1   **Vegetation and environments since the Last Glacial Maximum in the Southern**

2   **Tablelands, New South Wales**

3

4   Justine Kemp[1] and Geoff Hope

5

6   Department of Archaeology and Natural History, ANU College of Asia and the Pacific, The

7   Australian National University, Canberra, 0200.

8

9   1. Corresponding author. Present address Australian Rivers Institute, Griffith University,

10   Nathan, Queensland, 4122

11   Ph: +61 7 3735 4820

12   Fax: +61 7 3735 7615

13   Email: j.kemp@griffith.edu.au

14

15   **Abstract**

16   Regional changes in vegetation and environment in the last16 ka have been

17   reconstructed from Micalong and Willigobung Swamps (35 °S), montane fens at 980 m and

18   780 m AHD on the western Southern Tablelands of NSW. Micalong Swamp lies close to the

19   subalpine treeline at this latitude, and both sites approach the modern dry/montane forest

20   ecotone. Their vegetation histories record shifts in temperature and precipitation and are the

21   first reported pollen records from the western montane slopes of NSW. A radiocarbon-based

22   chronology indicates that Micalong Swamp supported a swampy, gravel floodplain within

23   alpine grassland before 16.1 ka. Organic fen sedimentation developed <11.8 ka at

24   Willigobung, and 11.7 ka at the higher elevation Micalong Swamp. Subalpine woodland

25   may have become established at 1000 m by 16.1 ka. Wet forest elements were present at

26   both sites around 10 ka and persisted for 3-4 ka. Shallow lake sediments between 10 and 8

27   ka supports the evidence for wetter conditions in the early Holocene. In the late Holocene a

28   re-expansion of subalpine flora between 0.9 and 2.7 ka preceeded by shallow lake

29   sedimentation is consistent with the regional evidence for neoglacial cooling at this time.

30

31   Keywords

32   southeastern Australia, late Quaternary, pollen, vegetation history, fen peatlands,

33   charcoal

34

35

36   **Introduction**

37   A comparison of late Quaternary climate change in the Northern and the Southern

38   Hemispheres is a subject of ongoing debate and major research efforts are presently

39   underway to integrate regional records from the Southern Hemisphere in order to facilitate a

40   hemispheric and global analysis (e.g. Barrows *et al.*, 2013; Lorrey, *et al.*, 2013). Even in

41   some temperate regions of Australia this aim has been thwarted by a lack of data (Reeves et

42   al., 2013). In southeastern Australia, much of the continuous record of changing

43   environments comes from pollen histories extracted from lakes, fens and peat bogs. Lake

44   records are scarce below the alpine zone, and periodic drying and low organic contents have

45   adversely affected pollen preservation and increased the dating uncertainties (e.g. Singh and

46   Geissler, 1985; Dodson, 1986). Alpine and montane peat bogs have better pollen

47   preservation, but their small scale yields essentially local vegetation histories. In southern

48   NSW, fen peatlands were widespread until the introduction of European-style agriculture,

49   which resulted in the widespread incision and erosion of organic valley fills, particularly in

50   the middle and lower reaches of the river systems (Prosser et al. 1994; Wasson et al., 1998;

51   Johnston and Brierley, 2006). The preserved remnants of these fens remain sufficiently

52   numerous to capture the regional pollen rain and are less susceptible to erosion, drying and

53   fire. This paper provides a regional synthesis of vegetation change from the NSW Southern

54   Tablelands, and presents two new records from montane fens in the upper Murrumbidgee

55   basin. As the first pollen records reported from the western montane belt of the Southern

56   Tablelands, they fill an important gap in our knowledge of late Quaternary environments in

57   the region.

58

59   **Environmental setting**

60   The NSW Southern Tablelands (35-37° S) is a c.180 km wide belt of mountain ranges

61   and tablelands that separates the interior lowlands of the Murray Basin from the coastal plain

62   (Fig. 1). Its eastern edge is defined by the Great Escarpment and coastal ranges over 1000 m.

63   On its western edge, stepped plateaux climb to 1500 m elevation with peaks rising over 2000

64   m along the Snowy Mountains. Cirque basins and glacial moraine are found on the highest

65   peaks and cosmogenic dates indicate that a series of glaciations occurred between 60 and 17

66   ka (Barrows *et al*., 2001). Relict periglacial landforms above 1000 m were active during the

67   last glacial maximum (Galloway, 1965; Barrows *et al*., 2004). On the northern ranges of the

68   Australian Alps the treeline lies at 1900 m, which exceeds the highest peaks in the area, but

69   the orographic treeline falls to ~1300 m on exposed plateau surfaces (McDougall and Walsh,

70   2007). Sub-alpine vegetation prevails above 1500 m and is dominated by *Eucalpytus*

71   *pauciflora* (snow gum) woodland with a grass or shrub understorey. In valley bottoms above

72   1000 m the treeline may be inverted owing to cold air drainage. Montane wet forest occupies

73   altitudes between 900 and 1500 m at this latitude (Costin, 1954). The regional climate is

74   dominated by the eastward progression of the subtropical high pressure belt. Summers are

75   warm to hot and winters are cold with regular, severe frosts that play an important role in

76   mechanical weathering of soils above 1000 m (Costin, 1954). The dominant moisture source

77   is fronts embedded in the travelling westerlies in winter with a secondary, summer source

78   from low pressure systems located in the Tasman Sea (Gentilli, 1986).

79

80   *Micalong Swamp*

81   Micalong Swamp (35.318° S, 148.524° E) is located on the northwest plateau of the

82   Fiery Range (Fig. 1). The plateau is underlain by Silurian - Devonian dolerites intruded by

83   younger granite (Ollier, 1978). The fen sits at 980 m and extends downstream for ~4 km

84   within a 200 m wide, fault-aligned valley near the headwaters of Micalong Creek.

85   Surrounding hills rise to 1200 m elevation. The valley fill comprises ~1 km^2 of topogenous

86   fen with an average depth of 4 m, grading downstream to humic silty flats now being actively

87   incised by the stream (Hope and Southern, 1983). Climate records available from Bondo

88   Forestry station, 5 km westwards at 840 m, indicate mean summer (January) temperatures of

89   18.2 °C and mean winter (July) temperature of 4.2 °C. These are likely to exceed

90   temperatures at Micalong Swamp where high local relief concentrates cold air in the valley

91   bottoms. Average annual precipitation at Bondo is 1240 mm with a slight winter maximum,

92   and precipitation decreases with altitude and distance westward to 816 mm at Tumut, 26 km

93   westward at 300 m elevation (Bureau of Meteorology, 2011).

94   Hope and Southern (1983) surveyed the local vegetation at Micalong Swamp.

95   Vegetation on the valley slopes is *Eucalyptus stellulata - E.pauciflora – E. camphora*

96   woodland with a grassy understorey of *Polystichum* and *Blechnum* ferns and scattered small

97   trees of *Acacia melanoxylon*, *Lomatia* and *Polyscias*. Below 1000 m large areas were cleared

98   for conifer plantations in 1921. Remnant patches above 900 m are tall open forest dominated

99   by *E. dalrympleana* with an understorey characteristic of both wet and dry forests including

100   *Tasmannia lanceolata*, *Dicksonia antarctica* and *Acacia dealbata*, and shrub species of

101   Fabaceae and Asteraceae *Daviesia*, *Platylobium*, *Helichysum*, *Olearia*, and *Cassinia.* Open

102   forest of *E. dives* or *E. radiata* dominates below 900 m with *Callitris* at lower altitudes. The

103   fen is dominated by *Carex gaudichaudiana* with a fringing montane *Sphagnum* bog that

104   includes shrub species of *Leptospermum*, *Epacris*, *Hakea* and *Baeckea* (Hope *et al.*, 2009).

105   Other aquatic taxa represented in the fen include Poaceae, other graminoids in the

106   Cyperaceae, Juncaceae, Orchidaceae and Restionaceae, fern species in *Blechnum* and

107   *Adiantum*, and herbs such as *Epilobium*, Apiaceae-Araliaceae, *Myriophyllum*, *Ranunculus*,

108   *Neopaxia* and *Stellaria*. The fen margins have introduced weeds including blackberry (*Rubus*

109   *fruticosus*), *Centaurium*, clovers (*Trifolium and Medicago*), *Plantago* and flatweeds such as

110   *Hypochoeris radicata.*

111

112   Evidence for intense Aboriginal occupation of Micalong Swamp comes from

113   scattered flakes of quartz and chert around the banks and from nine known occupation sites

114   in the catchment (Hiscock, 1983). Backed blades were also found by Flood (1980: 213),

115   which suggests that occupation has been continuous for at least 4 ka. An aboriginal presence

116   has been registered at 9.4 ka at similar elevations near Yarrangobilly, 46 km to the south

117   (Aplin *et al.*, 2010). The precise use the aborigines made of the fen is unknown although

118   reliable water is likely to have been a precious resource in the Tablelands (Hiscock, 1983,

119   2008). Hume and Hovell encountered the "mountain swamp" on their exploration of the

120   region in 1824 (Bland, 1831). They sighted distant fires but no Aborigines in this open

121   country with good grass, which had the appearance of being regularly burnt. Later, "The

122   Micalong" supported several pastoral families, a school and sawmill, and the swamp

123   provided drought-free pasture for thousands of cattle in the summer months and was the

124   northern entrance of a much-used stock route into the high country until the late C19th. In

125   the 1880s, gold was mined briefly at Chinaman's Creek, a tributary to the main swamp (Fig.

126   2A). Regular grazing in the summer months was conducted until the 1950s and is apparent

127   from fence lines that still stand on the fen. During this time, the vegetation on and around the

128   fen was burnt every 4-5 years to discourage shrub growth and to sweeten the sedge for cattle.

129   Nowadays, disturbance from these activities appears to be minimal. In 1969, the slopes

130   around the lower half of the fen were cleared to make way for plantations of *Pinus radiata*.

131   Since then, a dense shrub understorey has developed under native forest and introduced

132   species such as blackberry have proliferated (L. Hall, L. Webb, R. Franklin pers. comm.).

133   The fen is included in the Micalong Swamp Flora Reserve, a 526 ha reserve which was

134 gazetted in June 1985 and is administered by NSW State Forests. Despite this protection,

135 stock sometimes enter the reserve (Hope *et al*., 2012).

