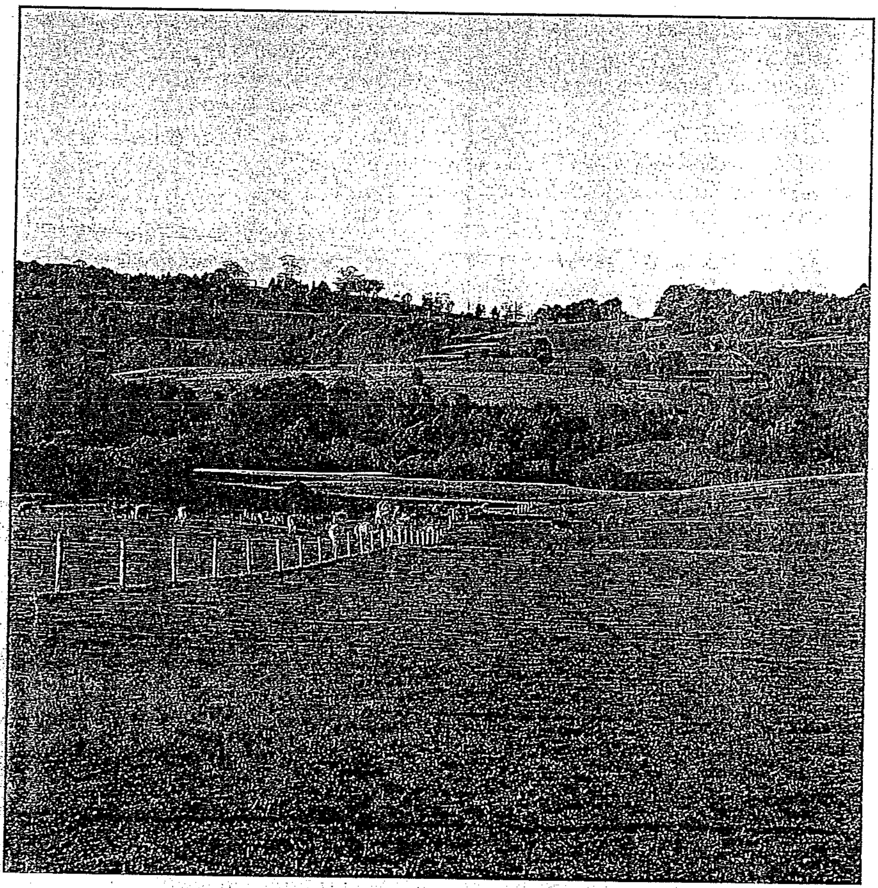
Robertson Plateau Rainforest: remnants of the Yarrawa Brush

Phillip Kodela

The Yarrawa Brush once covered much of the basalt plateau surface around Robertson on the Central Tablelands of NSW. Early explorers described the diversity and dense nature of the "brush" while travelling across the plateau to the coast. Mills (1987, 1988) describes the rainforest remaining, and illustrates the likely extent of the original continuous forest distribution.

The plateau rainforest contains a mixture of warm-temperate and cool-temperate taxa. Early accounts of the flora indicate that some rainforest species now mainly restricted to the Illawarra escarpment and coastal plains, e.g. *Livistona australis,* may have been more common on the plateau surface prior to European settlement of the area in the early 19th century. The fertile krasnozem soils and relatively high rainfall in the area were ideal for dairying and potato growing. It is unknown how many rainforest species may have been affected by vegetation clearing and fragmentation; practices that would have altered internal rainforest climates and possibly their ability to support subtropical elements in the flora. Fragmentation has reduced protection from cold temperatures, frosts, strong winds, fire and weed and pest invasions. Clearing may have resulted in an increase in the incidence of frosts that could have suppressed some species from regenerating (see Duff and Stocker, 1989).



Rainforest remnants near Robertson on the Central Tablelands. It is unknown how many rainforest species have been affected by vegetation clearing and fragmentation. Photo: Phillip Kodela

The small remnant stands of rainforest throughout the area vary in structure and species composition: Robertson Nature Reserve is relatively undisturbed and displays the best potential of these forests. Common canopy trees include *Doryphora sassafras, Ceratopetalum apetalum* and *Quintinia sieberi.* The rainforest is characterised by shade tolerant secondary layer trees, shrubs, tree ferns, erect ground ferns, and an abundance of lithophytic and epiphytic ferns and bryophytes. Rainforest on exposed hilltops tends to contain fewer species and has a single lower tree layer. Many canopy trees are multistemmed, possibly reflecting adaptation to the seasonally cold conditions, as well as evidence of regrowth in areas of logging. Table One lists plant species recorded from rainforest stands located west of the Illawarra escarpment (see Kodela, 1990). Escarpment species may occur in remnants nearer the eastern plateau edge.

Most rainforest remnants are found on private land and are often exposed to semi-clearing, burning, rubbish dumping and trampling by stock. Common introduced species that penetrate the rainforest include *Ligustrum sinese, Ilex aquifolia, Prunus laurocerasus, Cestrum elegans* and *Hedera helix.* In highly disturbed remnants ground surfaces are bare or with pasture herbs growing in light gaps. However through weeding and careful management it is possible for these rainforest remnants to be rehabilitated. One example is of a property near Robertson township where animals were fenced-out, weeds cleared and runoff redirected from a patch of rainforest. After about 15 years of minimal disturbance this stand now has seedlings, the return of ground species, resprouting of old trees and is expanding over fences.

The Robertson rainforest patches contain an interesting flora of scientific and educational value. They provide an important habitat for wildlife and benefit landowners by helping to control erosion, maintain water catchments and provide natural windbreaks (Anon., 1989b). The NSW National Parks and Wildlife Service in 1989 published two leaflets providing guidelines for the removal of weeds and management of the rainforest remnants through a community effort. Such measures are now needed to ensure the conservation of Robertson's rainforest remnants.

Acknowledgement

I am grateful for discussions with Allan Stiles who is currently investigating the ecology of the Robertson rainforest remnants.

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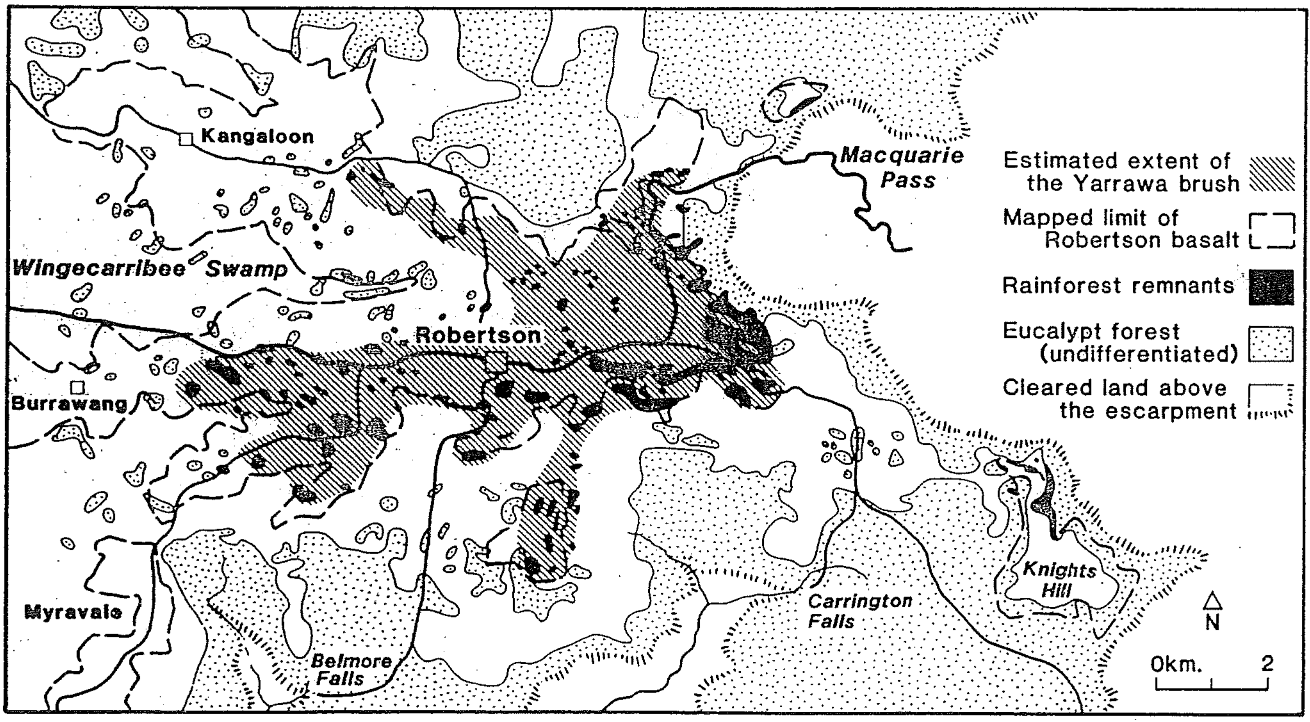


The present and former extent of the Yarrawa Brush.

Courtesy Kevin Mills, from *Australian Geographer* 19(2)

Table 1: Plant species recorded from Robertson rainforest patches, remnants of the Yarrawa Brush, N.S.W.

Mosses

LEMBOPHYLLACEAE	*Camptochaete arbuscula*
	C. vaga
METEORIACEAE	*Papillaria crocea*
	P.? leuconeura
PTEROBRYACEAE	*Trachyloma diversinerve*
PTYCHOMNIACEAE	*Hampeella pallens*
RHACOPILACEAE	*Rhacopilum cuspidigerum* var. *convolutaceum*
THUIDIACEAE	*Thuidium sparsum*

Ferns

ADIANTACEAE	*Pellaea falcata*	Sickle Fern
ASPIDIACEAE	*Lastreopsis acuminata*	Shiny Shield Fern
	L. microsora	Creeping Shield Fern
	Polystichum proliferum	Mother Shield Fern
ASPLENIACEAE	*Asplenium attenuatum*	Spleenwort
	A. australasicum	Bird's Nest Fern, Crow's Nest
	A. flabellifolium	Necklace Fern
BLECHNACEAE	*Blechnum patersonii*	Strap Water Fern
	Doodia aspera	Prickly Rasp Fern
CYATHEACEAE	*Cyathea australis*	Rough Tree Fern
	Dicksonia antarctica	Soft Tree Fern
DAVALLIACEAE	*Arthropteris tenella*	
DENNSTAEDTIACEAE	*Dennstaedtia davallioides*	Lacy Ground Fern
POLYPODIACEAE	*Microsorum diversifolium*	Kangaroo Fern
	M. scandens	Fragrant Fern
	Pyrrosia rupestris	Rock Felt Fern

Herbs (u- uncommon, found in disturbed sites)

APIACEAE	*Hydrocotyle* (*acutiloba*) laxiflora		
ARACEAE	*Gymnostachys anceps*	Settler's Flax	
ASTERACEAE	*Gnaphalium gymnocephalum*		u
BORAGINACEAE	*Cynoglossum latifolium*		
CARYOPHYLLACEAE	*Stellaria flaccida*	Starwart	
CYPERACEAE	*Carex appressa*	Tussock Sedge	u
GERANIACEAE	*Geranium homeanum*		
LAMIACEAE	*Prunella vulgaris	Self-Heal	u
PLANTAGINACEAE	*Plantago debilis*		u
POACEAE	various pasture species in disturbed areas		
RANUNCULACEAE	*Ranunculus plebius*	Hairy Buttercup	u
ROSACEAE	*Acaena* sp.		u
RUBIACEAE	*Galium propinquum*		u
SCROPHULARIACEAE	*Veronica notabilis*		u
	V. plebeia	Trailing Speedwell	u
SOLANACEAE	*Solanum arviculare*	Kangaroo Apple	-to shrub
	*S. chenopodioides		u
	S. pungetium	Jagged Nightshade	-to low shrub
URTICACEAE	*Australina pusilla*		
	Elatostema reticulatum		
	Urtica incisa	Scrub Nettle	-to low shrub
VIOLACEAE	*Viola hederacea*	Ivy-leaved Violet	
XANTHORRHOEACEAE	*Lomandra longifolia*	Spiny Mat Rush	u

Trees and shrubs (s-shrub, t-tree)

AQUIFOLIACEAE	**Ilex aquifolium*	Holly	s,t
ASTERACEAE	*Cassinia trinerva*	Three-veined Cassinia	s,t
	Olearia argophylla	Musk Daisy-bush	s,t
ATHEROSPERMATACEAE	*Doryphora sassafras*	Sassafras	t
CAPRIFOLIACEAE	*Sambucus australasica*	Elderberry	s
CUNONIACEAE	*Ceratopetalum apetalum*	Coachwood	t
EBENACEAE	*Diospyros australis*	Black Plum	t
ELAEOCARPACEAE	*Elaeocarpus holopetalus*	Black Oliveberry	t
	E. kirtonii	White Quandong	t
ESCALLONIACEAE	*Polysoma cunninghamii*	Featherwood	t
	Quintinia sieberi	Possumwood	t
EUCRYPHIACEAE	*Eucryphia moorei*	Pinkwood	t
FABACEAE	*Acacia melanoxylon*	Blackwood	t
ICACINACEAE	*Pennantia cunninghamii*	Brown Beech	t
LAURACEAE	*Cryptocarya microneura*	Murrogun	t
MELIACEAE	*Synoum glandulosum*	Scentless Rosewood	t
MONIMIACEAE	*Hedycarya angustifolia*	Native Mulberry	s,t
MYRSINACEAE	*Rapanea howittiana*	Brush Muttonwood	t
MYRTACEAE	*Acmena smithii*	Lillypilly	t
	Eucalyptus fastigata	Brown Barrel	t
OLEACEAE	**Ligustrum sinese*	Small-leaved Privet	s,t
	Notelaea venosa	Native Olive	s,t
PINACEAE	**Pinus radiata* (Robertson Nature Reserve)		t
PITTOSPORACEAE	*Citriobatus pauciflorus*	Orange Thorn	s
	Pittosporum undulatum	Sweet Pittosporum	t
PROTEACEAE	*Stenocarpus salignus*	Scrub Beefwood	t
ROSACEAE	**Prunus laurocerasus*		s,t
RUBIACEAE	*Coprosma quadrifida*	Prickly Coprosma	s,t
RUTACEAE	*Acronychia oblongifolia*	Common Acronychia	t
SAPINDACEAE	*Alectryon subcinereus*	Native Quince	t
SOLANACEAE	**Cestrum elegans*		s
THYMELAEACEAE	*Pimelea ligunstrina* ssp. *hypericina*		s
VIOLACEAE	*Hymenanthera dentata*	Tree Violet	s,t
WINTERACEAE	*Tasmannia insipida*	Brush Pepperbush	s

Climbers

APOCYNACEAE	*Parsonsia brownii*	Mountain Silkpod
	P. straminea	Common Silkpod
ARALIACEAE	**Hedera helix*	English Ivy
ASCLEPIADACEAE	*Marsdenia rostrata*	Common Milk Vine
	Tylophora barbata	Bearded Tylophora
BIGNONIACEAE	*Pandorea pandorana*	Wonga Vine
CAPRIFOLIACEAE	**Lonicera japonica*	Japanese Honeysuckle
CELASTRACEAE	*Celastrus australis*	Staff Vine
CUNONIACEAE	*Aphanopetalum resinosum*	Gum Vine
DILLENIACEAE	*Hibbertia scandens*	Twining Guinea Flower
GESNERIACEAE	*Fieldia australis*	Fieldia
MENISPHERMACEAE	*Sarcopetalum harveyanum*	Pearl Vine
ORCHIDACEAE	*Dendrobium pugioniforme*	Dagger Orchid
PHILESIACEAE	*Eustrephus latifolius*	Wombat Berry
	Geitonoplesium cymosum	Scrambling Lily
RANUNCULACEAE	*Clematis aristata*	Toothed Clematis
	C. glycinoides	Forest Clematis
ROSACEAE	**Rubus discolor*	Blackberry, Bramble
	R. hillii	Molucca Bramble
	R. rosifolius	Rose-leaf Bramble
	R *R.* (sp. aff. *moorei*) nebulosus	Green-leaved Bramble
RUBIACEAE	*Morinda jasminoides*	Morinda
SMILACACEAE	*Smilax australis*	Austral Sarsparilla

* represents introduced taxa

DAY 3.

Thirlmere Lakes National Park is described at:
http://www.environment.nsw.gov.au/NationalParks/parkHome.aspx?id=N0033

Picton is described at:
http://www.stonequarry.com.au/towns/picton.html

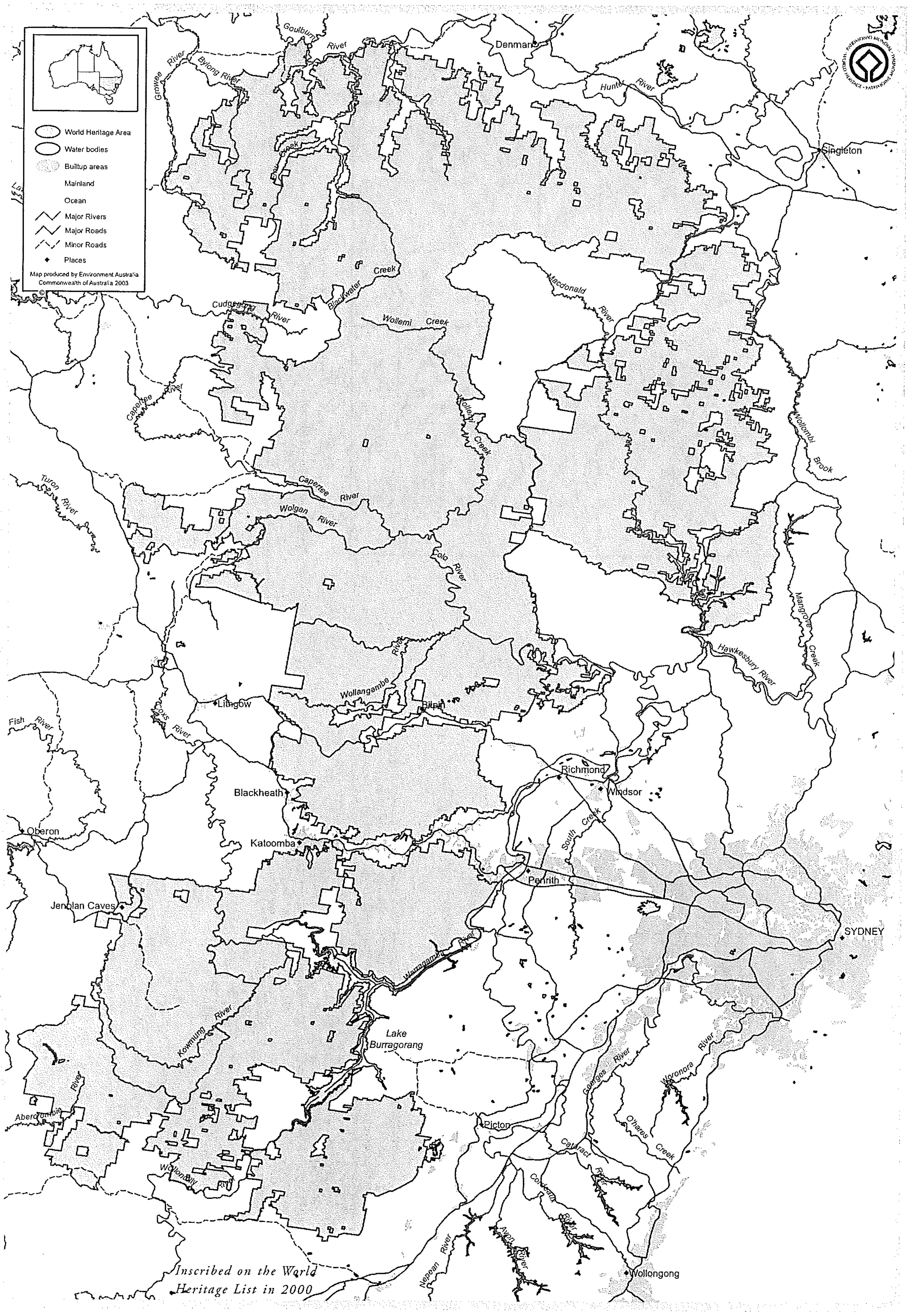
Information about the Blue Mountains and Leura is available at:
http://www.bluemts.com.au/tourist/towns/Leura.asp

Thirlmere Lakes National Park

TLNP is a part of the Greater Blue Mountains World Heritage Area (an area the size of Belgium!). TLNP contains five reed-fringed freshwater lakes, abundant with waterbirds and surrounded by quiet patches of forest. This is a hidden gem in Sydney: it is a peaceful place and the undisturbed lake systems have enormous scientific value.

Blue Mountains National Park

Blue Mountains National Park is also a part of the Greater Blue Mountains World Heritage Area. It is a very well-visited and much loved park (more than three million people visit every year) due to outstanding lookouts, walking tracks and an unusually diverse range of vegetation communities.



Inscribed on the World Heritage List in 2000

The Greater Blue Mountains Area

The Vegetation History of the Holocene at Dry Lake, Thirlmere, New South Wales

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Rose, S. and Martin, H.A. (2007). The vegetation history of the Holocene at Dry Lake, Thirlmere, New South Wales. *Proceedings of the Linnean Society of New South Wales* **128**, 15-55.

At the beginning of the Holocene, Dry Lake was a lake, with a fringe of cyperaceous reeds. *Eucalyptus* and *Allocasuarina* were the dominant trees and Asteraceae Tubuliflorae were prominent in the understorey. Between 8 ka and 2 ka, the lake became shallower, and the reeds grew over the surface of the developing swamp, forming peat. An hiatus in peat deposition between 5 ka and 2ka was followed by the formation of a thin layer of diatomite. Eutrophic conditions would be required to allow large populations of diatoms and burning seems the most likely way of increasing the nutrient mobility on the poor sandstone soils of the catchment.

By 2 ka, the lake had become a peat swamp. *Angophora/Corymbia* pollen had increased dramatically, most likely representing *Angophora* on these alluvial flats. The shrub layer had also become more diverse. *Allocasuarina* did not decrease through the Holocene, unlike the record of many other Holocene sites. The likely reasons for this difference are probably related to site-specific environmental conditions. With European settlement, all trees decreased dramatically and grasses increased. Today, Dry Lake only contains water in exceptionally wet periods.

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KEYWORDS: *Casuarina/Allocasuarina* decline, freshwater sponge, Holocene, palynology, Thirlmere Lakes, vegetation history.

INTRODUCTION

Dry Lake is one of a series of freshwater lakes associated with an incised former river valley at Thirlmere. The Thirlmere Lakes are rare examples of very old, small lakes that have aged very slowly as a result of the stable geological nature and small size of the catchment (Horsfall et al., 1988). The initial development of the lakes was related to tectonic activity associated with the formation of the Lapstone Monocline, Kurrajong and Nepean Faults which beheaded a river that probably originally flowed westwards, leaving the isolated, sinuous channel that now contains the lakes (Timms, 1992). At this time, or sometime later, the drainage direction changed and today Dry lake drains in a north-easterly direction along Cedar Creek and the Thirlmere Lakes drain westwards along Blue Gum Creek (Fig. 1). Presently, Dry Lake only contains water intermittently in wet years, when the water depth approximates 60 cm.

The basal sediments of Dry Lake have been radiocarbon dated at about 10,000 years before present which approximates the beginning of the Holocene when the climate had mainly recovered from the peak of the glacial period but there was a lag in the recovery of the vegetation. The Holocene thus records the establishment of the present vegetation. *Allocasuarina/Casuarina* was usually more prominent following the last glacial period but during the Holocene, it declined and *Eucalyptus/Corymbia* rose to dominance (Clarke, 1983).

This paper presents the Holocene history of the vegetation at Dry Lake and compares it with Lake Baraba, one of the Thirlmere Lakes (Black et al., in press), some 4 km to the south.

THE ENVIRONMENT

The former river valley that includes Dry Lake is incised in Hawkesbury Sandstone, but the surrounding higher plateau surfaces retain cappings of Ashfield Shale, the lower member of the Wianamatta Group, which overlies the Hawkesbury Sandstone. Both formations are of Triassic age (Herbert, 1980).

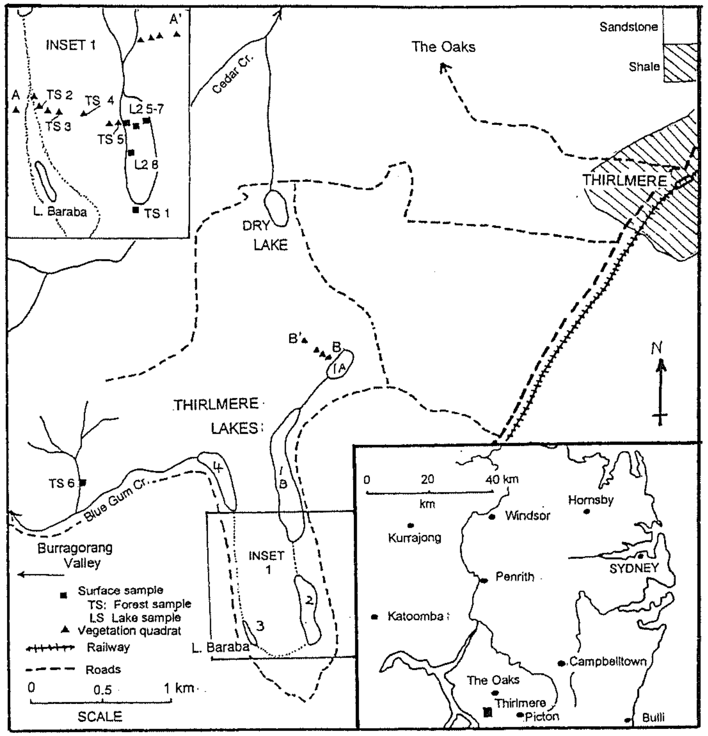

Figure 1. Locality map.

Although Hawkesbury Sandstone dominates the landforms and soils occurring in the study area, there is a shale outcrop on the ridge to the east of Dry Lake (Fig. 1). This may be either the Ashfield Shale or a shale lens in the sandstone, as it is very close to the contact between the two formations. The soils developed on the sandstone are uniform sandy loams with some organic staining in the upper horizons. They are acid, of low nutrient status and low water retaining capacity, and vary in depth and drainage, depending on the topography.

Thirlmere has warm to hot summers and cool to mild winters (Bureau of Meteorology website, BoM, 2005). The average annual rainfall of the nearest station, Picton, is 820 mm and it is received in two relatively wet periods from January to March and in June. The median rainfall for each month is greater than 25 mm (BoM, 2005). There is considerable variation in rainfall and after long dry spells, the Thirlmere Lakes dry out. Known dry lake stages occurred about 1902, 1929 and 1940 (Rose, 1981).

The Thirlmere Lakes were first sighted by Europeans in 1798. By 1833, many settlers had arrived at the Oaks, north of Thirlmere, and mixed farming flourished. Timber cutters logged mostly *Eucalyptus deanei*, especially along Blue Gum Creek (Woods, 1980). Most of these activities were more intense on the better soils of the shale areas and on the alluvial flats. Present land uses consists of residential

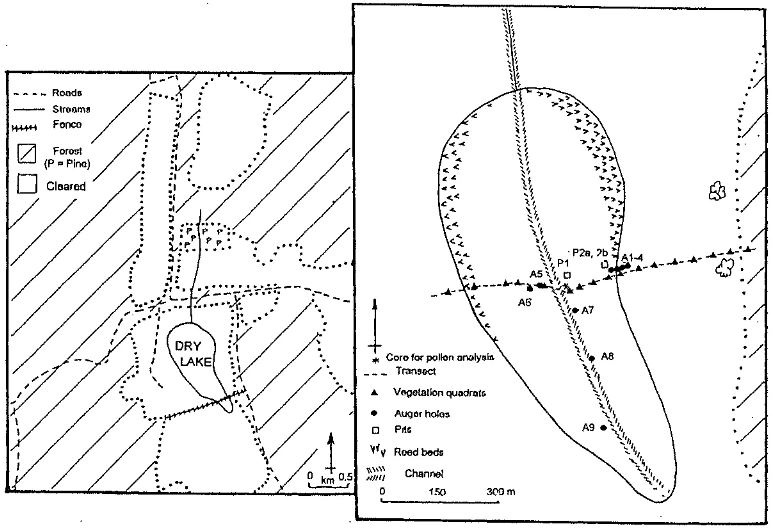

Figure 2. Dry Lake and environs.

housing and small farms.

Four main vegetation units described by Pidgeon (1937; 1941) apply to this area and they are: 1), the *Eucalyptus deanei* and *Eucalyptus elata* tall open forest in the gullies; 2), the Mixed *Eucalyptus* Association of the ridges and slopes; 3), the *Angophora floribunda/ Melaleuca linariifolia* forest of the alluvial fans and 4), the aquatic vegetation of swamps and lakes. The mixed *Eucalyptus* Forest Association constitutes the major part of this study area. The National Park was completely burnt in 1955 and has suffered considerable damage from local fires since then (R. Kinntish, pers. comm.). Dry Lake has been cleared of native vegetation and is predominantly a grassland but it is assumed that the native vegetation would have been much the same as that in the surrounding areas.

METHODS

Field work was carried out during 1981 when the vegetation survey was undertaken. (Appendix 1). Quantitative data on plant distributions were obtained from quadrats along transects (Rose, 1981). The vegetation map was prepared using aerial photographs and the field survey (Figs 1, 2).

The stratigraphy of Dry Lake sediments was investigated by auger holes and two pits (Fig. 2) which were limited to a depth of 1.5 m by heavy clay. A core, located near the centre of the lake but where there was minimal disturbance and away from local pollen sources, was chosen for pollen analysis. This core was taken using a Hiller corer. Samples for radiocarbon dating were taken from the pits and analysed by the then Radiocarbon Laboratory of the University of New South Wales. All of the samples were stored in a 4°C cold room to suppress microbial growth until work could proceed.

Surface samples of soils, mosses and lake sediments were collected (Figs 1, 2) to study pollen deposition under the present vegetation and assist in the interpretation of pollen in the core. Lake surface sediments were sampled using a weighted cylinder on a line.

Sediment samples 2 cm in length and 3 cm apart were taken from Pit 1 for organic matter analysis. Duplicated samples were oven-dried (105°C) and ignited in a muffle furnace to 500°C. During ignition, structurally bound water is lost, but in highly organic sediments, the major loss on ignition is from the organic matter (Bengtsson and Enell, 1990).

Pollen preparations from the sediment core were spiked with *Alnus* of a known concentration, treated with hydrofluoric acid to remove siliceous material, boiled in 10% sodium hydroxide to remove of humic acids, disaggregated with ultrasonic vibration, followed by standard acetolysis (Moore et al., 1991). Surface samples were treated in the same way, with the addition of sieving to remove sand, leaves, twigs etc. and omitting the *Alnus* spike. Reference pollen used for identification was only treated with standard acetolysis. The residues were mounted in silicone oil (viscosity of 2,000 centistokes) or glycerine jelly, using grade 0 coverslips.

Siliceous fossils were recovered from a known volume of sediment using an acid sequence (hydrochloric, nitric and sulphuric acids) and then dehydrating the residue in absolute alcohol. The residue was made up to a known volume, and with constant agitation, a known aliquot was extracted, the alcohol allowed to evaporate and mounted in Napthrax in toluene (Lacey, 1963).

Pollen was identified by comparison with a reference collection using the x 1000 magnification objective. Where it was not possible to identify some grains, they are listed as unknowns. The pollen of members of the family Myrtaceae is similar and it requires a careful analysis of the finer morphological features to separate them (Chalson and Martin, 1995). In this study, three groups were distinguished: *Angophora/Corymbia*, *Eucalyptus* and *Melaleuca/ Leptospermum* (Appendix 2). The name on the pollen diagram and probable source in the vegetation is listed in Appendix 3.

Pollen was counted using the x 400 objective of a Zeiss microscope. Tests to assure an adequate count showed 160-200 grains was sufficient. Some samples had insufficient pollen for an adequate count, and this is indicated on the pollen diagram.

Counts were made of sponge spiclues on a Zeiss microscope, using the x 250 and x 400 objectives. Only one species of sponge was present and the spicules consisted of megascleres, gemmoscleres and fragments of both. Three quarters of a sclere was counted as a whole sclere and more than one quarter as a fragment. Counts were made along transects spaced evenly across the slide to ensure a representative count. Knowing the ratio of the area counted to total area of the slide, and the volume of the aliquot to total volume of residue, the counts were converted to numbers of scleres per volume of sediment.

RESULTS

The Lake Sediments.

The sequence of sediments in the central part of Dry Lake is as follows, from top to bottom (Fig. 3):

1) A layer of little decomposed fibrous peat, composed of rhizomes, root and stems of cyperaceous reeds (probably *Lepironia articulata*).
2) Well humified black clayey peat with abundant roots, rhizomes and seeds of cyperacous reeds.
3) A fine sandy clay, yellowish in colour and with sharp upper and lower boundaries. When dry, this material was light and powdery. This description resembled that of diatomite (Birks and Birks, 1980) and microscopic examination showed it consisted almost entirely of siliceous sponge spicules, diatoms and sand grains. Organic content was minimal.
4) A sandy peaty clay may or may not be present, was usually less than 3 cm thick and had a diffuse lower boundary.
5) A black clay layer with light to medium texture appeared highly organic. Boundaries between all clay layers were diffuse.
6) This medium textured clay formed the bulk of the sediment sequence. It was a greyish brown colour, with frequent yellowish-red mottles. At certain depths, red (iron) streaks or small iron stained clay concretions (< 3 mm diameter) appeared along old roots or root channels. At greater depths, the concretions formed continuous blocky structures or large single blocks (< 2 cm diameter).
7) The clay layer below was distinguished by its heavy texture and pallid colour, although the transition was diffuse. The clay may be mottled, but no concretions were found here.

Each layer was represented across the whole of the lake and only changed significantly at the lake margins where the sediments showed alternate layers of sand, clay and peat, although some sand was almost always present (Fig. 3).

Loss on ignition was an approximate guide to the organic matter content of the sediment. The values for the peat were high, around 45-60%, but fell to about 15% in the diatomaceous layer. Values peaked at 25% for the sandy peaty clay layer, then declinde to 10% in the clay layers and finally dropped to 5-7% in the pallid clay (Fig. 3).

Radiocarbon dates are shown in Table 1 and on Fig. 3. The lowermost date is 8,780 ±160 radiocarbon years, which corresponds to 9,791 calibrated years BP, the whole of the Holocene. Surface peat was

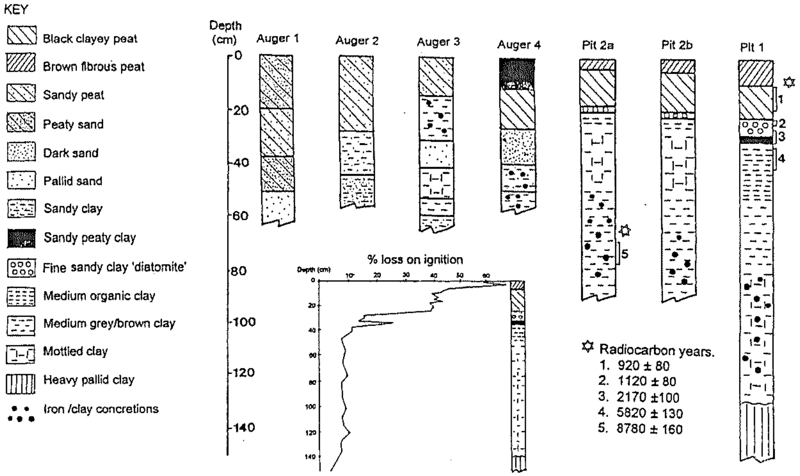

Figure 3. The stratigraphy of the sediments of Dry Lake.

Table 1. Radiocarbon dates. Calibrated years has been calculated according to the Radiocarbon Calibrated Program Calib Rev5.0.2 (Stuiver and Reimer, 1986-2005)

Sample Depth (cm)	Material dated	Radiocarbon years BP	Calibrated years BP
Pit 1			
10-20	Black clayey peat (humic acid fraction)	920±80 (NSW 375)	795
22-24	Charcoal Humic acid in charcoal Peat (around charcoal)	1,120±80 (NSW 381) 1,560±120 (NSW 380) 1,660±90 (NSW 384)	986 1,417 1,499
24-32	Diatomite (humic acid fraction)	2,170±100 (NSW 376)	2,101
38-45	Organic clay (humic acid fraction)	5,820±130 (NSW 377)	6,570
Pit 2			
73-83	10 cm length of wood Wood (humic acid fraction)	8,780±160 (NSW 387) 8,060±300 (NSW 388)	9,791 8,899

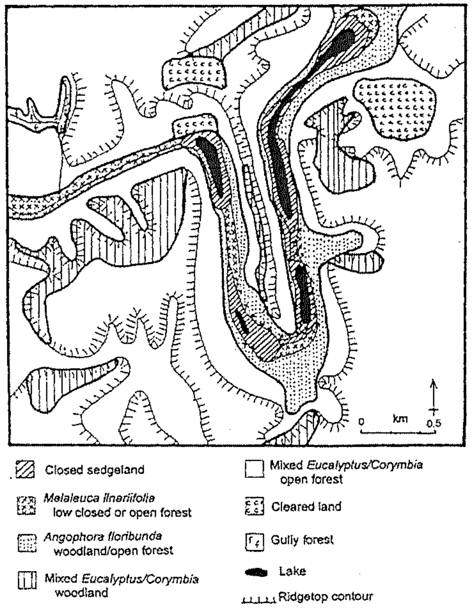

Figure 4. The vegetation of the Thirlmere Lakes region.

deposited most rapidly, i.e., 24-26 cm in 1,100 years and the diatomaceous earth (about 5 cm in depth) represents another 1,000 years. There appears to be an hiatus in the sediments, representing a period of zero or minimal deposition, or a period of erosion, between the diatomaceous earth (2,170±100 C^{14} years, see Table 1 for calibrated years) and the organic clay (5,820±130 ^{14}years) immediately below it. Wood and charcoal dates are regarded as the most reliable, whereas humic acids may move from their place of origin and contaminate material elsewhere. Table 1 reveals that where charcoal and humic acids have been dated from the same stratigraphic layer, there is relatively little difference.

Sedimentary history

The alternation of fine clay, peat and coarse sediments on the lake margin reflects the advance and retreat of the littoral zone in response to fluctuating water levels. Increasing clay content away from the littoral zone reflects deeper water where the dominant process is the settling of fine particle sizes. The peat indicates organic material accumulated more rapidly than it decomposed, reflecting a consistently high water table.

From the beginning of the Holocene up to about 6-5,000 years ago, the site was a lake depositing clay. The pallid clay, the deepest layer, the mottling and the iron concretions in the layer above the pallid clay suggest a fluctuating water table and the lake may have dried out periodically. It is not clear what happened in the period 5-2,000 years BP, represented by the hiatus in the sediments.

An explanation for the 5 cm. thick diatomite layer must remain speculative. An explosion in the diatom population would require a considerable quantity of nutrients, and it is unlikely that the sandstone substrate of the catchment could supply these nutrients. Burning appears the most likely way of increasing the nutrient mobility. Unfortunately, an hiatus provides no evidence at all.

For the last 2-1,000 years, the lake has been shallow enough to allow the rooted swamp vegetation. The Holocene history is thus the evolution of a lake gradually filling up with sediments.

The Vegetation

Appendix 1 lists all the species in the study area and Fig. 4 shows the general distribution and extent of the vegetation units which are as follows:

1. Low closed forest with emergent trees dominated by *Eucalyptus deanei* (Fig. 5), up to 35 m tall. This unit is restricted to the floors and steep-sided gullies. Below this tall open forest canopy is a low closed forest with a great diversity of small rainforest trees, including *Pomaderris* spp., *Backhousia myrtifolia*, *Acmena smithii*, *Doryphora sassafras*, *Ceratopetalum gummiferum*. *C. apetalum* and *Stenocarpus salignus*. Below this is a closed scrub with many sclerophyllous species, including *Grevillea mucronata*, *Leptospermum trinervium*, *Persoonia levis* and *Lomatia silaifolia*. Abundant twiners are also present, including *Smilax australis*, *Cissus antarctica* and *Sarcopetalum harveyanum*. The ground cover is a closed fern/

Figure 5. Low closed forest with emergent *Eucalyptus* species is restricted to the floor of steep gullies.

herbland with *Gleichenia microphylla, Blechnum nudum, Sticherus flabellatus, Drosera auriculata* and many orchids.

The gully is protected from wind and fire, and is moist and well shaded. The soils are of variable thickness and are highly organic. Other more open gullies have some of these characteristics but are dominated by sclerophyllous shrubs and do not have such a complex structure.

