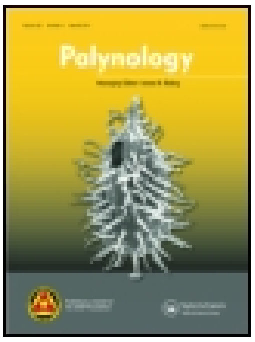

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Terrestrial and marine floral response to latest Eocene and Oligocene events on the Antarctic Peninsula

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ABSTRACT
Palynological results from opposite sides of the northernmost Antarctic Peninsula provide insight on terrestrial vegetation and sea-surface conditions immediately before the Eocene–Oligocene transition (EOT), through Early Oligocene glacial conditions and the subsequent Late Oligocene interglacial interval. A latest Eocene sample set from the uppermost La Meseta Formation on Seymour Island, James Ross (back-arc) Basin, records a low-diversity *Nothofagus* (southern beech)-dominated vegetation with some podocarp conifers similar to Valdivian-type forest found today in Chile and Argentina. Marine organic-walled phytoplankton include leiospheres and Eocene dinoflagellate cysts such as *Vozzhennikovia rotunda*, *V. apertura*, *Senegalinium asymmetricum* and *Spinidinium macmurdoense*. Immediately before the EOT near the top of the section the decrease in terrestrial palynomorphs, increase in reworked specimens, disappearance of key dinocysts, and overwhelming numbers of sea-ice-indicative leiospheres plus the small dinoflagellate cyst *Impletosphaeridium* signal the onset of glacial conditions in a subpolar climate. Early to Late Oligocene samples from the Polonez Cove and Boy Point formations on King George Island, South Shetland Islands (magmatic arc), yielded an extremely depauperate terrestrial flora, likely resulting in part from poor vegetation cover during the Polonez Glaciation but also because of destruction of vegetation due to continued regional volcanism. The prevalence of sea-ice-indicative leiospheres in the marine palynomorph component is consistent with polar to subpolar conditions during and following the Polonez Glaciation.

KEYWORDS
Antarctica; Seymour Island; King George Island; palynology; Eocene; Oligocene

1. Introduction

The interval from the early Eocene through to the Eocene–Oligocene Transition (EOT, ca. 34 Ma) represents a global cooling trend marked by a high-latitude sea-surface temperature decrease from ~18 °C in early Eocene to ~6 °C transitioning into the Oligocene (Stott et al. 1990; Liu et al. 2009). The ~12 °C temperature change has been correlated with increasing deep-sea benthic foraminiferal oxygen isotope ($\delta^{18}O$) values, and decreasing atmospheric carbon dioxide concentrations (Zachos et al. 1996, 2001, 2008; Prothero & Berggren 2014). This major cooling trend was accompanied by substantial ice growth in Antarctica. Ice growth continued with some fluctuations as temperatures decreased from 'greenhouse' conditions approaching the EOT, to the Oligocene–present day 'icehouse' or glacial state in Antarctica (Prothero et al. 2003; Lear et al. 2008).

This paper reports palynological results from a master's of science (MS) project by Madison Kymes (2015), originally based on two sample sets provided by Krzysztof P. Krajewski and Andrzej Tatur from King George Island in the South Shetland Islands (Figure 1). These included the current Lower to Upper Oligocene set from the Polonez Cove and the Boy Point formations, as well as a Lower Miocene set from the Cape Melville Formation, reported earlier in Warny et al. (2016). For comparison, an additional sample set was selected from the uppermost Eocene sediments on Seymour Island in the Weddell Sea (Figure 1). Together these studies cover three small but significant slices of time during the Cenozoic shift to icehouse conditions in West Antarctica. They are compared with earlier results in the region from well-dated SHALDRIL cores (Anderson et al. 2011; Warny & Askin 2011a, 2011b; Griener et al. 2013; Feakins et al. 2014). This MS project is a small part within the broader objectives of the authors and their colleagues of clarifying Antarctica's Cretaceous and Cenozoic vegetation and climate history.

2. Geological setting

2.1. La Meseta Formation, Seymour Island

The older (Eocene) sample set discussed here is from Seymour Island, which lies within the James Ross (back-arc) Basin, southeast of the tip of the Antarctic Peninsula (Figure 1(B)) at 64°17′S latitude and 56°45′W longitude. The island is roughly 20.5 km long and 9.6 km wide, showing slopes from sea level up to a pronounced plateau or mesa at roughly 200 m above sea level (Elliot et al. 1975). Seymour Island outcrops lack permanent ice

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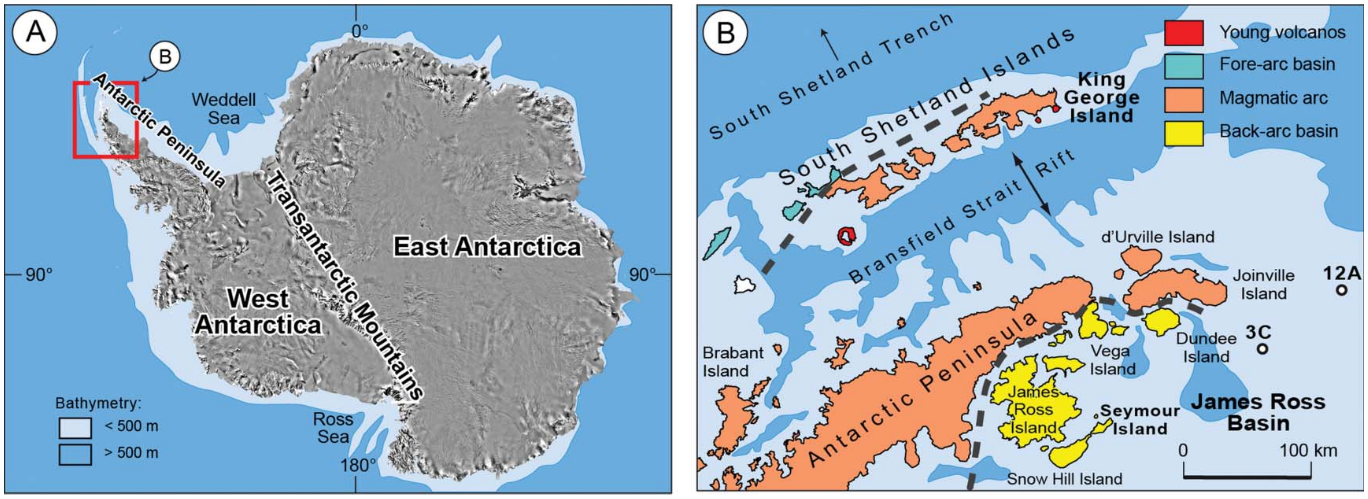

Figure 1. (A) Map of Antarctica showing the location of the Antarctic Peninsula; the red rectangle is the part enlarged in (B). (B) Locations of Seymour Island, King George Island, and SHALDRIL II sites 3C and 12A in the northern Antarctic Peninsula region.

and are thus well exposed, and contain a rich assortment of well-preserved marine and terrestrial macro- and microfossils.

The selected samples are from the uppermost sediments of the La Meseta Formation (Rinaldi et al. 1978; Elliot & Trautman 1982) (Figure 2). La Meseta Formation siliciclastic strata crop out on the northern third of the island, filling a valley incised into the upper Palaeocene Cross Valley Formation, itself incised into Maastrichtian to lower Palaeocene sediments of the López de Bertodano and Sobral formations, which are exposed in the south-western two-thirds, and also the northern tip of the island. Following the initial three-fold subdivision of the formation by Elliot & Trautman (1982), various authors have described and subdivided this complex back-arc shelfal succession of shallow marine, estuarine and deltaic sands, silts, muddy sediments and shellbeds. Seven lithofacies (designated Tertiary Eocene La Meseta/Telm 1–7) were mapped in detail by Sadler (1988). Porębski (1995, 2000) recognised three major eustatically controlled depositional sequences, with subdivisions that are more tectonically influenced. Marenssi & Santillana (1994) and Marenssi et al. (1998a, 1998b) divided the formation into six primarily eustatically controlled depositional sequences or allomembers. The stratigraphic scheme of Marenssi and colleagues is followed here.

The Seymour Island sample set was collected from the top of the La Meseta Formation (Submeseta Allomember according to Marenssi et al. 1998a, 1998b) along the side of a gully

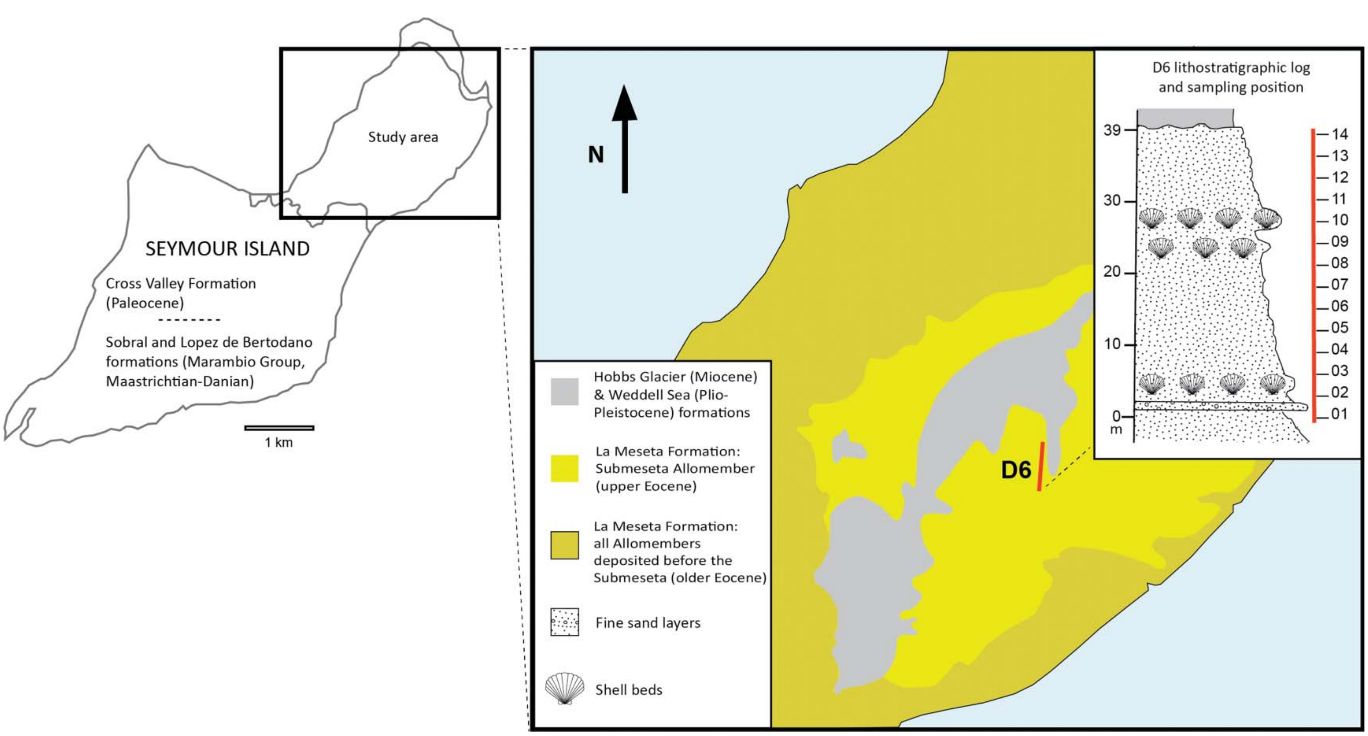

Figure 2. Simplified geological map of northern Seymour Island, showing the La Meseta Formation with the distribution of the Submeseta Allomember in relationship to other La Meseta allomembers. The location of the D6 section is marked by a red line. The relationship of the sample location with the lithology sampled is presented in the inset to the right.