136

137 *Willigobung Swamp*

138   Willigobung (or Tarcutta) Swamp (35.66° S, 148.04° E) sits on the steep western

139 slopes of the Australian Alps in a headwater valley of Tarcutta Creek in the upper

140 Murrumbidgee Basin (Fig. 1). The valley is underlain by Silurian granite. The fen lies at 780

141 m between hills that rise to 1020 m and extends for 3.3 km down valley (Fig. 2B). Climate

142 data from Tumbarumba Post Office, 14 km S at 645 m give mean January temperature as

143 20.4 °C and July as 5.2 °C, with an average annual precipitation of 980 mm (Bureau of

144 Meteorology, 2013: 1885-2012).

145

146   Prior to European settlement fen swamp was extensive along Tarcutta Creek. In 1872

147 a "large swamp" occupied 13 km of the valley at the confluence of Umbango and Tarcutta

148 Creeks, which "years ago was covered with rushes which looked like fields of growing grain"

149 (*The Empire*, 1 April, 1872). In wet seasons it became a shallow lake visited by innumerable

150 waterfowl (Balliere's NSW Gazetteer and Road Guide, 1866). Much of the valley floor

151 eroded in response to agricultural development or was drained for cattle pasture in the 1930s,

152 but remnants are preserved near Tarcutta township and in the headwaters of Tarcutta Creek

153 (Page and Carden, 1988). Willigobung Swamp is now the westernmost large sedge fen in

154 southern NSW and is regarded as degraded (Hope *et al*., 2012). A water exclusion zone

155 presently pertains to the fen (Department of Infrastructure Planning and Natural Resources,

156 2005).

157   In 1984, the late Janet Williams described the sediments and vegetation of

158 Willigobung Swamp (Williams, 1985). In comparison with other fens, the bog vegetation is

159   depauperate and is dominated by sedge (*Carex gaudichaudiana*) with minor representation

160   by weeds and native species including *Agrostis*, *Epilobium*, *Erodium*, *Hydrocotyle*,

161   *Hypericum, Juncus*, *Lythrum*, and *Veronica*. In 1872, the catchment of Tarcutta Creek was

162   described as "sixty miles of finely grassed, undulating, open forest country" (*The Empire*, 1

163   April, 1872). Remnants of tall eucalypt forest persist in the upper catchment, which is now

164   dominated by *Pinus radiata* plantation, grazing, orchards and vineyards. Drainage to permit

165   sheep and cattle grazing has caused drying of the centre of the lower end of the fen but the

166   upper reaches are less affected. Some *Eucalyptus stellulata* around the fen may be a remnant

167   of subalpine woodland that formed in response to cold air drainage along the valley floor.

168

169   **Methods**

170   *Sediments and subsampling*

171   A preliminary investigation of Micalong Swamp in 1982 established that organic

172   sedimentation commenced prior to 14 ka (Tab. 1; Hope and Southern, 1983). In 1993 new

173   cores were extracted 30 m from the location on the fen as the 1982 core. The stratigraphy

174   across the fen was tested at ~ 20 m intervals using a combination of D-section and Livingston

175   piston corers to define variations in sediment fill. A 5.7 m core was collected in 1993 with

176   0.2 m overlap between barrel lengths, and retained for more detailed analysis (MS-3; Figs 2

177   & 4A). Sediments were described in the field and the core stored in PVC tubes and plastic

178   for transport. Exploratory coring of Willigobung Swamp was carried out by Williams using

179   identical methods to Micalong Swamp, and the deepest section selected for analysis in 1984

180   (WG-1: Fig. 4B).

181   In the laboratory 5 mm thick slices were extracted at 10 cm intervals except for the

182   top 5 cm, which was sampled at 1 cm intervals. Subsamples of 2 cm^3 were retained for

183   pollen and charcoal analysis, and the remainder was transferred to beakers to obtain estimates

184　of water and organic carbon content in order to provide a measure of the local site

185　productivity and the influx of inorganic sediments. Water content was calculated as the

186　difference between wet and oven dry weight and expressed as a percentage of the total.

187　Organic carbon in peat sediments was estimated from loss on ignition and expressed as the

188　proportion of combustible to oven-dry sediment mass. Samples were oven dried at 105 °C

189　for 24 h and combusted at 550 °C for 4 hr. Organic content of clay-rich sediments was

190　measured by gas chromatograph following Hieri *et al*. (2001).

191

192　*Radiocarbon dating*

193　　　　Samples of bulk peat from the organic sediments were radiocarbon-dated using liquid

194　scintillation techniques at the Australian National University (ANU) following procedures

195　outlined in Gupta and Polach (1985). Sedge fragments from the lacustrine clays underlying

196　the fen sediments were graphitised at ANU and analysed using accelerator mass spectrometry

197　(AMS) at the Australian Nuclear Science and Technology Organisation. Radiocarbon ages

198　were calibrated using the Southern Hemisphere curve of INTCAL13 using Calib 7.0.0

199　(Stuiver et al., 2005; Hogg *et al*., 2013).

200

201　*Pollen and charcoal*

202　　　　Pollen samples were prepared following standard techniques (Fægri and Iverson,

203　1964) and were identified with the aid of a reference collection held at the Australian

204　National University. A minimum of 200 pollen grains or the whole slide was counted. Raw

205　pollen counts were expressed as relative frequencies of the dryland pollen sum, which was

206　based on most dryland taxa including herbs. For Micalong Swamp this included

207　*Podocarpus*, *Pomaderris*, *Tasmannia*, *Eucalyptus*, other Myrtaceae, Casuarinaceae,

208　Asteraceae (Tubuliflorae and Liguliflorae), Ericaceae <20 µm, Fabaceae, Proteaceae,

209   *Callitris*, Poaceae, Caryophyllaceae, *Plantago*, *Chionogentias*, *Astelia* and fern spores

210   (monolete and trilete). For Willigobung Swamp, *Cyathea* and *Dicksonia* were distinguished

211   from other ferns. Aquatic pollen and spores were expressed as a percentage of the total

212   pollen to minimise the influence of local variations in the vegetation. It was not always

213   possible to distinguish dryland vegetation from swamp taxa since several important fen taxa

214   (eg. Poaceae) are also well represented in the regional vegetation. Shrub Ericaceae was

215   excluded from the dryland pollen sum since *Epacris* species are often prominent in swamp

216   communities. All representatives of the Apiaceae-Araliaceae family were also excluded;

217   high frequencies of Apiaceae-Araliaceae pollen suggested a dominantly local source,

218   probably the aquatic *Hydrocotyle*.

219   Relative pollen frequencies and the pollen diagrams were constructed using TILIA

220   1.7.14 (Grimm, 1990). The pollen diagram was separated into zones subjectively and based

221   on numerical analysis using CONISS, which uses a multivariate method for quantitative

222   definition of pollen frequency data (Grimm, 1987). Major zone boundaries correlate with

223   changes in the relative abundance of *Eucalyptus,* which is likely to reflect major changes in

224   forest cover. Slides prepared for pollen analysis were used to obtain quantitative estimates of

225   charcoal (8-100 µm - microcharcoal). An automated counting program was used to estimate

226   the area of charcoal per slide, which identifies material below a specified light density as

227   charcoal, and estimates of charcoal area were converted to volumetric units of original

228   sediment in mm^2 ml^{-1} (Dolman, 1991).

229

230   **Results**

231   *Micalong Swamp*

232   *Stratigraphy and Chronology*

233   Water, organic carbon and charcoal volume are given in Fig. 3. The depth of the valley fill

234   could not be determined, but the rounded, fine gravels fining upwards to sands and clayey

235   sands suggest the floodplain sequence of a gravel-bed river (Fig. 4). This is overlain by 1.5

236   m of silty clay containing sedge macrofossils suggesting sedimentation in a shallow lake.

237   The top 3.9 m of black, peaty clay units indicates a productive sedge fen, interrupted by two

238   <30 cm silty clay units that indicate a return to shallow lake sedimentation. The top ~30 cm

239   below the surface peat mat (~10 cm) was not recovered owing to high water content. At the

240   time of sampling the water table was at the surface with surface flow across the swamp at

241   0.12 m s^{-1}.

242   The radiocarbon age for MS82 indicates that organic sedimentation in the valley had

243   commenced before 14.3 ka BP, although the disparity between the basal organic sediment

244   ages of cores MS82 and MS3 may indicate erosion by a migrating stream. The AMS

245   radiocarbon ages on sedge fragments in the underlying sandy clays yielded younger ages than

246   the basal organic sediment ages of 11.9 and 14.3 ka (Tab. 1), and may have been

247   contaminated by organic sediments during coring. If so, such minor contamination would

248   have little effect on the dates on the bulk peats. The basal clay ages have been excluded from

249   the age-depth model, which used the mid-point of calibrated date ranges for a linear

250   regression with sample depth as the independent variable. Some additional uncertainty in

251   ages <3.5 ka is owing to higher water content and lower compaction of the surface mat. The

252   appearance of European introductions above 10 cm marks a level around 100 cal a BP.

253

254   While speculative, the model gives a regular relationship with depth ($r^2 = 0.99$),

255   although the changes in mineral content suggest that the sedimentation rate was not constant

256   and may include some gaps. Nevertheless the age model provides an approximate age for the

257   valley sedimentation and environmental changes in the area. Downward extrapolation of the

258   overall sedimentation rate places the onset of lacustrine sedimentation at ~16.1 ka.

259

260

261   *Biostratigraphy*

262   Dryland pollen counts ranged from 38 to 157 with poor preservation giving counts <50 in

263   three samples (Fig. 5). The record was divided into five zones based on the CONISS results

264   and the proportion of major dryland pollen types.

265

266   *Zone MS I (520 - 570 cm; <16.1 ka BP)*

267   Sediments are dominantly sub-angular yellow-brown sands below 540 cm, overlain by beds

268   of reddish-yellow and grey sandy clays with abundant Cyperaceae above 532 cm. Organic

269   carbon is mostly <1 % and charcoal increases from 4 mm^2 ml^{-1} to 16 mm^2 ml^{-1}.

270   Herbaceous pollen dominates the pollen spectra. Poaceae reaches values of 80 % and

271   exhibits a general decline in favour of Asteraceae, but both reach their maximum

272   representation in this zone with pollen of other herbs, including *Astelia*, *Plantago*, and

273   *Chionogentias* occasionally recorded. *Eucalyptus*, the most numerous woody taxon,

274   fluctuates around 15 % of the dryland pollen. *Tasmannia* and *Podocarpus* recur at

275   proportions <3 %. *Casuarina* and Chenopodiaceae are present at uniformly low levels.