2. Mixed *Eucalyptus/Corymbia* forest is the most extensive unit occupying the well drained slopes and ridges. The structure of the tree canopy is variable, with open forest on the more sheltered sites and south-facing ridges, with *Eucalyptus piperita, E. resinifera, E. punctata, Corymbia gummifera* and *C. eximia* (Fig. 6A). Low open forest and woodland occupies the steep slopes, especially those with a northern or westerly aspect and along stony areas of the central ridge. Woodlands occur on the most extreme sites with greatest exposure to westerly winds and excessive drainage and here *C. eximia* and *E. racemosa* are the main species, with minor occurrences of the species mentioned above. Small trees of *Persoonia levis, P. linearis, Allocasuarina torulosa* and *Xylomelum pyreformis* are occasionally found here.

The understorey is typically an open heath, dominated by the families Proteaceae and Fabaceae (especially *Acacia* spp.). Other common species include *Pimelea linifolia, Platysace linearifolia* and *Eriostemon* spp. The shrub layer is diverse and highly variable, due to a complex of environmental factors. At sites impacted upon by recent fire, the shrub layer has reduced diversity and density. The main species are *Acacia* spp., *Indigofora australis* and *Hibbertia aspera* (Fig. 6B). The groundcover is a dense sward of *Imperata cylindrica* and *Pteridium esculentum*.

The groundcover is generally open on ridgetops and steep rocky slopes and closed on the footslopes and nearer the lake margins. The herbs include *Opercularia* spp., *Viola betonicifolia, Pratia purpurascens, Gonocarpus tetragynus* and climbers *Glycine clandestina* and *Kennedia rubicunda* are more important on moister ground, including the alluvial areas adjacent to the lakes and southern facing slopes. In most other situations, grasses and *Lomandra* species predominate. *Lomandra obliqua* is common on well drained slopes and ridges and *L. longifolia* is abundant on the moister foot slopes.

3. *Angophora floribunda* dominated woodland and open forest is found on alluvial fans adjacent to and between lakes. *A. floribunda* is not common on other sites. Other tree species which are common at these sites include *Eucalyptus resinifera, E. piperita* and *Corymbia gummifera*. Smaller trees include *Allocasuarina littoralis, Banksia serrata* and *Persoonia levis*.

The shrub layer of this woodland is an open heath similar to that of the Mixed *Eucalyptus/Corymbia* Forest but *Banksia spinulosa* and *Pultenaea villosa* are often important components. *P. villosa* is generally restricted to these alluvial areas and may be locally dominant.

Groundcover is usually closed grass/herbland. On the most poorly drained sites, *Lepidosperma longitudinale, Schoenus* spp. and *Baloskion gracilis* are important. Alluvial fans are characterised by deep soils, gentle slopes and the site drainage is moderate to poor.

4. *Melaleuca linariifolia* low closed or low open forest is mostly confined to a narrow area fringing the lake margins and along the swampy parts of Blue Gum Creek. It is most extensive on flat, low lying and periodically inundated sites adjacent to the lakes (Fig. 7).

The canopy is dominated by *M. linariifolia*, open or closed and 6 to 7 m high. *A. floribunda* is often present, usually as saplings on the drier landward margins of the unit. A few shrubs occur, e.g. *Viminaria juncea, Acacia longifolia* and *Pultenaea villosa*. At some sites, this unit and the *A. floribunda* woodland/open forest are difficult to distinguish and the *M. linariifolia* low open forest gives way to *Angophora* forest as the site becomes less subjected to periodic inundation.

The groundcover is closed or open sedgeland with *Schoenus* spp., *Lepidosperma longitudinale* and *Juncus* spp. The lakes contain occasional dead *M. linariifolia* stumps in 2 m of water, indicating a period of low water level which must have existed long enough for

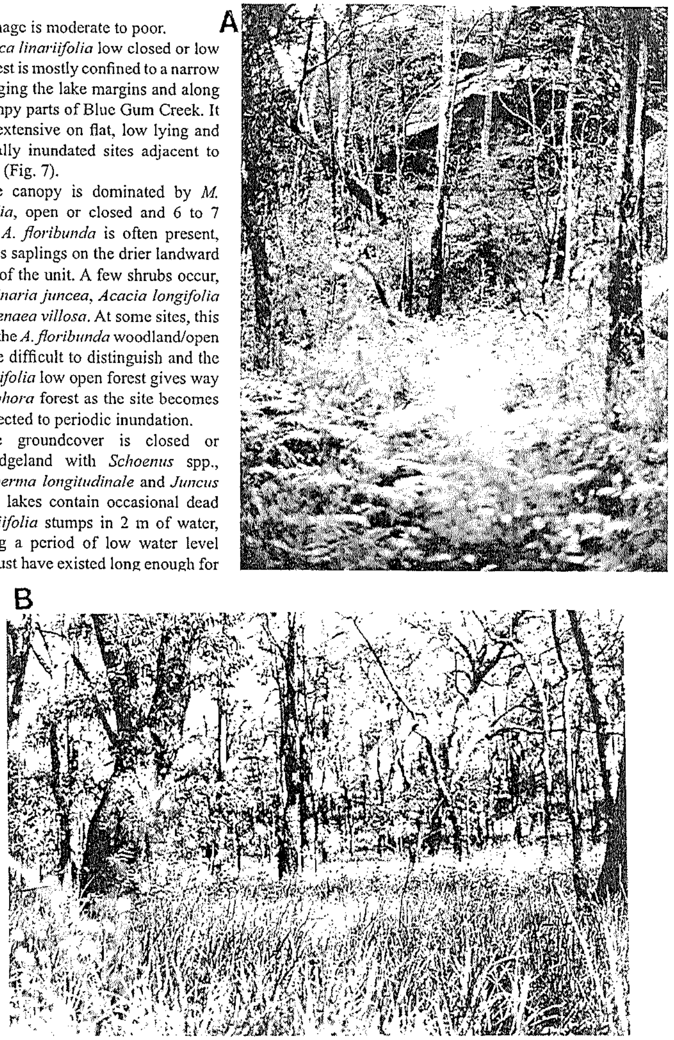

Figure 6. Mixed *Eucalptus/Corymbia* forest. A, more sheltered site. B, a site with a reduced shrub layer and a ground cover of *Imperata cylidrica* and *Pteridium esculentum*, the result of fire in recent years.

Figure 7. ***Melaleuca linariifolia*** **low closed or open forest at the lake edge.**

M. linariifolia to become well established.

5. A closed sedgeland occurs as a continuous fringe around and between each lake. Aquatic vegetation is usually distinctly zoned according to water depth, however, there is considerable overlap between species distribution as shown on Fig. 8 and some species may change their distribution over time. For example, Vorst (1974) noted that *Elaeocharis sphacelata* grew on the landward side of *Lepironia articulata,* but it now has a patchy distribution on both the landward and lakeward sides of *L. articulata.* This may have been caused by the lowering of water levels since 1974.

   The distribution of aquatic plants, especially rhizomatous sedges is probably constantly changing with water level fluctuations and possibly competition. Lake 3 of Thirlmere Lakes (Lake Baraba) is almost dry and covered by an extensive sedgeland of *Lepidosperma longitudinale* onto which *Melaleuca linariifolia* is encroaching (Fig. 9).

6. Dry Lake. The land around Dry Lake is mostly cleared (see Fig. 2). The vegetation on the slopes adjacent to the lake is largely grassland/herbland with native species, e.g. *Imperata cylindrica, Themeda australis, Goodenia hederacea, Pratia purpurescens* and *Wahlenbergia* spp., and introduced species, including *Paspalum dilatatum, Echinopogon* spp., *Setaria geniculata, Hypochoeris radicata, Plantago lanceolata, Conyza* spp. and *Verbena bonariensis*. Regrowth of trees and shrubs is occurring over most of the land and is most advanced nearest the swamp where the soils are moister.

   Dry Lake itself is a swamp but it has surface water in wetter periods. It is surrounded by a discontinuous fringe of *Leipidosperma longitudinale* which appears to be advancing onto the swamp (Fig 10). A patchy cover of herbs on the lake includes *Gonocarpus micranthus, Dichondria repens* and some grasses. The wettest patches are almost bare apart from the occasional *Polygonum decipiens* and *Hypochoeris radicata.* In 1981, a dead reed, probably *Lepironia articulata*, covered most of the lake basin. Live rhizomes of the reed are abundant in the peat. A channel dug through the centre of the basin and containing about 60 cm of water has some *Eleocharis sphacelata, Potamogeton tricarinatus, Persicaria orientale* and several other sedges.

   Towards the eastern margin of Dry Lake, inside the fringe of *L. longitudinale*, there are a number of old tree stumps, some of which are quite large (up to 40 cm in diameter). They are not *Melaleuca linariifolia* but are possibly *Eucalyptus/Corymbia* or *Angophora* spp. They probably represent a period of reduced moisture balance which was long enough and suitable for the growth of trees.

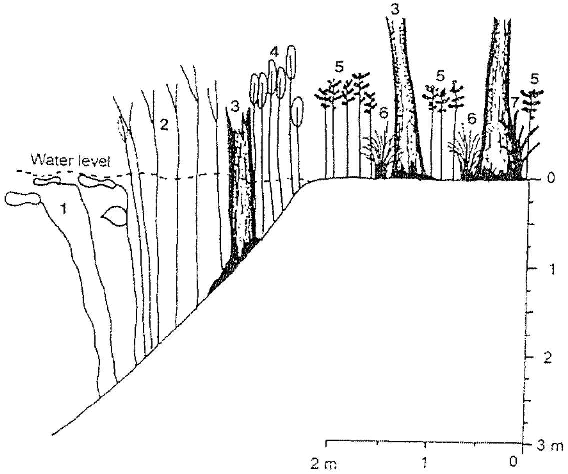

Figure 8 Aquatic vegetation. 1, ***Brasenia schreberi.*** 2, ***Lepironia articulata.*** 3, ***Melaleuca linariifolia*** **stump.** 4, ***Eleocharis sphacelata.*** 5, ***Lepidosperma longitudinale.*** 6, ***Baloskion gracilis.*** 7, ***Schoenus brevifolius*** **and** ***S. melanostachys.***

Modern Pollen Deposition

Pollen is produced by the contemporaneous vegetation, but a multitude of factors affect the representation of pollen in the sediments (Birks and Birks, 1980; Dodson, 1983; Moore et al., 1991), hence it is not possible to relate fossil pollen assemblages directly to the vegetation which produced it.

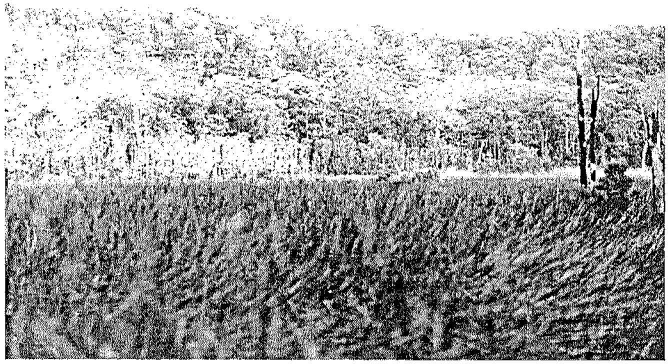

Figure 9. An extensive sedgeland on an almost dry Thirlemere lake.

Samples taken from beneath the present vegetation give some information about modern pollen deposition which may be used for interpretation of the fossil assemblages. Table 2 describes the surface sample sites and the associated vegetation growing there, and Fig. 11 shows the surface sample pollen spectra.

Comparison of the representation of the pollen with the taxon in the vegetation allows recognition of well-represented taxa, where pollen and vegetation representation are similar, over-representation, where pollen abundance exceeds abundance in the vegetation and under-representation, with pollen abundance less than abundance in the vegetation. This

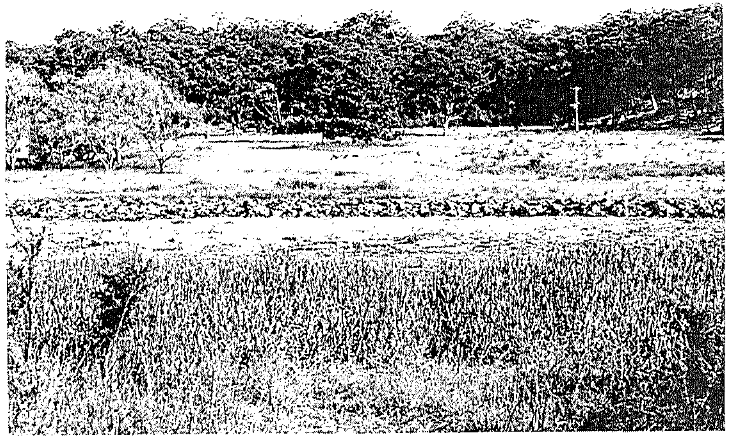

Figure 10. Dry Lake, showing the central drainage channel and marginal *Leipidosperma longitudinale*. The surrounding slopes are cleared.

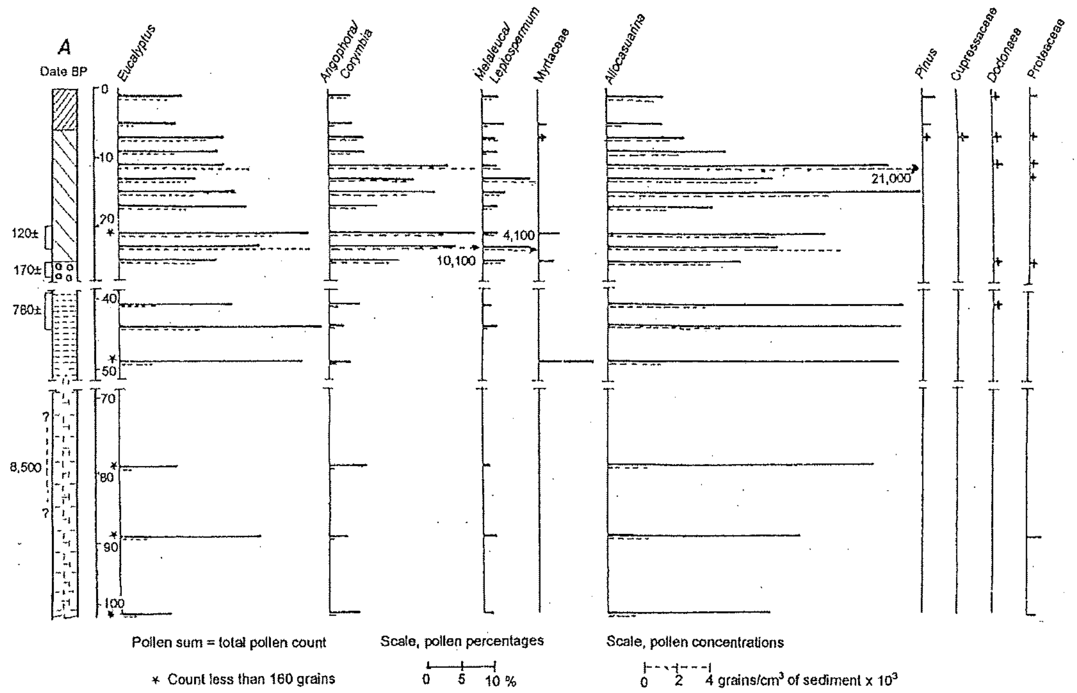

Figure 12. The pollen spectra of the Dry Lake sediments. For the probable source of the pollen for each name on the pollen diagram, see Appendix 3. +, rare, present but not counted.

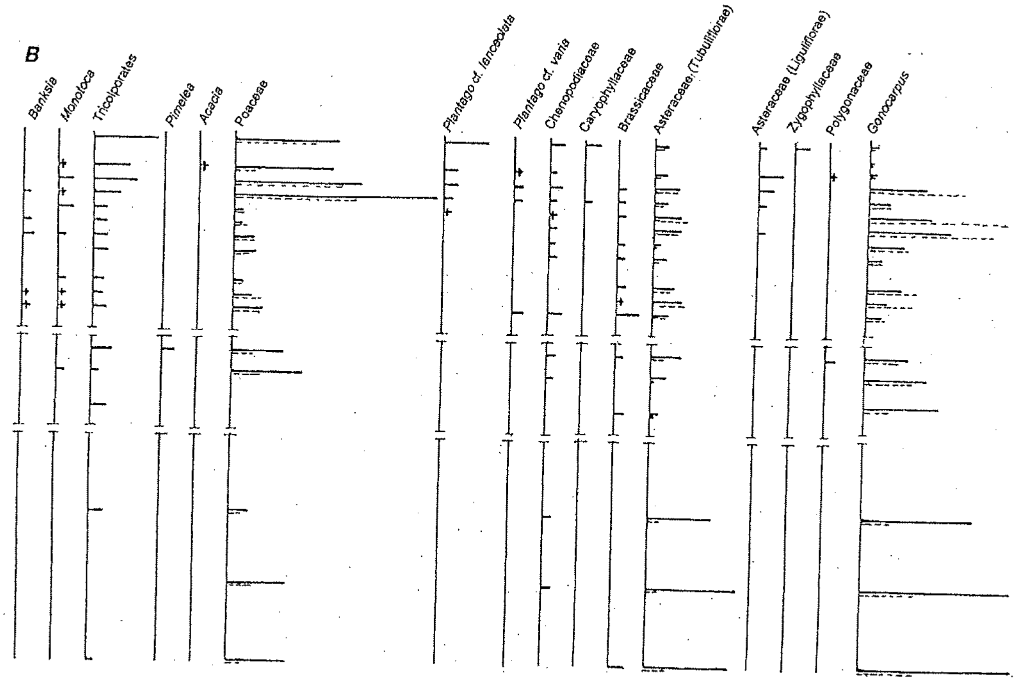

Figure 12 (continued). The pollen spectra of the Dry Lake sediments. For the probable source of the pollen for each name on the pollen diagram, see Appendix 3. +, rare, present but not counted.

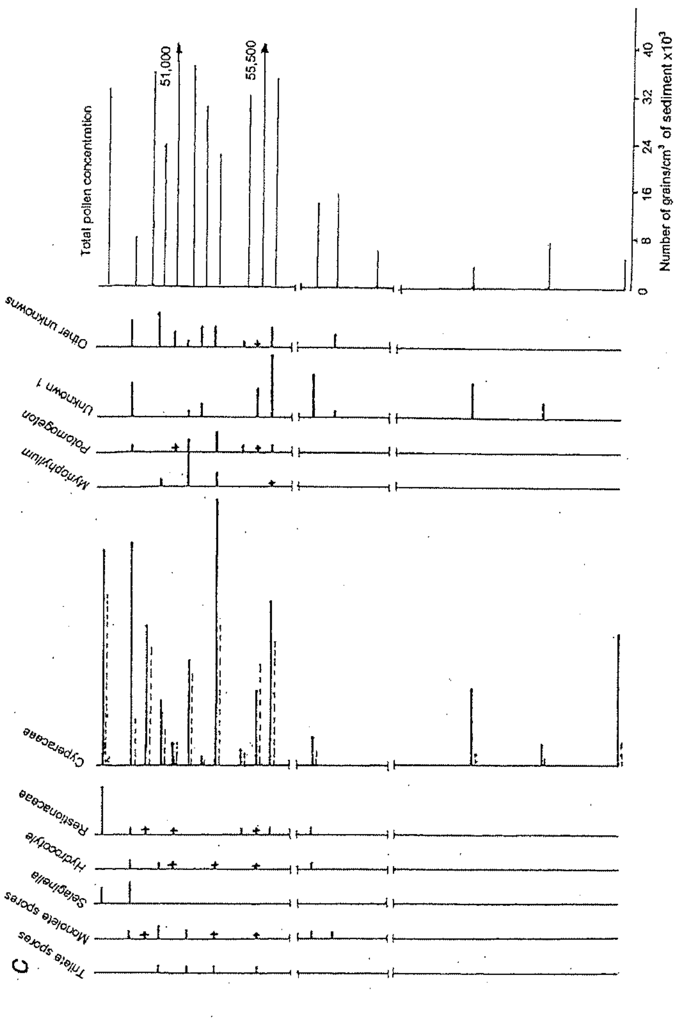

Figure 12 (continued). The pollen spectra of the Dry Lake sediments. For the probable source of the pollen for each name on the pollen diagram, see Appendix 3. +, rare, present but not counted.

In summary, the early Holocene vegetation was a *Eucalyptus/Allocasuarina/Casuarina* woodland/forest, with Asteraceae (Tubuliflorae) prominent in the understorey. *Gonocarpus* was probably common around the lake. In the late Holocene, *Angophora* woodland was present also and there was a diversity of shrubs in the understorey. The lake had become a peat swamp and Cyperaceae grew on and/or around the swamp. After Europeans arrived, the trees decreased and, grasses increased markedly. Today, *Angophora* woodland is found on the deeper, moister soils of the alluvial fans, hence its development around Dry Lake in the late Holocene probably indicates a wetter climate at that time.

Siliceous microfossils

Treatment for the recovery of siliceous microfossils yielded sponge scleres, diatoms, plant phytoliths and sand grains. Only sponge scleres were studied in detail, however some observations of diatoms or plant phytoliths are reported here.

Freshwater sponges occur in most semi-permanent and permanent inland waters of Australia. Distribution of the species are not uniform and is largely governed by physiochemical properties of the environment. Only one species of sponge, *Radiospongilla sceptroides* Haswell is present in the Thirlmere Lakes system (NPWS, 1997). This species has a wide but scattered distribution east of the Dividing Range and has a preference for non-alkaline environments (Racek, 1969). *R. sceptroides* produces a vivid green pigment and lives mainly on fallen logs, branches and leaves in the littoral zone where water fluctuations are most frequently experienced (Racek, 1969). It is thought that the relative abundance of sponge scleres could be used as an indicator of water depth and lake level fluctuations.

Two surface samples were studied: SS 1 from the lake margin and SS 2 from the lake centre (Fig. 13). The lake margin had 20 times the megasclere (body scleres) numbers than found at the lake centre. The lake margin is the habitat of the sponge and few scleres are apparently transported to the lake centre in this low energy environment. There were also appreciable numbers of gemmoscleres (carried on the gemmules), showing that the sponges were gemmulating in the not too distant past. Today, *R. sceptroides* does not form gemmules which are produced in response to adverse environmental conditions (Racek, 1969; NPWS, 1997).

Few scleres were found in the clays at the base of the sediments. The lake was probably much larger and deeper then and the sponge habitat would have been too far away for many of their scleres to be deposited at this site. There are two peaks in the values for megascleres: at 31 cm and a much larger one at 51cm, the latter at the base of the diatomite. These peaks suggest that the lake had become shallower and smaller, such that the sponge habitat was close to this site. The megasclere content was moderate through most of the profile, declining towards the surface.

Gemmoscleres were also found throughout the profile, and in appreciable numbers. The ratio of gemmoscleres to megascleres is an indicator of the harshness of the conditions (Racek, 1969). The two surface samples from Thirlmere Lakes have extremely small ratios, which indicate that conditions today are not often harsh enough to induce the sponges to form gemmules. The highest ratio of gemmoscleres to megascleres were found at the base of the diatomite. The ratio of megasclere fragments to entire megascleres was quite high, especially in the lake margin sample. This ratio may indicate how well the sponge remains were preserved in the sediments, especially at depth. However, the large number of fragmented sponge remains in the shallowest depths probably indicate mechanical breakage and being silica, the scleres do not decompose.

The high concentration of megascleres and gemmoscleres at the base of the diatomite were associated with a high concentrations and diversity of diatoms. Phytoliths were abundant also, and all these siliceous microfossils, being comparable to sand grains which are more common in the littoral zone, suggest that the lake was shallow and swamp plants were growing on or close to the site. The diatomite also contains a higher content of sand grains than any, which is indicative of shallow water of the littoral zone, the habitat of *R. sceptroides*.

In general, high concentrations of phytoliths were found from 50 cm upwards, or in that part of the profile that is organic. This high concentration implies that swamp vegetation had colonized the lake surface from the 50 cm level upwards. Below this level, the abundance of phytoliths was low, suggesting that little swamp vegetation was nearby and the lake was too deep for its growth.

DISCUSSION

The history of Dry Lake

In the early Holocene (from 10 ka), Dry Lake was relatively deep, with a calm, low energy environment depositing clay. The margins probably supported some cyperaceous reeds and *Gonocarpus*, but a fringe of paperbarks (*Melaleuca linariifolia*), similar to the

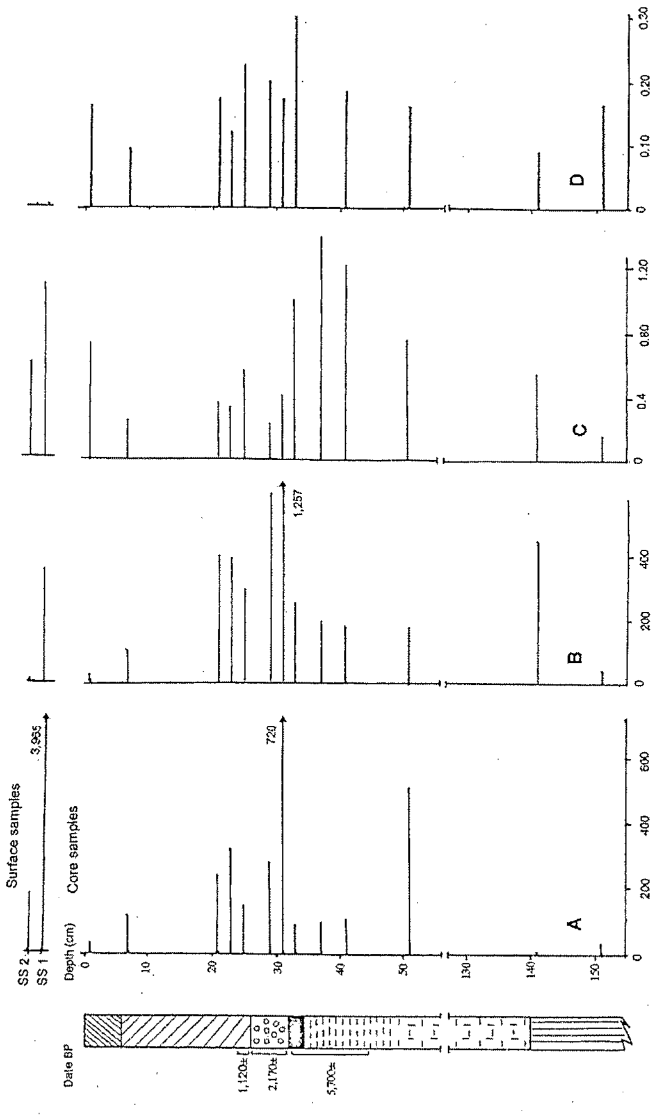

Figure 13. Sponge microfossils. A, Number of megascleres/cm3 sediment x 10^3. B, Number of gemmoscleres /cm³ sediment x 10^3. C, ratio of megasclere fragments to whole megascleres. D, Ratio of gemmoscleres to megascleres.

Thirlmere Lakes today, was lacking. The freshwater sponge, *Radiospongilla sceptroides,* lived round the margin of the lake, amongst fallen debris. *Eucalyptus* spp. and *Allocasuarina* were the dominant trees in the surrounding vegetation and Asteraceae (Tubuliflorae) was prominent in the understorey, probably as a shrub. Some grasses (Poaceae), Proteaceae, tricolporates (most likely shrubs) and Chenopodiaceae were also present in the early Holocene. Although generally high, lake levels must have been very variable and the lake probably dried up for extended period(s), causing the formation of the pallid and mottled clays at the deepest parts of the lake.

Between 8 ka and 5 ka, the lake became shallower and the fringing swamp vegetation grew over much of the lake surface. In the catchment, density of the *Eucalyptus* and *Allocasuarina* trees increased somewhat, Asteraceae was much reduced and shrubs and herbs increased in diversity, with *Dodonaea, Monotoca, Pimelea*, Brassicaceae and Portulacaceae being recorded.

From 5 ka to 2 ka, there was an hiatus in the deposition of the sediment, or the sediments that were deposited were subsequently eroded. Unfortunately, this means there is no information for this period.

About 2 ka, a shallow lake returned, probably covered with swamp vegetation and sufficiently nutrient rich to support large populations of diatoms and sponges. It is not clear how this nutrient rich status was achieved, given the nutrient-poor sandstone of the catchment. Decaying swamp vegetation would increase the nutrient status, but it would require a high nutrient status to produce a good plant cover in the first place. Burning may also mobilize nutrients. Unfortunately, there is no evidence about which is the more likely hypothesis in this case. This enriched nutrient status did not last long, and the diatom and sponge populations decreased to 'normal' levels. The lake remained shallow and probably supported swamp vegetation over most of its surface.

After 2 ka, the *Angophora/Corymbia* group increased dramatically. Today, *Angophora* dominates the alluvial fans and soils adjacent to the lakes, and *Corymbia* is more common on well-drained slopes and ridges, hence this increase around Dry Lake was more likely to have been *Angophora*. This change suggests a somewhat moister environment. *Eucalyptus* and *Allocasuarina* probably decreased slightly, *Melaleuca/Leptospermum* increased, but not sufficiently to indicate a fringe of *Melaleua* around the lake. The diversity of shrubs and herbs increased further, and there was a considerable increase in cyperaceous swamp cover.

The introduced *Pinus, Plantago* cf *lanceolata* and Asteraceae (Liguliflorae: probably *Hypochoeris radicata*) denote the zone of European influence. All the trees, viz. *Eucalyptus* spp, *Angophora/Corymbia* and *Allocasuarina* decreased markedly, no doubt the result of timber cutting. Grasses and the tricolporates, which could include any number of crop plants and weeds, would have been the result of agriculture. The cyperaceous reeds around the swamp remained, much the same as previously.

Comparisons with Other Studies

The history of the vegetation from a core in Lake Baraba (Thirlmere Lake 3 of this study, see Fig. 1), has been reported by Black et al. (in press). Lake Baraba is some 4 km south of Dry Lake. Peat began forming in the early Holocene, ~8.5 ka, earlier than at Dry Lake. Thus in contrast to Dry Lake, Lake Baraba had become shallow enough for the growth of swamp vegetation. At Lake Baraba, the dominant trees were Casuarinaceae which declined in the early Holocene, with a concurrent increase in Myrtaceae, thought to be the development of the fringing *Melaleuca* forest (Black et al., in press) which is present around the lake today. In contrast, at Dry Lake, *Allocasuarina* did not decrease, a fringing *Meleleuca* forest did not develop, and *Angophora* became prominent by the mid Holocene. At Dry Lake, the lake became shallow enough to support swamp vegetation and peat formation about the mid Holocene, later than at Lake Baraba. *Allocasuarina* remained prominent at Dry Lake until the European zone, unlike Lake Baraba where it remained low through most of the Holocene.

These differences between the two sites may be attributed to the differences in local topography. Lake Baraba is confined within a relatively narrow valley which is likely to afford some protection and provide more favourable moisture relationships than the Dry Lake locality, which is more open, in a broad alluvial flat. This topographic difference may explain why Dry Lake did not develop a fringing *Melaleuca* forest. Although these two sites are only 4 km apart, the limited nature of pollen dispersal, where most pollen falls close to the source (Birks and Birks, 1980; Dodson, 1983; Kodela, 1990) ensures that these local differences in the vegetation are recorded in the sediments.

A decline of Casuarinaceae, when *Eucalyptus* replaced Casurarinaceae, may be found in a number of Holocene sites in southern Australia and is usually dated between 7.5 and 4.5 ka. Importantly, not all Holocene sites show this decline (Clark,1983; Dodson, 1994; 2001; Lloyd and Kershaw, 1997). It has been suggested that anthropogenic fire may have been the cause of this change in dominant species, but the charcoal records generally do not support this hypothesis (Dodson, 2001; Kershaw et al.; 2002; Black et al., in press). Another likely cause, a rising water table or salinity, may be supported by an increase in Chenopodiaceae pollen (Crowley, 1994; Cupper et al., 2000), but studies in the vegetation show that some species of Casuarinaceae are more salt tolerant than certain species of *Eucalyptus* (Ladd, 1988). The anatomy of the branchlets of Casuarinaceae, with their restricted photosynthetic tissue, make it a poor competitor with broad leaved species. Anatomicaly, Casuarinaceae species are very xeromorphic and in comparative studies, Casuarinaceae is more drought tolerant than *Eucalyptus* (Ladd, 1988).

As the climate ameliorated after the last glacial period, the grasslands/shrublands were invaded by Casuarinaceae which were in turn replaced by *Eucalyptus* in the Holocene (Clarke, 1983). The climate in the last glacial period was much drier, hence the change in vegetation parallels the climatic change, viz. the increase in moisture. Casuarinaceae remained on poor or harsh sites as it appears to tolerate these conditions better than *Eucalyptus* (Ladd, 1988).

At Dry Lake, *Eucalyptus* and *Angohpora/Corymbia* increase, but Casuarinaceae does not decrease until it was logged by Europeans. Casuarinaceae was prized by the early settlers as firewood and it was the fuel of choice for bakeries. Its timber was in demand for shingles, tool handles, beer barrels and many other used (Entwisle, 2005). Indeed, the Oaks, some 15 km to the north of Thirlmere (Fig. 1) was so named for the abundant sheoaks (*Allocasuarina torulosa*). When the botanist George Caley passed through the district in 1804, he saw 'a large tract of grazing land abounding with sheoaks' (Woods, 1982).

The Casuarinaceae pollen has not been identified further; but it is assumed to be *Allocasuarina* in this study because there are only two species in the area today: *A. littoralis* and *A. torulosa*. *A. littoralis* is an understorey tree in woodland or occasionally tall heath, on sandy or otherwise poor soils. *A. torulosa*, also an understorey tree, is found in open forests to tall open forests, generally on higher nutrient soils and moisture situations than *A. littoralis* (Plantnet, 2005). The alluvial flat around Dry Lake would have been suitable for *A. torulosa*, but at Lake Baraba, in a sandstone valley, *A. littoralis* seems more likely. Thus the different history of Casuarinaceae at the two sites may have been the consequence of different species, as well as the different topography and soils.

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APPENDIX 1A

Species list of plants in the Thirlmere National Park, compiled from field work and augmented from a list prepared by the National Herbarium of New South Wales (*). +, introduced species.

Life forms: T, tree with single stem, > 8 m tall. S, shrub, woody plant < 8 m tall. H, herbs, non-woody plants. epiH, epiphitic herbs. aqH, aquatic herbs, growing in wet or periodically wet areas. C, creeper, prostrate herb or shrub. TW, twiner, climbing plant.

Pollination mechanisms (Poll'n Mech), from Faegri and van de Pijl (1971), Dodson (1979), Armstrong (1979), Ford et al. (1979) and Pyke (1981): A, anemophilous, wind pollinated. E, entomophilous, insect pollinated. O, pollination by other animals, e.g. birds, mammals. S, self pollinated. H, hydrophilous, water pollinated.

Nomenclature follows Harden (1992; 1993; 200; 2002) and Plantnet (2005).

