

1 **Southern high-latitude terrestrial climate change during the Paleocene–**
2 **Eocene derived from a marine pollen record (ODP Site 1172, East**
3 **Tasman Plateau)**

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26 **ABSTRACT**

27 Reconstructing the early Paleogene climate dynamics of terrestrial settings in the high
28 southern latitudes is important to assess the role of high-latitude physical and
29 biogeochemical processes in the global climate system. However, whereas a number
30 of high-quality Paleogene climate records has become available for the marine realm
31 of the high southern latitudes over the recent past, the long-term evolution of coeval
32 terrestrial climates and ecosystems is yet poorly known. We here explore the climate
33 and vegetation dynamics on Tasmania from the middle Paleocene to the early Eocene
34 (60.7 – 54.2 Ma) based on a sporomorph record from Ocean Drilling Program (ODP)
35 Site 1172 on the East Tasman Plateau. Our results show that three distinctly different
36 vegetation types thrived on Tasmania under a high-precipitation regime during the
37 middle Paleocene to early Eocene, with each type representing different temperature
38 conditions: (i) warm-temperate forests dominated by gymnosperms that were
39 dominant during the middle and late Paleocene (excluding the middle/late Paleocene
40 transition); (ii) cool-temperate forests dominated by southern beech (*Nothofagus*) and
41 araucarians that transiently prevailed across the middle/late Paleocene transition
42 interval (~59.5 to ~59.0 Ma); and (iii) paratropical forests rich in ferns that were
43 established during and in the wake of the Paleocene–Eocene Thermal Maximum
44 (PETM). The transient establishment of cool-temperate forests lacking any frost-
45 sensitive elements (i.e., palms and cycads) across the middle/late Paleocene transition
46 interval indicates markedly cooler conditions, with the occurrence of frosts in winter,
47 on Tasmania during that time. The integration of our sporomorph data with previously
48 published TEX₈₆-based sea-surface temperatures from ODP Site 1172 documents that
49 the vegetation dynamics on Tasmania were closely linked with the temperature
50 evolution in the Tasman sector of the Southwest Pacific region. Moreover, the

51 comparison of our season-specific climate estimates for the sporomorph assemblages
52 from ODP Site 1172 with the $\text{TEX}_{86}^{\text{L}}$ - and $\text{TEX}_{86}^{\text{H}}$ -based temperature data suggests a
53 warm bias of both calibrations for the early Paleogene of the high southern latitudes.

54

55 **1 Introduction**

56 The Southern Ocean is an important region for early Cenozoic (65–34 Ma) climates,
57 being the dominant region for deep-water formation during that time (Thomas et al.,
58 2003; Sijp et al., 2011; Hollis et al., 2012). South Pacific sea-surface and global
59 intermediate water temperatures increased from the late Paleocene to the early
60 Eocene, with maximum warmth during the Early Eocene Climatic Optimum (EECO;
61 53–51 Ma), followed by a cooling trend during the middle and late Eocene (Zachos et
62 al., 2001; 2008; Bijl et al., 2009; Hollis et al., 2012). This cooling trend ultimately
63 culminated in the establishment of a continental-scale ice shield on Antarctica during
64 the earliest Oligocene (e.g., Zachos et al., 1994; 2008; Barrett, 1996), which
65 represented a decisive step in the Earth’s transition from a “greenhouse” into an
66 “icehouse” world.

67 Organic geochemical surface-water temperature proxy records from the high-latitude
68 Southwest Pacific Ocean (notably TEX_{86} ; Bijl et al., 2009) closely mirror trends in the
69 benthic foraminiferal oxygen isotope data from the late Paleocene to the early
70 Oligocene (Zachos et al., 2001; 2008), which lends further support to the suggestions
71 that the southern ocean was the main region for deep-water formation (Thomas et al.,
72 2003). Irrespective of the calibration used, Southwest Pacific TEX_{86} -derived sea-
73 surface temperatures (SSTs) were relatively cool during the early and middle
74 Paleocene. During the late Paleocene and early Eocene, SSTs gradually rose to
75 tropical values ($>26^{\circ}\text{C}$), with maxima being reached during the Paleocene-Eocene

76 Thermal Maximum (PETM; Sluijs et al., 2011) and the EECO (Bijl et al., 2009;
77 Hollis et al., 2009; 2012). Towards the end of the early Eocene (49–50 Ma), a
78 pronounced SST cooling of $\sim 4^{\circ}\text{C}$ occurred on the Australo-Antarctic margin; this
79 cooling has been attributed to the onset of westbound surface-water throughflow
80 across the Tasmanian Gateway (Bijl et al., 2013a). A similar cooling trend is
81 registered for surface waters off New Zealand (Hollis et al., 2009; 2012) and in the
82 Tasman sector of the Southwest Pacific Ocean (Bijl et al., 2009; Hollis et al., 2012).
83 Strikingly low SSTs are recorded for the high-latitude Southwest Pacific Ocean
84 during the interval spanning the middle/late Paleocene transition (59.5–59.0 Ma);
85 TEX₈₆-derived SST decreased by $\sim 3^{\circ}\text{C}$ during that time (Bijl et al., 2009; Hollis et al.,
86 2012; 2014). Along with this SST drop, lowered sea level and marked bathyal erosion
87 suggest that a transient growth of an Antarctic ice sheet may have occurred (Hollis et
88 al., 2014).

89 While an increasing amount of data has become available on the marine climate
90 evolution in the southern high latitudes during the early Paleogene, the coeval
91 terrestrial climate dynamics of that region are yet poorly documented (e.g., Passchier
92 et al., 2013). For the Paleocene, paleobotanical records reflect the thriving of
93 temperate, gymnosperm-rich forests dominated by podocarps in Southeast Australia
94 (e.g., Macphail et al., 1994; Greenwood et al., 2003; Greenwood and Christophel,
95 2005), on Seymour Island (Antarctica; Askin, 1990), and in New Zealand
96 (Mildenhall, 1980; Raine et al., 2009).

97 In contrast, highly diverse angiosperm forests containing taxa that today are restricted
98 to tropical environments characterize the early Eocene vegetation in the higher-
99 latitude Southwest Pacific region. This vegetation is widely known from Southeast
100 Australia (Macphail et al., 1994; Greenwood et al., 2003; Greenwood and

101 Christophel, 2005), Tasmania (Truswell, 1997; Carpenter et al., 2012) and New
102 Zealand (Raine et al., 2009; Handley et al., 2011); notably, it also thrived on the
103 Wilkes Land margin of the Antarctic continent, i.e., at paleo-latitudes of $\sim 70^\circ$ South
104 (Pross et al., 2012; Contreras et al., 2013).

105 The pronounced vegetation turnover from temperate forests during the Paleocene to
106 near-tropical forests during the early Eocene suggests a marked, climatically driven
107 change in terrestrial environments in the high southern latitudes. However, the
108 transitional process between these two vegetation types and the underlying change in
109 terrestrial climate conditions of the Southwest Pacific region have remained poorly
110 understood. The gaps in the documentation of terrestrial climate dynamics during the
111 early Paleogene appear particularly pronounced considering the coeval datasets for
112 the marine realm from the same region (Bijl et al., 2009; 2013a; Hollis et al., 2009;
113 2012; 2014). This is due to the fact that prior paleobotanical studies are mainly based
114 on stratigraphically discontinuous outcrops that provided only limited insights into the
115 Paleocene and early Eocene vegetation of the region (Greenwood et al., 2003). In
116 addition, available studies on sporomorphs from the early Paleogene of the Southwest
117 Pacific region have predominantly focussed on the taxonomical characterization of
118 the assemblages and the generation of biostratigraphic schemes (e.g., Stover and
119 Evans, 1973; Stover and Partridge, 1973; Truswell, 1997; MacPhail, 1999). In any
120 case, estimates of terrestrial temperatures in the high southern latitudes and a
121 comparison with the currently available SST estimates from the marine realm can
122 strongly enhance the understanding of the climate evolution in the high southern
123 latitudes during the early Paleogene.

124 In light of the above, we here explore the vegetation response to high-southern-
125 latitude climate forcing from the Paleocene to the “hothouse” conditions of the early

126 Eocene based on a new, chronostratigraphically well-calibrated (Bijl et al., 2013b)
127 sporomorph record from Ocean Drilling Program (ODP) Site 1172 off eastern
128 Tasmania. We quantitatively evaluate the compositional variations of the sporomorph
129 assemblages and carry out quantitative sporomorph-based paleoclimatic
130 reconstructions. For a further assessment of the terrestrial climatic conditions in the
131 Southwest Pacific region, we apply the same paleoclimate reconstruction approach to
132 previously published sporomorph records from Southeast Australia (Bass Basin,
133 Gippsland Basin, Southeast Highlands) and New Zealand. Finally, we compare our
134 terrestrial paleoclimate estimates with previously published TEX_{86} - (i.e., $\text{TEX}_{86}^{\text{L}}$ and
135 $\text{TEX}_{86}^{\text{H}}$ calibrations; Kim et al., 2010) based SST reconstructions from the same site
136 (Bijl et al., 2009; 2013b; Hollis et al., 2014) in order to contribute to a better
137 understanding of the early Paleogene climate dynamics in the high southern latitudes.

138

139 **1.2 Regional setting and paleoceanography**

140 During the early Paleogene, Tasmania and the ETP were located at $\sim 65^{\circ}\text{S}$, much
141 closer to Antarctica than today (Exon et al., 2004b). Paleoceanographic patterns as
142 determined by winds and gateway configuration were likely vital for regional climates
143 on land (Sijp et al., 2011). The study site was located close to the Tasmanian
144 promontory, which hampered deep ocean exchange between the Southwest Pacific
145 and the Australo-Antarctic Gulf for most of the early Paleogene (Shipboard Scientific
146 Party, 2001b; Stickley et al., 2004; Fig. 1). During the Paleocene and early Eocene,
147 the Tasman region was under the persistent influence of the Antarctic-derived Tasman
148 Current; in contrast, the Australo-Antarctic Gulf (west of Tasmania) was bathed by
149 the low-latitude-derived Proto-Leeuwin Current (Huber et al., 2004; Sijp et al., 2011;
150 see Fig. 1). This paleoceanographic configuration determined marine biogeographical

151 patterns in the region (Huber et al., 2004; Bijl et al., 2011; 2013a). The onset of the
152 deepening of the Tasmanian Gateway at ~49–50 Ma initiated a westbound Antarctic
153 Counter Current flowing along the Antarctic margin from the Pacific into the
154 Australo-Antarctic Gulf (Bijl et al., 2013a). Continued rifting through the Eocene and
155 accelerated deepening of the Tasmanian Gateway (~35.5 Ma) led to the inflow of
156 Australo-Antarctic Gulf waters through the Tasmanian Gateway into the southern
157 Pacific during the early Oligocene (Stickley et al., 2004; Sijp et al., 2011). These
158 paleoceanographic reorganizations had important effects on terrestrial climates in the
159 Australo-Antarctic region (Bijl et al., 2013a).

