harding (2009)
<i>Dracodinium waipawaense/D. varielongitudum</i>	53.40	0.10	50.00	0.40	53.40	0.10	51.30	0.10	Bujak and Mudge (1994)
<i>Elytrocysta brevis</i>	64.00	0.30	33.60	0.30					
<i>Enneadocysta dictyostila</i>	45.20	0.20	33.40	0.30	Transantarctic flora				
<i>Enneadocysta multicornuta</i>	46.20	0.20	35.50	0.20					
<i>Eocladopyxis peniculata</i>	47.50	0.10	33.60	0.30					
<i>Glaphyrocysta semitecta</i>	39.70	0.20	39.10	0.20	40.60	0.10			Bujak et al. (1980)
<i>Glaphyrocysta ordinata</i>	61.90	0.20	56.30	0.20					
<i>Histiocysta palla</i>	44.60	0.20							
<i>Homotryblium tasmaniense</i>	50.90	0.40	45.70	0.10					
<i>Hystrichokolpoma bullatum</i>	50.90	0.20	47.80	0.20					
<i>Hystrichokolpoma rigaudiae</i>	53.50	0.20							
<i>Hystrichokolpoma spinosum</i>	50.90	0.20							
<i>Hystrichokolpoma truncatum</i>	50.90	0.20	45.20	0.20					
<i>Hystrichostrogylon membraniphorum</i>	49.40	0.20							
<i>Impagidinium cassiculum</i>	54.30	0.10	52.10	0.30					
<i>Impagidinium crassimuratum</i>	55.20	0.10							
<i>Impagidinium parvireticulatum</i>	44.00	0.20	35.60	0.10					
<i>Kisselevia insolens</i>	51.80	0.20							
<i>Lingulodinium machaerophorum</i>	58.20	0.60							
<i>Lophocysta</i> spp.	41.00	0.10	39.00	0.20					
<i>Membranophoridium perforatum</i>	51.80	0.20	45.50	0.20					
<i>Nematosphaeropsis labyrinthus</i>	50.00	0.30							
<i>Octodinium askiniae</i>	53.90	0.10			Transantarctic flora				
<i>Palaeocystodinium golzowense</i>			51.50	0.20					
<i>Palaeoperidinium pyrophorum</i>	68.20	0.30	59.20	0.20	73.60	0.10	59.30	0.10	Bujak and Mudge (1994)
<i>Phthanoperidinium comatum</i>	45.70	0.20							
<i>Phthanoperidinium stockmansii</i>	57.20	0.20							
<i>Polysphaeridium subtile</i>	59.50	0.30	38.30	0.30					
<i>Samlandia delicata</i>	55.20	0.20	49.00	0.30					
<i>Schematophora obscura</i>	53.70	0.10	48.50	0.10					
<i>Schematophora speciosa</i>	35.95	0.05							
<i>Selenopemphix</i> spp.	49.50	0.30							
<i>Spinidinium macmurdoense</i>	55.50	0.20			Transantarctic flora				
<i>Spinidinium schellenbergii</i>	62.10	0.20			Transantarctic flora				
<i>Spiniferites</i> sp. B Brinkhuis et al., 2003a	62.50	0.20							
<i>Stoveracysta ornata</i>	35.20	0.20							
<i>Thalassiphora delicata</i>	62.50	0.20			59.50	0.10	39.10	0.10	Bujak et al. (1980), Köthe (1990)
<i>Thalassiphora pelagica</i>	55.30	0.20							
<i>Vozzhennikovia apertura</i>	65.10	0.40			Transantarctic flora				
<i>Vozzhennikovia</i> sp. cf. <i>V. roehliae</i>	53.60	0.20	52.40		Transantarctic flora				
<i>Vozzhennikovia stickleyae</i>	54.20	0.10			Transantarctic flora				
<i>Wetzeliella articulata</i>	52.10	0.30	51.30	0.50					
<i>Wetzeliella samlandica</i>	52.00	0.10	51.70	0.10					
<i>Wilsonidium echinosuturatum</i>	45.20	0.20	40.70	0.20					
<i>Wilsonidium ornatum</i>	51.80	0.30	49.70	0.20					

ocean water. A major advancement in high-latitude palaeoclimatology has been the development of organic palaeothermometers (Brassell et al., 1986; Müller et al., 1998; Schouten et al., 2002; Kim et al., 2010). Particularly useful for high-latitude marine palaeoenvironmental reconstructions are the organic biomarker proxies, such as TEX₈₆ for sea surface temperature (SST; Schouten et al., 2002; Kim et al., 2010). These tools were applied on many sites in the Southern Ocean in the past decade, also on the successions used to define our dinocyst zonation proposed here. Following the first publication of the Palaeocene–Eocene sea surface temperature evolution of the southwest Pacific Ocean at ODP Site 1172 (Bijl et al., 2009), more recent high-resolution organic biomarker analyses were undertaken on the PETM (Sluijs et al., 2011) and the MECO (Bijl et al., 2010) at this site.

The compilation of these TEX₈₆ records (Fig. 8) shows good coherence in trends with the global stack of benthic foraminiferal oxygen isotopes, as previously indicated (Bijl et al., 2009). This has supported the notion that the South Pacific Ocean was the predominant source for intermediate-water formation in the Eocene (Thomas et al., 2003; Huber et al., 2004; Huber and Caballero, 2011; Sijp et al., 2011; Hollis et al., 2012). The temperature trends as recorded at Site 1172 are remarkably consistent with those from other regions in the South Pacific Ocean, such as the multi-proxy temperature reconstructions from New Zealand (Hollis et al., 2009, 2012). The terrestrial and marine temperature reconstructions from the Wilkes Land Margin (Site U1356; Pross et al., 2012; Bijl et al., in press) confirm the marked warmth during the early Eocene, followed by gradual cooling. The consistency between benthic foraminiferal oxygen isotope-temperature trends and those from the Southern Ocean surface waters provides additional backup for the robustness of the dinocyst stratigraphy proposed here. From ~50 Ma onwards we note the dominance of endemic Antarctic dinocysts in the southwest Pacific Ocean (ODP Site 1171 and 1172; Fig. 8; Bijl et al., 2011), which is linked to the influence of the Antarctic-derived Tasman Current in the region (Bijl et al., 2011, in press). It has been particularly difficult to chronostratigraphically calibrate the records with dominance of endemic dinocysts, since their overwhelming abundance dilutes the presence of dinocysts that are well-calibrated chronostratigraphically. With the dinocyst zonation proposed here, we provide a tool to calibrate also the successions with dominance of endemic dinocysts.

7. Concluding remarks

The combined magneto-, chemo- and biostratigraphically calibrated sediment records from ODP Sites 1172 and 1171 in the Tasmanian sector and IODP Site U1356 from the Wilkes Land Margin, Antarctica now provide a solid framework for dinocyst stratigraphy in the Southern Ocean. It also portrays the evolution of Southern Ocean shelf settings from greenhouse to icehouse conditions. We here provide the calibrated ages for key dinocyst events based on the Geomagnetic Polarity Time Scale of Vandenberghe et al. (2012) in Table 2, as an update compared to those published earlier (Williams et al., 2004; Escutia et al., 2011). Antarctic-endemic as well as cosmopolitan species are included, and an error is given for each datum. These errors include those caused by calibration uncertainties, sample spacing and/or core recovery. Ongoing work on the late Eocene–early Oligocene should allow continuation of the dinocyst stratigraphy upwards. The result will be a robust tool for dating Palaeogene sediments from marginal marine settings throughout the Southern Ocean, to portray the environmental and climatological evolution of the early Palaeogene Southern Ocean.

