

1 How likely was a green Antarctic Peninsula during warm Pliocene interglacials? A critical  
2 reassessment based on palynofloras from James Ross Island

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17

18 ABSTRACT

19

20 The question whether Pliocene climate was warm enough to support a substantial vegetation  
21 cover on Antarctica is of great significance to the ongoing and controversial debate on the  
22 stability or dynamism of Antarctic ice sheets during warm periods with high greenhouse gas  
23 concentrations. Here we present a systematic palynological comparison of pollen and  
24 dinoflagellate cyst assemblages from Early Pliocene diamictites collected from the northern  
25 and eastern Antarctic Peninsula. The sedimentary successions are exceptionally well dated  
26 using a combination of <sup>40</sup>Ar/<sup>39</sup>Ar and <sup>87</sup>Sr/<sup>86</sup>Sr isotope analyses on interbedded lavas and  
27 pristine bivalve molluscs. Well-preserved pectinid shells and cheilostome bryozoans suggest  
28 that the palynomorph-bearing sediments were deposited during warmer Pliocene  
29 interglacials. The palynological analyses presented here do not identify any *in-situ* pollen and  
30 spores which indicate the presence of substantial vegetation cover. Direct comparisons  
31 between palynomorph assemblages of Pliocene diamictites and the underlying Cretaceous  
32 succession, which included fluorescence microscopy, show that most of the palynomorphs  
33 are reworked from Upper Campanian and Lower Maastrichtian sediments. Our study

34 suggests a local provenance for most of the Hobbs Glacier diamictites, whilst sediments at  
35 the western coast might have been produced by ice sheets from the Antarctic Peninsula. The  
36 presence of the acritarch *Leiosphaeridia* indicates sea-ice during Pliocene interglacials with  
37 summer sea surface temperatures ranging from -2 to +5°C. Whilst this implies near modern  
38 climate conditions during the Late Neogene, the presence of the dinoflagellate cyst  
39 *Bitectatodinium tepikiense* at one location suggests that sea surface temperatures might have  
40 been substantially warmer during some interglacials. The absence of *in-situ* pollen and spores  
41 in the James Ross Island diamictites cannot be taken as proof of non-existent vegetation.  
42 However, this paper presents indirect multiple proxy evidence which makes the presence of a  
43 substantial Pliocene vegetation cover on James Ross Island unlikely and supports previous  
44 reconstructions of a permanent ice sheet on the West Antarctic Peninsula throughout the Late  
45 Neogene.

46

47 *Keywords:* Pliocene; Antarctica; vegetation; palynomorphs; Neogene; sea ice.

48

## 49 **1. Introduction**

50

51 A recent research focus has been on polar regions which may experience  
52 environmental conditions similar to those of the warm interglacial periods of the Pliocene (ca.  
53 5.3 to 2.6 Ma ago) towards the end of this century (IPCC, 2007; Salzmann et al., 2009; Lunt  
54 et al., 2010). During the Pliocene, global mean annual surface temperature was about 2-3°C  
55 higher than pre-industrial levels (Haywood et al., 2000) with elevated atmospheric CO<sub>2</sub>  
56 concentrations ranging between 270 and 450 ppmv (Pagani et al., 2010; Seki et al., 2010).  
57 This warming was particularly accentuated at high latitudes. For the Canadian high Arctic,  
58 recent multi-proxy studies suggest Pliocene mean annual temperatures were about 19 °C  
59 warmer than at present (Ballantyne et al., 2010). In contrast to the Arctic, Pliocene  
60 palaeoenvironmental reconstructions of the southern polar regions are scarce and there is a  
61 great uncertainty in estimating the magnitude of temperature increase and ice sheet extent  
62 during the warm interglacials of the Neogene. Antarctica holds by far the largest amount of  
63 freshwater on Earth. Given current climate concerns, it is of vital importance to understand  
64 how southern polar environments and ice sheets responded and might respond in the future to  
65 increasing temperatures under high greenhouse gas concentrations.