160

161 **2 Material and methods**

162 The middle Paleocene to early Eocene strata studied here were recovered at ODP Site
163 1172, which is located ~100 km east of Tasmania on the western side of the East
164 Tasman Plateau (ETP; 43°57.6' S, 149°55.7' E; Fig. 1) (Shipboard Scientific Party,
165 2001b).

166

167 **2.1 Age model, lithology and depositional environment**

168 We here follow the corrected sample depths for ODP Hole 1172D as published in
169 Sluijs et al. (2011) based on detailed correlation of the X-ray fractionation core
170 scanning to the γ -ray downhole log. The age model of the studied sequence is based
171 on the magnetostratigraphy, chemostratigraphy and dinoflagellate cyst (dinocyst)
172 biostratigraphy as presented in Bijl et al. (2013b). For the interval studied (60.7–54.2
173 Ma), the age model is based on three magnetic reversals confidently correlated to the
174 Geomagnetic Polarity Time Scale (GPTS) of Vandenberghe et al. (2012), the PETM
175 (~56 Ma), which exhibits a negative carbon isotope excursion of ~3‰ between

176 611.89 and 611.86 rmbsf (revised meters below sea floor) (Sluijs et al., 2011), and
177 several dinocyst first and last occurrence data that have been calibrated regionally
178 following Crouch et al. (2014). The magnetostratigraphic age model for the Paleocene
179 section (Röhl et al., 2004) was adjusted by Bijl et al. (2010) on the basis of the
180 recognition of the PETM in Core 1172D-15R (611.8 rmbsf; Sluijs et al., 2011). The
181 missing interval between Cores 16R and 17R (~620 rmbsf) represents a ~1.3-Ma-long
182 hiatus that spans the time interval correlative to between infra-Subchrons C26n and
183 C25n (57.7–59 Ma; Bijl et al., 2010; 2013b).

184 The upper 60 cm of section in Core 17R (i.e., below the hiatus) are heavily disturbed
185 and have many sediment characteristics more consistent with Core 16R than with the
186 underlying sediment (Röhl et al., 2004). We therefore follow Röhl et al. (2004) in
187 their suggestion that this interval represents caved material of late Paleocene age.

188 The Middle Paleocene to lower Eocene succession of ODP Site 1172 consists mainly
189 of gray to grayish brown clay- and siltstones with low abundances of calcareous and
190 siliceous microfossils (Shipboard Scientific Party, 2001a; Röhl et al., 2004).

191 Environmentally, the succession is interpreted to reflect very shallow to restricted
192 marine conditions, with marked runoff from the nearby shores (Röhl et al., 2004).

193 Any study on sporomorphs from marine sediments critically relies on the
194 identification of the source region in order to provide meaningful paleoclimatic
195 information. An in-depth discussion of this issue is provided in Section 4.1
196 (“Constraints on sporomorph source region”).

197

198 **2.2 Sample processing and data analysis**

199 Eighty-nine samples from the Paleocene and Eocene of ODP Site 1172, originally
200 processed at the Laboratory of Palaeobotany and Palynology, Utrecht University (Bijl

201 et al., 2011), were here reanalysed for terrestrial palynomorphs. Sample processing
202 followed standard palynological techniques, including treatment with HCl (10%) and
203 HF (38%) and sieving through a 15 µm nylon mesh (e.g., Pross, 2001). The
204 microscope slides were prepared using glycerine jelly as a mounting medium. The
205 residues and slide preparations are stored in the collection of the Laboratory of
206 Palaeobotany and Palynology at Utrecht University. Whenever possible, 300
207 sporomorphs (excluding reworked specimens) were analysed per sample and
208 determined to the species level; this required the analysis of up to six slides per
209 sample. The analyses were performed using a light microscope at 200x magnification;
210 morphological details were studied with a magnification of 1000x. Sporomorph
211 identifications are mainly based on Couper (1960), Harris (1965), Stover and
212 Partridge (1973), Truswell (1983), Raine et al. (2008), and Truswell and Macphail
213 (2009). The botanical affinities are given following Macphail et al. (1994), Raine
214 (1998), and Truswell and Macphail (2009). All sporomorph data (including
215 photomicrographs of key taxa) are provided in the Supplementary Information.
216 Rarefaction was applied to evaluate sporomorph diversity; this allows to estimate the
217 number of sporomorph species at a constant sample size (Raup, 1975). Detrended
218 Correspondence Analysis (DCA) is an ordination technique that was used to analyse
219 floral composition change through time.
220 To constrain the source region of the sporomorphs from ODP Site 1172, we compared
221 the floristic composition of our record with coeval sporomorph records from
222 Southeast Australia (Bass Basin – data from Blevin 2003; Gippsland Basin –
223 Department of Primary Industries, 1999; Southeast Highland sections – Taylor et al.,
224 1990) and New Zealand (Middle Waipara and Otaio River sections – Pancost et al.,
225 2013) using DCA (see Fig. 1 for locations and Table 1 for further details and

226 references). From all records derived from **drillholes**, only data from core or sidewall
227 core samples were evaluated to avoid potential contamination by caving. To exclude a
228 bias as it could have been introduced into our comparison through different
229 taxonomic criteria, we have standardized all datasets using broader groups of taxa
230 (e.g., *Gleicheniidites* spp./*Clavifera* spp., *Phyllocladidites* spp., *Nothofagidites* spp.
231 [*fusca* group]) when necessary. Due to the differences in sample sizes, sporomorph
232 percentages were used as input for the DCA, and only samples with counts ≥ 100
233 individuals were evaluated.

234

235 **2.3 Sporomorph-based climate reconstructions**

236 Quantitative sporomorph-based climate estimates were carried out following the
237 bioclimatic analysis approach of Greenwood et al. (2005). For each taxon with a
238 known nearest living relative (NRL; Table 2), climatic profiles were generated with
239 regard to mean annual temperature (MAT), coldest month mean temperature
240 (CMMT), warmest month mean temperature (WMMT), and mean annual
241 precipitation (MAP). The climate profiles are derived from (i) the dataset of Pross et
242 al. (2012), which is mainly based on distribution data from the Australian National
243 Herbarium online database (Australian National Herbarium, 2011) and the
244 mathematical climate surface software ANUCLIM 5.156 (Houlder et al., 1999), and
245 (ii) the PALAEOFLORA database, which contains climatic information for a plant
246 taxon based on its global distribution (Utescher and Mosbrugger, 2013). Following
247 Greenwood et al. (2005), the climatic values for each assemblage were calculated
248 based on the zone of overlap of the majority of taxa from that assemblage with respect
249 to a given climate parameter. This overlap interval was calculated using the 10th
250 percentile (as lower limit) and 90th percentile (as upper limit) of the total range of the

251 NLRs recorded in that assemblage. The climate estimate is given as the midpoint
252 between the lower and upper limits, with the error spanning from the lower to the
253 upper limit. Only samples with counts ≥ 100 individuals were used in the climate
254 reconstructions.

255 Paleoclimate estimates based on the NLR concept may be influenced by a number of
256 factors that need to be considered prior to the application of NLR-based
257 reconstruction methods (e.g., Mosbrugger and Utescher, 1997; Mosbrugger, 1999;
258 Pross et al., 2000; Utescher et al., 2000). These factors include (i) the potential
259 misidentification of the fossil taxa and/or NLRs; (ii) the potentially incomplete
260 coverage of the climatic tolerances of the NLRs; (iii) potentially unidentified
261 differences between the climatic tolerances of fossil taxa and their NLRs; and (iv) a
262 weakening of the connection between fossil taxa and NLRs the further one goes back
263 in time. Generally, these issues become increasingly important with the age of the
264 floras analyzed and may diminish the significance of the results (e.g., Poole et al.,
265 2005). They can, however, be identified and corrected via the application of multi-
266 proxy approaches. In particular, the NLR concept has been successfully applied to
267 both macrofloral and sporomorph assemblages from the early Paleogene of the higher
268 southern latitudes (Greenwood et al., 2003; Carpenter et al., 2012; Pross et al., 2012;
269 Contreras et al., 2013); the validity of the NLR-based results has been demonstrated
270 through the comparison with data from other, independent proxies.