Acknowledgments

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Appendix 1

Dinoflagellate cyst species list

- Achilleodinium biformoides* (Eisenack, 1954) Eaton, 1976
Achomosphaera alcornu (Eisenack, 1954) Davey and Williams, 1966a
Achomosphaera crassipellis (Deflandre and Cookson, 1955) Stover and Evitt, 1978
Achomosphaera ramulifera [Plate I; a] (Deflandre, 1937) Evitt, 1963
Adnatosphaeridium multispinosum Davey and Williams, 1966a
Adnatosphaeridium sp. A [Plate I; b, c]
Remarks. This species of *Adnatosphaeridium* is characterized by having processes that are united by trabeculae connecting, perforate distal platforms. The species will be formally described elsewhere.
Aiora fenestrata (Deflandre and Cookson, 1955) Cookson and Eisenack, 1960
Aireiana spp. Cookson and Eisenack, 1965a
Alterbidinium acutulum (Wilson, 1967a) Lentin and Williams, 1985 emend. Khowaja-Ateequzzaman et al., 1991 [Plate I; d]
Alterbidinium distinctum (Wilson, 1967b) Lentin and Williams, 1985
Apectodinium homomorphum (Deflandre and Cookson, 1955) Lentin and Williams, 1977 emend. Harland, 1979 [Plate I; e, f, Plate VII; j]
Apectodinium hyperacanthum (Cookson and Eisenack, 1965b) Lentin and Williams, 1977 [Plate I; g, h, Plate VII; k]
Apectodinium parvum (Alberti, 1961) Lentin and Williams, 1977 emend. Harland, 1979
Apectodinium quinquelatum (Williams and Downie, 1966b) Costa and Downie, 1979
Apteodinium australiense (Deflandre and Cookson, 1955) Williams, 1978
Arachnodinium antarcticum Wilson and Clowes, 1982 [Plate I; i, j]
Areoligera senonensis Lejeune-Carpentier, 1938
Areoligera sentosa Eaton, 1976
Areoligera sp. Lejeune-Carpentier, 1938 [Plate I; k]
Areosphaeridium arcuatum Eaton, 1971 emend. Stover and Williams, 1995
Batiacasphaera cassicula Wilson, 1988 [Plate I; l]
Brigantedinium spp. Reid, 1977
Cannosphaeropsis spp. Wetzel, 1933 emend. Williams and Downie, 1966a; Duxbury, 1980; Marheinecke, 1992
Cassidium filosum Wilson, 1988
Cassidium fragile (Harris, 1965) Drugg, 1967
Cerebrocysta bartonensis Bujak in Bujak et al., 1980

Plate I. a: *Achomosphaera ramulifera* 1172D-11R-1W, 113–115 cm; b: *Adnatosphaeridium* sp. U1356A-101R-1W, 10–12 cm; c: *Adnatosphaeridium* sp. U1356A-101R-1W, 10–12 cm; d: *Alterbidinium acutulum* 1172D-10R-2W, 10–12 cm; e: *Apectodinium homomorphum* 1172D-13R-3W, 135–137 cm; f: *Apectodinium homomorphum* U1356A-103R-4W, 20–22 cm; g: *Apectodinium hyperacanthum* 1172D-15R-5W, 100–102 cm; h: *Apectodinium hyperacanthum* 1172D-15R-5W, 100–102 cm; i: *Arachnodinium antarcticum* 1172D-7R-6W, 135–137 cm; j: *Arachnodinium antarcticum* U1356A-97R-1W, 60–63 cm; k: *Areoligera* sp. 1172D-14R-1W, 55–57 cm; l: *Batiacasphaera* sp. 1172D-12R-4W, 10–12 cm; m: *Cerebrocysta delicata* 1172D-5R-3W, 38–40 cm; n: *Charlesdowniea coleothrypta* U1356A-101R-1W, 10–12 cm; and o: *Charlesdowniea columnata* 1172D-11R-5W, 40–42 cm. Scale bar = 25 µm.

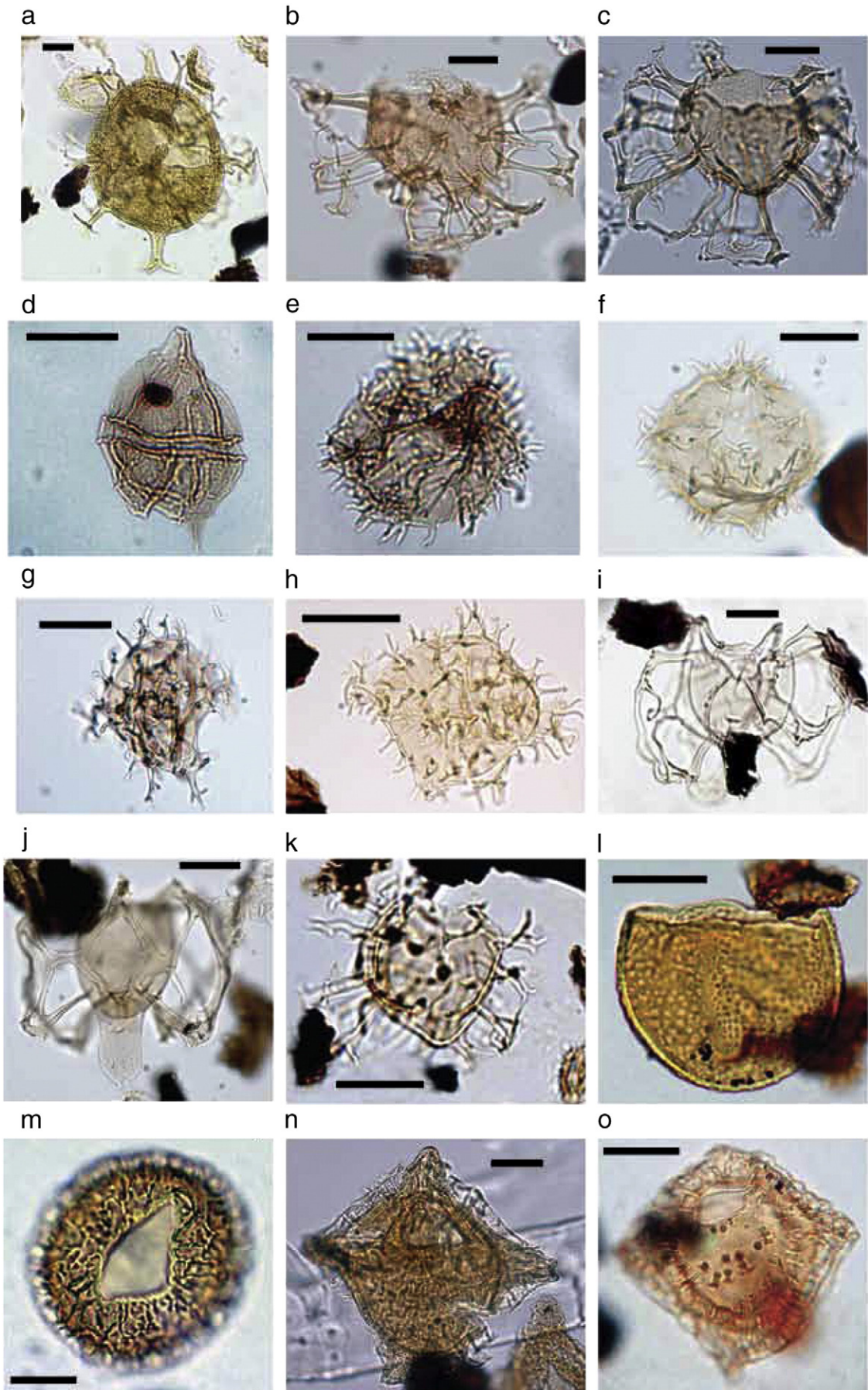


Plate I.

Cerebrocysta waipawaensis (Wilson, 1988) Fensome et al., 2009 [Plate I; m]

Charlesdowniea coleothrypta (Williams and Downie, 1966b) Lentin and Vozzhennikova, 1989 [Plate I; n]

Remarks. We consider the *Kisselovia coleothrypta* from Wilson (1988) *C. coleothrypta* specimen presented by Brinkhuis et al. (2003a; Plate P1; fig. 34, 35) to be *Charlesdowniea columna*. For a further comparison of these two species see under *C. columna*

Charlesdowniea columna (Michoux, 1988) Lentin and Vozzhennikova, 1990 [Plate I; n, Plate II; a]

Remarks. The difference between this species and *Charlesdowniea coleothrypta* is subtle, even when comparing the holotypes. The other specimens of *C. columna* presented by Michoux (1988; plate 1, fig. 5–6) show much more distinct separation from *C. coleothrypta*. The most distinctive difference between *C. coleothrypta* and *C. columna* are the perforate simulate platforms that connect the processes on the dorsal and ventral plates of *C. coleothrypta*, and lack on *C. columna*. The presence of thin platforms however is sometimes difficult to see under light microscopy. There are further subtle differences in the more rounded outline and few thick processes on the dorsal and ventral side of *C. columna* compared to the more rhomboidal *C. coleothrypta*, with many thin processes.