66 This paper presents palynological analyses of exceptionally well dated, Early Pliocene  
67 to Late Miocene samples from the Antarctic Peninsula located at the northernmost edges of  
68 the Antarctic Ice Sheet (Fig.1). Due to its geographical position and topography, the  
69 Peninsula environment is very sensitive to climate change and temperatures have risen  
70 rapidly throughout the last decades resulting in a recent substantial thinning of the West  
71 Antarctic Ice Sheet (Vaughan et al., 2003; Pritchard et al., 2009; Steig et al., 2009). For the  
72 Middle Miocene (ca. 14 Ma), multiple palaeoecological proxies suggest that East Antarctica  
73 was still warm enough to support a substantial tundra vegetation in coastal regions, before  
74 further cooling brought a full polar climate to this region (Lewis et al., 2008; Williams et al.,  
75 2008; Warny et al., 2009). However, despite further rapid cooling, temperatures during  
76 Pliocene interglacials might still have been warm enough to cause a substantial reduction in  
77 sea-ice cover (e.g. Hillenbrand and Ehrmann, 2005) and fluctuation of the West Antarctic ice  
78 sheet (Naish et al., 2009), which might have collapsed during the maxima of Pliocene warmth  
79 (Pollard and DeConto, 2009). Pliocene vegetation reconstructions based on climate models  
80 indicate the presence of woody *Nothofagus*-dominated tundra shrub vegetation in coastal  
81 regions of Antarctica during Pliocene warm periods (Fig.1, Salzmann et al., 2008). However,  
82 palaeobotanical data which could support these model simulations are extremely scarce. Most  
83 uncertainties in reconstructing Pliocene Antarctic vegetation are caused by the dynamic  
84 origin of sedimentary deposits which have been disturbed and reworked through glacial  
85 transport. Reworking strongly hampers an unambiguous identification of *in-situ* material  
86 which provoked controversial debates about existing Pliocene environmental reconstructions  
87 and dating using age-diagnostic microfossils (Francis and Hill, 1996; Stroeven et al., 1996;  
88 Harwood and Webb, 1998; Wilson et al., 2002).

89 The aim of this paper is to test whether the Antarctic Peninsula was covered by a  
90 substantial vegetation cover during warm Pliocene interglacials. We present a systematic  
91 analysis and comparison of palynomorph assemblages from Pliocene diamictites taken from  
92 coastal, ice-free regions of James Ross Island, northern Antarctic Peninsula, (Fig. 1, Nelson  
93 et al., 2009). Well-preserved bivalve shells and interbedded lavas allow an exceptionally  
94 good dating control via  $^{40}\text{Ar}/^{39}\text{Ar}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope analyses (Smellie et al., 2006; Smellie  
95 et al., 2008). To distinguish between *in-situ* and reworked material, we compare Neogene and  
96 underlying Cretaceous sediments using a multi-method approach, including:

97 a) fluorescence microscopy to identify taphonomic histories (e.g. van Gijzel, 1967; Yeloff  
98 and Hunt, 2005)

- 99 b) colour and preservation of palynomorphs to identify thermal maturation (e.g. Pirrie et al.,  
100 1997; Prebble et al., 2006b)
- 101 c) age indicative dinoflagellate cysts (e.g. Troedson and Riding, 2002; Williams et al.,  
102 2004)
- 103 d) potentially age indicative acritarchs (e.g. Hannah, 2006; Warny et al., 2006; Warny et al.,  
104 2007)
- 105 e) potentially age indicative ratio of pollen taxa (Fleming and Barron, 1996)

106

107 The paper presents both a reconstruction of the Neogene environmental history of  
108 James Ross Island and a systematic feasibility study of different methods previously applied  
109 in Antarctic palynological studies.

110

## 111 **2. Geographical setting and previous work on the Pliocene of James Ross Island**

112

113 James Ross Island is a volcanic island located on the eastern side of the northern  
114 Antarctic Peninsula (Fig. 1). The island is occupied by a large central polygenetic shield  
115 volcano which is covered by a 200-400 m thick ice cap rising to more than 1600 m a.s.l.  
116 (Nelson et al., 2009). The regional stratigraphy is characterised by 5 km of marine  
117 volcanoclastic sediments of the James Ross Basin comprising a stratigraphical succession of  
118 Jurassic deep marine mudstones at its western margins, overlain by Lower Cretaceous to  
119 Upper Eocene back-arc basin sediments (e.g. Pirrie et al., 1992). Neogene glaciomarine  
120 sediments unconformably overlie Cretaceous sediments, or are interbedded within extensive  
121 basaltic lavas of the James Ross Island Volcanic Group (JRIVG). The Neogene diamictites  
122 sampled here belong to the Hobbs Glacier Formation of Pirrie et al. (1997), and are exposed  
123 at the low-lying, ice-free regions of the northern and eastern coasts of James Ross Island (Fig.  
124 1a; Smellie et al., 2006). The diamictites were deposited as debris flows presumably close to  
125 the grounding-line of marine-terminating glaciers. A full explanation of the stratigraphy and  
126 geology for each sample site was given by Nelson et al. (2009).

127

128 Samples from Forster Cliff, Cascade Cliff, Pecten Spur and Ekelöf Point (Fig. 1a)  
129 contain numerous, relative intact fossil pectinid shells of *Austrochlamys* sp. and cheilostome  
130 bryozoans (Fig. 2). The good preservation of macrofossils and a dominance of local JRIVG  
131 clast lithologies suggest that the bivalves have not been transported far within the glaciogenic  
debris flow deposits (Nelson et al., 2009). The bivalves were probably living on the sea floor

132 during periods of ice advance during warm Late Neogene interglacials. Growth increment  
133 analyses coupled with stable isotope data ( $\delta^{18}\text{O}/\delta^{13}\text{C}$ ) indicate much reduced sea ice with  
134 environmental conditions allowing growth throughout much of the year, even during the  
135 coldest winters (Williams et al., 2010). Mean Annual Range of Temperature (zs-MART)  
136 analyses of fossil bryozoans sampled at Cascade Cliff (Fig. 1a) indicate increased seasonality,  
137 and an overall warmer climate for the Weddell Sea region during the Early Pliocene (Clark et  
138 al., 2010).