Species	Life form	Poll'n Mech.	Occurrence/ distribution
MYRTACEAE			
Angophora floribunda (Sm.) Sweet	T	A, E, O	Very abundant, lower slopes only
Corymbia eximia (Schauer) K.D. Hill & L. A. S. Johnson	T	A, E, O	Very abundant, esp. ridgetop plateaux
C. gummifera (Gaertn.) K.D. Hill & L.A. S. Johnson	T	A, E, O	Abundant
Eucalyptus agglomerata Maiden	T	A, E, O	Occasional
E. botryoides Sm.	T	A, E, O	*
E. oblonga Blakely.	T	A, E, O	Occasional, mostly steeper slopes
E. piperita Sm	T	A, E, O	Very abundant
E. punctata DC	T	A, E, O	Occasional
E. racemosa Cav.	T	A, E, O	Occasional
E. resinifera Sm.	T	A, E, O	Rare
E. sieberi L. Johnson	T	A, E, O	Occasional, esp. near ridgetop plateaux
Leptospermum trinervium J. Thompson	S	A. E.	Common, mostly on slopes
L. polygalifolium Salsb.	S	A, E	Rare, mostly on slopes
L. juniperium Sm.	S	A, E	Occasional, mostly lake margins
Kunzea ambigua (Sm.) Druce	S	A, E, O	*
Melaleuca linariifolia Sm	T	A, E, O	Abundant, mainly lake margins
M. thymifolia Sm.	S	A, E, O	Occasional, along lake margins
PROTEACEAE			
Banksia integrifolia L. f.	T or S	E, O	*
B. serrata L.f.	T or S	E, O	Abundant, mainly lake margins
B. spinulosa Sm.	S	E, O	Very abundant
Grevillea arenaria R. Br.	S	E, O.	*
G. mucronulata R. Br.	S	E, O	Very abundant
Hakea dactyloides Cav.	S	E, O	Occasional, moist sites
H. salicifolia (Vent.) B.L. Burtt.	S	E,O	*
H. sericea Schrad. & J.C. Wendl.	S	E, O	Rare
Isopogon anemonifolius Knight	S	E	Occasional
Lambertia formosa Sm.	S	E, O	abundant
Persoonia lanceolata Andrews	S	E	*
P. laurina Pers.	S	E	Occasional, esp. ridgetop plateaux
P. levis (Cav.) Domin	S	E	Occasional
P. linearis Andrews	S	E	Occasional
Petrophile pedunculata R. Br.	S	E	Occasional
P. pulchella R. Br.	S	E	*
P. sessilis Sieber ex Schult.	S	E	*
Telopea speciosissima R. Br.	S	E	Occasional
Xylomelum pyriformis Sm.	T	E	Occasional
FABACEAE			
1) MIMOSOIDAE			
Acacia decurrens Willd.	T	E	Occasional esp. moist gullies/slopes
A. falcata Steud.	S	E	*
A. falciformis DC.	T	E	*
A. floribunda Willd.	S	E	*
A. implexa Benth.	S	E	*
A. linifolia Willd.	S	E	Abundant
A. longifolia (Andrews) Willd.	S	E	Abundant esp. after fire
A. myrtifolia Willd.	S	E	Occasional, ridgetop plateaux
A. parramattensis Tindale	S	E	Very abundant
A. suaveolens (Sm.) Willd.	S	E	Occasional
A. terminalis J.F. MacBr.	S	E	Occasional ridgetop plateaux
A. ulicifolia Court	S	E	Abundant
2) FABOIDAE			
Bossiaea buxifolia A.Cunn.	S	E	Rare
B. heterophylla Vent.	S	E	Occasional
B. lenticularis DC.	S	E	*
B. neo-anglica F. Muell.	S	E	*
B. obcordata Druce	S	E	Occasional
B. rhombifolia Sieber ex DC.	S	E	Occasional
Daviesia corymbosa Sm.	S	E	Rare
Desmodium rhytidophyllum F. Muell ex Benth.	S or TW	E	*
D. varians (Labill.) G. Don	TW	E	*
Dillwynia glaberrima Sm.	S	E	*

D. parvifolia R.Br.	S	E	*
D. phylicoides A. Cunn. sp. complex	S	E	Abundant
Glycine clandestina J.C. Wendl.	TW	E	Abundant
Gompholobium grandiflorum Sm.	S	E	*
G. latifolium Sm.	S	E	*
G. minus Sm.	S	E	Occasional
Hardenbergia violacea (Schneev.) Stearn	C	E	Very abundant
Hovea linearis (Sm.) R. Br.	S	E	Occasional
Indigofera australis Willd.	S	E	Abundant
Kennedia rubicunda Vent.	TW	E, O	Occasional
Mirbelia rubiifolia (Andrews) G. Don	S	E	*
Podolobium ilicifolium (Andrews) Crisp & P.H. Weston.	S	E	Occasional esp. rocky slopes
Pultenaea flexilis Sm.	S	E	Very abundant
P. linophylla Schrad. & J.C. Wendl.	S	E	*
P. villosa Andrews.	S	E	Occasional esp. alluvial fans
Viminaria juncea (Schrad,) Hoffsgg..	S	E	Occasional esp. damp sites
RUTACEAE			
Boronia ledifolia (Vent.) J. Gray ex. DC.	S	E	Occasional, esp. rocky slopes
B. polygalifolia Sm.	S	E	*
Eriostemon australasius Pers.	S	E, O	Occasional
E. hispidula. (Spreng.) Paul G. Wilson	S	E, O	Abundant
ERICACEAE			
Astroloma humifusum R. Br.	S	E, O	*
Epacris pulchella Cav.	S	E, O	Rare
Leucopogon lanceolatus (Sm.) R. Br. var. *lanceolatus*	S	E	Abundant
Lissanthe sapida R. Br.	S	E	Rare
L. strigosa R.Br.	S	E	Occasional
Monotoca elliptica R.Br.	S	E	Occasional
M. scoparia R.Br.	S	E	Occasional
Styphelia angustifolia DC.	S	E	*
DILLENIACEAE			
Hibbertia aspera DC.	S	E	Very abundant
H. diffusa DC.	S	E	Occasional
H. obstusifolia DC.	S	E	Occasional, moister slopes
H. serpyllifolia DC	S	E	Occasional, moister slopes
GOODENIACEAE			

Coopernookia barbata (R. Br.) Carolin	S	E	Occasional
Dampiera purpurea R. Br.	S	E	Occasional, moister slopes
Goodenia hederacea Sm.	C	E	Occasional, lake margins
Scaevola ramosissima K. Krause	H	E	Occasional
CASUARINACEAE			
Allocasuarina littoralis (Salisb.) L. Johson	T	A	Very abundant, lake margins, footslopes
A. torulosa (Aiton) L. Johnson	T	A	Occasional, upper slopes, ridgetops
EUPHORBIACEAE			
Amperea xiphoclada (Spreng.) Druce	S	E	Occaisional
Breynia oblongifolia Muell. Arg.	S	E	*
Phyllanthus gasstroemii Muell. Arg.	S	E	Abundant
P. occidentalis J.T. Hunter & J.J. Bruhl	S	E	Abundant
Poranthera ericifolia Rudge	S	E	*
P. microphylla Brongn.	H	E	*
RUBIACEAE			
Galium binifolium N.A. Wakefield	H	A	*
G. propinquum A. Cunn.	H	A	*
Opercularia aspera Gaertn.	H	A	Abundant on lake margin, moist areas
O. diphylla Gaertn.	H	A	*
O. varia Hook. f.	H	A	Abundant on lake margin, moist areas
Pomax umbellata Benth.	H or S	A	Very abundant
APIACEAE			
Actinotus helianthi Labill.	H	E	Occasional
Centella asiatica Urb.	C	E	*
Hydrocotyle acutiloba. N.A. Wakefield	H	A, E	*
H. laxiflora DC.	H	A, E	*
H. peduncularis. A. Rich.	H	A, E	*
Platysace linearifolia C. Norman	S	E	Abundant.
LAURACEAE			
Cassytha glabella R. Br.	TW		*
C. pubescens R. Br.	TW		*
Cinnamomum camphora $^+$T. Nees & C.H. Eberm	T	A, E	One specimen observed
RANUNCULACEAE			
Clematis aristata R. Br. ex Ker Gawl.	TW	E	*
VIOLACEAE			
Hybanthus monopetalum (Schultes) Domin.	H	E	*
Viola betonicifolia Sm.	H	E	Occasional, moist areas

V. hederacea Labill.	H	E	Occasional, moist areas
CRASSULACEAE			
Crassula sieberiana (Schultes & Schultes. f.) Druce	H	E	*
DROCERACEAE			
Drosera spathulata Labill.	H	E	Occasional, damp places
POLYGONACEAE			
Persicaria hydropiper (L.) Spach.	H	E	*
Acetosella vulgaris Fourr.	H	E	Occasional, moist sites
OXALIDACEAE			
Oxalis corniculata $^{+}$ L.	H	E	Occasional, esp. disturbed sites
GERANIACEAE			
Geranium homeanum Turcz.	H	E	*
HALORAGACEAE			
Gonocarpus micranthus Thunb.	C	E	Occasional esp. near lake margins
G. tetragynus Labill.	H	E	Occasional, moist places
Myriophyllum variifolium Hook. f..	Aq H	A	*
THYMELEACEAE			
Pimelea linifolia Sm.	S	E, S	Very abundant
PITTOSPORACEAE			
Billardiera scandens Sm.	TW	E	Occasional, shady slopes
Bursaria spinosa Cav.	S	E	Occasional
PASSIFLORACEAE			
Passiflora edulis $^{+}$ Sims	TW	E	One specimen observed
HYPERICACEAE			
Hypericum gramineum G. Forst.	H	E	*
ELAEOCARPACEAE			
Elaeocarpus reticulatus Sm.	T	E	Occasional, only moist gullies
Tetratheca thymifolia Sm.	S	E	Rare
MALVACEAE			
Sida rhombifolia $^{+}$ L.	S	E	*
CUNONIACEAE			
Ceratopetalum gummiferum Sm.	T	E	Occasional, only moist gullies
ROSACEAE			
Rubus parvifolius L.	S	E	*
R. fruticosus $^{+}$ species complex	S	E	Rare, disturbed sites
STACKHOUSIACEAE			
Stackhousia monogyna Labill.	H	E	*

S. viminea Sm.	H	E	*
LORANTHACEAE			
Unidentified	S	O	Rare, host *Eucalyptus* spp.
SANTALACEAE			
Exocarpos cupressiformis Labill.	T	A, E	Occaisional
E. strictus R. Br.	T	A, E	Rare, moist gullies
Leptomeria acida R. Br..	S	A, E	Rare
SAPINDACEAE			
Dodonaea triquetra Benth.	T	E	Occasional, moist slopes
LOGANIACEAE			
Mitrasacme polymorpha R. Br.	S	E	Occasional
APOCYNACEAE			
Parsonsia straminea F. Muell.	TW	E	Rare
Marsdenia flavescens A. Cunn.	TW	E	Rare, moist, shaded positions
M. suaveolens R. Br.	TW	E	Occasional, esp. shaded slopes
Tylophora barbata R. Br.	TW	E	*
MENYANTHACEAE			
Villarsia exaltata G. Don	H	H, E	* near water
CAPRIFOLIACEAE			
Lonicara japonica $^{+}$ Thunb. ex Murray	TW	E	*
PLANTAGINACEAE			
Plantago lanceolata $^{+}$ L.	H	A, E	Occasional esp. disturbed sites
CAMPANULACEAE			
Wahlenbergia graniticola Carolin	H	E	Occasional
W. stricta (R. Br.) Sweet	H	E	*
W. communis Carolin	H	E	*
LOBELIACEAE			
Isotoma axillaris Lindl.			*
Pratia purpurascens (R. Br.)F. Wimmer.	C	E	Occasional esp. moist sites
STYLIDIACEAE			
Stylidium graminifolium Willd.	H	E	Occasional esp. open sunny sites
S. laricifolium Rich.	H.	E	*
S. lineare Sw. ex Willd.	H	E	*
ASTERACEAE			
Bidens pilosa $^{+}$ L.	H	A, E	
Brachycome aculeata R. Br.	H	A, E	*
B. angustifolia Cunn. ex DC.	H	A, E	abundant

Cassinia aculeata R. Br.	S	A, E	Occasional, shady slopes
C. aureonitens N.A. Wakefield	S	A, E	*
C. longifolia R. Br.	S	A, E	Occasional, shady slopes
C. quinquefaria R. Br.	S	A, E	*
Conzya albida $^{+}$ Willd. ex Sprengel	H	A, E	Weed on disturbed sites
C. parva $^{+}$ Cronq.	H	A, E	Weed on disturbed sites
Coreopsis lanceolata $^{+}$ L.	H	A, E	*
Facelis retusa $^{+}$ Sch. Bip.	H	A, E	*
Gnaphalium gymnocephalum DC.	H.	A, E	*
Helichrysum elatum DC.	H or S	A, E	Occasional esp. gullies, very moist slopes
H. scorpiodes Labill.	H	A, E	Occasional
Hypochaeris radicata $^{+}$ L.	H	A, E	Abundant esp. moist disturbed sites
Lagenophora stipitata (Labill.) Druce	H	A, E	Shady slopes
Olearia microphylla Maiden & Betche	S	A, E	Occasional, mostly shady slopes
O. viscidula Benth.	S	A, E	*
Ozonthamnus adnatus DC..	S	A, E	*
O. diosmifolium (Vent.) DC	S	A, E	*
Podolepis jaceoides Voss	H	A, E	Occasional
Pseudognaphalium. luteoalbum $^{+}$ (L.) Hillard & B.L. Burtt	H	A, E	Occaisional
Senecio lautus $^{+}$ G. Forst. ex Willd.	H	A, E	Weed, on disturbed ground
S. linearifolius A. Rich.	H	A, E	*
S. quadridentatus Labill.	H	A, E	Weed, on disturbed ground
S. velleioides A. Cunn. ex DC.	H	A, E	*
Sigesbeckia orientalis L.	H	A, E	*
SOLANACEAE			
Solanum pungetium R. Br.	H	E	Occasional, esp. moist areas
CONVOLVULACEAE			
Dichondria repens J.R. Forst. & G Forst	C	E	Occasional esp. lake margins
Polymeria calycina R. Br.	C	E	*
SCROPHULARIACEAE			
Veronica plebeia R. Br.	H	E	*
LENTIBULARIACEAE			
Utricularia australis R. Br.	aqH	E	Rare, floating on open water > 2m deep
ACANTHACEAE			
Brunoniella pumilio (R. Br.) Bremek.	H	E	*
VERBENECEAE			
Verbenea bonariensis L.	H	E	Occasional, disturbed sites

LAMIACEAE			
Ajuga australis R.Br.	H	E	*
Scutellaria humilis R. Br.	H	E	*
POTAMOGETONACEAE			
Potamogeton tricarinatus A. Benn.	aqH	a	*
XYRIDACEAE			
Xyris complanata R. Br.	H	E	Rare in damp places
ANTHERICACEAE			
Arthropodium milleflorum (DC.) J.F. Macbr.	H	E	*
Laxmannia gracilis R. Br	H	E	*
Tricoryne simplex R. Br.	H	E	*
PHORMIACEAE			
Dianella caerulea Sims	H	E	Occasional
D. revoluta R. Br.	H	E	*
Stypandra glauca R. Br.	H	E	Occasional, only northern end of park
Thelionema caespitosum (R. Br.) R.J.F. Hend.	H	E	Occasional
SMILACACEAE			
Smilax glyciphylla Sm.	TW	?	Occasional, moist slopes
LUZURIAGACEAE			
Eustrephus latifolius Ker Gawl.	TW	E	Occasional, moist slopes
Geitonoplesium cymosum R. Br.	TW	E	Rare, moist slopes only
IRIDACEAE			
Patersonia glabrata R. Br.	H	E	*
P. sericea R. Br.	H	E	*
LOMANDRACEAE			
Lomandra confertifolia (F.M. Bailey) Fahn ssp. *rubiginosa* R.T. Lee	H	E	Occasional
L. cylindrica R.T. Lee	H	E	Occasional
L. filiformis (Thunb.) J. Britten	H	E	*
L. glauca Ewart	H	E	*
L. gracilis R.T. Lee	H	E	Occasional
L. longifolia Labill.	H	E	Abundant esp. footslopes
L. multiflora (R. Br.) J. Britten	H	E	Rare
L. obliqua J.R. Macbr.	H	E	Abundant
XANTHORRHOEACEAE			
Xanthorrhoea sp.	S	E	Occasional along ridgetop plateaux
HAEMODORACEAE			

Haemodorum planifolium R. Br.	H	E	*
PHILYDRACEAE			
Philydrum lanuginosum Banks & Sol. ex Gaertn.	aqH	E	*
ORCHIDACEAE			
Acianthus caudatus R. Br.	H	E	Occasional, moist slopes
A. exsertus R. Br.	H	E	*
A. fornicatus R. Br.	H	E	Occasional, moist slopes
Chiloglottis formicifera FitzG.	H	E	Occasional, only moist places
C. reflexa Druce	H	E	*
Corybas aconitiflorus K.D. Koenig & Sims	H	E	*
Dendrobium speciosum Sm.	epH	E	Occasional, shady rock outcrops
Diuris maculata Sm.	H	E	*
Liparis reflexa (R. Br) Lindl.	H	E	*
Microtis unifloia (Forst. f.) Reichb. f	H	E,S	*
Pterostylis sp.	H	E	*
JUNCACEAE			
Juncus articulatus $^+$ L.	H	A	*
Juncus continuus L.A.S. Johnson	H	A	*
J. planifolius R. Br.	H	A	*
J. prismatocarpus R. Br.	H	A	*
RESTIONACEAE			
Baloskion gracilis (R. Br.) B.G. Briggs & L.A.S. Johnson	H	A	Occasional, lake margins
Empodisma minus (Hook.f.) L.A.S. Johnson & D.F. Cutler	H	A	Occasional, lake margins
Lepyrodia mulleri Benth.	H	A	*
L. scariosa R. Br.	H	A	*
CYPERACEAE			
Baumea arthrophylla (Nees) Broeck.	H	A	*
B. teretifolia Palla	H	A, E	*
Baumea sp. nov.	H	A, E	*
Bolboschoenu fluviatilis (Torrey) Soják	H	A, E	*
Caustis flexuosa R. Br.	H	A, E	Occasional, rocky slopes, plateau tops
Cyperus laevis R. Br.	H	A, E	Occasional, moist sites
Eleocharis atricha R. Br	H	A, E	Occasioal
E. sphacelata R. Br	aqH	A, E	Abundant, in open water
Isolepis inundatus Hook. f.	H	A, E	*

Lepidosperma laterale R. Br	H	A, E	Occasional
L. longitudinale Labill.	H	A, E	Abundant, margins of lakes
Lepironia articulata Domin.	aqH	A, E	Very abundant, mostly open water
Schoenus brevifolius R. Br	H	A, E	Occasional, lake margins
S. melanonstachys R. Br	H	A, E	Occasional, lake martins
S. villosus R. Br	H	A, E	*
CABOMBACEAE			
Brasenia schreberi Gmelin	aqH	E	Occasional, open water only
POACEAE			
Anisopogon avenaceus R. Br	H	A	*
Aristida ramosa R. Br	H	A	Occasional
A. vagans Cav	H	A	*
Austrostipa rudis Spreng. ssp. *nervosa* (J. Vickery) J. Everett & S.W.L. Jacobs	H	A	*
Briza maxima $^+$ L.	H	A	*
Cymopogon refractus (R. Br) A. Camus	H	A	*
Dichelachne rara (R. Br) J. Vickery	H	A	*
Digitaria ramularis (Trin.) Henrad.	H	A	Occasional esp. footslopes
Echinopogon caespitosus $^+$ C.E. Hubb.	H	A	*
E. ovatus $^+$ (G. Forst,) P. Beauv.	H.	A	Occasional esp. open areas
Entolasia marginata (R. Br) Hughs	H	A	*
E. stricta (R. Br) Hughs	H	A	*
Eragrostis leptostachya Steud.	H	A	*
Imperata cylindrica P. Beauv. var. *major* (Nees) C.E. Hubb.	H	A	Abundant esp. after burning
Microlaena stipoides (Labill.) R. Br	H	A	*
Panicium simile Domin	H	A	*
Paspalidium gracile (R. Br.) Hughes	H	A	*
Paspalum dilatatum $^+$ Poir.	H	A	Occasional esp. disturbed footslopes
Pseudoraphis paradoxa (R. Br.) Pilger	H	A	*
Setaria gracilis $^+$ Kunth.	H	A	Occasional
S. pubescens R. Br.	H	A	*
Themeda australis (R.Br.) Stapf.	H	A	Abundant
FERNS/FERN ALLIES			
SELAGINELLACEAE			
Selaginela uliginosa (Labill.) Spring			Occasional, damp places
OPHIOGLOSSACEAE			
Botrychium australe R.Br.			*

DICKSONIACEAE	
Calochlaena dubia (R.Br.) M. Turner & R. White	Only in very moist gullies
CYATHACEAE	
Cyathea sp.	Rare, moist gullies
DENNSTAEDTIACEAE	
Hypolepis muelleri N.A. Wakef.	Occasional, moist creek banks
Pteridium esculentum (Forst f.) Cockayne	Abundant, esp. disturbed areas
LINDSAEACEAE	
Lindsaea microphylla Sw.	Rare, moist gullies
ADIANTACEAE	
Adiantum aethiopicum L.	Occasional, moist gullies
A. hispidulum Sw.	*
SINOPTERIDACEAE	
Cheilanthes distans (R.Br.) Mett.	*
C. austrotenuifolia Quirk & Chambers	Occasional, esp. rock outcrops
DAVALLIACEAE	
Davallia pyxidata Cav.	Rare, on rockfaces in moist areas
BLECHNACEAE	
Blecknum cartilagineum Sw.	abundant, rocky, shaded slopes
Doodia aspera R.Br.	Occasional, moist slopes

APPENDIX 1B

The species in the gully forest (site TS 6, Fig. 1).

Species	Family	Presence outside gully
Trees, 10-30 m		
Eucalyptus deanei Maiden	Myrtaceae	-
E. *elata* Dehnh.	"	-
E. piperita Sm.	"	+
Small trees and shrubs < 10 m		
Doryphora sassafras Endl.	Monimiaceae	-
Grevillea mucronata R. Br.	Proteaceae	+
Hakea salicifolia (Vent.) B.L. Burtt.	"	-
Lomatia silaifolia (Sm.) R. Br	"	+
Persoonia levis (Cav.) Domin.	"	+
P. linearis Andrews.	"	+
P. mollis R. Br.	"	-
Stenocarpus salignus R. Br.	"	-
Pittosporum revolutum Dryand.	Pittosporaceae	-
Elaeocarpus reticulatus Sm.	Elaeocarpaceae	+
Lasiopetalum ferrugineum Sm. var, *ferrugineum*	Sterculiaceae	-
Bertya pomaderriodes F. Muell.	Euphorbiaceae	-
Callicoma serratifolia Andrews	Cunoniaceae	-
Ceratopetalum apetalum D. Don	"	-
C. gummiferum Sm.	"	+
Acacia decurrens Willd.	Fabaceae	-
A. elata Benth.	"	-
A. parramattensis Tindale	"	+
Pultenaea flexilis Sm.	"	+
Acmema smithii (Poir.) Merr. & Perry	Myrtaceae	-
Backhousia myrtifolia Hook. f. & Harv.	"	-
Tristaniopsis sp aff. *laurina* (smith) Peter G. Wilson & Waterhouse	"	+
Leptospermum trinervium (Sm.) J. Thompson	"	+
Allocasuarina torulosa (Aiton) L. Johnson	Casuarinaceae	+
Pomaderris intermedia Sieber	Rhamnaceae	-
Pomaderris sp. unidentified	"	-
Exocarpos strictus R. Br.	Santalaceae	-
Correa reflexa Vent. var. *reflexa*	Rutaceae	-
Nematolepis squameum (Labill.) Eng.	"	-
Dodonaea triquetra J.C. Wendl.	Sapindaceae	+
Astrotricha latifolia Benth.	Aralaceae	+
Dracophpyllum secundum R. Br.	Ericaceae	-
Leucopogon lanceolatus (Sm.) R. Br.var. *lanceolatus*	"	+
Logania albiflora Druce	Loganiaceae	-
Notelea sp. unidentified	Oleaceae	-
Rapanea variabilis Mez.	Myrsinaceae	-
Dampiera purpurea R. Br.	Goodeniaceae	+
Cassinia aculeata R. Br.	Asteraceae	+
Ground cover, herbs and shrubs < 1 m		
Viola bentonicifolia Sm.	Violaceae	+
Drosera auriculata Backh.ex Planch.	Droseraceae	+
Solanum sp. unidentified	Solonaceae	+
Corybas frimbriatus (R. Br.) Rchb. f.	Orchidaceae	+

Gahnia sp unidentified	Cyperaceae	-
Hibbertia obtusifolia DC.	Dilleniaceae	+
Climbers		
Cassytha glabella R. Br.	Cassythaceae	-
Sarcopetalum harveyanum F. Muell.	Menispermaceae	-
Smilax australis R. Br.	Smilacaceae	+
Cissus antarctica Vent.	Vitaceae	-
Eustrephus latifolius Ker Gawler	Luzuriagaceae	+
Geitonoplesium cymosum R. Br.	"	+
Pachycauls		
Cyathea australis (R. Br.) Domin.	Cyatheaceae	-
Ground ferns		
Todea barbara (L.) T. Moore	Osmundaceae	-
Gleichenia microphylla R. Br.	Gleicheniaceae	-
Sticherus sp.	"	-
Hymenophyllum cupressiforme Labill.	Hymenophyllaceae	-
Calochlaena dubia (R. Br.) M. Turner	Cyatheaceae	-
Pteridium esculentum (Forst.f.) Cockayne	Dennstaediaceae	+
Adiantum aethopicum L.	Adiantaceae	+
Cheilanthes austrotenuifolia Quirk & Chambers	Sinopteridaceae	+
Pyrrosia rupestris (R. Br.) Ching	Polypodiaceae	-
Aspenium flabellifolium Cav.	Aspleniaceae	-
Blechnum cartilagineum Sw.	Blechnaceae	+
B. nudum (Labill.) Mett. ex Luerssen.	"	-
Doodia aspera R. Br.	"	+

APPENDIX 2

The identification of pollen of the family Myrtaceae.

Fig. 14 illustrates the pollen characters used and Table 3 presents the distribution of these characters amongst the species. These morphological characters were insufficient to reliably identify species but they have been used to place the species in distinctive groups which are defined thus:

Angophora/Corymbia group: Large-sized grains, 26 (30-40) 45 µm (mean in brackets), with x (rarely w) type pore and a thick exine, 2-4 µm.
Eucalyptus group: Medium-sized grains, 18 (21-25) 28 µm, with x (rarely w) type pore and medium-thickness exine, 1.5-3.0 µm.
Melaleuca/Leptospermum group: Small sized grains, 10 (13-19) 23 µm, with only y and z type pore and thin exine, <1-1 µm.

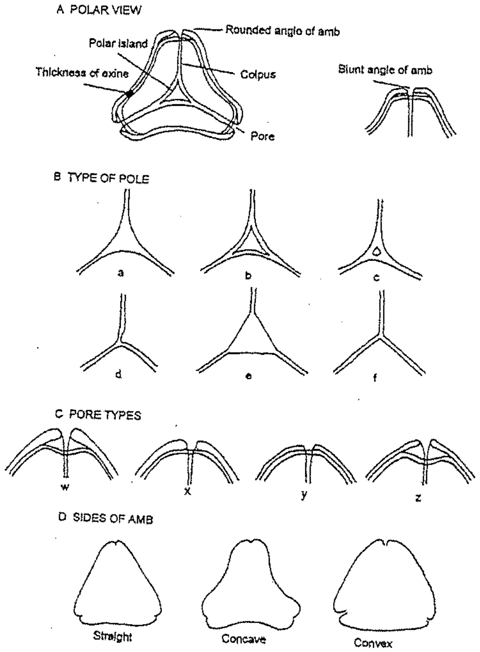

Figure 14. The morphological characters used to identify pollen grains of Myrtaceae

Table 3. Pollen morphological characters used to identify myrtaceous pollen groups. ( ) infrequent occurrence.

Species	Equatorial diameter Mean (µm) Range	Type of pole	Type of pore	Amb angle	Amb sides	Exine pattern	Exine thickness (µm)
	***Angophora/Corymbia* pollen group**						
Angophora floribunda	30±1.7 (26-33)	f (e) a	x (w)	round	straight	faint	2-3
Corymbia eximia	40.7±2.8 (35-45)	a, c (f)	x	round	straight	-	2-4
C. gummifera	40.0±3.0 (33-45)	b, a (f)	x	round	convex	-	2.5
	***Eucalyptus* pollen group**						
Eucalyptus punctata	23.8±1.3 (18-27)	a	w (x)	round	straight & concave	-	1.5-2
E. piperita	21.0±1.3 (18-24	a	x	round	straight & concave	-	
E. tereticornis	23.4±1.3	a	x	round	straight	-	1.5-2
E. globoidea	24.8±2.0 (20-28)	a	x (w)	round	straight & concave	-	1.5-3
	***Melaleuca/Leptospermum* pollen group**						
Melaleuca thymoides	19.6±1.4 (18-23)	f (a)	z	round	concave	-	to 1
M. linariifolia	15.4±1.4 (13-18)	f	z	round	concave	-	to 1
Leptospermum juniperinum	13.0±1.8 (10-19)	f	z	round	concave	-	to 1
L. trinervium	13.5±1.4 (12-16)	f	y	blunt	straight	coarse, granular	to 1
Tristaniopsis sp. aff laurina	14.4±1.1 (12-17)	a	z	blunt	straight & concave	-	to 1
Acmena smithii	14	f	-	round	straight & concave	-	to 1
Backhousia myrtifolia	18.0 (14-21)	f	z	round	concave	faint	<1

APPENDIX 3

Pollen type name on pollen diagrams and probable source in the vegetation. For full lists of species in each genus, see Appendix 1A

Pollen type	Probable source in present day vegetation
Pollen types found on both surface sample and fossil pollen diagrams.	
Eucalyptus	*Eucalyptus* spp.
Angophora/Corymbia	*A. floribunda, C. eximia, C. gummifera*
Melaleuca/Leptospermum	*Melaleuca* spp. and *Leptospermum* spp., *Acmena smithii, Tristaniopsis* sp., *Backhousia myrtifolia.*
Myrtaceae	Any other species in the family
Allocasuarina	*A. torulosa, A. littoralis*
Pinus	*Pinus* spp., most likely *P. radiata*
Cupressaceae	Native *Callitris* or other intoduced species
Dodonaea	*Dodonaea triquetra*
Proteaceae	All species in the family, excluding *Banksia* spp.
Banksia	*Banksia* spp.
Monotoca	*Monotoca* spp.
Tricolporates	Includes species from Fabaceae (excluding Acacia), Rutaceae, Dilleniaceae, *Goodenia hederaceae, Ampera xyphoclada,* Violaceae, *Bursaria spinosa,* Stylidiaceae
Tricolporate 2 (15 um grains)	Mainly *Elaeocarpus reticulatus, Ceratopetalum* spp.
Pimelea	*Pimelea linifolia*
Acacia	*Acacia* spp.
Poaceae	Poaceae species
Plantago cf *lanceolata*	*Plantago lanceolata* (introduced)
Plantago cf *varia*	*Plantago varia* (native)
Chenopodiaceae	Chenopodiaceae species (not in Appendix 1) probably herbs
Caryophyllaceae	Caryophyllaceae, as above
Brassicaceae	Brassicaceae, as above
Asteraceae Tubuliflorae	Asteraceae species, excluding *Hypochoeris radicata*
Asteraceae Liguliflorae	Probably only *Hypochoeris radicata*
Zygophyllaceae	Probably *Tribulus terrestris*, but the plant was not observed
Polygonaceae	*Persicaria decipiens, P. hydropiper, P. orientale*
Gonocarpus	*Gonocarpus* spp.
Trilete spores	*Cyathea* sp, *Pteridium* sp. *Adiantum* spp. *Cheilanthes* spp.
Monolete spores	*Blechnum* spp., *Davallia* sp., *Doodia* sp.
Sellaginella	*Sellaginella uliginosa*
Hydrocotyle	*Hydrocotyle* spp.

Restionaceae	Restionaceae species
Cyperaceae	Cyperaceae species
Myriophyllum	*Myriophyllum variifolium*
Potomogeton	*Potomogeton tricarinatus*
Unknown 1 (inaperturate)	Inaperturate grain with coarse granular pattern, thin exine, 20-25 um diameter.
Unknowns	All other unidentified grains

Other pollen types on surface sample pollen diagram

Platysace	*Platysace linearifolia*
Leucopogon	*Leucopogon* spp
Monosulcate	Liliaceae (sensu. lat.)
Exocarpus	*Exocarpus* spp.
Goodeniaceae	*Scaveola ramossisima*
Apocynaceae	*Parsonsia straminea*
Portulacaceae	*Portulaca oleracea*
Loranthaceae	Mistletoe on *Eucalyptus* spp.
Lomandra	*Lomandra* spp

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A >43,000-year vegetation and fire history from Lake Baraba, New South Wales, Australia

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Abstract

Palaeoenvironmental sequences that describe the vegetation of the last glacial maximum (LGM) and of the subsequent climatic amelioration are relatively rare in the Australian, Southeast Asian and Pacific region (SEAPAC region). Here, we present the results of a palynological investigation from Lake Baraba, located in eastern Australia, which extends beyond 43 ka. Bands of oxidised sediment prior to the LGM suggest lake level fluctuations, however, lacustrine clays continued to be deposited throughout the LGM and into the early Holocene when the deposition of peat was initiated. The vegetation, a *Casuarina* woodland/shrubland with a mixed understorey, remained relatively stable from >43 kyr to the early Holocene, suggesting that this sclerophyllous vegetation was resilient to changes in climate. The vegetation of the LGM at Lake Baraba does not conform to previous descriptions of a treeless south-eastern Australia, and it is possible that it was a refugium for woodland. Myrtaceae expanded at the expense of Casuarinaceae from the early Holocene, with charcoal analyses suggesting that fire was an unlikely explanation. There was no apparent relationship between Aboriginal site usage and fire activity and hence how Aboriginal people used fire at Lake Baraba remains speculative.

1. Introduction

This paper describes a >43,000-year pollen and charcoal record from Lake Baraba, located in southeastern Australia, which investigates the nature of vegetation and fire in the landscape over a period which includes the last glacial maximum (LGM) and subsequent climatic amelioration. This palaeoecological record, compared and contrasted with existing studies from southeastern Australia, enhances our understanding of the history and development of the extant vegetation. Furthermore, this record suggests that the vegetation surrounding the site during the late glacial was unlike previous descriptions in southeastern Australia, thereby suggesting a greater diversity of land-cover. Characterising the vegetation of various locations during the late glacial period is useful for various endeavours including validation of climate and earth system models.

The climate of the LGM in Australia, ~21–18 ka, was inhospitable with cooler, drier and windier conditions (Markgraf et al., 1992; Allan and Lindsay, 1998) coupled with reduced atmospheric CO_2 content (Petit et al., 1999). It is estimated that precipitation levels were about half present day values in the mid-latitudes (Allan and Lindsay, 1998) and mean annual temperatures were up to 10 °C cooler in southeastern Australia (Kershaw, 1995). Sea levels during the LGM were ~120–135 m lower than current levels (Lambeck and Chappell, 2001; Yokoyama et al., 2001) resulting in Australia being about one-third larger than it is today (Markgraf et al., 1992).

There are only 33 sites in the Australian, Southeast Asian and Pacific region (SEAPAC region) that have a record of vegetation during the LGM (Dodson, 1994; Kershaw, 1995; Pickett et al., 2004). At the peak of the LGM, about 20 ka, previous studies indicate the vegetation of southern Australia was a semi-arid grassland-steppe, dominated by Asteraceae and Poaceae and with small patches of mesic communities (Dodson, 1994; Hope, 1994; Kershaw, 1995, 1998). More recently, Pickett et al. (2004) have suggested xerophytic shrubs/woodlands characterised the LGM rather than steppe vegetation. The exposed continental shelf of southeastern Australia at the LGM, however, was covered in shrub, heath and woodland communities dominated by myrtaceous shrubs, Asteraceae and Chenopodiaceae (Harle, 1997).

Palynological studies suggest a relatively rapid climatic amelioration following the LGM with increases in arboreal taxa (e.g. *Eucalyptus*, *Casuarina*). The Pleistocene–Holocene boundary (~11 ka) has been described as a period of rapid climate change with temperatures and moisture regimes beginning to reach modern values (Kershaw, 1995). The re-expansion of vegetation communities dominated by trees also dates to about this time. Changes to the vegetation have been relatively minor throughout the Holocene, but this perceived stability may be related to palynological invisibility of subtle changes within families (e.g. Myrtaceae, Casuarinaceae) (Clark, 1983). A number of records in south-eastern Australia show an increase in *Eucalyptus* at the expense of *Casuarina* starting from various times during the Holocene (e.g. Ladd et al., 1992; Devoy et al., 1994; Harle, 1998; Gale and Pisanu, 2001). The cause of this has been attributed variously, but most often to the role of fire.

The period 7–5 kyr has been described as the precipitation peak, or Holocene Climatic Optimum in Australia and the period 4–2 kyr was perhaps cooler and drier (Kershaw et al., 2002). Lees (1992) linked the changes to enhanced climatic variability from 5.5 kyr onward, suggesting this may be associated with sea level stabilisation and consequently, ENSO fluctuations. More recently, Gagan et al. (2004) suggested that the onset of modern ENSO periodicities, identified by palaeo-records from the tropical Pacific, began ~5 kyr with an abrupt strengthening in magnitude from ~3 ka.

The mid-late Holocene is also believed to have been an important period of change for humans in south-eastern Australia with technological changes in the archaeological record perhaps associated with 'intensification' (e.g. Lourandos, 1980, 1983). The 'intensification' of Australian Aboriginal populations during the mid-late Holocene, however, is controversial (e.g. Rowland, 1999) and may involve increased archaeological visibility. Often-quoted archetypes of technological 'breaks' have recently been demonstrated to be less abrupt 'introductions' (Hiscock and Attenbrow, 1998) and rising sea levels and the subsequent loss of the continental shelf for living space must have had an impact on the Aboriginal people (Attenbrow, 2004). The ecological consequences resulting from the use of fire by Aboriginal people are uncertain (Bowman, 1998).

2. The environment

Lake Baraba is one of the Thirlmere Lakes (34°13′S 150°13′E), located about 100 km to the southwest of Sydney, New South Wales (Fig. 1). The lakes are an upland fluviatile system contained in an entrenched meander (Timms, 1992) at an altitude of 305 m asl. Tectonic activity beheaded a river that probably originally flowed westwards, leaving the isolated, sinuous channel that now contains the lakes (Timms, 1992). The valley system and the lakes may potentially be up to 15 million years in age which is unusually old for such small lakes (Horsfall et al., 1988).

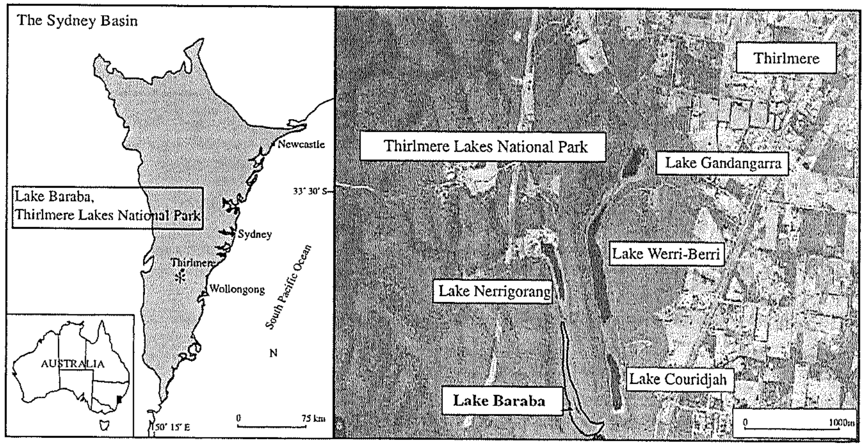

Fig. 1. Location of Lake Baraba.

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The flora within Thirlmere Lakes National Park is typical of the Sydney Sandstone complex and is particularly diverse with over 400 species from 250 genera represented (Benson and Howell, 1994; National Parks and Wildlife Services (NPWS), 1995). It is predominantly dry sclerophyll woodland and forest formations of mixed *Eucalyptus/Corymbia/Casuarina*. Sydney Peppermint (*Eucalyptus piperita*) and Red Bloodwood (*Corymbia gummifera*) are common. The 8 ha Lake Baraba is largely infilled and is mostly covered by swamp species dominated by sedges. Species found on the swamp surface include Pithy Sword-sedge (*Lepidosperma longitudinale*), Scale-rush (*Lepyrodia muelleri*) and Zig-zag Bog-rush (*Schoenus brevifolius*) (Fairley, 1978). Aquatic vegetation of the site includes Tall Sedge (*Lepironia articulata*), Tall Spike-rush (*Eleocharis sphacelata*), Woolly Frogmouth (*Philydrum lanuginosum*), Water Lily (*Brasenia schrebi*) and the algae *Chara fibrosa*. The paperbark tree, *Melaleuca linariifolia*, also grows on the swampy edges of the site.

The Thirlmere Lakes experience a warm temperate climate with average temperatures ranging from 25 to 33 °C in summer and 5 to 15 °C in winter. The average annual rainfall is 804 mm (BoM, 2005). Fire is a regular event in dry sclerophyllous vegetation and during the 20th century at Thirlmere Lakes there has been an average of one large and intense wildfire every 7.5 years (Noakes, 1998).

The traditional custodians of the Thirlmere Lakes region are the D'harawal and Gundangarra people (NPWS, 1995). The lakes and wetlands of the Thirlmere Lakes would have provided a plentiful supply of food and ethnographic evidence suggests that the Aboriginal people of the region frequently applied fire to the landscape (NPWS, 1995). Evidence for the earliest occupation of the Sydney Basin is from Wentworth Falls, which has been dated at ~22,000-year BP (Stockton and Holland, 1974). Attenbrow (2004) has suggested that the establishment of Aboriginal sites increased from 8 kyr with the habitation rates of these sites generally increasing until the arrival of European people. The Gundangurra and D'harawal populations declined in the 1800s largely due to conflict with and diseases introduced by European people.

3. Methods

A 6.35 m sediment core was extracted from a swampy section of Lake Baraba using a Russian D-section corer (Jowsey, 1966) in June 2003. The stratigraphy of the core was described using a modified version of the Troels-Smith method (Kershaw, 1997) and was photographed. Five subsamples of the core (147–153, 275–285, 347–353, 464–472 and 595–601 cm) were submitted for radiocarbon dating. Radiocarbon ages were calibrated with CALIB v5 (Stuiver et al., 2005) using the IntCal04.14c (Reimer et al., 2004) and ShCal04.14c (McCormac et al., 2004) data sets. Where ages are reported in the text these are calibrated ages based on a polynomial equation derived from graphing the midpoint of the depth of the dated sediment sections against calendar ages.

Macroscopic charcoal, which is thought to represent local or catchment fire events (Whitlock and Millspaugh, 1996), was analysed using a modified version of the 'Oregon sieving method' (Long et al., 1998) and image analysis (Mooney and Black, 2003). Volumetric subsamples were taken at every 5 cm from the core and dispersed for 24 h in 8% sodium hypochlorite (bleach) to remove the pigment from organic matter and hence aid in the identification of charcoal. This material was washed through a 250 μm sieve and the collected material was photographed in a petrii dish using a digital camera (Nikon Coolpix 4500). The area of charcoal was calculated using image analysis software (Scion Image Beta 4.02 for Windows).

Pollen samples were prepared using standard palynological techniques (Faegri and Iverson, 1975). Volumetric samples were taken every 10 cm along the core and at every 5 cm between 600 and 635 cm, and exotic pollen (*Alnus*) was added as a spike. The samples were deflocculated with hot 10% NaOH and then sieved through a 150 μm mesh. Silicates were removed using heavy liquid (i.e. $ZnBr_{2(aq.)}$) separation and organic matter with acetolysis. Samples were mounted in silicon oil and the palynomorphs were counted at 400 × magnification until 200 grains were identified. The pollen counts were expressed as percentages, with all grains contributing to the pollen sum. If the pollen count was very low (<50 grains) they were omitted from the pollen diagram. The pollen data was stratigraphically grouped into different zones using the CONISS cluster analysis feature of Tilia Graph (Grimm, 1992). Significant changes in other analysed parameters were also considered when formulating the zones.

The interpretation of the pollen diagram relies on the identification, representation and source habitat for each palynomorph, as described in Table 1.

Loss-on-ignition (LOI) analysis was used to calculate the proportion of organic material contained in sediments (Bengtsson and Enell, 1986). Sediment samples of a known volume were taken at 5 cm intervals through the sequence and their mass determined. After drying at 105 °C for 24 h, the samples were combusted at 550 °C for 4 h to estimate organic content. LOI was expressed as a percentage (of oven dried mass) that represents the proportion of organic (or combustible) matter in the sample.

4. Results

4.1. Core stratigraphy and chronology

The lowermost section of the sediment core recovered from Lake Baraba, from 410 to 635 cm, consisted of dark grey organic clays abruptly alternating with light yellow/orange clays with each section approximately 50 cm in depth. From 410 to 80 cm the core consisted of dark organic peat, however, a slightly sandier peat was found between 130 and 95 cm. The upper 80 cm of the core was generally dark in colour, and was a sandy peat.

