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Vegetation and environments since the Last Glacial Maximum in the Southern Tablelands, New South Wales

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ABSTRACT: Regional changes in vegetation and environment in the last 16 ka have been reconstructed from Micalong Swamp and Willigobung Swamp (35°S) on the western Southern Tablelands of New South Wales (NSW). Micalong Swamp lies at 980 m above sea level (a.s.l.), which is close to the subalpine treeline at this latitude. Willigobung Swamp (780 m a.s.l.) approaches the modern ecotone between dry and wet montane forest formations. The sites are sensitive to shifts in temperature and precipitation and are the first reported pollen records from the western montane slopes of NSW. A radiocarbon-based chronology indicates that Micalong Swamp was a swampy, gravel floodplain surrounded by alpine grassland before 16.1 ka. Subalpine woodland may have become established at 1000 m by 16–14 ka. Organic fen sedimentation developed <11.8 ka at Willigobung, and ~11.7 ka at the higher elevation Micalong Swamp. Wet forest elements were present at both sites around 10 ka and persisted for 3–4 ka. Sedimentation in a shallow lake or fen between 10 and 8 ka supports this evidence for wetter conditions in the early Holocene. In the late Holocene an expansion of subalpine flora between 2.7 and 0.9 ka preceded by shallow lake/fen sedimentation is consistent with regional evidence for neoglacial cooling.
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KEYWORDS: charcoal; fen peatlands; late Quaternary; pollen; south-eastern Australia; vegetation history.

Introduction

A comparison of late Quaternary climate change in the Northern and Southern Hemispheres is a subject of ongoing debate and major research efforts are presently underway to integrate regional records from the Southern Hemisphere to facilitate hemispheric and global analyses (e.g. Barrows *et al.*, 2013). Even in some temperate regions of Australia this aim has been thwarted by a lack of data (Reeves *et al.*, 2013). In south-eastern Australia, much of the continuous record of changing environments comes from pollen histories extracted from lakes, fens and peat bogs. Lake records are scarce below the alpine zone, and periodic drying and low organic contents have adversely affected pollen preservation and increased the dating uncertainties (e.g. Singh and Geissler, 1985). Alpine and montane peat bogs have better pollen preservation, but their small scale yields essentially local vegetation histories. In southern New South Wales (NSW), fen peatlands were widespread until the introduction of European-style agriculture, which resulted in the incision and erosion of organic valley fills, particularly in the middle and lower reaches of the river systems (Wasson *et al.*, 1998). The preserved remnants of these fens remain sufficiently numerous to capture the regional pollen rain and are less susceptible to erosion, drying and fire. This paper reviews vegetation change in the NSW Southern Tablelands, and presents two new records from montane fens in the upper Murrumbidgee Basin. As the first pollen records reported from the western montane belt of the Southern Tablelands, they fill an important gap in our knowledge of late Quaternary environments in the region.

Environmental setting

The NSW Southern Tablelands (35–37°S) is an ~180-km-wide belt of mountain ranges and tablelands that separates the interior lowlands of the Murray Basin from the coastal plain (Fig. 1). Its eastern edge is defined by the Great Escarpment and coastal ranges over 1000 m. On its western edge, stepped plateaux climb to 1500 m elevation with peaks rising over 2000 m along the Snowy Mountains. Cirque basins and glacial moraine are found on the highest peaks and cosmogenic dating of moraine has identified a series of glaciations between 60 and 17 ka (Barrows *et al.*, 2001). Relict periglacial landforms above 1000 m were active during the last glacial maximum (Galloway, 1965; Barrows *et al.*, 2004). On the northern ranges of the Australian Alps the treeline lies at 1900 m, which exceeds the highest peaks in the area, but the orographic treeline falls to ~1300 m on exposed plateau surfaces (McDougall and Walsh, 2007). Subalpine vegetation prevails above 1500 m and is dominated by *Eucalyptus pauciflora* (snow gum) woodland with a grass or shrub understorey. In valley bottoms above 1000 m the treeline may be inverted owing to cold air drainage. Montane wet eucalypt forest occupies altitudes between 900 and 1500 m at this latitude (Costin, 1954). The regional climate is temperate with a distinctly warm and dry summer (Stern *et al.*, 2000). In winter, the dominant source of moisture results from fronts embedded in the westerly winds, and regular, severe frosts play an important role in the mechanical weathering of soils above 1000 m (Costin, 1954).

Micalong Swamp

Micalong Swamp (35.318°S, 148.524°E) is located on the north-west plateau of the Fiery Range (Fig. 1). The plateau is underlain by Silurian–Devonian dolerites intruded by younger granite. The fen sits at 980 m and extends downstream for ~4 km within a 200-m-wide, fault-aligned valley near the headwaters of Micalong Creek. Surrounding hills rise to 1200 m elevation. The valley fill comprises ~1 km^2 of topogenous fen with an average depth of 4 m, grading downstream to humic silty flats now being actively incised by the stream (Hope and Southern, 1983). Climate records available

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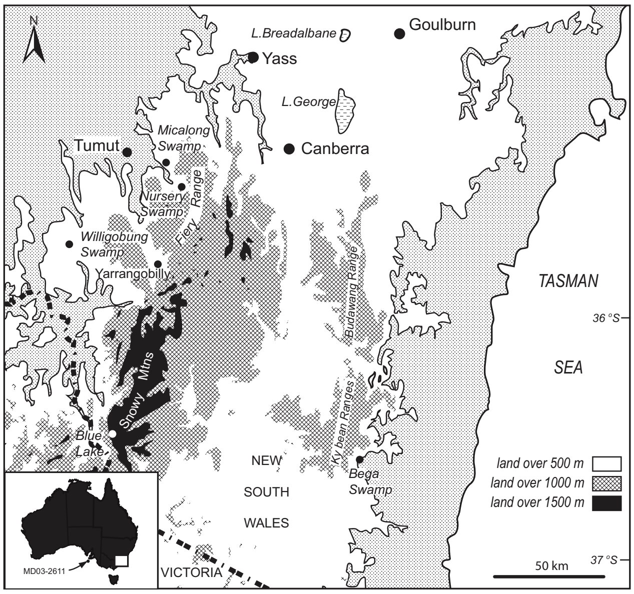

Figure 1. Map of the Southern Tablelands, NSW, showing the locations of places mentioned in the text.

from Bondo Forestry Station, 5 km westwards at 840 m, indicate a mean January temperature of 18.2 °C and mean winter temperature of 4.2 °C. Average annual precipitation at Bondo is 1240 mm with a slight winter maximum, and precipitation decreases with altitude and distance westward to 816 mm at Tumut, 26 km westward at 300 m elevation (Bureau of Meteorology, 2013).

Hope and Southern (1983) surveyed the local vegetation at Micalong Swamp. The fen is dominated by *Carex gaudichaudiana* with a fringing montane *Sphagnum* bog that includes shrub species of *Leptospermum, Epacris, Hakea* and *Baeckea* (Hope *et al.*, 2009). Other aquatic taxa represented in the fen include Poaceae, other graminoids in the Cyperaceae, Juncaceae, Orchidaceae and Restionaceae, fern species in *Blechnum* and *Adiantum*, and herbs such as *Epilobium*, Apiaceae–Araliaceae, *Myriophyllum, Ranunculus, Neopaxia* and *Stellaria*. The fen margins have introduced weeds including blackberry (*Rubus fruticosus*), *Centaurium*, clovers (*Trifolium* and *Medicago*), *Plantago* and flatweeds such as *Hypochoeris radicata*.