271

272 **2.4 Statistical examination of the connection between floristic** 273 **composition and temperature**

274 To examine the correlation between the floristic composition of our sporomorph
275 record from ODP Site 1172 (as represented by DCA Axis 1 sample scores; Figs. 2, 4)

276 and $\text{TEX}_{86}^{\text{L}}$ - and $\text{TEX}_{86}^{\text{H}}$ -derived SST values from the same site (Bijl et al., 2013b;
 277 Hollis et al., 2014), we applied a state space model. State space models or dynamic
 278 linear models allow data distributed along time to be interpreted as the combination of
 279 several components, such as trends, or seasonal or regressive components (Petris et
 280 al., 2009; see West and Harrison, 1997, for further details on the advantages and
 281 development of the method). In essence, we modelled the dynamics of the 'true' (but
 282 unknown) SST and DCA Axis 1 sample scores in time, and modelled the observed
 283 values as deviations from these true values.
 284 The model was fitted with a Bayesian approach. The likelihood is defined by
 285 Equations (1) and (2), with both SST and DCA for each time point where either one
 286 or both was measured. We compared 60 SST data points with our 40 values of the
 287 DCA Axis 1 scores. Because only six of the SST data points and DCA Axis 1 sample
 288 scores are from the exact same depths, we treated the missing data with multiple
 289 imputation; in essence, we estimated them as extra parameters to be estimated (e.g.,
 290 Gelman et al., 2003). The cross-covariance between two points was calculated
 291 following Equation (3) and the final correlation using Equation (4).

$$293 \quad SST_i \sim N(x_{\text{SST}}(t(i)), t_{\text{SST}}^2) \quad \text{Eq. (1)}$$

$$294 \quad DCA_i \sim N(x_{\text{DCA}}(d(i)), t_{\text{DCA}}^2) \quad \text{Eq. (2)}$$

$$295 \quad \Delta d \begin{pmatrix} \sigma_{11}^2 & \rho\sigma_{11}\sigma_{22} \\ \rho\sigma_{11} & \sigma_{22} \end{pmatrix} + \begin{pmatrix} \sigma_{\text{SST}}^2 & 0 \\ 0 & \sigma_{\text{DCA}}^2 \end{pmatrix} \quad \text{Eq. (3)}$$

$$296 \quad \text{corr}(\text{SST}, \text{DCA}) = \frac{\Delta t \rho \sigma_{\text{DCA}} \sigma_{\text{SST}}}{\sqrt{(\Delta dt + \tau_{\text{DCA}}^2)(\Delta t \sigma_{\text{SST}}^2 + \tau_{\text{SST}}^2)}} \quad \text{Eq. (4)}$$

297

298 The model was fitted using OpenBUGS run through the BRugs package (Thomas et
 299 al., 2006) of the R software for statistical computing (R Development Core Team,

300 2011) fitted in a Bayesian framework using the BRugs package. The R script and
301 further explanation of the analysis is given in the Supplementary Information.

302

303 **3 Results**

304 **3.1 Sporomorph results from ODP Site 1172**

305 Of the 89 palynological samples processed from the Middle Paleocene to Lower
306 Eocene of ODP Site 1172, 40 samples yielded sporomorph counts ≥ 100 individuals
307 and were further used in our analyses. The preservation of sporomorphs is generally
308 good. A total of 197 sporomorph types were identified. A range chart with the relative
309 abundances of key taxa is presented in Fig. 2; a full account of the identified taxa and
310 their abundance data along with photomicrographs of key taxa is provided in the
311 Supplementary Information. Based on rarefied values, the entire study interval is
312 characterized by rich sporomorph assemblages (mean \pm s.d. = 29.2 ± 3.4 taxa/sample
313 at 100 individuals, $n = 40$). Remarkably low sporomorph species numbers are
314 recorded for the samples corresponding to the PETM (22.8 and 24.5 species/sample at
315 100 individuals; Fig. 2). The DCA results of our sporomorph record yield distinctly
316 different values for the Axis 1 and Axis 2 sample scores (Fig. 3a). They allow to
317 define three sample groups, with each sample group being characteristic for specific
318 time intervals of our record (Fig. 3a). These intervals are: (i) the middle (60.7 – 59.5
319 Ma) and late Paleocene (59.0 – 55.6 Ma); (ii) the middle/late Paleocene transition
320 (~59.5 to ~59.0 Ma); and (iii) the early Eocene including the PETM (55.6 – 54.2 Ma).
321 All three sample groups comprise characteristic sporomorph assemblages that are
322 portrayed in the following.

323

324 **3.1.1 Middle Paleocene (60.7 – 59.5 Ma) and late Paleocene (59.0 –**

325 **55.6 Ma) intervals**

326 The sporomorph assemblages from the middle and late Paleocene intervals (excluding
327 the middle/late Paleocene transition, see below) are represented by 20 samples. They
328 are dominated by gymnosperm pollen, which on average accounts for 45% of all
329 sporomorphs. The gymnosperm pollen is represented mainly, in the order of
330 decreasing abundances, by *Podocarpidites* spp. (botanical affinity: Podocarpaceae;
331 podocarps), *Dilwynites granulatus* (*Wollemia* [Wollemi pine]/*Agathis* [Kauri];
332 Macphail et al., 2013), *Phyllocladidites mawsonii* (*Lagarostrobos franklinii*; Huon
333 pine), and *Araucariacites* spp. (*Araucariaceae*; *Agathis* [Kauri] and *Araucaria*) (Fig.
334 2). Other abundant sporomorphs are, in the order of decreasing abundances,
335 *Cyathidites* spp. (probably *Cyatheaceae*), *Nothofagidites* spp. (*Nothofagus*; southern
336 beech), *Gambierina* spp., *Gleicheniidites* spp. (*Gleicheniaceae*), and *Ceratosporites*
337 spp. (*Lycopodiaceae*, *Selaginellaceae*).

338 Although the sporomorph assemblages from the middle to late Paleocene have very
339 similar floristic compositions, differences exist with regard to the percentages of some
340 taxa (Fig. 2). For instance, the early part of the middle Paleocene exhibits relatively
341 high (~30%) percentage of podocarpaceous pollen (mainly *Podocarpidites* spp.
342 [*Podocarpaceae*; podocarps] and *Phyllocladidites mawsonii* [*Lagarostrobos franklinii*;
343 Huon pine]). In contrast, the latest Paleocene is characterized by lower abundances of
344 these taxa (~14%), but exhibits higher percentages of *Cyathidites* spp. (~18%) and the
345 constant presence of *Myricipites harrisii* (probably *Casuarinaceae*; sheoak).
346 Remarkably, both the middle and late Paleocene are characterized by the presence of
347 *Arecipites* spp. (*Arecaceae*; palms) and *Cycadopites* spp. (*Cycadales*).

348

349 **3.1.2 Middle/late Paleocene transition interval (59.5 – 59.0 Ma)**

350 The sporomorph assemblages of the middle/late Paleocene transition interval are
351 represented by ten samples. They exhibit higher percentages of *Araucariacites* spp.
352 (*Araucariaceae*; ~19%), *Nothofagidites* spp. (*Nothofagus*; ~13%), and *Ceratosporites*
353 spp. (*Lycopodiaceae*, *Selaginellaceae*; ~6%) than the assemblages from the under-
354 and overlying Paleocene strata described in Section 3.1.1 above (Fig. 2). Other
355 abundant taxa are, in the order of decreasing abundances, *Cyathidites* spp.
356 (*Cyatheaceae*), *Dilwynites granulatus* (*Wollemia/Agathis*) and *Gleicheniidites* spp.
357 (*Gleicheniaceae*). The percentages of podocarpaceous types (*Podocarpidites* spp.
358 [*Podocarpaceae*] and *Phyllocladidites mawsonii* [*Lagarostrobos franklinii*]) are lower
359 (~10%) than in assemblages from the under- and overlying middle and late Paleocene.
360 Notably, the assemblages from the middle/late Paleocene transition interval are
361 devoid of *Arecipites* spp. (*Arecaceae*; palms) and *Cycadopites* spp. (*Cycadales*)
362 pollen.

363

364 3.1.3 PETM and early Eocene interval (55.6 – 54.2 Ma)

365 Assemblages from the PETM are documented in two samples with counts ≥ 100
366 individuals. They are characterized by high percentages (up to 39%) of *Dilwynites*
367 *granulatus* (*Wollemia/Agathis*). Other abundant taxa are, in the order of decreasing
368 abundances, *Cyathidites* spp. (*Cyatheaceae*), *Araucariacites* spp. (*Araucariaceae*), and
369 *Gleicheniidites* spp. (*Gleicheniaceae*). The assemblages of the PETM interval are
370 further characterized by the presence of *Malvacipollis* spp. (*Euphorbiaceae*, probably
371 *Eumalvoideae*) and *Myricipites harrisii* (probably *Casuarinaceae*). Findings of
372 *Spinizonocolpites prominatus* (*Nypa* palm) are restricted to the PETM and the earliest
373 Eocene (Fig. 2).

374 Sporomorph assemblages of the early Eocene interval are documented in 8 samples.

375 They show in general very high percentages (mean: 20%) of *Cyathidites* spp.
376 (probably Cyatheaceae; Fig. 2). Other abundant taxa are, in the order of decreasing
377 abundances, *Dilwynites granulatus* (*Wollemia/Agathis*), *Araucariacites* spp.
378 (*Araucariaceae*), *Podocarpidites* spp. (*Podocarpaceae*), and *Phyllocladidites mawsonii*
379 (*Lagarostrobos franklinii*). The early Eocene interval is also characterized by
380 relatively high percentages of *Proteacidites* spp. (~7%) and the constant presence of
381 *Malvacipollis* spp. (*Euphorbiaceae*, probably *Eumalvoideae*), *Myricipites harrisii*
382 (probably *Casuarinaceae*), *Arecipites* spp. (*Arecaceae*; palms), and *Cycadopites* spp.
383 (*Cycadales*).

384

385 **3.2 Sporomorph-based paleoclimate estimates**

386 The paleoclimate estimates derived from the sporomorph assemblages from ODP Site
387 1172 are presented in Fig. 4. Weighted averages with their respective propagated
388 errors are given in Table 3. For the middle Paleocene (60.7–59.5 Ma), all
389 reconstructed temperature parameters yield relatively cool values (MAT = 9 – 16°C;
390 CMMT = 5 – 9°C; WMMT = 15 – 22°C). A pronounced further cooling is
391 documented in all temperature parameters for the middle/late Paleocene transition
392 interval (59.5–59.0 Ma). The reconstructed values represent the lowest temperatures
393 of the entire record; values are 8 – 14°C for MAT, 4 – 7°C for CMMT and 15 – 20°C
394 for WMMT (see Fig. 4). Markedly higher temperatures prevailed during the late
395 Paleocene (59.0–55.6 Ma) and early Eocene (55.6–54.2 Ma), with estimates for that
396 interval being on the order of 11 – 22°C for MAT, 6 – 18°C for CMMT and 17 –
397 26°C for WMMT. The highest temperatures of the entire study interval are recorded
398 for the Paleocene/Eocene transition interval (including the PETM); MAT, CMMT and
399 WMMT reached values of ~22°C, ~18°C and ~26°C, respectively, during that time

400 (Fig. 4). The sporomorph-based MAP estimates yield high (138 – 208 cm/yr; see Fig.
401 4 and Table 3), near-constant values throughout the sequence studied.