Table 1
The pollen and spores quantified in the Lake Baraba sediment, and their indicative value

Pollen or spore	*Indicative value*
Myrtaceae[a]	• Predominantly shrubs and trees of natural vegetation communities but includes species used for wind-breaks. • Myrtaceae pollen thought to be well or over-represented. • Includes *Eucalyptus, Corymbia* and some *Melaleuca* of which some species are indicative of wet swampy conditions.
Casuarinaceae	• Indicates natural vegetation both shrubs and trees in a wide range of habitats. • Casuarinaceae pollen generally very over-represented (e.g. in coastal heaths if Casuarinaceae pollen represented >20% of the total count it can be assumed that it was growing locally whereas counts of <10% suggest that it was locally rare or perhaps coming from a regional source). • Includes *Casuarina* spp. and *Allocasuarina* spp.
Banksia	• Common as an understorey in pre-disturbed woodland communities and also in heath formations and probably indicative of drier vegetation communities although it includes some swamp growing representatives. • Extra-local source and under-represented.
Acacia	• Generally indicative of drier native woodland communities but some members indicative of moist forests (e.g. *A. melanoxylon*). Thick stands of young *Acacia* may be indicative of recent disturbance, including fire. • Very poor dispersal characteristics and under-represented.
Chenopodiaceae	• A generally high salt tolerance means that the family is probably indicative of salt marshes around edge of the lake. • It is a well to over-represented pollen type.
Poaceae	• Often indicative of open and drier vegetation communities. Introduced pasture also represented by the family. • Regional pollen source that is well-to-over represented. • Includes many species of grasses.
Asteraceae	• Herb and shrub species of more open vegetation communities. • The family is a component of regional pollen rain and is over- represented in pollen diagrams.
Pinus	• Mostly *P. radiata* (Monterey Pine), an introduced tree indicating post-European sediments. • A well to over-represented pollen type.
Cyperaceae	• Sedges indicative of wet and swampy areas. • Considered to be well to over-represented in pollen diagrams.
Restionaceae	• Herbaceous species of a variety of habitats, however generally swamp taxa. • Restionaceae are often under-represented in pollen diagrams.'
Pteridium spp.	• Wide range of habitats, usually well-drained. Also commonly associated with disturbance, either part of post-fire or old-field successionary sequence. • Well-to-over represented (Dodson, 1983).
Other trilete spores and other ferns	• Generally understorey species indicative of wetter patches in the landscape. • These spores are usually well-represented (Ladd, 1979).
Haloragaceae	• Either a herb of wetter areas (e.g. *Haloragis* spp.) or freshwater aquatic environment (*Myriophyllum* spp.) that is well-represented in pollen diagrams.

Sources: Dispersal and Representation: Dodson (1983), Ladd (1979). Indicator value: Kodela and Dodson (1988).
[a] Myrtaceae pollen was not identified to the component genera since separation is not reliable.

LOI values were found to be very low, averaging ~8%, between 425 and 635 cm. The values increase quite abruptly between 390 and 425 cm after which they remain very high (~90%), with the exception of a drop at 360 cm. LOI values decrease to an average of ~67% between 95 and 130 cm and between 0 and 95 cm they become variable with values ranging between 17% and 100%.

The results of the ^{14}C dating of the deposit suggest that the base of the analysed profile is greater than 43,000 yr BP (Table 2). Pollen analysis revealed the first appearance of the exotic taxon *Pinus*, representing European occupation, at 10 cm.

4.2. Pollen

Fig. 2 shows the pollen counts and the zones identified. Zones 2, 4 and 6 were largely defined on the basis of low

Table 2
Radiocarbon ages and calibration for Lake Baraba sediments

Sample depth (cm)	Dating material and technique	^{14}C date BP with 1σ error	Cal. years BP with 2σ error	Lab code
147–153	Bulk sample organic sediment; standard ^{14}C	4 130±70	4 421–4 821	β-186144
275–285	Bulk sample organic sediment; standard ^{14}C	5 950±60	6 549–6 887	β-192607
347–353	Bulk sample organic sediment; standard ^{14}C	6 750±80	7 433–7 675	β-186145
464–472	Bulk sample organic sediment with high clay content; AMS ^{14}C	19 411±196	22 541–23 716	NZA-21524 (Wk-15818)
595–601	Sieved charcoal; AMS ^{14}C	>43 630	N/A	β-192608

Calibration results from CALIB v5 (Stuiver et al., 2005). The mid-points of calibrated year ranges are used in age–depth model calculations.

pollen concentrations, and serve to separate them from the adjoining relatively pollen-rich zones.

Zone 1 (634 cm): the one sample in this zone is dominated (~80% of the total count) by an unknown palynomorph that may possibly be an algal spore. Casuarinaceae pollen makes up ~10% of this zone with the remainder of the count composed of Halagoraceae, Myrtaceae, Poaceae, Podocarpaceae and Proteaceae. If the unknown palynomorph is disregarded, the composition of the pollen spectrum is similar to the zones above it. Total pollen concentrations are low in this zone.

Zone 2 (610–630 cm): of the seven samples examined in this zone two were void of pollen (620 and 630 cm). There were trace levels of Casuarinaceae, monolete spores, Podocarpaceae, Poaceae, Myrtaceae, Asteraceae, Chenopodiaceae, Cyperaceae and *Dodonaea*. Total pollen concentrations were very low in this zone and have been omitted from the pollen diagram.

Zone 3 (560–610 cm): this zone was dominated by Casuarinaceae (~60%) with Myrtaceae and Halagoraceae each representing ~10% of pollen counted. Poaceae, Asteraceae, *Acacia* spp. and *Dodonaea* spp. were represented although in small concentrations. The representation of monolete and trilete spores varied considerably in this section (~4% to ~25%). Several grains of Proteaceae, Podocarpaceae, Fabaceae, Euphorbiaceae, Cyperaceae and Chenopodiaceae were also seen. Total pollen concentrations were low in this zone.

Zone 4 (520–560 cm): pollen was very sparse and has been omitted from the pollen diagram. Casuarinaceae was most common, followed by monolete/trilete spores, Halagoraceae and Podocarpaceae.

Zone 5 (490–520 cm): the pollen spectrum in this zone is very similar to Zone 3, with Casuarinaceae dominating, although *Dodonaea* was absent. Total pollen concentrations were slightly elevated in this section.

Zone 6 (460–490 cm): pollen was very sparse in this zone, however, Casuarinaceae (57%), trilete/monolete spores (10%), Poaceae (9%), Halagoraceae (8%), Myrtaceae (6%), Asteraceae (3%), Podocarpaceae (3%) and Chenopodiaceae (2%) were identified.

Zone 7 (410–460 cm): this zone is characterised by a high proportion of Casuarinaceae (~60%). Halagoraceae representation was high near the base, but decreased (from ~30% to 1%) through the zone. Myrtaceae (7.5%) and Poaceae (5%) are the only two other palynomorphs that are reasonably well represented. Total pollen concentrations are relatively high.

Zone 8 (230–410 cm): this zone is characterised by a substantial decrease in Casuarinaceae and an increase in Myrtaceae pollen. Poaceae concentrations are slightly elevated during this zone (~10%) and Cyperaceae, trilete spores and Restionaceae steadily increase through this zone. *Dodonaea* spp., Fabaceae and Halagoraceae also persist throughout this zone although in low concentrations. Chenopodiaceae increased through the zone and decreased towards the top. Total pollen concentrations are decreasing in this zone.

Zone 9 (170–230 cm): there were very high concentrations of fungal spores throughout this zone and pollen was very sparse and actually absent in samples where fungal concentrations were especially high. The samples that did contain palynomorphs were dominated by Cyperaceae (24%), Myrtaceae (20%), Casuarinaceae (19%), Poaceae (18%) and trilete spores (5%).

Zone 10 (10–170 cm): Casuarinaceae and Myrtaceae each represented ~30% of the total pollen counted in this zone. Poaceae decreased from a high of ~50% and Halagoraceae increased abruptly to an average of ~30% in the upper part of this zone. Cyperaceae representation was generally low with the exception of two peaks at 60 and 80 cm. Trilete and monolete spores persisted throughout this zone. Total pollen concentrations were slightly elevated in the lower part of this zone and became very high in the upper part.

Zone 11 (0–10 cm): *Acacia* spp., which is poorly dispersed (Dodson, 1983), represented ~5% of the total pollen sum. There were moderate concentrations of Myrtaceae, Casuarinaceae and Poaceae. Monolete spores peak at 10 cm representing ~35% of the pollen sum. Total pollen concentrations were relatively low when compared to the upper part of the previous zone.

4.3. Macroscopic charcoal

Most of the analysed sediment profile from Lake Baraba has low levels of charcoal (Fig. 3), with peaks at 240, 270 and 400 cm, a series of higher peaks at 230–200 cm and

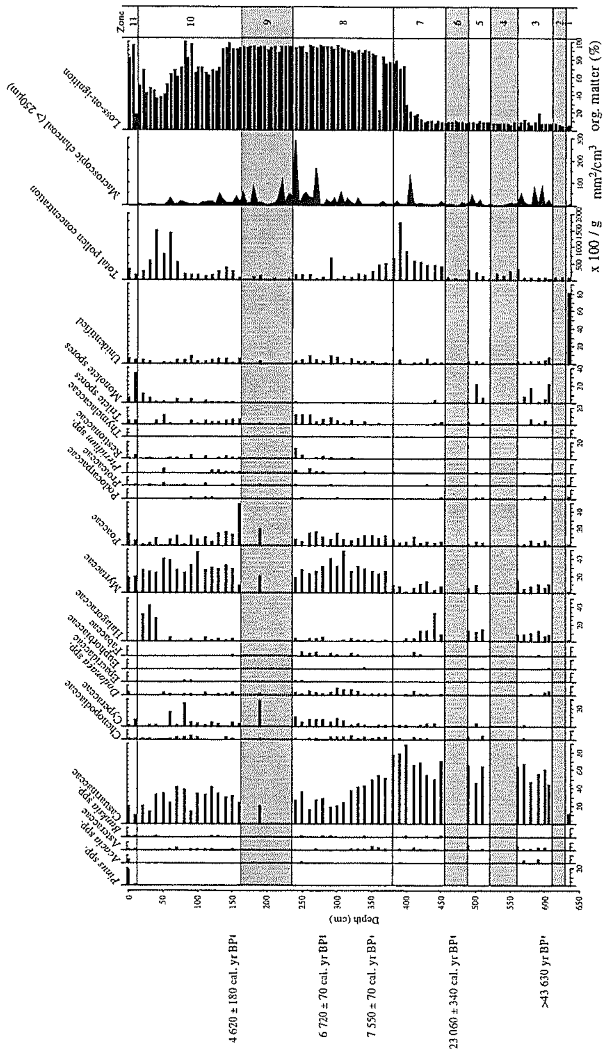

Fig. 2. Pollen, charcoal, organic matter and pollen zonation for Lake Baraba. All pollen are represented as a percentage of the total count.

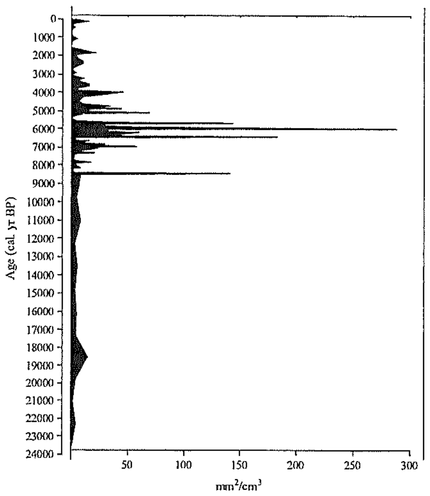

Fig. 3. Macroscopic charcoal curve versus age for the radiocarbon dated section of the Lake Baraba sequence.

minor peaks at 170–130 cm. Macroscopic charcoal concentrations were extremely low between 470 and 455 cm and are very low until 405 cm. Charcoal is relatively low but variable between 405 and 275 cm and then increases abruptly and remains very high and variable until 200 cm. Between 185 and 55 cm there is a decreasing trend in charcoal concentrations, from being relatively high to moderately low, but it remains variable throughout this interval. The upper samples (50–0 cm) have very low charcoal concentrations with some samples almost void of charcoal. There is much less charcoal found in the clays when compared to the peat sediment.

5. Discussion

5.1. Sedimentary history

Fig. 4 presents a summary of the sedimentary history at the location of the sampled sediment core on Lake Baraba and gives the age–depth relationship.

Sediments deeper than 595–601 cm are >43 630 ^{14}C years in age. The site was initially a lake slowly accumulating clays (~0.04 mm/year). Extrapolation of the rate of sedimentation suggests that the base of the analysed profile could be 55 kyr or older and hence it is speculated that the record may extend well into Marine Isotope Stage (MIS) 3 (~59–24 ka). MIS 3 is an interstadial that corresponds with cool and moist conditions in southeastern Australia suggested by high lake levels (e.g. Bowler, 1981, 1986; Wasson and Clark, 1988). During the latter part of the period conditions became increasingly drier and colder (Allan and Lindsay, 1998) culminating with the LGM.

The yellow/red/orange bands and mottling (605–635, 510–555 and 410–262 cm) indicate oxidising conditions and are likely to reflect periodic drying of the lake. Uniform dark organic and grey clays (the colour representing iron in the ferrous state), however, indicate anaerobic conditions and were deposited when the lake was more permanent. Pollen is best preserved during permanently wet conditions and hence more pollen was recovered from the dark clays and very little from the yellow clays up to the LGM (Fig. 4). Thus drier conditions alternated with wetter periods in the period leading up to the LGM leading to pollen-poor and relatively pollen-rich zones. This means that the vegetation record is not continuous, and given the resolution of the dating, the pre-Holocene sediment record of the site may also include gaps.

It is difficult to assess just how 'dry' or permanent the lake may have been prior to the LGM. During historic times the lakes within Thirlmere Lakes National Park have been noted to recede significantly during times of drought, e.g. 1902, 1928 (NPWS, 1995), so it appears that they are hydrologically sensitive. Thus, the sedimentary record of Lake Baraba, at a minimum, may indicate no more than the variation in moisture balance seen in historical times.

Reviews of lake levels in southeastern Australia (e.g. Harrison, 1993; Allan and Lindsay, 1998) indicate wetter conditions prevailed between 30 and 24 ka, and drier conditions from 24 ka, through the LGM until 12 kyr (Harrison, 1993). Again, it is uncertain as to how 'wet' or how 'dry' these phases were. Reconstructed lake levels in the interior of southeastern Australia have also revealed mixed results, with some lakes being low and others either high or intermediate (Harrison and Dodson, 1993).

In the early Holocene (~8.5 ka), peat started accumulating at Lake Baraba and the rate of sedimentation increased markedly (~0.67 mm/year). This indicates that at the site of the sampled core the lake had become shallow enough to facilitate swamp vegetation and peat formation. Peat accumulation has continued until the present although there was a hiatus, perhaps in response to a dry period, between ~6 and 5.2 ka, indicated by high levels of fungal spores. Harrison (1993) described a dry phase between 6 and 5 kyr and Pickett et al. (2004) reported increased moisture stress in the vegetation of the mid-Holocene. Chalson (1991) also identified the period ~6.5–5.5 kyr as a time of oscillations between wet and dry conditions which is roughly coincidental with the Lake Baraba record. Allan and Lindsay's (1998) synopsis of south-eastern Australian lake levels shows a marked drop between 5 and 4 kyr which is asynchronous with the Lake Baraba record.

5.2. The vegetation history

The pollen profile suggests relatively stable vegetation with only one marked change, viz the decrease in Casuarinaceae and increase in Myrtaceae from the early Holocene. However, given the broad classification of the palynomorphs there may well have been undetected changes of species within the pollen groups.

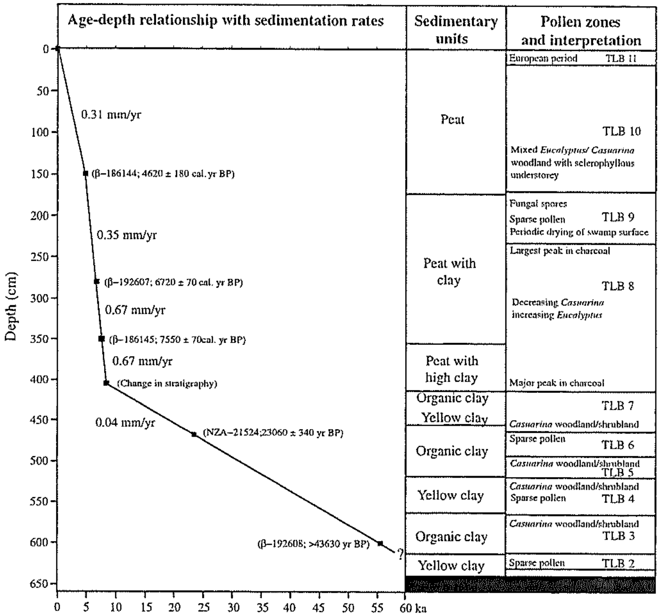

Fig. 4. A comparison between the rates of sedimentation, sediment type and the pollen zones.

The terrestrial vegetation of zones 2–7, from >43 kyr to the early Holocene, was dominated by Casuarinaceae woodland/shrubland, at the time that the yellow/brown and dark grey clay bands were deposited. Halagoraceae is present in moderate frequencies in the dark clay bands, which could indicate the aquatic *Myriophyllum* in the lake. There is little evidence of any swamp vegetation (e.g. Cyperaceae and Restionaceae), suggesting that if it existed it must have been confined to a small zone around the lake. At this level of pollen identification, it appears that the composition of the terrestrial vegetation was much the same from >43 kyr through the LGM, until the beginning of the Holocene. If shrubby forms of Casuarinaceae replaced trees under the harsher climate of the LGM the palynology could not detect this.

When the palynology of the LGM at Lake Baraba is compared with other records from southeastern Australia the results are at odds with the general perception of treeless vegetation communities. Notably, however, Dodson (1975) also described a relatively high proportion of arboreal (*Eucalytus* and Casuarinaceae) pollen in the period encompassing ~35 to ~10 kyr at Lake Leake in southeastern South Australia. The comparatively low representation of Asteraceae and chenopods during the LGM at Lake Baraba suggests that the site was not covered by steppe grassland and further distinguishes this vegetation from the Lake Leake record and elsewhere in southeastern Australia (Table 3). The prominence of Casuarinaceae and the relatively minor representation of Poaceae at Lake Baraba during the late glacial period are also unusual. This may reflect the geological environment, as Lake Baraba is located on a relatively infertile substrate. At Lake Baraba sclerophyllous vegetation dominated by Casuarinaceae appears to have continued to occupy the site throughout the late glacial suggesting that the site acted as a possible refugium. Halagoraceae, dominated by *Myriophyllum* spp., also indicates shallow and fluctuating water levels during this time.

The climatic events that may have been experienced in Australia during deglaciation, such as the Antarctic Cold Reversal (~12.9–14.5 ka) (Blunier et al., 1997), are not evident in the Lake Baraba palaeoecological record. This is not to say that they were not experienced at the site but, more likely, the resolution of the record at this time was

Table 3
A comparison between the average percentages for the south-eastern mainland pollen data set for major taxa at selected time-slots from Kershaw (1995, p. 661) with the pollen record from Lake Baraba

Time slots	*Casuarina*		*Eucalyptus*		Poaceae		Asteraceae		Chenopodiaceae		*Myriophyllum*		Restionaceae	
Pre-European	14	**20**[a]	42	**28**[b]	19	**1**	12	**0**	9	**2**	6	**32**	7	**0**
6 kyr	20	**26**[a]	37	**18**[b]	21	**7**	9	**1**	5	**1**	6	**3**	6	**12**
9 kyr	16	**65**[a]	28	**6**[b]	34	**10**	13	**4**	7	**2**	12	**4**	5	**0**
12 kyr	4	**54**[a]	17	**14**[b]	45	**5**	23	**1**	15	**1**	3	**13**	3	**0**
LGM	3	**57**[a]	7	**6**[b]	44	**9**	35	**3**	11	**2**	21	**8**	1	**0**

Kershaw (1995) used 71 pollen diagrams with only 12 of which covered all time periods.
Lake Baraba results are bolded.
[a] Casuarinaceae.
[b] Includes all Myrtaceae species.

too coarse to register any changes. Furthermore, if the site acted as some sort of refugium during the LGM it is unlikely that smaller changes such as the ACR would register in the record. Clark (1983) has previously suggested an inability of palynology to detect subtle changes in fire-adapted vegetation.

In southeastern Australia the Holocene generally depicts recovery of the vegetation and climate to its present-day status. Patterns resembling the modern vegetation began to be established from the late Pleistocene/early Holocene, when the climate approached that of today (Harrison and Dodson, 1993; Dodson, 1994; Kershaw, 1998). Dodson (1994) suggested that lowland vegetation was largely insensitive to environmental change during the Holocene, and our results concur with this overview. At Lake Baraba, vegetation similar to today began to establish from about 8.5 ka.

From ~8.5 ka, when peat accumulation started, Casuarinaceae declined and Myrtaceae increased. This change could indicate that *Eucalyptus*, the dominant genus of the vegetation today, increased at the expense of Casuarinaceae. In southeastern Australia, typical lowland forests of the early Holocene forests were dominated by Casuarinaceae (Lloyd and Kershaw, 1997) and a decline in Casuarinaceae and increase in *Eucalyptus* (or Myrtaceae) pollen is a feature of many Holocene pollen records (Dodson, 1974; Clark, 1983; D'Costa et al., 1989; Ladd et al., 1992; Devoy et al., 1994; Harle, 1998; Gale and Pisanu, 2001). The decline in Casuarinaceae has been dated as early as 7.5 kyr (D'Costa et al., 1989; Aitken and Kershaw, 1993) and as late as 4.5 kyr (Hooley et al., 1980). At Lake Baraba Myrtaceae, most likely eucalypts or paperbarks, expanded at the expense of Casuarinaceae from ~8.5 ka.

The reasons for this rise in *Eucalyptus* at the expense of Casuarinaceae throughout the Holocene have been debated (Dodson, 1974; Hooley et al., 1980; Clark, 1983; D'Costa et al., 1989) with competitive exclusion, increased moisture and altered fire regimes most commonly suggested (Lloyd and Kershaw, 1997). Crowley (1994) and Cupper et al. (2000) have suggested that the Holocene decline in Casuarinaceae was linked to soil salinity but this is an unlikely reason for the decline in Casuarinaceae at Lake Baraba considering the freshwater setting.

The fire sensitivity of the Casuarinaceae family has been controversial (e.g. see Clark, 1983), however, the Casuarinaceae palynomorph includes species that are fire tolerant and those that rely of fire for regeneration (Ladd, 1988). Fire activity at Lake Baraba gradually increased from ~7.5 kyr and abruptly increased at ~6.7 kyr where it remained high until ~5.5 kyr. The decline in Casuarinaceae and associated rise in Myrtaceae precedes this increase in fire activity by ~1000 years. This suggests that fire activity was a *response* to the establishment of the more fire-prone Myrtaceae and swamp vegetation, rather than the *cause* of this change in vegetation.

Ladd (1988) has suggested that the morphology of *Casuarina* species means that they are poor competitors with broad-leaved species. At Lake Baraba we suggest that the pre-swamp environmental conditions were more suitable for Casuarinaceae but this declined as a swamp formed in the early Holocene. The relationship between the Casuarinaceae/Myrtaceae ratio and the evolution of the lake to a swamp (indicated by the organic content) is depicted in Fig. 5. The lake environment corresponds with a low Myrtaceae/Casuarinaceae ratio between ~20 and 8.5 ka. Swamp conditions are indicated by a high Myrtaceae/Casuarinaceae ratio from ~8.5 kyr to present.

Chalson (1991) undertook palynological analysis on seven swamps in the Blue Mountains, New South Wales to find a trend to wetter conditions from 11 to 8 kyr with maximum moisture from 8 to 6.5 ka. A similar pattern is detected at Lake Baraba with Restionaceae and trilete spores, likely to be wet indicators, increasing from ~8.6 kyr to a maximum representation at ~6 ka.

The fungal spores of Zone 9 (6–5.2 ka) suggest the swamp surface periodically dried out (Pals et al., 1980; Elsik, 1996) but these dry periods were not severe enough to disrupt peat production. This zone follows the two peaks of major fire activity, which continued at lower levels through the zone. It is likely that dry spells allowed increased fire activity. During this time there was a decreased tree cover and Cyperaceae and Poaceae pollen are elevated which may reflect this postulated drier climate.

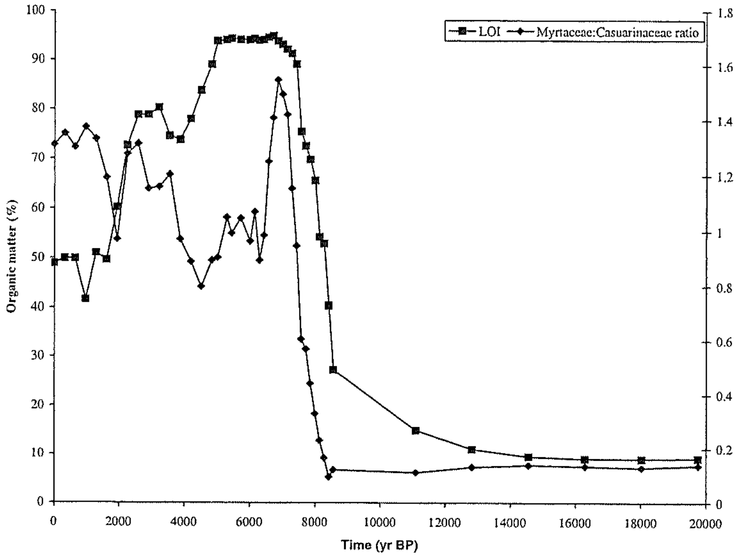

Fig. 5. A comparison between the Myrtaceae/Casuarinceae ratio and the organic content of the sediment from loss-on-ignition.

Very high concentrations of charcoal in the latter part of Zone 8 (~6 ka) suggest high fire activity, and this may have also influenced the tree cover during Zone 9 (6–5.1 ka).

By 6 kyr and especially after ~5 kyr, the vegetation composition is similar to the *Eucalyptus*/*Casuarina* woodland that grows on the site presently. The 6 kyr biome reconstruction by Pickett et al. (2004) also implies that the broad-scale pattern of Australian vegetation at this time was largely similar to the contemporary environment. The surface samples that include the European period have decreased concentrations of tree pollen (i.e. Casuarinaceae and Myrtaceae) perhaps caused by land clearing and logging postdating European colonisation.

5.3. Fire history

At Lake Baraba charcoal was found in all parts of the analysed profile but varied markedly, implying that fire has been a persistent but variable component of the environment. Kershaw et al. (2002) compiled a number of charcoal records throughout the Australasian region that cover the LGM. When the Lake Baraba record is compared with these records it has comparatively little charcoal during the LGM (Table 4). Reconciling the general treeless description of the vegetation at the LGM in south-eastern Australia with a high charcoal abundance is a task that is yet to be completed. It should be noted, however, that many of these previous records analysed smaller charcoal fractions, perhaps reflecting larger source areas (Clark, 1988), and this may partially explain this observation. Fire was a more significant feature of the Holocene at the site, however, the aforementioned changes to the sedimentary environment should be considered. The initiation of the swamp in the early Holocene means that fire may have impacted on the site itself occasionally, thereby increasing charcoal delivery.

Anthropogenic fire must also be considered since fire is often attributed to the presence of Aboriginal people. Attenbrow (2004) recently analysed archaeological data from 58 sites in Sydney and the NSW South Coast, including the hinterland, to determine the rate of Aboriginal habitation establishment and the number of habitations used in each millennium. Fig. 6 shows that charcoal at Lake Baraba and the number of habitations used in the region both gradually increase from the LGM to the early Holocene. From ~7 to 8 kyr this relationship breaks down, with the number of habitations increasing more rapidly whilst charcoal content declines steadily. As site usage is only a coarse measure of past population levels, at best (Attenbrow, 2004), the influence of humans on fire in this environment warrants further investigation.

Wang et al. (1999) have suggested the possibility that the expansion of *Eucalyptus* in the mid-Holocene "marks the development of fire as a management strategy" by

Table 4
The key Australasian sites that have a record of charcoal throughout the Last Glacial Maximum

Site	Abundance of charcoal[a]	Charcoal measure	Reference
Lombok Ridge, eastern Indian Ocean	Very high	Particles/cm^3	Wang et al. (1999)
Banda Sea, west of New Guinea	Very high	Particles/cm^2/year + mg/cm^2/year	van der Kaars et al. (2000)
ODP site 820 offshore, NE Queensland (QLD)	Very low	Particles/cm^3	Moss (1999), Moss and Kershaw (1999)
Lynch's Crater, NE QLD	High	Particles/cm^3	Kershaw (1986)
Lake George, New South Wales (NSW) southern highlands	Very low	Surface area%/unit volume of sediment	Singh et al. (1981), Singh and Geissler (1985)
Lake Wangoon, western Victoria	Very high	Particles/cm^3	Edney et al. (1990), Harle (1998)
Egg Lagoon, NW Tasmania (TAS)	Very high	mm^2/cm^3	D'Costa (1997)
Lake Selina, western TAS	Very high	Not given	Colhoun et al. (1999)
Darwin Crater, western TAS	Very high	Not given	Colhoun and van de Geer (1988)
Lake Euramoo, NE QLD	Low	Particles/gm/year	Haberle (2005)
Lake Baraba, Sydney Basin, NSW	Very low	Area (mm^2/cm^3)	

The scale for abundance of charcoal was based on the ranking of charcoal in the time periods formulated by Kershaw et al. (2002, p. 6).

[a] Relative abundance of charcoal when compared to the rest of the sequence.

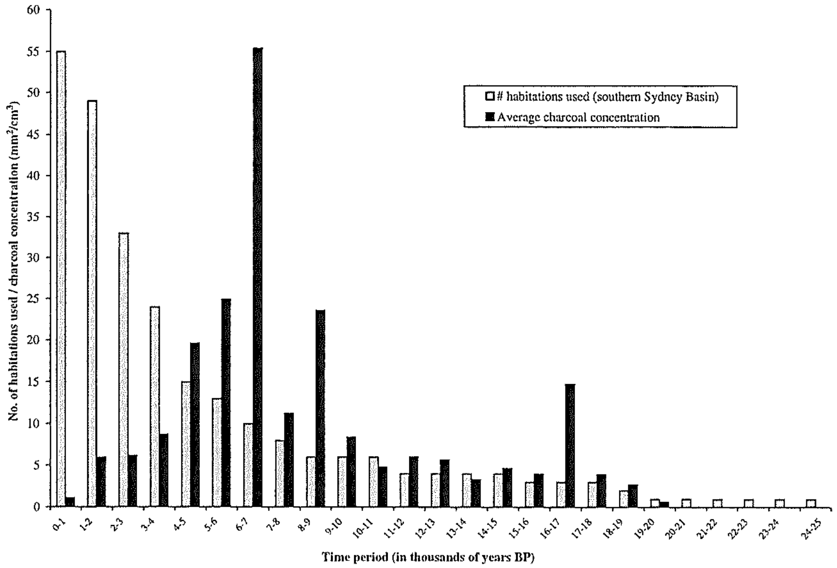

Fig. 6. A comparison between the average charcoal values for Lake Baraba and the number of habitation sites used in the region for millennial time scales. Source of archaeological data: Attenbow (2004; Table A4/1).

Aboriginal people associated with intensification. As the increase in Myrtaceae at Lake Baraba began from ~8.5 ka, Wang et al.'s (1999) suggestion that the "genetically plastic" eucalypts became adapted to Aboriginal fires regimes in the mid-Holocene is not supported by the Lake Baraba data.

As an alternative explanation, the gradual increase in charcoal at Lake Baraba from the LGM may reflect the likely increase in biomass accompanying climatic amelioration. It is entirely plausible that other changes in fire during the Holocene may also be unrelated to human activity. Peaks in charcoal appear to be related to times of vegetation or environmental change and fires are possibly more frequent or intense at times of climatic instability (Edney et al., 1990; Haberle et al., 2001; Kershaw et al., 2002; Black and Mooney, 2006). As an example, at Lake Baraba the increase in fire activity from 6.7 kyr may reflect the onset of modern ENSO activity, and the decrease in fire from about 5.5 kyr the cessation of the response to this continuing variability. Notably, Kershaw et al. (2002) suggested that 7–5 kyr was a period of less fire in south-eastern Australia.

6. Conclusion

The analyses of the Lake Baraba sequence resulted in a vegetation, fire and sedimentary history dating to >43 kyr and included the LGM and subsequent climatic amelioration. There were abrupt sedimentary changes between black organic clays and yellow/orange clays prior to the LGM and this is likely to be due to lake level fluctuations. Prior to the early Holocene the site was a lake depositing clay. Peat formation began from ~8.5 kyr indicative of the change from a lake to a swamp due to the infilling of the site.

The vegetation remained the same from >43 kyr to the early Holocene, most probably a *Casuarina* woodland/shrubland with a mixed understorey. The sclerophyllous vegetation adapted to the relatively infertile substrate of the site appears to be relatively resilient to changes in climate, or the site was a refugium. Myrtaceae expanded at the expense of Casuarinaceae from the early Holocene. This shift in vegetation preceded any increase in fire and hence it is unlikely that this was the cause.

Fire activity was low during the Pleistocene and especially low during the LGM. Fire activity increased during the Holocene although the record does not concur with the broad pattern of Holocene fire activity described by Kershaw et al. (2002). There was no apparent relationship between Aboriginal site usage and fire activity and hence how Aboriginal people influenced fire activity at Lake Baraba remains speculative. Local biotic and abiotic factors (e.g. the change in the depositional environment from a lake to a swamp) may have been important controls of fire activity and charcoal deposition at the site.

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The Lapstone Structural Complex, New South Wales

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The Lapstone Structural Complex forms the most prominent topographic feature in the Sydney region. The complex consists of a number of related folds and faults, trending generally north–south, which together form a large south-plunging structure between Kurrajong Heights and Lapstone. The east-facing escarpment of the Blue Mountains, formerly called the Lapstone Monocline, varies in its character, being sometimes a single monocline, sometimes a double monocline and sometimes a normal or high-angle reverse fault. Faulting west of Kurrajong and at Glenbrook is part of a series of overlapping *en echelon* faults, west-side down, and sometimes overturned, rather than a single fault. This fault system forms the west side of the complex. Significant minor structures associated with major features include thrusts, minor folds, joint systems, tectonic breccias, sedimentary injections and igneous dykes. Many of the minor structures show a marked parallelism with the major structures.

The main period of deformation forming the complex is believed to have taken place in the Early Tertiary, but the overall structure has a long and complex history. Field evidence suggests that sinistral strike–slip faulting played a part in the deformation, particularly of the near-surface rocks. Basement block faulting was also significant, producing the Cumberland Basin and associated structures when the main Lapstone structures were formed. Basement structural control is believed to consist of the northerly extension of the western edge of the Eden–Comerong–Yalwal Rift intersected by elements of the east-trending Lachlan Lineament.

Key words: basement lineaments, block-faulting, minor structures, monocline, normal and high-angle reverse faults, structural complex, strike–slip.

INTRODUCTION

The Lapstone Structural Complex, 60 km west of Sydney, consists of a number of structures (generally elongated north–south) between Warragamba in the south and the Colo River, a distance of some 50 km (Figs 1, 2). One of these structures forms the Lapstone–Kurrajong escarpment, the most prominent topographic feature in the Sydney region. The escarpment marks the abrupt eastern edge of the Blue Mountains Plateau where it abuts against the Cumberland Plain (Fig. 3). Work by Branagan (1969, 1975) and Herbert (*in* Smith 1979), demonstrated that the Kurrajong and Glenbrook Faults were separate members of a series of *en echelon* faults, west-side down, situated west of the main escarpment, and generally parallel with it (Fig. 4).

Intimately associated with the major structures is a variety of small-scale structures. These have received little attention previously, but their study has proved important in elucidating the deformational history of the region.

Branagan and Pedram (1982) presented a preliminary account of the findings reported in this paper, and detailed discussion of some aspects was given by Pedram (1983). Some conceptual ideas on the faulting were presented by Branagan (1983).

STRATIGRAPHY

The Lapstone Structural Complex consists mainly of sedimentary rocks of Triassic age, relicts of Tertiary gravel, and minor occurrences of igneous rocks (mainly dykes and necks) and Quaternary sediments.

Triassic rocks

The Hawkesbury Sandstone, the major unit exposed along the complex, is characteristically cross-bedded. It is overlain in places by up to 6 m of Mittagong Formation, consisting largely of laminated siltstone. This unit is overlain occasionally by Ashfield Shale. When the Mittagong Formation is absent, the Ashfield Shale rests disconformably on the Hawkesbury Sandstone.

Post-Triassic Sediments

Post-Triassic sediments are limited in extent, patches of gravel disconformably overlying the

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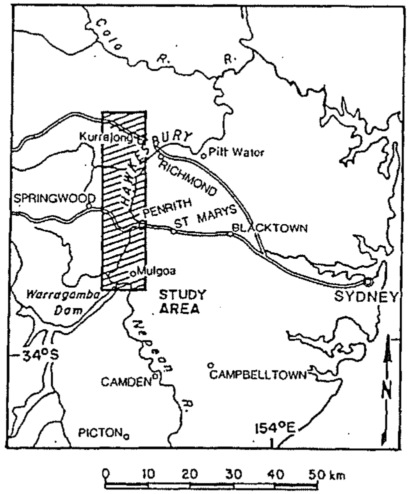

Fig. 1 Locality map.

Triassic rocks (Fig. 4). Despite their sporadic distribution, these deposits give important clues to the history of tectonism.

Generally the gravels can be divided into four groups based on their topographic occurrences: (1) on the Blue Mountains Plateau; (2) on the limb of the South Lapstone Monocline (see below); (3) on the high-level surface of the Cumberland Plain; and (4) in the present Nepean–Hawkesbury River drainage system. Gobert (1976) named the third of these the Rickaby's Creek Formation, and the fourth the Cranebrook Formation. Gobert (1978) included the first two with the Rickaby's Creek Formation as did Pedram (1983) and Bishop (1986), but they may be older. The first three groups of gravels have a varying degree of cementation and those on the plateau and monocline are lateritized.

All four groups contain pebbles derived essentially from the same locations — the drainage basins of the Cox and Wollondilly Rivers to the southwest — and the main source may be the thick Permian fluvioglacial gravels in that region. Bishop

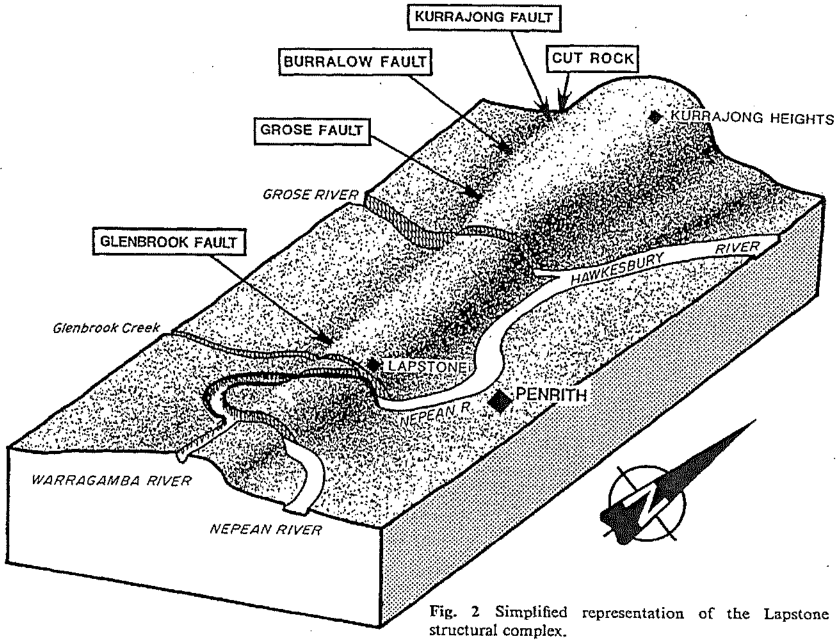

Fig. 2 Simplified representation of the Lapstone structural complex.

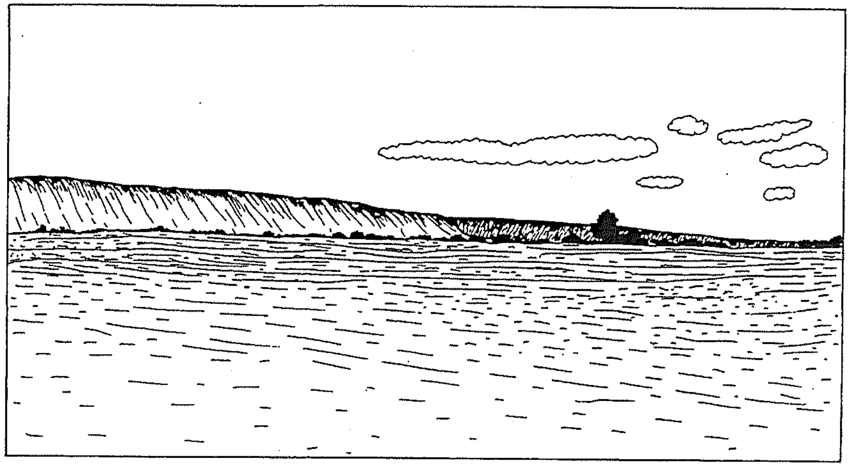

Fig. 3 Lapstone structure. View towards the north from Cranebrook showing Mount Riverview Fault and 'step back' west at Grose River.