Vegetation surrounding the fen is *Eucalyptus stellulata – E. pauciflora – E. camphora* woodland with a grassy understorey of *Polystichum* and *Blechnum* ferns and scattered small trees of *Acacia melanoxylon, Lomatia* and *Polyscias*. Large areas have been cleared for conifer plantation but remnant native vegetation above 900 m is tall open forest dominated by *E. dalrympleana* with an understorey characteristic of both wet and dry forests, including *Tasmannia lanceolata, Dicksonia antarctica* and *Acacia dealbata*, and shrub species of Fabaceae and Asteraceae: *Daviesia, Platylobium, Helichrysum, Olearia* and *Cassinia*. Below 900 m, open forest of *E. dives* or *E. radiata* dominates with *Callitris* appearing at lower altitudes.

Evidence for Aboriginal occupation of Micalong Swamp comes from scattered flakes of quartz and chert around the banks and from nine known occupation sites in the catchment (Hiscock, 1983). Backed blades were also found by Flood (1980, p. 213), which suggests continuous occupation for at least 4 ka. The precise use the Aborigines made of the fen is unknown, although reliable water is likely to have been a precious resource in the Tablelands (Hiscock, 1983). Hume and Hovell encountered the 'mountain swamp' on their exploration of the region in 1824 (Bland, 1831). They sighted distant fires but no Aborigines in this open country with good grass, which had the appearance of being regularly burned. In the late 19th century, 'The Micalong' supported several pastoral families, and was the northern entrance of a much-used stock route into the high country. Gold was mined briefly at Chinaman's Creek (Fig. 2A). Summer grazing and regular burns were conducted until the 1950 s. Nowadays, disturbance from these activities appears to be minimal except for the legacy of introduced weeds. In 1969, the slopes around the lower half of the fen were cleared to make way for *Pinus* plantation. The fen was gazetted as part of the Micalong Swamp Flora Reserve in 1985.

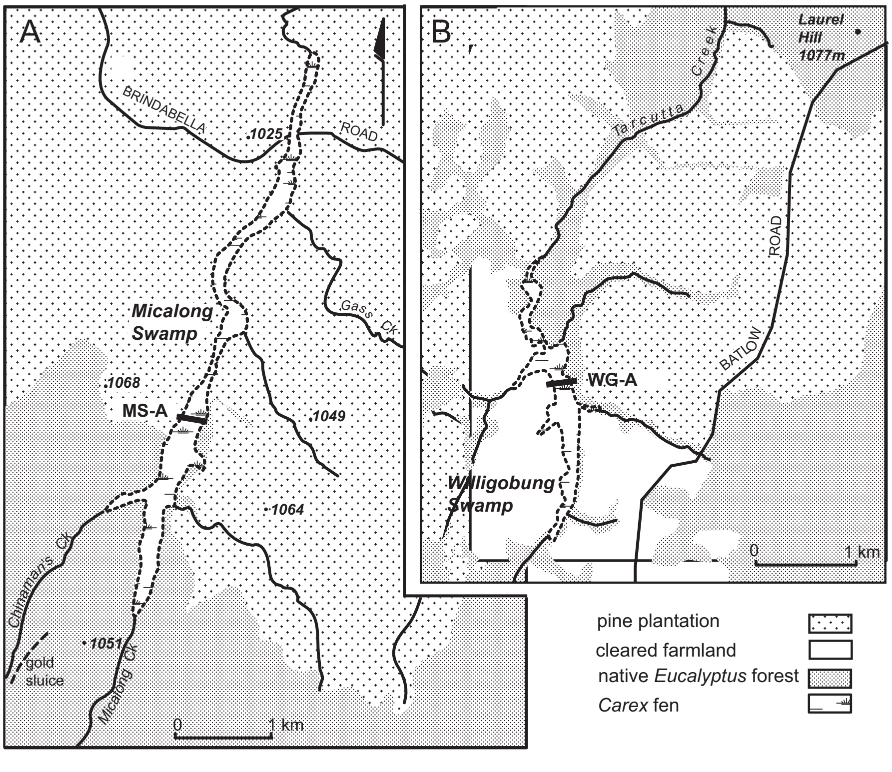

Figure 2. (A) Micalong Swamp, Fiery Ranges, NSW. (B) Willigobung Swamp near Tumbarumba, NSW.

Willigobung Swamp

Willigobung (or Tarcutta) Swamp (35.66°S, 148.04°E) sits on the steep western slopes of the Australian Alps in the upper Murrumbidgee Basin (Fig. 1). The valley is underlain by Silurian granite. The fen lies at 780 m between hills that rise to 1020 m and extends for 3.3 km down valley (Fig. 2B). Climate data from Tumbarumba Post Office, 14 km south at 645 m, give mean January temperature as 20.4 °C and July as 5.2 °C, with an average annual precipitation of 980 mm (Bureau of Meteorology, 2013: 1885–2012).

Before European settlement fen swamp was extensive along Tarcutta Creek. In 1872, a 'large swamp' occupied 13 km of the valley at the confluence of Umbango and Tarcutta Creeks (*The Empire*, 1 April 1872). In wet seasons it became a shallow lake visited by innumerable waterfowl (Balliere, 1866). Much of the valley floor eroded in response to agricultural development or was drained for pasture in the 1930 s, but remnants are preserved near Tarcutta township and in the headwaters of Tarcutta Creek (Page and Carden, 1988). Willigobung Swamp is now the westernmost large sedge fen in southern NSW and is regarded as degraded (Hope *et al.*, 2012).

In 1984, the late Janet Williams described the sediments and vegetation of Willigobung Swamp (unpublished data). In comparison with other fens, the vegetation is depauperate and is dominated by sedge (*Carex gaudichaudiana*) with minor representation by weeds and native species, including *Agrostis*, *Epilobium*, *Erodium*, *Hydrocotyle*, *Hypericum*, *Juncus*, *Lythrum* and *Veronica*. In 1872, the catchment of Tarcutta Creek was described as 'sixty miles of finely grassed, undulating, open forest country' (*The Empire*, 1 April 1872). Remnants of tall eucalypt forest persist in the upper catchment, which is now dominated by *Pinus radiata* plantation, grazing, orchards and vineyards. Drainage to permit sheep and cattle grazing has caused drying of the lower end of the fen but the upper reaches are less affected. Some *Eucalyptus stellulata* around the fen may be a remnant of subalpine woodland that formed in response to cold air drainage along the valley floor.

Methods

Sediments and subsampling

A preliminary investigation of Micalong Swamp in 1982 established that organic sedimentation commenced before 14 ka (Table 1; Hope and Southern, 1983). In 1993, variations in sediment fill were defined from D-section and Livingston cores recorded at ~20-m intervals across the fen. A 5.7-m core with 0.2-m overlap between barrel lengths was collected for detailed analysis in 1993 (MS-3; Figs 2 and 4A). Sediments were described in the field and the core stored in PVC tubes and plastic for transport. Exploratory coring of Willigobung Swamp was carried out by Williams using identical methods to Micalong Swamp, and the deepest section selected for analysis in 1984 (WG-1: Fig. 4B).

In the laboratory 5-mm-thick slices were extracted at 10-cm intervals except for the top 5 cm, where 10-mm slices were sampled at 1-cm intervals. Subsamples of 2 cm^3 were retained for pollen and charcoal analysis, and the remainder was transferred to beakers to obtain estimates of moisture and organic carbon content to provide a measure of the local site productivity and the influx of inorganic sediments. Moisture content was calculated as the difference between wet and oven-dry weight (105 °C) and expressed as a percentage of the total wet weight. Organic carbon in peat sediments was estimated from loss on ignition and expressed as the proportion of combustible to oven-dry sediment mass. Samples were oven dried at 105 °C for 24 h and combusted at 550 °C for 4 h. Organic content of clay-rich sediments was measured by gas chromatograph following Heiri *et al.* (2001).