Charlesdowniea edwardsii (Wilson, 1967c) Lentin and Vozzhennikova, 1989 [Plate II; b]

Cleistosphaeridium diversispinosum Davey et al., 1966 emend. Eaton et al., 2001 [Plate II; c]

Cleistosphaeridium placacanthum (Deflandre and Cookson, 1955) Eaton et al., 2001 emend. May, 1980

Cleistosphaeridium polypetellum (Islam, 1983) Stover and Williams, 1995 [Plate II; d, e]

Cordosphaeridium fibrospinosum (Davey and Williams, 1966b) emend. Davey, 1969a [Plate II; f, Plate VII; l]

Cordosphaeridium gracile (Eisenack, 1954) Davey and Williams, 1966b emend. Davey and Williams, 1966b

Cordosphaeridium minimum (Morgenroth, 1966a) Benedek, 1972

Cordosphaeridium? sp. A [Plate VII; m]

Remarks. This species is characterized by having, fibrous, sponge-like antapical processes, of which the antapical is elongate and slim. This species is tentatively assigned to *Cordosphaeridium*, and will be formally described elsewhere.

Corrudinium incompositum (Drugg, 1970) Stover and Evitt, 1978

Corrudinium obscurum Wilson, 1988

Corrudinium regulare Clowes and Wilson, 2006 [Plate II; g]

Cribroperidinium sp. A [Plate II; h]

Remarks. This species of *Cribroperidinium* is characterized by having a dark, thick shagreenate to scabrate wall. The species will be formally described elsewhere.

Cribroperidinium spp. Neale and Sarjeant, 1962

Damassadinium crassimuratum (Wilson, 1988) Fensome et al., 1993 [Plate II; i, j]

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

Deflandrea antarctica Wilson, 1967b [Plate II; k]

Deflandrea convexa Wilson, 1988 [Plate III; l]

Deflandrea cygniformis Pöthe de Baldis, 1966

Deflandrea phosphoritica Eisenack, 1938

Deflandrea sp. A sensu Brinkhuis et al., 2003a

Diphyes colligerum (Deflandre and Cookson, 1955) Cookson, 1965a [Plate II; m]

Ditastodinium paradoxum (Brosius, 1963) Eaton, 1976

Dracodinium rhomboideum (Alberti, 1961) Costa and Downie, 1979

Dracodinium varielongitudum (Williams and Downie, 1966b) Costa and Downie, 1979 [Plate II; n]

Dracodinium waipawaense (Wilson, 1967c) Costa and Downie, 1979 [Plate II; o]

Eisenackia circumtabulata Drugg, 1967 [Plate III; a]

Eisenackia reticulata (Damassa, 1979a) Quattrocchio and Sarjeant, 2003

Elytrocysta brevis Stover and Hardenbol, 1994 [Plate III; b, Plate VII; n]

Enneadocysta brevistila Fensome et al., 2006

Enneadocysta dictyostila (Menéndez, 1965) Stover and Williams, 1995 emend. Sarjeant, 1981 [Plate III; c, d]

Enneadocysta multicornuta (Eaton, 1971) Stover and Williams, 1995 emend. Stover and Williams, 1995 [Plate III; e]

Enneadocysta pectiniformis (Gerlach, 1961) Stover and Williams, 1995 emend. Sarjeant, 1984; Stover and Williams, 1995

Enneadocysta sp. A sensu Brinkhuis et al., 2003a

Remarks. This species resembles *E. dictyostila*, with the exception of the two, rather than one antapical processes that are distally connected into a perforate platform (see Brinkhuis et al., 2003a). The species will be formally described elsewhere.

Eocladopyxis peniculata Morgenroth, 1966a emend. McLean, 1976 [Plate III; f]

Eocladopyxis? sp. A [Plate III; g, h]

Remarks. This dinocyst is questionably assigned to *Eocladopyxis*. The archeopyle seems to involve the apical plates and occasionally the precingular plates as well. It has a coarsely perforate surface, but lacks the processes typical for *E. peniculata*. The species will be formally described elsewhere.

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

Florentinia reichartii Sluijs and Brinkhuis, 2009

Gelatia inflata Bujak, 1984

Glaphyrocysta delicata Wilson, 1988 [Plate III; i]

Glaphyrocysta divaricata (Williams and Downie, 1966a) Stover and Evitt, 1978

Glaphyrocysta exuberans (Deflandre and Cookson, 1955 ex Eaton, 1976) Stover and Evitt, 1978 emend. Sarjeant, 1986

Plate II. a: *Charlesdowniea columna* U1356A-98R-5W, 0–3 cm; b: *Charlesdowniea edwardsii* 1172D-11R-1W, 111–113 cm; c: *Cleistosphaeridium diversispinosum* 1172D-11R-2W, 10–12 cm; d: *Cleistosphaeridium polypetellum* U1356A-102R-1W, 10–12 cm; e: *Cleistosphaeridium polypetellum* U1356A-103R-2W, 40–42 cm; f: *Cordosphaeridium fibrospinosum* 1172D-15R-5W, 100–102 cm; g: *Corrudinium regulare* 1172A-42X-1W, 85–87 cm; h: *Cribroperidinium* sp. A U1356A-105R-6W, 95–98 cm; i: *Damassadinium crassimuratum* 1172D-11R-6W, 40–42 cm; j: *Damassadinium crassimuratum* 1172D-10R-2W, 10–12 cm; k: *Deflandrea antarctica* 1172D-12R-1W, 10–12 cm; l: *Deflandrea convexa* 1172D-5R-1W, 40–42 cm; m: *Diphyes colligerum* 1172D-13R-2W, 90–92 cm; n: *Dracodinium varielongitudum* U1356A-104R-2W, 120–122 cm; and o: *Dracodinium waipawaense* 1172D-12R-7W, 10–12 cm. Scale bar = 25 µm.

Plate III. a: *Eisenackia circumtabulata* U1356A-105R-4W, 0–2 cm; b: *Elytrocysta brevis* 1172D-14R-5W, 10–12 cm; c: *Enneadocysta dictyostila* 1172D-5R-3W, 38–40 cm; d: *Enneadocysta dictyostila* 1172D-5R-1W, 40–42 cm; e: *Enneadocysta multicornuta* 1172D-13R-3W, 105–107 cm; f: *Eocladopyxis peniculata* 1172D-5R-4W, 38–40 cm; g: *Eocladopyxis* sp. A U1356A-101R-1W, 60–62 cm; h: *Eocladopyxis* sp. A U1356A-101R-1W, 60–62 cm; i: *Glaphyrocysta delicata* 1172D-12R-7W, 10–12 cm; j: *Glaphyrocysta pastielsii* U1356A-99R-2W, 40–43 cm; k: *Histiocysta palla* U1356A-100R-1W, 10–13 cm; l: *Homotryblium tasmaniense* 1172D-10R-2W, 10–12 cm; m: *Homotryblium tasmaniense* U1356A-101R-1W, 60–63 cm; n: *Hystrichokolpoma bullatum* 1172D-12R-2W, 10–12 cm; and o: *Hystrichokolpoma bullatum* 1172D-12R-7W, 10–12 cm. Scale bar = 25 µm. (see on page 20)

Plate IV. a: *Hystrichokolpoma rigaudiae* U1356A-103R-1W, 10–12 cm; b: *Hystrichokolpoma truncatum* U1356A-98R-1W, 100–103 cm; c: *Hystrichosphaeridium truswelliae* U1356A-101R-1W, 80–82 cm; d: *Hystrichosphaeridium tubiferum* U1356A-98R-1W, 100–103 cm; e: *Hystrichostogylon membraniphora* 1172D-11R-5W, 40–42 cm; f: *Impagidinium cassiculum* U1356A-104R-2W, 40–42 cm; g: *Impagidinium maculatum* 1172D-12R-2W, 10–12 cm; h: *Impagidinium parvireticulatum* 1172D-10R-2W, 10–12 cm; i: *Kisselevia insolens* 1172D-13R-2W, 90–92 cm; j: *Kisselevia?* sp. cf. *K. ornata* U1356A-101R-1W, 10–12 cm; k: *Kisselevia* sp. A 1172D-13R-2W, 40–42 cm; l: *Membranophoridium perforatum* 1172D-11R-6W, 104–106 cm; m: *Membranophoridium perforatum* 1172D-12R-7W, 65–67 cm; n: *Palaeoperidinium pyrophorum* 1172D-24R-5W, 38–40 cm; and o: *Palaeoperidinium pyrophorum* 1172D-24R-5W, 20–22 cm. Scale bar = 25 µm. (see on page 21)