downcutting the central/south-eastern side of the mesa (Figures 2 and 3), from monotonous unconsolidated sands and silts with shell beds and concretionary horizons. Strontium-isotope analyses conducted on *Cucullaea* specimens collected throughout the La Meseta Formation by Dutton et al. (2002 and references therein; Ivany et al. 2008) had supported the previous palaeontologically assigned age range of late Early Eocene to Late Eocene; however, more recent results suggest the oldest La Meseta sediments may be Mid rather than late Early Eocene (Douglas et al. 2014), with the entire formation ranging in age from 45 to 34 Ma. Specifically, for the uppermost beds sampled in this study (upper Submeseta Allomember, or upper Telm7), Dutton et al. (2002), Ivany et al. (2008) and Douglas et al. (2014) place these sediments between 36 and 34 Ma. These upper beds underlie the Miocene glacigenic Hobbs Glacier Formation (Marenssi et al. 2010) and the Pliocene–Pleistocene till of the Weddell Sea Formation (Zinsmeister and deVries 1983; Gaździcki et al. 2004) that tops the mesa. The discovery, off the opposite northern side of the mesa, by Ivany et al. (2006) of three thin layers of sediments (pebbly mudstone; diamict; pebbly mudstone) between the uppermost La Meseta Formation and the overlying Weddell Sea Formation provides more certain age and palaeoclimatic control. Ivany et al. (2006) report $^{87}Sr/^{86}Sr$ ratios of bivalves yielding ages of 33.57–34.78 Ma from the uppermost La Meseta Formation at their locality, confirming an EOT age at the top of the formation (E–O boundary 33.9 Ma, Gradstein et al. 2012). Dinoflagellate cysts indicate a late Eocene and earliest Oligocene age, respectively, for the lower and upper pebbly mudstone (Ivany et al. 2006), with the intervening diamict suggesting glacial ice at the EOT. Our sample set from a section on the opposite side of the mesa is likely of similar latest Eocene age to the uppermost La Meseta beds dated by Ivany et al. (2006; see also Dutton et al. 2002; Ivany et al. 2008; Douglas et al. 2014).

2.2. Polonez Cove Formation and Boy Point Formation, King George Island

The younger (Oligocene) sample set discussed here is from King George Island, located approximately 120 km off the northern coast of the Antarctic Peninsula at 62°01′S latitude and 58°33′W longitude (Figure 1(B)). King George Island is roughly 95 km long and 25 km wide, making it the largest of the South Shetland Islands. The South Shetland Islands are part of a magmatic arc, detached from the northern Antarctic Peninsula magmatic arc by the Bransfield Strait (Figure 1(B)). The Bransfield Rift is less than 4 million years old, with oceanic crust dating from about 1.3 Ma (Barker & Austin 1998). Thus, the studied sedimentary units representing the back-arc basin (Seymour Island) and the magmatic arc (King George Island) were deposited in relatively close proximity to each other on opposite sides of the Antarctic Peninsula in the latest Eocene and Oligocene.

The geological history of King George Island is substantially more complicated than that of the Seymour Island sediments. The Eocene through Oligocene of King George Island reflects a complex history of volcanism, glaciation and marine transgressions. The studied sample set is from part of the Chopin Ridge Group (Birkenmajer 1980) exposed on the western side of King George Bay (Figure 4). The Chopin Ridge Group includes porphyritic lava flows and pyroclastics, marine tillites, associated glaciogenic sediments and sandstones, divided into five formations (in ascending order): the Mazurek Point Formation or Lions Cove Formation, Polonez Cove Formation, Boy Point Formation and Wesele Cove Formation (Birkenmajer 2001). The sample set was collected from the Polonez Cove Formation and basal Boy Point Formation along a section at Linton Knoll (Figures 4 and 5(A)). Supplementary samples from the Polonez Cove Formation were collected at Conglomerate Bluff, located approximately 2 km to the south-east from Linton Knoll

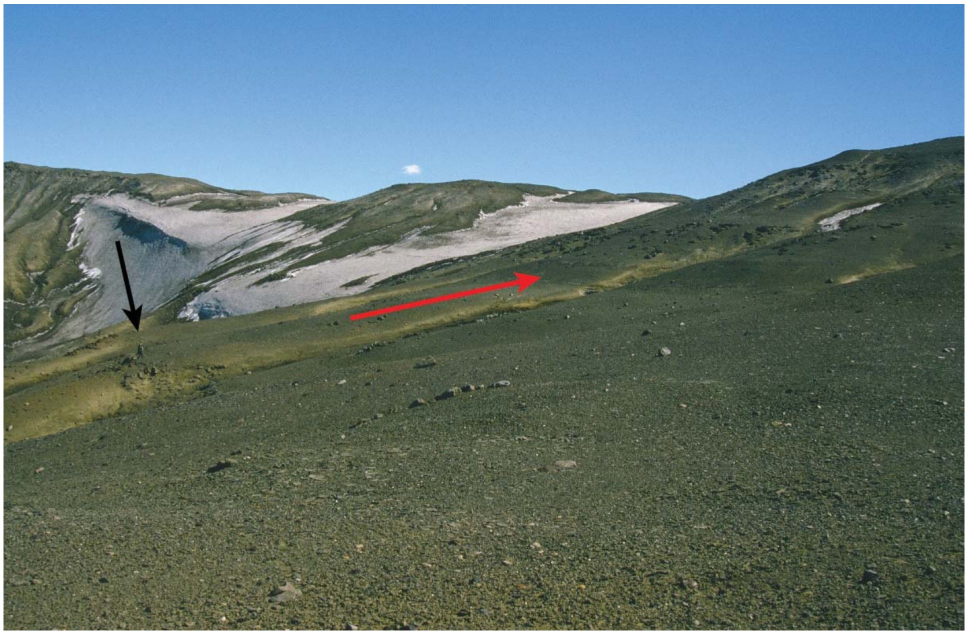

Figure 3. Photograph looking to the south-east on Seymour Island of section D6 towards a person (black arrow) standing on the resistant bed near the section base (between samples 1 and 2). The red arrow indicates the direction of the D6 section.

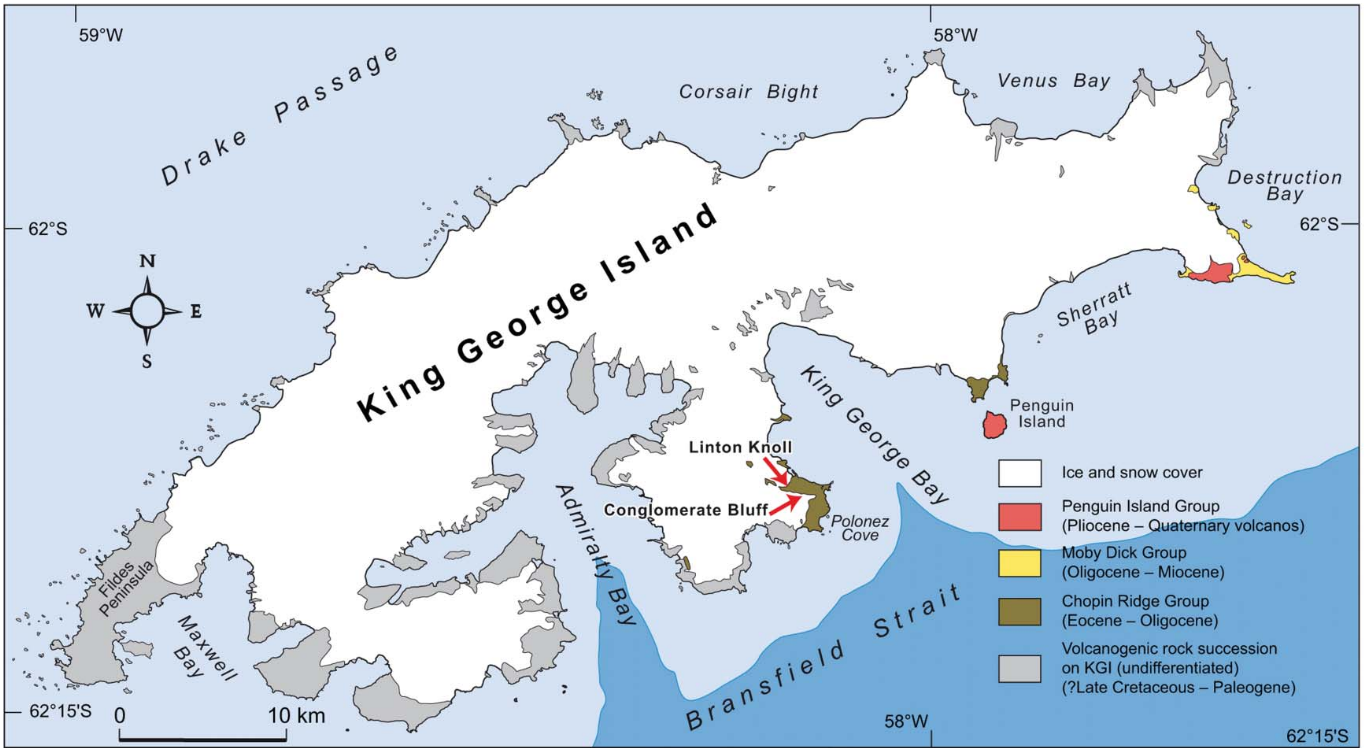

Figure 4. Geological map of King George Island, showing the distribution of the Chopin Ridge Group and the location of Linton Knoll and Conglomerate Bluff sections.

(Figures 4 and 5(B)). Their stratigraphic position is compiled on the Linton Knoll section (Figure 6).