276   Shrub Ericaceae become relatively numerous at around 5 % towards the top of the zone and

277   Proteaceae and Fabaceae appear in minor proportions. Fern spores are consistently less than

278   5 %. The swamp flora is dominated by Cyperaceae, which declines from 20 % to 5 % at the

279   top of the zone. *Myriophyllum* and Restionaceae and swamp shrubs species of Myrtaceae

280   and Ericaceae >20 µm comprise <5 % of the total pollen sum.

281

282   *Zone MS II (335 - 520 cm; 10.0 – 16.1 ka BP)*

283   Sediments change abruptly from grey clay with lenses of sandy clay and gravelly clay, to

284   black, fibrous peaty mud at 386 cm, accompanied by an increase in organic carbon content

285   from 1 % to 11 %. Charcoal increases to 170 mm^2 ml^{-1} with a pronounced peak at 380-360

286   cm.

287   Pollen spectra are dominated by Asteraceae and Poaceae, which alternate in

288   dominance until 385 cm when pollen of Casuarinaceae and *Eucalyptus* increases to 10 % and

289   20 % of the dryland sum, respectively. *Podocarpus* disappears from the record, and the

290   proportions of shrub species of Ericaceae and Myrtaceae decrease. *Tasmannia* and Fabaceae

291   frequencies are higher in this zone. Caryophyllaceae adds to the herb flora and becomes

292   relatively prolific in the upper part of the zone. Fern spores are consistently ~4 %.

293   Substantial changes in the swamp flora are apparent from the steady increase in Cyperaceae

294   after 530 cm, and peaks in *Hydrocotyle* and Apiaceae-Araliaceae accompany the change to

295   more organic sedimentation.

296

297   *Zone MS III (110 - 335 cm; 2.7 - 10.0 ka BP)*

298   Sediments are brown and grey-brown fibrous peaty mud with regular changes in humification

299   and clay content. Organic carbon content reaches 21 % in organic sediments and 3-5 % in

300   clayey sediments. Charcoal reaches 1290 mm^2 ml^{-1} between 250 and 270 cm, then falls to

301   ~160 mm^2 ml^{-1}.

302   An increase in *Eucalyptus* occurs between 270 cm and 140 cm, where it exceeds 50 %

303   of the dryland pollen at the expense of Poaceae and, to a lesser extent, Asteraceae.

304   Casuarinaceae achieves several peaks accompanied by higher proportions of shrub and small

305   tree species of Myrtaceae and Proteaceae, and monolete and trilete fern spores, especially in

306   the lower half of the zone where they reach proportions of 10 % and 20 %, respectively.

307 *Tasmannia* peaks in the upper part of the zone, where *Podocarpus* and *Pomaderris* also

308 reappear. Fabaceae is not recorded and shrub species of Ericaceae appear sporadically.

309 Chenopodiaceae declines to <5 %, but increases, together with *Callitris*, towards the end of

310 the zone. In the fen, Cyperaceae fluctuates together with *Hydrocotyle*, alternating with

311 *Myriophyllum*, Restionaceae and *Epacris*.

312

313 *Zone MS IV (45 - 110 cm; 0.6 – 2.7 ka BP)*

314 Sediments are dark brown fibrous peaty mud with root and leaf macrofossils. Organic

315 content is <25 % and charcoal averages 170 mm^2 ml^{-1}. This zone is marked by a substantial

316 decline in *Eucalyptus* to proportions <20 % and substantial increases in Asteraceae, Poaceae,

317 *Callitris* and Chenopodiaceae. *Tasmannia* and Ericaceae disappear from the record.

318 Proteaceae, *Podocarpus* and Fabaceae are occasionally recorded. Of the herbs, only

319 Caryophyllaceae makes an appearance in this zone and fern spores fall to insignificant levels.

320 A single grain of introduced *Pinus* is attributed to contamination. Cyperaceae dominates the

321 aquatic flora with minor *Myriophyllum*, Restionaceae, *Hydrocotyle* and *Epacris*.

322

323 *Zone MS V (0 - 45 cm; AD 1993 – 0.6 ka BP)*

324 Sediments are dark brown fibrous peaty clay with root and leaf macrofossils with a watery

325 zone causing poor recovery between 40 and 10 cm. Organic carbon content reaches 70 % at

326 the surface, where charcoal peaks at 750 mm^2 ml^{-1} above previous levels of ~175 mm^2 ml^{-1}.

327 *Eucalyptus* pollen increases to 35 % and Asteraceae declines to <10 %. Cyperaceae pollen

328 dominates the aquatic flora. Shrub species of Myrtaceae are not recorded. Chenopodiaceae

329 remains at 5 %. Introduced *Pinus* and Asteraceae Liguliflorae appear in the top 2 cm.

330

331 **Willigobung Swamp**

332   *Stratigraphy and Chronology*

333   Sediments, organic carbon and charcoal volumes for Willigobung Swamp are given in Fig. 6.

334   The lowest 1.45 m consists of grey clay-silt with lenses of organic sediments below 4.95 m

335   suggest sedimentation in a shallow or seasonal lake was replaced by organic fen

336   sedimentation for short periods. Grey clay between 4.95 and 400 cm indicates a return to

337   shallow lake sedimentation. Above 4 m organic content increases and the top 2 m of fibrous

338   peat indicate an established sedge fen.

339   The age-depth model was constructed from the two calibrated radiocarbon ages of 6.5

340   ka BP (~368 cm) and 10.6 ka BP (~523 cm) (Tab. 1) following the same procedure as for

341   Micalong Swamp. European pollen is found only in the top few centimetres so 5 cm is

342   considered to be 100 cal BP. If a constant sedimentation rate between these points is

343   assumed the mean sedimentation rates of the lower core is 0.38 mm yr^{-1} increasing to 0.65

344   mm yr^{-1} after 6.5 ka. The basal age of ~11.6 ka BP is based on extrapolation. As for

345   Micalong Swamp this simple linear model provides an indication of the age of individual

346   levels but may conceal changes in sedimentation rate or gaps in the record.

347

348   *Biostratigraphy*

349   Dryland pollen counts range from 32 to 229 with five samples achieving counts <50 (Fig. 7).

350   The pollen record was divided into four zones based on the CONISS results.

351

352   *Zone WG I (495 -540 cm; 9.9- <11.2 ka BP)*

353   Basal sediments comprise grey clay with thin beds of fibrous peat. Organic content averages

354   20 % and charcoal averages 64 mm^2 ml^{-1}. Cyperaceae and Apiaceae-Araliaceae dominate the

355   fen pollen. The dryland pollen sum comprises ~50 % herbs, mostly Asteraceae and Poaceae.

356   Monolete and trilete fern spores excluding the tree ferns *Cyathea* and *Dicksonia* represent a

357   further 7-28 %. *Eucalyptus* pollen are >10 % with small but significant sclerophyll elements:

358   Casuarinaceae (<7 %), shrub Myrtaceae (<11 %), and at the end of the zone, *Dodonaea*.

359   Levels of 3-5 % chenopod pollen are recorded.

360

361   *Zone WG II (331-495 cm; 5.9 – 9.9 ka BP)*

362   Sediment is grey clay with ~10 % organic content becoming more organic above 400 cm.

363   Charcoal averages 62 mm^2 ml^{-1}. Greater diversity in the bog pollen is marked by the decline

364   in Cyperaceae and Apiaceae-Araliaceae and consistent representation of *Lycopodium*. The

365   zone is characterised by moderate levels of wet forest elements *Tasmannia* (5 %) with tree

366   and ground ferns comprising 3 % and 39 % of the dryland pollen, respectively. *Eucalyptus*

367   frequencies average 12 % and *Dodonaea* is not recorded. Poaceae and Asteraceae fall to ~15

368   % and chenopods fall to 3 %.

369

370   *Zone WG III (113-331 cm; 2.0 – 5.9 ka BP)*

371   Organic clay gives way to fibrous sedge peat above 215 cm. Loss-on-ignition percentages

372   increase from ~15 % to 60 % at the top of the zone, except between 170-210 cm (2.5– 3.1 ka

373   BP) when they fall to ~10 %. Charcoal falls from 260 mm^2 ml^{-1} to ~ 70 mm^2 ml^{-1} above 210

374   cm. Cyperaceae dominates the aquatic pollen but Apiaceae-Araliaceae proportions are

375   intermittently higher than in the preceding zone. *Lycopodium* virtually disappears.

376   Sclerophyll elements *Casuarina* and Myrtaceae dominate the dryland pollen with *Eucalyptus*

377   frequencies averaging 22 % and Ericaceae 2 %. Traces of *Cyathea* appear but *Dicksonia* is

378   not present above 250 cm (4.4 ka BP). Other trilete and monolete ferns average 13 % rising

379   to 40 % at 122 cm. Chenopod proportions are slightly higher (5 %).

380

381   *Zone WG IV (0 – 113 cm; 1984 AD – 2.0 ka BP)*

382   Fibrous sedge peat continues to the surface. Charcoal declines to ~50 mm^2 ml^{-1} above 50 cm

383   (625 a BP). The aquatic pollen is dominantly Cyperaceae and Apiaceae-Araliaceae with

384   apparently low diversity. Herb pollen exceeds forest pollen in the dryland sum with Poaceae

385   at 23 %. Frequencies of Asteraceae decrease from >30 % to ~20 % above 50 cm. *Eucalyptus*

386   decreases to 13 % with continuing representation by Casuarinaceae and Myrtaceae. Above

387   70 cm chenopod frequencies rise to ~12 %. An influx of *Pinus* and Poaceae is apparent near

388   the surface.

389

390   **Late Quaternary vegetation and environmental reconstruction**

391   Rounded fluvial gravels and sands at the base of the Micalong infill indicate a

392   competent fine gravel-bed river working a narrow floodplain before ~16.1 ka. Cyperaceae

393   with *Epacris* heath probably occupied wet ground along the banks with *Myriophyllum*

394   occupying shallow pools in the valley bottom. High proportions of Poaceae pollen suggest a

395   local source, possibly from well-grassed, steep slopes surrounding the site at this time. Herbs

396   constitute 80-90 % of the dryland pollen, suggesting an open or treeless landscape. The

397   dominance of Asteraceae and Poaceae with subalpine and alpine indicator species *Astelia*,

398   *Plantago*, Caryophyllaceae and Apiaceae-Araliaceae suggests alpine steppe or tussock

399   grassland that was gradually replaced by alpine herbfield or open shrubland. Pollen taxa

400   suggest a mosaic of alpine heath including tall shrub forms of *Tasmannia* and *Podocarpus*,

401   Ericaceae, Asteraceae and Myrtaceae occurring in closed heathlands similar to that common

402   along rocky waterways up to 1950 m AHD in the Kosciuszko National Park (McDougall and

403   Walsh, 2007). Dwarf forms of *Tasmannia, Epacris, Richea* and shrub Proteaceae (e.g. *Orites*

404   and *Grevillea*) may have formed open heathland with areas of grassland in the upper

405   catchment, but the efficient dispersal characteristics of *Podocarpus* raises the possibility of

406   *fjaeldmark* or heath communities occupying the summit of higher ranges. The open

407   landscape at the time would have made the fen sensitive to extra-local and regional

408   vegetation, and the low frequencies of *Eucalyptus*, together with *Callitris* and chenopods,

409   may reflect drier forest occupying lowlands to the west. The low occurrence of charcoal is

410   consistent with low fire frequencies in the alpine zone (McDougall and Walsh, 2007).