402

403 **4 Interpretation**

404 **4.1 Constraints on sporomorph source region**

405 Several lines of evidence suggest that eastern Tasmania was the main source of the
406 sporomorphs encountered in the Middle Paleocene to Lower Eocene of ODP Site
407 1172. The distance of this site to the paleo-shoreline of eastern Tasmania during the
408 Paleocene–early Eocene was on the order of ~100 km, whereas the minimum distance
409 to George V Land (Antarctica) amounted to ~500 km (Fig. 1). A Tasmanian source is
410 further suggested based on the distribution pattern of reworked Permian and Triassic
411 sporomorphs. The assemblages from ODP Site 1172 are characterized by the constant
412 presence of elements reworked from Permian and Triassic strata (e.g.,
413 *Cannanoropollis* spp., *Protohaploxypinus* spp., *Alisporites* spp.; see Supplementary
414 Information, Plate II); the percentages of reworked sporomorphs reach up to 16% of
415 the total assemblages. A similar input of reworked Permian and Triassic material is
416 known for sporomorph assemblages from Paleocene–Eocene strata along the
417 Australo-Antarctic Gulf (Otway Basin; Harris, 1965) and from the Eocene of the
418 Wilkes Land margin (Contreras et al., 2013). In the Tasmania region, reworked
419 Permian and Triassic sporomorphs are recorded in the Paleocene–Eocene of the Bass
420 Basin (Partridge et al., 2003) as well as in Eocene strata off western Tasmania and on
421 the South Tasman Rise (Truswell, 1997). This pattern is consistent with the fact that
422 sporomorph-bearing sediments of Permian and Triassic age occur in several regions
423 of Tasmania (e.g., Playford, 1965; Truswell, 1978; Calver et al., 1984). In contrast,
424 reworked sporomorphs on the continental shelf off George V Land (Antarctica; Fig.

425 1) comprise only taxa with Cretaceous and Cenozoic ages (Truswell, 1983). A similar
426 picture emerges for the Cenozoic of the Gippsland Basin where Permian and Triassic
427 sporomorphs occur only sporadically and in low numbers (see reports in Department
428 of Primary Industries, 1999).

429 A further constraint on the source of the sporomorphs at ODP Site 1172 comes from
430 the DCA-based comparison of the floristic composition of the Site 1172 record with
431 other coeval Paleocene–Eocene sporomorph records from Southeast Australia (Bass
432 and Gippsland Basins, Southeast Highlands) and New Zealand (Middle Waipara and
433 Otaio River sections) (Fig. 3b; see Fig. 1 and Table 1 for site locations and details on
434 records). It suggests marked differences in floristic compositions between most
435 records, a result that can be further corroborated for the Bass and Gippsland Basins
436 based on carbon-isotope data from both basins. The Paleocene–Eocene successions of
437 these basins exhibit distinctly different bulk carbon isotope values, which is
438 interpreted to reflect the signal from different plant communities contributing to the
439 organic carbon input into the basins during that time (Boreham et al., 2003).
440 However, despite the floristic differences between the records analysed, there is a
441 remarkable similarity in DCA scores between the records from ODP Site 1172 and
442 the Bass Basin (Fig. 3b), which is located mainly on the shelf off northern Tasmania,
443 but also extends into Northeast Tasmania (Moore et al., 1984). This similarity further
444 corroborates the scenario of a Tasmanian source for the ODP Site 1172 sporomorph
445 assemblages.

446

447 **4.2 Floristic and climatic evolution**

448 Based on our qualitative and quantitative results from the sporomorph record from
449 ODP Site 1172, three main vegetation types prevailed on Tasmania from the middle

450 Paleocene to early Eocene. These vegetation types (i) exhibit different floristic
451 compositions based on the DCA results (Figs. 2 and 3a), (ii) show similar diversities
452 based on the rarefaction results (Fig. 2), and (iii) represent specific climatic conditions
453 based on our sporomorph-derived paleoclimatic reconstructions (Fig. 4). The floristic
454 characteristics and climatic requirements of all three vegetation groups are discussed
455 in the following sections.

456

457 **4.2.1 Middle Paleocene (60.7 – 59.5 Ma) and late Paleocene (59.0 –** 458 **55.6 Ma) intervals**

459 During both time intervals, the flora of Tasmania was characterized by gymnosperm-
460 rich forests dominated by podocarps; Araucariaceae, ferns, protealeans and
461 *Nothofagus* were further important components of the vegetation. Arecaceae (palms)
462 and Cycadales were present during both time intervals. Although the middle
463 Paleocene and late Paleocene forests exhibited a strongly similar composition,
464 important differences existed. Podocarps reached a markedly stronger dominance
465 during the middle Paleocene than during the late Paleocene, whereas the late
466 Paleocene was characterized by higher abundances of ferns (mainly Cyatheaceae) and
467 the presence of Casuarinaceae (Fig. 2).

468 With regard to modern analogues, these forests bear resemblance to the extant warm-
469 temperate, Podocarpaceae-dominated forests of Southeast Australia and New Zealand
470 (e.g., Kershaw, 1988). Based on the structure of extant temperate forests from the
471 southern latitudes (Kershaw, 1988; Enright and Hill, 1995; Veblen et al., 1996; Reid
472 et al., 1999), the overstorey of Tasmanian forests during the middle and late
473 Paleocene was dominated by Podocarpaceae and, to a somewhat lesser extent,
474 Araucariaceae and *Nothofagus*. The understorey, in turn, was likely dominated by

475 ferns, with Cyatheaceae being particularly abundant during the late Paleocene.
476 Considering the habitats of their extant representatives, Arecaceae (palms),
477 Cycadales, Proteaceae, and Casuarinaceae formed parts of both the over- and
478 understorey (compare Johnson and Wilson, 1993; Hill, 1994; Morley, 2000; Jones,
479 2002).

480 Climatically, the presence of tree ferns (i.e., Cyatheaceae), Arecaceae and Cycadales
481 implies mild climates with no or merely rare frost events. Owing to physiological
482 constraints (including manoxylic wood, large, unprotected buds, soft, water-rich
483 tissues, and a near-absence of frost-“hardening” mechanisms), all these plants are
484 unable to cope with sustained freezing (Sakai and Larcher, 1987; Wing and
485 Greenwood, 1993); today, they only occur in settings with CMMT $\geq 5.5^{\circ}\text{C}$
486 (Greenwood and Wing, 1995; Utescher and Mosbrugger, 2013).

487

488 **4.2.2 Middle/late Paleocene transition interval (59.5 – ~59.0 Ma)**

489 Across the middle/late Paleocene boundary, the warm-temperate forests
490 characterizing the vegetation on Tasmania during most of the middle and late
491 Paleocene as described above were transiently replaced by cool-temperate forests
492 dominated by *Nothofagus* (mainly *N. fusca* type) and Araucariaceae. Ferns,
493 podocarps and protealeans were further prominent components of this vegetation.
494 Palms (Arecaceae) and Cycadales, as they occurred both during the preceding part of
495 the middle (60.7–59.5 Ma) and the subsequent part of the late Paleocene (59.0–55.6
496 Ma; see above), were absent (Fig. 2). In light of the age control and the temporal
497 resolution of our record, these cool-temperate forests prevailed on Tasmania for ~0.5
498 Ma (based on the duration of elevated *Nothofagus* percentages) respectively ~0.3 Ma
499 (based on the absence of tropical to subtropical indicators such as palms and

500 Cycadales). The 1.3-Myr-long hiatus precludes us from firmly determining the
501 complete duration of the cold interval in the mid-Paleocene (Fig. 2), however from
502 marine records from New Zealand we deduce a duration of 0.5 Ma (Waipara section
503 and ODP Site 1121; Hollis et al., 2014).

504 Today, vegetation dominated by *Nothofagus* (*N. fusca* type) is typical of cool-
505 temperate forests from southern Australia and New Zealand (Kershaw, 1988).
506 Considering the structure of such forests (e.g., McGlone et al., 1996; Reid et al.,
507 1999), the vegetation thriving during the middle/late Paleocene transition interval was
508 characterized by a canopy dominated by *Nothofagus* and open understories dominated
509 by ferns (mainly Cyatheaceae and the parent plants of *Ceratosporites* spp.
510 [Selaginellaceae, Lycopodiaceae]). Araucariaceae were also present. Because extant
511 members of Araucariaceae are tall trees generally confined to the lower mid-latitudes
512 (Kershaw and Wagstaff, 2001), their presence appears at first sight incompatible with
513 an occurrence of cool-temperate forests. However, members of the genus *Araucaria*
514 also thrive in cold temperate forests in mountainous areas of Chile (Veblen, 1982) and
515 can withstand frost events as cold as -15°C (Prentice et al., 1992), which supports our
516 observation that Araucariaceae were a component of the cool-temperate forests of
517 Tasmania across the middle/late Paleocene transition.

518 Based on the overall floristic evidence, Tasmania witnessed a transient period of
519 cooler conditions lasting from ~ 59.5 to ~ 59.0 Ma. In light of the frost sensitivity of
520 Areaceae, Cycadales and Cyatheaceae (compare Section 4.2.1), the decline or total
521 absence of these taxa across the middle/late Paleocene transition (Fig. 2) suggests
522 harsher winters (with particularly frequent and/or cold frost events) during that time.
523 Such lower temperatures are corroborated by the comparison with coeval $\text{TEX}_{86}^{\text{L}}$ -
524 and $\text{TEX}_{86}^{\text{H}}$ -based SST data from ODP Site 1172 (Bijl et al., 2009; 2013b; Hollis et

525 al., 2014). For the interval from ~59.4 to ~59.0 Ma, they show the lowest values of
526 the entire Paleocene–Eocene SST record (Fig. 4, Table 3).