(1986), after studying imbricated structures within the Lapstone gravels, thought there had been no significant change in the direction of flow of the Nepean River system transporting the gravels during its long history.

Although the age of the gravels on the monocline is not well defined, all the authors who have studied them, for example Branagan and Packham (1967), Taylor (1970), Gobert (1978), Bishop *et al* (1982) and Bishop (1986), suggest a Tertiary age of Miocene or possibly older. Gravels of the present Nepean–Hawkesbury river system at Cranebrook north of Penrith (GR 862270) have been dated at 45 000 years BP (Nanson *et al* 1987).

Igneous rocks

Igneous rocks in the area are confined to a few volcanic dykes and necks. They are mainly basaltic and are now largely altered to clay. A west-trending dyke is exposed at Bellbird Hill, Kurrajong-Heights (GR 803862), and one trending 350° is present at Glenbrook (GR 812608). In the Grose Valley there are three vertical and almost parallel dykes trending north–northwest. These dykes follow the trend of the nearby Grose Fault.

Basaltic breccia necks exist at Diamond Hill near Kurrajong (GR 833874), at Norton's (GR 798508) and Bent's (GR 810427) Basins adjacent to the main eastern monocline–fault structure. The Green Scrub Basalt north of the area (GR 798942) appears to be cut by the Kurrajong Fault and rests on the Ashfield Shale. Wellman and McDougall (1974) determined the age of this basalt as 18.8 Ma.

MAJOR STRUCTURES

The Lapstone–Kurrajong escarpment can be divided from south to north into four structural zones: the Nepean Fault, South Lapstone Monocline, Mount Riverview Fault, and North Lapstone Monocline (Fig. 4).

The Nepean Fault

This feature is the dominant structure south of Mulgoa. The fault is well-exposed at Bent's Basin where a zone of sandstone overlain by shale, some 80 m wide, dips mainly easterly at 80°, but there is one exposure of overturned beds dipping 85° to the west. The dipping beds abut in the west against almost horizontal sandstone. Although there is topographic expression of the fault scarp for some kilometres to the south, the fault is poorly exposed elsewhere and has been only cursorily examined in this study. Sherwin and Holmes (1986) indicated that it is sometimes a monocline. From field

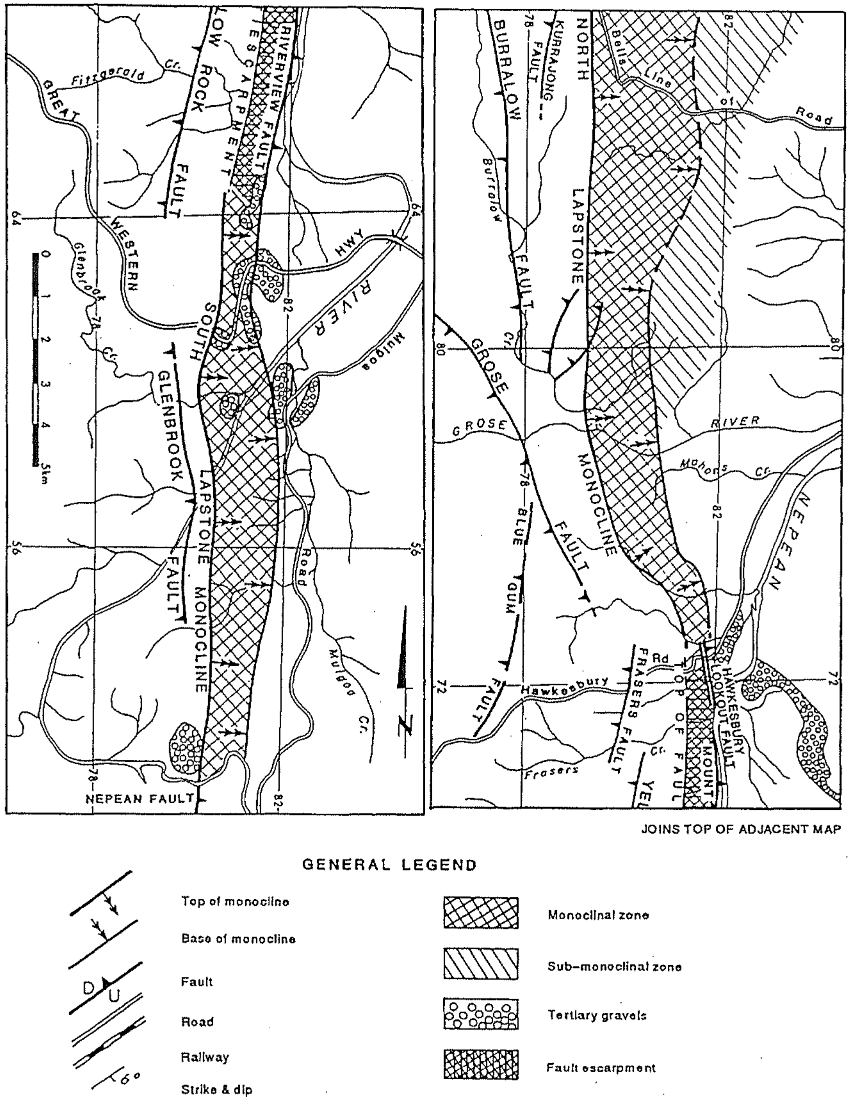

Fig. 4 Map of Lapstone Structural Complex.

evidence the fault appears to dip nearly vertically or steeply east, and the displacement is east-side down.

Interpretation of seismic surveys south of Bent's Basin by Herbert (1989) indicates a complex system of faults. These are mainly in two separate zones: the Nepean Fault system; and, 7 km to the west, the Oakdale Fault system. The Nepean Fault appears to be a high-angle reverse fault dipping steeply west.

South Lapstone Monocline

From Mulgoa north to the Old Bathurst Road the escarpment follows the South Lapstone Monocline, an elongate north–south structure. Its extreme southern point lies east of the Warragamba River where its dip gradually decreases and its topographic position is taken by the Nepean Fault. The general dip of the structure in the area west of Mulgoa and Wallacia is approximately 8° towards the east. In this region the structure is 1–1.7 km wide.

Farther north, the Monocline transects the Nepean River and Glenbrook Creek. Near Glenbrook Creek the structure consists of two parallel and north–south-trending flexures separated by a short section of horizontal beds (Fig. 5). The more westerly of the two flexures is present north of Mount Portal (GR 808596) where the dip is about 10° eastwards. Within a short distance both south and north of Glenbrook Creek these two flexures merge and form one monoclinal structure.

On Mitchell's Pass Road (Fig. 6) two monoclinal flexures are again exposed. The smaller of the two flexures, between Lennox Bridge (GR 808626) and Elizabeth Lookout, has a maximum dip of 14° towards the southeast. The main structural feature lies east of Elizabeth Lookout (GR 813626). The Hawkesbury Sandstone north of the lookout is almost flat-lying, but becomes gently tilted (5°) towards the southeast. Over a horizontal distance of 300 m the dip gradually increases to 42° and the monoclinal structure abruptly becomes strongly shattered. The shattered zone lies along the strike of the Mount Riverview Fault (see below), and is most likely related to it. The shattered zone is present in a deformed sequence of alternating shale and sandstone overlain by lateritized gravel. The dipping beds are broadly curved to form a sub-monocline, and have a maximum dip of 87°. Within a short distance eastwards the curved beds regain their horizontal position.

Thus the character of the South Lapstone Monocline changes (Figs 5, 6), having considerable variation in the flexuring and amount of easterly dip of the monoclinal beds, and also in the width and amplitude of the monoclinal zone.

Mount Riverview Fault

On the Old Bathurst Road (GR 810636) the dip of the monocline decreases substantially (15° to the east), but the slope of the scarp remains high (up to 50°). Slab failure along the foresets in the cross-bedded Hawkesbury Sandstone is generally responsible for the slope of the scarp. North of the Old Bathurst Road as far as the Hawkesbury Lookout (GR 822723) the escarpment is formed by a steep to vertical fault, named by Pedram (1983) the Mount Riverview Fault, which has an east-side down displacement of some 200 m. As for the Nepean Fault, Herbert (1989) suggests this is a high-angle reverse fault, but his very steep structure is placed some distance west of the escarpment and his interpretation may be complicated by bifurcation of the fault. Pedram (1983) postulated such bifurcation south of Hawkesbury Lookout, naming the separate Hawkesbury Lookout Fault. This fault is exposed on the Hawkesbury Lookout Road (GR 821724), sandstones and shales dipping steeply east to overturned (80° to the west) in a zone nearly 100 m wide. The nearly vertical west side of this zone is well-defined but the eastern edge is not exposed (Fig. 7).

North Lapstone Monocline

Immediately north of Hawkesbury Lookout the escarpment swings northwestwards for some 2 km to the Grose River (Figs 3, 4).

The Grose Valley, Burralow Creek valley and Paterson Hill areas (GR 795780) are tectonically more disturbed than other parts of the complex and contain a series of monoclines, warps, faults and anticlinal structures. Whilst all these structures are probably the direct result of tectonism, the Paterson Hill Anticline (GR 795780) could have formed by valley bulging (Bryan *et al* 1966). The amount of dip of the monoclinal structure varies in different localities in the Grose Valley, attaining a maximum dip of 45° towards the north at the junction of the Grose River and Burralow Creek; the average dip of the monocline in this area is 12° towards 070°.

At the Grose River, the escarpment swings north (Figs 3, 4, 8) and continues in this direction to beyond the Colo River. In the Grose Vale–Kurrajong area the monocline is 1.6 km wide. Exposures of Ashfield Shale along the monocline are sporadic, but dips up to 15° towards the east are

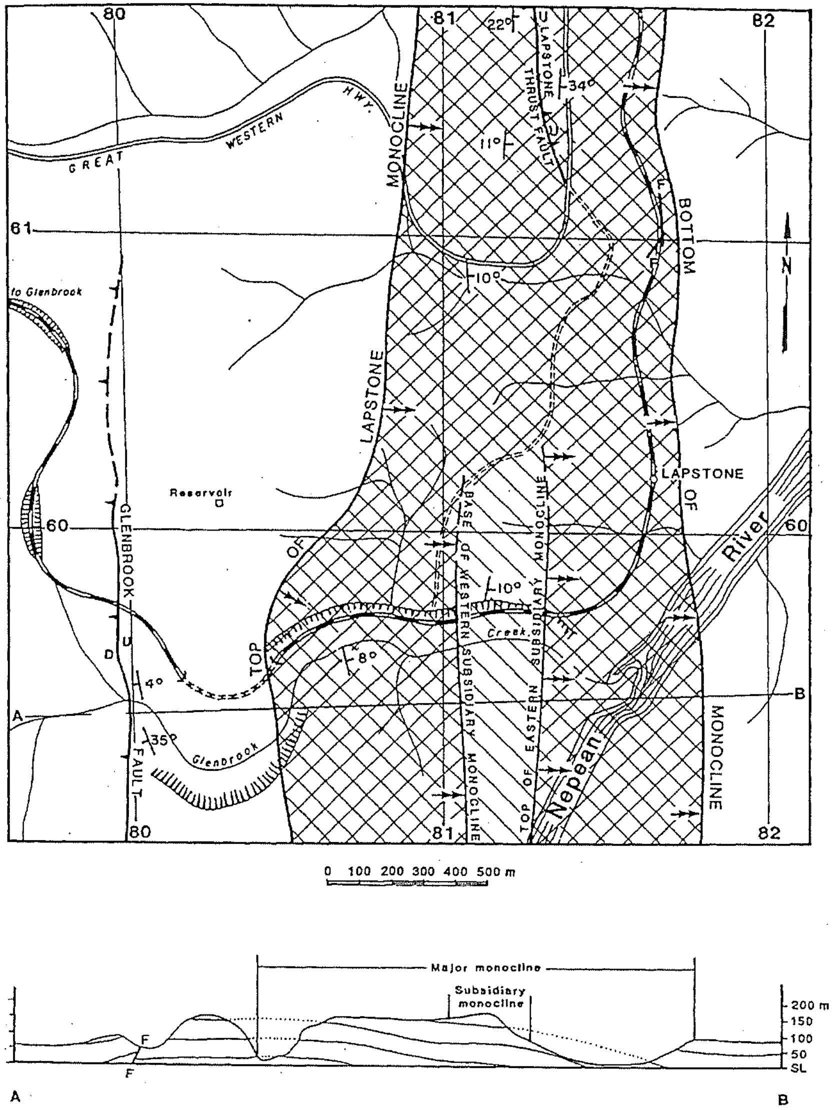

Fig. 5 Structure of Glenbrook–Lapstone district.

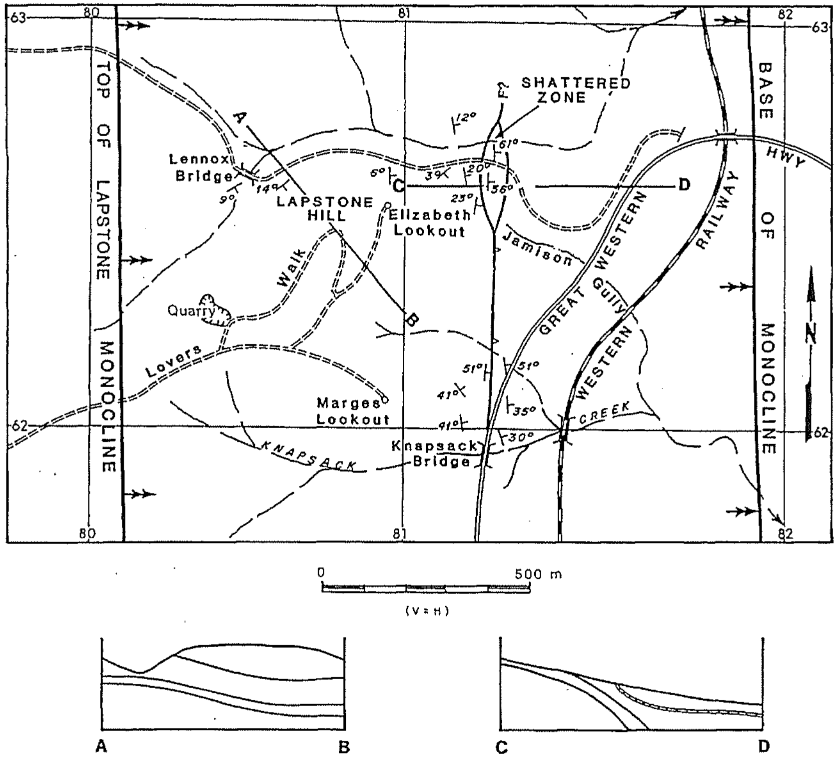

Fig. 6 Structure of Mitchells Pass Road area.

present. Within this area, topographic evidence, such as a noticeable break in slope (Fig. 8), indicates a sudden localized increase in dip of part of the structure, suggesting the formation of several monoclinal flexures. North of the Grose River a progressively larger area is incorporated in the warping, which also has a greater vertical extent than to the south.

In this study the monocline has only been examined in detail as far as the Mountain Lagoon Fire Trail road (GR 800950), some 7 km north of Kurrajong Heights (Fig. 1): information on the structure farther north has been given by Galloway (1965), Branagan (1969) and Henry (1987). Detailed mapping of this area is still required.

The *En Echelon* Faults

Pedram (1983) referred the series of west-side down *en echelon* faults west of the main escarpment collectively to the Kurrajong Fault System. The system runs north–south, nearly parallel with the Lapstone Monocline–Fault System. Work by Herbert (*in* Smith 1979) and the present authors established the position of seven faults, named by Herbert the Kurrajong, Burralow, Grose, Blue Gum, Fraser, Yellow Rock and Glenbrook Faults (Fig. 4). In the absence of key horizons the amount of displacement on these faults cannot be measured accurately. At Cut Rock, David (1902) assessed the throw of the Kurrajong Fault as 423 feet (130 m).

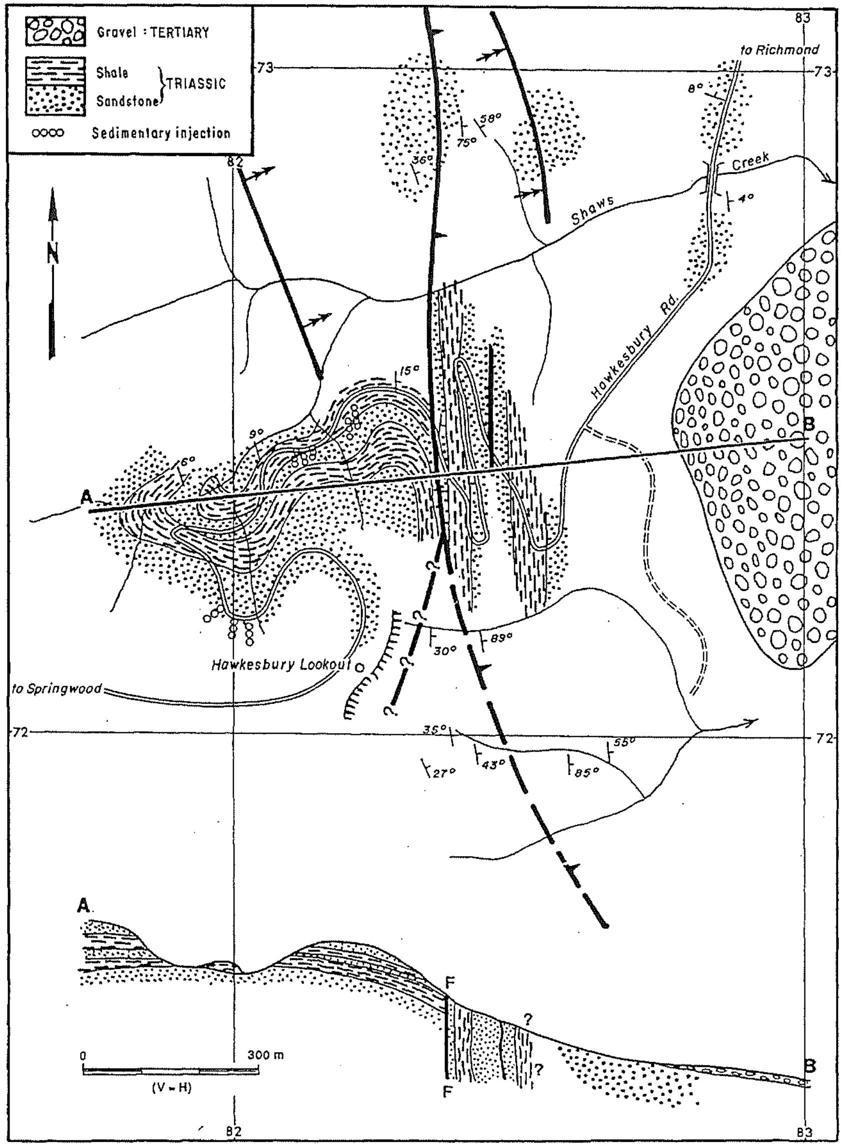

Fig. 7 Geology of Hawkesbury Lookout road section.

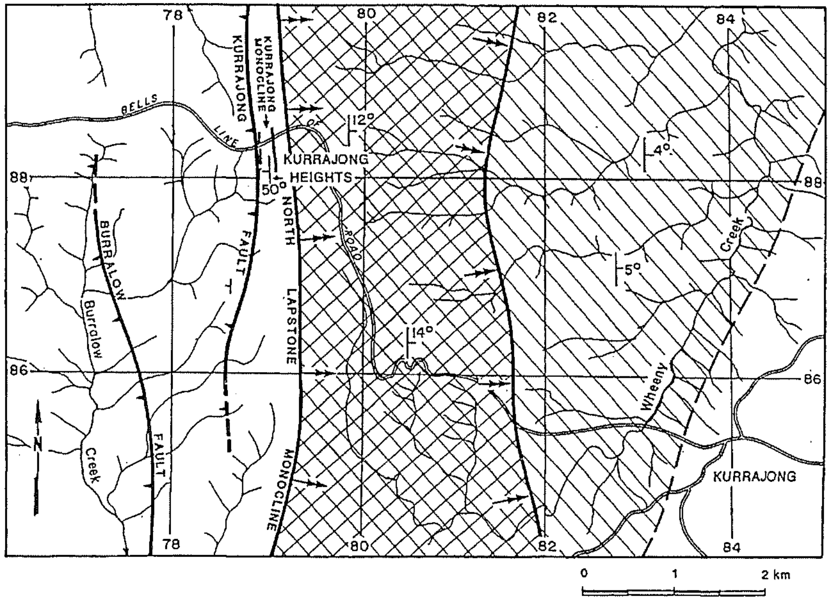

Fig. 8 Structure of Kurrajong Heights area.

However the throw of the Grose Fault does not exceed 100 m, while the downthrow on the Glenbrook Fault is approximately 70 m; that is, the amount of vertical displacement of the system decreases southwards.

The Kurrajong Fault is well-exposed on Bell's Line of Road at Cut Rock (GR 787884). The downthrow is to the west but the beds in the fault zone (3–4 m wide) are overturned and dip 80° to the east. West of the fault zone the beds gradually attain a westerly dip and then eventually become horizontal. This fault forms a well defined scarp north from Cut Rock to Mountain Lagoon, but then swings slightly northeasterly and gradually dies out. It has not yet been studied at its northern extremity. South of Cut Rock the fault edges towards the west, being traced to GR 785852 where it dies out (Fig. 8).

One hundred and fifty metres east of the Kurrajong Fault at Cut Rock the almost horizontal Hawkesbury Sandstone changes its attitude and dips west, increasing to a maximum of 50° immediately adjacent to the fault. This change is the direct result of drag on the fault. Although this small monocline seems of local extent (Fig. 8), a similar feature is present on the Mountain Lagoon Fire Trail some 7 km to the north. Minor faulting associated with this drag is discussed below.

The Burralow Fault is present about 1 km west of the Kurrajong Fault and nearly parallel to it (Fig. 8). Displacement of about 80 m (west-side down) has produced the Burralow Swamp valley west of the scarp. Outcrops of this fault occur in Burralow Creek and at GR 777829. The fault zone consists of parallel vertical cleavage planes cutting through quartz–pebble conglomerate. Inclined slickenlines on some surfaces indicate an element of strike–slip movement.

At GR 779776 the northwest–southeast-trending Grose Fault crosses the Grose River (Fig. 4). This fault forms a prominent westerly facing scarp on both sides of the river, but its displacement declines markedly towards its southeastern extremity and the fault dies out 2 km west of Hawkesbury Lookout. At its northerly end it is the locus of the dyke swarm, previously mentioned, which extends several kilometres northwest (Crook 1956). The spatial relationship between the Kurrajong, Burralow and Grose Faults is clearly visible from the south-southwest, from Warrimoo on the Great Western Highway (GR 778659).

The Blue Gum, Fraser and Yellow Rock faults are similar in character to the above faults but have smaller throws and more limited lateral extent (Fig. 4).

In the Glenbrook Gorge area there are two separate faults: the more easterly and minor unnamed fault has tilted the strata to dip 29–293°, while the larger Glenbrook Fault has dragged the beds so that they dip 50–251°. This fault forms a prominent scarp across Glenbrook Creek. North of the gorge the scarp swings slightly west and rapidly becomes less prominent south of the Great Western Highway (Fig. 5).

The Glenbrook Fault is exposed south of Glenbrook Creek at GR 800586, the rocks being nearly vertical over a width of several metres. The fault also cuts across the deep gorge of the Nepean River at its junction with Euroka Creek (GR 803572), where there is a breccia zone, in places recemented by a network of quartz veins. The considerable degree of local disturbance suggests there were possibly several or more separate movements on the fault. Crossing the Nepean at Euroka Creek the fault shows lessening displacement to the south, as indicated by a diminishing west-facing scarp, and dies out north of the junction of the Nepean and Warragamba rivers.

MINOR STRUCTURES

The minor structures are those which have a limited extent (up to 50 m) in individual outcrop. These consist of folds, a variety of faults, joints, igneous dykes and sedimentary injections. Some of these structures are believed to have formed during a period of westerly directed compression. The folds have small amplitudes but comparatively high dips. The axes are parallel to the principal structures of the area and have generally been formed in the vicinity of the main structures. These can be examined near Lapstone Railway Station (GR 816605 and 815615) and near Glenbrook (GR 815588). At the first site a bed of consolidated bouldery gravel, up to 8 m thick, overlying Triassic sandstone, appears to have been involved in the regional folding, and is also deformed by several steeply dipping faults.

Numerous high- and low-angle normal faults, thrusts and shatter zones are present. At Cut Rock (within the Kurrajong 'Monocline') a series of seven small steep easterly dipping normal faults crops out, immediately east of the Kurrajong Fault (Fig. 9). The amount of displacement does not exceed 0.6 m and in all faults the eastern blocks are downthrown, that is, in the opposite sense to the nearby major fault. The direction of movement suggests that rebounding has followed the deformation which caused the major faulting.

Small-scale low-angle thrust faults are common throughout the region, particularly on the Hawkesbury Lookout Road (GR 823725), and are present within or in the vicinity of major folds or faults. Their strikes remain parallel with major structures except in Burralow Creek (GR 798782) where thrusts within the North Lapstone Monocline have a tendency to strike east rather than north, possibly because of the nearby Paterson Hill Anticline.

Overturned beds have been mentioned earlier. A tectonic origin is supported by the geophysical profiles identifying high-angle reverse faults (Herbert 1989). However in some localities overturning may have been caused by slumping.

Zones of intense shattering are present in massive sandstones in the old Lapstone Zig-Zag cutting, just west of the Great Western Highway (GR 813613), and on Mitchell's Pass Road, where the South Lapstone Monocline attains its maximum dip (Figs 5, 6). These may be part of a single zone extending some 1.5 km. Such zones have been recorded at a number of localities in the Sydney region (Branagan 1977, 1985; Norman 1986; Branagan *et al* 1988; Mills *et al* 1989) and are believed to be mainly caused by strike–slip shearing.

Joint planes are common throughout the region and several domains can be recognized. Stereographic projections of poles to jointing are given in Pedram (1983) and Norman (1986). Data from the Blue Mountains, adjacent to or removed from the complex, for example Woodford and Katoomba–Blackheath, were given by Mauger *et al* (1984). Common to all the regions is a northwest-trending set. These joints appear to have formed early, perhaps by shearing, and are the foci for intrusion of dykes at Bellbird Hill, Grose River and at Luddenham (south-southeast of Penrith) during a later tensional period. East–west- and north–south-trending joints, apparently induced by tension during formation of a broad north–south-trending fold, are restricted to the complex.

At Bellbird Hill, northeast iron-filled joints (Norman 1986), are apparently radial tension structures caused by monoclinal folding. Planar but tight north–northeast- to northeast-trending conjugate joints cut across the northeast master joints and apparently formed subsequent to the main folding events.

In summary, there were probably four periods of joint formation: one (by shearing) prior to the main

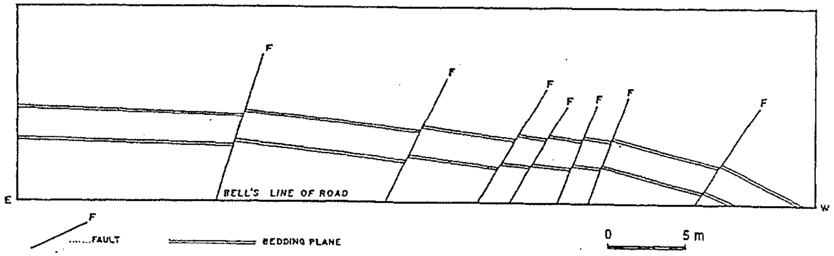

Fig. 9 Small-scale normal faults at Cut Rock (within the Kurrajong Monocline).

period of deformation; two (mainly tensional) associated with that event; and a more recent period (possibly shear).

Clastic dykes are abundant and are mainly offshoots of shale beds or lenses associated with joint systems; in all cases the shale has been injected into overlying sandstone. Thickness of these dykes varies from 10 mm to more than 1 m, for example at Lapstone Railway Station (GR 817603) and in the Hawkesbury Lookout area (GR 822725; Fig. 7). On Mitchell's Pass Road (GR 810625) sedimentary dykes form an interconnected network. The injections are consistent with a sudden release of pressure after slow deformation. The shaly material became plastic under load but was restrained. Following brittle failure of the sandstones, the plastic shale penetrated recently formed joint openings and other available spaces.

DISCUSSION

The general north–south orientation of the major structures and many of the minor ones suggests that the major stress directions were generally the same during periods of deformation, even though there may have been change from tension to compression. However, asymmetries in the regional pattern indicate that the deformation history was not simple. The Kurrajong portion of the complex is topographically nearly three times higher than the Lapstone part and the width of the disturbed area is greater in the north. Furthermore, deformation is generally greater on the eastern side.

Whilst much of the present configuration can be attributed to relatively recent movements (probably Tertiary) it is believed that some features of the complex were inherited from earlier events. Broadly, the history of the complex is in three parts: (1) tectonism prior to formation of the Sydney Basin (i.e. pre-Permian); (2) movements during Sydney Basin sedimentation (Permian and Triassic); and (3) movements well after sedimentation ceased.

A deep-seated basement structure is believed to be present below the complex (Qureshi 1984; Harrington & Korsch 1985). If the boundaries of the 'Eden–Comerong–Yalwal' Rift (McIlveen 1974) are extended north from the Shoalhaven River beneath the Sydney Basin rocks, the western edge runs beneath the Lapstone region (Fig. 10). The lowest part of the Lapstone complex and the adjacent Cumberland Plain are in an area where an eastern extension of the Bathurst Batholith and the Lachlan Lineament (Scheibner 1974) would intersect the north-trending structure (Fig. 10). Such an intersection could well be the locus for episodic movements during and after basin sedimentation.

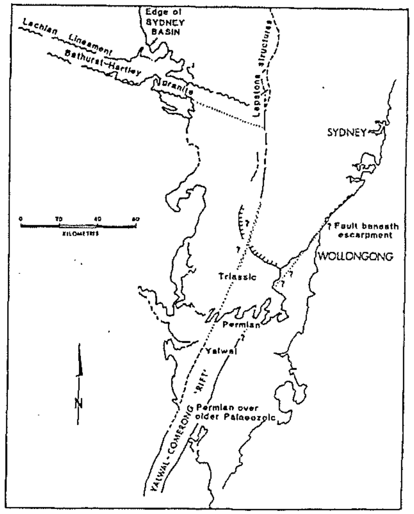

Fig. 10 Conjectural relations between basement structures and Lapstone Structural Complex.

During the sedimentary history of the Sydney Basin there was certainly structural control of sedimentation, due to basement deformation and contemporaneous tectonism (Raggatt 1938; Branagan & Johnson 1970). Adjustments in the basement during the Early Triassic may have initiated the Cumberland Basin and caused the restricted area of deposition of the Mittagong Formation and the overlying Ashfield Shale (Branagan 1969; Herbert 1979). After sedimentation ceased, uplift possibly accentuated topographic variation by adjustment along structural weaknesses echoing those in the basement. Compressive forces continued to act from the northeast in Late Triassic times (Branagan *et al* 1988; Moelle & Branagan 1988; Mills *et al* 1989). Herbert (1989) believes this was the time of major development of the structural complex.

With the onset of sea-floor spreading in the Late Cretaceous, basement weaknesses were reactivated. Ollier (1982) implied that the Lapstone structures formed at this time as part of his Great Escarpment. Norman (1986) fixed the date of formation as about the same time. It is believed that adjustments at this time gave the complex its present form.

Deformation (relative uplift) of the Lapstone Complex continued through the mid-Tertiary but was uneven and probably slow, producing the southerly plunging, flat-topped anticline with a larger east flank (Fig. 2). Uplift may have been initiated in the north and proceeded southwards, explaining the southerly courses taken by the Grose River and Glenbrook Creek which cut through the barrier. Movements at this time may have caused features such as Thirlmere Lakes (GR 735100), suggested by Fanning (1983) as pre-Miocene, and Howes Swamp (GR 820490) which has an enigmatic history (Henry 1987). However, Rawson (1989) postulates continuing slow movements of the whole complex throughout the Cainozoic, as did Cotton (1921).

At some time the stress pattern changed and brittle deformation produced the major faults on both sides of the complex. A left-lateral deforming couple (i.e. west-side south) could have produced the present fault pattern, together with the flexure in the North Lapstone Monocline in the Grose Valley area, as supported by the slickenlines on faults surfaces, shatter zones and jointing at Bellbird Hill.

The gravels on the monocline are suggested as Miocene in age by Gobert (1978) and Bishop (1986), who believed that they predate deformation. They are not preserved on the steeper fault faces and it is believed that they may have a wider spread of age through the Tertiary, and were reworked down the monocline during several periods of deformation.

Iron-filled joints formed during tensional deformation of the eastern monoclinal structure (Norman 1986), and the lateritization of some of the gravels (Bishop *et al* 1982) may be attributed to the same period of iron migration (?Early Miocene), which supports the idea that the gravels may be, in part at least, Early Tertiary, and that the main deformation may date from that epoch.

Earthquakes in the region in 1801, 1886 and 1919 (Cotton 1921) indicate that the structure is still mildly active.

To gain a better understanding of the formation of the Lapstone Structural Complex the total extent of the structure must be mapped in detail and the relation between various named structures at the southern end of the complex needs to be clarified. There is presently no agreement about the nature, location, or age of formation of these structures (Bunny 1972; Scheibner 1974; Mullard *et al* 1983; Sherwin & Holmes 1986).

The overall pattern does not fit the strike–slip pattern in which a divergent wrench fault is accompanied by a component of extension (Harding *et al* 1985). Rather there is no evidence of major extension of the area for the past 40 Ma. Osborne (1948) suggested two periods of deformation, mainly of compression and shear, with minor tension. He believed the main movements forming the complex took place early in the Tertiary. This suggestion is supported by Willan (1923), Norman (1986) and the present work.

SUMMARY

In summary the structure is the result of three major events:

(i) Permian and Triassic sediments were draped over a well-developed north-trending structure intersected by easterly trending structures — an extensional event.

(ii) Compression (mainly from the northeast) and uplift of both basement and basin sediments took place during and immediately following cessation of sedimentation. This 'thin-skin' type adjustment formed a broad warp.

(iii) Early Tertiary adjustments to the near-surface rocks, caused by compressional strike–slip, formed the elements of the complex visible today.

(iv) Later minor adjustments took place.

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The fire, human and climate nexus in the Sydney Basin, eastern Australia

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Abstract: It is widely believed that Australian Aborigines utilized fire to manage many landscapes; however, to what extent this use of fire impacted on Australia's ecosystems remains uncertain. The late Pleistocene/Holocene fire history from three sites within the Sydney Basin (Gooches Swamp, Lake Baraba and Kings Waterhole) were compared with archaeological and palaeoclimatic data. The Gooches Swamp record appeared to be most influenced by climate and there was an abrupt increase in fire activity from the mid Holocene perhaps associated with the onset of modern El Niño-dominated conditions. The Kings Waterhole site also displayed an abrupt increase at this time, however there was a marked decrease in charcoal from ~3 ka. Similarly Lake Baraba displayed low levels of charcoal in the late Holocene. At both Kings Waterhole and Lake Baraba archaeological evidence suggests intensified human activity in the late Holocene during this period of lower and less variable charcoal. It is hence possible that Aboriginal people strongly influenced fire activity in some areas of the Sydney Basin during the late Holocene perhaps in response to the increased risk of large intense fires as an ENSO-dominated climate became more prevalent. The fire history within the Sydney Basin varies both temporally and spatially and therefore it is inappropriate to apply a single fire regime to the entire region for landscape management. This work also has implications for future fire incidence associated with climatic variability under an enhanced Greenhouse effect.

Keywords: Holocene fire history, climate history, archaeological history, Aborigine impacts, eastern Australia.

Introduction

This study presents contiguous charcoal records from three sites, Gooches Swamp, Lake Baraba and Kings Waterhole, which are all located within the Greater Blue Mountains World Heritage Area in southeastern Australia. The aim of the study was to untangle the influence of climate and people on the late Quaternary fire activity of the region. It is assumed that the three sites have experienced a similar climate throughout this time and therefore any differences in fire activity may be attributed to either the different anthropogenic influences or local biotic or abiotic factors at the various sites. The individual fire and vegetation histories of the three sites have previously been discussed separately (ie, Black and Mooney, 2006, 2007; Black *et al.*, 2006) however this paper aims to compare the three records and to identify trends across the region.

Jones (1969) suggested that Aboriginal people used 'fire-stick farming' to increase or manipulate biotic resources. This has contributed to a popular notion that Aboriginal people controlled a fire regime consisting of frequent, low-intensity fire used with well-defined seasons but over small spatial scales (mosaic or patch burning). There remains much controversy over this generalization and also whether this anthropogenic fire regime impacted on the species composition, structure and distribution of Australia's vegetation (Bowman, 1998). There are those that believe Australian Aboriginal fire regimes had minimal or no impact on vegetation (eg, Horton, 1982) while others have suggested that the use of fire has profoundly and irreversibly altered vegetation patterns (eg, Singh *et al.*, 1981; Flannery, 1994). Clark (1983) and MacPhail (1980) suggested that Aboriginal people may not have altered vegetation patterns but their use of fire was responsible for the continuation of vegetation zones and that they may have affected the rate of vegetation change. Head (1989) argued that Aboriginal people were trying to maintain a balance between the need to fire a landscape for resource manipulation and the need to protect other areas where particular plants grew, such as in rainforests. Head (1989) hence argued that anthropogenic fire practices contributed to the maintenance of a mosaic of vegetation associations.

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Palaeoecological studies can provide information on past vegetation and fire activity and have resulted in a better understanding of the prehistory of fire (Wasson and Clark, 1987). In Australia there have been ambiguities associated with interpretations of previous charcoal analyses, leading Bowman (1998) to suggest that palaeoecological studies do not objectively shed light on the issue of Aboriginal use of fire. Despite taphonomic and other concerns the analysis of charcoal 'remains the best palaeoecological tool for reconstructing fire regimes on millennial time scales' (Hallett and Walker, 2000: 403).

The prehistory of fire is of relevance to the management of fire in the contemporary environment. As an example, the argument that Aboriginal people applied a low intensity/high frequency fire regime to Australia's vegetation is often used as a justification for hazard reduction burning (Gill, 1977). Gill (1977) has warned against the adoption of simplistic concepts of Aboriginal use of fire and generalizations over the entire continent. This is demonstrated, as described by Benson and Redpath (1997), by many vegetation types (eg, rainforest, wet sclerophyll forest, alpine shrublands and inland chenopod shrublands) that would now be rare if they had been burnt frequently by Aboriginal people.

The argument for the application of hazard reduction burning in national parks is often more strongly asserted following severe bushfire seasons. Keith (1996) found that frequent widespread burning of the Sydney Sandstone flora could be responsible for local extinctions of plant species and that recolonization from unaffected sites occurs extremely slowly. In New South Wales the application of frequent, low intensity fire has also been listed as a 'key threatening process' to biodiversity under the *Threatened Species Conservation Act* 1995 (NSW).

It is impossible to separate whether charcoal in sedimentary sequences originated from anthropogenic or natural fire events caused, for example, by lightning. However, one possible method to resolve this is by comparing charcoal records with archaeological data and palaeoclimatic proxies in an attempt to separate human and other influences. Bowman (1998), for example, has highlighted the importance of comparing palaeoecological and archaeological data to better understand fire history. Here the three charcoal records, reflecting local fire activity, will be compared with each other and nearby archaeological information, the latter used as an index of human activity through time.

The Holocene period, from ~11 500 cal. yr BP is generally described as a relatively stable interglacial. Nonetheless there is increasing evidence that the climate of the Holocene contained some variability including abrupt changes, at least in the Northern Hemisphere (eg, Bond and Lotti, 1995; deMenocal *et al.*, 2000; Maasch *et al.*, 2003). In southeastern Australia Kershaw *et al.* (2002) identified the period of 7–5 ka as the Holocene precipitation peak (the Holocene Climatic Optimum), the period between 4 and 2 ka as a drier and perhaps cooler period, and a return to wetter conditions over the last 2000 years.

One aspect of Holocene climatic variability that has received some attention, and which greatly influences eastern Australia's climate (Nicholls, 1985), is El Niño-Southern Oscillation (ENSO) events. ENSO is thought to have progressively achieved modern characteristics during the Holocene, although consensus on the timing is yet to emerge (eg, McGlone *et al.*, 1992; Shulmeister and Lees, 1995; Shulmeister, 1999; Rodbell *et al.*, 1999; Clement *et al.*, 2000; Sandweiss *et al.*, 2001; Moy *et al.*, 2002; Riedinger *et al.*, 2002; Gagan *et al.*, 2004).