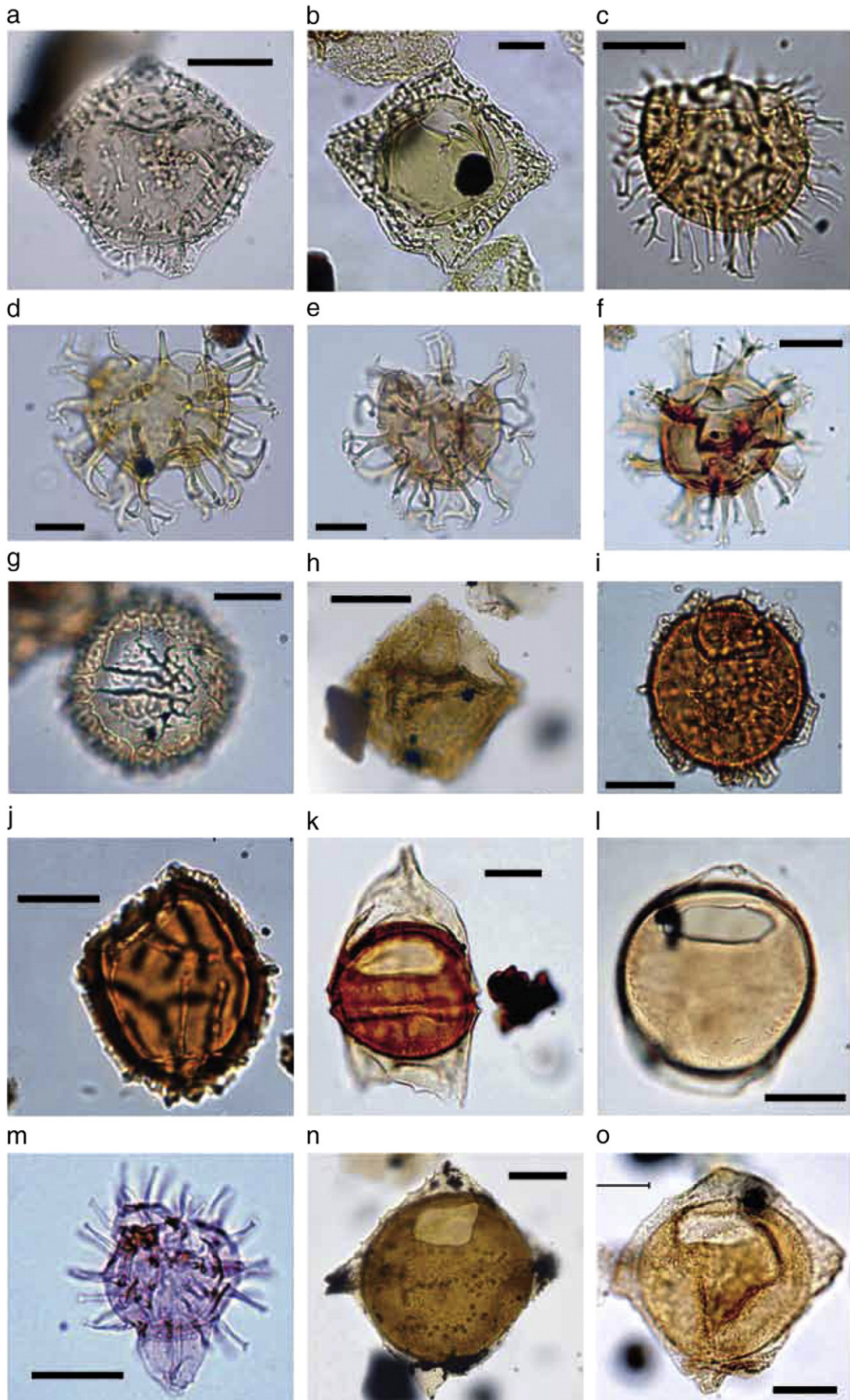


Plate II.

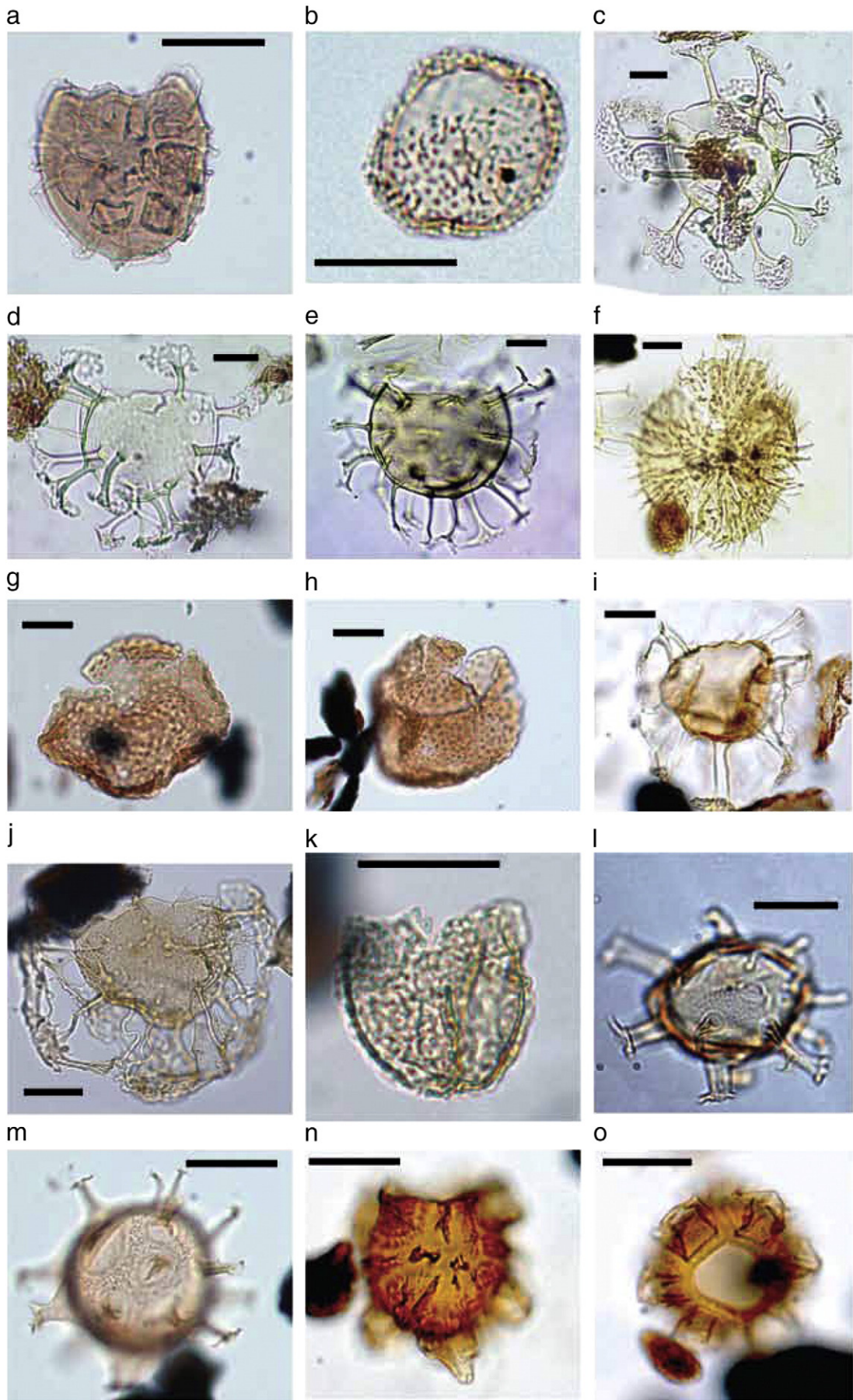


Plate III (caption on page 18).