527

528 **4.2.3 PETM and Early Eocene interval (55.6 – 54.2 Ma)**

529 During the early Eocene, the composition of the forests on Tasmania was distinctly
530 different from that of the temperate forests thriving during the Paleocene (Figs. 2, 3a);
531 the underlying floristic turnover coincides with the onset of the PETM (see DCA Axis
532 1 sample scores in Fig. 2). Based on our sporomorph data, the early Eocene
533 vegetation was dominated by ferns and different angiosperms (mainly Proteaceae,
534 Casuarinaceae and Euphorbiaceae/Eumalvoideae). Remarkably, taxa that were
535 common during the Paleocene (e.g., *Ceratosporites* spp. [Lycopodiaceae,
536 Selaginellaceae] and *Gambierina* spp. [extinct clade]) declined dramatically in
537 abundance or disappeared completely during that time (Fig. 2). Because extant
538 Selaginellaceae and Lycopodiaceae are cosmopolitan families (Jermy, 1990;
539 Øllgaard, 1990), it is difficult to connect the disappearance of these taxa on Tasmania
540 during the earliest Eocene with specific ecological and climatic conditions.

541 The coexistence of frost-tolerant (e.g., Araucariaceae, Podocarpaceae) and
542 thermophilous taxa (e.g., Casuarinaceae, Arecaceae [palms]) suggests the presence of
543 paratropical forests *sensu* Morley (2000). In particular, the occurrence of *Nypa* from
544 the PETM onward into the early Eocene suggests the presence of tropical mangrove
545 vegetation along the coast of Tasmania. A similar vegetation, also containing
546 thermophilous taxa such as *Nypa* and *Gymnostoma* (Casuarinaceae), is documented
547 in early Eocene macrofloras from western Tasmania (Pole, 2007; Carpenter et al.,
548 2012). Hence, forests on Tasmania during the early Eocene consisted temporarily of
549 at least two vegetation associations: (i) A mangrove association characterized by

550 *Nypa*, which is only recognized during the PETM and the earliest Eocene, and (ii) a
551 paratropical association characterized by the coexistence of frost-tolerant taxa (i.e.,
552 Araucariaceae, Podocarpaceae and *Nothofagus*) and thermophilous elements such as
553 palms and Casuarinaceae.

554 Considering the ecology of the nearest living relatives of the plants represented by the
555 encountered sporomorphs, the overstorey vegetation during the early Eocene
556 comprised taxa such as Araucariaceae, Podocarpaceae and *Nothofagus*, whereas the
557 understorey was probably dominated by ferns (mainly Cyatheaceae). Members of the
558 Proteaceae, Casuarinaceae, Cycadales, Arecaceae (palms), and
559 Euphorbiaceae/Eumalvoideae may have been both components of the over- and the
560 understorey (Johnson and Wilson, 1993; Hill, 1994; Morley, 2000; Jones, 2002).

561 The number of sporomorph species registered at ODP Site 1172 remained relatively
562 constant from the middle Paleocene to the early Eocene (Fig. 2). This observation is
563 in contrast to Southeast Australia, where sporomorph assemblages from non-marine
564 and marginal marine settings (Partridge, 1976) exhibit a considerably higher diversity
565 during the early Eocene than during the Paleocene (Macphail et al., 1994; see Section
566 4.3.2. below). The reasons behind this discrepancy may be sought in the particularly
567 high sea level during the early Eocene as it is recorded regionally based on
568 sedimentological and paleontological data from ODP Site 1172 (Exon et al., 2004a)
569 and globally (Miller et al., 2005; Cramer et al., 2011). Owing to the selective nature
570 of marine sporomorph transport as a function of transport distance (e.g., Moss et al.,
571 2005), the higher sea level during the early Eocene than during the Paleocene
572 potentially caused a diversity decrease of the sporomorph assemblages at ODP Site
573 1172 (see also below).

574 Our data suggest that the floristic change connected to the PETM is similar to that

575 registered for the early Eocene. However, unravelling the exact anatomy of vegetation
576 change across the PETM at ODP Site 1172 is difficult due to the low sporomorph
577 yields in the respective sediments at that site. In addition, the interpretation of the
578 available data is hampered by the sea-level rise during the PETM (Sluijs et al., 2011);
579 the transgression-induced change in depositional setting towards more distal
580 conditions may have caused a bias in the composition and diversity patterns of
581 sporomorph assemblages, with the resulting assemblages being skewed towards a
582 dominance of easily transported sporomorphs (compare Traverse, 1994; 2008). In
583 light of this bias, the high abundances (up to 39%; Fig. 2) of *Dilwynites granulatus*
584 (*Wollemia/Agathis*) and the remarkably low diversities (Fig. 2) in the PETM samples
585 from ODP Site 1172 likely represent a change in depositional setting rather than a
586 true paleoecological signal. This interpretation is supported by the higher abundances
587 of the same species (~35%) in early Paleogene sediments deposited in distal
588 environments of the Bass Basin when compared to the markedly lower abundances
589 (~10%) in coeval sediments from nearshore settings in the same basin (see reports in
590 Partridge et al., 2003). Nevertheless, our data show that the environmental
591 perturbations connected to the PETM had a profound impact on the vegetation on
592 Tasmania. They lead to the extirpation of various ferns (e.g., *Perinomonoletes* spp.,
593 *Ceratosporites* spp. [Lycopodiaceae, Selaginellaceae]) and angiosperms (e.g.,
594 *Gambierina rudata*, *Nothofagidites* sp. 1 [*Nothofagus*]), and the appearance of new
595 angiosperms mainly within the Proteaceae family (e.g., *Proteacidites grandis*).

596

597 **4.3 Integration with other terrestrial vegetation records and** 598 **temperature estimates from the southern high latitudes**

599 Our results from ODP Site 1172 yield a ~6.5-Ma-long vegetation record for the

600 Tasman sector of the SW Pacific region spanning from the middle Paleocene to the
601 early Eocene. To obtain insights into the potential regional differentiation of
602 terrestrial ecosystems and climates in the high southern latitudes during that time, we
603 have integrated our data from ODP Site 1172 with the available information on
604 terrestrial ecosystems and temperatures from other parts of the SW Pacific domain.
605 Our integration is augmented by newly generated temperature estimates for
606 previously published sporomorph records from Southeast Australia and New Zealand
607 (see Tables 1 and 3 for further information on records evaluated and results). Because
608 other continuous, stratigraphically well-calibrated vegetation records across the
609 middle/late Paleocene transition interval are not yet available for the SW Pacific
610 region, we focus our comparison on the middle Paleocene, late Paleocene and early
611 Eocene.

612

613 **4.3.1 Middle and late Paleocene**

614 Paleobotanical records for the middle and late Paleocene are well known from
615 Southeast Australia (e.g., Bass Basin – Macphail et al., 1994; Blevin, 2003; Gippsland
616 Basin – Stover and Partridge, 1973; Macphail et al., 1994; Department of Primary
617 Industries, 1999). In summary, the middle and late Paleocene vegetation in this region
618 consisted predominantly of warm temperate forests characterized by podocarps,
619 Araucariaceae and ferns; angiosperms were represented mainly by Proteaceae (e.g.,
620 Taylor et al., 1990; Macphail et al., 1994; Greenwood et al., 2003; Greenwood and
621 Christophel, 2005). Similar warm temperate forests dominated by podocarps and
622 Araucariaceae, and with a strong contribution of Proteaceae, thrived on New Zealand
623 (Mildenhall, 1980; Raine et al., 2009).

624 Based on our results, Podocarpaceae together with Araucariaceae, Cyatheaceae and

625 Proteaceae were also the prevailing group of plants during the middle and late
626 Paleocene on Tasmania (Fig. 2; compare also Section 4.2.1). However, important
627 floristic differences existed between Southeast Australia, New Zealand and Tasmania
628 (Fig. 3b); they are mainly based on the restriction of certain sporomorph taxa to
629 specific regions (e.g., *Liliacidites* spp., *Cibotioidites tuberculiformis* – New Zealand;
630 *Ilexpollenites* spp. – Southeast Australia [Bass and Gippsland Basins, Southeast
631 Highlands]; *Tripunctisporis maastrichtiensis* – New Zealand, Bass Basin and
632 Tasmania). Despite the differences in floristic composition, the remarkable
633 dominance of Podocarpaceae and Araucariaceae in Southeast Australia, Tasmania and
634 New Zealand suggests that warm-temperate forests dominated by gymnosperms were
635 the prevalent vegetation type in the Southwest Pacific region during the middle and
636 late Paleocene. Moreover, thermophilous taxa such as palms, Olacaceae (*Anacolosa*)
637 and Cupanieae first appeared and/or increased significantly in abundance and
638 diversity during the latest Paleocene in Southeast Australia (Kemp, 1978; Macphail et
639 al., 1994). On New Zealand, typical tropical taxa (e.g., Cupanieae, *Austrobuxus*
640 [Euphorbiaceae], *Nyssa*) also begin to appear during the latest Paleocene prior to the
641 PETM (Crouch and Brinkhuis, 2005; Raine et al., 2009). Hence, the arrival of
642 thermophilous elements indicates the onset of warmer conditions in the Southwest
643 Pacific region during the latest Paleocene. A scenario of warm conditions is further
644 corroborated by MAT estimates reaching ~18°C as derived from latest Paleocene
645 macrofloras in Southeast Australia (Greenwood et al., 2003).

646 Considering our sporomorph-based climate estimates for Southeast Australia and
647 Tasmania (Table 3), temperatures were higher during the late Paleocene than during
648 the middle Paleocene. Hence, the overall climatic and vegetation signal suggests that
649 terrestrial settings across the Southwest Pacific region consistently experienced a

650 pronounced warming during the late Paleocene.