The Mazurek Point Formation and the Lions Cove Formation (Eocene) comprise basaltic/andesitic substratum for the overlying glacio-marine and volcanogenic formations along the outcrop belt of the Chopin Ridge Group (Birkenmajer 2001; Pańczyk & Nawrocki 2011). The overlying Polonez Cove Formation is subdivided into six members, though not all are present at every location (Birkenmajer 1980, 1982; Porębski & Gradzinski 1987; Troedson & Smellie 2002). These are (in ascending order): the Krakowiak Glacier, Bayview, Low Head, Siklawa, Oberek and Chlamys Ledge members. Lodgement till at the base of the Polonez Cove Formation and the associated glacio-marine sediments, together making up the Krakowiak Glacier Member, represent the Polonez Glaciation (Birkenmajer 1987). The name Krakowiak Glacier Member was based on the presence of a small glacial body that existed along the Chopin Ridge, and it was introduced by K. Birkenmajer in 1980. It is sad to note that this ice body has now fully vanished as a result of the warming trend in West Antarctica (K. Krajewski, pers. comm.). A late Early Oligocene age is indicated from Sr dating of carbonate material from the Krakowiak Glacier Member and the Low Head Member (ca. 30–28 Ma, Dingle et al. 1997; Dingle & Lavelle 1998). Unpublished strontium isotope results point to even older geological ages (Early Oligocene, ca. 32–30 Ma) of parts of the glacio-marine deposits of the Krakowiak Glacier Member (K. Krajewski, pers. comm.). Younger Ar–Ar dates were derived from the interfingering and overlying basaltic lavas and hyaloclastic rocks in the Low Head Member and Oberek Cliff Member, although precision of these measurements is low (29–22 Ma, Smellie et al. 1998; Troedson & Smellie 2002). The upper part of the Polonez Cove Formation, which comprises shallow marine basaltic sandstones (Chlamys Ledge Member), gave a single late Oligocene strontium age (27.1 ± 0.3 Ma) on the basis of a *Chlamys* shell analysis (K. Krajewski, pers. comm.). The whole-rock K–Ar ages obtained from the overlying terrestrial Boy Point Formation (ca. 24–22 Ma) indicate an age of youngest Oligocene/oldest Miocene, though they might in part reflect a reset by younger thermal events (Birkenmajer & Gaździcki 1986). The Boy Point Formation consists mostly of dacitic rocks, with the lower informal member (Loud Waterfall member) dominated by dacitic clastic deposits, and the upper informal member (Linton Knoll member) dominated by agglomerates and lavas. A Late Oligocene age for the formation is suggested here on the basis of geological correlation.

3. Studied materials

Thirty samples were analysed for palynology: 14 from Seymour Island (Table 1), and 16 from King George Island (Table 2). The 14 Seymour Island samples were collected from the uppermost La Meseta Formation for R. Askin in December 1986 and were obtained for this study from the Polar Rock Repository, Byrd Polar and Climate Research Center, The Ohio State University. These 14 samples are from the top of the Submeseta Allomember (or upper Telm7 in the terms of Sadler 1988) and were collected at 3-m intervals through a 39-m section of monotonous fine sands and silts (Figure 2).

The 16 samples from King George Island included sandstones to mudstones and were collected from the Linton Knoll (11 samples) and Conglomerate Bluff (five samples) sections (Figures 4–6). Fourteen of these samples were taken from some members of the Polonez Cove Formation, and two samples from the base of the Boy Point Formation. They were collected

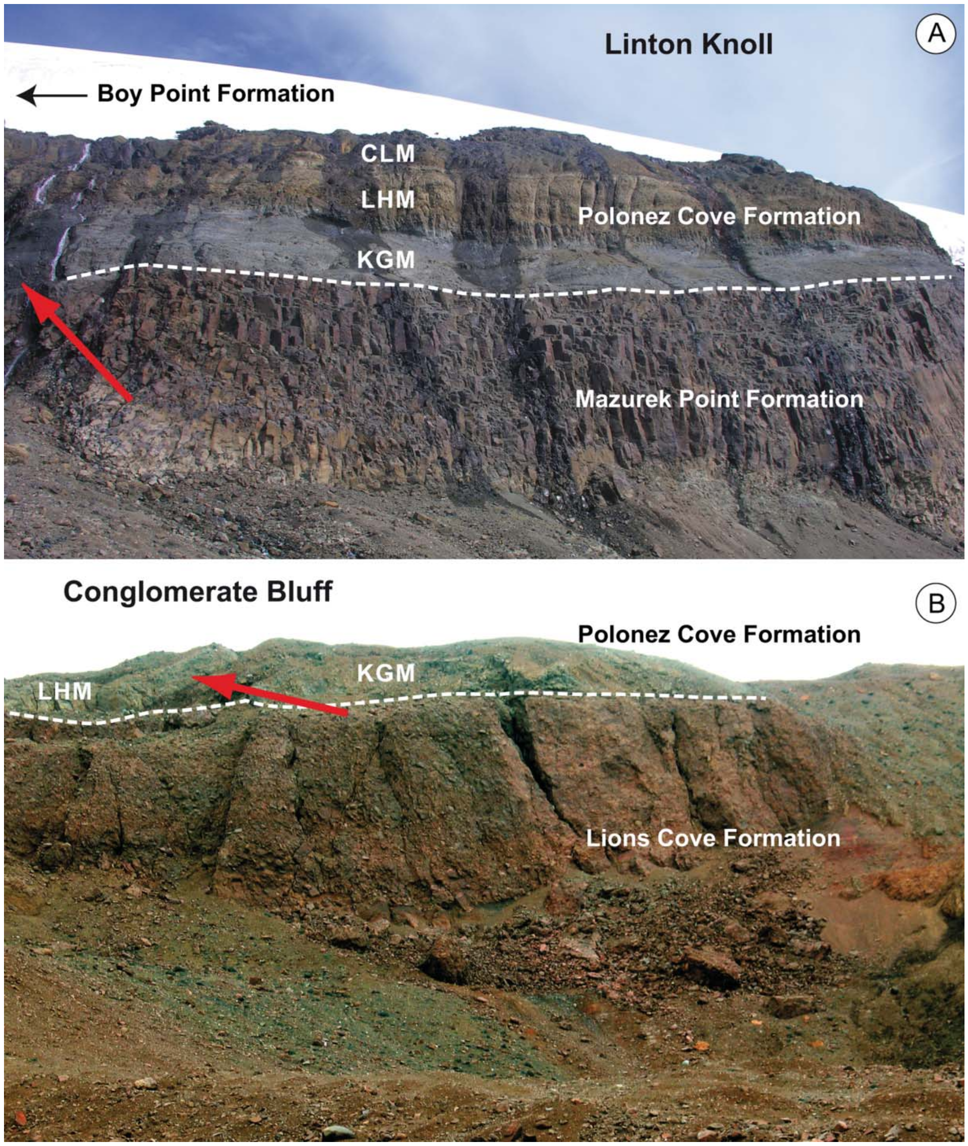

Figure 5. (A) Photograph of the section at Linton Knoll. (B) Photograph of the section at Conglomerate Bluff. King George Bay, King George Island. Red arrows indicate directions of the sections. KGM – Krakowiak Glacier Member; LHM – Low Head Member; CLM – Chlamys Ledge Member.

during the Polish Academy of Sciences (PAS) two-part expedition, which took place in January 2007 and January 2009.

4. Methods

All samples were processed using standard chemical palynological processing techniques. Dry sediment was weighed and spiked with a known quantity of *Lycopodium* spores to allow for calculation of palynomorph concentrations. Dry sediment was successively treated with hydrochloric acid, hydrofluoric acid and heavy liquid separation (e.g. Brown 2008). Samples were sieved between a 10- and 250-μm fraction, and the remaining residue was mounted on microscope slides using glycerin jelly.

Palynological analysis was conducted in the Louisiana State University's Center for Excellence in Palynology (CENEX) lab. When possible, 300 palynomorphs were tabulated per sample, using an Olympus BX41 microscope. Palynomorphs were identified to the lowest taxonomic level possible. After palynomorphs were tallied, palynomorph concentration was calculated for each specimen using the equation from Benninghoff (1962): $C = (P_c \times L_t \times T)/(L_c \times W)$, where C = concentration (per gramme of dried sediment, gdw^{-1}), Pc = the number of palynomorphs counted, L_t = the number of *Lycopodium* spores per tablet, T = the total number of *Lycopodium* tablets added per sample, L_c = the number of *Lycopodium* spores counted and W = the weight of dried sediment.

All specimens analysed from the assemblages were identified at the time of scanning and counting as being either reworked or *in situ* (considered penecontemporaneous with deposition), before palaeoenvironmental conditions could be considered. High numbers of reworked specimens are commonplace in Antarctic Cenozoic assemblages, in large part because of glacial and/or fluvial scouring and redeposition of mainly unconsolidated sediments. When age-restricted species older than Eocene or Oligocene were found (e.g. Cretaceous species), they could be easily recognised as reworked. However, for species with longer age ranges, it is often difficult to differentiate between reworked and *in situ* in Antarctic successions,