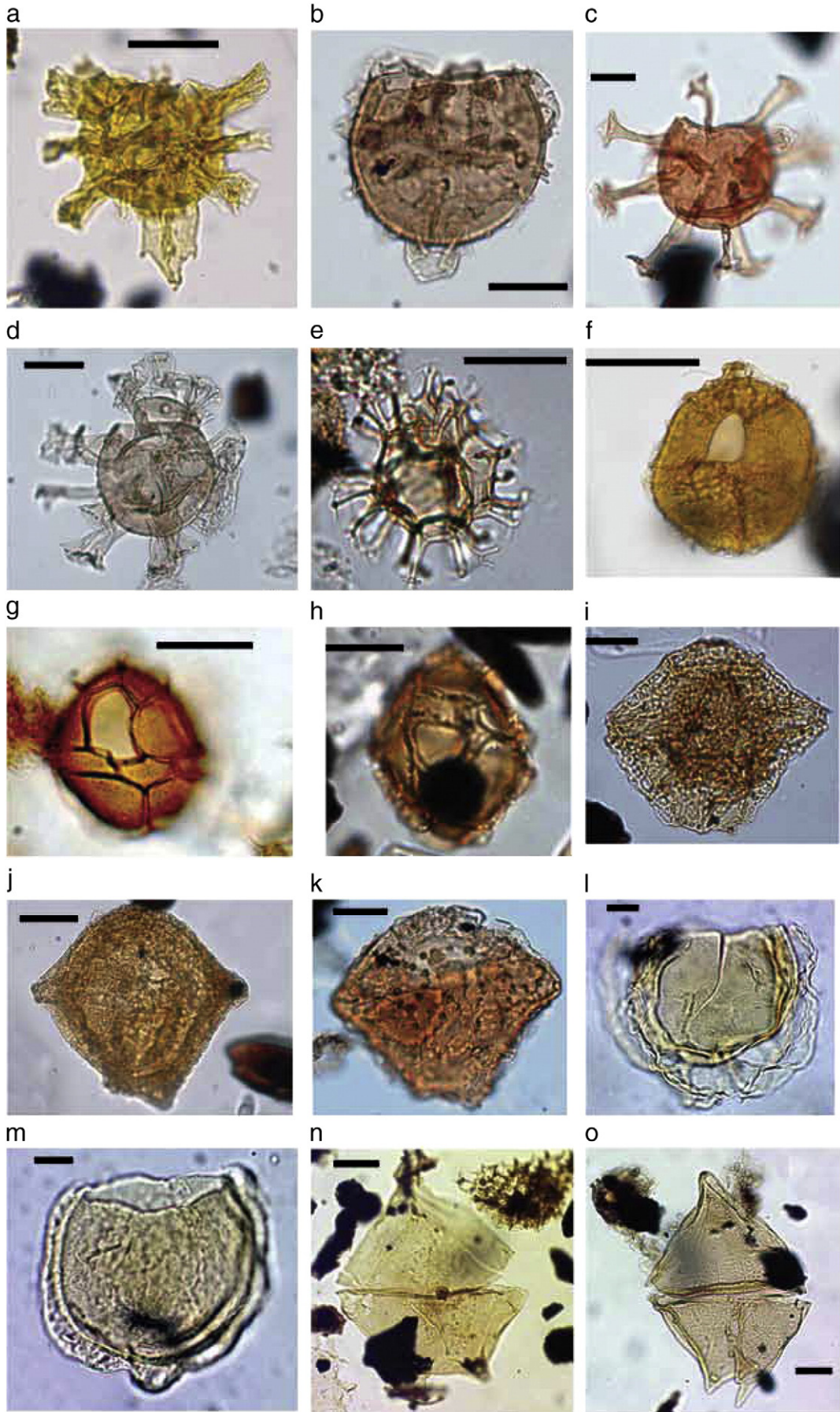


Plate IV (caption on page 18).

Glaphyrocysta ordinata (Williams and Downie, 1966a) Stover and Evitt, 1978

Glaphyrocysta pastielsii (Deflandre and Cookson, 1955 ex De Coninck, 1965) Stover and Evitt, 1978 emend. Sarjeant, 1986 [Plate III; j]

Glaphyrocysta retiintexta (Cookson, 1965a) Stover and Evitt, 1978

G. semitecta (Bujak in Bujak et al., 1980) Lentin and Williams, 1981

Hafniasphaera septata (Cookson and Eisenack, 1967) Hansen, 1977 emend. McLean, 1971

Hemiplaciphora semilunifera Cookson and Eisenack, 1965a

Heteraulacacysta porosa Bujak in Bujak et al., 1980

Histiocysta palla Davey, 1969b [Plate III; k]

Homotryblium tasmaniense Cookson and Eisenack, 1967 [Plate III; l, m]

Hystrichokolpoma bullatum Wilson, 1988 [Plate III; n, o]

Hystrichokolpoma pusillum Biffi and Manum, 1988

Hystrichokolpoma rigaudiae Deflandre and Cookson, 1955 [Plate IV; a]

Hystrichokolpoma salacia Eaton, 1976

Hystrichokolpoma spinosum Wilson, 1988

Hystrichokolpoma truncatum Biffi and Manum, 1988 [Plate IV; b]

Hystrichosphaeridium truswelliae Wrenn and Hart, 1988 [Plate IV; c, Plate VII; o]

Hystrichosphaeridium tubiferum (Ehrenberg, 1838) Deflandre, 1937 [Plate IV; d]

Remarks. *H. truswelliae* is distinguished *H. tubiferum* in having hollow open infundibular processes that forms distally fenestrate, edged platforms, whereas the processes of *H. tubiferum* are tubiform. Occasionally, poor preservation of the distal ends of the processes compromises proper speciation.

Hystrichosphaeropsis spp. Deflandre, 1935 emend. Sarjeant, 1966; Sarjeant, 1982

Hystrichostrogylon membraniphorum Agelopoulos, 1964 [Plate IV; e]

Impagidinium aculeatum (Wall, 1967) Lentin and Williams, 1981

Impagidinium cassiculum Wilson, 1988 [Plate IV; f]

Impagidinium crassimuratum Wilson, 1988

Impagidinium dispertitum (Cookson and Eisenack, 1965a) Stover and Evitt, 1978

Impagidinium maculatum (Cookson and Eisenack, 1961) Stover and Evitt, 1978 [Plate IV; g, Plate VIII; a]

Impagidinium paradoxum (Wall, 1967) Stover and Evitt, 1978

Impagidinium parvireticulatum Wilson, 1988 [Plate IV; h]

Impagidinium victorianum (Cookson and Eisenack, 1965a) Stover and Evitt, 1978

Impagidinium sp. A sensu Crouch and Hollis, 1996

Kisselevia insolens Eaton, 1976 [Plate IV; i, Plate VIII; b]

Kisselevia? sp. cf. *Kisselevia ornata* Vozzhennikova, 1967 [Plate IV; j]

Kisselevia? sp. A [Plate IV; k; Plate VIII; c]

Remarks. This species consists of 2 layers and lacks a spherical endocyst, which assigns it to *Kisselevia* rather than *Charlesdowniea*, following the concepts of Lentin and Vozzhennikova (1989). However, some features, such as the perforate platforms supported by short processes, are characteristic of *Charlesdowniea*. We questionably assign this species, to be formally described elsewhere, to *Kisselevia*.

Lejeunecysta hyalina (Gerlach, 1961) Arztner and Dörhöfer, 1978 emend. Kjellström, 1972

Lingulodinium machaerophorum (Deflandre and Cookson, 1955) Wall, 1967

Lophocysta spp. Manum, 1979

Mavinia esutiana Houben et al., 2011

Melitasphaeridium pseudorecurvatum (Morgenroth, 1966a) Bujak et al., 1980

Membranoporphidium perforatum Wilson, 1988 [Plate IV; l, m]

Nematospaeropsis labyrinthus (Ostenfeld, 1903) Reid, 1974

Ochetodinium spp. Damassa, 1979b

Octodinium askiniae Wrenn and Hart, 1988 [Plate V; a]

Oligosphaeridium complex (White, 1842) Davey and Williams, 1966b

Operculodinium centrocarpum (Deflandre and Cookson, 1955) Wall, 1967

Palaeocystodinium golzowense Alberti, 1961 [Plate V; b]

Palaeoperidinium pyrophorum (Ehrenberg, 1838 ex Wetzel, 1933)

Sarjeant, 1967 emend. Sarjeant, 1967; Gocht and Netzel, 1976; Evitt et al., 1998 [Plate IV; n, o]

Paucisphaeridium inversibuccinum (Davey and Williams, 1966b) Bujak et al., 1980

Paucisphaeridium? spp. (pars.) [Plate V; c, d, e, Plate VIII; d, e]

Remarks. Several new species tentatively assigned to *Paucisphaeridium* have been identified at several of the studied sites. These will be formally described elsewhere.