Radiocarbon dating

Samples of bulk peat from the organic sediments were radiocarbon-dated using liquid scintillation techniques at the Australian National University (ANU) following procedures outlined by Gupta and Polach (1985). Sedge fragments from the lacustrine clays underlying the fen sediments were graphitized at ANU and analysed using accelerator mass spectrometry (AMS) at the Australian Nuclear Science and Technology Organisation. Radiocarbon ages were calibrated using the Southern Hemisphere curve of INTCAL13 using Calib 7.0.0 (Stuiver *et al.*, 2005; Hogg *et al.*, 2013).

Pollen and charcoal

Pollen samples were prepared following standard techniques (Faegri and Iverson, 1964) and were identified with the aid of a reference collection held at the ANU. A minimum of 200 pollen grains or the whole slide was counted. Raw pollen counts were expressed as relative frequencies of the dryland pollen sum, which was based on most dryland taxa, including herbs. For Micalong Swamp this included *Podocarpus*, *Pomaderris*, *Tasmannia*, *Eucalyptus*, other Myrtaceae, Casuarinaceae, Asteraceae (Tubuliflorae and Liguliflorae), Ericaceae <20 μm, Fabaceae, Proteaceae, *Callitris*, Poaceae, Caryophyllaceae, *Plantago*, *Chionogentias*, *Astelia* and fern spores (monolete and trilete). For Willigobung Swamp, *Cyathea* and *Dicksonia* were distinguished from other ferns. Aquatic pollen and spores were expressed as a percentage of the total pollen to minimize the influence of local variations in the vegetation. It was not always possible to distinguish dryland vegetation from swamp taxa because several important fen taxa (eg. Poaceae) are also well represented in the regional

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

Depth (cm)	Sample code	Material dated	Age (^{14}C a BP ± 1σ)	Calibrated age (cal a BP ± 1σ)
Micalong Core MS3				
120–124	ANU 8827	Bulk peat	3330 ± 180	3540 ± 280
276–280	ANU 8828	Bulk peat	6870 ± 200	7720 ± 200
385–389	ANU 8829	Bulk peat	10 260 ± 230	11 910 ± 490
520–529	ANU 8830	AMS peat	9900 ± 330	11 340 ± 575
559.5–560	ANU 8832	AMS peat	1030 ± 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	6530 ± 130
515–530	ANU 4385	Peaty clay	9420 ± 110	10 580 ± 170

vegetation. Shrub Ericaceae was excluded from the dryland pollen sum as *Epacris* species are often prominent in swamp communities. All representatives of the Apiaceae–Araliaceae family were also excluded; high frequencies of Apiaceae–Araliaceae pollen suggested a dominantly local source, probably the aquatic *Hydrocotyle*.

Relative pollen frequencies were determined and pollen diagrams were constructed using TILIA 1.7.14 (Grimm, 1990). The pollen diagram was separated into zones using CONISS, which uses a multivariate method for quantitative definition of pollen frequency data (Grimm, 1987). Slides prepared for pollen analysis were used to obtain quantitative estimates of charcoal (8–100 μm – microcharcoal). An automated counting program was used to estimate the area of charcoal per slide, which identifies dark material in a specified band of light densities but omits extremely opaque objects that might be minerals. The estimate of charcoal area is reported as mm^2 mL^{-1} of original sediment (Dolman, 1991).

Results

Micalong Swamp

Stratigraphy and chronology

Moisture, organic carbon and charcoal volume are given in Fig. 3. The depth of the valley fill could not be determined, but the corer penetrated into rounded, fine gravels fining upwards to sands and clayey sands (Fig. 4). The top ~30 cm below the surface peat mat (~10 cm) was not recovered owing to high moisture content. At the time of sampling the water table was at the surface with surface flow across the swamp at $0.12\,m\,s^{-1}$.

The radiocarbon age for MS82 indicates that organic sedimentation in the valley had commenced before 14.3 ka, although the disparity between the basal organic sediment ages of cores MS82 and MS3 may indicate erosion by a migrating stream. The AMS radiocarbon ages on sedge fragments in the underlying sandy clays yielded younger ages than the basal organic sediment ages of 11.9 and 14.3 ka (Table 1), which may have been contaminated by organic sediments during coring. Dating basal sediments has been an ongoing issue with alpine and sub-alpine fens in south-east Australia, but minor contamination would have little effect on the bulk peat ages. The basal clay ages have been excluded from the age–depth model, which used the mid-point of calibrated date ranges for a linear regression with sample depth as the independent variable. Some additional uncertainty in ages <3.5 ka is due to higher moisture content and lower compaction of the surface mat. The appearance of exotic pollen above 10 cm reflects European land uses that date to about AD 1850 (100 cal a BP).

While speculative, the model gives a near linear relationship with depth ($r^2 = 0.99$), although the changes in mineral content suggest that the sedimentation rate was not constant and may include gaps. Nevertheless the age model provides an approximate age for the valley sedimentation and environmental changes. Downward extrapolation of the overall sedimentation rate places the onset of fine-textured sedimentation at ~16.1 ka.

Biostratigraphy

Dryland pollen counts ranged from 38 to 157 with poor preservation giving counts <50 in three samples (Fig. 5). The record was divided into five zones based on the CONISS results and the proportion of major dryland pollen types.

Zone MS I (570–520 cm; <16.1 ka). Sediments are dominantly sub-angular yellow–brown sands below 540 cm, overlain by beds of reddish yellow and grey sandy clays with abundant Cyperaceae above 532 cm. Organic carbon is mostly <1% and charcoal increases from 4 to 16 mm^2 mL^{-1}.

Herbaceous pollen dominates the pollen spectra. Poaceae reaches values of 80% and exhibits a general decline in favour of Asteraceae, but both reach their maximum representation in this zone with pollen of other herbs, including *Astelia*, *Plantago* and *Chionogentias*, occasionally recorded. *Eucalyptus*, the most numerous woody taxon, fluctuates around 15% of the dryland pollen. *Tasmannia* and *Podocarpus* recur at proportions <3%. *Casuarina* and Chenopodiaceae are present at uniformly low levels. Shrub Ericaceae become relatively numerous at around 5% towards the top of the zone and Proteaceae and Fabaceae appear in minor proportions. Fern spores are consistently <5%. The swamp flora is dominated by Cyperaceae, which declines from 20 to 5% at the top of the zone. *Myriophyllum* and Restionaceae

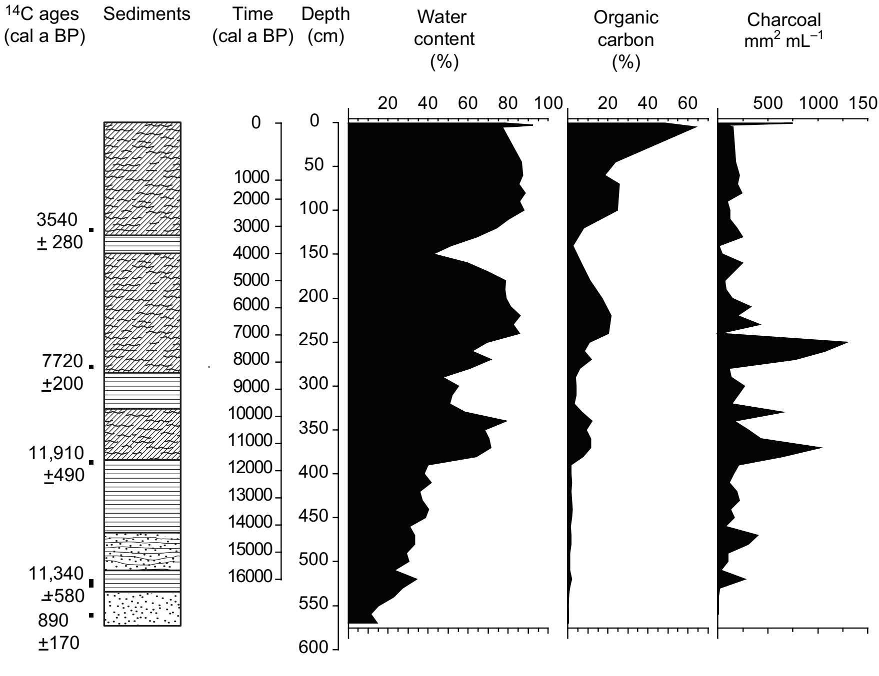

Figure 3. Sediments, water content, loss on ignition and charcoal counts for core MS3 at Micalong Swamp. See Fig. 4 for key to sediments.