651

652 **4.3.2 PETM and Early Eocene**

653 The effects of the PETM on terrestrial ecosystems in the high southern latitudes are
654 yet poorly constrained. Available records from Southeast Australia (Bass and
655 Gippsland Basins) covering the PETM and the earliest Eocene suggest the widespread
656 presence of *Nypa* during that time (Partridge, 1976). Climatically, this indicates a
657 MAT >21.7°C (Utescher and Mosbrugger, 2013). For the South Island of New
658 Zealand, sporomorph data from nearshore marine sediments document the
659 development of *Nypa* mangrove swamps and the appearance of pollen from the
660 thermophilous subfamily Cupanieae connected to the PETM interval (Handley et al.,
661 2011); moreover, the PETM is characterized by a percentage increase of fern spores
662 as well as of Euphorbiaceae/Eumalvoideae and Myrtaceae pollen at the expense of
663 gymnosperm pollen percentages (Handley et al., 2011). Similarly, sporomorph data
664 for the North Island of New Zealand as available from the Tawanui section show the
665 presence of *Nypa* pollen connected to the PETM (Crouch and Visscher, 2003).
666 However, besides a marked increase of *Dilwynites granulatus* (*Wollemia/Agathis*)
667 pollen, no other significant changes in floristic composition occur (Crouch and
668 Visscher, 2003). Considering that the PETM sediments of the Tawanui section are
669 part of a transgressive systems tract (Crouch and Brinkhuis, 2005; Sluijs et al., 2008),
670 the high abundances of *Dilwynites granulatus* (*Wollemia/Agathis*) may represent a
671 taphonomic rather than a paleoecological signal as suggested for the sporomorph
672 record of the PETM from ODP Site 1172 (see Section 4.2.3).
673 With regard to the early Eocene, the majority of vegetation records in the Southwest
674 Pacific region come from Southeast Australia; they suggest that by early Eocene

675 times the warm temperate, conifer-dominated forests of the late Paleocene had been
676 replaced by more diverse, meso- to megathermal angiosperm forests (Macphail et al.,
677 1994; Greenwood et al., 2003; Greenwood and Christophel, 2005). Although
678 sporomorph percentages are extremely variable within the available records from
679 Southeast Australia, Araucariaceae, Casuarinaceae, Euphorbiaceae/Eumalvoideae,
680 Proteaceae, and ferns are generally the dominant taxa; typical tropical elements such
681 as *Nypa*, *Anacolosa* and Cupanieae are also recorded (Kemp, 1978; Macphail et al.,
682 1994). This trend in vegetation development during the early Eocene is also
683 documented for Tasmania.

684 On New Zealand, early Eocene sporomorph assemblages exhibit a mixed Paleocene-
685 Eocene character, with a continued high abundance of conifer pollen (Crouch and
686 Visscher, 2003; Raine et al., 2009). However, thermophilous taxa such as Cupanieae,
687 Casuarinaceae and Euphorbiaceae (*Austrobuxus*) are constantly present in these
688 records (Pocknall, 1990; Raine et al., 2009), and Casuarinaceae pollen abruptly
689 started to dominate the sporomorph assemblages from ~54.5 Ma onwards (Raine et
690 al., 2009). On the Wilkes Land margin (Antarctica), paratropical vegetation has been
691 recorded during the early Eocene (53.9–51.9 Ma) with the notable presence of
692 thermophilous taxa such as Arecaceae (palms) and Bombacoideae (Pross et al., 2012;
693 Contreras et al., 2013),

694 With regard to temperature conditions, early Eocene macrofloras from Southeast
695 Australia suggest a MAT of ~19°C from ~56 to ~53 Ma (Greenwood et al., 2003),
696 which is very similar to our MAT estimates for coeval sporomorph records (~55.8–
697 54.3 Ma; lower *Malvacipollis diversus* zone of Partridge (2006; Table 1) from the
698 Bass and Gippsland Basins (~18°C; Table 3). On the Wilkes Land margin, climatic
699 estimates for the early Eocene (53.9–51.9 Ma) suggest a MAT of ~16°C for the

700 lowland regions (Pross et al., 2012). Although occasionally MAT values as high as
701 ~23°C are recorded during the earliest Eocene at ODP Site 1172, the MATs for this
702 time interval are on the order of 12 – 14°C (Fig. 4). This is markedly lower than those
703 from Southeast Australia, and even lower than those from the Wilkes Land margin.
704 Considering that our sporomorph-derived climate data from ODP Site 1172 mainly
705 reflect climate conditions along the coast of eastern Tasmania (compare discussion on
706 sporomorph source region in Section 4.1), these relatively low values may suggest
707 that the eastern part of Tasmania was influenced by the relatively cool Tasman
708 Current (Fig. 1). However, this argument is not supported by the TEX₈₆-derived SSTs
709 from ODP Site 1172 for the early Eocene, which are much higher (mean: 23°C -
710 TEX₈₆^L, 28°C - TEX₈₆^H; Bijl et al., 2013b). Terrestrial, macroflorally derived
711 temperatures on the order of 24°C from western Tasmania (Carpenter et al., 2012)
712 suggest that this region was significantly warmer than the eastern part of Tasmania.
713 Alternatively, another potential explanation for this discrepancy is that the sea-level
714 rise during the early Eocene biased the composition of the sporomorph assemblages at
715 ODP Site 1172 (compare Section 4.2.3) towards a dominance of easily transported
716 and/or particularly abundant sporomorphs indicative of cool conditions at the expense
717 of rarer sporomorphs indicative of warmer conditions. This scenario is supported by
718 the fact that many thermophilous plants from the Lower Eocene of the Southwest
719 Pacific region (e.g., *Arecaceae* [palms], *Cupanieae*, *Ilex*, *Nypa*) are mainly insect-
720 pollinated (Bush and Rivera, 1998; Barfod et al., 2011). Hence, these taxa reach only
721 low abundances in pollen spectra when compared to wind-pollinated taxa, and they
722 are not likely to be transported over larger distances before they settle (Jackson,
723 1994).

724 Despite of the potential bias on the early Eocene sporomorph assemblages at Site

725 1172, the supraregional replacement of temperate forests by paratropical forests
726 during the early Eocene on Southeast Australia, New Zealand and Tasmania and the
727 widespread occurrence of *Nyssa* palms during the PETM in the same regions
728 consistently indicate a pronounced reorganization of the vegetation during the early
729 Eocene in the high southern latitudes connected to the PETM.

730

731 **4.4 Integration with other precipitation records from the southern high** 732 **latitudes**

733 Based on our paleoclimatic results from the sporomorph record of ODP Site 1172,
734 MAP on Tasmania was relatively constant (~180 cm/yr) from the middle Paleocene to
735 the early Eocene (Fig. 4; Table 3). These values are comparable to the present-day
736 precipitation received by rainforests in western Tasmania at ~42 °S (185 cm/yr,
737 Corinna; Bureau of Meteorology, 2012), along the west coast of the South Island of
738 New Zealand (212 cm/yr; Westport; NIWA, 2012), northern Australia (180 cm/year,
739 Darwin Botanic Gardens; Bureau of Meteorology, 2012) and on the east coast of New
740 Caledonia (197 cm/year, Puoébo; Pesin et al., 1995). The high-precipitation regime on
741 Tasmania during the early Paleogene as deduced from the sporomorphs is further
742 corroborated by the dominance of the dinocyst genus *Senegalinium* at ODP Site 1172
743 during this time interval (Sluijs et al., 2011); this genus is characterized by many
744 freshwater-tolerant species (Sluijs et al., 2005; Brinkhuis et al., 2006). Hence, the
745 observed *Senegalinium* dominance, which is best explained by substantial freshwater
746 input, is well compatible with high precipitation on Tasmania and a resulting strong
747 freshwater influx on the Tasmanian continental shelf during the early Paleogene.

748 Because of the general lack of precipitation data from other sites at high southern
749 latitudes we can mainly compare our estimates from Tasmania with values deduced

750 from other coeval paleobotanical records. Based on our results from sporomorph
751 assemblages from Southeast Australia (Table 3), this region experienced similarly
752 high precipitation (MAP: ~200 cm/yr) during the early Paleogene; this is consistent
753 with MAP mean estimates (186–240 cm/yr) as derived from macrofloral records from
754 the Upper Paleocene to Lower Eocene of the same region (Greenwood et al., 2003).
755 On the Wilkes Land margin (Antarctica), high precipitation values (MAP mean: ~132
756 cm/yr) are also suggested for the early Eocene (Pross et al., 2012). These high
757 precipitation values (>100 cm/yr) have been corroborated recently by alkaline major
758 element geochemistry for Eocene sediments from Antarctica (Passchier et al., 2013).
759 Based on the overall precipitation data, Tasmania and the Australia-Antarctic region
760 experienced high rainfall conditions during the early Paleogene, comparable with
761 present-day rainforests from southern latitudes. This lends support to modeling
762 studies that include high atmospheric humidity as an important warming mechanism
763 for the higher latitudes (e.g., Abbot et al., 2009).

764

765 **4.5 Comparison with marine temperature evolution**

766 Based on our sporomorph data (as evidenced in the Axis 1 sample scores of the DCA
767 results, which represent the variation in floristic composition along the studied
768 interval; Fig. 4) and the $\text{TEX}_{86}^{\text{L}}$ and $\text{TEX}_{86}^{\text{H}}$ data of Bijl et al. (2009; 2013b) and
769 Hollis et al. (2014), there is a strong correlation between the vegetation composition
770 on eastern Tasmania and SST at ODP Site 1172 (Fig. 4). This connection is clearly
771 borne out by our results from the state space model, where there is a very strong
772 correlation of 0.997 when DCA Axis 1 sample scores are compared with $\text{TEX}_{86}^{\text{L}}$
773 (95% highest posterior density: 0.633–0.999 based on Equation [4]; compare Section
774 2.4) and 0.978 when DCA Axis 1 sample scores are compared with $\text{TEX}_{86}^{\text{H}}$ (95%

775 highest posterior density: 0.879–0.997 based on Equation [4]; compare Section 2.4).
776 Hence, the strong correlation between the temperature variability derived from TEX₈₆
777 and the floristic composition recorded at ODP Site 1172 demonstrates the impact of
778 temperature on the vegetation dynamics in the Southwest Pacific region during the
779 early Paleogene.

780 A close coupling between the temperature evolution in the marine and the terrestrial
781 realms is also evident through the comparison of our sporomorph-based temperature
782 estimates (notably WMMTs) with the TEX₈₆-derived SSTs (Fig. 4 and Table 3); it is
783 only during the early Eocene that the pronounced warming trend recorded by TEX₈₆^L
784 and TEX₈₆^H is not clearly reflected in the sporomorph-based temperature estimates,
785 likely due to the sea-level increase during the early Eocene (compare Sections 4.2.3
786 and 4.3.2).