Pentadinium laticinctum Gerlach, 1961 emend. Benedek et al., 1982 [Plate V; f]

Phthanoperidinium alectrolophum (Eaton, 1976) [Plate V; g]

Phthanoperidinium comatum (Morgenroth, 1966b) Eisenack and Kjellström, 1972

Phthanoperidinium crenulatum (de Coninck, 1975) Lentin and Williams, 1977 emend. Heilmann-Clausen, 1985

Phthanoperidinium stockmansii (de Coninck, 1975) Lentin and Williams, 1977 [Plate V; h, i]

Phthanoperidinium sp. A sensu Goodman and Ford, 1983

Phthanoperidinium sp. B sensu Goodman and Ford, 1983

Plate V. a: *Octodinium askiniae* 1172D-10R-2W, 10–12 cm; b: *Palaeocystodinium golzowense* U1356A-104R-1W, 50–52 cm; c: *Paucisphaeridium?* sp. 1172D-14R-1W, 60–62 cm; d: *Paucisphaeridium?* sp. 1172D-14R-2W, 150–152 cm; e: *Paucisphaeridium?* sp. 1172D-14R-2W, 30–32 cm; f: *Pentadinium laticinctum* U1356A-100R-1W, 10–13 cm; g: *Phthanoperidinium alectrolophum* U1356A-100R-1W, 104–107 cm; h: *Phthanoperidinium stockmansii* 1172D-9R-6W, 40–42 cm; i: *Phthanoperidinium stockmansii* 1172D-9R-6W, 40–42 cm; j: *Polysphaeridium subtile* 1172D-12R-4W, 10–12 cm; k: *Pyxidinoopsis waipawaensis* 1172D-11R-3W, 135–137 cm; l: *Rhombodinium subtile* U1356A-105R-4W, 99–101 cm; and m: *Samlandia delicata* U1356A-100R-1W, 104–107 cm. Scale bar = 25 µm.

Plate VI. a: *Samlandia septata* U1356A-104R-6W, 70–72 cm; b: *Schematophora obscura* 1172D-13R-3W, 105–107 cm; c: *Schematophora obscura* U1356A-102R-1W, 30–32 cm; d: *Senegalinium* sp. 1172D-15R-7W, 10–12 cm; e: *Senegalinium* sp. 1172D-12R-4W, 10–12 cm; f: *Senegalinium* sp. 1172D-15R-7W, 10–12 cm; g: *Spinidinium macmurdoense* 1172D-13R-7W, 35–37 cm; h: *Spinidinium schellenbergii* U1356A-98R-1W, 100–103 cm; i: *Spinidinium schellenbergii* 1172D-6R-2W, 38–40 cm; j: *Spiniferites* sp. B Brinkhuis et al., 2003a U1356A-101R-1W, 80–82 cm; k: *Tectatodinium pellitum* U1356A-99R-2W, 0–3 cm; l: *Thalassiphora pelagica* 1172D-12R-2W, 10–12 cm; m: *Vozzhennikovia apertura* 1172D-18R-1W, 40–42 cm; n: *Vozzhennikovia apertura* 1172D-14R-4W, 10–12 cm; and o: *Vozzhennikovia* sp. cf. *V. roehliae* 1172D-13R-3W, 135–137 cm. Scale bar = 25 µm. (see on page 24)

Plate VII. a: *Vozzhennikovia* sp. cf. *V. roehliae* 1172D-13R-3W, 135–137 cm; b: *Vozzhennikovia stickleyae* 1172D-14R-4W, 10–12 cm; c: *Wetzelia astra* 1172D-13R-1W, 40–42 cm; d: *Wetzelia samlandica* 1172D-13R-2W, 40–42 cm; e: *Wetzelia samlandica* 1172D-13R-2W, 40–42 cm; f: *Wilsonidium echinosuturatum* 1172D-5R-4W, 38–40 cm; g: *Wilsonidium ornatum* 1172D-12R-5W, 40–42 cm; h and i: dinocyst gen. et sp. indet. U1356A-104R-6W, 70–72 cm; j: *Apectodinium homomorphum* 1172D-15R-5W, 100–102 cm; k: *Apectodinium homomorphum* 1172D-15R-5W, 100–102 cm; l: *Cordosphaeridium fibrospinosum* 1172D-15R-5W, 10–12 cm; m: *Cordosphaeridium* sp. A U1356A-103R-1W, 90–92 cm; n: *Elytrocysta brevis* 1172D-14R-2W, 115–117 cm; and o: *Hystrichosphaeridium tubiferum* 1172D-15R-5W, 100–102 cm. Scale bar = 25 µm. (see on page 25)

Plate VIII. a: *Impagidinium maculatum* 1172D-14R-4W, 10–12 cm; b: *Kisselevia insolens* U1356A-101R-1W, 120–121 cm; c: *Kisselevia* sp. A 1172D-13R-2W, 40–42 cm; d: *Paucisphaeridium?* sp. 1172D-14R-1W, 140–142 cm; e: *Paucisphaeridium?* sp. 1172D-14R-1W, 140–142 cm; f: *Senegalinium* sp. 1172D-14R-4W, 10–12 cm; g: *Senegalinium* sp. 1172D-14R-2W, 115–117 cm; h: *Senegalinium* sp. 1172D-14R-2W, 115–117 cm; i: *Spinidinium macmurdoense* 1172D-14R-4W, 10–12 cm; j: *Vozzhennikovia apertura* 1172D-14R-1W, 10–12 cm; k: *Vozzhennikovia apertura* 1172D-14R-1W, 10–12 cm; l: *Wetzelia samlandica* 1172D-13R-2W, 40–42 cm; m: *Wetzelia samlandica* 1172D-13R-2W, 40–42 cm; n: dinocyst gen. et sp. indet. U1356A-105R-1W, 75–77 cm; and o: dinocyst gen. et sp. indet. U1356A-104R-6W, 70–72 cm. Scale bar = 25 µm. (see on page 26)

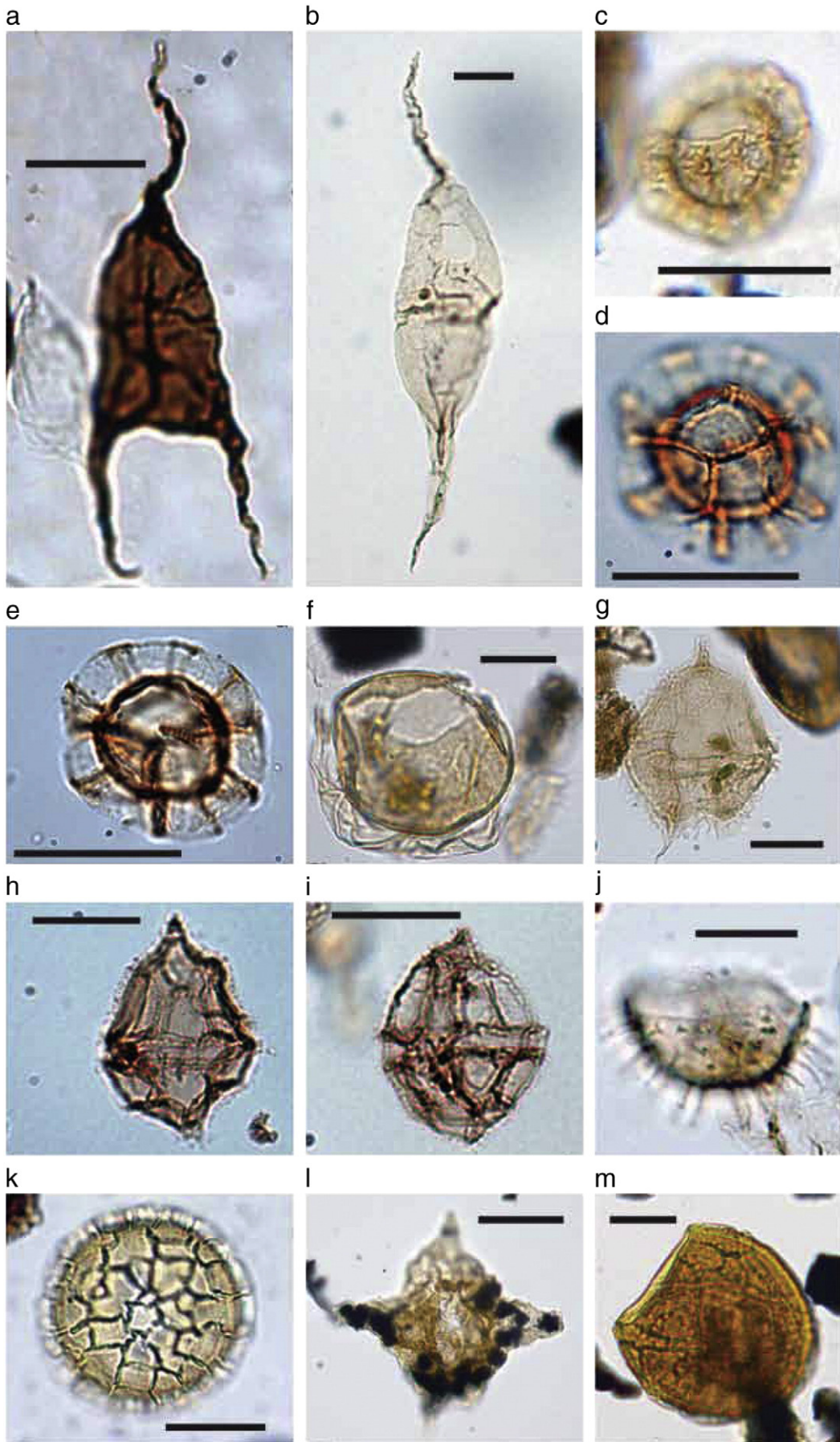


Plate V.