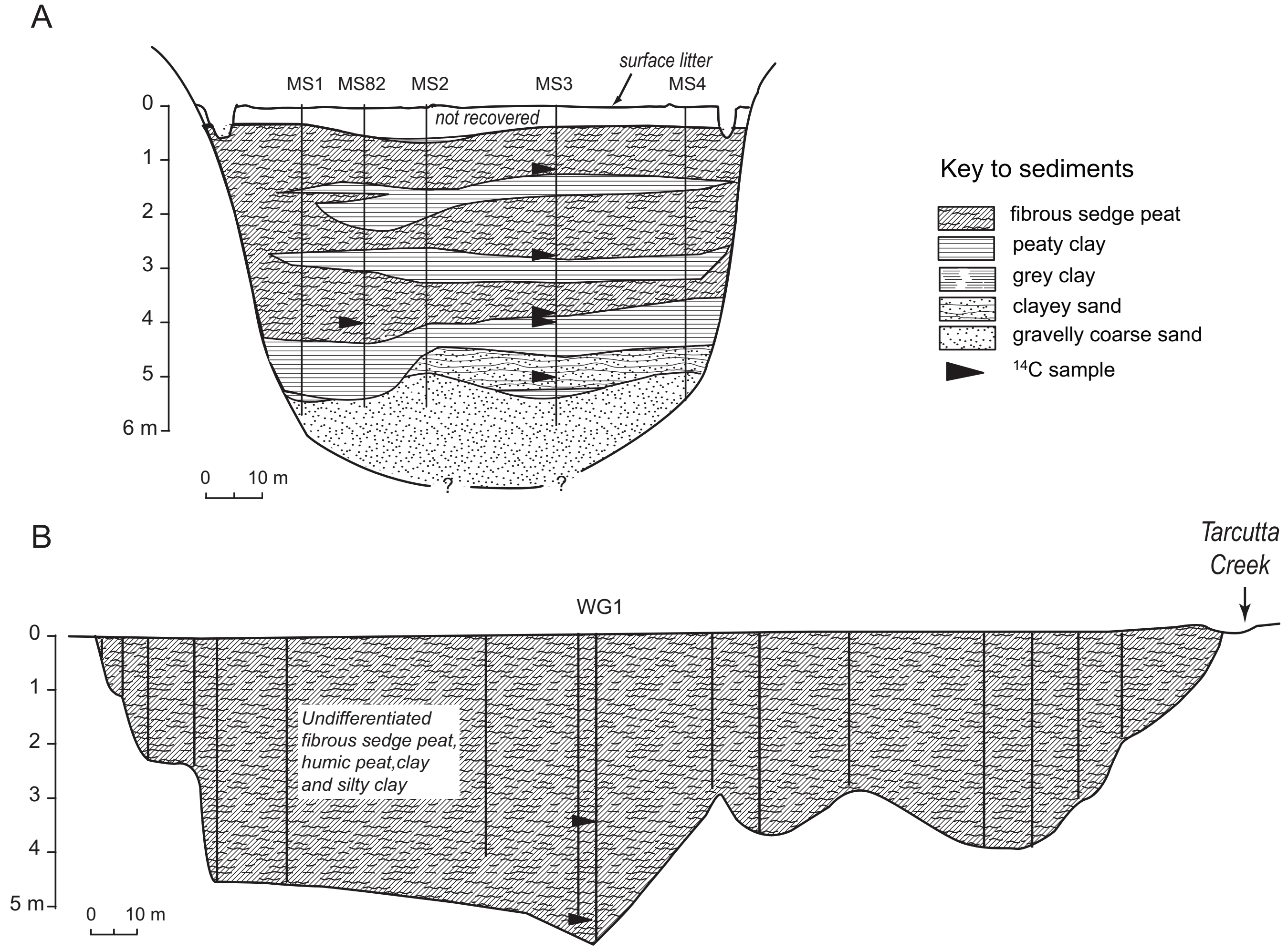

Figure 4. Stratigraphic cross-sections at (A) Micalong Swamp (MS-A) and (B) Willigobung Swamp (WG-A) (Fig. 2).

and swamp shrubs species of Myrtaceae and Ericaceae >20 μm comprise <5% of the total pollen sum.

Zone MS II (520–335 cm; 16.1–10.0 ka). Sediments change abruptly from grey clay with lenses of sandy clay and gravelly clay to black, fibrous peaty mud at 386 cm, accompanied by an increase in organic carbon content from 1 to 11%. Charcoal increases to 170 mm^2 mL^{-1} with a pronounced peak at 380–360 cm.

Pollen spectra are dominated by Asteraceae and Poaceae, which alternate in dominance until 385 cm when pollen of Casuarinaceae and *Eucalyptus* increases to 10 and 20% of the dryland sum, respectively. *Podocarpus* disappears from the record, and the proportions of shrub species of Ericaceae and Myrtaceae decrease. *Tasmannia* and Fabaceae frequencies are higher in this zone. Caryophyllaceae adds to the herb flora and becomes relatively prolific in the upper part of the zone. Fern spores are consistently ~4%. Substantial changes in the swamp flora are apparent from the steady increase in Cyperaceae after 530 cm, and peaks in *Hydrocotyle* and Apiaceae–Araliaceae accompany the change to more organic sedimentation.

Zone MS III (335–110 cm; 10.0–2.7 ka). Sediments are brown and grey–brown fibrous peaty mud with regular, visible changes in humification and clay content. Organic carbon content reaches 21% in organic sediments and 3–5% in clayey sediments. Charcoal reaches 1290 mm^2 mL^{-1} between 250 and 270 cm, then falls to ~160 mm^2 mL^{-1}.

An increase in *Eucalyptus* occurs between 270 and 140 cm, where it exceeds 50% of the dryland pollen at the expense of Poaceae and, to a lesser extent, Asteraceae. Casuarinaceae achieves several peaks accompanied by higher proportions of shrub and small tree species of Myrtaceae and Proteaceae, and monolete and trilete fern spores, especially in the lower half of the zone where they reach proportions of 10 and 20%, respectively. *Tasmannia* peaks in the upper part of the zone, where *Podocarpus* and *Pomaderris* also reappear. Shrub species of Ericaceae appear sporadically. Chenopodiaceae declines to <5%, but increases, together with *Callitris*, towards the end of the zone. In the fen, Cyperaceae fluctuates together with *Hydrocotyle*, alternating with *Myriophyllum*, Restionaceae and *Epacris*.