411   Sediments of this age were not recovered from Willigobung Swamp.

412   Finer sediments with abundant sedge macrofossils accumulate at Micalong Swamp

413   after 16.1 ka (MS II), suggesting that the accumulation of organic or mineral sediments

414   created a shallow fen that flooded seasonally or episodically, possibly by snowmelt. A steep

415   rise in Cyperaceae pollen together with an increase in organic sedimentation marks the onset

416   of warmer conditions. At Willigobung this transition occurs before 11.2 ka, but with an

417   intermittent return to shallow lake sedimentation. Apiaceae-Araliaceae and Caryophyllaceae

418   pollen appear to have contributed to the marginal fen communities more than at present.

419   Both families are considered alpine and subalpine indicators, but several species are

420   widespread at lower altitudes and both are found on the site today in damp ground within the

421   marginal *Sphagnum* bog (Hope and Southern, 1983). While these may have formed an

422   important part of regional herbfield communities, dominantly local dispersal of both pollen

423   types implies a prolific local distribution. At Micalong Swamp, parallel increases in species

424   of *Hydrocotyle*, a mat-forming herb commonly found in boggy places, supports this

425   reconstruction. Substantial increases in the abundance of Cyperaceae point to the

426   development of closed sedgeland although the absence of standing water is indicated by the

427   almost complete disappearance of *Myriophyllum* towards the end of this zone.

428

429   Through the remainder of the late glacial, the regional vegetation at Micalong Swamp

430   was dominantly grassland, but the sustained increase in *Eucalyptus* suggests woodland

431   expanded nearby or on higher slopes above the frost hollow. The fen was probably

432   surrounded by a marginal heathland that included *Epacris*. Ericaceae - *Podocarpus* heath

433   may have occupied higher, exposed slopes. Rare appearances of *Pomaderris* pollen may

434   indicate a presence along the stream in a similar association to bog communities along

435   drainage lines in the Barrington Tops at elevations up to 1500 m (Whinam and Chilcott,

436   2002). At a lower elevation, high proportions of herb pollen are recorded at Willigobung

437   Swamp by 11.2 ka (WG I), but significant levels of Casuarinaceae and *Dodonaea* suggest an

438   open sclerophyll woodland was already established on the slopes. Casuarinaceae spp. may

439   have expanded along waterways near the site, possibly *Casuarina cunninghamii*, which

440   grows along streams nearby at elevations up to 1000 m. Casuarinaceae species are also

441   common on skeletal or shallow soils on drier slopes to the west, including *Allocasuarina*

442   *verticellata*, which appears in pure stands or with *Eucalyptus* in grassy woodland up to

443   elevations of 900 m.

444   After 10.0 ka, clear evidence for forest cover at Micalong Swamp is suggested by the

445   rise in *Eucalyptus* and Casuarinaceae, confining Asteraceae and other herbs to the damp

446   fringes of the bog. Shrub species of Proteaceae and Myrtaceae may have formed part of the

447   forest, but high frequencies of Poaceae suggest a grassy understorey persisted until 7.8 ka.

448   The tree fern, *Dicksonia*, may have been a pioneer in the development of wet forest, but

449   alternative sources for the trilete ferns include understorey ferns *Polystichum* or *Calochlaena.*

450   Monolete ferns possibly present include *Blechnum*, *Adiantum* (maidenhair), *Pteridium*, as

451   well as *Gleichenia* which today are common along stream margins. Higher rates of mineral

452   sedimentation from 9.7 – 8.2 ka and 3.9 - 3.2 ka indicate a return to episodic flooding,

453   possibly owing to increases in rainfall since forest was established by this time.

454   Tall shrub-rich forest, indicated by an expansion of tree and ground ferns, appears to

455   have reached its maximum extent at Micalong Swamp between 10.0 and 6.8 ka. Wetter

456   conditions are also suggested by the flooding of the fen at 9.7-8.2 ka. The periodic

457   alternation of Casuarinaceae-Poaceae with *Eucalyptus*-Myrtaceae and ferns suggests that

458   open *Eucalyptus-Allocasuarina* forest alternated with a denser, more structured *Eucalyptus*

459   forest in drier periods throughout the Holocene. Visible charcoal layers in some of the clay

460   layers could indicate that fire contributed to higher sediment yields. Larger peaks in charcoal

461   in montane sedge fens may indicate more frequent burning of the bog or catchment during

462   extended droughts (Hope and Kershaw, 2005). At Willigobung, the development of wet

463   forest around the same time at 9.9 ka is marked by an expansion of tree and ground ferns and

464   *Tasmannia*. Shallow lake sedimentation is apparent from 9.9 to 7.5 ka. After 5.9 ka, wet

465   forest elements decline and a noticeable increase in charcoal suggests higher burning

466   frequencies in a tall open forest.

467   Around 2.7 ka, a substantial decline in *Eucalyptus* at Micalong Swamp is

468   accompanied by an increase in Asteraceae and Poaceae pollen suggesting forest retreat. The

469   substantial frequencies of *Callitris* pollen and, to a lesser extent, Casuarinaceae imply an

470   eastward expansion of dry sclerophyll forest, with more open conditions at the fen making it

471   receptive to Chenopodiaceae. Charcoal counts do not support a change in biomass burning at

472   this time, but high resolution macrocharcoal analysis is needed to compile the fire recurrence

473   intervals through time at both of these sites. Floristically, the fen is depauperate and is

474   dominated by Cyperaceae. The high organic content of the sediments is consistent with slow

475   decay in cooler conditions. By 0.9 ka, *Eucalyptus* forest had returned to previous levels, but

476   high Poaceae frequencies and the decline in shrub pollen suggest open woodland. The late

477   Holocene is a more complex interval at Willigobung Swamp. A wetter period marked by an

478   increase in fern spores at 4.4 ka is accompanied by an increase in mineral sedimentation,

479   possibly from seasonal flooding. This is followed by a period of increased Poaceae and

480   Asteraceae between 1.3 and 0.8 ka BP. More open conditions at this time are suggested by

481   the increase in chenopod frequencies. At both sites, the appearance of *Pinus* pollen marks the

482 regional establishment of conifer plantations, and the proliferation on the bog surface of

483 introduced herbs of Asteraceae (Liguliflorae) such as *Hypochoeris radicata*.

484

485 **Discussion**

486   Micalong and Willigobung Swamps are the only vegetation sequences extending into

487 the Pleistocene yet reported from the montane western slopes of the Southern Tablelands. In

488 general terms, they present similar features to sites from similar altitudes on the eastern

489 slopes such as Nursery Swamp (1092m, Hope, 2006), Bega Swamp (1080m) (Donders *et al.*,

490 2007) and Bogong Creek Swamp (1005 m, Hope, unpublished). Basal ages on seeds or char

491 in the sandy clays of these three fens range from 14,260±250, 15,850±280, and 16,420±410

492 cal BP, respectively, providing support for the tentative age model for Micalong Swamp.

493   Their records can also be compared with a number of shrubby subalpine bogs at

494 higher altitudes extending from the Snowy Mountains (Martin, 1986; 1999) through the Blue

495 Mountains (Robbie and Martin, 2007), and the Barrington Tops c.1000 m (Dodson, 1987).

496 Detailed records available from the submerged canyon of the Murray River on the South

497 Australian continental shelf have a close affinity with terrestrial records in southeast

498 Australia (MD03-2611: Gingele *et al.*, 2005; Calvo *et al.*, 2007; Moros *et al.*, 2009; Lopez

499 dos Santos *et al.*, 2013). On land, high-resolution records of the Holocene are now available

500 from Lake Keilambete and Gnotuk (Wilkins *et al.*, 2013), together with a high lake level

501 record from Lake George (Fitzsimmons and Barrows, 2010).

502   The structure of late glacial vegetation assemblages is difficult to determine from

503 pollen records owing to the appearance of well represented plant families and genera such as

504 *Grevillea*, *Podocarpus*, Myrtaceae, and Asteraceae in both alpine and montane tracts.

505 Proportions of <10 % *Eucalyptus pauciflora* (snow gum) pollen have been reported in 100 m

506 clearings within modern snow gum woodland, suggesting that its dispersal characteristics are

507 poorer than montane eucalypts (Martin, 1986; 1999), which are well dispersed upslope and

508 regionally, and may produce high frequencies of pollen above the treeline (e.g. Raine, 1974).

509 Extensive subalpine woodland on high plateau surfaces may therefore be invisible in pollen

510 records, and the rise of *Eucalyptus* in late glacial spectra may reflect the approach of montane

511 or drier lowland forest communities rather than the migration of the treeline. Most analysts

512 infer treeless conditions in the southeast highlands above 600 m AHD during the LGM and

513 late glacial (e.g. Singh and Geissler, 1985; Dodson, 1986; Hope, *et al*., 2004). Below this

514 elevation, open woodland persisted at coastal and inland sites (Dodson and Wright, 1989;

515 Williams *et al*., 2006). A lower limit to the climatic tree line in southern NSW is defined by

516 Mountain Lagoon, which records forest up to 500 m elevation on the eastern ranges at the

517 LGM (Robbie and Martin, 2007), but lower precipitation, low CO_2 and higher wind speeds

518 may have contributed to treelessness on the NSW tablelands (Dodson, 1998; Hope *et al*.,

519 2004; Ferrara *et al*., 2001). Micalong and Willigobung straddle the LGM treeline,

520 hypothesised to lie at 975 m based on the former extent of periglacial landforms at 35°S

521 (Galloway, 1965). The modern treeline in the southern Australian Alps lies at 1700-1800 m

522 and is defined by the 10 °C mean January isotherm (Slatyer, 1988), but descends northwards

523 to <1300 m on the exposed plateau surface near Kiandra where January mean temperature is

524 13.4 °C (BoM, 2013). Treeless conditions at Micalong Swamp imply that summer

525 temperatures were at least 4 -7 °C lower (making an allowance for elevation), but an

526 expansion of the grassy frost hollow would be produced by a reduction of as little as 1-2 °C

527 in mean summer temperature.