139  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope dates of pectinid shells (*Austrochlamys* sp.) and  $^{40}\text{Ar}/^{39}\text{Ar}$  dates from  
140 underlying and overlying lavas show that most palynomorph-bearing diamictites were  
141 deposited after 3.69 Ma, during the Zanclean stage (Table 1; Smellie et al., 2006; Smellie et  
142 al., 2008; unpublished data). The  $^{40}\text{Ar}/^{39}\text{Ar}$  ages provide the best estimate for the depositional  
143 ages of the sediments, whereas the wide range of  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope dates indicate some  
144 reworking of the pectinid shells. Previous palynological analyses of Neogene diamictites  
145 collected near Hamilton Point on southeast James Ross (Fig. 1) recorded only few *in-situ*  
146 Late Neogene dinoflagellate cysts (Pirrie et al., 1997). The vast majority of palynomorphs  
147 were interpreted as being reworked from the Upper Cretaceous. Neogene pollen and spores  
148 could not be identified and this prevented any reconstruction of potential vegetation on James  
149 Ross Island during warm Pliocene interglacials.

150

### 151 **3. Methods**

152

#### 153 **3.1 Palynology**

154 Fifty-four Neogene diamictites and five underlying Cretaceous sandstones, collected  
155 in the Austral summer of 2006-2007 on the northern and western snow-free coastal regions of  
156 James Ross Island (Fig. 1a, Nelson et al., 2009), were processed in the palynology laboratory  
157 of the British Geological Survey. Preparation of the samples followed standard techniques  
158 involving hydrochloric and hydrofluoric acids (Faegri and Iversen, 1989). In order to identify  
159 a potential bias on fluorescence colours of palynomorphs by different preparation techniques,  
160 selected samples were processed using both acid -and non-acid techniques (Riding and  
161 Kyffin-Hughes, 2010). The paper focuses on 12 samples from nine locations (Fig. 1a) with  
162 good palynomorph preservation, allowing a total count of ca 130-280 pollen and spores and  
163 10-360 dinoflagellate cysts and acritarchs per sample (Fig. 3, Table 2). Palynomorphs were  
164 identified using literature (e.g. Duane et al., 1992; Williams et al., 2004; Raine et al., 2008).

165 For the three sample locations, Hamilton Point, Roundel Point and the Watchtower,  
166 palynomorph assemblages were analysed from both the Pliocene and underlying Cretaceous  
167 successions to facilitate the identification of *in-situ* and reworked material. The Cretaceous  
168 samples are D6.212.1, D6.221.1 and D6.209.2. Colour and preservation were noted for each  
169 grain and compared between samples.

170

### 171 **3.2. Fluorescence Microscopy**

172 Fluorescence microscopy has become a widely used technique in palynology to  
173 identify reworked and *in-situ* material because the fluorescence colour of palynomorphs  
174 changes with increasing age (e.g. van Gijzel, 1967; Waterhouse, 1998; Yeloff and Hunt,  
175 2005). For this study, grains were examined with 100x and 400x magnification under UV-  
176 fluorescence using an OlympusBH-2 microscope with high pressure mercury burner and 330-  
177 385 exciter filter following techniques described by Yeloff and Hunt (2005). The  
178 fluorescence colour of palynomorphs in the Cretaceous samples was used as a “calibration  
179 standard” to identify potentially younger, *in-situ* palynomorphs in the Upper Neogene  
180 diamictites. Particular attention has been paid to the comparison of *Nothofagidites* pollen  
181 which occurs in both the Cretaceous and Neogene of the Antarctic Peninsula.

182

### 183 **3.3. Statistical Analysis**

184 In order to identify groups of palynomorphs and their provenance, non-parametric  
185 multivariate tests were applied using the statistical software package PRIMER (release 6,  
186 Primer-E Ltd). Similarity matrices were constructed employing the Bray Curtis similarity  
187 measure after square root-transforming data to reduce the weight of highly dominant taxa.  
188 The relationship between samples was based on two dimensional ordination of similarity  
189 matrices calculated from mean values and is presented by two-dimensional non-metric  
190 multidimensional scaling plots (nMDS, Fig. 4). The extent to which the rank order of  
191 distance between samples in the ordination agrees with the rank from the similarity matrices  
192 is indicated by the stress coefficient (i.e. the lower the stress, the better the agreement).