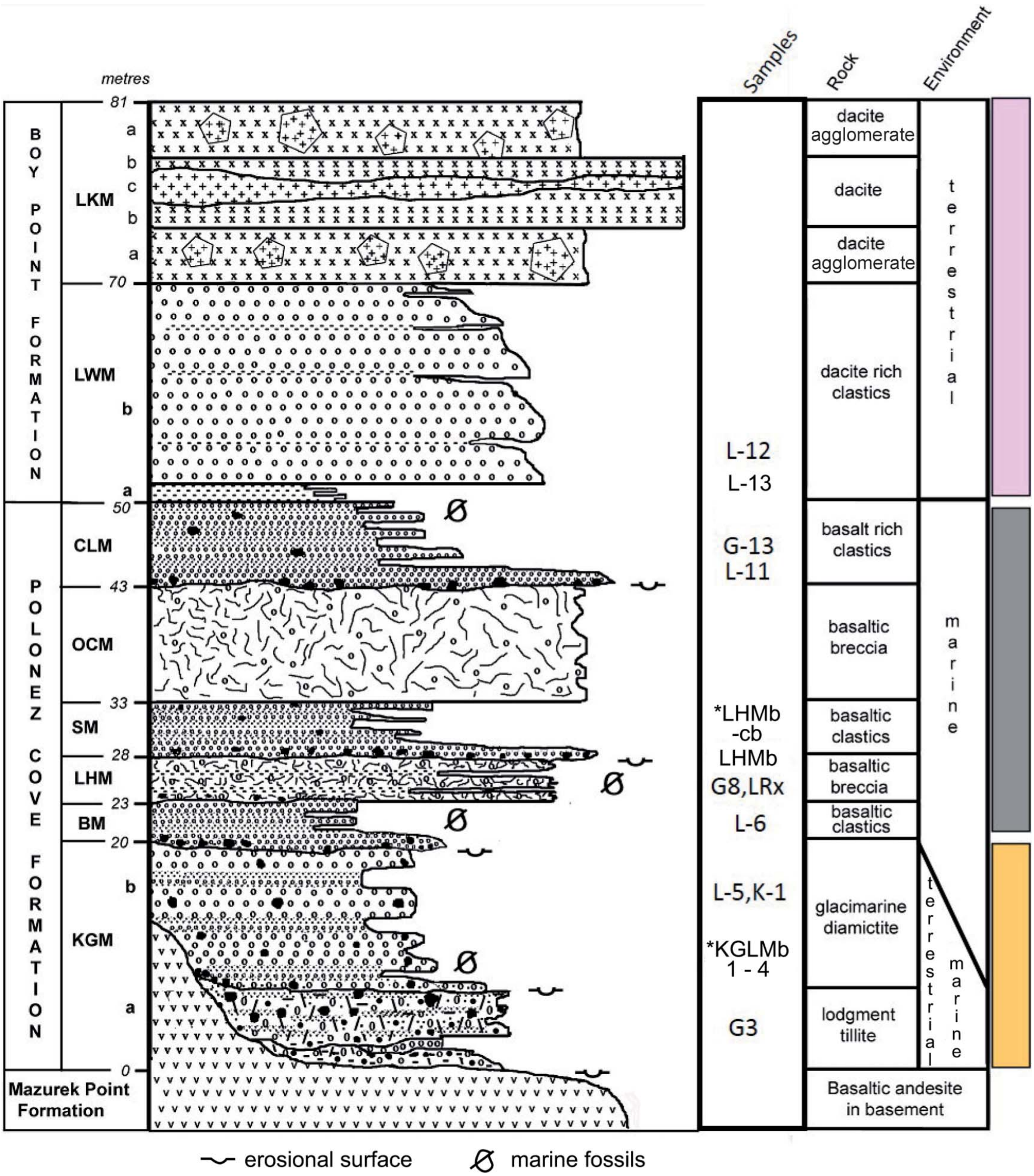

Figure 6. Detailed section of the Polonez Cove Formation at Linton Knoll showing samples collected during the PAS expeditions in 2007 and 2009. * indicates stratigraphic location of samples from the adjacent Conglomerate Bluff section. Polonez Cove Formation: KGM – Krakowiak Glacier Member; BM – Bayview Member; LHM – Low Head Member; SM – Siklawa Member; OCM – Oberek Member; CLM – Chlamys Ledge Member. Boy Point (BP) Formation: LWM – Loud Waterfall member; LKM – Linton Knoll member.

because of minimal time and depths of burial of eroded strata and subsequent lack of differences in preservation and thermal maturities between reworked and *in situ* grains. Where possible, differentiation of reworked specimens was done on the basis of subtle to more overt differences in the preservation of the grains (e.g. battered specimens, presence of corrosion) as well as the thermal maturity of their walls. Some thick-walled cryptogam spores were counted as reworked. Some specimens, if differentiation was not possible, were counted as *in situ*, resulting in taxa such as *Nothofagidites* spp. (*brassii* group) being

Table 1. Palynomorph concentration for the uppermost Eocene D6 section of the La Meseta Formation.

Sample name	Elevation (m)	Palynological counts	Concentration of palynomorphs (gdw^{-1})
D6-14	39	300	753
D6-13	36	300	634
D6-12	33	300	759
D6-11	30	300	812
D6-10	27	300	652
D6-09	26	300	557
D6-08	21	300	669
D6-07	18	300	760
D6-06	15	300	873
D6-05	12	300	844
D6-04	9	300	776
D6-03	6	300	987
D6-02	3	86	373
D6-01	0	98	119

included as part of the penecontemporaneous flora, though these 'warmer-climate' species are typically considered as becoming scarce and possibly disappearing from the region in the latest Eocene (e.g. Chen 2000; R. Askin, pers. comm.).

5. Results

5.1. Palynological results from the La Meseta Formation

The 14 La Meseta samples yielded well-preserved palynomorphs, but with a fairly low diversity. The overall numbers of palynomorphs counted are shown in Figure 7, and our interpretations of *in situ* vs. reworked species in Figure 8. Table 3 provides raw counts. Note that specimens considered to be *in situ* (interpreted as derived from the penecontemporaneous terrestrial and marine flora) are differentiated in blue, and reworked specimens in red, throughout the figures and tables. Selected *in situ* specimens are illustrated in Plate 1.

Palynomorph concentrations are low in these sandy sediments and range from 119 to 987 per gramme of dried sediments (Table 1), which is far less than the concentrations (varying from 700 to 100,000) of recovered palynomorphs from the late Eocene 3C section (Figure 1(B)) sampled by the SHALDRIL programme offshore and north-east of Seymour Island (Warny & Askin 2011a), and from many older samples of the La Meseta Formation. Both of the latter sample sets generally have a higher mud content and thus tend to be more productive. Interestingly, the preparations recovered in this study contain higher concentrations of palynomorphs than most of the same uppermost La Meseta samples summarised by Askin (1997). Several factors may explain this mismatch in palynomorph concentration between the two studies: a larger amount of sample was processed in the current study, recent improvements in processing techniques may have resulted in more abundant organic matter being recovered, or the processed sample fraction may have contained a slightly higher proportion of finer (muddy) sediment.

Age-indicative dinoflagellate cysts occur throughout most of the section, from D6-01 to D6-12 (Figure 7; Table 3). They are absent in the uppermost part (samples D6-13, D6-14). The presence of *Vozzhennikovia rotunda* (Lentin & Williams 1981), *V. apertura* (Lentin & Williams 1981), *Senegalinium asymmetricum* (Stover & Evitt 1978) and *Spinidinium macmurdoense* (Wilson 1967) in the La Meseta samples is consistent with Eocene age, based on age ranges from Ocean Drilling Program's (ODP) Publication 189 (Sluijs et al. 2003; see also the Supporting Information discussion in Douglas et al. 2014 with their reference to the recent biostratigraphic age model of Bijl et al. 2013). It is noted that even though *Vozzhennikovia* spp. and *S. macmurdoense* are shown by Bijl et al. (2013) to range into the Early Oligocene, other dating methods restrict the La Meseta Formation to the Eocene (see Geological setting, Section 2).

Reworked palynomorphs occur throughout the section, becoming progressively more common above the basal samples, and after some fluctuations again increasing in the uppermost portion of the section in samples D6-13 and especially D6-14. Reworked species of palynomorphs range from Permian to Palaeocene in age and have been well documented on Seymour Island (e.g. Askin & Elliot 1982; Bowman et al. 2012). Identified reworked taxa are mostly Cretaceous to Paleogene in age.

Presumed penecontemporaneous or '*in situ*' specimens predominate throughout section D6, with terrestrial pollen of *Nothofagidites* spp. the most abundant in the lower samples (D6-01 to D6-07) and marine leiospheres dominating the upper samples (D6-08 to D6-14), illustrating a trend to a more marine assemblage upsection. Some other observations within these broad trends are summarised below.

D6-01 to D6-07. This lower part of the section contained the most varied (though hardly diverse) terrestrial palynoflora. The predominant *Nothofagidites* (southern beech) pollen considered *in situ* are mainly *N.* spp. (*fusca* group), with *Nothofagidites* species of the *brassii* and *menziesii* groups. Other angiosperm pollen include *Myricipites harrisii* and *M. parvus*, *Peninsulapollis* spp. and *Proteacidites* spp. Some podocarpaceous conifer pollen, *Phyllocladidites* spp. and *Podocarpidites* spp. (Table 3), occur in these lower samples. Other conifer pollen were observed throughout the section, but they were interpreted at the time of scanning as reworked specimens (see Section 4, Methods).

Table 2. Palynomorph concentrations of reworked (Rw) and *in situ* palynomorphs from Polonez Cove and Boy Point formation samples.

Sample name	Elevation (m)	Palynological counts	Concentration of palynomorphs (gdw^{-1}) (Rw)	Concentration of palynomorphs (gdw^{-1}) (in situ)
L-12	55	11	41	9
L-13	48	7	5	4
G-13	46	11	1	1
L-11	43	46	9	20
LHMb	26	101	4	20
LHMb-cb	26*	40	7	10
G8	25	37	73	44
LRx	25	46	8	21
L-6	21	73	11	18
L-5	14	54	4	10
K-1	14	64	15	21
KGLMb-4	7*	95	29	33
KGLMb-3	7*	45	4	18
KGLMb-2	7*	10	7	1
KGLMb-1	7*	0	0	0
G3	5	40	44	117

* Samples from Conglomerate Bluff, with their stratigraphic position shown on the Linton Knoll section.

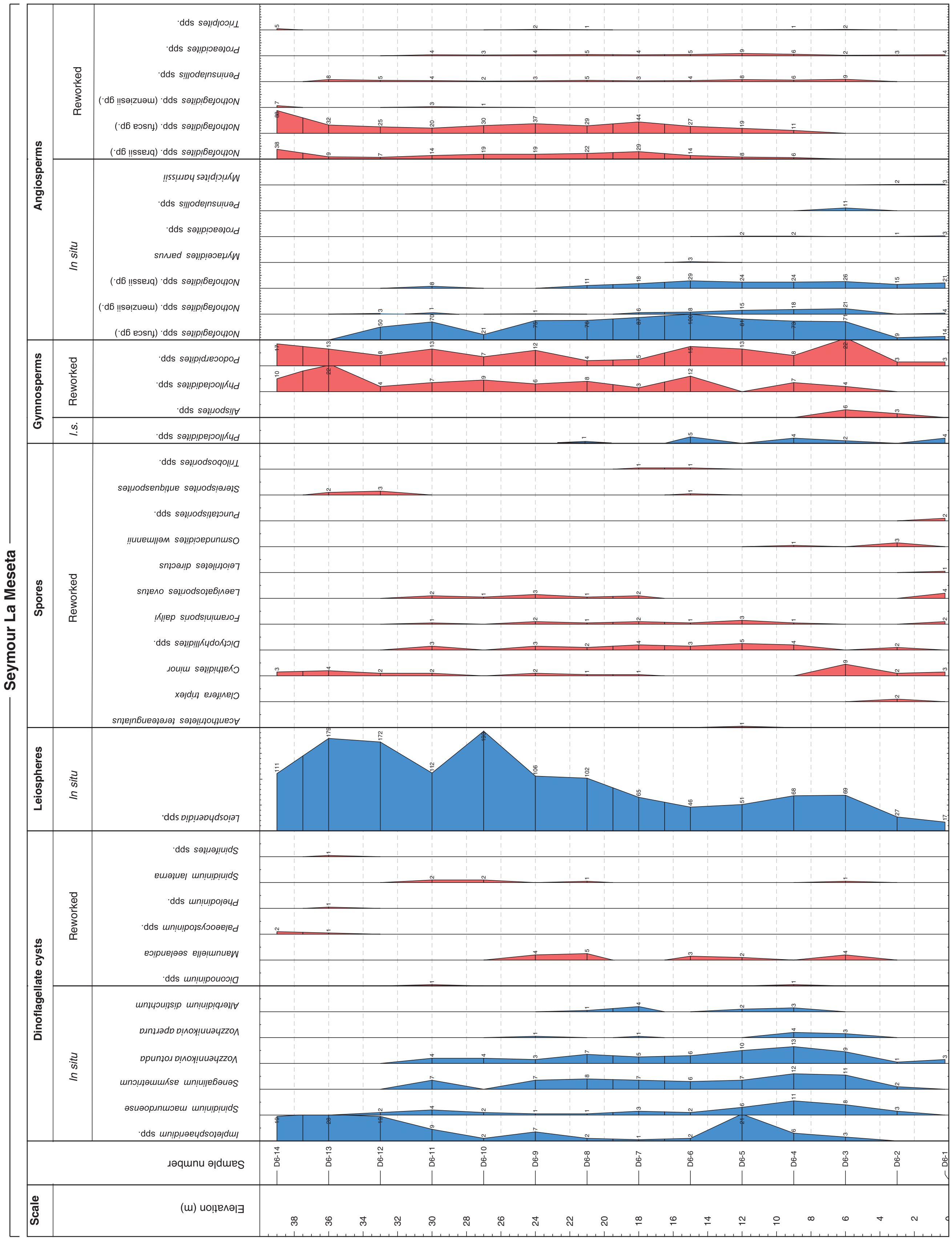

Figure 7. Overall frequency (raw counts) of palynomorph species observed in the La Meseta Formation of Seymour Island; blue = *in situ* and red = reworked.