528   The regional pattern of forest development in the deglaciation is consistent with the

529 pattern of temperature emerging from marine records of SST in SE Australia. Beginning at

530 17-18 ka, a rapid increase in sea surface temperatures (SST) of 4 °C is apparent from MD03-

531 2611 and in the Tasman Sea (Barrows *et al*., 2007; Calvo *et al*., 2007; RS147-GC7: Lopes

532   dos Santos *et al*., 2012). Radiocarbon ages on basal organic sediments overlying glacial and

533   periglacial rubble suggest that conditions were sufficiently warm for peat development by

534   18.2 ka in the Australian Alps, with the final retreat of glaciers effected between 16.8 and

535   15.9 ka (Costin, 1972; Barrows *et al*., 2001). This may have been responsible for a regional

536   expansion of forest around 18 ka in the Barrington Tops (Sweller and Martin, 2001). The

537   vegetation was probably subalpine at Micalong Swamp by 15.8 ka, although chronological

538   uncertainties in the basal sediments make it difficult to be precise about the timing.

539   A return to cooler temperatures or an interruption in the warming trend was registered

540   by lower SST during the Antarctic Cold Reversal (ACR: 14-12.5 ka) between 16-13 ka in the

541   Australian coastal waters and Southern Ocean (Barrows *et al*., 2007; Calvo *et al*., 2007,

542   Lopes dos Santos *et al*., 2012). On land, high illite levels at MD-2611, interpreted as

543   indicating enhanced fluvial activity between 15 and 13 ka, coincide with active migration of

544   snowmelt-engorged rivers in the Murrumbidgee and Goulburn catchments (Bowler, 1978;

545   Page *et al*., 1996; Gingele *et al*., 2007). Regional pollen records show no evidence for

546   vegetation change, but the prolonged cold interval may have contributed to the late

547   appearance of forest in most montane records.

548   After 13 ka, a second rapid increase in SST is apparent in MD03-2611 and by 11 ka

549   temperatures had risen to modern levels (Fig. 1, Bostock *et al*., 2005; Barrows *et al*., 2007;

550   Calvo *et al*., 2007; dos Santos *et al*., 2013). Between 12 and 11 ka the East Australian

551   Current, which conveys tropical waters down the east coast of Australia, extended rapidly

552   southward, increasing SST regionally (Bostock *et al*., 2006). At the same time, the

553   Subtropical Front, which delineates subtropical from subantarctic waters in the Southern

554   Ocean, had migrated south of its present position (Sikes *et al*., 2009). With the flooding of

555   the Bass Strait at 9.6 ka, modern ocean circulation was established (Blom and Alsopp, 1988).

556   The combined effect of these changes would have been to increase tropical heat transport to

557   southern and SE Australia, increasing moisture levels and reducing continentality at inland

558   locations.

559   A range of terrestrial evidence suggests that the Last Glacial-Interglacial Transition

560   transition was relatively arid in the Tablelands. River flows in the Murray Basin registered at

561   MD03-2611 were low between 12 and 14 ka (Gingele, *et al*., 2005; Moros *et al*., 2009), and

562   high quartz and titanium levels in the same core indicate a return to arid conditions (De

563   Deckker *et al*., 2012). OSL ages on shorelines at Lake George suggest lake levels were low

564   between 14 and 10 ka (Fitzsimmons and Barrows, 2010). Mountain Lagoon remained a

565   shallow fen until deeper water appeared around 10 ka (Robbie and Martin, 2007). Pollen

566   records from NSW suggests forest developed later in western compared to eastern sites,

567   possibly owing to a steep E-W precipitation gradient. On the eastern ranges, *Eucalyptus*

568   woodland extended up to 1000 m at Gooches Crater by at least 14.5 ka (Black and Mooney

569   2006). Open woodland was already established at higher elevations on the Barrington Tops

570   by 12.9 ka and cool temperate rainforest communities were established by 10.2 ka (Dodson *et*

571   *al*., 1986). In the western ranges, montane forest developed around 10.0 ka and wet forest

572   did not expand until ~8-9 ka. Forest also developed later in sites such as Bega Swamp

573   located near modern rainshadows, which may have been enhanced at this time. There, forest

574   developed at 10.5 ka, and wet forest did not expand until 7.5 ka (Hope *et al*., 2004; Donders,

575   2007).

576   The vegetation records from the Southern Highlands tend to produce a picture

577   of stable climates through the Holocene, although more sensitive indicators of climate change

578   indicate effective precipitation was variable after 10 ka (Moros *et al*., 2009; Kemp *et al*.,

579   2012; Wilkins *et al*., 2013). At Lake George the highest Holocene shorelines occur at 8-10

580   ka (Fitzsimmons and Barrows, 2010), but a continuous record from Lake Keilambete

581   suggests high lake levels lasted only 1000 years centred at 7.2 ka (Wilkins *et al*., 2013). In

582   pollen records this interval is usually characterised by consistent representation of

583   *Pomaderris* indicating the development of more extensive wet forest (the "*Pomaderris* rise")

584   (Macphail, 1981), but the interval is short-lived at some sites such as Club Lake and Blue

585   Lake, which today lie above the montane forest zone (Bowler *et al*., 1976; Martin, 1986).

586   *Pomaderris* is virtually absent at both Micalong and Willigobung suggesting that

587   precipitation remained marginal for wet forest, but variations in effective precipitation may

588   be the cause of alternations between drier and wetter forest elements at Micalong Swamp.

589   The return to subalpine woodland or daisy-rich grassland at Micalong Swamp

590   between 2.7 and 0.9 ka implies a return to colder conditions, an expansion of subalpine

591   woodland and/or the valley bottom frost hollow. The change is not apparent at Willigobung,

592   200 m lower in elevation, but support for regional cooling comes from renewed periglacial

593   action in the Australian Alps between 3.2 and 1.4 ka (Costin *et al*., 1967; Costin, 1972;

594   Martin, 1986) and in a general resurgence in bog growth between 4.1 and 2.5 ka (Macphail

595   and Hope, 1985; Dodson *et al*., 1986). A phase of increased hillslope instability in the

596   Southern Tablelands between 3.1 ka and 1.1 ka BP may reflect an increase in cold climate

597   weathering at higher elevations (Williams, 1978; Harrison, 1980; Erikson *et al*., 2006).

598   Elevated lake levels at Lakes Keilambete, Gnotuk and George at 4.0 - 2.1 ka (Fitzsimmons

599   and Barrows, 2010; Wilkins *et al*., 2013) suggest cooling was responsible for the increase in

600   lake levels at this time.

601

602   **Conclusions**

603   Micalong and Willigobung Swamps provide apparently complete records of

604   vegetation from late glacial times to the present, and are the first vegetation records from the

605   montane, western slopes of the NSW Southern Tablelands. Pollen records suggest the

606   development of full forest cover was established at ~10 ka, and was delayed 2-3 ka behind

607   some sites in the coastal ranges. Wet forest expansion occurred relatively late at 8-9 ka and

608   remained limited throughout the Holocene. Evidence for a neoglacial cooling at higher

609   elevations between 2.7 and 0.9 ka is consistent with other terrestrial records in southeastern

610   Australia. High resolution analysis of macrocharcoal, supported by higher resolution dating

611   based on identified material such as seeds or charcoal, in these and other regional records is

612   needed to explore the effects of changing fire regimes on vegetation.

613

614   **Acknowledgments**

622

623   **References**

624   Aplin KP, Ford F, Hiscock P. 2010. Early Holocene human occupation and environment

625   of the southeast Australian Alps: New evidence from the Yarrangobilly Plateau. In

626   *Altered Ecologies: Fire, Climate and Human Influence on Terrestrial Landscapes,*

627   Haberle S, Stevenson J, Prebble M (eds). ANU E Press: Canberra; 187-212.

628   Balliere FF. 1866. *Balliere's NSW Gazetteer and Road Guide*. FF Balliere: Sydney.

629   Barrows TT, Stone JO, Fifield LK, Cresswell RG. 2001. Late Pleistocene glaciation of

630   the Kosciuszko Massif, Snowy Mountains, Australia. *Quaternary Research* **55**:

631   179-189.

632   Barrows TT, Stone JO, Fifield LK. 2004. Exposure ages for Pleistocene periglacial

633   deposits in Australia. *Quaternary Science Reviews* **23**: 697-708.

634   Barrows TT, Juggins S, De Deckker P, Calvo E, Pelejero C. 2007. Long-term sea surface

635   temperature and climate change in the Australian–New Zealand region.

636   *Palaeoceanography* **22**: PA2215.

637   Barrows TT, Alloway B, Reeves J. 2013. The AUSTRALASIAN-INTIMATE project

638   special volume. *Quaternary Science Reviews* **74**: 1-3.

639   Black MP, Mooney SD. 2006. Holocene fire history from the Greater Blue Mountains

640   World Heritage Area, New South Wales, Australia: the climate, humans and fire

641   nexus. *Regional Environmental Change* **6**: 41-51.

642   Bland W. 1831. *Journey of Discovery to Port Phillip, New South Wales; by Messrs.*

643   *W.H.Hovell, and Hamilton Hume: in 1824 and 1825*. A.Hill, Printer: Sydney.

644   Blom WM, Alsop DB. 1988. Carbonate mud sedimentation on a temperate shelf: Bass

645   Basin, southeast Australia. *Sedimentary Geology* **60**: 269-280.

646   Bostock HC, Opdyke BN, Gagan MK, Kiss AE, Fifield LK. 2006. Glacial/interglacial

647   changes in the East Australian current. *Climate Dynamics* **26**: 645-659.

648   Bowler JM, Hope GS, Jennings JN, Singh G, Walker D. 1976. Late Quaternary climates

649   of Australia and New Guinea. *Quaternary Research* **6**: 359-394.

650   Bowler JM. 1978. Quaternary climate and tectonics in the evolution of the Riverine Plain,

651   southeastern Australia. In *Landform Evolution in Australasia*, Davies JL, Williams

652   MAJ (eds). Australian National University Press: Canberra; 70-112.

653   Bureau of Meteorlogy Climate Data Online. Available at

654   http://www.bom.gov.au/climate/data/. Last accessed 19 November, 2013.