193

## 194 **4. Results**

195

### 196 **4.1 Palynomorphs**

197 The palynomorph assemblages of the samples from James Ross Island are dominated  
198 by the pollen *Nothofagidites lachlaniae*, *N. flemingii*, *Podocarpidites* and *Peninsulapollis*,  
199 and the spores *Cyatheacidites*, *Lycopodiumsporites* and *Laevigatosporites ovatus* (Fig. 3).  
200 Other abundant taxa which regularly occur in most samples are *Alisporites*, *Proteacidites* and  
201 *Microcachryidites antarcticus*. Sample 5.30.11 from Lachman Crags, located on northwest  
202 James Ross Island (Fig. 1), differs from all other samples in showing low percentages of  
203 *Nothofagidites* and a higher diversity of Pteridophyta. The *Nothofagidites lachlaniae*/*N.*  
204 *flemingii* ratio is slightly higher in samples located in southeast James Ross Island (e.g.  
205 Hobbs Glacier D6.204, Hamilton Point D6.212, Roundel Point D6.209). Pairs of Cretaceous  
206 and Neogene samples collected at the same locations show very similar pollen and spore  
207 assemblages. This is in particular true for Roundel Point (D6.209), which is characterised by  
208 abundant *Podocarpidites*.

209 With the exception of sample D5.30.11 from Lachman Crags, all samples yielded a  
210 relatively rich and diverse assemblage of dinoflagellate cysts and acritarchs (Table 2). The  
211 most abundant dinoflagellate cysts are *Exochosphaeridium* and *Isabelidinium*, with the latter  
212 particularly frequent in samples from southeast James Ross Island (e.g. Hobbs Glacier  
213 D6.204, Hamilton Point D6.212, Roundel Point D6.209). Again, the palynomorph  
214 assemblages from pairs of Cretaceous and Neogene samples collected at the same location  
215 are very similar. *Trichodinium castanea* occurs in high numbers in both Cretaceous and  
216 Neogene samples from Roundel Point (D6.209). Most of the dinoflagellate cysts in the  
217 Neogene samples can be confidentially attributed to the Late Cretaceous (e.g. *Isabelidinium*  
218 *pellucidum*, *Odontochitina porifera*, *Nelsoniella tuberculata*), whereas only two samples at  
219 Cascade Cliffs (D5.8.9) and Hobbs Glaciers (D6.204.9) contain dinoflagellate cysts  
220 indicative of Eocene to Oligocene (*Deflandrea heterophlycta*, *Enneadocysta partridgei*) and  
221 Miocene (*Bitectatodinium tepikiense*) ages (Harland, 1978; Stover et al., 1996; Williams et  
222 al., 2004). The dinoflagellate cyst *Impletosphaeridium* spp. is abundant in all samples,  
223 whereas *Leiosphaeridia* was recorded in the Pliocene samples only.

224

#### 225 **4.2 Preservation, fluorescence colour and thermal maturity**

226 The palynomorphs exhibit variable preservation in all samples independent of their  
227 age. Different stages of deterioration, caused by oxidation and mechanical damage, were  
228 recorded for the same taxa (e.g. *Nothofagus lachlaniae*) in both Cretaceous and Pliocene

229 samples. High, age-independent variability was also observed of the colour of palynomorphs  
230 which allowed no reliable estimates of thermal maturity.

231 Fluorescence strongly varied with taxon, ranging from yellow-orange to red-brownish  
232 colours. No differences in fluorescence colour was recorded between the Cretaceous and  
233 Pliocene samples. *Nothofagidites* pollen, for example, gave a generally weak red-brownish  
234 fluorescence signal which varied with preservation, independent of the age. The age-  
235 diagnostic Paleogene dinoflagellate cysts *Deflandrea heterophlycta* and *Enneadocysta*  
236 *partridgei* are the only exception, showing a very bright, almost bluish colour. The difference  
237 in fluorescence colour may indicate that they are younger (van Gijzel, 1967). However, the  
238 Miocene to Holocene dinoflagellate cyst *Bitectatodinium tepikiense* (see Harland, 1978;  
239 Stover et al., 1996; Pirrie et al., 1997), gave a surprisingly weak fluorescence signal which did  
240 not significantly differ from those of the Cretaceous reworked taxa.

241

#### 242 **4.3 Multidimensional scaling: patterns of similarities**

243 The two dimensional non-metric multidimensional scaling (nMDS) shows very  
244 similar relationship patterns of samples for pollen/spores and dinoflagellate cysts/acritarchs,  
245 suggesting that both assemblages were controlled by similar environmental forcing (Fig. 4).  
246 The nMDS plot also shows that the Neogene palynomorphs strongly resemble their  
247 Cretaceous counterparts. Similarities between the Neogene and the underlying Cretaceous  
248 samples are often greater than between samples of similar age. The nMDS plot also indicates  
249 that the samples with the largest geographical distance often show the greatest dissimilarities  
250 in palynomorph assemblages. Samples from the northeastern part of James Ross Island  
251 (Lachman Crags D5.30.1, Cascade Cliffs D5.8.9, Forsters Cliff D5.10.2) closely resemble  
252 each other and are distinctively different from samples from the southeast (e.g. Hamilton  
253 Point D6.212, Watchtower D6.221 and Roundel Point D6.209).