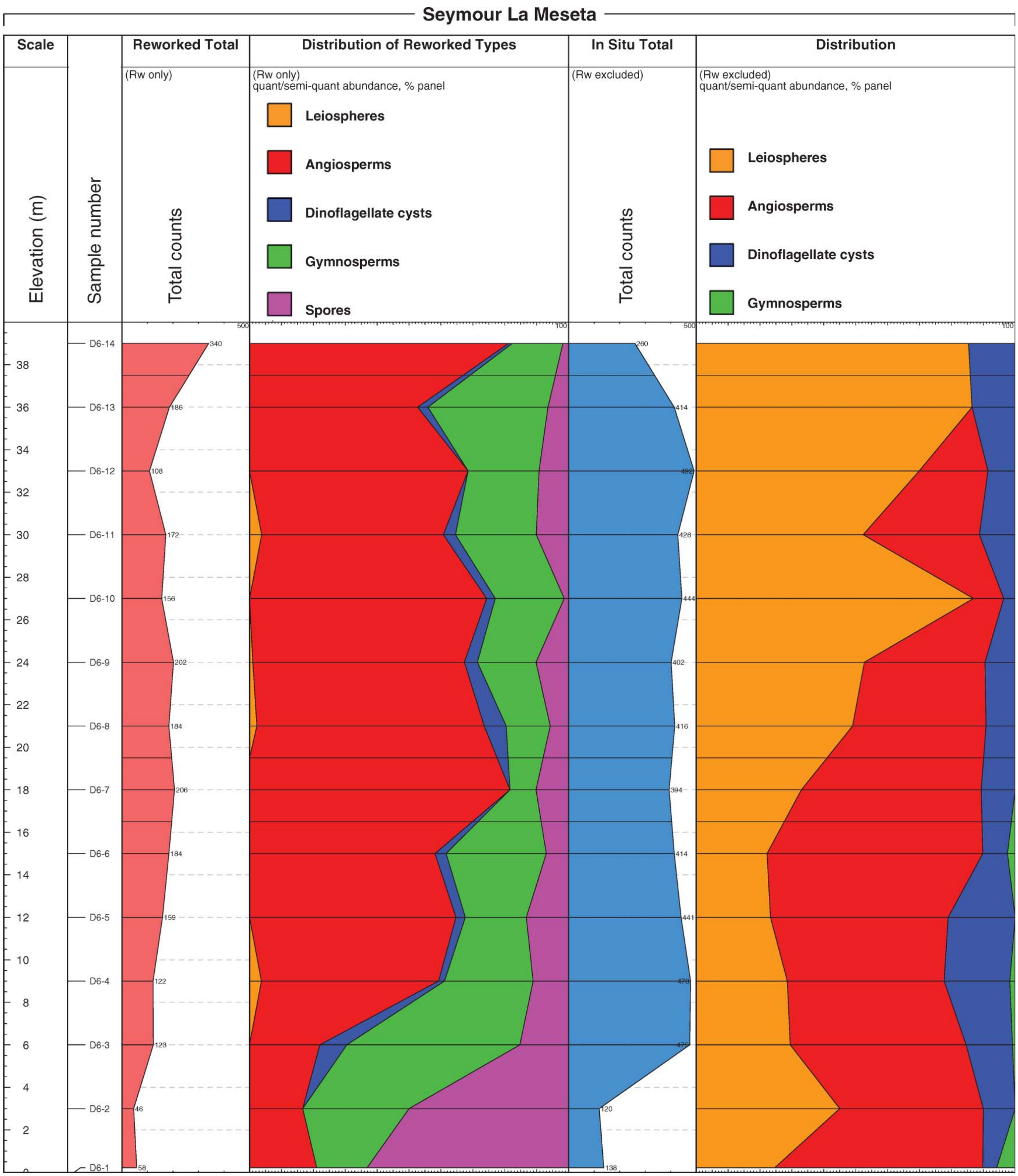

Figure 8. Relative abundance of reworked (Rw) and *in situ* palynomorphs in La Meseta Formation samples.

In the marine dinoflagellate cyst component, taxa typical of the Antarctic Eocene are most common in this part of the section, and a small peak in abundance in *Impletosphaeridium* spp. occurs in sample D6-05.

D6-08 to D6-12. The marine component, which dominates in this part of the section, is marked by increasing numbers of leiospheres, included as the sphaeromorph acritarch *Leiosphaeridia* spp. Dinoflagellate cysts show slight decreases in numbers compared with the underlying part of the section. Diversity has dropped off drastically in the terrestrial assemblage. Apart from the last conifer pollen considered *in situ* in this study in sample D6-08, only pollen of *Nothofagidites* (mainly *fusca* group)

Table 3. Palynomorph counts for the uppermost Eocene D6 section of the La Meseta Formation. Reworked specimens are listed in pink and in situ specimens are listed in blue.

SAMPLE #	DEPTH IN M	Dinoflagellate cysts: *Alterbidinium distinchtum*	*Diconodinium* sp.	*Impletosphaeridium* spp.	*Manumiella seelandica*	*Paleocystodinium* sp.	*Phelodinium* sp.	*Senegalinium asymmetricum*	*Spinidinium lanterna*	*Spinidinium macmurdoense*	*Spiniferites* spp.	*Vozzhennikovia apertura*	*Vozzhennikovia rotunda*	Algae: *Leiosphaeridia* spp.	*Pterospermella australiensis*
D6-14	39			19		2								111	
D6-13	36			28		1	1				1			179	
D6-12	33			19						2				172	
D6-11	30		1	9				7	2	4			4	112	3
D6-10	27			2					2	2			4	193	
D6-9	24			7	4			7		1		1	3	106	1
D6-8	21	1		2	5			8	1	1			7	102	2
D6-7	18	4		1				7		3		1	5	65	
D6-6	15			2	3			6		2			6	46	
D6-5	12	2		21	2			7		6			10	51	
D6-4	9	3	1	6				12		11		4	13	68	2
D6-3	6			3	4			11	1	8		3	9	69	
D6-2	3							2		3			1	27	
D6-1	0												3	17	

SAMPLE #	Spores: *Acanthotriletes tereteangulatus*	*Clavifera triplex*	*Cyathidites minor*	*Dictyophyllidites* spp.	*Foraminisporis dailyi*	*Laevigatosporites ovatus*	*Leiotriletes directus*	*Osmundacidites wellmannii*	*Punctatisporites* sp.	*Stereisporites antiquasporites*	*Trilobosporites* spp.	Gymnosperms: *Alisporites* sp.	*Microcachryidites antarcticus*	*Phyllocladidites* spp.	*Phyllocladidites* spp.	*Podocarpidites* spp.	*Podocarpidites* spp.
D6-14			3												10		17
D6-13			4							2					22		13
D6-12			2							3					4		8
D6-11			2	3	1	2									7		13
D6-10						1									9		7
D6-9			2	3	2	3									6		12
D6-8			1	2	1	1								1	8		4
D6-7			1	4	2	2					1				3		5
D6-6				3	1					1	1			5	12		15
D6-5	1			5	3											3	10
D6-4				4	1			1						4	7	2	6
D6-3			9									6	2	2	4	7	15
D6-2		2	2	2				3				3					3
D6-1			3	2		4	1		2					4			3

SAMPLE #	Angiosperms: *Myricipites harrisii*	*Myrtaceidites parvus*	*Nothofagidites* spp. (*brassii* gp.)	*Nothofagidites* spp. (*brassii* gp.)	*Nothofagidites* spp. (*fusca* gp.)	*Nothofagidites* spp. (*fusca* gp.)	*Nothofagidites* spp. (*menziesii* gp.)	*Nothofagidites* spp. (*menziesii* gp.)	*Peninsulapollis* spp.	*Peninsulapollis* spp.	*Proteacidites* spp.	*Proteacidites* spp.	*Tricolpites* spp.	*Triporopollenites* spp.	Reworking: Reworked Counts Marine	In Situ Counts Marine non sea ice	In Situ Marine sea-ice indicator	Reworked Counts Terrestrial	In Situ Counts Terrestrial
D6-14				38		88		7					5		2	0	130	168	0
D6-13				9		32				8					3	0	207	90	0
D6-12				7	50	25	3			5					0	2	191	54	53
D6-11			8	14	70	20	1	3		4		4		7	6	15	121	80	79
D6-10			0	19	21	30		1		2		3		4	2	6	195	76	21
D6-9			0	19	75	37	1			3		4	2	3	5	12	113	96	76
D6-8			11	22	76	29				5		5	1	5	8	17	104	84	88
D6-7			18	29	87	44	6			3		4		5	0	20	66	103	111
D6-6		3	29	14	100	27	8			4		5		6	3	14	48	89	145
D6-5			24	8	81	19	15			8	2	9		13	2	25	72	76	125
D6-4			24	6	73	11	18			6	2	6	1	8	3	43	74	57	123
D6-3			26		71		21		11	9		2	2	4	5	31	72	53	138
D6-2	2		15		9						1	3		5	0	6	27	23	27
D6-1	3		21		14		4				3	4		10	0	3	17	29	49

are the in situ species.

are the reworked species.

are considered to be penecontemporaneous with deposition.

D6-13 and D6-14. These upper two assemblages are entirely marine and composed mainly of leiospheres along with the small chorate dinoflagellate cyst *Impletosphaeridium* spp. This latter form fluctuates in abundance through the section above sample D6-02, reaching a peak in sample D6-13. No other *in situ* dinocysts or any *in situ* terrestrial components were observed. There is no change in total frequencies of specimens recovered compared with the underlying part of the section (Table 1).