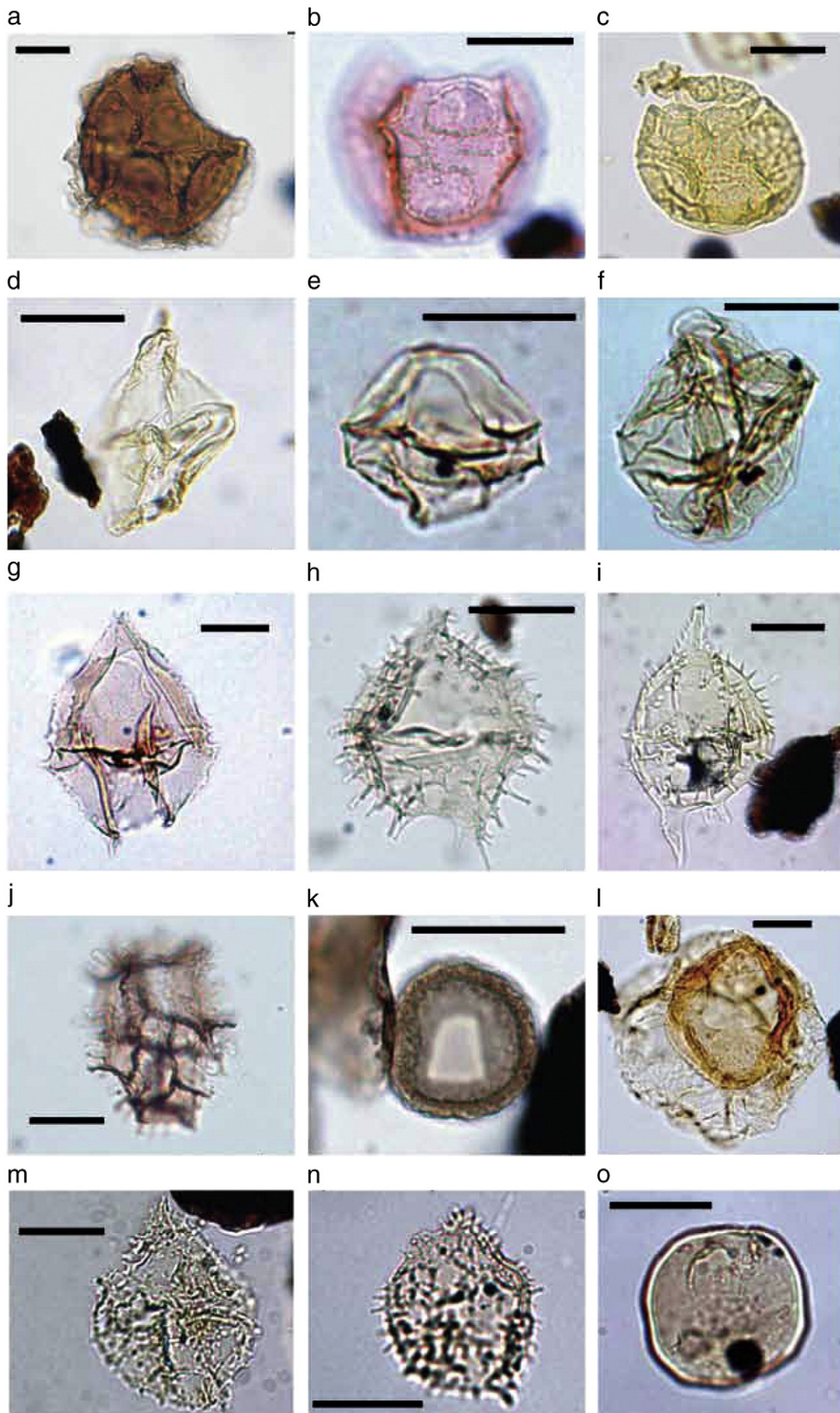


Plate VI (caption on page 22).

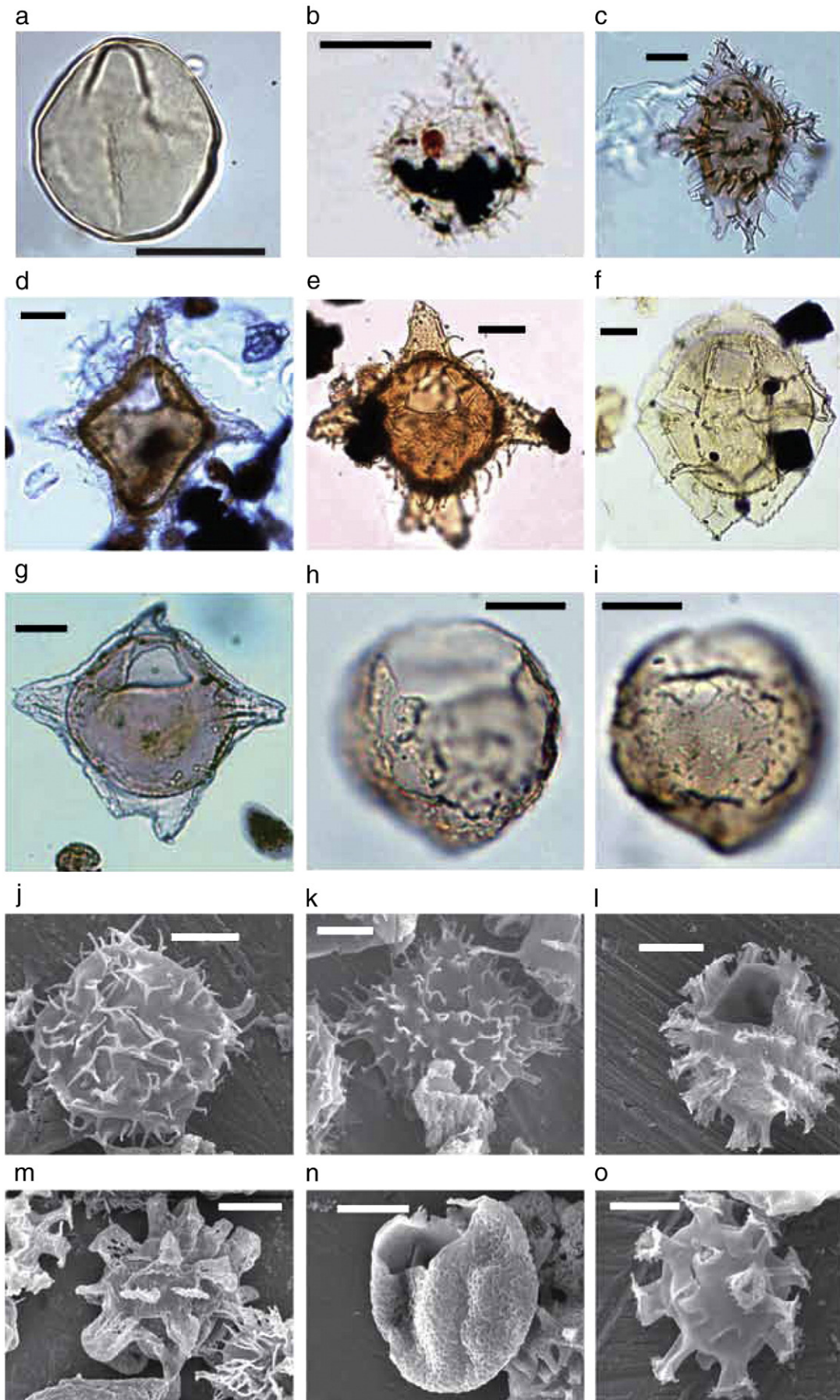


Plate VII (caption on page 22).