655   Calvo E, Carles Pelejero C, De Deckker P, Logan GA. 2007. Antarctic deglacial pattern

656   in a 30 kyr record of sea surface temperature offshore South Australia. *Geophysical*

657   *Research Letters* **34**: L13707.

658   Costin AB. 1954. *A Study of the Ecosystems of the Monaro Region of New South Wales*

659   *with Special Reference to Soil Erosion*. Government Printer: Sydney.

660   Costin AB. 1972. Carbon-14 dates from the Snowy Mountains Area, southeastern

661   Australia, and their interpretation. *Quaternary Research* **2**: 579-590.

662   Costin AB, Thom BG, Wimbush DW, Stuiver M. 1967. Nonsorted steps in the Mt.

663   Kosciusko area, Australia. *Geological Society of America Bulletin* **78**: 979-992.

664   De Deckker P, Moros M, Perner K, Jansen J. 2012. Influence of the tropics and southern

665   westerlies on glacial interhemispheric asymmetry. *Nature Geoscience* **5**: 266-269.

666   Department of Infrastructure, Planning and Natural Resources (N.S.W.). 2005. *Guide to*

667   *the Water Sharing Plan for the Tarcutta Creek Water Source*. Unpublished guide

668   05_029, NSW Department of Natural Resources: Sydney.

669   Dodson JR. 1986. Holocene vegetation and environments near Goulburn, New South

670   Wales. *Australian Journal of Botany* **34**: 231-249.

671   Dodson JR. 1987. Mire development and environmental change, Barrington Tops, New

672   South Wales, Australia. *Quaternary Research* **27**: 73-81.

673   Dodson JR. 1998. Timing and response of vegetation change to Milankovitch forcing in

674   temperate Australia and New Zealand. *Global and Planetary Change* **18**: 161-174.

675   Dodson JR, Greenwood PG, Jones RL. 1986. Holocene forest and wetland dynamics at

676   Barrington Tops, New South Wales. *Journal of Biogeography* **13**: 561-585.

677   Dodson JR, Wright RVS. 1989. Humid to subhumid vegetation shift on Pilliga

678   Sandstone, Ulungra Springs, New South Wales. *Quaternary Research* **32**: 182-192.

679   Dolman G. 1991. Carbonised particle automated counting software. Unpublished

680   software.

681   Donders TH, Haberle SG, Hope GS, Wagner F, Visscher H. 2007. Transition of the eastern

682   Australian climate system from the post-glacial to the present day ENSO mode.

683   *Quaternary Science Reviews* **26**: 1621-1637.

684   Eriksson MG, Olley JM, Kilham DR, Pietsch T, Wasson RJ. 2006. Aggradation and

685   incision since the very late Pleistocene in the Naas River, south-eastern Australia.

686   *Geomorphology* **81**: 66-88.

687   Faegri K, Iverson J. 1964. *Textbook of Pollen Analysis*. Munksgaard: Copenhagen.

688   Farrera I, Harrison SP, Prentice IC, Ramstein G, Guiot J, Bartlein PJ, Bonnefille R, Bush

689   M, Cramer W, von Grafenstein U, Holmgren K, Hooghiemstra H, Hope G, Jolly D,

690   Lauritzen S-E, Ono Y, Pino S, Stute M, Yu G. 1999. Tropical climates at the Last

691   Glacial Maximum: a new synthesis of terrestrial palaeoclimate data. I. Vegetation,

692   lake-levels and geochemistry. *Climate Dynamics* **15**: 823-856.

693   Fitzsimmons KE, Barrows TT. 2010. Holocene hydrologic variability in temperate

694   southeastern Australia: an example from Lake George, NewSouthWales. *The*

695   *Holocene* **20**: 585-597.

696   Flood JM. 1980. *The Moth Hunters: Aboriginal Prehistory of the Australian Alps*.

697   Australian Institute of Aboriginal Studies: Canberra.

698   Galloway RW. 1965. Late Quaternary climates in Australia. *Journal of Geology* **73**: 603-

699   618.

700   Gentilli J. 1986. Climate. In *Australia - A Geography Vol. 1 The Natural Environment,*

701   Jeans N. (ed.). Sydney University Press: Sydney; 14-48.

702   Gingele F, De Deckker P, Norman M. 2007. Late Pleistocene and Holocene climate of SE

703   Australia reconstructed from dust and river loads deposited offshore the River

704   Murray mouth. *Earth and Planetary Science Letters* **255**: 257-272.

705   Gupta SK, Polach H. 1985. Radiocarbon Dating Practices at ANU. Australian National

706   University Press, Canberra.

707   Grimm EC. 1987. CONISS: A Fortran 77 program for stratigraphically constrained

708   cluster analysis by the method of incremental sum of squares. *Computers and*

709   *Geosciences* **13**: 13-35.

710   Grimm EC. 1990. TILIA and TILIA GRAPH: PC spreadsheet and graphics software for

711   pollen data. INQUA - Commission for the Study of the Holocene. *Working Groups*

712   *on Data-Handling Methods Newsletter* **4**: 5-7.

713   Harrison SM. 1980. The geomorphic history of the Breadalbane Basin, New South Wales.

714   Unpublished M.Sc. thesis, Macquarie University, Sydney.

715   Heiri O, Lotter AF, Lemcke G. 2001. Loss on ignition as a method for estimating organic and

716   carbonate content in sediments: reproducibility and comparability of results. *Journal of*

717   *Palaeolimnology* **25**: 101-110.

718   Hiscock P. 1983. A preliminary archaeological investigation of peat bog areas in the

719   Southern Tablelands, New South Wales. A report to the National Parks and

720   Wildlife Service, New South Wales in conjuction with Dr. G Hope and Ms. W.

721   Southern. In *Organic Deposits of the Southern Tablelands*, Hope G, Southern W,

722   Appendix 4.

723   Hiscock P. 2008. *Archaeology of Ancient Australia*. Routledge: Milton Park.

724   Hogg AG, Hua Q, Blackwell PG, Buck CE, Guilderson TP, Heaton TJ, Niu M, Palmer JG,

725   Reimer PJ, Reimer RW, Turney CSM, Zimmerman SRH. 2013. SHCAL13 Southern

726   Hemisphere Calibration, 0–50,000 years cal BP. *Radiocarbon* **55**: 1889-1903.

727   Hope G, Kershaw AP, van der Kaars S, Xiangjun S, Liew P, Heusser LE, Takahara H,

728   McGlone M, Miyoshi N, Moss PT. 2004. History of vegetation and habitat change

729   in the Austral-Asian region. *Quaternary International* **118-119**: 103-126.

730   Hope GS. 2006. Histories of wetlands in the Australian Capital Territory and the bog

731   recovery program. In *Caring for Namadgi Science and People*, McCue K, Lenz S,

732   Freidrich S (eds.). Proceedings of the NPA ACT Symposium Canberra May 2006,

733   National Parks Association ACT: Canberra; 129-144.

734   Hope GS, Clark RL. 2008. A tale of two swamps: subalpine peatlands in the Kelly-Scabby

735   area of Namadgi National Park. In *Corridors for Survival in a Changing World,*

736   McCue K, Lenz S (eds). National Parks Association ACT: Canberra; 61-76.

737   Hope GS, Kershaw AP. 2005. Montane swamps of eastern Australia. In *The Peatlands of*

738   *the Australasian Region*, Whinam J, Hope GS (eds). In G.M. Steiner, (Ed.), *Moore*

739   *- von Sibirien bis Feuerland, Biologiezentrum der Oberoesterreichischen*

740   *Landesmuseen Neue Serie* **35**, Linz: 397-434.

741   Hope GS, Nanson R, Flett I. 2009. *The peat-forming mires of the Australian Capital*

742   *Territory*. Technical Report 19, Territory and Municipal Services, ACT Government:

743   Canberra; 57 pp.

744   Hope GS, Nanson R, Jones P. 2012. *The peat-forming bogs and fens of the Snowy Mountains*

745   *of New South Wales*. NSW Parks and Wildlife Service Technical Report; 81 pp.

746   Hope GS, Southern W. 1983. *Organic deposits of the Southern Tablelands region, New*

747   *South Wales*. National Parks and Wildlife Service: Sydney.

748   Johnston P, Brierley G. 2006. Late Quaternary river evolution of floodplain pockets along

749   Mulloon Creek, New South Wales, Australia. *The Holocene* 16: 661-674.

750   Kemp J, Radke LC, Olley J, Juggins S, De Deckker P. 2012. Holocene lake salinity

751   changes in the Wimmera, southeastern Australia, with evidence for millennial-

752   scale climate variability. *Quaternary Research* **77**: 65-76.

753   Lorrey A, Bostock H, Phipps S, Reeves J. 2013. Announcing SHAPE: Southern

754   Hemisphere Assessment of PalaeoEnvironments. *Quaternary Australasia* **30**: 31-

755   32.

756   Lopes dos Santos RA, Spooner MI, Barrows TT, De Deckker P, Sinninghe Damsté JS,

757   Schouten S. 2013. Comparison of organic (UK' 37, TEXH 86, LDI) and faunal

758   proxies (foraminiferal assemblages) for reconstruction of late Quaternary sea

759   surface temperature variability from offshore southeastern Australia.

760   *Paleoceanography* **28**: 377-387.

761   Macphail, MK. 1981. Fossil Pomaderris apetala-type pollen in North-West Nelson: reflecting

762   extension of wet sclerophyll forests in south-eastern Australia? *New Zealand Journal*

763   *of Botany* **19**: 17-22.

764   Macphail MK, Hope GS. 1985. Late Holocene mire development in montane

765   southeastern Australia: a sensitive climatic indicator. *Search* **15**: 344-349.

766   Martin ARH. 1986. Late glacial and Holocene alpine pollen diagrams from the Kosciusko

767   National Park, New South Wales, Australia. *Review of Palaeobotany and*

768   *Palynology* **47**: 367-409.

769   Martin ARH. 1999. Pollen analysis of Digger's Creek Bog, Kosciuszko National Park:

770   Vegetation history and tree-line change. *Australian Journal of Botany* **47**: 725-744.

771   McDougall KL, Walsh NG. 2007. Treeless vegetation of the Australian Alps.

772   *Cunninghamia* **10**: 1–57.