Westerling and Swetnam (2003) suggested that the history of fire in the Western USA contained climatic signals. Furthermore, Haberle and Ledru (2001) suggested that periods of rapid climate change or climatic variability lead to increased fire activity. Increased fire activity has also been variously linked with climatic variability associated with ENSO (eg, Swetnam and Betancourt, 1990; Goldammer, 1999; Haberle and Ledru, 2001; Haberle *et al.*, 2001; Siegert *et al.*, 2001; Kitzberger, 2002; Kershaw *et al.*, 2002).

Haberle and Ledru (2001) identified an alignment in the fire activity from a number of sites in Indonesia and Papua New Guinea, and Central and South America from the mid Holocene and attributed this to the intensification of ENSO variability.

There is a relationship between ENSO and severe fire seasons in Australia, since El Niño events are generally associated with drier and warmer than average conditions, and La Niña events with conditions that are wetter and cooler than average (Lindesay *et al.*, 2004). Edwards (2002) found a particularly strong link between the Southern Oscillation Index and fire season severity in southeastern Australia.

Site description

The sites used in this study are located within the Sydney Basin, on the central east coast of New South Wales, Australia. The Sydney Basin is a geological province of approximately 3.7 million ha consisting of a number of discrete physiographic units that include the Blue Mountains Plateau to the west, the Wollemi-Colo and Hawkesbury Plateau to the north, the Woronora Plateau and Southern Highlands to the south and the central Cumberland Plain (Herbert, 1983) (Figure 1).

The Sydney Basin is dominated by a temperate climate characterized by warm summers and no dry season, although a subhumid climate pertains in the northern parts of the Basin and small areas of Montane climate in the Blue Mountains (National Parks and Wildlife Service (NPWS), 2004). Average annual rainfall is variable across the Basin according to altitudinal changes and the distance from the coast. Shallow skeletal sands are found on the sandstone plateaus and these soils have poor water-holding potential, are very acidic and infertile (Herbert, 1983). Elsewhere soils may be metres deep and enriched by silt and organic matter.

The considerable variation in geology, soils and topography across the Sydney Basin has resulted in one of the most species-diverse botanical divisions in Australia (NPWS, 2004) and includes communities of dry and wet sclerophyllous forests and woodlands, warm temperate rainforests, heath, mangroves and freshwater swamp communities (Benson, 1986, 1992). Heath and woodland are commonly found on the rocky platforms and ridgetops whereas taller open forests occur on the deeper plateau soils and on the lower slopes (Benson, 1986, 1992). Communities of the sandstone plateaus surrounding Sydney are dominated by *Angophora*, *Corymbia* and *Eucalyptus* species and the understorey often consists of members of the Epacridaceae, Fabaceae, Mimosaceae, Proteaceae and Rutaceae families (Benson, 1986, 1992).

The sites utilized herein are all organic deposits associated with freshwater swamps in sandstone-dominated landscapes. In the Sydney Basin freshwater swamp communities are relatively small and isolated and occur as hanging swamps on the sandstone plateaus, as wet depressions where drainage is impeded or on poorly drained Quaternary deposits (Campbell, 1983; Fairley and Moore, 2000). Floristic composition varies locally in relation to soil moisture gradients such that the vegetation on these swamps often consists of complex mosaics of sedges, herbs and shrubs that can tolerate poorly drained habitats.

The locations of the three sites are shown in Figure 1. Gooches Swamp (~33°27'S, 150°16'E, 960 m a.s.l.) is a narrow, elongated swamp in a low headwater valley located on the Newnes Plateau

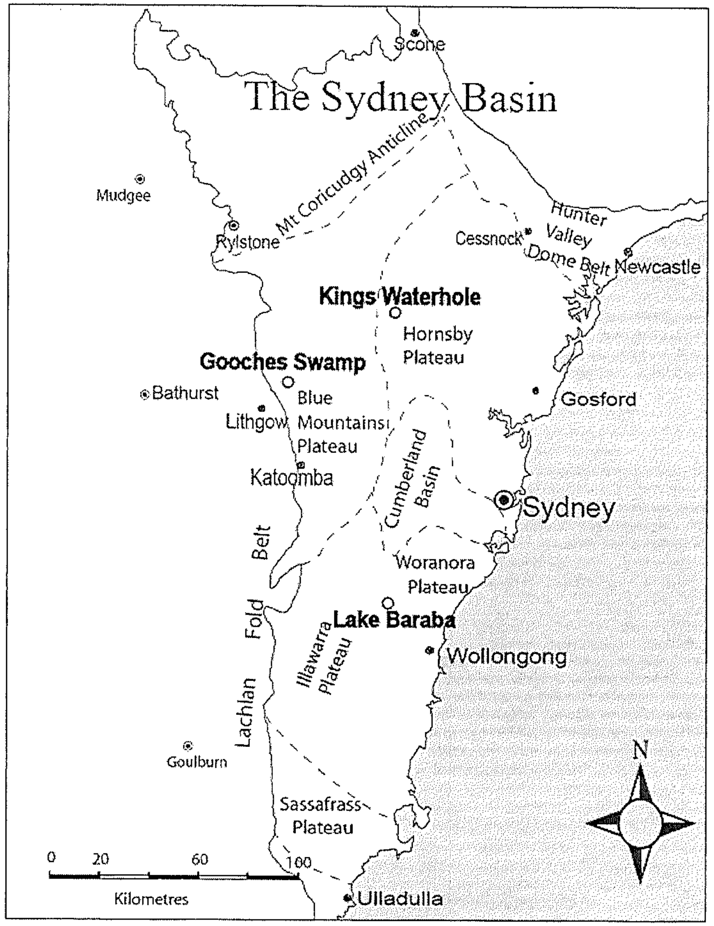

Figure 1 The major physiographic units of the Sydney Basin and the location of the three sites (source: Herbert, 1983)

in the Blue Mountains. Kings Waterhole (33°1'S, 150°40'E, 280 m a.s.l.) is a low relief valley infilled with Quaternary sand and peat located within Wollemi National Park, northwest of Sydney. Lake Baraba (34°13'S, 150°13'E, 305 m a.s.l.), is an infilled lake within an entrenched meander at Thirlmere Lakes National Park, in the southwest part of the Sydney Basin. More detailed descriptions of the three sites are given elsewhere (in Black and Mooney, 2006, 2007; Black *et al.*, 2006).

Kings Waterhole and Lake Baraba share similar environmental settings. Average annual rainfall and temperatures, altitude and the swamp and surrounding vegetation communities are broadly similar. Gooches Swamp is located at an elevation of 960 m and hence experiences a slightly different climatic regime to the other sites, with greater variations in temperature throughout the year and a higher average annual rainfall. The surface of Gooches Swamp is dominated by shrubs (eg, *Baeckea linifolia, Grevillea acanthifolia* subsp. *acanthifolia, Epacris paludosa* and *Leptospermum* spp.) and sedges (eg, *Restio australis, Baloskion australe, Empodisma minus, Lepyrodia scariosa* and *Lepidosperma limicola*) (Keith and Benson, 1988). The surface vegetation at Lake Baraba and Kings Waterhole is dominated by sedges and rushes (eg, *Lepironia articulata, Eleocharis sphacelata, Philydrum lanuginosum, Brasenia schrebi*). Lake Baraba is largely infilled but some open water exists at some distance from the site of sampling.

The three sites were inhabited by different Aboriginal language groups in pre-European times. The landscape surrounding Gooches Swamp may have been a place of interaction or a transport corridor for various Aboriginal groups including the Dharug (or Daruk) and Gundungurra people (Stockton and Holland, 1974; Horton, 1994). Aboriginal occupation of the Blue Mountains is often described as spasmodic because of climatic variations and the altitude, rugged topography and limited resources (Stockton, 1970; Stockton and Holland, 1974; Flood, 1980). The archaeological history of the Blue Mountains remains relatively poorly understood with only a limited number of sites studied in detail. The earliest evidence of Aboriginal occupation in the Blue Mountains is dated to ~22.4 ka (Stockton and Holland, 1974).

Bowdler (1981) suggested that Aboriginal occupation of the Blue Mountains was sporadic between 14 000 and 12 000 yr BP followed by a hiatus and then an intensification from the mid to late Holocene. Stockton (2005) suggested that winter and cold conditions generally may have been less of a constraint on occupation than has previously been forwarded. Stockton (2005) also hypothesized that the Blue Mountains may have experienced relatively moister conditions during the glacial period and transition, compared with surrounding regions and may therefore have served as a haven for plants and animals, including people. However Hesse *et al.* (2003) suggested that vegetation was severely reduced and sand dunes were active in the Upper Blue Mountains during the last glacial maximum therefore making the area inhospitable at this time.

The territory of the Darginung (also written Darkinjung, Darkinjang and Darkinung) covered an area south from the Hunter River, including portions of the Macdonald and Colo Rivers and lower Hawkesbury River at Wisemans Ferry (Mathews, 1897; Tindale, 1974; Dharug and Lower Hawkesbury Historical Society, 1988; Attenbrow, 2003, 2004). Kings Waterhole is situated within this territory. The Darginung were believed to be mobile hunter-gatherers, who used several base camps as well as many activity locations (eg, sites for hunting and gathering, tool manufacture, etc.) and transit or short-term camps within their country (Attenbrow, 2003, 2004).

The traditional custodians of Lake Baraba are the D'harawal and Gundangarra people. The lakes and wetlands of the Thirlmere Lakes were likely to represent a plentiful supply of food and ethnographic evidence suggests that the Aboriginal people of the region frequently applied fire to the landscape (NPWS, 1995). Attenbrow (2004) has suggested that the establishment of Aboriginal sites in the region increased from ~8 ka, with the habitation rates of these sites generally increasing until the arrival of European people.

Methods

Sediment cores were extracted from Gooches Swamp, Lake Baraba and Kings Waterhole using a Russian d-section corer (Jowsey, 1966) to depths of 3.55 m, 6.35 m and 5.55 m, respectively. Cores were photographed and stratigraphics described using a modified version of the Troels-Smith method (Kershaw, 1997). The sedimentary sequences were dated using both conventional radiocarbon dating and Atomic Mass Spectrometry (AMS) at Beta Analytical Inc., Florida and Rafter Radiocarbon Laboratory, New Zealand. Four, five and three radiocarbon dates were acquired for the Gooches Swamp, Lake Baraba and Kings Waterhole sequences, respectively. These dates were calibrated with CALIB v5 (Stuiver *et al.*, 2005) using the IntCal04.14c (Reimer *et al.*, 2004) and ShCal04.14c (McCormac *et al.*, 2004) data sets.

Macroscopic charcoal was analysed using a modified version of the 'Oregon sieving method' (Long *et al.*, 1998) and image analysis (Mooney and Black, 2003). Volumetric subsamples were taken from contiguous 1 cm sections for the Gooches Swamp core, and at contiguous 2.5 cm sections for the Lake Baraba and Kings Waterhole sedimentary sequences. The samples were placed in 8% sodium hypochlorite (bleach) for 24 h to remove the pigment from organic matter and, hence, aid in the identification of charcoal. This was then washed through a 250 μm sieve and the collected material was photographed in a petrii dish using a four megapixel digital camera. The area of charcoal was calculated using image analysis software (Scion Image Beta 4.02 for Windows). Results are expressed as mm^2 of charcoal per cm^3 of sample. The sedimentation rates at Gooches Swamp, King Waterhole and the peat section of Lake Baraba were close to linear and hence the concentration of charcoal was not re-expressed as an influx of charcoal per unit area and time.

The charcoal curves of the three sites were statistically analysed using psimpoll v 4.25 (Bennett, 2005). Skewness and kurtosis were tested and a Runs test was used to assess whether the data are showing a trend or just random or normally distributed values with q values >0.05 indicating random data. Three types of correlations (Linear, Spearman's and Kendall's) were carried out to test for changes in charcoal representation with age. It has been suggested that a negative correlation (ie, increased charcoal with younger age) could reflect anthropogenic or taphonomic influences. Fourier transformation was used in order to detect peaks in spectral density, indicative of cyclical changes in the charcoal data and to identify cycles that could be associated with known climatic cycles.

The three charcoal records were compared with local archaeological sequences. The Gooches Swamp record was compared with the Capertee 3 archaeological sequence (approximately 35 km from the site) (McCarthy, 1964; Hiscock and Attenbrow, 1998, 2004; Attenbrow, 2004, 2005); the Kings Waterhole record was compared with the Upper Mangrove Creek archaeological record (approximately 30 km from the site) (Attenbrow, 2003, 2004); and the Lake Baraba record was compared with a regional summary of archaeological records compiled by Attenbrow (2004).

Charcoal values for each of the three sites were averaged using a 200 yr moving window and then compared with palaeoclimatic information including the Moy *et al.* (2002) proxy record of changes in ENSO activity throughout the Holocene; seasonality, based on the difference between January and July insolation at 30°S throughout the Holocene using the data from Berger (1992); and also a general summary of past climates for southeastern Australia (Lees, 1992; Shulmeister, 1999; Kershaw *et al.*, 2002).

Results

Stratigraphy and chronology

The results of radiocarbon dating for Gooches Swamp, Lake Baraba and Kings Waterhole are given in Table 1. The basal dates of the three sedimentary sequences are 14.2 ka (Gooches Swamp), >43 ka (Lake Baraba) and 6.1 ka (Kings Waterhole), respectively. The sediments of Gooches Swamp and Kings Waterhole both displayed a relatively constant rate of accumulation and were composed of humified peat interspersed with clay, charcoal and sand. At Lake Baraba, peat was found above 172 cm, a transition layer of peat and clay from 172 to 410 cm, which became more clayey with depth, and clay below 410 cm. The sedimentation rate of the clays at Lake Baraba is much lower (ie, 0.04 mm/yr) than within the peat (~0.67 mm/yr). Based on the chronology the sample resolution for Gooches Swamp is ~40 yr, Lake Baraba is ~77 yr (between 0 and 410 cm) and ~630 yr (>410 cm) and Kings Waterhole is ~27 yr.

Table 1 Radiocarbon dates and calibration for Gooches Swamp, Lake Baraba and Kings Waterhole sediments

Site sample depth (cm)	^{14}C date BP with 1σ error	Cal. yr BP* (2σ error)	Lab. code
Gooches Swamp			
48–53	1760 ± 60	1419–1811	β-169992
80–90	2450 ± 60	2333–2708	β-192605
150–156	4950 ± 130	5322–5912	β-169993
295–307	10 360 ± 140	11 646–12 737	β-169994
Lake Baraba			
147–153	4130 ± 70	4421–4821	β-186144
275–285	5950 ± 60	6549–6887	β-192607
347–353	6750 ± 80	7433–7675	β-186145
464–472	19 411 ± 196	22 541–23 716	NZA-192608
595–601	> 43 630	N/A	β-192608
Kings Waterhole			
147–154	2220 ± 60	2003–2327	β -186146
348–353	3280 ± 70	3269–3635	β -186147
547–553	5560 ± 90	6014–6491	β -186148

Calibration results from CALIB v5 (Stuiver *et al.* 2005). The midpoint of the entire calibrated year range is used in age-depth model calculations. (Beta Analytical Inc., Florida and Rafter Radiocarbon Laboratory, New Zealand carried out the radiocarbon dating.)

Charcoal analysis

The charcoal records of the three sites are presented in Figure 2. For the purpose of comparison the charcoal record of Lake Baraba has been truncated at 14.2 ka (430 cm) ie, the basal date of Gooches Swamp. At Gooches Swamp macroscopic charcoal is relatively high between 250 and 281 cm (~9.8–11.1 ka), 232 and 244 cm (~9.1–9.6 ka), 97 and 150 cm (~3.5–5.7 ka), 67 and 87 cm (~2.3–3.1 ka) and 0 and 6 cm (the late European period). There are low levels of charcoal between 325 and 353 cm (~12.9–14 ka), 287 and 315 cm (~11.3–12.5 ka), 150 and 232 cm (~5.7–9 ka), 87 and 97 cm (~3.1–3.5 ka), and from 40 to 25 cm (~1.1–0.5 ka) and 6–13 cm (early European occupation).

Most of the analysed sediment profile from Lake Baraba has low levels of charcoal, with peaks at 240 (~6 ka), 270 (~6.4 ka) and 400 cm (~8.4 ka), a series of higher peaks at 230–200 cm (~5.9–5.4 ka) and minor peaks at 170–130 cm (~5–4 ka). Macroscopic charcoal concentrations are very low between 430 and 405 cm (~13.6–8.5 ka), relatively low but variable between 405 and 275 cm (~8.5–6.5 ka) but increase abruptly to remain very high and variable until 200 cm (~5.4 ka). Between 185 and 55 cm (~5.2–1.7 ka) there is a decreasing trend in charcoal concentrations, from relatively high to moderately low and variable throughout this interval. The upper samples (50 to 0 cm, past ~1.5 ka) have very low charcoal concentrations with some samples almost devoid of charcoal. There was much less charcoal found in the clays when compared with the peat sediment.

Macroscopic charcoal is present throughout the entire sequence at Kings Waterhole, although the concentrations of charcoal vary considerably. Charcoal is initially low between 555 and 515 cm (~6.1 and 5.7 ka) but then increases dramatically to remain high and variable between 515 and 265 cm (~5.7 ka and 3 ka) with the exception of a period of reduced charcoal deposition between 470 and 430 cm (~5.2 and 4.8 ka). Charcoal decreases rapidly at 265 cm (~3 ka) and remains generally low from this time to the present. Charcoal deposition for the top 80 cm (the past ~1000 yr) is especially low.

Statistical analysis

The results of the skewness, kurtosis and runs test are presented in Table 2. The skewness and kurtosis results of all three sites are positive and significant, indicating a common, non-normal shape or distribution. The positive kurtosis results reflect the 'peaky' nature of all three records. The *q*-values at all three sites are <0.05, suggesting that the data are not random.

The three correlation co-efficients (ie, Linear, Spearman's and Kendall's) for the sites are given in Table 3. Gooches Swamp and Lake Baraba display a negative value for all three correlation co-efficients, suggesting increasing levels of charcoal with younger age. Gooches Swamp is the only site that shows a significant trend.

A number of significant cycles are identified from the spectral analyses (Figure 3), however, some caution is necessary as sample resolution and record length can influence the outcome. At Gooches Swamp 41 yr, 1300 yr, 2600 yr and 5900 yr cycles were significant, at Lake Baraba a 73 yr, 3700 yr and 8000 yr cycle were identified and Kings Waterhole had a 54 yr and a 6100 yr significant cycle. The 41, 54 and 71 yr cycles found at Gooches Swamp, Kings Waterhole and Lake Baraba, respectively, are associated with the sampling resolution of the records and hence are not relevant to the analyses. Similarly the 8000 and the 6100 yr cycles from Lake Baraba and Kings Waterhole are a function of the record length and hence also should be ignored. This means the only significant cycles are the 3700 yr for Lake Baraba, and the 1300 yr and 2600 yr cycles from Gooches Swamp (although the 2600 yr cycle at Gooches Swamp is likely to be linked to the 1300 yr cycle).

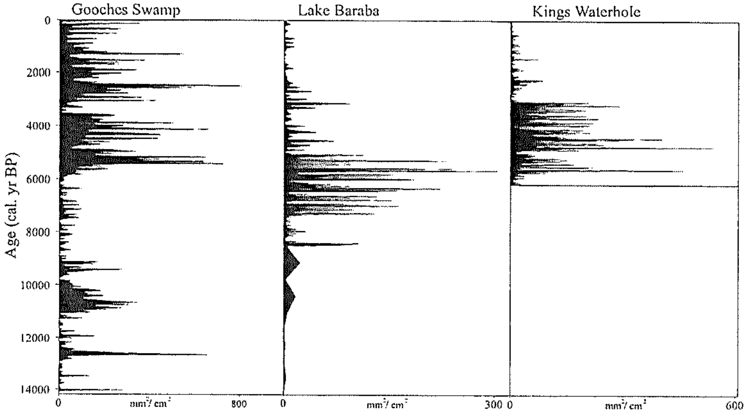

Figure 2 The results of the macroscopic charcoal analysis for Gooches Swamp, Lake Baraba and Kings Waterhole

Table 2 Statistical analysis results for the three sites' charcoal data

Site	Mean	Standard deviation	Skewness	Kurtosis	Runs (q)
Gooches Swamp	119.3582	144.6212	2.1352*	5.5980*	9.572E-03
Lake Baraba	46.9872	79.7630	2.5422*	7.0829*	1.96E-11
Kings Waterhole	44.6821	66.6278	2.6908*	9.4131*	1.03E-11

*Significant at $P \leq 0.05$.

Table 3 Results of the correlation for the three sites' charcoal data

Site	Linear correlation	Spearman's correlation	Kendall's correlation
Gooches Swamp	−0.3442*	−0.4384*	−0.294*
Lake Baraba	−0.0654	−0.0283	−0.0159
Kings Waterhole	0.3820	0.5914	0.3915

*Significant at $P \leq 0.05$.

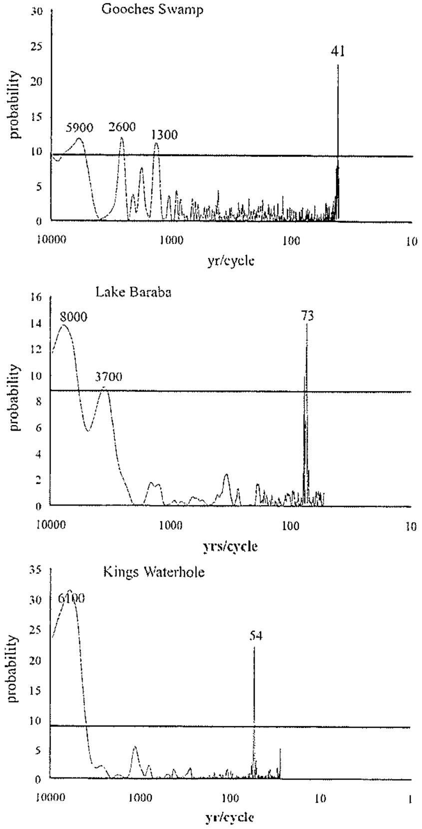

Figure 3 The results of the spectral analysis (Fourier's analysis). Results are significant at the 0.05 level

Comparison with archaeological records

Comparisons of the Gooches Swamp charcoal record with the Capertee 3 archaeological sequence, the Lake Baraba record with the summary of the southern Sydney Basin archaeological data, and the Kings Waterhole with the Upper Mangrove Creek archaeological sequence, are shown in Figures 4, 5 and 6, respectively.

At Gooches Swamp discard rates and average charcoal concentrations are both relatively low between ~9.7 and 6 ka, however average charcoal concentrations were high between ~6 and 3.6 ka whilst discard rates remain low. Artefact concentrations are highest between ~3.6 and 1.7 ka, with the layer ~3–2.3 ka having the highest discard rates. The latter layer corresponds with the very high levels of charcoal. The period ~1.7 ka to present has very low artefact discard rates corresponding with relatively high levels of charcoal accumulation.

Charcoal at Lake Baraba and the number of habitations used in the region both gradually increase from the last glacial maximum (~21–18 ka) to the early Holocene (Figure 6). From ~8 to 7 ka this relationship breaks down, with the number of habitations increasing more rapidly whilst charcoal content declines steadily. Very high levels of habitation use and establishment in the past 4–3 ka correspond with very low levels of macroscopic charcoal.

Macroscopic charcoal levels at Kings Waterhole are relatively high and variable between 6.1 and 3 ka and this corresponds with low numbers of artefacts, base camps and activity locations in archaeological data for the Upper Mangrove Creek catchment (Figure 6). At 3 ka there is a dramatic increase in the number of artefacts and base camps and this is associated with a marked drop in charcoal. Charcoal remains very low to the present, whilst the three indices of the prehistoric presence remain high.

Comparison with climatic data

The three charcoal records are compared with the frequency of ENSO events (Moy *et al.*, 2002), and seasonality based on changes in insolation associated with Milankovitch orbital parameters and a climatic summary of southeastern Australia (Figure 7).

The Gooches Swamp charcoal record displays increases in charcoal with the onset of climatic amelioration and the Pleistocene/Holocene transition. There are very low levels of

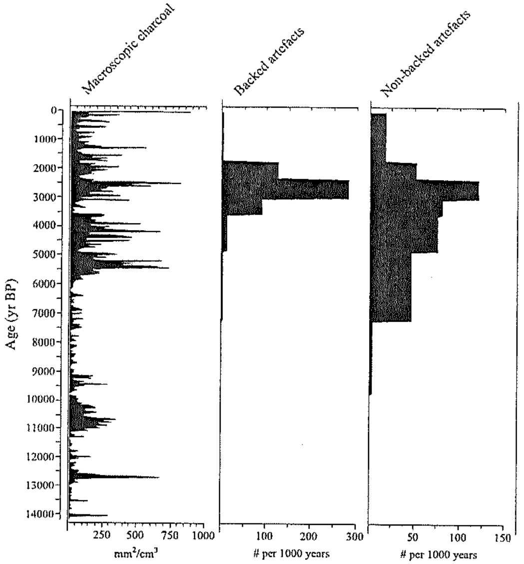

Figure 4 A comparison of the Gooches Swamp macroscopic charcoal curve with the number of backed and non-backed artefacts from Capertee 3 (Hiscock and Attenbrow, 1998, 2004)

charcoal during the Holocene Climatic Optimum (~9–6 ka) and a dramatic increase in charcoal from the mid Holocene when ENSO frequencies increased. Charcoal remains high and variable from this time to the present under an ENSO-dominated climate. The seasonality increases throughout the Holocene and begins to plateau from the mid Holocene. The Gooches Swamp macroscopic charcoal record follows this general trend, although the changes are much more abrupt.

Kings Waterhole shows an increase in charcoal associated with the onset of an ENSO-dominated climate, however charcoal decreases dramatically at 3 ka whilst ENSO events remained relatively frequent. Similarly there is no obvious relationship with the degree of seasonality and the Kings Waterhole curve.

The increase in charcoal from ~8 ka at Lake Baraba does not seem to be associated with any dramatic change in ENSO frequency (Figure 7). There is a large decrease in charcoal from the mid Holocene at Lake Baraba and this occurs at the same time that ENSO is likely to have began to influence southeastern Australia's climate. There is no clear association with the seasonality record and the Lake Baraba charcoal curve.

Discussion

There are key differences between the three fire records presented in this study that could, at least on one level, lead to questions regarding the underlying assumptions of this research, namely that charcoal records from sediment sequences are interpretable in terms of palaeo-fire regimes. This assumption has, however, been tested in a diversity of landscapes against historic fires and/or dendrochronology (fire scars), demonstrating that macroscopic charcoal does reflect local fire events (eg, Whitlock and Millspaugh, 1996; and summarized in Whitlock and Larsen, 2001). This suggests that the differences in the three charcoal records across the Sydney Basin reflect real spatial differences in fire.

The fire history of Gooches Swamp appears to be most greatly influenced by climate. The Gooches Swamp record displays an increase in fire activity associated with the Lateglacial/Holocene transition, followed by a decrease associated with the relatively stable Holocene Climatic Optimum. The Gooches Swamp charcoal record also shows an apparent relationship with the increased frequency of ENSO events from the mid Holocene, suggesting a dramatic change in fire activity. During the twentieth century large, intense fires occurred approximately every decade in the Blue Mountains (Cunningham, 1984): based on the similarities in the charcoal curve from the European period and the preceding ~5000 yr we suggest that a similar fire regime was a feature of this landscape since the mid Holocene.

Haberle *et al.* (2001) constructed a regional cumulative charcoal curve based on ten sites from Indonesia and Papua New Guinea. When this is compared with the Gooches Swamp charcoal record, smoothed using a 41 point running average to match the resolution of Haberle *et al.*'s (2001) regional charcoal curve, strong similarities are apparent (Figure 8). Haberle *et al.* (2001) linked the changes in fire activity in this region with the onset of climatic variability during the postglacial transition and with the onset of modern ENSO from the mid to late Holocene.

The charcoal record from Gooches Swamp also shows some similarity with the seasonality curve (Figure 7), with an increase in fire activity occurring when seasonality increased, although the changes at Gooches Swamp were much more abrupt. Here fire activity may undergo a non-linear change in response to the linear forcing in a manner similar to that proposed for African climate by deMenocal *et al.* (2000).

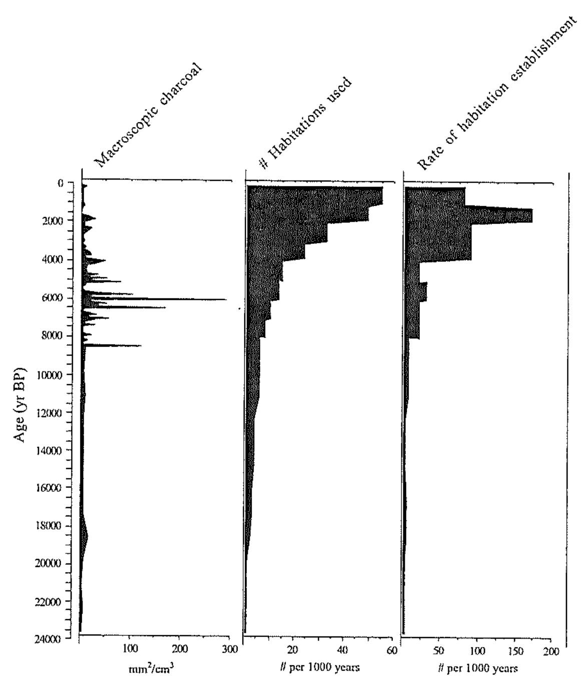

Figure 5 A comparison of the Lake Baraba charcoal curve with a summary of the archaeological data from the southern Sydney Basin compiled by Attenbrow (2004)

Turney *et al.* (2004) identified a 1490 yr cycle based on spectral analysis of peat humification data from Lynchs Crater in northern Queensland. They associated this cycle with changes in precipitation and long-term changes in ENSO. A similar cyclicity in palaeo-ENSO has been identified in southern Ecuador (Moy *et al.*, 2002) and North America (Wang *et al.*, 2000). The 1300 yr cycle identified in the Gooches Swamp charcoal record may be related to these palaeo-ENSO cycles, further suggesting the climatic control of fire activity at Gooches Swamp.

Based on the comparison of the Capertee 3 archaeological sequence and the Gooches Swamp charcoal curve there does not appear to be any clear association between human activity and fire. However, as previously discussed, the archaeological history of the Blue Mountains is not well understood and it is possible that future archaeological investigations may reveal a stronger relationship. As an example, archaeological evidence from the Sydney region suggests that there were increases in Aboriginal activity from the mid to late Holocene. However, the evidence at hand suggests that the fire history of the Gooches Swamp landscape is responding predominately to climatic controls.

The variability in charcoal at Gooches Swamp since the mid Holocene may also be related to changes in the biotic and abiotic dynamics of the swamp. It is plausible that as the sediment has built up through time the vegetation on the swamp surface has burnt more frequently. This scenario, however, is not supported by the palynology at the site (Black and Mooney, 2006), which demonstrates little vegetation change during the Holocene that would be expected with any seral development of the vegetation. The water-table is likely to have risen concurrently with the accumulation of sediment, since the sediment is accumulating as a result of a rock-fall dammed constriction.

Charcoal values at Lake Baraba are very low during the late Pleistocene/early Holocene and increase dramatically at ~8.5 ka. During this time the number of habitations used in the region by Aboriginal people increase also, hence changes in fire activity could be attributed to humans. Alternatively the increase in charcoal may be related to burning of increased biomass accompanying climatic amelioration.

Abiotic influences are also likely to have affected the charcoal record at Lake Baraba since there is a change in the depositional environment at ~8.5 ka. This change, from a lake to a swamp environment, would occasionally allow fire to consume the vegetation of the swamp surface, thereby explaining why more charcoal was found in the peat sediments compared with the lacustrine clays of Lake Baraba. There is no clear relationship between ENSO frequency and the fire history of Lake Baraba. At this site

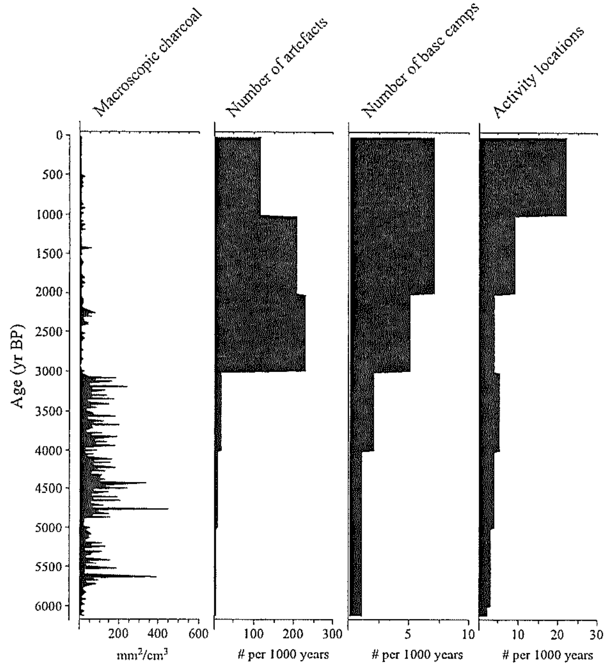

Figure 6 A comparison of the Kings Waterhole charcoal curve with the archaeological data from the Upper Mangrove Creek catchment (Attenbrow, 2004)

there is a marked decrease in charcoal in the late Holocene as regional archaeological indices increase dramatically.

Charcoal increases abruptly at 5.7 ka at Kings Waterhole and this is coeval with the increase at Gooches Swamp and hence is also likely to be associated with the onset of 'modern' ENSO conditions. Charcoal values remain high and variable from this time until 3 ka and this probably reflects intense fires under an ENSO-dominated climate. At 3 ka charcoal decreases dramatically and remains low for the rest of the record, a trend that mirrors that of Lake Baraba. At Kings Waterhole there is no evidence of any depositional change nor any major vegetation change, as indicated by palynology (Black and Mooney, 2007), to have impacted on the charcoal record. This marked change at 3 ka is, however, temporally associated with changes in the archaeological record of the Upper Mangrove Creek catchment and hence this change in fire activity is likely to be associated with human activity.

The decreased level of charcoal in the late Holocene at both Lake Baraba and Kings Waterhole are hence thought to indicate an anthropogenic change to the fire regime. As to why less charcoal was deposited at these sites under intensified human activity is perhaps best related to a frequent low-intensity fire regime associated with the management of natural resources (eg, Nicholson, 1981; Gott, 2005). Whitlock and Larsen (2001) suggested that fire regimes characterized by 'frequent and efficient ground fires' do not produce much charcoal. Regular low-intensity fires are likely to consume less biomass and hence the production and deposition of charcoal is low, especially if fires within the catchment were relatively small in area.

Previous Australian studies have attributed changes in charcoal to the intensity of fire. Singh *et al.* (1981: 43) argue that the 'greater amounts of charcoal particles and the large fluctuations . . . may be consistent with a pattern of intermittent high-intensity fires with considerable accumulation of litter between them' from Lashmars Lagoon. They also suggest that relatively small amounts of charcoal with lower variability may reflect more frequent and less intense fires but with less accumulation of fuel. Hope (1994) also interprets increases in charcoal as reflecting a change in fire regime from frequent burning to periodic, destructive and intense fires ignited by lightning or the occasional human visitation.

This suggests that during the late Holocene at Lake Baraba and Kings Waterhole Aboriginal people may have intensively managed the landscape. The data also imply that at these sites the swamp surface was not burnt, which is somewhat at odds with previous general descriptions (eg, Gott, 2005) but may reflect the utility of the vegetation found at both sites. Preventing the burning of the swamp surface, by applying high frequency/low intensity to the woodland surrounding the sites, may have protected certain resources, for example food such as turtles and freshwater crustaceans, which survive within these swamps. Perhaps the risk of more intense fires under an ENSO-dominated climate meant that there was an increased need for Aboriginal people to manage fire in some landscapes (eg, Lake Baraba and Kings Waterhole) and the attendant climatic variability also resulted in changes to other management strategies for food procurement.

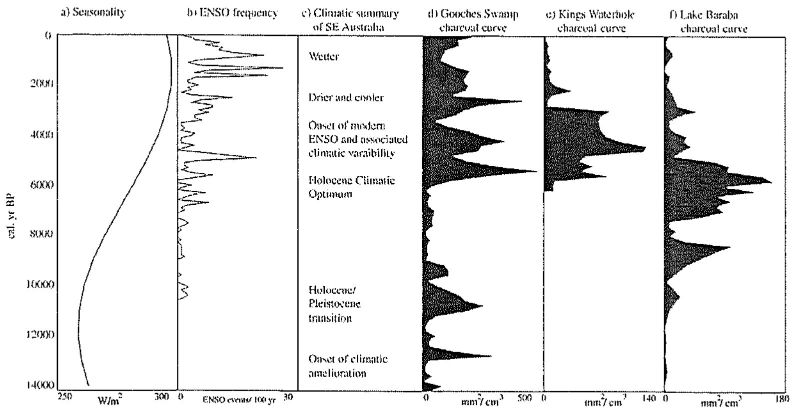

Figure 7 (a) Seasonality at 30°S based on the difference in insolation between summer and winter (Berger, 1992). (b) The frequency of ENSO events per 100 years based on Moy *et al.* (2002). (c) The climatic summary of southeastern Australia (Lees, 1992; Shulmeister, 1999; Kershaw *et al.*, 2002). (d) The smoothed Gooches Swamp charcoal record constructed by summing the 200 yr values. (e) The smoothed Kings Waterhole charcoal record constructed by summing the 200 yr values. (f) The smoothed Lake Baraba constructed by summing the 200 yr values

Conclusion

The three fire records presented here from the Sydney Basin display some key differences, however a number of generalizations can be drawn from the study. The study also has implications for a much wider audience, as the separation of human and natural causes of environmental change is a significant and global endeavour. Similarly, the role of indigenous people in prehistoric landscapes, how fire responds to climate change and variability and the application of palaeoenvironmental information to contemporary environmental issues all have wide applicability.

In southeastern Australia pre-European fire activity is popularly associated with Aboriginal people, however at Gooches Swamp climate appears to be the dominant control of fire activity over the last ~14 200 years. The Gooches Swamp record was most greatly influenced by climate with periods of climatic instability, such the Lateglacial transition and the onset of ENSO-dominated climates from the mid Holocene, associated with higher levels of charcoal. We suggest that the elevated levels of charcoal are due to an increased frequency of intense fires in the catchment and on the woody, wet heath vegetation of the swamp surface. It appears that the Gooches Swamp record is responding to a regional climatic signal resulting in strong similarities with Haberle *et al.*'s (2001) charcoal curve from the Sahul region. At Gooches Swamp anthropogenic influences are not readily discernable, based on the current archaeological data from the Blue Mountains.

At Kings Waterhole an increase in charcoal occurred at about the same time as at Gooches Swamp, also likely reflecting ENSO-related climatic variability. However, at Kings Waterhole charcoal levels decreased dramatically at the same time as Aboriginal activity intensified in the region. This decrease was also found at Lake Baraba and an altered regime to small scale, less intense but more frequent fires caused by anthropogenic activity is suggested as a cause. Although humans are likely to have manipulated fire, it is probable that this occurred within a framework dictated by the prevailing climate of the time. For example, the risk of more intense fires under a strengthened ENSO-dominated climate may have increased the need for Aboriginal people to closely manage fire, especially in these fire-prone vegetation communities. This creates a complex nexus between climate and humans, resulting in significant variability in fire through time in the region. The charcoal record of Lake Baraba was complicated since there was a change in the depositional environment from a lake to a swamp at ~8.5 ka and this had taphonomic implications for charcoal representation.

The spatial and temporal variations in fire activity within the small geographical region of the Sydney Basin mean that there is not a single pre-European fire management strategy that can be applied across the entire region. The conclusions of this study mirror those of Head (1989: 41) who noted that there is a common assumption that Aborigines 'had a single ongoing impact': this erroneous assumption ignores climatic change and human population and cultural changes. Furthermore, the predominance of climate as a control on past fire activity has been described by Kohen (1996) and Kershaw *et al.* (2002). Kohen (1996: 20–21) concluded 'perhaps what we are observing in the last few thousand years is the struggle between anthropogenic fires and climate, with climate seeming to come out in front in most situations'. Similarly Kershaw *et al.* (2002: 19) observed that '(the) relative importance of climate and human influence is difficult to assess but evidence . . . suggests that climate was the major driving force'.

This study also highlights the important influences of climate change and variability on fire activity. At Gooches Swamp fire was not necessarily linked with a drier climate but there was an apparent increase in fire activity during periods of climate change. The longer temporal perspective afforded by this study demonstrates that fire appears to be related to ENSO through time, however the nature of this relationship requires

DAY 4.