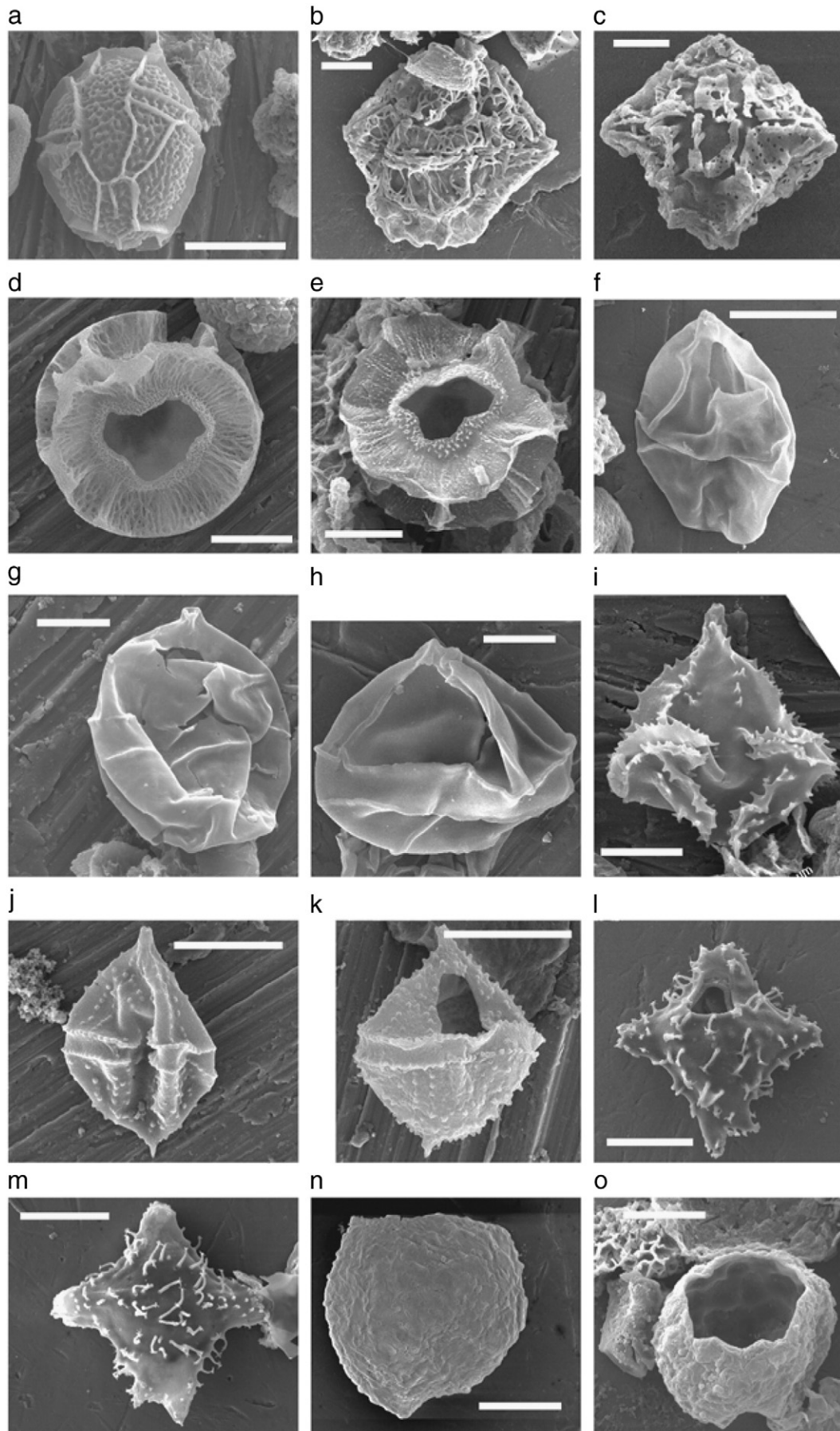


Plate VIII (caption on page 22).

Polysphaeridium subtile Davey and Williams, 1966b emend. Bujak et al., 1980 [Plate V; j]
Pyxidinosphaera delicata Wilson, 1988 [Plate I; k]
Reticulosphaera acticoronata (Benedek, 1972) Bujak and Matsuoka, 1986 emend. Bujak and Matsuoka, 1986
Rhombodinium draco Gocht, 1955
Rhombodinium subtile Wilson, 1988 [Plate V; l]
Samlandia delicata Wilson, 1988 [Plate V; m]
Samlandia septata Wilson, 1988 [Plate VI; a]
Samlandia chlamidophora Eisenack, 1954
Schematophora obscura Wilson, 1988 [Plate VI; b, c]
Schematophora speciosa Deflandre and Cookson, 1955 emend. Stover, 1975
Selenopemphix armata Bujak in Bujak et al., 1980
Selenopemphix nephroides Benedek, 1972 emend. Bujak et al., 1980; Benedek and Sarjeant, 1981
Senegalium spp. Jain and Millepied, 1973 emend. Stover and Evitt, 1978 [Plate VI; d, e, f, Plate VIII, f, g, h]
Spinidinium luciae Wrenn and Hart, 1988
Spinidinium macmurdoense Wilson, 1967b [Plate VI; g, Plate VIII; i]
Spinidinium schellenbergii Sluijs et al., 2009b [Plate VI; h, i, Plate VIII; j, k]
Remarks. Sluijs et al. (2009b) provided a reanalysis of the *Spinidinium/Vozzhennikovia* complex.
Spiniferites pseudofurcatus (Klumpp, 1953) Sarjeant, 1981
Spiniferites ramosus (Ehrenberg, 1838) Mantell, 1854
Spiniferites sp. B sensu Brinkhuis et al., 2003a [Plate VI; j]
Stoveracysta kakanuiensis Clowes, 1985
Stoveracysta ornata (Cookson and Eisenack, 1965a) Clowes, 1985
Tectatodinium pellitum Wall, 1967 emend. Head, 1994 [Plate VI; k]
Thalassiphora delicata Williams and Downie, 1966a emend. Eaton, 1976
Thalassiphora pelagica (Eisenack, 1954) Eisenack and Gocht, 1960 [Plate VI; l]
Turbiosphaera filosa (Wilson, 1967b) Archangelsky, 1969
Turbiosphaera galeata Eaton, 1976
Turbiosphaera sagena Levy and Harwood, 2000
Vozzhennikovia apertura (Wilson, 1967b) Lentini and Williams, 1976 [Plate VI; m, n]
Vozzhennikovia netrona Levy and Harwood, 2000 emend. Sluijs et al., 2009b
Vozzhennikovia roehliae Sluijs et al., 2009b
Vozzhennikovia sp. cf. *V. roehliae* Sluijs et al., 2009b [Plate VI; o, Plate VII; a]
Remarks. This species of *Vozzhennikovia* occurs in Subchron C24n, and shows morphological resemblances to *V. roehliae* Sluijs et al., 2009b. Ornamentation (in the form hollow verrucae) is faintly visible, and the cingulum is slightly indented. However, the outline of the cyst is more rounded compared to *V. roehliae* with no apical or antapical horns. While *V. roehliae* sensu stricto has a consistent 3I archeopyle, the archeopyle of the species found here is consistently 2a, and the operculum is consistently adnate to 4". The species will be formally described elsewhere.
Vozzhennikovia stickleyae Sluijs et al., 2009b [Plate VII; b]
Remarks. Sluijs et al. (2009b) provided a reanalysis of the *Spinidinium/Vozzhennikovia* complex.
Wetzeliella articulata Wetzel in Eisenack, 1938 [Plate VII; c]
Wetzeliella astra Denison in Costa et al., 1978
Wetzeliella samlandica Eisenack, 1954 [Plate VII; d, e, Plate VIII; l, m]
Wilsonidium echinosuturatum (Wilson, 1967c) Lentini and Williams, 1976 [Plate VII; f]
Wilsonidium ornatum (Wilson, 1967c) Lentini and Williams, 1976 [Plate VII; g]
Ynezidium waipawaense (Wilson, 1988) Lucak-Clark and Helenes, 2000
Dinocyst gen. et sp. indet. [Plate VII; h, i; Plate VIII; n, o]

Remarks. This dinocyst species is spherical in polar view, with a clear edged apical archaeopyle. The offset sulcal nudge and occasionally large antapical bulge clearly indicates dorso-ventral compression. Based on these observations, this species belongs to the *Areoligera* family. Species within the genus *Areoligera* spp. are, however, characterized by processes or process complexes indicating para-tabulation. The outer wall of this species however is finely rugulate with no expression of para-tabulation. The species will be formally described elsewhere.

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