Zone MS IV (110–45 cm; 2.7–0.6 ka). Sediments are dark brown fibrous peaty mud with root and leaf macrofossils. Organic content is <25% and charcoal averages 170 mm^2 mL^{-1}. This zone is marked by a substantial decline in *Eucalyptus* to proportions <20% and substantial increases in Asteraceae, Poaceae, *Callitris* and Chenopodiaceae. *Tasmannia* and Ericaceae disappear from the record. Proteaceae, *Podocarpus* and Fabaceae are occasionally recorded. Of the herbs, only Caryophyllaceae makes an appearance in this zone and fern spores fall to insignificant levels. A single grain of introduced *Pinus* is attributed to contamination. Cyperaceae dominates the aquatic flora with minor *Myriophyllum*, Restionaceae, *Hydrocotyle* and *Epacris*.

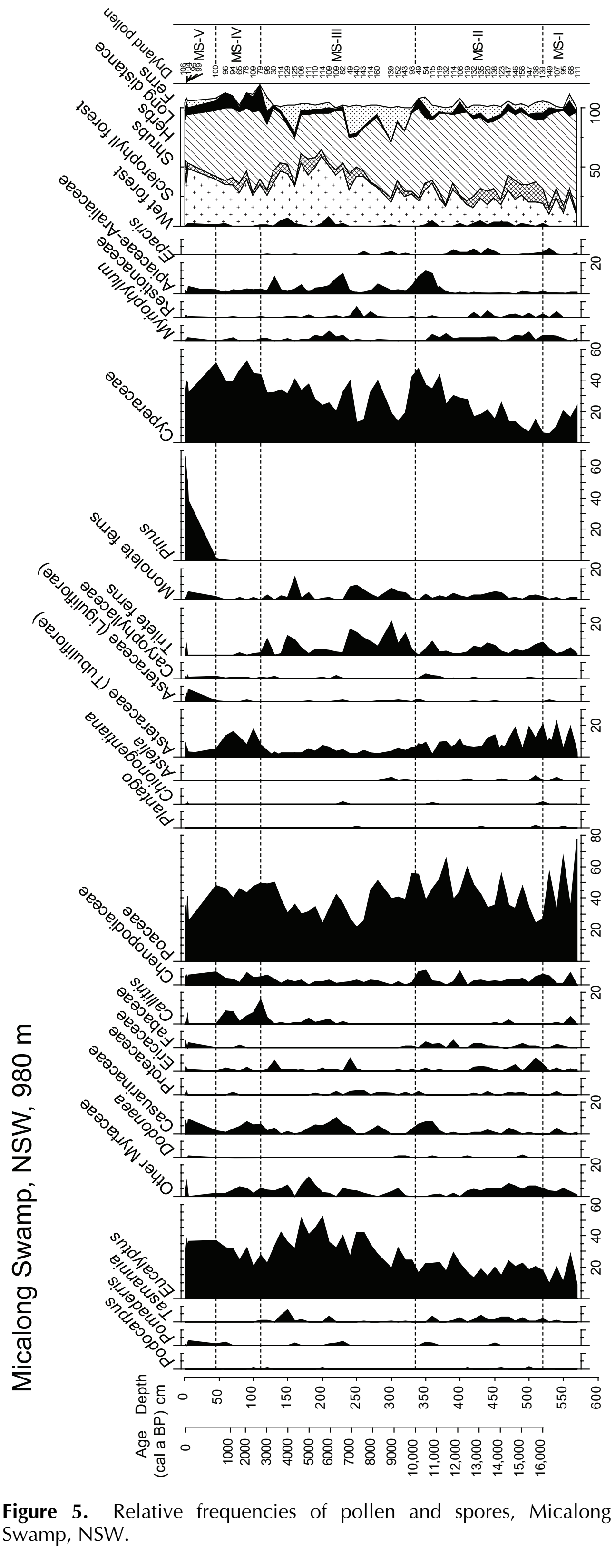

Figure 5. Relative frequencies of pollen and spores, Micalong Swamp, NSW.

Zone MS V (45–0 cm; 0.6 ka – AD 1993). Sediments are dark brown fibrous peaty clay with root and leaf macrofossils with a watery zone causing poor recovery between 40 and 10 cm. Organic carbon content reaches 70% at the surface, where charcoal peaks at 750 mm^2 mL^{-1}, above previous levels of ~175 mm^2 mL^{-1}. *Eucalyptus* pollen increases to 35% and Asteraceae declines to <10%. Cyperaceae pollen dominates the aquatic flora. Shrub species of Myrtaceae are not recorded. Chenopodiaceae remains at 5%. Introduced *Pinus* and Asteraceae Liguliflorae appear in the top 2 cm.

Willigobung Swamp

Stratigraphy and chronology

Sediments, organic carbon and charcoal volumes for Willigobung Swamp are given in Fig. 6. The age–depth model was constructed from the two calibrated radiocarbon ages of 6.5 ka (~368 cm) and 10.6 ka (~523 cm) (Table 1) following the same procedure as for Micalong Swamp. European pollen is found only in the top few centimetres so 5 cm is considered to represent 100 cal a BP. If a constant sedimentation rate between these points is assumed the mean sedimentation rates of the lower core is 0.38 mm a^{-1} increasing to 0.65 mm a^{-1} after 6.5 ka. The basal age of ~11.6 ka is based on extrapolation. As for Micalong Swamp this simple linear model provides an indication of the age of individual levels but may conceal changes in sedimentation rate or gaps in the record.

Biostratigraphy

Dryland pollen counts range from 32 to 229 with five samples recording counts <50 (Fig. 7). The pollen record was divided into four zones based on the CONISS results.

Zone WG I (540–495 cm; <11.2–9.9 ka). Basal sediments comprise grey clay with thin beds of fibrous peat. Organic content averages 20% and charcoal averages 64 mm^2 mL^{-1}. Cyperaceae and Apiaceae–Araliaceae dominate the fen pollen. The dryland pollen sum comprises ~50% herbs, mostly Asteraceae and Poaceae. Monolete and trilete fern spores excluding the tree ferns *Cyathea* and *Dicksonia* represent a further 7–28%. *Eucalyptus* pollen are >10% with small but significant sclerophyll elements: Casuarinaceae (<7%), shrub Myrtaceae (<11%) and, at the end of the zone, *Dodonaea*. Levels of 3–5% chenopod pollen are recorded.

Zone WG II (495–331 cm; 9.9–5.9 ka). Sediment is grey clay with ~10% organic content becoming more organic above 400 cm. Charcoal averages 62 mm^2 mL^{-1}. Greater diversity in the bog pollen is marked by the decline in Cyperaceae and Apiaceae–Araliaceae and consistent representation of *Lycopodium.* The zone is characterized by moderate levels of wet forest elements *Tasmannia* (5%) with tree and ground ferns comprising 3 and 39% of the dryland pollen, respectively. *Eucalyptus* frequencies average 12% and *Dodonaea* is not

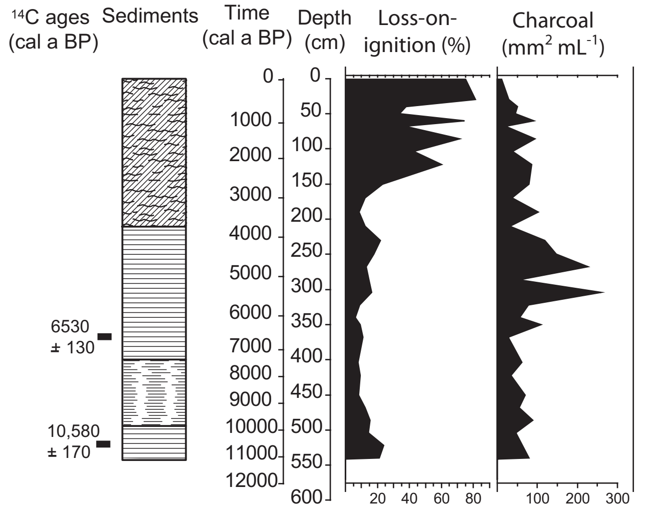

Figure 6. Sediments, loss-on-ignition and charcoal counts for Willigobung Swamp. See Fig. 4 for key to sediments.