5.2. Palynological results from the Polonez Cove Formation and Boy Point Formation

Unlike most of the La Meseta Formation samples, Polonez Cove and Boy Point Formation samples contain very few palynomorphs (Table 2). The overall number of identifiable palynomorphs observed is summarised in Figure 9, our interpretations of *in situ* vs. reworked specimens are given in Figure 10, and counts are given in Table 4. The listed samples are from the Krakowiak Glacier Member (KGM), Bay View Member (BM), Low Head Member (LHM), and the Chlamys Ledge Member (CLM) of the Polonez Cove Formation (listed from oldest to youngest), and from the lower Boy Point (BP) Formation (Figure 6).

The concentrations of total *in situ* palynomorphs ranged from 0 to 117 per gramme of dried sediments, and the concentrations of reworked palynomorphs ranged from 0 to 73 per gramme of dried sediments (Table 2), which is substantially lower than concentrations of up to 2000 recovered palynomorphs from the late Oligocene 12A section (Figure 1(B)) sampled by the SHALDRIL programme off the Antarctic Peninsula (Warny & Askin 2011b). Many of the latter samples contained higher proportions of fine-grained carbonaceous material and thus likely more palynomorphs, as well as being deposited in a marine environment more conducive to palynomorph deposition than the diamictites and volcanobreccias of the Polonez Cove samples.

There were no age-diagnostic marine *in situ* palynomorphs observed in these samples. Radiometric dating for these beds is outlined in Section 2.2 (Geological setting). Leiospheres dominate in these very sparse assemblages, typically in overwhelming abundance. Of the non-leiosphere fraction, most specimens are reworked (~85% of the non-leiosphere fraction). Many reworked specimens are of such high thermal maturity that they are unidentifiable, and thus are not included in any counts. The identifiable reworked assemblages, readily differentiated from *in situ* by their darker exines, are of possible Jurassic but mainly Cretaceous and Paleogene age, and include rare dinoflagellate cysts and fluctuating proportions of terrestrial cryptogam spores, podocarp conifer pollen and various angiosperm pollen (Figures 9 and 10; Table 4).

The *in situ* assemblage throughout the Polonez Cove Formation and Boy Point Formation composite section is notable for its extreme lack of diversity, being composed almost entirely of the marine sphaeromorph acritarchs *Leiosphaeridia* spp. The few exceptions to this observation in the Polonez Cove Formation (see Table 4) include the following.

- A few specimens of terrestrial angiosperm pollen *Chenopodipollis* sp. occur in the basal KGM (sample G- 3, from a marine lodgement till, Figure 6), and in the LHM (samples G-8, LHMb-cb (Conglomerate Bluff), LHMb),

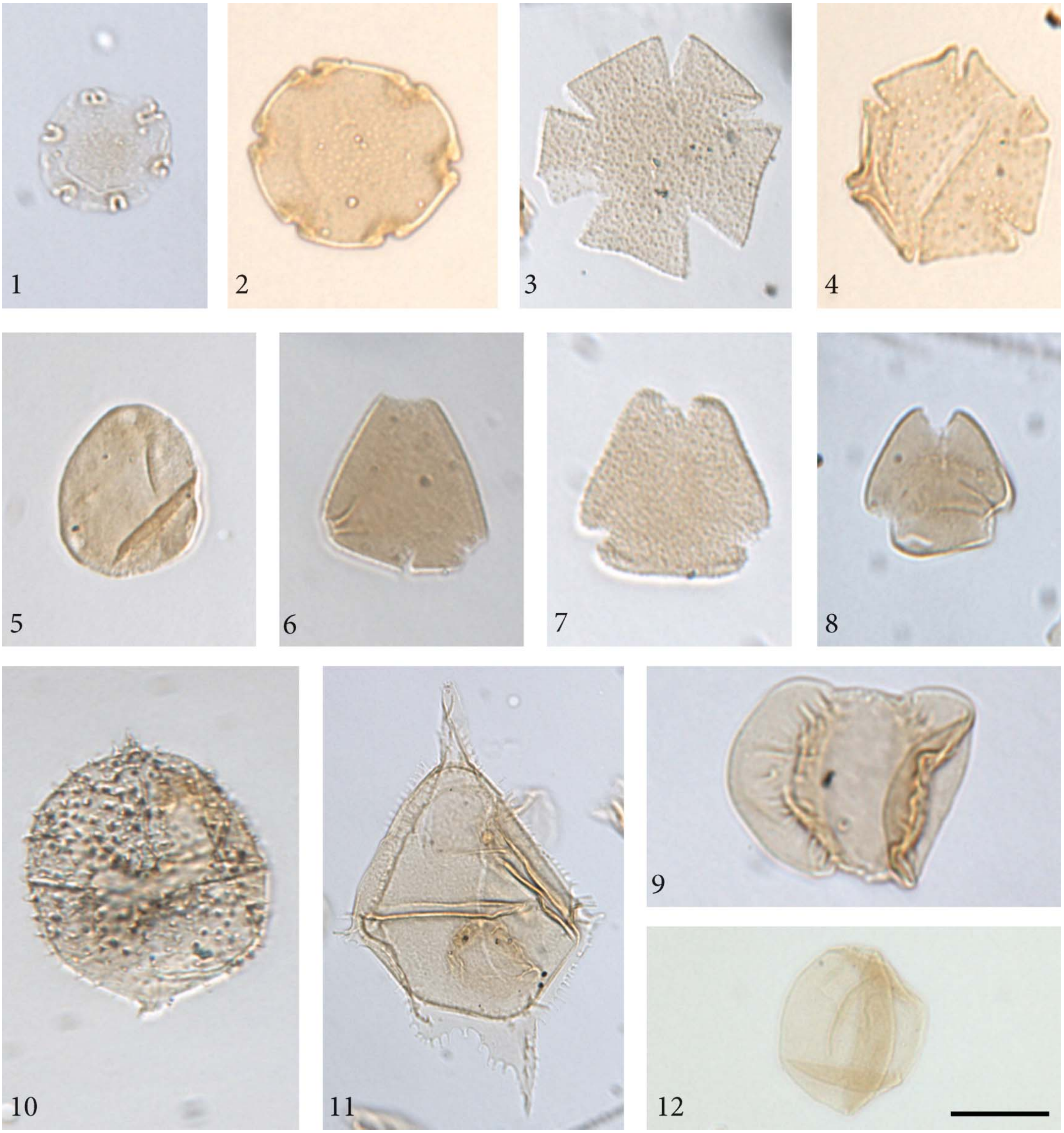

Plate 1. Light photomicrographs of palynomorphs considered *in situ*. Images 1–11 are from the La Meseta Fomation, Seymour Island, and 12 is from the Polonez Cove Formation, King George Island. **1–4. Various beech pollen grains: 1–2**. Fusca group: *Nothofagidites rocaensis-saraenesis* complex (1. sample D6-09 16.2 × 139.1; 2 sample D6-08 15.9 × 141.7); **3.** Menziesii group: *Nothofagidites* sp. cf. *N. asperus* (sample D6-11 15.5 × 117.5), **4.** Brassii group: *Nothofagidites mataurensis* (sample D6-05 4.1 × 143.5). **5–8. Other angiosperms: 5.** *Myricipites harrisii* (sample D6-01 14.2 × 119.4), **6.** *Proteacidites* sp. cf. *P. parvus* (sample D6-01 13.4 × 143.9), **7.** *Peninsulapollis askiniae* (sample D6-03 16.2 × 147.3), **8.** *Peninsulapolis gillii* (sample D6-03 3.4 × 144.4). **9. Gymnosperm:** *Phyllocladidites* sp. cf. *P. exiguus* (sample D6-08 13.3 × 147.6). **10–12. Marine palynomorphs: 10.** *Vozzhennikovia rotunda* (sample D6-01 6.3 × 117.8), **11.** *Spinidinium macmurdoense* (sample D6-12 14.6 × 144.9), **12.** *Leiosphaeridia* sp. (Sample G-13 12.1 × 141.0). All images were taken at 60× under oil immersion. Scale bar = 20 μm.

- There are rare occurrences of podocarp conifer pollen (*Phyllocladidites* spp. and *Podocarpidites* spp.) in the lower part of the section (samples G3 and L-6),
- Scattered occurrences of *Nothofagidites* spp. (*fusca* group) were observed in the basal KGM (sample G-3), in the upper glacimarine KGM (samples K1, L5), and in some of the volcaniclastic marine samples of the BM (sample L-6), LHM (sample G-8) and CLM (sample L-11),
- The highest abundance of leiospheres was encountered in the LHM (sample LHMb), and the dinocyst *Impletosphaeridium* spp. occurs near the top of the Polonez Cove Formation in the CLM (sample L-11).

Table 4. Palynomorph counts from Polonez Cove and Boy Point formation samples. Reworked specimens are listed in pink and in situ specimens are listed in blue.

			Dinoflagellate cysts					Spores				Gymnosperms				Angiosperms										Reworking				
MEMBER/FORMATION	SAMPLE NAME	Sample #	*Deflandrea* spp.	*Diconodinium* sp.	*Impletosphaeridium* spp.	*Odontochitina* spp.	*Leiosphaeridia* spp.	*Calamospora* spp.	*Cyathidites minor*	*Dictyophyllidites* spp.	*Stereisporites antiquasporites*	*Alisporites* sp.	*Microcachryidites antarcticus*	*Phyllocladidites* spp.	*Podocarpidites* spp.	*Chenopodipollis* spp.	*Haloragacidites* spp.	*Myricipites* spp.	*Nothofagidites* spp. (*brassii* gp.)	*Nothofagidites* spp. (*fusca* gp.)	*Nothofagidites* spp. (*fusca* gp.)	*Peninsulapollis* spp.	*Proteacidites* spp.	*Tricolpites* spp.	*Triporopollenites* spp.	Reworked Counts Marine	In Situ Counts Marine **non** sea ice	In Situ Marine sea-ice indicator	Reworked Counts Terrestrial	In Situ Counts Terrestrial
BP	L-12	16					2	1				1		2				1							4	0	0	2	9	0
	L-13	15					3								2									1	1	0	0	3	4	0
CLM	G-13	14					4		2						2						1	1			1	0	0	4	7	0
	L-11	13			3		27				4				4		2			2	7					0	0	30	17	2
LHM	LHMb	12					83			1				3	4	1		1			6				2	0	0	83	17	1
	LHMb-cb	11					22		1			2			3	1	2	1			2			1	5	0	0	22	17	1
	G8	10				1	13								6	3	2			1	7				4	1	0	13	19	4
	LRx	9					34		2					2	4						3	1				0	0	34	12	0
BM	L-6	8	1				42			2				3	5				5	2	8		3		2	1	0	42	28	2
KGM	L-5	7					39		2			1			6			2		1					3	0	0	39	14	1
	K-1	6					31	1	9	2					3					2	11			4		0	0	31	30	2
	KGLMb-4	5		1			51					3		21					3		11			4	1	1	0	51	43	0
	KGLMb-3	4					37					2			1						5					0	0	37	8	0
	KGLMb-2	3					1				2				5						2					0	0	1	9	0
	KGLMb-1	2					0																			0	0	0	0	0
	G3	1				2	10		1				2		7	3	2	2		5				4	2	2	0	10	20	8

are the in situ species.

are the reworked species.