787 The terrestrial, sporomorph-derived MATs are markedly cooler than the SSTs derived
788 from TEX₈₆^L and TEX₈₆^H (Fig. 4), which based on the traditional perception of the
789 TEX₈₆ proxy are supposed to represent surface-water MAT (e.g., Schouten et al.,
790 2002). At the same time, the TEX₈₆-derived SSTs are closely related to the
791 sporomorph-derived WMMTs (Fig. 4, Table 3). These observations suggest that
792 TEX₈₆-based temperatures may be biased towards warm conditions when applied to
793 early Paleogene records from the high southern latitudes. Such a warm (summer) bias
794 has also been suggested for other early Paleogene records from the high southern
795 latitudes based on different multiproxy approaches (Bijl et al., 2009; 2013a; Sluijs et
796 al., 2011; Hollis et al., 2012; Pancost et al., 2013).

797

798 5 Conclusions

799 The middle Paleocene to early Eocene vegetation on Tasmania as reconstructed from

800 the sporomorph record of ODP Site 1172 was characterized by three different forest
801 types that thrived in high-precipitation regimes under different temperature
802 conditions. These forest types were: (i) warm-temperate rainforests dominated by
803 Podocarpaceae during the middle and late Paleocene; (ii) cool-temperate rainforests
804 dominated by *Nothofagus* and Araucariaceae that transiently prevailed across the
805 middle/late Paleocene transition interval (iii) paratropical rainforests dominated by
806 Cyatheaceae during the early Eocene with the remarkable presence of the mangrove
807 palm *Nypa* during the PETM and the earliest Eocene. The comparison with other,
808 previously published floral records from the Southwest Pacific region (including
809 Southeast Australia and New Zealand) supports the validity of our data for Tasmania.
810 It shows that temperate forests were replaced by paratropical forests during the early
811 Eocene throughout the Southwest Pacific region. This reorganisation in vegetation
812 composition included an increase in fern (mainly Cyatheaceae) and angiosperm
813 abundances (e.g., Proteaceae, Euphorbiaceae/Eumalvoideae, Casuarinaceae) at the
814 expense of gymnosperms (mainly podocarps).

815 The integration of terrestrial (i.e., floristic) and previously published marine (i.e.,
816 TEX₈₆-based SST) climate information from ODP Site 1172 shows that the surface-
817 water cooling of ~3°C across the middle/late Paleocene transition interval (~59.5 to
818 ~59.0 Ma) was paralleled by a transient demise of frost-sensitive plants (i.e., palms
819 and cycads) and the establishment of cool-temperate forests dominated by *Nothofagus*
820 and Araucariaceae on Tasmania. This suggests that cooler conditions (and notably
821 harsher winters with strong and/or frequent frosts) prevailed on Tasmania during that
822 time.

823 In light of the statistically robust connection between the floristic composition of the
824 sporomorph record from ODP Site 1172 and the previously published TEX₈₆- based

825 SST record from the same site, the vegetation dynamics on Tasmania during the
826 middle Paleocene to early Eocene were mainly driven by temperature; precipitation
827 remained high (with a MAP mean of ~180 cm/yr) throughout that time. Based on the
828 comparison of our sporomorph-derived temperatures with the TEX₈₆-based SSTs, we
829 conclude that TEX₈₆^L- and TEX₈₆^H-derived temperatures for the high southern
830 latitudes of the early Paleogene are likely biased towards summer conditions.

831

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845

846 **TABLE AND FIGURE LEGENDS**

847

848 **Table 1.** Sporomorph datasets evaluated in this study from the Southeast Australia
849 (Bass Basin, Gippsland Basin, Southeast Highlands) and New Zealand (Middle

850 Waipara and Otaio River sections). Asterisks indicate data derived from palynological
851 reports in Department of Primary Industries (1999). Plus signs denote data derived
852 from the Appendix C of Blevin (2003). Biozones and ages are based on Stover and
853 Evans (1973), Stover and Partridge (1973) and Partridge (2006).

854

855 **Table 2.** List of fossil sporomorph taxa from the Middle Paleocene to Lower Eocene
856 of ODP Site 1172 with known botanical affinities and literature source, the nearest
857 living relative (NLR) used in the climate reconstruction, and database where climate
858 profiles of the NLRs are derived from. Database (1) = PALAEOFLORA (Utescher
859 and Mosbrugger, 2013), Database (2) = Pross et al. (2012). Taxa used in the climatic
860 evaluation are printed in boldface.

861

862 **Table 3.** Sporomorph-based climate estimates for Paleocene to early Eocene records
863 from Southeast Australia (Bass Basin, Gippsland Basin, Southeast Highlands), New
864 Zealand (Middle Waipara and Otaio River sections) and ODP Site 1172. SST values
865 given for each stratigraphic interval represent average values of the data of Bijl et al.
866 (2013b) and Hollis et al. (2014), with (H) and (L) denoting TEX_{86}^H (calibration error
867 $\pm 2.5^\circ C$) respectively TEX_{86}^L (calibration error $\pm 4.0^\circ C$). Sporomorph-derived climate
868 estimates are based on the methodology of Greenwood et al. (2005) and are presented
869 with the weighted averages and their respective propagated errors (See
870 Supplementary Information for further details). MAT = Mean Annual Temperature,
871 CMMT = Coldest Month Mean Temperature, WMMT= Warmest Month Mean
872 Temperature, MAP = Mean Annual Precipitation.

873

874 **Figure 1.** Map of the Southwest Pacific Ocean showing the early Eocene (~53 Ma)
875 continental configuration, illustrating modern continents (gray), areas shallower than
876 300 m (blue) and locations of ODP Site 1172 and localities listed in Table 1. SM =
877 Southern Monaro Sections (Southeast Highlands), B = Burong-1, K = Kingfish-8, Ko
878 = Konkon-1, MW-OS = Middle Waipara and Otaio River sections, P = Poonboon-1,
879 R = Roundhead-1, S = Sweetlips-1, T = Turrum-4, ETP = East Tasman Plateau.
880 Modified after Cande and Stock (2004) and Sluijs et al. (2011).

881

882 **Figure 2.** Relative abundances of selected sporomorph taxa ([A] angiosperms, [G]
883 gymnosperms, [P] pteridophytes) representative of the middle Paleocene to early
884 Eocene assemblages from ODP Site 1172. DCA Axis 1 scores represent the
885 fluctuations in floristic composition between samples. Relative abundances and DCA
886 results are based on samples with counts ≥ 100 individuals only. Numbers of
887 sporomorph species are rarefied at 100 individuals. The intervals corresponding to the
888 middle/late Paleocene transition and PETM are marked by horizontal blue and red
889 bars, respectively. Age model and dinocyst zonation after Bijl et al. (2013b).

890

891 **Figure 3.** Comparison of the floristic composition based on the DCA sample scores
892 for (a) middle Paleocene to early Eocene sporomorph assemblages from ODP Site
893 1172 (Axis 1: 14.6 % of variance; Axis 2: 9.6 % of variance); (b) Paleocene/early
894 Eocene sporomorph assemblages from Southeast Australia (Bass Basin, Gippsland
895 Basin, Southeast Highlands), New Zealand (Middle Waipara and Otaio River
896 sections) and ODP Site 1172 (Axis 1: 38.9 % of variance; Axis 2: 23 % of variance).
897 Results are based on samples with counts ≥ 100 individuals only.

898

899 **Figure 4.** Comparison of the sporomorph-derived climate estimates, SST values
900 based on $\text{TEX}_{86}^{\text{L}}$ and $\text{TEX}_{86}^{\text{H}}$, and DCA Axis 1 sample scores from the Middle
901 Paleocene to Lower Eocene of ODP Site 1172. Sporomorph-derived climate estimates
902 are based on the methodology of Greenwood et al. (2005). Error bars represent the
903 minimum and maximum estimates determined using that method. SST data are from
904 Bijl et al. (2009; 2013b) and Hollis et al. (2014). Sporomorph-derived climate
905 estimates and DCA results are based on samples with counts ≥ 100 individuals only.
906 The intervals corresponding to the middle/late Paleocene transition and the PETM are
907 marked by horizontal blue and red bars, respectively. Age model and dinocyst
908 zonation after Bijl et al. (2013b).

909

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Table 1

Section	Region	Age	Pollen Biozone	Authors
Southern Monaro sections	highlands of southeastern Australia	60 – 58 Ma	Lygiestepollenites balmei	Taylor et al., 1990
* Burong-1	onshore Gippsland Basin	late Paleocene	Upper L. balmei	Partridge and Macphail, 1997
* Kingfish-8	offshore Gippsland Basin	early Eocene	Lower Malvacipollis diversus	Partridge, 1992
+ Konkon-1	Bass Basin	middle to late Paleocene, early Eocene	L. balmei and Lower M. diversus	Partridge, 2003
Otaio and Middle Waipara sections	New Zealand	58 – 56 Ma		Pancost et al., subm.
+ Poonboon-1	Bass Basin	late Paleocene, early Eocene	Upper L. balmei, Lower M. diversus	Partridge, 2003
* Roundhead-1	offshore Gippsland Basin	middle to late Paleocene, early Eocene	L. balmei, Lower M. diversus	Partridge, 1989
* Sweetlips-1	offshore Gippsland Basin	middle to late Paleocene	L. balmei	Partridge, 1989
* Turrum-4	offshore Gippsland Basin	middle to late Paleocene	L. balmei	Partridge, 1993
* Turrum-4	offshore Gippsland Basin	middle to late Paleocene	L. balmei	Partridge, 1993