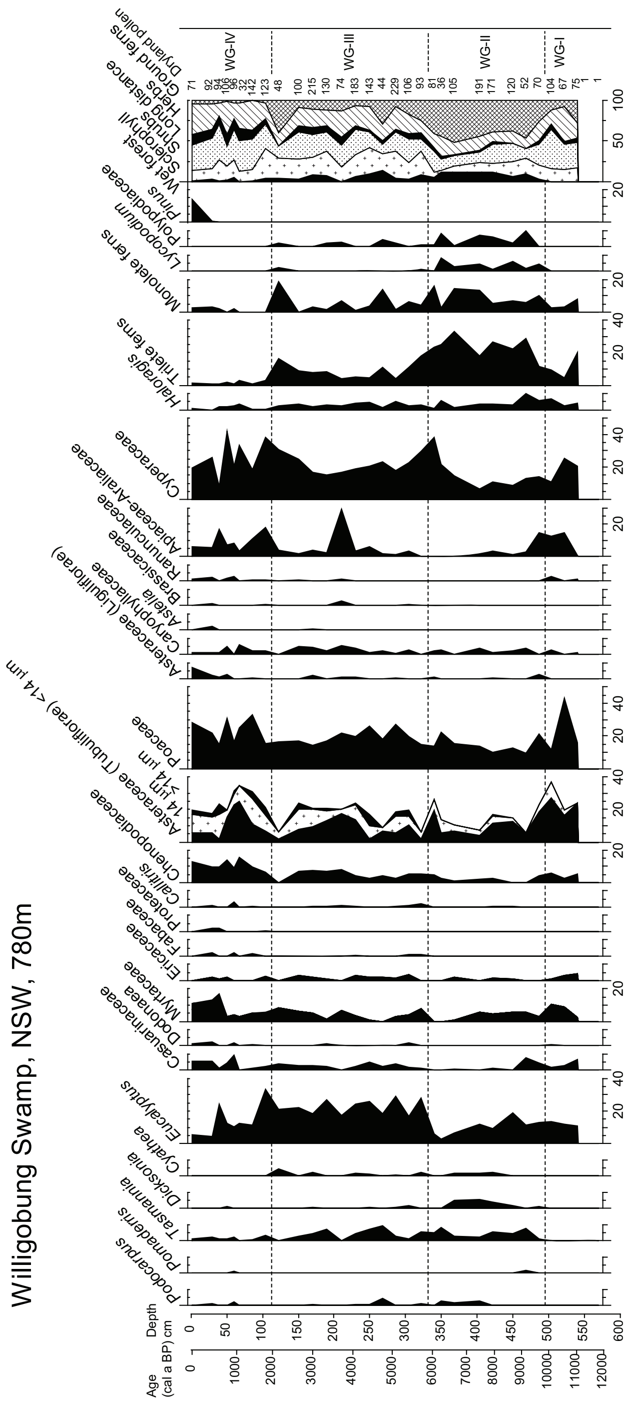

Figure 7. Relative frequencies of pollen and spores, Willigobung Swamp, NSW.

recorded. Poaceae and Asteraceae fall to ~15% and chenopods fall to 3%.

Zone WG III (331–113 cm 5.9–2.0 ka). Organic clay gives way to fibrous sedge peat above 215 cm. Loss-on-ignition percentages increase from ~15 to 60% at the top of the zone, except between 210 and 170 cm (3.1–2.5 ka) when they fall to ~10%. Charcoal falls from 260 to ~70 mm^2 mL^{-1} above 210 cm. Cyperaceae dominates the aquatic pollen but Apiaceae–Araliaceae proportions are intermittently higher than in the preceding zone. *Lycopodium* virtually disappears. Sclerophyll elements *Casuarina* and Myrtaceae dominate the dryland pollen with *Eucalyptus* frequencies averaging 22% and Ericaceae 2%. Traces of *Cyathea* appear but *Dicksonia* is not present above 250 cm (4.4 ka). Other trilete and monolete ferns average 13%, rising to 40% at 122 cm. Chenopod proportions are slightly higher (5%).

Zone WG IV (113–0 cm; 2.0 ka BP – AD 1984). Fibrous sedge peat continues to the surface. Charcoal declines to ~50 mm^2 mL^{-1} above 50 cm (625 a BP). The aquatic pollen is dominantly Cyperaceae and Apiaceae–Araliaceae with apparently low diversity. Herb pollen exceeds forest pollen in the dryland sum with Poaceae at 23%. Frequencies of Asteraceae decrease from >30 to ~20% above 50 cm. *Eucalyptus* decreases to 13% with continuing representation by Casuarinaceae and Myrtaceae. Above 70 cm chenopod frequencies rise to ~12%. An influx of *Pinus* and Poaceae is apparent near the surface.

Late Quaternary vegetation and environmental reconstruction

Rounded fluvial gravels and sands at the base of the Micalong infill indicate a sandy gravel-bed river excavating a narrow floodplain before ~16.1 ka. Cyperaceae with *Epacris* heath probably occupied wet ground along the banks with *Myriophyllum* occupying shallow pools in the valley bottom. High proportions of Poaceae pollen suggest a local source, possibly from well-grassed, steep slopes surrounding the site at this time. Herbs constitute 80–90% of the dryland pollen, suggesting an open or treeless landscape. The dominance of Asteraceae and Poaceae with subalpine and alpine indicator species *Astelia, Plantago,* Caryophyllaceae and Apiaceae–Araliaceae suggests alpine steppe or tussock grassland that was gradually replaced by alpine herbfield or open shrubland. Pollen taxa suggest a mosaic of alpine heath, including shrub forms of *Tasmannia* and *Podocarpus*, Ericaceae, Asteraceae and Myrtaceae in closed heathlands similar to that common along rocky waterways up to 1950 m Australian Height Datum (AHD) in the Snowy Mountains (McDougall and Walsh, 2007). Dwarf forms of *Tasmannia, Epacris, Richea* and shrub Proteaceae (e.g. *Orites* and *Grevillea*) may have formed open heathland with areas of grassland in the upper catchment, but the efficient dispersal characteristics of *Podocarpus* raises the possibility of *fjaeldmark* or heath communities occupying the summit of higher ranges. The open landscape at the time would have made the fen sensitive to extra-local and regional vegetation, and the low frequencies of *Eucalyptus*, together with *Callitris* and chenopods, may reflect drier forest occupying lowlands to the west. The low occurrence of charcoal is consistent with low fire frequencies in the alpine zone (McDougall and Walsh, 2007). Sediments of this age were not recovered from Willigobung Swamp.

Finer sediments with abundant sedge macrofossils accumulated at Micalong Swamp after 16.1 ka (MS II), suggesting that mineral sediments were deposited in a shallow lake or sedge fen that flooded episodically or seasonally, possibly by snowmelt. Higher levels of *Myriophyllum* also suggest slow flowing or shallow water. A steep rise in Cyperaceae pollen together with an increase in organic sedimentation marks the onset of warmer conditions. At Willigobung, a similar sedimentological change suggests that the transition occurred before 11.2 ka with an intermittent return to shallow lake or fen sedimentation. Apiaceae–Araliaceae and Caryophyllaceae pollen appear to have contributed to the marginal fen communities more than at present. Both families are considered alpine and subalpine indicators, but several species are widespread at lower altitudes and both are found on the site today in damp ground within the marginal *Sphagnum* bog (Hope and Southern, 1983). While these may have formed an important part of regional herbfield communities, dominantly local dispersal of both pollen types implies a prolific local distribution. At Micalong Swamp, parallel increases in species of *Hydrocotyle*, a mat-forming herb commonly found in boggy areas, supports this reconstruction. Substantial increases in the abundance of Cyperaceae point to the development of closed sedgeland, although the absence of standing water is indicated by the almost complete disappearance of *Myriophyllum* towards the end of this zone.