773   Moros M, De Deckker P, Jansen E, Perner K, Telford RJ. 2009. Holocene climatic

774   variability in the Southern Ocean recorded in a deep-sea sediment core off South

775   Australia. *Quaternary Science Reviews* **28**: 1932–1940.

776   Ollier CD. 1978. Tectonics and geomorphology of the eastern highlands. In *Landform*

777   *Evolution in Australasia,* Davies JL, Williams MAJ (eds). Australian National

778   University Press: Canberra; 5-47.

779   Page K, Carden YR. 1988. Channel Adjustment Following the Crossing of a Threshold:

780   Tarcutta Creek, Southeastern Australia. *Australian Geographical Studies* **36**: 289-

781   311.

782   Page K, Nanson G, Price D. 1996. Chronology of Murrumbidgee River palaeochannels

783   on the Riverine Plain, southeastern Australia. *Journal of Quaternary Science* **11**:

784   311-336.

785   Prosser I, Chappell J, Gillespie R. 1994. Holocene valley aggradation and gully erosion in

786   headwater catchments, south-eastern highlands of Australia. *Earth Surface*

787   *Processes and Landforms* 19: 465-480.

788   Raine JI. 1974. *Pollen sedimentation in relation to the Quaternary vegetation history of*

789   *the Snowy Mountains of New South Wales*. Unpublished Ph.D. Thesis, Australian

790   National University: Canberra.

791   Reeves JM, Barrows TT, Cohen TJ, Kiem AS, Bostock HC, Fitzsimmons KE, Jansen JD,

792   Kemp J, Krause C, Petherick L. 2013. Climate variability over the last 35,000 years

793   recorded in marine and terrestrial archives in the Australian region: an OZ-

794   INTIMATE compilation. Quaternary Science Reviews 74, 21-34.

795   Robbie A, Martin HA. 2007. The History of the Vegetation from the Last Glacial

796   Maximum at Mountain Lagoon, Blue Mountains, New South Wales. *Proceedings*

797   *of the Linnean Society of New South Wales* **128**: 57-80.

798   Sikes EL, Howard WR, Samson CR, Mahan TS, Robertson LG, Volkman JK. 2009.

799   Southern Ocean seasonal temperature and Subtropical Front movement on the

800   South Tasman Rise in the late Quaternary. *Paleoceanography* **24**: PA2201.

801   Singh G, Geissler EA. 1985. Late Cainozoic history of vegetation, fire, lake levels and

802   climate at Lake George, New South Wales. *Philosophical Transactions of the*

803   *Royal Society of London Series B* **311**: 379-447.

804   Slatyer RO. 1989. Alpine and valley bottom treelines. In *The Scientific Significance of the*

805   *Australian Alps,* Good RB (ed.). Australian Alps National Parks Liaison

806   Committee: Canberra; 169-184.

807   Stuiver M, Reimer PJ, Reimer RW. 2005. CALIB 5.0. [WWW program and

808   documentation]. .

809   Sweller S, Martin HA. 2001. A 40,000 year vegetation history and climatic interpretations

810   of Burraga Swamp, Barrington Tops, New South Wales. *Quaternary International*

811   **83-85**: 233-244.

812   Wasson RJ, Mazari RK, Starr B, Clifton G. 1998. The recent history of erosion and

813   sedimentation on the Southern Tablelands of southeastern Australia: sediment flux

814   dominated by channel incision. *Geomorphology* 24: 291-308.

815   Whinam J, Chilcott N. 2002. Floristic description and environmental relationships of

816   *Sphagnum* communities in NSW and the ACT and their conservation management.

817   *Cunninghamia* **7**: 463-500.

818   Williams J. 1985. A preliminary palaeoecology of Tarcutta Swamp, Tumbarumba, New

819   South Wales. Unpublished report, Department of Geography, Australian National

820   University.

821   Williams MAJ. 1978. Late Holocene hillslope mantles and stream aggradation in the

822   Southern Tablelands, N.S.W. *Search* **9**: 96-7.

823   Williams NJ, Harle KJ, Gale SJ, Heijnis H. 2006. The vegetation history of the last

824   glacial–interglacial cycle in eastern New South Wales, Australia. *Journal of*

825   *Quaternary Science* **21**: 735-750.

826   Wilkins D, Gouramanis C, De Deckker P, Fifield K, Olley J. 2013. Holocene lake-level

827   fluctuations in Lakes Keilambete and Gnotuk, southwestern Victoria, Australia.

828   *The Holocene* **23**: 784–795.

829

830

831 Table 1 Radiocarbon ages on organic and mineral sediments at Micalong and Willigobung

832 Swamps

Depth (cm)	Sample Code	Material dated	Age ^{14}C a B.P.	Calibrated age
Micalong Core				
MS3				
120-124	ANU 8827	Bulk peat	3,330±180	3540 ± 280
276-280	ANU 8828	Bulk peat	6,870±200	7720 ± 200
385-389	ANU 8829	Bulk peat	10,260±230	11,910 ± 490
520-529	ANU 8830	AMS peat	9,900±330	11,340 ± 575
559.5-560	ANU 8832	AMS peat	1,030±185	890 ± 170
Micalong Core				
MS-82				
380-390	ANU 3342	Bulk clayey peat	12,330±250	14,330 ± 470
Willigobung				
Swamp WSA				
360-375	ANU 4384	peat	5770 ± 120	6,530 ± 130
515-530	ANU 4385	peaty clay	9420 ± 110	10,580 ± 170

833

834 Figure 1. Map of the Southern Tablelands, New South Wales showing the locations of places
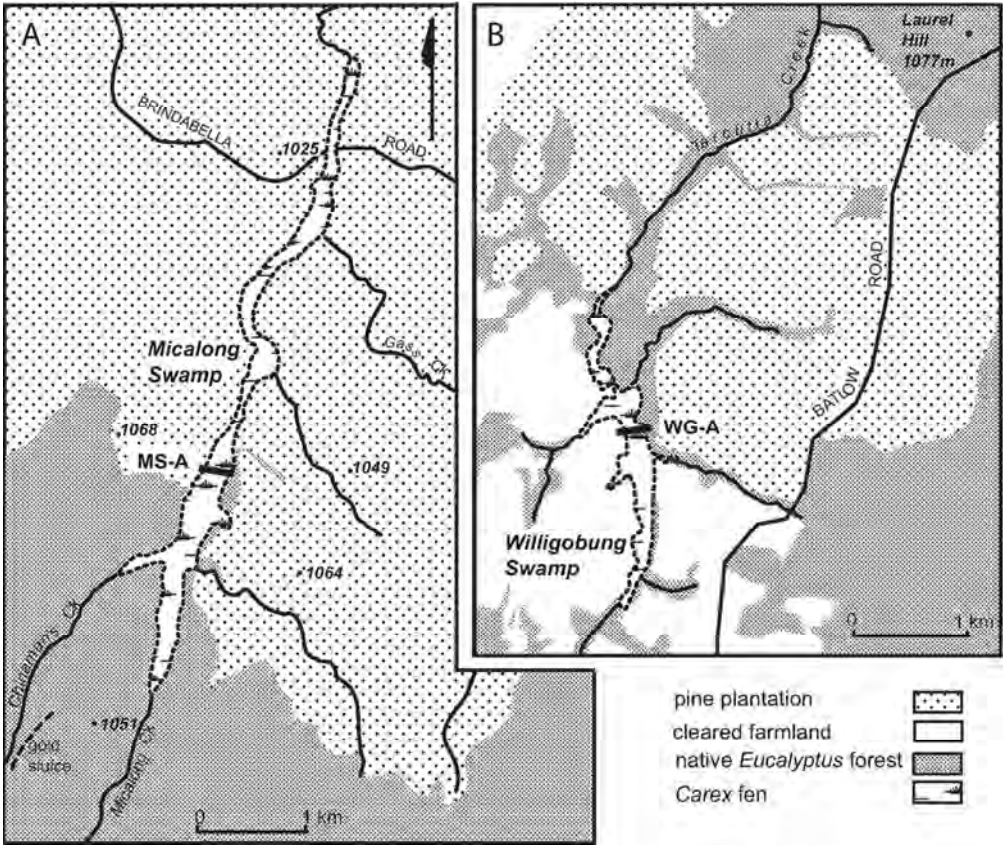
835 mentioned in the text.

836 Figure 2. A. Micalong Swamp, Fiery Ranges, N.S.W. B. Willigobung Swamp near
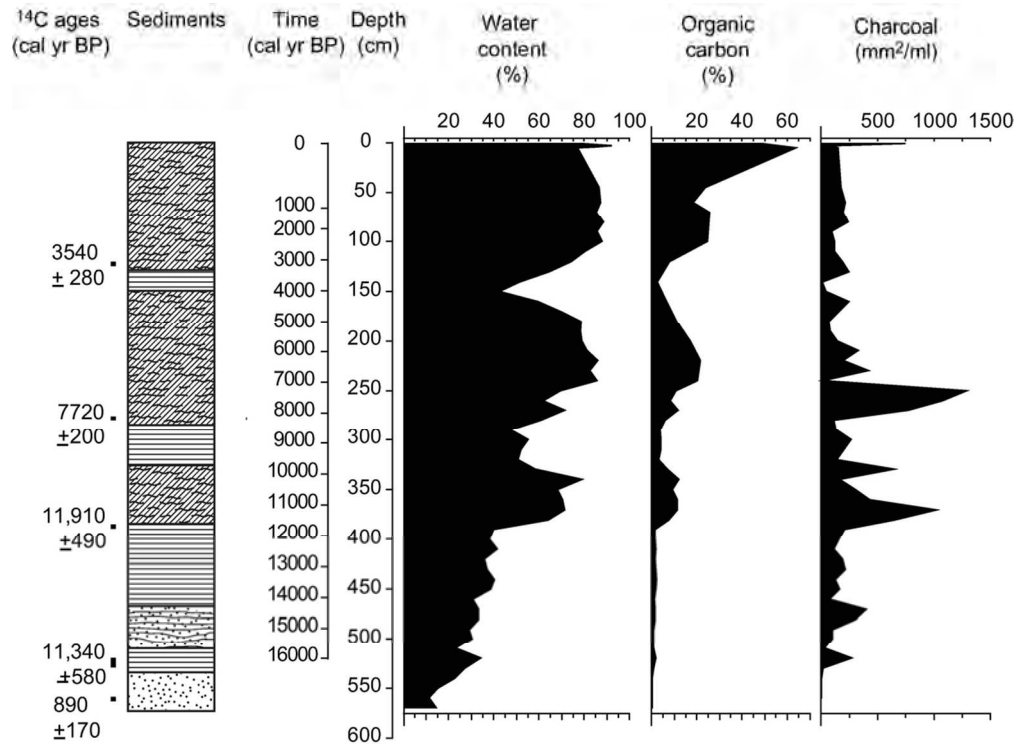
837 Tumbarumba, N.S.W.