KGM = Krakowiak Glacier Member; BM = Bay View Member; LHM = Low Head Member; CLM = Chlamys Ledge Member; BP = Bay Point Formation.

The two assemblages from the basal Boy Point Member are very sparse, consisting of a few leiospheres. No *in situ* terrestrial material was observed.

6. Discussion

6.1. Uppermost La Meseta Formation

6.1.1. Terrestrial vegetation

Amongst the terrestrial component, *Phyllocladidites* spp. and *Podocarpidites* spp. represent southern podocarp conifers which, together with the southern beech *Nothofagidites* spp. (*fusca* gp.) and *Nothofagidites* spp. (*menziesii* gp.), thrive in cool temperate humid climates (Veblen et al. 1996; Farjon 2010). As noted in Section 4 (Methods), the penecontemporaneous nature of *Nothofagidites* spp. (*brassii* gp.) through this section is equivocal. Thus, for the lower D6 section of this La Meseta data-set, we can infer the environment was comparable to the cool temperate Valdivian-type forest found in parts of modern-day Chile, as described in Veblen et al. (1996), although the diversity of the recovered La Meseta assemblages is somewhat lower. Podocarp conifer pollen interpreted as *in situ* were not observed above sample D6-08, and above this level the only woody taxa were *Nothofagidites* spp. These too disappeared before the upper two samples. This conclusion, however, assumes correct reworked vs. *in situ* interpretations. We note that Chen (2000) reported *Nothofagidites* spp. in sample D6-13, and Askin (unpublished data) recorded apparently *in situ* podocarp conifer and *Nothofagidites* pollen in both samples D6-13 and D6-14, albeit very sparse in the upper sample. Overall, the frequency and relative abundance of terrestrial pollen decrease towards the top of the section, which suggests deteriorating climatic conditions (also considering the other palynomorph data noted below) and possibly a shift from forest to more stunted woodland-shrubby trees surviving in colder temperatures. The composition of the latest Eocene pollen record is ambiguous, but if penecontemporaneous, the presence of woody plants suggests that land temperatures remained above the ~10 °C January mean that delimits the modern austral polar-alpine treeline (Raine 1998; Körner and Paulsen 2004).

6.1.2. Marine and sea-ice influence

Small numbers of the typical Eocene dinocysts *Senegalinium asymmetricum*, *Spinidinium macmurdoense* and *Vozzhennikovia* spp. occur through much of the section, becoming less frequent upsection. These *in situ* dinoflagellates died out near the top of the section, coincident with an increase in the small dinocyst *Impletosphaeridium* spp. and great abundance of leiospheres. The leiospheres, assigned to *Leiosphaeridia* spp., a group usually associated with sphaeromorph acritarchs, are known to be abundant at the limit between pack ice and sea ice (Mudie 1992; Troedson & Riding 2002; Warny et al. 2006). Similar to *Leiosphaeridia* spp., *Impletosphaeridium* spp. are believed to be present during sea-ice formation (Warny et al. 2007).

6.1.3. Environmental trends

Several simultaneous trends in environmental indicators are evident in the upper part of the section, from sample D6-08 to the top. Approaching the end of the Eocene, the data include a dearth of penecontemporaneous terrestrial palynomorphs, the overwhelming abundance of *in situ* sea-ice-indicative leiospheres, increased numbers of sea-ice-indicative *Impletosphaeridium* spp., decreasing numbers of other *in situ* dinoflagellates, and towards the top an increasing relative abundance of reworked specimens. Together these imply a less

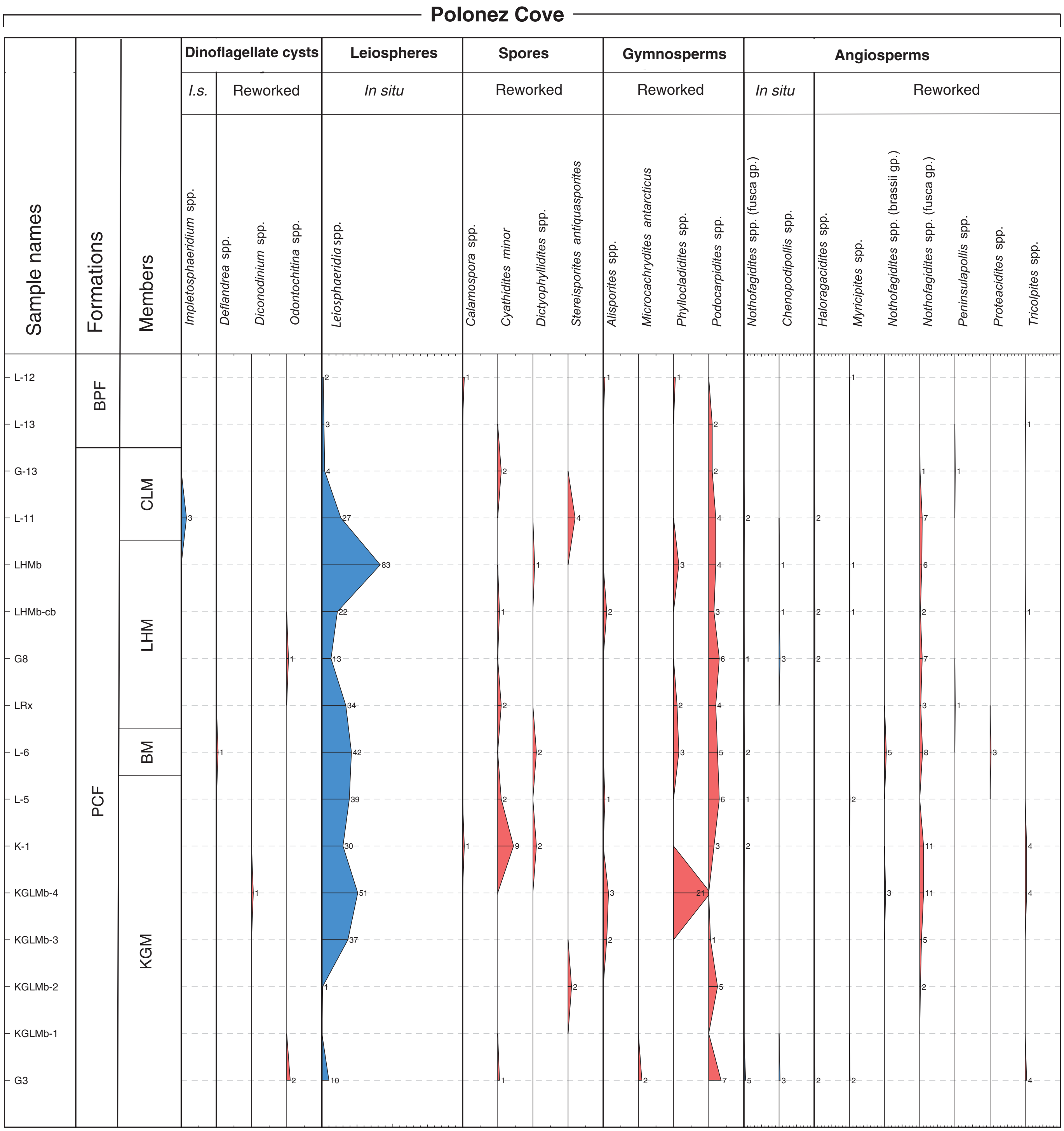

Figure 9. Overall frequency (raw counts) of palynomorph species observed in the Polonez Cove and Boy Point samples from King George Island. For details about the position of samples in relation to the formations and sampled members, see Figure 6. Blue = *in situ* and red = reworked.

vegetated, more glacially dominated environment for the uppermost part of the La Meseta Formation.

Our data corroborate the marine latest Eocene temperature record for Seymour Island (e.g. Dutton et al. 2002; Ivany et al. 2006, 2008), and echo the marked cooling at the EOT in the Zachos et al. (2008) δ^{18}O curve. This trend was also evidenced by the microtexture analysis of sand grains (Anderson et al. 2011) from D6 samples (D6-03, D6-05, D6-07) which revealed high-stress glacially induced surface textures from relatively low (<33%) occurrence, compared with younger, more glacially influenced sediments from the area, to medium abundance higher in the section. This analysis supported encroaching glacial activity in the vicinity in the latest Eocene. By the EOT, the presence of glacial ice was also indicated by the Ivany et al. (2006) report of diamict at the Eocene–Oligocene boundary on Seymour Island.

Interestingly, the Late Eocene palynomorph assemblages described from SHALDRIL II 3C sediment cores offshore and