Through the remainder of the Lateglacial, the regional vegetation at Micalong Swamp was dominantly grassland, but the sustained increase in *Eucalyptus* suggests woodland expanded nearby or on higher slopes above the frost hollow. The fen was probably surrounded by a marginal heathland that included *Epacris*. Ericaceae–*Podocarpus* heath may have occupied higher, exposed slopes. Rare appearances of *Pomaderris* pollen may indicate a presence along the stream in a similar association to bog communities along drainage lines in the Barrington Tops at elevations up to 1500 m (Whinam and Chilcott, 2002). At a lower elevation, high proportions of herb pollen are recorded at Willigobung Swamp by 11.2 ka (WG I), but significant levels of Casuarinaceae and *Dodonaea* suggest an open sclerophyll woodland was already established on the slopes. Casuarinaceae species may have expanded along waterways near the site, possibly *Casuarina cunninghamii*, which grows along streams nearby at elevations up to 1000 m. Casuarinaceae species are also common on skeletal or shallow soils on drier slopes to the west, including *Allocasuarina verticellata*, which appears in pure stands or with *Eucalyptus* in grassy woodland up to elevations of 900 m.

After 10.0 ka, clear evidence for forest cover at Micalong Swamp is suggested by the rise in *Eucalyptus* and Casuarinaceae, confining Asteraceae and other herbs to the damp fringes of the bog. Shrub species of Proteaceae and Myrtaceae may have formed part of the forest, but high frequencies of Poaceae suggest a grassy understorey persisted until 7.8 ka. The tree fern *Dicksonia* may have been a pioneer in the development of wet forest, but alternative sources for the trilete ferns include understorey ferns *Polystichum* or *Calochlaena*. Monolete ferns possibly present include *Blechnum*, *Adiantum* (maidenhair), *Pteridium* and *Gleichenia*, which today are common along stream margins. Higher rates of mineral sedimentation from 9.7 to 8.2 ka, and from 3.9 to 3.2 ka, indicate a return to episodic flooding, possibly owing to increases in rainfall since forest was established by this time.

Shrub-rich forest, indicated by an expansion of tree and ground ferns, appears to have reached its maximum extent at Micalong Swamp between 10.0 and 6.8 ka. Wetter conditions are also suggested by the flooding of the fen at 9.7–8.2 ka. The periodic alternation of Casuarinaceae–Poaceae with *Eucalyptus*–Myrtaceae and ferns suggests that open *Eucalyptus*–*Allocasuarina* forest alternated with a denser, more structured *Eucalyptus* forest in drier periods throughout the Holocene. Visible charcoal layers in some of the clay layers could indicate that fire contributed to higher sediment yields. Larger peaks in charcoal in montane sedge fens may indicate more frequent burning of the bog or catchment during extended droughts. At Willigobung, the development of wet forest around the same time at 9.9 ka is marked by an expansion of tree and ground ferns and *Tasmannia*. Shallow lake sedimentation is apparent from 9.9 to 7.5 ka. After 5.9 ka, wet forest elements decline and a noticeable increase in charcoal suggests higher burning frequencies in a tall open forest.

Around 2.7 ka, a substantial decline in *Eucalyptus* at Micalong Swamp is accompanied by an increase in Asteraceae and Poaceae pollen, suggesting forest retreat. The substantial frequencies of *Callitris* pollen and, to a lesser extent, Casuarinaceae imply an eastward expansion of dry sclerophyll forest, with more open conditions at the fen making it receptive to Chenopodiaceae. Charcoal counts do not support a change in biomass burning at this time, but charcoal levels partly reflect the sedimentation rate; high-resolution macrocharcoal analysis is needed to compile the fire recurrence intervals through time at both of these sites. Floristically, the fen is depauperate and is dominated by Cyperaceae. The high organic content of the sediments is consistent with slow decay in cooler conditions. By 0.9 ka, *Eucalyptus* forest had returned to previous levels, but high Poaceae frequencies and the decline in shrub pollen suggest open woodland. The late Holocene is a more complex interval at Willigobung Swamp. A wetter period marked by an increase in fern spores at 4.4 ka is accompanied by an increase in mineral sedimentation, possibly from seasonal flooding of the fen. This is followed by a period of increased Poaceae and Asteraceae between 1.3 and 0.8 ka. More open conditions at this time are suggested by the increase in chenopod frequencies. At both sites, the appearance of *Pinus* pollen marks the regional establishment of conifer plantations, and the proliferation on the bog surface of introduced herbs of Asteraceae (Liguliflorae), such as *Hypochoeris radicata*.

Discussion

Micalong and Willigobung Swamps are the only vegetation sequences extending into the Pleistocene yet reported from the montane western slopes of the Southern Tablelands. In general terms, they present similar features to sites from similar altitudes on the eastern slopes, such as Nursery Swamp (1092 m, Hope, 2006), Bega Swamp (1080 m) (Donders *et al.*, 2007) and Bogong Creek Swamp (1005 m, G. Hope, unpublished data). Basal ages on seeds or charred plant remains in the sandy clays of these three are 14 260 ± 250, 15 850 ± 280 and 16 420 ± 410 cal a BP, respectively, providing support for the tentative age model for Micalong Swamp.

Their records can also be compared with several shrubby subalpine bogs at higher altitudes extending from the Snowy Mountains (Martin, 1986, 1999) through the Blue Mountains (Robbie and Martin, 2007) and the Barrington Tops at ca. 1000 m (Dodson, 1987). Detailed records from the submerged canyon of the Murray River on the South Australian continental shelf have a close affinity to terrestrial records in south-east Australia (MD03-2611: Calvo *et al.*, 2007; Gingele *et al.*, 2007; Lopes dos Santos *et al.*, 2013). On land, high-resolution records of the Holocene are now available from Lakes Keilambete and Gnotuk (Wilkins *et al.*, 2013), together with a high lake level record from Lake George (Fitzsimmons and Barrows, 2010).

The structure of Lateglacial vegetation assemblages is difficult to determine from pollen records owing to the appearance of well-represented plant families and genera, such as *Grevillea*, *Podocarpus*, Myrtaceae and Asteraceae, in both alpine and montane tracts. Proportions of <10% *Eucalyptus pauciflora* (snow gum) pollen have been reported in 100-m clearings within modern snow gum woodland, suggesting that its dispersal characteristics are poorer than montane eucalypts, which are well dispersed upslope and regionally, and may produce high frequencies of pollen above the treeline (Martin, 1986, 1999). Extensive subalpine woodland on high plateau surfaces may therefore be invisible in pollen records, and the rise of *Eucalyptus* in Lateglacial spectra may reflect the approach of montane or drier lowland forest communities rather than migration of the treeline.