254

### 255 **5. Discussion**

256

#### 257 **5.1. Identification of *in-situ* and reworked palynomorphs in the Pliocene diamictites**

258 Well-preserved fossil pectinid shells of *Austrochlamys* sp. and cheilostome bryozoans  
259 suggest that the pollen-bearing sediments have not been transported over long distances and  
260 were probably deposited during relatively warm Pliocene periods (Nelson et al., 2009).  
261 However, whilst macrofossils are deposited *in-situ*, many organic-walled microfossils are

262 transported or reworked from older sediments. Our palynological analysis of pollen and  
263 spores has identified *Nothofagus*-dominated forest vegetation with *Podocarpus*, Proteaceae  
264 and ferns growing in a moist warm-temperate climate. Similar vegetation communities have  
265 been reconstructed for the Antarctic Peninsula from the Late Cretaceous to the Paleogene  
266 (e.g. Askin, 1997; Dettmann and Thomson, 1987; Troedson and Riding, 2002). Reworking  
267 from older sediments is also shown by age-indicative dinoflagellate cysts such as  
268 *Isabelidinium pellucidum*, *Odontochitina porifera* and *Nelsoniella tuberculata*. Detailed  
269 descriptions of Late Cretaceous dinoflagellate cyst assemblages from James Ross Island were  
270 given by Dettman and Thomson (1987), Dolding (1992) and Keating (1992). However,  
271 although it is evident that most of the palynomorphs are reworked from the Cretaceous, the  
272 presence of *Bitectatodinium tepikiense* at Hobbs Glacier also indicates that Late Neogene *in-*  
273 *situ* palynomorphs have also been preserved. This raises the question as to which pollen and  
274 spores could also originate from the local Neogene *Nothofagus*-dominated tundra on James  
275 Ross Island, which may have been similar to tundra shrub vegetation previously  
276 reconstructed for the Miocene and possibly Pliocene coastal regions of East Antarctica  
277 (Francis and Hill, 1996; Lewis et al., 2008; Warny et al., 2009). In the following section, we  
278 will discuss and review various methods applied to identify *in-situ* palynomorphs. Their  
279 unambiguous identification is the first necessary step towards a robust reconstruction of  
280 Pliocene vegetation and climate on the West Antarctic Peninsula.

281

### 282 5.1.1. The *Nothofagidites lachlaniae*/*N. flemingii* pollen ratio

283 The question whether or not *Nothofagus* was present during warm Neogene  
284 interglacials is a focus of many palaeobotanical studies on Antarctica (e.g. Fleming and  
285 Baron, 1996; Francis and Hill, 1996). Whereas fossil leaves or woods provide direct evidence  
286 for its presence, vegetation reconstructions using fossil *Nothofagidites* pollen are strongly  
287 hampered by pollen morphological constraints. As the geographical distribution of the  
288 southern beech genus *Nothofagus* ranges from warm temperate forest to cold polar tundra  
289 shrub, any meaningful palaeoenvironmental reconstruction requires an unambiguous  
290 identification to species level. However, the most abundant southern beech pollen in samples  
291 from James Ross Island is classified as *Nothofagidites lachlaniae* and *N. flemingii*, both  
292 referring to pollen types rather than real plant species. Because of uncertainties in the  
293 identification of the nearest living analogue, indirect measures such as the dominance of  
294 morphotypes (Hill and Truswell, 1993) or ratio of pollen types (Fleming and Baron, 1996)

295 have been postulated to infer the presence of *in-situ* *Nothofagidites* pollen. In their study,  
296 Fleming and Baron (1996) interpreted the dominance of *N. lachlaniae* pollen and low  
297 abundances of *N. flemingii* in marine cores as an indicator for the presence of *Nothofagus*  
298 tundra on Antarctica during the Pliocene. Our systematic comparison of Pliocene and  
299 underlying Cretaceous samples from James Ross Island strongly questions this approach in  
300 showing a clear dominance of *N. lachlaniae* pollen types in all samples. Variations in the  
301 ratio of *N. lachlaniae* versus *N. flemingii* pollen occurs in samples from the northeast of  
302 James Ross Island (e.g. Lachman Crags, D5.30.11) and points to changes in sediment  
303 provenance rather than implying the presence of *in-situ* material and the existence of past  
304 *Nothofagus* tundra shrub.