Information on "Hanging Swamps" is available at:http://www.aabr.org.au/index.php?option=com_content&task=view&id=55&Itemid=74

The Edge

The Edge is a cinema experience (with a six storey high screen) which purports to explain "the story of discovery and coming to terms with the ancient, complex and fragile Blue Mountains". It is pitched at the wrong level for this group but contains some absolutely stunning footage of inaccessible parts of the Blue Mountains (including the Wollemi pines).

A Holocene History of the Vegetation of the Blue Mountains, New South Wales

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The Greater Blue Mountains Area has been inscribed on the World Heritage list for its exceptionally diverse *Eucalyptus* communities. Hanging swamps in this region, listed as 'vulnerable ecological communities', accumulate sediments that contain the palaeoenvironmental record. Seven of these swamps have been studied, revealing a history of the vegetation, climate and fire regimes.

Palynological analysis of each swamp reveals a history of the surrounding vegetation. There are similarities and parallel changes between some of the swamps allowing generalities about the climate of the Holocene to be made. In the early Holocene, about eleven to nine thousand years ago (11-9 ka), the vegetation was more wooded and the climate was probably somewhat warmer and wetter. By the mid Holocene about 6-4 ka, trees were less dominant in the vegetation suggesting that the climate was probably drier. By 3-2 ka, wooded vegetation had mostly returned, and after 2 ka, *Baeckea, Leptospermum, Kunzea* and *Melaleuca* species increased somewhat, with further increases in European settlement time, possibly reflecting a reduction or thinning of the wooded canopy.

Charcoal analysis of the accumulated sediments suggest that there was more fire in the early Holocene when trees increased the biomass. There was less fire through the mid Holocene when the biomass was lower, but it increased with the return to more wooded vegetation in the late Holocene. In particular, the woody shrubs of *Baeckea, Leptospermum, Kunzea* and *Melaleuca* increased with an increase in charcoal, probably because these shrubs benefit from a more open canopy, but they also grew on the swamps hence could deposit charcoal directly into the sediments. Charcoal values are particularly high after European settlement. It is possible that the disruption of Aboriginal burning practices allowed the increased growth of woody shrubs and hence a much greater fuel load.

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KEY WORDS: Blue Mountains, Climate change, Fire history, Palynology, Vegetation history.

INTRODUCTION

The Greater Blue Mountains Area was inscribed on the World Heritage List in December 2000. The Blue Mountains are a deeply incised sandstone plateau rising to over 1,300 m at its highest point. This plateau is thought to have enabled the survival of a rich diversity of plant and animal life by providing a refuge from climatic changes during the recent geological history. It is particularly noted for its wide representation of habitats, from wet and dry sclerophyll, mallee heathlands, as well as localised swamps, wetlands and grassland. Ninety one species of eucalypts are found in the Greater Blue Mountains Area and twelve of these are believed to occur only in the Sydney sandstone region (Australian Government, Department of the Environment and Water Resources, 2007a).

The area has been described as a natural laboratory for studying the evolution of the eucalypts (Australian Government, Department of the Environment and Water Resources, 2007a). The steep terrain and sharp environmental gradients have allowed for major evolutionary change in some taxa, resulting in exceptional biodiversity, particularly within the eucalypt communities that dominate the place. Importantly, the evolutionary processes underpinning this diversity are believed to be ongoing, resulting in an evolutionary 'laboratory' that is exceptional in the world (Australian Government, Department of the Environment and Water Resources, 2007a).

Peat formation on sandstone, the substrate of most of the Blue Mountains, is very unusual. The hanging swamps of the Blue Mountains are especially notable and have lower sediment loads and accumulate organic matter more slowly than valley swamps and swamps along watercourses. They are also easily eroded with any disturbance. The small geographic distribution and demonstrable threat has meant that these hanging swamps are now listed as 'vulnerable ecological communities' under the NSW Threatened Species Conservation Act of 1995 ((Australian Government, Department of the Environment and Water Resources, 2007b; Sullivan, 2007)

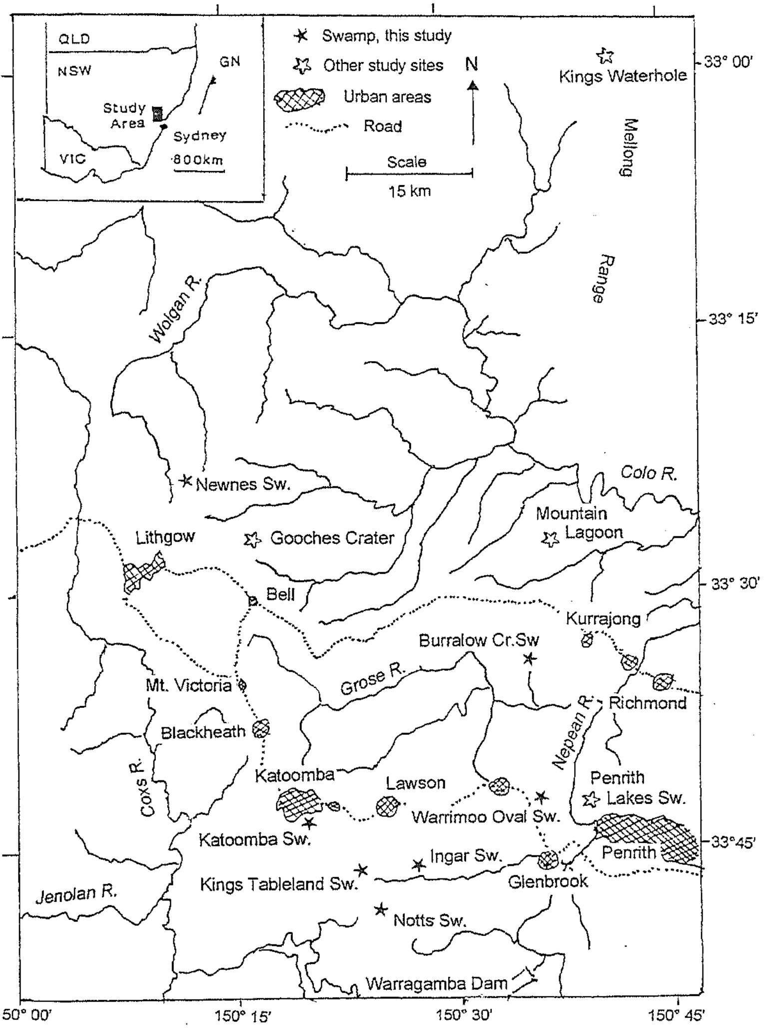


Figure 1. Locality map.

Seven swamps in an altitudinal sequence in the Blue Mountains (Fig. 1) were chosen for a palynological study and are described in Chalson and Martin (this volume). A method to identify *Eucalyptus* pollen to species was developed (Chalson and Martin, 1995) with the aim of revealing the history of the eucalypt communities of the region. At the beginning of the Holocene, 10,000 years ago, the climate was approaching that of today, but there have been changes through the Holocene (Allan and Lindsay, 1998). The history of the Holocene is thus the history of vegetation very like that of today.

THE ENVIRONMENT

Geology and geomorphology

The Blue Mountains consist of a deeply dissected plateau rising from the Cumberland Plain in the east, along the Lapstone Monocline. Elevation is about 30 m in the east to over 1,000 m in the west. The sedimentary rock units are Triassic in age and curve upwards, from east to west, towards the edge of the Sydney Basin. In the east, Wianamatta Shale outcrops along the side of the Lapstone Monocline. West of the Monocline, the underlying Hawkesbury Sandstone Formation outcrops and further west, underlying the Hawkesbury Sandstone, the Grose Sub-Group of the Narrabeen Group outcrops. The Grose Sub-Group is divided into a number of formations and the ones encountered in this study are as follows: The Banks Wall Sandstone Formation, within which is found the Wentworth Falls Claystone Member, and the basal Burra-Moko Head Sandstone Formation, which is the most prominent cliff-forming unit in the Blue Mountains (Bembrick, 1980).

The plateau surface is undulating with small creeks forming upland valleys. In areas where Hawkesbury Sandstone is the underlying rock type, the upland valleys progressively increase in gradient as they incise below the plateau surface and develop steeply inclined V-shaped gorges with only minor benching in the valley sides. To the west, where the Banks Wall Sandstone formation is the underlying rock type, the valley sides and floors slope gently and the streams do not incise but flow across a series of swamps and sandy peat deposits. Eventually, the streams cut through a sandstone layer into claystone or shale when a nickpoint (often a waterfall) is formed (Langford-Smith, 1976).

The development of the swamps in these two areas varies enormously. The eastern region supports few swamps which are usually associated with large streams that have a central channel and flowing water. In the western region, there are more swamps and they are developed in broad shallow valleys with no marked central stream but rather experience a general slow flow of water across the whole area (Langford-Smith, 1976).

The climate

Maximum temperatures in the Blue Mountains relate strongly to altitude. Average January maxima are highest at the lower altitudes, 29 °C at Richmond and lowest at the higher altitudes, 23 °C at Mt. Victoria. Average minimum temperatures generally decrease from east to west. The July minima range from 3.4 °C at Richmond to –0.8 °C at Lithgow (Table 1). Temperatures as low as –3 °C have been recorded from Katoomba (BoM, 2006; Bureau of Meteorology, 1979).

Rainfall patterns relate to elevation and distance from the coast. The average annual rainfall increases from 806 mm at Richmond to 1424 mm at Newnes (Table 1). The driest months are usually July to September and the wettest are December to March (BoM, 2006; Bureau of Meteorology, 1979).

Winds from the west or northwest dominate all the year, although there are significant easterly and northeasterly winds during the summer months of November to April. Fogs frequently occur on the higher Blue Mountains, with Katoomba and Mt. Victoria recording an average of 55 and 90 fog days per year, respectively (BoM, 2006). Frosts occur on 35 to 40 days of the year, mostly between April and November. Snow falls most frequently in July and August: Katoomba and Mt. Victoria have and average of 3 and 10 snow days per year, respectively (Bureau of Meteorology, 1979).

Soils

The quartz-rich sandstones in the area are low in most nutrients, and thus soil and alluvium derived from sandstones are low in nutrients. The soils are mainly lithosols and yellow podzolics with small areas of red and lateritic podzolic soils and sandy alluvial soils in the valleys. Most of the soils are moderately acidic, with pH values of 4.5 to 5. In rugged terrain, rock commonly lies near or at the surface. The soil fertility in the valleys may be higher because of the accumulation of organic matter (Chalson, 1991)

Vegetation

The vegetation is almost entirely dry sclerophyll woodland and open forest, the 'Sydney Sandstone Complex' (Keith and Benson,1988) with localised swamps in the valleys. There are small patches of tall open forest or wet sclerophyll in specially favourable habitats, such as protected gorges. Heathlands are found in the harshest environments.

Table 1. Climatic Averages. Stations are arranged according to altitude.

Station and altitude (m)	Mean max. temp, hottest month, (Jan.) °C	Mean min. temp, coldest month, (June or July) °C	Mean annual rainfall, mm
[1]Richmond, 19-20 [3]	29.5	3.4	806
[2]Penrith, 27	-	-	786
[2]Springwood ~400	-	-	1076
[2]Kurrajong Heights, ~550	-	-	1253
[2]Lawson, 715	-	-	1260
[2]Wentworth Falls, ~900			1409
[1]Lithgow (Birdwood St.), 950	25.5	0.7	860
[1]Katoomba, 1030	23.1	2.5	1398
[1] Mt Victoria, 1064	23.0	1.7	1061
[2]Blackheath PO, 1065	-	-	1145
[1]Lithgow (Newnes Forest Centre), 1050	23.2	-0.8	1072

1 From BoM (2007). 2 From Bureau of Meteorology (1979)
3 Average of Richmond RAAF and Richmond UWS Hawkesbury

Open forest with *Angophora costata*, *Eucalyptus piperita*, *E. agglomerata* and *Syncarpia glomulifera* dominant is found in sheltered gullies with moist, well-drained soils on the Hawkesbury and Narrabeen Group sandstones. The understorey includes small trees of *Allocasuarina torulosa* and *Acacia elata*, with shubs of *Hakea dactyloides*, *Pultenaea flexilis* and *Dodonaea triquetra*. Tall open forest is restricted to the more sheltered gorges and is dominated by *E. deanei* with *Syncarpia glomulifera*, *Acacia elata*, *Ceratopetalum apetalum*, *Callicoma serratifolia* and *Angophora floribunda*. There is a distinctive riparian scrub of *Tristaniopsis laurina* and *Backhousia myrtifolia* along the larger water courses (Keith and Benson,1988),

Woodland and low woodland with *Corymbia gummifera*, *Eucalyptus sclerophylla* and *E. oblongata* dominant is widespread on ridges and open slopes on shallow, well-drained soils of the Hawkesbury and Narrabeen Group sandstones. *E. punctata*, *E. piperita* and *Angophora costata* may be present in the more sheltered sites. *E. sclerophylla* is particularly common on damper soils. The understorey is rich in shrubs of the Proteaceae, Myrtaceae and Fabaceae (Keith and Benson,1988).

There are other woodlands: the 'Tablelands Grassy Woodland Complex' with *Eucalyptus dives*, *E. mannifera*, *E. eugenioides*, *E. pauciflora*, *E. rubida*, *E. aggregata* and *E. stellulata* the common species. The 'Snow Gum Woodland' has *E. pauciflora*, *E. dalrympleana*, *E. rubida* and *E. stellulata* dominant (Keith and Benson,1988).

Open heath communities have *Eucalyptus stricta*, *Allocasuarina nana* and *Leptospermum trinervium*, *Phyllota squarrosa*, *Eriostemon obovalis*, *Epacris reclinata*, *Dracophyllum secundatum* and *Gleichenia rupestris* dominant. *Phyllota squarrosa* and *Eriostemon obovalis* are common in montane heaths whereas *Phyllota phylicoides* and *Eriostemon hispidula* are common on the Lower Blue Mountains heath. Many other smaller shrubs are found in these heath communities (Keith and Benson,1988).

Closed heath or 'Newnes Shrub Swamps' have *Leptospermum lanigerum*, *Baeckea linifolia*, *Grevillea acanthifolia* and *Xyris ustulata* dominant. They are found in shallow valleys above 1,000 m elevation in swamps, with poorly drained, acid and sandy peat soils. There is a ground cover of sedges including *Baloskion australe*, *Empodisma minus*, *Lepyrodia scariosa*, *L. anathria*, *Lepidosperma limicola* and small shrubs (Keith and Benson,1988).

Closed sedgeland, the 'Blue Mountains Sedge Swamps', have *Gymnoschoenus sphaerocephalus*, *Lepidosperma limicola*, *Xyris ustulata* and *Baeckea linifolia* dominant. These sedge swamps are found at lower altitudes than the closed heath swamps and occupy steep-sided basins (the 'hanging swamps'). They are intermittently waterlogged and have shallow sandy soils. Many sclerophyllous shrubs form an open heath (Keith and Benson,1988).

For a full description of the specific vegetation found at each site, see Chalson and Martin (this volume).

Human Occupation

The Blue Mountains, especially the lower part, was highly favourable to the hunter-gatherer, (Stockton,1993a). Movement was relatively easy on the ridges, water was not scarce while flora and fauna suitable for food were both plentiful and varied. The rivers were also a source of rock types used for tool making.

Campsites with an abundance of worked stone were particularly common in the Lower Blue Mountains. In the Upper Mountains, there were fewer campsites than in the Lower Mountains, but their concentration of flaked stone showed that they have been equally well used. The Central Mountains reveal many rockshelter sites where there were fewer stone artifacts than the Upper and Lower Mountains. However, there was a high concentration of rock art, engravings, paintings and axe grinding grooves. This suggests that the Upper and Lower Mountains were used for survival but the Central Mountains were more of religious and ritual significance (Stockton,1993a).

It is generally presumed that the climate in the Blue Mountains was too severe for year-round occupation during the ice age. However, protected sites such as the rock shelters would have been livable, especially if protected from the bitter westerly winds. (Stockton,1993b).

The oldest signs of occupation in the Blue Mountains were found at Kings Tableland, Wentworth Falls with the oldest date of 22,240 years BP. Walls Cave at Blackheath and Lyre Bird Dell, Leura both yielded dates of more than 12,000 years BP. There were other sites, e.g. Hazelbrook, to 7,200 years BP, Springwood Creek Rock Shelter, from 8,500 years BP up to European times and open sites, e.g. Jamison Creek. Evidence from the Nepean River, at the foot of the Blue Mountains suggests human occupation could go back to 40,000 years BP. In all, there were over 700 Aboriginal sites in the Blue Mountains (Stockton, 1993b; Attenbrow, 2002).

With the coming of Europeans, both Europeans and Aborigines avoided each other and early travelers in the Mountains rarely saw any Aborigines. Settlers followed the first crossing of the Mountains in 1813 by Blaxland, Lawson and Wentworth (Breckell, 1993) After some skirmishes about the land the settlers had taken, Aborigines and Europeans co-existed, though not without racist incidents (Smith, 1993).

METHODS

Seven swamps in an altitudinal sequence were chosen for study and they are described in Chalson and Martin (this volume). A study of the pollen in surface samples from swamps (Chalson and Martin this volume) provides insights that assist in the interpretation of the pollen spectra from the sediments. The description of the vegetation at each site is also presented in Chalson and Martin (this volume).

The swamps were systematically probed to identify the area where accumulating sediments were the deepest, using a Russian D-corer (Birks and Birks, 1980). The sediments and stratigraphy were described using the terminology of Birks and Birks (1980) Samples for radiocarbon dating were taken from a pit where possible, otherwise with repeated use of the D-corer until sufficient sediment was acquired. The standard radiocarbon dates were calibrated using the CalPal (Version March 2007) program.

Samples of sediment were taken from the core every 10 cm, or where it was thought there could be a critical change, every 5 cm. For pollen preparations, the core sediments were spiked with *Alnus* of a known concentration, treated with hydrochloric and hydrofluoric acids to remove siliceous material (Birks and Birks, 1980), oxidised with Schultz solution (a saturated solution of potassium perchlorate in nitric acid), cleared in 10% potassium carbonate and the residue was mounted in glycerine jelly (Brown, 1960). Reference pollen was treated with standard acetolysis (Moore et al., 1991) and also mounted in glycerine jelly.

Pollen was identified by comparing grains from the core with a collection of reference pollen. Special attention was paid to pollen of the family Myrtaceae which may be identified to species following the method in Chalson and Martin (1995).

Pollen was counted along transects across the slides and tests showed that a count of more than 140 grains adequately sampled the residues. The counts were presented as percentages of the total count and pollen concentrations were calculated for the most abundant pollen groups. Percentages are relative and a change in a single pollen group will affect percentages of all the other groups, but presenting both percentages and concentrations will reveal fluctuations in individual pollen groups.

The abundance of charcoal retained on a 150 μm sieve, as part of the palynological preparation, was estimated subjectively on a scale of 0 to 8. Counts of microscopic charcoal for a swamp at Kings Tableland showed that the two methods gave similar results, although the microscopic charcoal was more variable (Chalson, 1991).

RESULTS

Burralow Creek Swamp

Burralow Creek Swamp, at 33° 32'S, 150° 36' 38"E and 310-330 m altitude, is situated in a narrow V-shaped valley and follows the course of the creek for some 3.5 km. The substrate is Hawkesbury Sandstone, but Wiananatta Shale outcrops on the surrounding ridge-tops. The upper reaches of Burralow Creek drain urban areas and farmland areas. An isolated farm adjacent to the swamp was incorporated into the Blue Mountains National Park. Weed growth from this farm is confined to a small area and has not spread into the adjacent bushland.

Stratigraphy: Sediments were recovered to a depth of 310 cm. Clayey peat was found down to 10 cm, humic clay at 15-50 cm and humic sandy clay at 60-70 cm. Sand was encountered at 80-260 cm and clay/sand at 260-310 cm. The radiocarbon dates are presented in Table 2.

Swamp vegetation and surface pollen: Species of *Kunzea* and *Leptospermum* were dominant on the swamp but Restionaceae, Cyperaceae and *Selaginella* species were also present (Chalson and Martin, this volume). Surface sample pollen from the swamp (Chalson and Martin, this volume) showed appreciable *Leptospermum/Baeckea* and a considerable amount of Restionaceae or Cyperaceae in some samples. The fern spore content was low.

The pollen record: The pollen spectra from the sediments is presented in Figs 2A, 2B and has been divided into the following zones:

310 to140 cm, no pollen recovered.

Zone E, 130 cm, age ? > 1,200 cal yr BP (see Fig. 3 for estimated ages). *Angophora floribunda*, *Eucalyptus* spp. and possibly Casuarinaceae pollen were the most abundant of the possible arboreal groups. There was a moderate representation of Poaceae and *Selaginella* (Fig 2A) and other shrubs and herbs were present in low frequencies (Fig 2B).

120-110 cm, no pollen recovered.

Zone D, 100-90 cm, age c. 1,200 –1,000 cal yr BP. This zone had a very high proportion of *Selaginella* spores and low proportions of everything else, including tree pollen. The pollen concentrations showed a similar pattern to that of the percentages which revealed a change in the whole pollen spectrum, not only reflecting the addition of a large number of *Sellaginella* spores to spectra otherwise like that in zone E.

Zone C, 80-60 cm, age c. 1,000-800 cal yr BP The Sellaginella content had decreased considerably when compared with the zone brlow. There was a high proportion of Casuarinaceae and Myrtaceae, including *Eucalyptus* species and the Poaceae content was low.

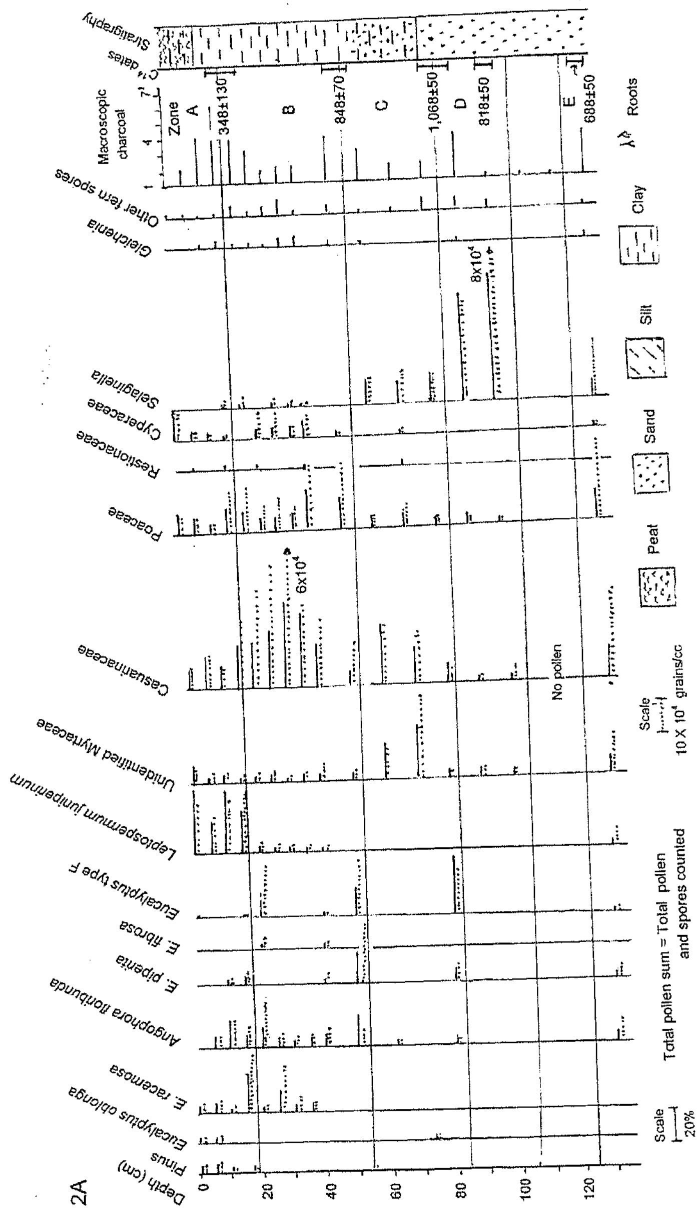
Zone B, 50-20 cm, age c.8700-250 cal yr BP. The Casuarinaceae content had increased and was the highest for the profile. *Eucalyptus* species and *Angophora floribunda* were well represented and *Leptospemum juniperinum* was present in low frequencies. There was a moderate content of Poaceae and Cyperaceae, with a diversity of fern spores. *Sellaginella* content was minimal.

Zone A, 15-0 cm, age c. 250-present, cal yr BP. European *Pinus* was found in this Zone and there was a high content of *L. juniperinum*. There was some change in the *Eucalyptus* species, Casuarinaceae declined. and the Poaceae content was moderate, when compared with the zone below.

Charcoal content was low to moderate through most of the profile, with a somewhat higher content at the base of Zone A, the zone of European influence.

Table 2. Radiocarbon ages for Burralow Creek Swamp

Depth (cm)	Material dated	Laboratory no.	Radiocarbon years (yr BP)	Calibrated age (cal yr BP.)
15-20	Humic clay	SUA-2607	250 ±50	348±130
50-60	Humic sandy clay	SUA-2608	830±60	848±70
80-90	Sand	SUA-2609	1,070±50	1068±50
95-105	Sand	SUA-2610	820±50	818±50
125-135	Sand	SUA-2611	660±55	688±50



Figures 2A, 2B. Burralow Creek Swamp pollen spectra. For probable source of the pollen type in the vegetation, see Appendix.

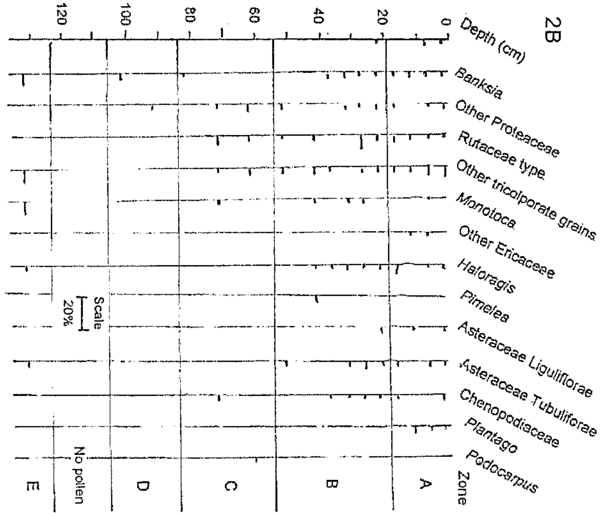


Figure 2 continued

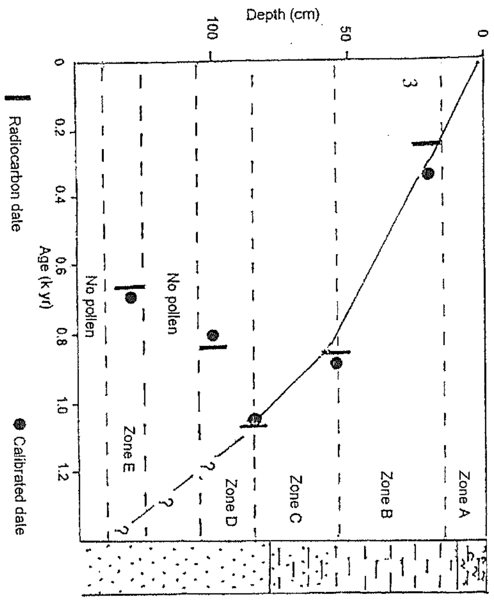


Figure 3. Burralow Creek Swamp summary diagram.

History of the vegetation: Initially, more than 1,200 cal yr BP, there was a mixed tree cover of Myrtaceous species and possibly Casuarinaceae with a moderate Poaceae understorey. *Selaginella*, was prominent on the swamp. A period of possibly a reduced tree cover followed, with an expanded swamp area with abundant *Selaginella* about 1.2-1.0 cal ka. Alternatively, if the swamp area was larger, the trees may have been further away, hence they contributed less pollen to the spectrum. The tree cover increased and *Selaginella* was much reduced by about 1-0.8 cal ka. At this time, the clay content of the sediments increased, perhaps indicating a less energetic water flow. Casuarinaceae became prominent about 0.8-0.25 cal ka with less Myrtaceae, although a diversity of species was identified. Simultaneously, *Sellaginella* decreased while Cyperaceae and Poaceae increased. In the European zone, there was some change in *Eucalyptus* species and a big decline in Casuarinaceae while *Leptospermum juniperinum* became prominent.

Fire was a constant factor in the environment, especially in the early part of the European zone.

Warrimoo Oval Swamp

Warrimoo Oval Swamp, at 33° 43' 21.44"S, 150° 36' 58.35"E and 190-200 m altitude, is situated in a V-shaped valley with a stream flowing through it. The substrate is Hawkesbury Sandstone, but Wiananatta shale outcrops on the surrounding ridge-tops. Substantial urban areas occur within a kilometre from the swamp and weed invasion is considerable.

Stratigraphy: Total depth recovered was 250 cm. The top 20 cm was peat, then sandy peat down to 50 cm. A layer of sand was found between 50 and 90 cm, then sandy silt down to 200 cm, then sand down to 250 cm when coring stopped (Fig. 4A). The radiocarbon dates are given in Table 3.

Swamp vegetation and surface pollen: Species of *Baeckea, Kunzea* and *Leptospermum* were dominant on the swamp. Cyperaceae, Juncaceae and *Gleichenia* species were also present (Chalson and Martin, this volume). The pollen spectra from the surface samples (Chalson and Martin, this volume) contained appreciable *Melaleuca*, *Baeckea/Leptospermum* and *Gleichenia* species.

The pollen record: The pollen spectra from the sediments are shown in Figs 4A, 4B.

Zone B, 250-130 cm, c. 4,700-2,200 cal yr BP (for estimated ages, see Fig. 5). Abundant *Gleichenia* denoted this zone, The Myrtaceae content was low, with some of the pollen identifiable to genus/species. There was a consistent content of Casuarinaceae and *Haloragis,* and Poaceae was almost entirely absent.

Zone A, 120 cm to surface, c. 2,200-present cal yr BP. There was very little *Gleichenia,,* together with an increase in the Myrtaceae and Casuarinaceae content, when compared with the zone below. The Poaceae, Cyperaceae and Restionaceae content was higher and the pollen flora considerably more diverse when compared the preceding zone. *Pinus* was found down to a depth of 20 cm, thus denoting the European influence, where *Baeckea/Leptospermum* species increased and Casuarinaceae decreased.

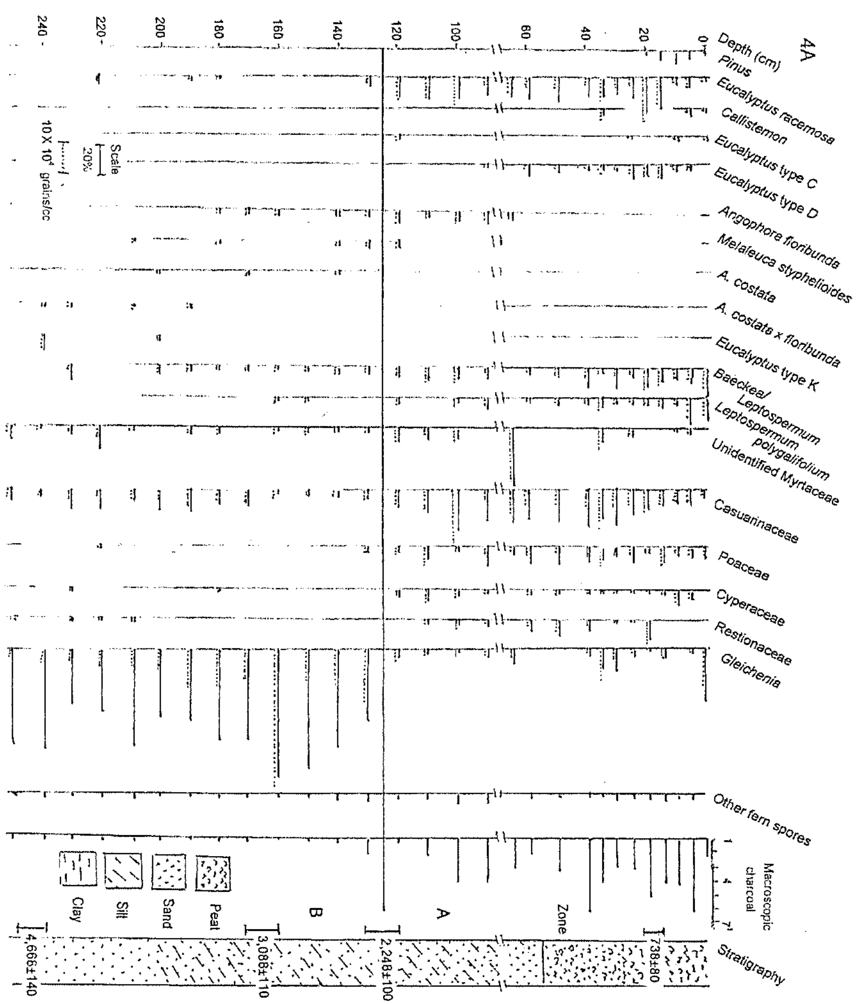
The charcoal content was consistently very low in zone B (4.7-2.2 cal ka) and higher in zone A (2.2 cal ka to present).

History of the vegetation: From about 4.7-2.2 cal ka, myrtaceous species and Casuarinaceae dominated open vegetation communities. The swamp supported abundant *Gleichenia*. About 2.2 cal ka, the tree cover of the dryland vegetation increased, with *Eucalyptus* spp and *Leptospermum* spp. becoming more diverse and abundant. Casuarinaceae was also more abundant. *Gleichenia* declined dramatically, but this change was not accompanied by any visible change in the sediments.

Fire appears to have been a rare feature of the environment when *Gleichenia* was dominant. With the change to a more diverse flora and increase of *Leptospemum* in the swamp community after 2.2 cal ka, fire was more common, particularly in the

Table 3. Radiocarbon ages for Warrimoo Oval Swamp

Depth (cm)	Material dated	Laboratory no.	Radiocarbon years (yr BP)	Calibrated age (cal yr BP)
15-25	Peat	SUA-2603	730±80	738±80
120-130	Sandy silt	SUA-2604	2,190±80	2,248±100
160-170	Sandy silt	SUA-2605	2,880±70	3,088±110
240-250	Sand	SUA-2606	4,060±80	4,668±140



Figures 4A, 4B. Warrimoo Oval Swamp pollen spectra. For probable source of the pollen type in the vegetation, see Appendix.

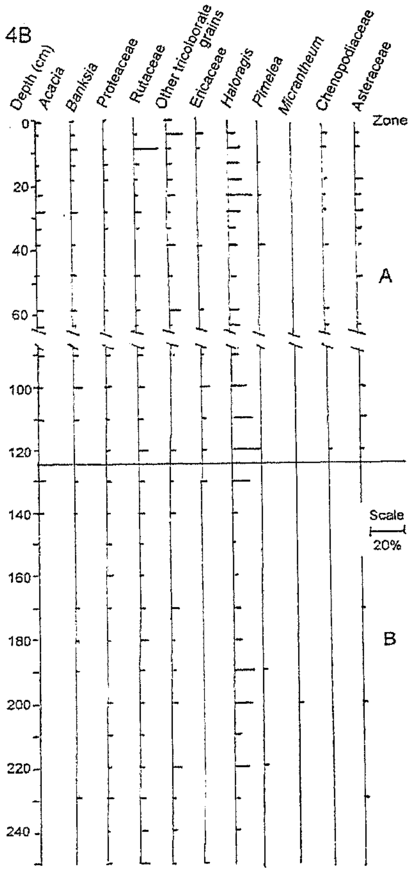


Figure 4 continued

European part at the top of the profile. There would have been a greater biomass after 2 cal ka, hence more fuel to burn, particularly on the swamp itself.

Notts Swamp

Notts Swamp, at 33° 48' 35.44" S, 150° 24' 27.66" E and about 682 m altitude is located in a shallow hanging valley. Below the swamp, Reedy Creek flows over a small cliff and follows a steep, narrow valley into the Kedumba Valley. The Wentworth Falls Claystone Member outcrops near the base of the swamp.

The lower third of the swamp is used for a market garden, but there is no sign of disturbance or weed invasion on the upper part of the swamp used for this study. There is no indication of European activities in the catchment upstream of the study site and the nearest settlement is some 7 km to the north-northeast.

Stratigraphy: The core recovered 130 cm of sediment. There was dark brown and greyish brown peat with roots down to 50 cm, then black or very dark greyish brown clay at 60-100 cm, with dark grey or light grey sandy silt at 110-130 cm. Pollen was recovered throughout the sequence, sometimes in very high concentrations. Radiocarbon ages are given in Table 4.

The swamp vegetation and surface pollen: Species of *Kunzea, Gahnia* and *Leptocarpus tenax* were dominant on the swamp. Species of *Gleichenia, Selaginella, Leptospermum*, Cyperaceae, Juncaceae and a number of sclerophyllous shrubs were also present (Chalson and Martin, this volume). In the surface samples, Myrtaceae, Casuarinaceae and Restionaceae were well represented. There was appreciable *Pinus* pollen also. (Chalson and Martin, this volume).

The pollen record: The pollen spectra from the sediments are presented in Fig. 6A, 6B and is zoned thus:

Zone D, 110-130 cm, c. ?7,300-4,500 cal yr BP (for estimated ages, see Fig. 7). Myrtaceae pollen content was low and Casuarinaceae moderate. The *Selaginella* spore content was appreciable at the base, decreasing through the zone. The Restionaceae and Poaceae content was moderate and the lowest for the profile.

Zone C, 100-80 cm, c. 4,500-2,400 cal yr BP. The Myrtaceae, Restionaceae and Poaceae representation increased but the *Selaginella* content was much reduced when compared with the zone below, and this change coincided with a change in sediments to clay. *Gleichenia* and other fern spores increased somewhat when compared with the zone below.

Zone B, 70-30 cm, c. 2,400 cal yr BP. to ?modern. There were more identifications of the mytaceous pollen, an increase in Restionaceae and few *Gleichenia* and other fern spores when compared with the zone below. The *Selaginalla* and Cyperaceae content was minimal.

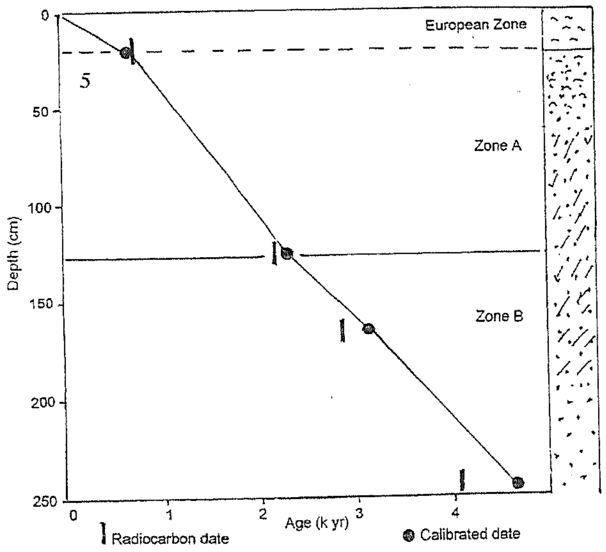


Figure 5. Warrimoo Oval Swamp summary diagram.

Zone A, 20-0 cm, modern. *Pinus* was found throughout the zone, indicating post European settlement. The Myrtaceae and Casuarinaceae pollen content was maintained. Restionaceae decreased towards the top and the Cyperaceae content, although low, is the greatest for the profile, when compared with the zones below

The charcoal content was very low at the base of the profile when *Selaginella* was prominent on the swamp, then increased after the decline in *Selagiella* and was consistently high in the European zone.

History of the Vegetation: About 7-4.5 cal ka, *Selaginella* was common on the swamp and the surrounding vegetation was an open woodland, with Casuarinaceae prominent. Fire was not common then. After about 4.5 cal ka, *Selaginella* was replaced by Restionaceae, the tree cover increased somewhat and fire became more common. The vegetation remained relatively stable until modern times when there was a slight decrease in Restionaceae and an increase in Cyperaceae. Charcoal abundance was higher when the tree cover was greater.