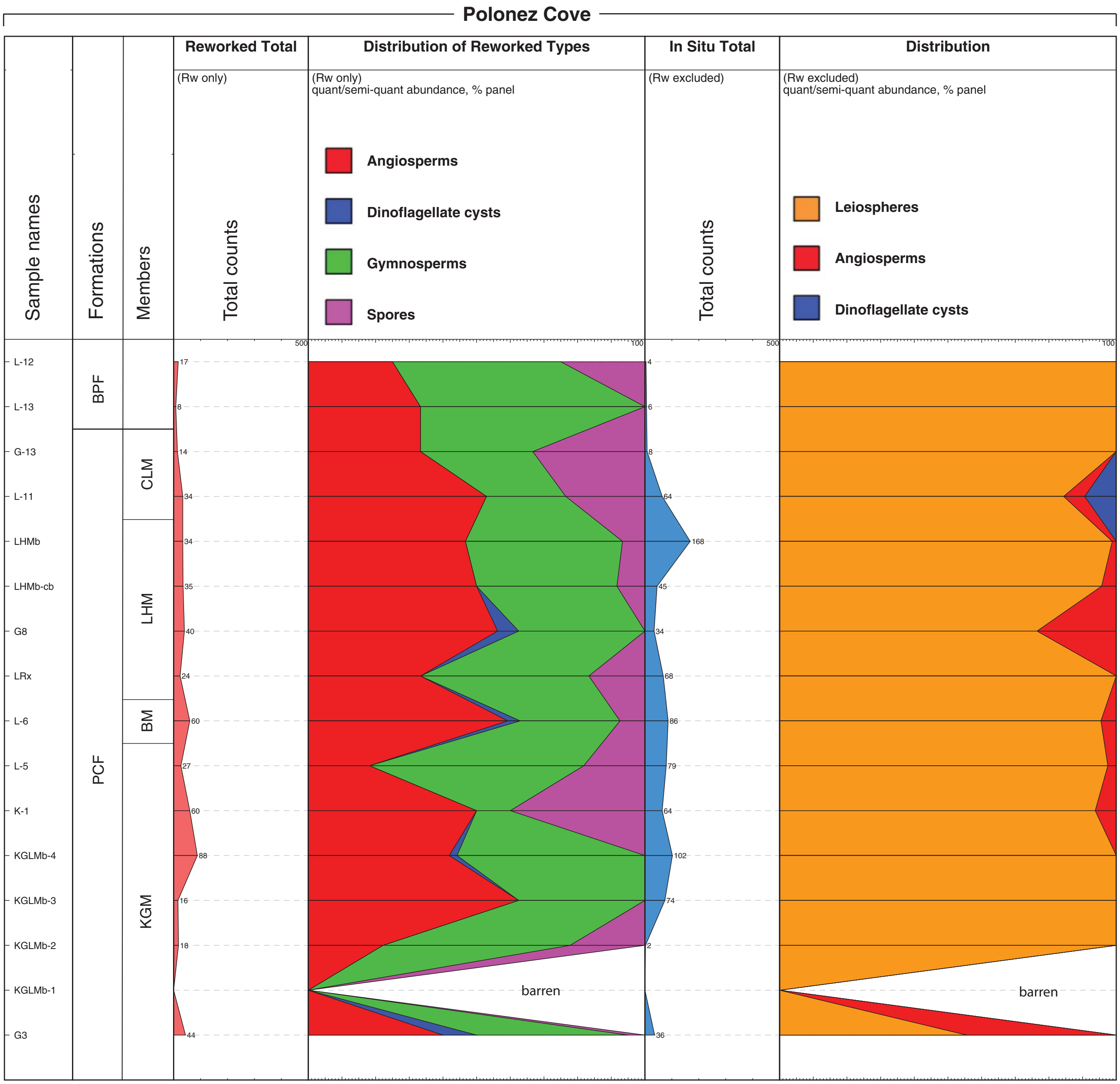

Figure 10. Relative abundance of reworked (Rw) and *in situ* palynomorphs in Polonez Cove and Boy Point Formation samples. For details about the position of samples in relation to the formations and sampled members, see Figure 6.

north-east of Seymour Island (Warny & Askin 2011a) may actually predate at least the upper D6 samples, rather than postdate the youngest La Meseta Formation sediments as concluded by Anderson et al. (2011) based on seismic evidence. Diatom stratigraphy placed the 3C cores between 37 and 32 Ma, and a strontium date halfway through the 3C composite section provided an age of 35.9 Ma (Bohaty et al. 2011). Both the marine and terrestrial 3C assemblages were more diverse and more abundant (see Section 5.1) than those encountered in the latest Eocene Seymour D6 samples, and the more refined chronostratigraphy for the top of the La Meseta Formation, as discussed in Section 2, supports this contention. Furthermore, although the upper 3C assemblages record significant cooling and a sea-level drop with an increase in erosion and reworking (Warny & Askin 2011a), these 3C samples lack the abundant sea-ice-indicative leiosphere acritarchs, and thus suggest sea-ice was not yet widespread during their deposition. This is in agreement with temperature data reconstructed by Feakins et al. (2014), who modeled leaf wax hydrogen isotopic evidence from the SHALDRIL II 3C sediments and combined their results with the pollen data of Warny & Askin (2011a). Their δD and modeling show cooling and drying conditions during that latest Eocene time, but with temperatures remaining above freezing, from ca. 7 to 2 °C and precipitation around 700 to 600 mma^{-1} with an isotopic shift in δD of about $-15‰$.

6.2. Polonez Cove Formation and Boy Point Formation

6.2.1. Terrestrial vegetation

Our sampling on King George Island covers a period from Early to Late Oligocene. Farther west on King George Island, the Cytadela flora of the Point Thomas Formation, previously thought to be of Early Oligocene age (e.g. Birkenmajer & Zastawniak 1989), is now believed to represent preglacial Eocene vegetation (Mozer 2012, 2013). In addition, the various Point Hennequin floras in the Mount Wawel Formation, previously thought to be of Late Oligocene age (Birkenmajer & Zastawniak 1989), are now included in the Eocene (Hunt & Poole 2003; Nawrocki et al. 2011; Mozer 2013). This is also the case for several other flora sites on King George Island (Mozer et al. 2015). Thus, the current study provides important new information on the Oligocene vegetation.

The Oligocene sections studied from the Polonez Cove Formation indicate that by that time, on the west side of the Antarctic Peninsula, vegetation was reduced to a sparse tundra flora consisting of a few herbaceous plants with rare podocarp conifers in the lower section and some southern beech. The woody beech plants were probably of prostrate habit, surviving in sheltered locations in severe conditions (e.g. Francis & Hill 1996; Raine 1998; Askin & Raine 2000). Although occasional *in situ* terrestrial pollen were observed, the vast majority of the terrestrial palynomorphs in the Polonez Cove samples were reworked, which is consistent with advanced ice sheet expansion, and ice erosion and transport on the Peninsula related to the Polonez Glaciation.

6.2.2. Sea-ice influence

As evidenced by the overwhelming dominance of leiospheres in most of our samples, plus some *Impletosphaeridium* spp. in one sample, sea ice persisted in the waning stages of the Polonez Glaciation, during deposition of the upper KGM and overlying shallow marine, glacially influenced (at least for the lower samples), and basaltic volcanism-dominated BM, LHM and CLM, and lowermost BP Formation.

6.2.3. Environmental trends and volcanism

Figures 9 and 10 highlight how the overall abundance, diversity and preservation of palynomorphs have diminished compared to those of La Meseta Formation. The lower Polonez Cove samples from the KGM represent sediments deposited during the Polonez Glaciation, with palynomorphs from the sea-ice flora and a few pollen from a very sparse periglacial terrestrial flora. The Antarctic periglacial tundra vegetation that survived from the EOT, and through the Oligocene and Miocene, in non-glaciated locations has been described from SHALDRIL cores off Seymour Island (Anderson et al. 2011; Warny & Askin 2011b) and from as far away as the southern Victoria Land margin of the Ross Sea (e.g. Raine 1998; Askin & Raine 2000; Raine & Askin 2001; Feakins et al. 2012; Greiner et al. 2015). Compared to these other records, the vegetation recovered from the Polonez Cove Formation was even sparser. Our data imply that local terrestrial vegetation barely survived through the Polonez Glaciation. The palynological record suggests conifers are present only in the lower part of the section. Southern beech fared a little better with their interpreted *in situ* record extending up into the late Oligocene top of the Polonez Cove Formation. Because of the scarcity of unambiguous terrestrial remains, we refrain from making comparisons to modern climate parameters (temperatures, etc.). The only recovered record of herbaceous plants considered *in situ* is pollen of Chenopodiaceae, a group that evidently survived well into the Neogene in the Antarctic Peninsula area (Warny & Askin 2011b). This great dearth of local vegetation is hardly surprising, considering the plants had to contend with numerous episodes of local volcanism as well as glacial climates and ice. The presence of Chenopodiaceae and very little else is consistent with these harsh conditions, as today these are typically weedy plants that are well adapted to disturbed and chemically challenging soils.

Farther to the east on King George Island, it seems that at least some vegetation regained a foothold in the region as it emerged from the worst of the volcanism. From the Destruction Bay Formation, of Late Oligocene age (25.3 Ma, Dingle & Lavelle 1998), Troedson & Riding (2002) described a 'moderately diverse' assemblage with abundant pollen of *Nothofagidites* spp. (*fusca* group), with, among other taxa, some podocarp pollen and *Cyathidites* (fern) spores, plus dinoflagellate cysts. Sparse, low-diversity assemblages of mainly podocarp pollen, with a few *Nothofagidites* pollen, *Cyathidites* and indeterminate spores, plus dinocysts, were reported by Troedson & Riding (2002) from the early Miocene Cape Melville Formation. Also from the early Miocene Cape Melville Formation, the *in situ* palynoflora described by Warny et al. (2016) contained *Nothofagidites* spp. (*fusca* group), rare podocarp pollen, moss spores (*Coptospora*), and pollen of Asteraceae, Caryophyllaceae (*Colobanthus*-type) and Chenopodiaceae. These assemblages, from sediments deposited during the Melville Glaciation, are somewhat richer in diversity than the Polonez assemblages and represent a periglacial tundra flora with components common to other Antarctic Miocene tundra assemblages (Warny et al. 2016).

Nearby, to the east of the tip of the Antarctic Peninsula, there are palynomorph assemblages of Late Oligocene age (24.0–28.6 Ma from diatom biostratigraphy, Bohaty et al. 2011) from the SHALDRIL II 12A sediment cores. Palynomorph concentrations, however, are substantially less at Polonez Cove and the terrestrial flora is far less diverse than that described from the 12A cores (Warny & Askin 2011b). Probably, as noted above, the intermittent volcanism has caused this dearth of terrestrial vegetation on the northern Antarctic Peninsula magmatic arc. On both sides of the northernmost peninsula the marine component is dominated by a sea-ice acritarch flora, but with a difference. The Polonez Cove samples are dominated by *Leiosphaeridia* spp., and the 12A samples by a *Micrhystridium/Leiosphaeridia* association, with the former acanthomorph acritarchs typically more common except for the uppermost two 12A samples where the leiospheres predominate. We note that the dinocyst *Impletosphaeridium* and the acritarch *Micrhystridium* are morphologically similar and likely occupied similar ecological niches. It is possible that the difference comes from the fact that the Polonez Cove samples are from a nearshore depositional site with closer proximity to glaciers and their freshwater outwash, while the SHALDRIL II 12A samples were from a more marine palaeoenvironment, albeit within a partly land-locked back-arc basin.

7. Conclusions

Palynomorph assemblages from the La Meseta Formation on Seymour Island, and from the Polonez Cove and Boy Point formations on King George Island, provide insight into latest Eocene and Oligocene climatic evolution in the northern Antarctic Peninsula. La Meseta Formation assemblages capture a small slice of time at the end of the Eocene, recording the shift from cool temperate, humid Valdivian-type forest to a more depauperate vegetation. This was accompanied by a decrease in typical Eocene dinoflagellate cysts, an increase in sea-ice-indicative marine phytoplankton, and an increase in reworked palynomorphs. We suggest these palynofloras record a shift from cool temperate to periglacial conditions and a subpolar climate just before the EOT boundary in the back-arc James Ross Basin.

By the early to late Oligocene, on the other side of the Antarctic Peninsula, land vegetation had been decimated by both glaciation and volcanism in the northern Antarctic Peninsula magmatic arc. The terrestrial palynomorph assemblage is mostly reworked and penecontemporaneous traces of terrestrial vegetation are sparse. We believe the apparent record of extremely reduced vegetative cover at this time is overprinted by regional volcanism and cannot be accurately used as an indicator of climate. The marine palynoflora does, however, indicate the presence of sea ice and thus a polar to subpolar climate.

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Disclosure statement

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