305

### 306 5.1.2. Colour and Preservation

307 The colour and preservation of fossil palynomorphs is a widely-used indicator of  
308 thermal maturation and hence the relative age of palynomorphs. The method has been  
309 successfully applied to distinguish between *in-situ* and reworked material in  
310 Paleogene/Neogene samples from Antarctica (e.g. Askin and Raine, 2000; Prebble et al.,  
311 2006a). The absence of any notable difference in colour or preservation of palynomorphs  
312 between the Cretaceous and Neogene control samples from James Ross Island might indicate  
313 absence of *in-situ* material. However, the high variability of preservation and colour within  
314 one sample generally questions the suitability of this approach for the palynological analyses  
315 of sediments from the Antarctic Peninsula. It should be noted that the Cretaceous sediments  
316 underlying the Hobbs Glacier formation largely consist of relatively soft, unconsolidated sand  
317 and siltstones which contain generally well preserved palynomorphs with a low thermal  
318 maturity. Damage and corrosion appears to be primarily the result of post-sedimentary glacial  
319 transport during the Neogene, and does therefore not necessarily imply an older age.

320

### 321 5.1.3. Fluorescence microscopy

322 The fluorescence colours of palynomorphs from Cretaceous and Neogene samples  
323 closely resemble each other, suggesting that they either have similar geological ages or  
324 similar taphonomic histories (van Gijzel, 1967). No difference in fluorescence colours could  
325 be recorded between the acid -and non-acid treated samples. Waterhouse (1998) noted that  
326 the fluorescence colour of palynomorphs can also change with increasing corrosion and  
327 oxidation. This could explain the surprisingly weak fluorescence colour signal of the much

328 younger, Late Neogene dinoflagellate cyst *Bitectatodinium tepikiense* occurring in samples  
329 from Hobbs Glacier. Post-sedimentary glacial transport and corrosion during the Neogene  
330 might have altered the fluorescence of both Cretaceous and Neogene palynomorphs from  
331 James Ross Island. The exceptionally strong fluorescence signal of the age-indicative Eocene  
332 to Oligocene dinoflagellate cysts *Deflandrea heterophlycta* and *Enneadocysta partridgei*  
333 might have been caused by a different taphonomic history and provenance rather than  
334 reflecting the younger geological age.

335

#### 336 5.1.4. Age-diagnostic acritarchs

337 The acritarch *Leiosphaeridia* and the dinoflagellate cyst *Impletosphaeridium* are  
338 regularly abundant in marine sediments from polar regions. Warny et al. (2007) concluded  
339 from the presence of high numbers of *Impletosphaeridium* in marine cores taken offshore the  
340 Antarctic Peninsula that the samples are likely to have been derived from sediments of  
341 Eocene to Miocene age. Our direct comparison of Late Neogene and Cretaceous samples  
342 from James Ross Island which are both rich in *Impletosphaeridium* strongly questions the  
343 suitability of this taxon for estimating geological ages. Given the highly abundant  
344 occurrences in some Upper Cretaceous samples from James Ross Island (e.g. D6.221.1,  
345 Table2), it is also highly unlikely that this acritarch, which is now extinct and has no modern  
346 analogue, could indicate proximate sea ice cover, as suggested by Warny et al. (2007).

347 Through mapping the modern distribution of the acritarch *Leiosphaeridia* in surface  
348 samples from the Arctic Ocean, Mudie (1992) showed that this acritarch occurs in high  
349 numbers at the contact margin between pack ice and seasonal ice. Accordingly,  
350 *Leiosphaeridia* has also been used in marine sediments from Antarctica as an indicator to  
351 reconstruct past sea-ice presence (e.g. Hannah, 2006; Prebble et al., 2006b; Warny et al.,  
352 2006). Given the ecological range and modern distribution of *Leiosphaeridia* in cold polar  
353 regions, it is likely that this acritarch in samples from James Ross Island are *in-situ* and have  
354 not been reworked from the warmer, presumably ice-free Cretaceous into the Upper Neogene  
355 diamictites. The absence of *Leiosphaeridia* in all Cretaceous control samples strongly  
356 supports this interpretation.

357

## 358 5.2. Provenance and glacier flow directions

359 Pirrie et al. (1997) concluded from sedimentological and palynological studies on  
360 diamictites from the Hobbs Glacier Formation in southeast James Ross Island that the

361 sediments were deposited by glaciers flowing from the Antarctic Peninsula towards the  
362 southeast. The majority of dinoflagellate cysts were derived from the Upper Campanian to  
363 Lower Maastrichtian strata of the Marambio Group. Our new data from different northern  
364 and eastern locations on James Ross Island show similar palynomorph assemblages and  
365 confirm the Late Cretaceous age and origin of most reworked palynomorphs. However, in  
366 showing local patterns and a close resemblance between Neogene and underlying Cretaceous  
367 palynomorphs, our study suggests a more local provenance of the Hobbs Glacier diamictites  
368 (Fig. 4). This finding corroborates detailed provenance studies by Nelson et al. (2009),  
369 suggesting that the main ice centres for the debris flows were situated on James Ross Island  
370 itself. According to their conceptual ice model, most diamictites in the east and northeast  
371 originated from a central large ice cap positioned over Mount Haddington (Fig. 1). Ice sheets  
372 from the Antarctic Peninsula delivered material across Prince Gustav Channel to the western  
373 parts of James Ross Island only. Again our new palynological data support this model in  
374 showing significantly different palynomorph assemblages for northwest James Ross Island  
375 (Lachman Crags, D5.30.11).