Most analysts infer treeless conditions in the south-east highlands above 600 m AHD during the Last Glacial Maximum (LGM) and Lateglacial (e.g. Singh and Geissler, 1985; Dodson, 1986; Hope *et al.*, 2004). Below this elevation, open woodland persisted at coastal and inland sites (Dodson and Wright, 1989; Williams *et al.*, 2006). A lower limit to the climatic treeline in southern NSW is defined by Mountain Lagoon, which records forest up to 500 m elevation on the eastern ranges at the LGM (Robbie and Martin, 2007), but lower precipitation, low carbon dioxide and higher wind speeds may have contributed to treelessness on the NSW tablelands (Dodson, 1998; Hope *et al.*, 2004).

Micalong and Willigobung straddle the LGM treeline, hypothesized to lie at 975 m based on the former extent of periglacial landforms at 35°S (Galloway, 1965). The modern treeline in the southern Australian Alps lies at 1700–1800 m and is defined by the 10 °C mean January isotherm (Slatyer, 1989), but descends northwards to <1300 m on the exposed plateau surface near Kiandra where January mean temperature is 13.4 °C (Bureau of Meteorology, 2013). Treeless conditions at Micalong Swamp imply that summer temperatures were at least 4–7 °C lower (making an allowance for elevation), but an expansion of the grassy frost hollow would be produced by a reduction of as little as 1–2 °C in mean summer temperature.

The regional pattern of forest development in the late Pleistocene is consistent with the pattern of temperature emerging from marine records of sea surface temperature (SST) in south-east Australia. Beginning at 17–18 ka, a rapid increase in SST of 4 °C is apparent from MD03-2611 and in the Tasman Sea (Calvo *et al.*, 2007; RS147-GC7: Lopes dos Santos *et al.*, 2013). Radiocarbon ages on basal organic sediments overlying glacial and periglacial rubble suggest that conditions were sufficiently warm for peat development by 18.2 ka in the Australian Alps (Costin, 1972), with the final retreat of glaciers effected between 16.8 and 15.9 ka (Barrows *et al.*, 2001). This may have been responsible for a regional expansion of forest around 18 ka in the Barrington Tops (Sweller and Martin, 2001). The vegetation was probably subalpine at Micalong Swamp by 15.8 ka, although chronological uncertainties in the basal sediments make it difficult to be precise about the timing.

A return to cooler conditions or an interruption in the warming trend was registered by lower SST during the Antarctic Cold Reversal (14–12.5 ka) between 16 and 13 ka in the Australian coastal waters and Southern Ocean (Calvo *et al.*, 2007; Lopes dos Santos *et al.*, 2013). On land, high illite levels in the Murray Canyon indicate enhanced fluvial activity between 15 and 13 ka and coincide with active migration of snowmelt-engorged rivers in the Murrumbidgee and Goulburn catchments (Page *et al.*, 1996; Gingele *et al.*, 2007). Regional pollen records show no evidence for vegetation change, but the prolonged cold interval may have contributed to the late appearance of forest in most montane records.

After 13 ka, a second rapid increase in SST is apparent in MD03-2611 and by 11 ka temperatures had risen to modern levels (Fig. 1; Calvo *et al.*, 2007; Lopes dos Santos *et al.*, 2013). Between 12 and 11 ka the East Australian Current, which conveys tropical waters down the east coast of Australia, extended rapidly southward, increasing SST regionally (Bostock *et al.*, 2006). With the flooding of the Bass Strait at 9.6 ka, modern ocean circulation was established (Blom and Alsop, 1988). The combined effect of these changes would have been to increase tropical heat transport to southern and south-east Australia, increasing moisture levels and reducing continentality at inland locations.

A range of terrestrial evidence suggests that the Last Glacial–Interglacial Transition was relatively arid in the Tablelands. River flows in the Murray Basin registered at MD03-2611 were low between 12 and 14 ka (Gingele *et al.*, 2007), and high quartz and titanium levels in the same core indicate a return to arid conditions (De Deckker *et al.*, 2012). Optically stimulated lumiscence ages on shorelines at Lake George suggest lake levels were low between 14 and 10 ka (Fitzsimmons and Barrows, 2010). Mountain Lagoon remained a shallow fen until deeper water appeared around 10 ka (Robbie and Martin, 2007). Pollen records from NSW suggest forest developed later in western compared with eastern sites, possibly owing to a steep E–W precipitation gradient. On the eastern ranges, *Eucalyptus* woodland extended up to 1000 m at Gooches Crater by at least 14.5 ka (Black and Mooney, 2006). Open woodland was already established at higher elevations on the Barrington Tops by 12.9 ka and cool temperate rainforest communities were established by 10.2 ka (Dodson *et al.*, 1986). In the western ranges, montane forest developed around 10.0 ka and wet forest did not expand until ~8–9 ka. Forest also developed later in sites such as Bega Swamp located near modern rainshadows, which may have been enhanced at this time. There, forest developed at 10.5 ka, and wet forest did not expand until 7.5 ka (Hope *et al.*, 2004; Donders *et al.*, 2007).

The vegetation records from the Southern Highlands tend to produce a picture of stable climates through the Holocene, although more sensitive indicators of climate change indicate effective precipitation was variable after 10 ka (Kemp *et al.*, 2012; Wilkins *et al.*, 2013). At Lake George the highest Holocene shorelines occur at 10–8 ka (Fitzsimmons and Barrows, 2010), but modelled lake levels from the composite Keilambete–Gnotuk record suggest high lake levels were limited to ~1000 years centred at 7.2 ka (Wilkins *et al.*, 2013). In pollen records this interval is usually characterized by consistent representation of *Pomaderris*, indicating the development of more extensive wet forest (the '*Pomaderris* rise') (Macphail, 1981), but the interval is short-lived at some sites such as Club Lake, which today lies above the montane forest zone (Martin, 1986). *Pomaderris* is virtually absent at both Micalong and Willigobung, suggesting that precipitation remained marginal for wet forest, but variations in effective precipitation may be the cause of alternations between drier and wetter forest elements at Micalong Swamp.

The return to subalpine woodland or daisy-rich grassland at Micalong Swamp between 2.7 and 0.9 ka implies a return to colder conditions, an expansion of subalpine woodland and/or the valley bottom frost hollow. The change is not apparent at Willigobung, 200 m lower in elevation, but support for regional cooling comes from renewed periglacial action in the Australian Alps between 3.2 and 1.4 ka (Costin, 1972; Martin, 1986) and in a general resurgence in bog growth between 4.1 and 2.5 ka (Macphail and Hope, 1985; Dodson *et al.*, 1986). A phase of increased hillslope instability in the Southern Tablelands between 3.1 and 1.1 ka may reflect an increase in cold climate weathering at higher elevations (Williams, 1978; Eriksson *et al.*, 2006). Elevated lake levels at Lakes Keilambete, Gnotuk and George at 4.0–2.1 ka (Fitzsimmons and Barrows, 2010; Wilkins *et al.*, 2013) suggest cooling rather than greater aridity was responsible for the environmental changes at this time.

Conclusions

Micalong and Willigobung Swamps provide apparently complete records of vegetation from Lateglacial times to the present, and are the first vegetation records from the montane, western slopes of the NSW Southern Tablelands. Pollen records suggest the development of full forest cover was established at ~10 ka, and was delayed 2–3 ka behind some sites in the coastal ranges. Wet forest expansion occurred relatively late at 9–8 ka and remained limited throughout the Holocene. Evidence for a neoglacial cooling at higher elevations between 2.7 and 0.9 ka is consistent with other terrestrial records in south-eastern Australia. High-resolution analysis of macrocharcoal, supported by higher resolution dating based on identified material such as seeds or charcoal, in these and other regional records is needed to explore the effects of changing fire regimes on vegetation.

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Abbreviations. ANU, Australian National University; AMS, accelerator mass spectrometry; LGM, Last Glacial Maximum; NSW, New South Wales; SST, sea surface temperature.

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