Table 2

Fossil taxon	Botanical affinity	Source	NLR used for climate analysis	database
<i>Araucariacites</i> spp.	Araucariaceae	Raine et al., 2008	Araucariaceae	1, 2
<i>Arecipites</i> spp.	Arecaceae	Nichols et al., 1973	Arecaceae	1
<i>Baculatisporites</i> spp.	Osmundaceae	Raine et al., 2008	Osmundaceae	1
<i>Banksiaeaidites arcuatus</i>	Proteaceae (<i>Banksia</i> , <i>Dryandra</i> , <i>Musgravea</i>)	Raine et al., 2008		
<i>Beaupreaidites</i> cf. <i>diversiformis</i>	Proteaceae (<i>Beauprea</i>)	Raine et al., 2008		
<i>Caryophyllidites</i> sp.	Caryophyllaceae	Raine et al., 2008		
<i>Ceratosporites</i> spp.	<i>Lycopodiaceae</i> , <i>Selaginellaceae</i>	Raine et al., 2008		
<i>Crassoretitriletes</i> cf. <i>vanraadshooveni</i>	<i>Lygodium</i>	Germeraad et al., 1968	<i>Lygodium</i>	1
<i>Cyathidites</i> spp.	Probably Cyatheaceae	Mohr, 2001	Cyatheaceae	1
<i>Cycadopites</i> spp.	Cycadales	Raine et al., 2008	Cycadales: <i>Bowenia</i> , <i>Lepidozamia</i> , <i>Macrozamia</i> , <i>Dacrycarpus</i>	1
<i>Dacrycarpites australiensis</i>	Podocarpaceae (<i>Dacrycarpus dacrydioides</i>)	Raine et al., 2008	<i>Dacrycarpus</i>	1
<i>Dacrydiumites florinii</i>	Podocarpaceae (<i>Dacrydium</i>)	Raine et al., 2008	<i>Dacrydium</i>	1
<i>Dacrydiumites</i> spp.	Podocarpaceae (<i>Dacrydium</i>)	Raine et al., 2008	<i>Dacrydium</i>	1
<i>Dilwynites granulatus</i>	Araucariaceae (<i>Wollemia/Agathis</i>)	Macphail et al., 2013		
<i>Dilwynites tuberculatus</i>	Araucariaceae (<i>Wollemia/Agathis</i>)	Macphail et al., 2013		
<i>Ephedripites</i> sp.	<i>Ephedra</i>			
<i>Gleicheniidites senonicus</i>	Gleicheniaceae	Raine et al., 2008	<i>Dicranopteris</i> , <i>Diplopterygium</i> , <i>Gleichenia</i> , <i>Sticherus</i>	1
<i>Gleicheniidites</i> spp.	Gleicheniaceae	Raine et al., 2008	<i>Dicranopteris</i> , <i>Diplopterygium</i> , <i>Gleichenia</i> , <i>Sticherus</i>	1
<i>Intratropopollenites</i> cf. <i>notabilis</i>	Sterculioideae?, Bombacoideae?, Tilioidae?	Raine et al., 2008		

<i>Malvacipollis diversus</i>	Euphorbiaceae (<i>Austrobuxus</i> , <i>Dissiliaria</i> , <i>Petalostigma</i>); Eumalvoideae?	Raine et al., 2008	Euphorbiaceae	1
<i>Microalatidites</i> spp.	Podocarpaceae (cf. <i>Phyllocladus</i>)	Raine et al., 2008	<i>Phyllocladus</i>	1
<i>Microcachrydites antarcticus</i>	Podocarpaceae (<i>Microstrobos</i> , <i>Microcachrys tetragona</i>)	Raine et al., 2008		
<i>Myricipites harrisii</i>	Casuarinaceae, possibly also Myricaceae	Raine et al., 2008	Casuarinaceae (all Australian species)	1
<i>Myrtaceidites</i> spp.	Myrtaceae	Raine et al., 2008	Myrtaceae	1
<i>Nothofagidites asperus</i> complex	Nothofagaceae (<i>Nothofagus</i> subg. <i>Lophozonia</i>)	Truswell and Macphail, 2009	<i>N. cunninghamii</i> , <i>N.</i> <i>moorei</i>	1
<i>Nothofagidites brachyspinulosus</i> complex	Nothofagaceae (<i>Nothofagus</i> subg. <i>Fuscospora</i>)	Truswell and Macphail, 2009	Nothofagaceae (<i>Nothofagus</i> subg. <i>Fuscospora</i>)	2
<i>Nothofagidites emarcidus</i> complex (including <i>N. endurus</i>)	Nothofagaceae (<i>Nothofagus</i>)	Truswell and Macphail, 2009	all subgenera (including <i>Brassospora</i>)	2
<i>Nothofagidites flemingii</i> complex	Nothofagaceae (<i>Nothofagus</i> subg. <i>Nothofagus</i>)	Raine et al., 2008	Nothofagaceae (<i>Nothofagus</i> subg. <i>Fuscospora</i>)	2
<i>Nothofagidites lachlaniae</i> complex	Nothofagaceae (<i>Nothofagus</i> subg. <i>Fuscospora</i>)	Raine et al., 2008	Nothofagaceae (<i>Nothofagus</i> subg. <i>Fuscospora</i>)	2
<i>Nothofagidites</i> sp.1	Nothofagaceae (<i>Nothofagus</i>)		all subgenera (including <i>Brassospora</i>)	2
<i>Nothofagidites</i> spp. undifferentiated	Nothofagaceae (<i>Nothofagus</i>)		all subgenera (including <i>Brassospora</i>)	2
<i>Osmundacidites</i> spp.	Osmundaceae	Raine et al., 2008	Osmundaceae	1
<i>Parvisaccites catastus</i>	Podocarpaceae (<i>Halocarpus</i>)	Raine et al., 2008		
<i>Phyllocladidites mawsonii</i>	<i>Lagarostrobos</i>	Raine et al., 2008	<i>Lagarostrobos</i>	2
<i>Podocarpidites ellipticus</i>	Podocarpaceae (<i>Podocarpus</i>)	Raine et al., 2008	<i>Podocarpus</i>	1
<i>Podocarpidites exiguus</i>	Podocarpaceae	Raine et al., 2008		
<i>Proteacidites adenanthoides</i>	Proteaceae (<i>Adenanthos</i>)	Raine et al., 2008	<i>Adenanthos</i>	2
<i>Proteacidites annularis</i>	Proteaceae (<i>Xylomelum</i> <i>occidentale</i> or <i>Lambertia</i>)	Raine et al., 2008	<i>Xylomelum</i> (all Australian species)	2

<i>Proteacididites</i> cf. <i>amolosexinus</i>	Proteaceae (<i>Knightia excelsa</i> type)	Raine et al., 2008		
<i>Proteacidites</i> cf. <i>adenanthoides</i>	Proteaceae (<i>Adenanthos</i>)	Raine et al., 2008	<i>Adenanthos</i>	2
<i>Proteacidites parvus</i>	Proteaceae (<i>Bellendena montana</i> type)	Raine et al., 2008	<i>Bellendena montana</i>	2
<i>Proteacidites reticulosabratus</i>	Proteaceae (<i>Gevuina/Hicksbeachia</i> type)	Raine et al., 2008	<i>Gevuina, Hicksbeachia</i>	2
<i>Proteacidites symphyonemoides/ P. pseudomoides</i>	Proteaceae (<i>Symphyonema, Carnarvonia</i>)	Raine et al., 2008	<i>Symphyonema, Petrophile</i>	2
<i>Pseudowinterapollis</i> sp.	Winteraceae	Raine et al., 2008		
<i>Retitriletes</i> cf. <i>rosewoodensis</i>	Lycopodiaceae (<i>Lycopodium</i>)	Raine et al., 2008		
<i>Retitriletes facetus</i>	Lycopodiaceae (<i>Lycopodium</i>)	Raine et al., 2008		
<i>Rubinella</i> cf. <i>major</i>	<i>Leptolepis?</i>	Raine et al., 2008		
<i>Spinizonocolpites prominatus</i>	<i>Nypa</i> (Arecaceae)	Muller 1968	<i>Nypa</i>	1
<i>Stereisporites</i> sp.	Sphagnaceae	Truswell and Macphail, 2009		
<i>Triporoletes</i> cf. <i>reticulatus</i>	cf. <i>Riccia beyrichiana</i>	Raine et al., 2008		
<i>Troporopollenites ambiguus</i>	Proteaceae (<i>Telopea truncata, Oreocallis pinnata</i>)	Raine et al., 2008		
<i>Tripunctisporites maastrichtiensis</i>	Sphagnaceae?			

Table 3

Age	Location	SST (°C)	MAT (°C)	CMMT (°C)	WMMT (°C)	MAP (cm/year)
early Eocene	ODP Site 1172	23.4 ± 1.7 (L) 27.8 ± 2.5 (H)	12.5 ± 3.8	6.9 ± 3.8	19.3 ± 3.7	180 ± 86
	Bass Basin		20.2 ± 4.8	12.3 ± 3.4	24.8 ± 2.4	198 ± 114
	Gippsland Basin		17.2 ± 6.4	9.1 ± 6	21.3 ± 3	201 ± 119
	Otaio section		18.9 ± 3.4	11.8 ± 1.1	24.1 ± 0.4	125 ± 24
late Paleocene	ODP Site 1172	22 ± 1.2 (L) 25.5 ± 1.1 (H)	12.7 ± 5.2	7.4 ± 3.3	20.9 ± 2.9	172 ± 98
	Bass Basin		15.8 ± 5.8	9.3 ± 4	21.5 ± 2.9	195 ± 112
	Gippsland Basin		15.8 ± 5.9	8.6 ± 4.1	20.4 ± 3.6	200 ± 108
	Southern Morano sections		15.3 ± 6.4	8.5 ± 3.8	20.7 ± 4.1	194 ± 105
	Middle Waipara section	14 ± 1.6 (L) 19.3 ± 1.7 (H)	15.2 ± 2.8	6.9 ± 2.4	15.1 ± 2.9	179 ± 98
middle/late Paleocene transition	ODP Site 1172	16.5 ± 1.5 (L) 21.2 ± 1.1 (H)	10.6 ± 3.9	5.9 ± 2.8	15 ± 2.4	177 ± 86
middle Paleocene	ODP Site 1172	18.1 ± 1.9 (L) 23.5 ± 1 (H)	11.2 ± 4.6	6.4 ± 3.5	15.2 ± 3.1	181 ± 89
	Bass Basin		14.8 ± 8.7	7.5 ± 5.1	19.9 ± 4.5	205 ± 121
	Gippsland Basin		14.1 ± 5.8	7.5 ± 4.4	19.3 ± 3.6	198 ± 99