376 The presence of Eocene/Oligocene dinoflagellate cysts in samples from Hobbs  
377 Glacier and Cascade Cliffs cannot be explained with existing glacier flow models. There is  
378 no evidence of Paleogene strata outcropping on James Ross Island and the closest Eocene  
379 formations are on Seymour and Cockburn islands (Pirrie et al., 1992), located about 15-20  
380 km to the east, which is contrary to the main direction of reconstructed ice flows. Given the  
381 vicinity of Seymour Island, it appears likely that the Paleogene dinoflagellate cysts were  
382 reworked into the Neogene diamictites through drifting icebergs or long-distance aeolian  
383 transport. The strong fluorescence signal of the Eocene/Oligocene dinoflagellate cysts  
384 supports this interpretation in suggesting a different taphonomic history.

385

### 386 **5.3. Pliocene environments: how likely was a vegetation cover?**

387 Our systematic analyses of pollen and spores in Neogene samples from James Ross  
388 Island give no evidence for a substantial vegetation cover on James Ross Island during warm  
389 Pliocene interglacials. Strong similarities between the Neogene and underlying Cretaceous  
390 palynomorph assemblages and fluorescence signals point to the absence of any *in-situ* pollen  
391 and spores of Late Neogene age. Unfortunately the absence of fossils can never be taken as  
392 proof of non-existence because sedimentary and post-sedimentary processes could have  
393 prevented the preservation or deposition of Pliocene pollen and spores. However, instead of

394 stressing the absence of palynomorphs as proof, we use a number of indirect proxies to assess  
395 the likelihood of vegetation on James Ross Island during Pliocene warm interglacials.

396 The presence of Paleogene and *in-situ* Late Neogene dinoflagellate cysts demonstrates  
397 that sedimentary conditions were favourable to the preservation of organic-walled  
398 microfossils. It seems therefore unlikely that pollen and spores originating from a potential  
399 Pliocene vegetation cover have been selectively destroyed. Late Neogene dinoflagellate cysts  
400 have been recorded at Hobbs Glacier in low numbers. However, Pirrie et al. (1997) also  
401 recorded coeval dinoflagellate cysts in samples from James Ross Island, indicating that,  
402 although in low numbers, *in-situ* palynomorphs appear to be a constant element of the  
403 palynological assemblage.

404 Smellie et al. (2009) presented evidence from sedimentology and modelling  
405 simulations, suggesting that the Antarctic Peninsula ice sheet (APIS) was present even during  
406 the warmest interglacials of the Pliocene. The study points out significant differences in the  
407 sensitivity of APIS to climate change compared to West and East Antarctica. It is likely that a  
408 permanent APIS, fed by high snow accumulation, could have also prevented the growth of  
409 vegetation on James Ross Island. The occurrence of *Leiosphaeridia* in samples from James  
410 Ross Island implies the presence of sea-ice with summer sea surface temperature ranging  
411 from ca. -2 to +5°C (Edwards et al., 1991; Mudie, 1992). This interpretation corroborates  
412 modelling simulations predicting sea-ice cover throughout the year during the Early Pliocene  
413 with seasonal temperature variation at the sea surface (0-5m) ranging from -1.69 °C in winter  
414 and +3.08 °C during summer (Lunt et al., 2008; Williams et. 2010). Percentages of  
415 *Leiosphaeridia* in the James Ross Island diamictites are comparatively low, and it is possible  
416 that sea ice cover was reduced during the Pliocene as suggested by Williams et al (2010)  
417 from growth increment analysis and stable isotopic data of fossil bivalves (*Austrochlamys*  
418 *anderssoni*) from Cockburn Island.

419 Whilst the presence of *Leiosphaeridia* suggests near-modern climate conditions in the  
420 West Antarctic Peninsula, recently published ZS-MART analyses of bryozoans in Late  
421 Neogene diamictites from Cascade Cliffs (Fig. 1a) points to much higher temperatures with  
422 increased seasonality (Clark et al. 2010). The palynomorph assemblage from Hobbs Glacier  
423 (D6.204.9) supports this interpretation in providing no evidence for the sea-ice indicator  
424 *Leiosphaeridia* coupled with the occurrence of *Bitectatodinium tepikiense*, indicative of  
425 warmer, sub-arctic to temperate sea surface temperatures (Edwards et al. 1991). The  
426 discrepancies in climate estimates from the Antarctic Peninsula diamictites result from

427 uncertainties in dating control. It is not clear from the isotope dates (Table 1) whether the  
428 palynomorphs analysed from different locations and different depths originate from the same  
429 warm interglacial period. It is highly likely that the James Ross Island diamictites cover  
430 various Late and Early Pliocene interglacials with different annual temperature ranges.