838   Figure 3. Sediments, water content, loss on ignition and charcoal counts for core MS3 at

839   Micalong Swamp. See Fig. 4 for key to sediments.

840   Figure 4. A. Stratigraphic cross-sections at A. Micalong Swamp (MS-A) and B. Willigobung

841   Swamp (WG-A) (Fig. 2).

842   Figure 5 Relative frequencies of pollen and spores, Micalong Swamp, N.S.W.

843   Figure 6. Sediments, loss-on-ignition and charcoal counts for Willigobung Swamp. See Fig. 4

844   for key to sediments.

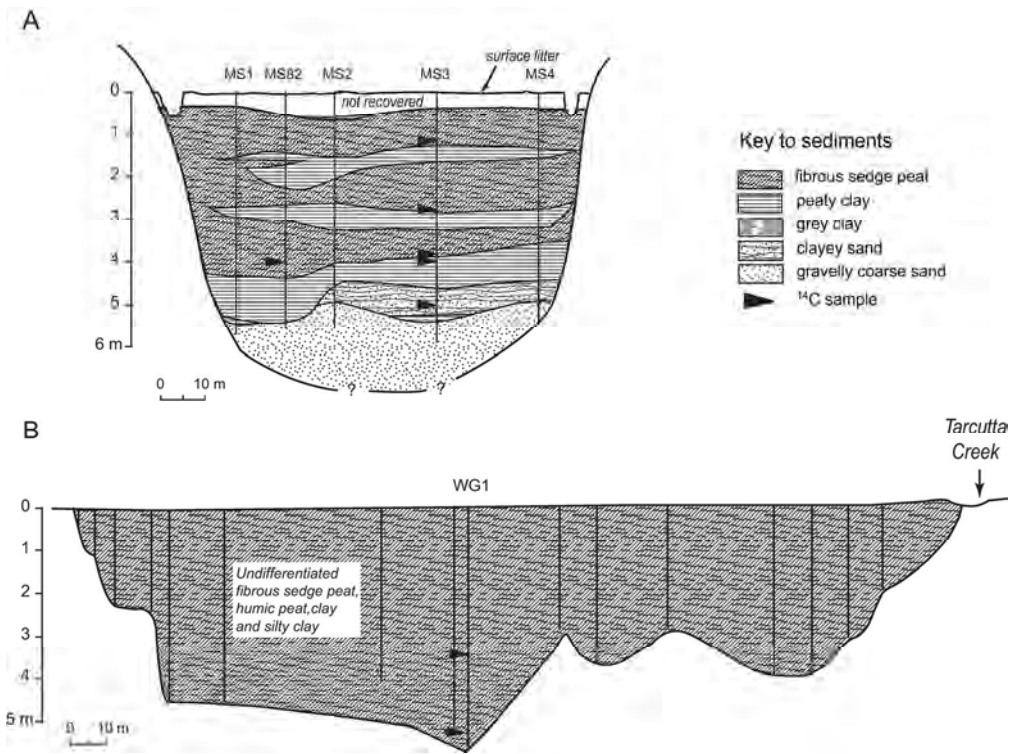845   Figure 7 Relative frequencies of pollen and spores, Willigobung Swamp, N.S.W.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
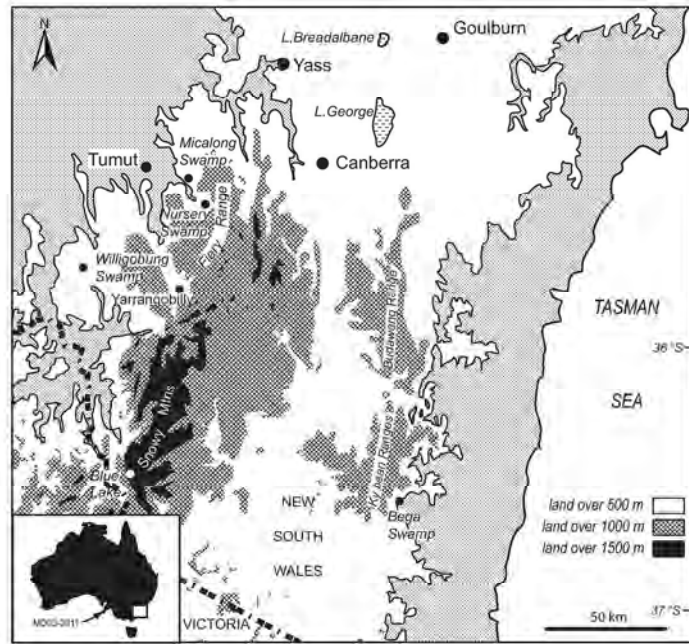
Map of the Southern Tablelands, New South Wales showing the locations of places mentioned in the text.
191x185mm (300 x 300 DPI)

Journal of Quaternary Science

A. Micalong Swamp, Fiery Ranges, N.S.W. B. Willigobung Swamp near Tumbarumba, N.S.W.
88x74mm (300 x 300 DPI)

Sediments, water content, loss on ignition and charcoal counts for core MS3 at Micalong Swamp. See Fig. 4
for key to sediments.
103x76mm (300 x 300 DPI)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
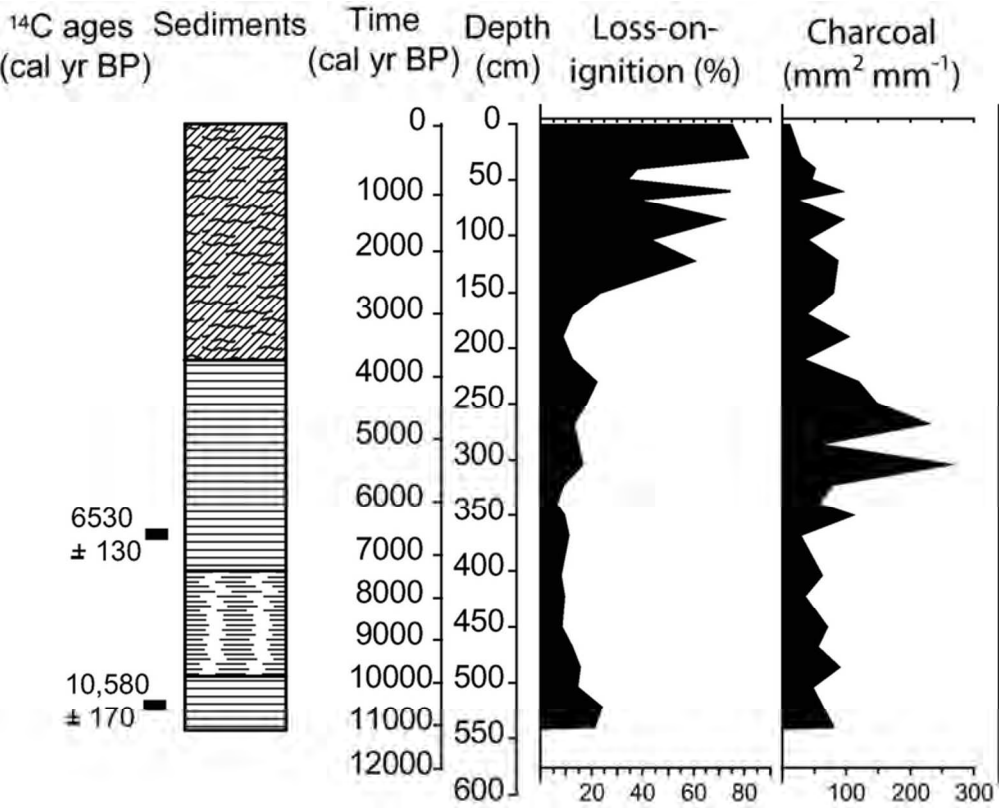49
50
51
52
53
54
55
56
57
58
59
60

A. Stratigraphic cross-sections at A. Micalong Swamp (MS-A) and B. Willigobung Swamp (WG-A) (Fig. 2).
145x108mm (300 x 300 DPI)
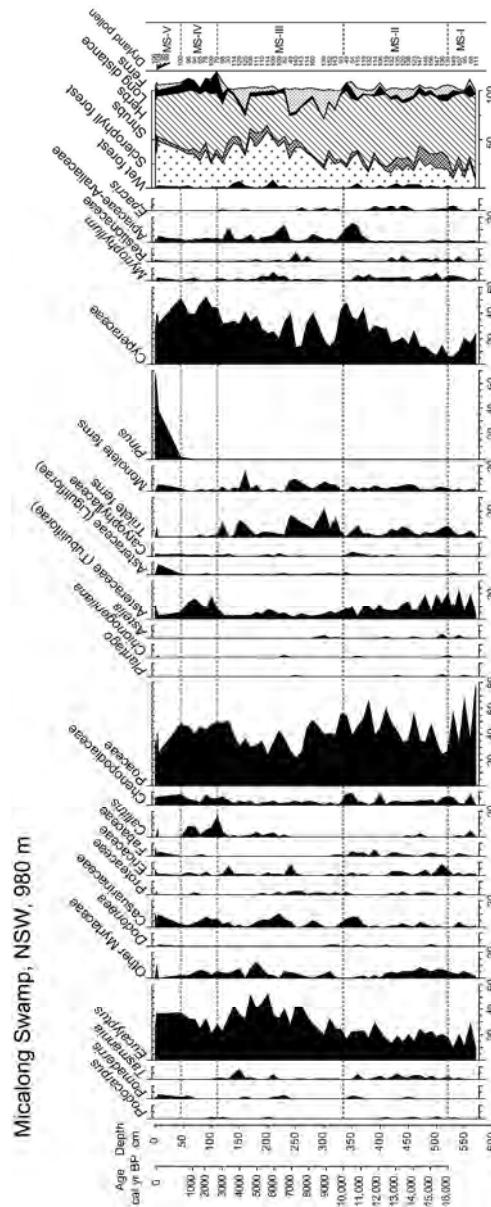
Relative frequencies of pollen and spores, Micalong Swamp, N.S.W.
271x669mm (300 x 300 DPI)

Sediments, loss-on-ignition and charcoal counts for Willigobung Swamp. See Fig. 4 for key to sediments.
71x58mm (300 x 300 DPI)

Relative frequencies of pollen and spores, Willigobung Swamp, N.S.W.
255x565mm (300 x 300 DPI)