431

## 432 **6. Conclusions**

433

434 Since the Oligocene, Antarctica has been shaped by ice sheets and glacial dynamics  
435 resulting in the reworking of sediments through post-sedimentary transport. Glacial  
436 dynamics, which increased with further cooling towards the end of the Miocene, strongly  
437 reduces the chances to find any *in-situ* microfossils and undisturbed fossil records which are  
438 required for an unambiguous reconstruction of Neogene Antarctic environments. Our new  
439 palynological analyses of Early Pliocene diamictites from James Ross Island failed to identify  
440 *in-situ* pollen and spores which could indicate the presence of substantial vegetation on the  
441 Antarctic Peninsula. Our systematic comparison of Pliocene and underlying Cretaceous  
442 assemblages using different palaeoecological methods furthermore revealed that some  
443 previously published palynological approaches to identify Late Neogene Antarctic  
444 environments cannot be applied to sediments from the Antarctic Peninsula. Such approaches  
445 include the use of colour of palynomorphs for estimating relative geological ages and pollen  
446 ratio to identify *in-situ* *Nothofagus* pollen. Our results highlight the importance of identifying  
447 the provenance of glacial sediments and their potential microfossil “contaminants” before  
448 attempting reconstructions of Neogene palaeoenvironments in Antarctica.

449 Whilst the absence of *in-situ* pollen and spores cannot be taken as a proof of non-  
450 existence of vegetation, we still conclude from this study, using indirect multiple evidence,  
451 that the presence of a substantial Pliocene vegetation cover on James Ross Island was rather  
452 unlikely, even during warm interglacials. Evidence which supports this conclusion includes:  
453 a) the presence of acritach *Leiosphaeridia*, indicating sea-ice and sea surface temperatures  
454 close to modern values.  
455 b) the presence of *in-situ* dinoflagellate cysts which indicate sedimentary conditions  
456 favourable to the preservation of palynomorphs. Selective destruction of *in-situ* pollen and  
457 spores is unlikely.

458 c) sedimentological characteristics of fossiliferous, pollen bearing diamicrites, signifying  
459 episodes of ice expansion during relatively warm interglacials of the Early Pliocene (see also  
460 Nelson et al., 2009).

461

462 Insufficient dating control prevents our palynomorph assemblages, indicating near  
463 modern conditions, to be related to specific periods of the Early Pliocene. The fossil  
464 palynomorph assemblages might represent communities which lived during the same or  
465 different interglacial periods. The sporadic occurrence of the sub-arctic to temperate  
466 dinoflagellate cyst *Bitectatodinium tepikiense* in one sample points to the existence of  
467 particularly warmer interglacials which might have not been adequately covered herein.  
468 Further research is needed to decipher and increase age and resolution control of interglacial  
469 records to enable a robust reconstruction of Late Neogene environments of the Antarctic  
470 Peninsula.

471

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477

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713  
714

715 **CAPTIONS FOR FIGURES AND TABLES**

716

717 Fig. 1. a) The locations of the Cretaceous and Neogene sample sites on James Ross Island. b)  
718 A climate-vegetation model simulation (BIOME4-HadAM3) of the Mid Pliocene (ca. 3 Ma)  
719 vegetation on Antarctica (after Salzmann et al., 2008).

720

721 Fig. 2: A sample of diamictite from Ekelöf Point, southeast James Ross Island (D6.260.x)  
722 with well-preserved *Pecten* shells (*Austrochlamys* sp.).

723

724 Fig 3: The relative abundances of selected pollen and spore taxa, expressed as percentages of  
725 the total counts of palynomorphs. Cretaceous samples are highlighted in yellow.

726

727 Fig. 4: Two dimensional non-metric multidimensional scaling (nMDS) for a) pollen and  
728 spores, and b) dinoflagellate cysts and acritarchs in the diamictites from James Ross Island.  
729 The samples from the northern and western coasts respectively are indicated by the following  
730 symbols: (▲) and (▼) The other symbols indicate pairs of Cretaceous and Pliocene samples  
731 from the west coast of James Ross Island.

732

733 Table 1. The ages of the Neogene palynomorph-bearing diamictites derived from the mean  
734  $^{87}\text{Sr}/^{86}\text{Sr}$  dates of pectinid shells (*Austrochlamys* sp.) and the  $^{40}\text{Ar}/^{39}\text{Ar}$  dates from the  
735 underlying and overlying basaltic lavas (after Smellie et al., 2006, 2008 and unpublished  
736 data).

737

738 Table 2: Total counts of dinoflagellate cyst and acritarch specimens. Age-diagnostic  
739 Paleogene/Neogene taxa are framed. The Cretaceous samples are highlighted in yellow.

740