Ingar Swamp

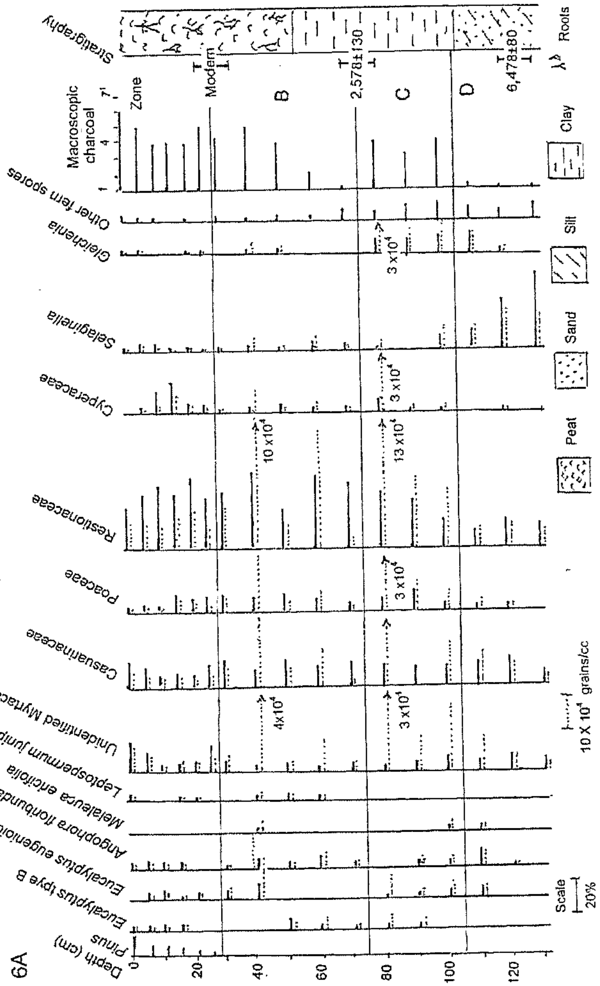
Ingar Swamp, at 33° 46' 11.65" S, 150° 27' 22.92" E and 584m altitude, is broad with many channels and hummocks of Cyperaceae forming ridges. The Banks Wall Sandstone Formation underlies the swamp and there are outcrops of the Wentworth Falls Claystone Member near the lower margin of the swamp. The swamp occupies the floor of a shallow hanging valley on the plateau surface. Below the swamp, Ingar Creek forms a waterfall where the valley gradient steepens.

Stratigraphy: The core recovered 155 cm of sediment. Peat with roots was found at 0-20 cm, then humic clay with roots at 25-110 cm, sandy humic clay at 120-130 cm, then sandy clay at 135-145cm, and silty clay at 150-155 cm. The radiocarbon ages are given in Table 5.

The swamp vegetation and surface pollen: Species of *Leptospermum*, Cyperaceae and Restionaceae were dominant on the swamp. *Gleichenia* and some sclerophyllous shrubs were also present (Chalson and Martin, this volume). The surface samples (Chalson and Martin, this volume) showed that most of the Myrtaceae pollen was

Table 4. Radiocarbon ages for Notts Swamp

Depth (cm)	Material dated	Laboratory no.	Radiocarbon years (yr BP.)	Calibrated age (cal. yr BP.)
25-35	Peat with roots	SUA 2653	1.O13±0.OO8x modern	Modern (<33)
75-85	Clay	SUA 2654	2,400±70	2,578±130
120-130	Sandy silt	SUA 2655	5,630±70	6,478±80



Fiuress 6A, 6B. Notts swamp pollen spectra. For probable source of the pollen type in the vegetation, see Appendix.

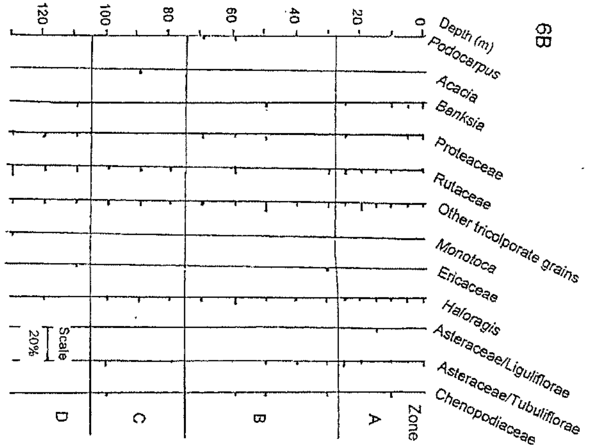


Figure 6 continued

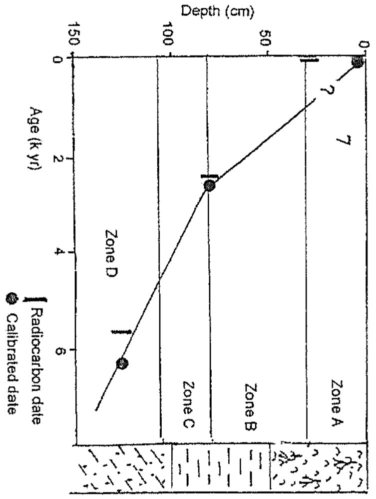


Figure 7. Notts swamp summary diagram.

Table 5. Radiocarbon ages for Ingar Swamp

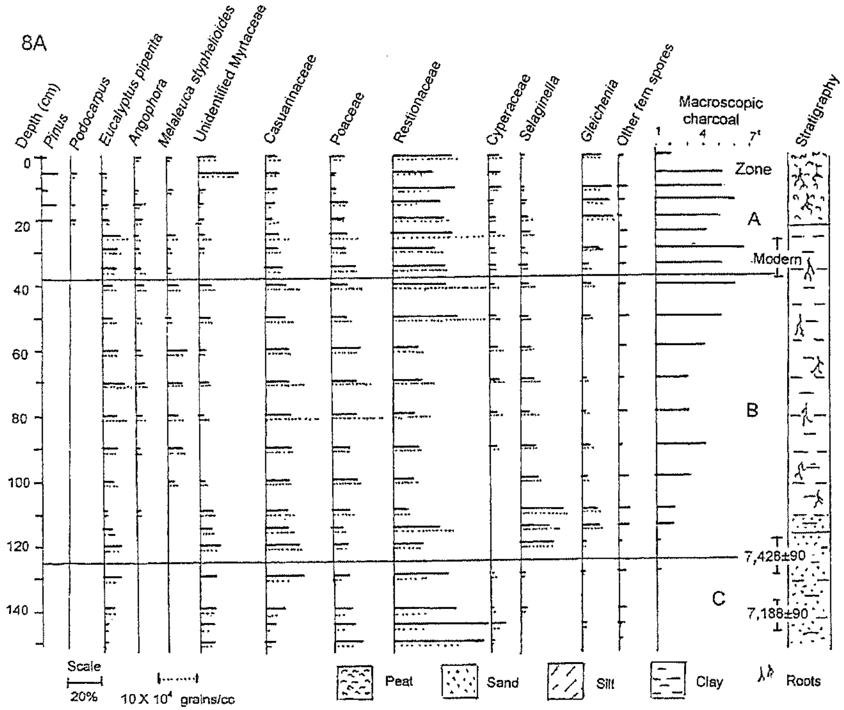
Depth (cm)	Material dated	Laboratory no.	Radiocarbon years (yr BP.)	Calibrated age (cal. yr BP.)
30-40	Humic clay with roots	BETA 20942	105.1±0.8% modern	Modern (<43)
120-130	Sandy humic clay	BETA 20943	6,460±100	7,428±90
140-150	Sandy clay	BETA 20944	6,220±100	7,188±90

unidentifiable. There was moderate Casuarinaceae and Poaceae.

The pollen record: The pollen spectra from the sediments is shown in Fig. 8A, 8B and has been zoned thus:

Zone C, 150-130 cm, c. 7,000 cal yr BP (see Fig. 9 for estimated ages). Abundant Restionaceae marked this zone. *Eucalyptus piperita*, other Myrtaceae and Casuarinaceae were prominent and there was a moderate content of Poaceae.

Zone B, 120-40 cm, c. 7,000-?2,200 cal yr BP. There was greater diversity here and more of tree/large shrub pollen, viz. *E. piperita*, *Angophora*, *Melaleuca*



Figures 8A 8B. Ingar swamp pollen spectra. For probable source of the pollen type in the vegetation, see Appendix.

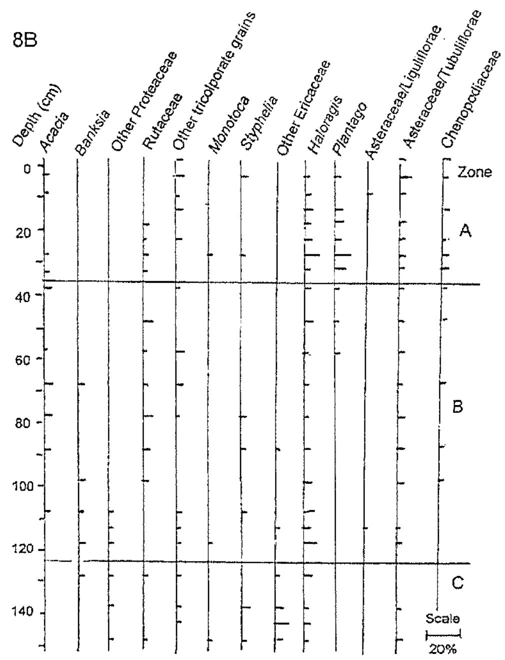


Figure 8 continued

styphelioides and Casuarinaceae, when compared with the zone below. There was a little more Poaceae but less Restionaceae than in the zone below. *Selaginella*, and to a lesser extent, *Gleichenia*, were moderate in the base of the zone.

Zone A, 40-0 cm, c. 2,200-0 cal yr BP to modern. *Pinus* was found down to 20 cm, marking European settlement. The dryland flora was similar to the zone below, but tree species declined with European influence. Restionaceae and *Gleichenia* were more abundant than in the zone below.

There was very little charcoal in the basal zone C, increasing in zone B and reaching a maximum in the European zone A.

History of the vegetation: Before 7 cal ka, the vegetation was relatively open, but after about 6 cal ka, the tree cover increased, especially Casuarinaceae. On the swamp, Restionaceae decreased but Cyperaceae, *Selagiella* and *Gleichenia* increased slightly. In the European zone, there was a slight decline in Casuarinaceae and an increase in the swamp species of Restionaceae and *Gleichenia*. Fire was relatively rare about 6 cal ka, but increased through time, to a peak in the European period.

Kings Tableland Swamp

Kings Tableland Swamp, at 33° 45' 47" S, 150° 22' 43" E and about 780-790 m altitude, is located in the floor of a steeply sloping small valley off Queen Victoria Creek. The valley floor steepens abruptly below the swamp and a waterfall cascades over a small cliff. The Banks Wall Sandstone Formation underlies the swamp and the Wentworth Falls Claystone outcrops near the base of the swamp. An area of development is found less than 1 km to the west where exotic conifers have been planted in the gardens.

Stratigraphy: The core sampled 220 cm of sediments which were peat down to 10 cm, then peaty sand at 15–20 cm, humic sand at 30-40 cm, peaty silt at 50 cm, humic sand at 60-90 cm, clay/sand at 100-120 cm and sand at 130-220 cm. Radiocarbon dates are given in Table 6.

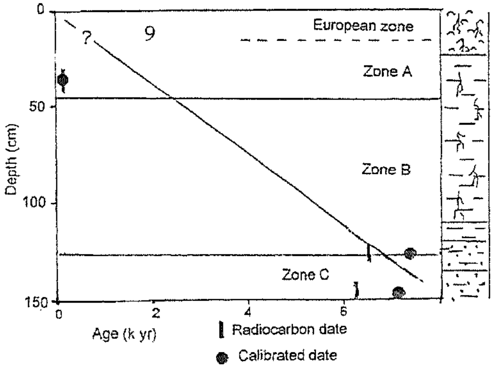


Figure 9. Ingar Swamp summary diagram

Table 6. Radiocarbon ages for Kings Tablelands Swamp

Depth (cm)	Material dated	Laboratory no.	Radiocarbon years (yr BP.)	Calibrated age (cal. yr BP.)
15-20	Peaty sand	SUA 2656	1.045±0.008 x modern	Modern (< 33)
50-60	Humic sand	SUA 2657	1,210±70	1,208±90
80-90	Humic sand	SUA 2658	2,410±70	2,578±130
155-160	Fine sand	SUA 2659	9,040±80	10,208±130

The swamp vegetation and surface pollen: *Leptospermum* species were dominant, but *Gleichenia* and sclerophyllous shrubs were also found on the swamp (Chalson and Martin, this volume). In the surface samples, the Myrtaceae content was low but Casuarinaceae was well represented (Chalson and Martin, this volume). The swamp taxa Restionaceae, *Selaginella* and *Gleichenia* were also well represented and the introduced *Pinus* was abundant.

The pollen record: The pollen spectra from the sediments (Figs 10A, 10B) have been zoned thus:

Zone C, 200-90 cm, c. ?>12,000-3,800 cal yr B P (see Fig. 11 for estimated ages). The Myrtaceae content was low and Casuarinaceae content moderate (Fig. 10A). Sclerophyllous shrubs and Restionaceae were well represented (Fig. 10B). *Gleichenia* and other fern spores were moderate. *Eucalyptus deanei* was found in the basal part of the zone and *Banksia* in the upper part.

Zone B, 80-30 cm, c. 3,800 cal yr BP to modern. This zone had some very high pollen concentrations which mirrored the spectra of the percentages, suggesting that the high concentrations result from slow sediment accumulation rather than the increased input of any one (or more) particular pollen type(s).

The Myrtaceae pollen proportion remained low but the Casuarinaceae representation had increased, when compared with the zone below. The proportion of Restionaceae and *Gleichenia* had decreased, but Cyperaceae and *Selagiella* had increased, in comparison with the zone below. Sclerophyllous shrubs were also well represented in this zone.

Zone A, 0-25 cm, modern. *Pinus* was found here, delimiting the European zone. The myrtaceous content had increased a little, especially *Melaleuca*. Casuarinaceae and Restionaceae decreased somewhat but *Gleichenia* increased considerably, when compared with the zone below.

The charcoal content was low to moderate in zones C and B, and increasing in the modern zone A.

History of the vegetation: The dearth of myrtaceous taxa, predominance of Casuarinaceae and the diversity and relative abundance of the shrubby taxa suggests a heathland, given that the two species of Casuarinaceae found in the region today, *Allocasuarina distyla* and *A. nana*, are shrubs/small trees. The swamp flora was dominated by Restionaceae throughout, with *Gleichenia* becoming prominent in modern times. Myrtaceae remains low until modern times, suggesting the surrounding vegetation remained relatively open. The charcoal content was relatively low until modern times, suggesting less fire activity, or lesser fuel to burn, until European times.

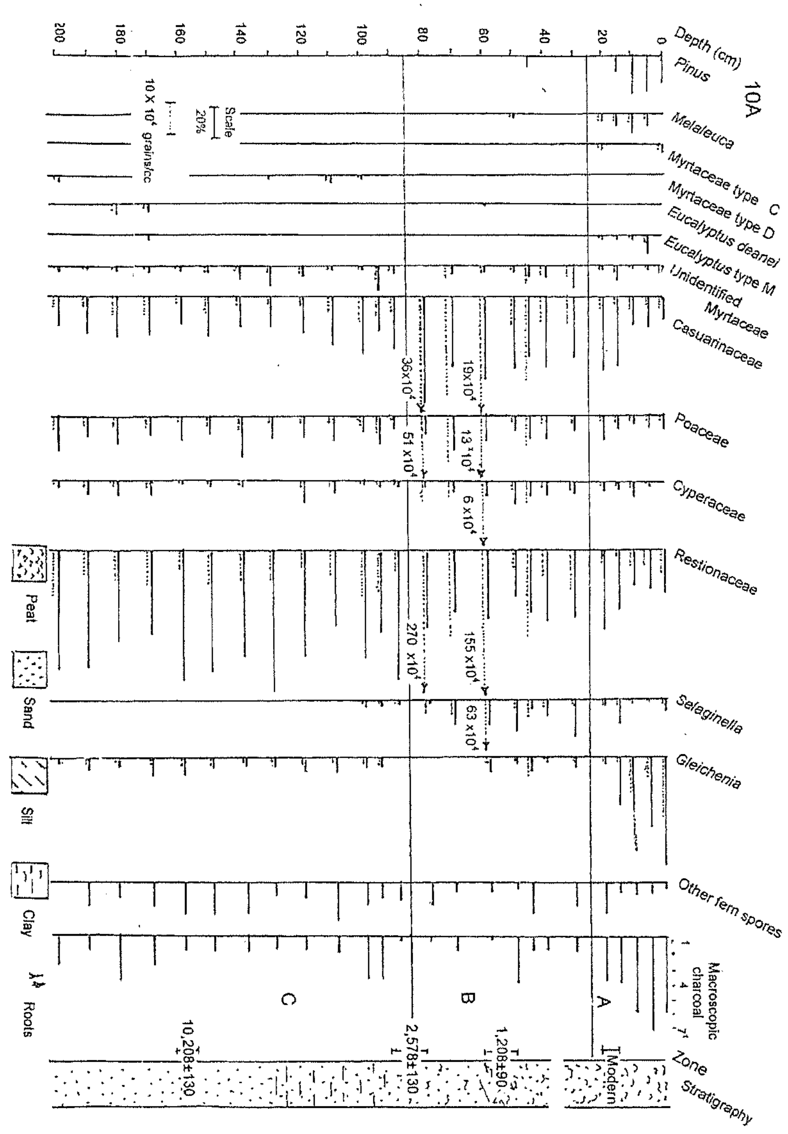
Katoomba Swamp

Katoomba Swamp, at 33° 43' 03" S, 150° 19' 18" E and 950 m altitude, is located in a small, shallow valley which is a tributary of Gordon Creek (Chalson and Martin, this volume). The Banks Wall Sandstone Formation underlies the swamp and the Wentworth Claystone Member outcrops near the base of the swamp, probably impeding drainage.

This swamp is surrounded by urban development. There is evidence of drainage ditches and a sealed road runs across the swamp. Much of it is (or has been) used for yards for light industry and horse paddocks. Housing extends to the edge of the swamp.

Stratigraphy: Two cores were necessary to recover sediments spanning the whole of the Holocene. Core 1 consisted of (1) dark greyish brown or dark brown, silty clay/humic clay/clay with roots, 0-20 cm, then (2) dark greyish brown, black, or dark grey silty or sandy clay at 25-80 cm, followed by (3) dark grey sand at 85 cm, (4) dark grey clay at 90 cm, (5) dark greyish brown or dark grey sandy or silty clay at 95-115 cm, (6) dark grey sand at 120 cm and (7) dark grey sandy clay at 125-130 cm.

The stratigraphy of core 2 consisted of (1) dark greyish brown, dark grey or dark brown silty clay at 0-30 cm, then (2) dark grey or dark brown sandy clay,



Figures 10A, 10B. Kings Tableland Swamp pollen spectra. For probable source of the pollen type in the vegetation, see Appendix.

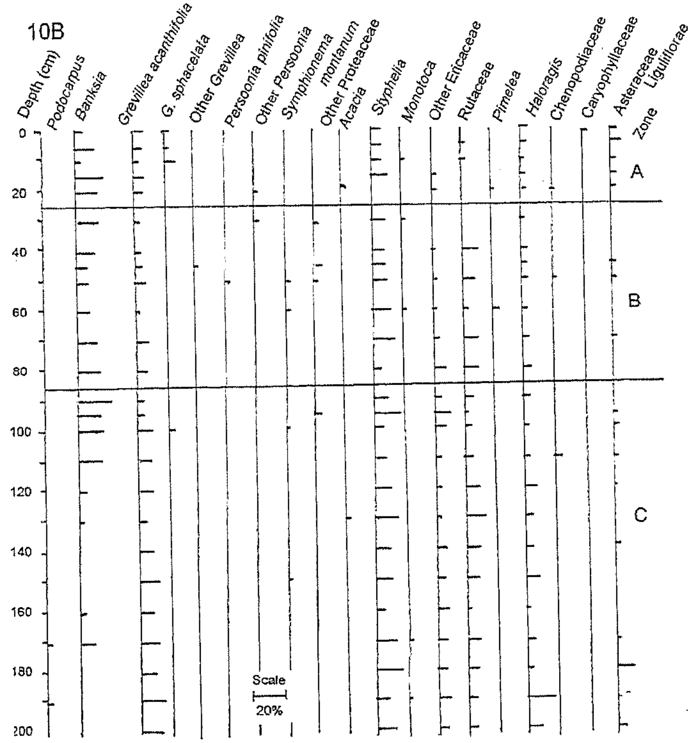


Figure 10 continued

35-40 cm, followed by (3) dark greyish brown sand at 42-48 cm and (4) dark grey clay or sandy clay at 50-55 cm. Radiocarbon dates are presented in Table 7.

The swamp vegetation and surface pollen: The moss *Dawsonia*, and species of Cyperaceae and Juncaceae were dominant on the swamp. *Kunzea* and *Leptospermum* species were also dominant and many sclerophyllous shrubs were found on the edge of the swamp, but the natural vegetation was highly disturbed here (Chalson and Martin, this volume). Poaceae (both native and introduced species) was the dominant pollen type in the surface samples, reflecting the urbanisation and the disturbance at the site. *Pinus* pollen was also present in appreciable amounts. Total Myrtaceae pollen was moderate and Casuarinaceae pollen was low. The swamp taxa, Restionaceae, Cyperaceae, *Selaginella* and *Gleichenia* were present in low proportions (Chalson and Martin, this volume).

The pollen record: Pollen recovery from the cores was good and some very high concentrations were found, especially in the clay (Figs 12A, 12B). The cores were zoned thus:

Core 2, Zone D, 55-0 cm, c. 12-11,000 cal yr BP (see Fig. 13 for estimated ages). The Myrtaceae content was low but *Eucalyptus oreades* and *E. pauciflora* had been identified. Casuarinaceae and Poaceae representation was moderate and Restionaceae was high (Fig. 12A). Asteraceae/Tubuliflorae and Ericaceae were prominent amongst the herbs and shrubs (Fig. 12B). The charcoal content was moderate throughout.

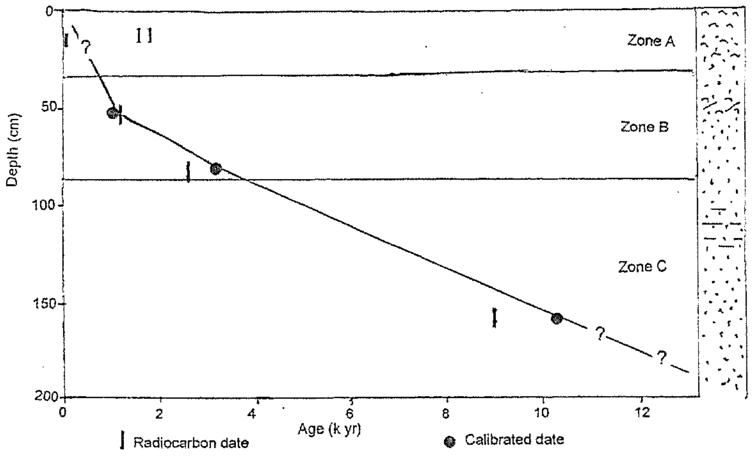


Figure 11. Kings Tableland Swamp summary diagram.

Core 1, zone C, 130-75 cm, c. 6,200-4,000 cal yr BP (for estimated ages, see Fig 13). The Myrtaceae representation was very low, lower than in the zone below, and *Eucalyptus* species were not recorded from most samples. Casuarinaceae representation was low also, Poaceae was moderate and Restionaceae high, all fairly similar to the zone below.

Core 1, zone B, 70-30 cm, c. 3,100-?1,500 cal yr BP. The Myrtaceae content had increased and *Eucalyptus oreades* was present through the zone, and this was the most notable difference when compared with the zone below. Casuarinaceae abundance was moderate and the Poaceae representation had decreased when compared to the zone below. Restionaceae abundance was a little less than in the zone below, decreasing further towards the top of the zone. *Haloragis* and *Grevillea acanthifolia* were prominent amongst the herbs and shrubs.

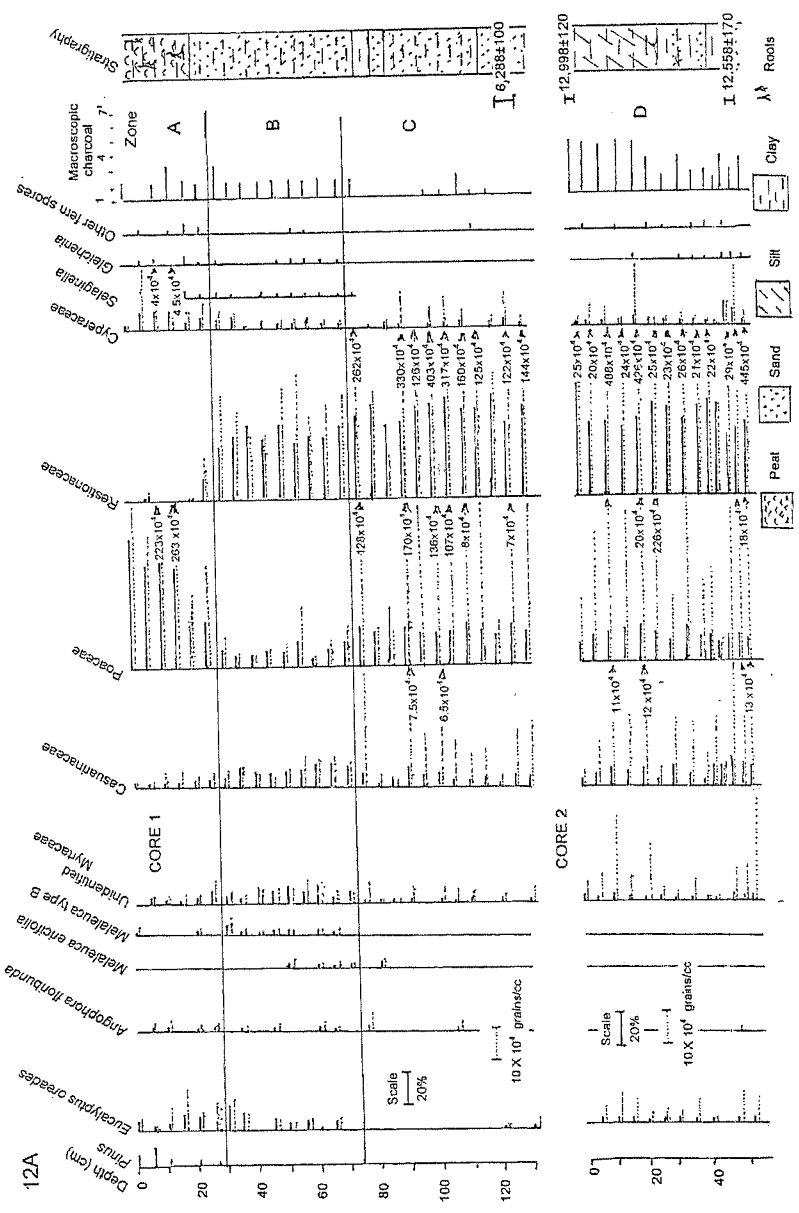
Core 1, zone A, 25-0 cm, c. ?1,500 cal yr BP to present. *Pinus* was consistently present, denoting the European zone. Total Myrtaceae and Casuarinaceae representation were low, decreasing somewhat from the base, but *E. oreades* and *A. floribunda* were found throughout the zone. Poaceae pollen increased markedly from the base of the zone but Restionaceae was very low at the very base, then virtually absent from the rest of the zone. Cyperaceae increased a little and Asteraceae/Liguliflorae was present throughout the zone.

The charcoal content was very low in zone C, then low through the rest of the core, with an occasional moderate value.

History of the vegetation: There was an open or sparse tree cover about 11-12 cal ka. By 6-5 cal ka, the site appears to have been almost treeless. About 4 cal ka, *E. oreades* returned to the site which became wooded once again. Restionaceae was dominant on the swamp and Poaceae was moderately common until 3 kyr BP, after which, both declined. In the European zone, Poaceae increased dramatically, no doubt reflecting urbanisation. At the same time Restionaceae decreased and almost vanished from the swamp. *E. oreades* remained dominant but it

Table 7. Radiocarbon ages for Katoomba Swamp

Depth (cm)	Material dated	Laboratory no.	Radiocarbon years (yr BP)	Calibrated age (cal. yr BP)
Core 1,125-130	Sandy clay	Beta 24545	5,450±80	6,288±100
Core 2, 0-5	Silty Clay	Beta 24547	11,030±130	12,998±120
Core 2, 50-55	Sandy Clay	Beta 24546	10,570±100	12,558±170



Figures 12A, 12B. Katoomba Swamp pollen spectra. For probable source of the pollen type in the vegetation, see Appendix.

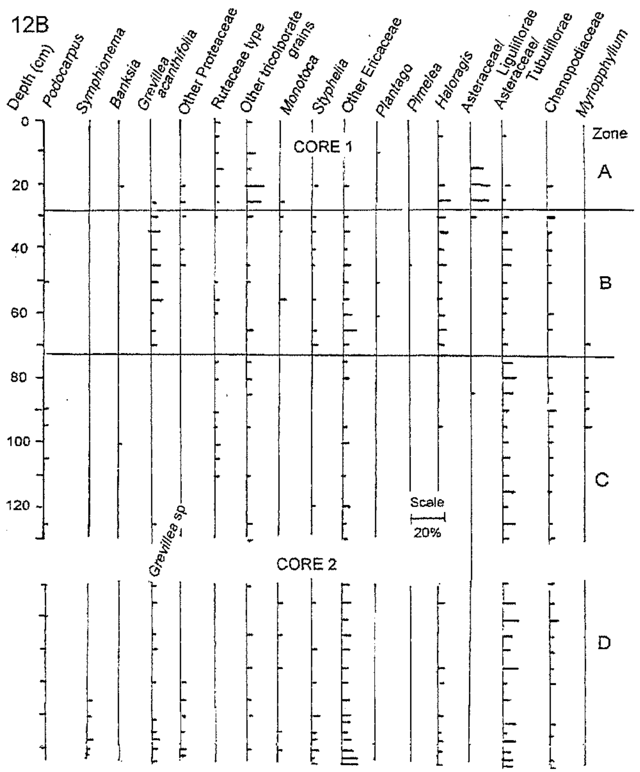


Figure 12 continued

decreased, along with Casuarinaceae in the time of the Europeans. Fire activity was low to moderate through most of the time.

Newnes Swamp

Newnes Swamp, at 33° 22' 57" S, 150° 13' 20" E and 1,060 m altitude, is located in a shallow hanging valley with pine plantations in close proximity. Regular burning maintains fire breaks for the young pine plantations. The swamp is underlain by the Burra-Moko Head Sandstone Member of the Banks Wall Sandstone Formation which has thin claystone interbeds, and it is likely that one of these clay layers impedes drainage and hence maintains the swamp.

Swamp stratigraphy: The core sampled 90 cm of sediment. Clay or peat with roots was found down to 20 cm, then sandy clay down to 35 cm, followed by sand to 55 cm, then sandy clay with roots down to 65 cm, then silty clay to 75 cm, and finally sand or sandy clay in layers to 90 cm. Radiocarbon dates are presented in Table 8.

The swamp vegetation and surface pollen: *Banksia* and *Kunzea* were dominant and *Baeckea*, *Leptospermum*, other sclerophyllous shrubs, Cyperaceae and Poaceae were also present on the swamp (Chalson and Martin, this volume). There was appreciable Myrtaceae pollen in the surface samples, but Restionaceae and *Gleichenia* were dominant in the surface pollen spectra. *Pinus* was present but not abundant. (Chalson and Martin, this volume).

The pollen record: Pollen recovery from the core was good and there was some exceptionally high concentrations, especially in the clay at 60-70 cm. The core was zoned thus (Figs 14A, 14B):

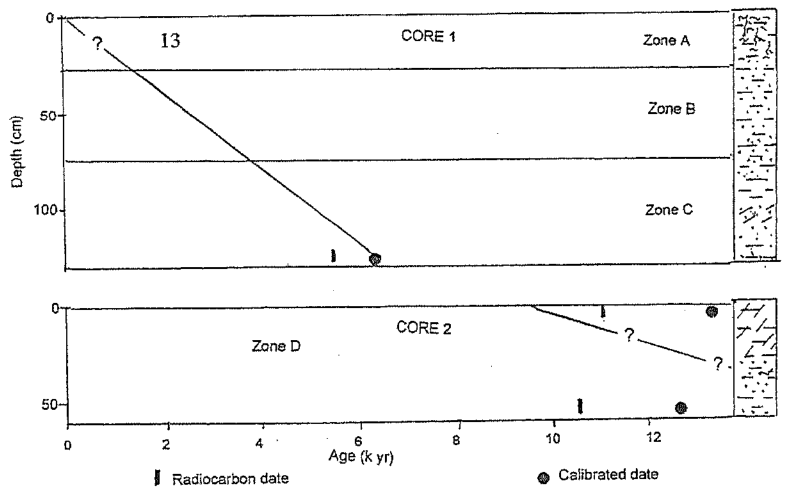


Figure 13. Katoomba Swamp summary diagram.

Zone D, 90-55 cm, c. 11,000-7,5 00 cal yr BP (see Fig. 15 for estimated ages). Myrtaceae pollen was low, but *Eucalyptus pauciflora/rubida* had been identified. Casuarinaceae was also low at the base of the zone, increasing upwards (Fig 2A). Asteraceae/ Tubuliflorae and Chenopodiaceae were prominent amongst the herbs and shrubs (Fig. 14B). Poaceae and Restionaceae were well represented.

Zone C, 50-40 cm, c. 7,500-1,800 cal yr BP There was very little Myrtaceae pollen, with only one record of a *Eucalyptus* species. Casuarinaceae pollen increased, *Haloragis* was moderate and Poaceae and Restionaceae were reduced when compared with the preceding zone.

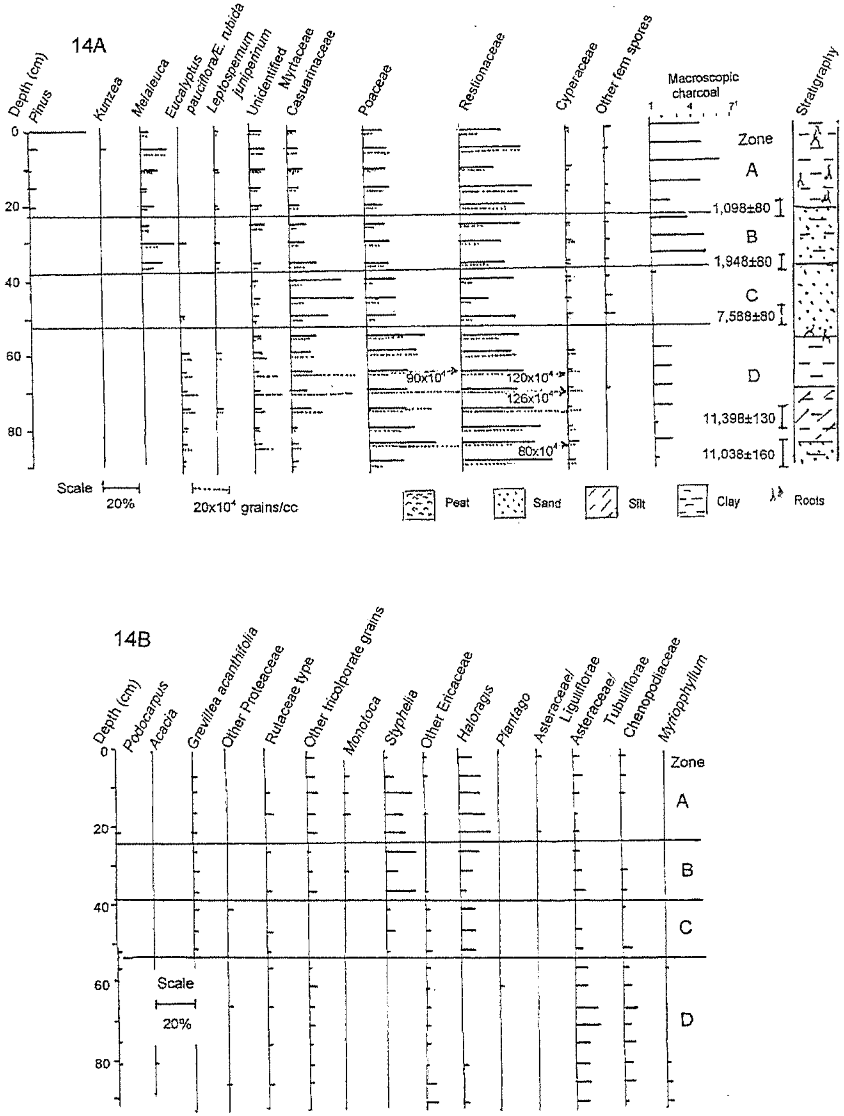
Zone B, 35-25 cm, c.1,800-?1,000 cal yr BP. *Melaleuca* representation was significant, Casuarinaceae had decreased, the shrubs were well represented, and Poaceae and Restionaceae remained low when compared with the previous zone.

Zone A, 20-0 cm, ?1,000 cal yr BP to present. *Melaleuca* continued to be the most significant of the Myrtaceae, *Styphelia* and *Haloragis* were appreciable, Poaceae remained low and Restionaceae was somewhat greater than the zone below. *Pinus* was present throughout the zone, denoting European activity.

The charcoal content was moderate in zone D, extremely low in zone C, and moderate to high in zones B and A.

Table 8. Radiocarbon ages for Newnes Swamp

Depth (cm)	Material dated	Laboratory no.	Radiocarbon years (yr BP)	Calibrated age (cal. yr BP)
20-25	Sandy clay	SUA 2648	1,090±70	1,098±80
35-40	Sandy clay	SUA 2649	1,930±70	1,948±80
50-55	Sand	SUA 2650	6,650±100	7,588±80
77-83	Silty clay	SUA 2651	9,820±90	11,398±130
87-93	Sand	SUA 2652	9,640±80	11,038±160



Figures 14A, 14B. Newnes Swamp pollen spectra. For probable source of the pollen type in the vegetation, see Appendix.

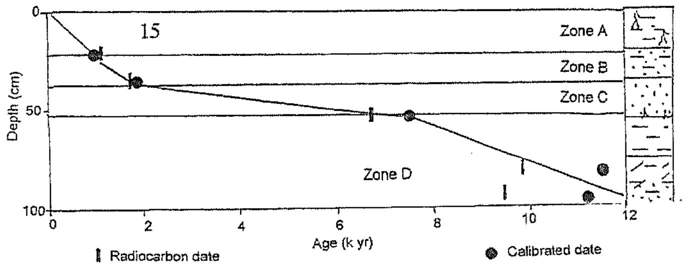


Figure 15. Newnes Swamp summary diagram.

History of the vegetation: The vegetation was open *Eucalyptus* woodland at 11 cal ka, but by about 7.5 cal ka, *Eucalyptus* species had disappeared, Casuarinaceae and the sclerophyllous shrubs increased, suggesting a heathland. After 2 ka, *Melaleuca* became prominent, possibly around or on the swamp. Burning was moderate to low in the early Holocene, very low in the mid Holocene when the vegetation was a shrubland or heath and after 2 ka, it was moderate to high, when *Melaleuca* had colonised the swamp.

DISCUSSION

Stratigraphy

All of the swamps chosen for this study are found associated with small streams in valleys of the rugged terrain of the Blue Mountains. While such sites may not be the first preference for palynology, they allow study in an area where the more favoured sites are rare. These small valley swamps rely on some barrier, often a clay substrate, to impede drainage and maintain the swampy conditions. The root mats of the vegetation stabilise the sediments and slow down the water flow, but if the vegetation is disturbed, then the sediments are prone to erosion. The swamps dry out occasionally but not seasonally. The vegetation can withstand mild or short droughts, but prolonged, severe droughts such as has been experienced in recent years destabilise the communities as some species die and others replace them. The swamps then become very vulnerable to fire, human trampling or even the next major rainfall event. Elimination of the vegetation cover over even a small area of the swamp leaves it vulnerable to subsequent erosion.

If the vegetation is destroyed and there is erosion, channelised water and higher energy flows deposit coarser grained sediment, such as sand. Eventually the vegetation re-establishes and stream flow slows down and finer particles, such as silt and clay are deposited.

It has been assumed that the sediments were deposited at a uniform rate: however, the resolution of dating does not allow this to be tested. Uniform rates of sedimentation are probably not the case at finer scales of resolution.

The peat layer at the top of the swamp is usually only 20 cm or less in thickness. While roots of the present vegetation may penetrate to a considerable depth, a discrete layer with roots at depth in some profiles suggests former peat or vegetation layers that have been buried, and the decay of most of the organic matter as the sediments accumulated. Also, there may be an appreciable humic content of the sediments at depths in the profile, a further indication of decayed vegetation.

Using the above description of the dynamics of the swamps, the sediments are interpreted as follows:

Burralow Swamp: There is only some 1.2 cal ka represented here, with sand at depth, then grading to clay and peat at the top. The rate of accumulation of the sand was rapid, with the clay and peat accumulating much slower (from Fig. 3). It is likely that the whole of this profile post-dates an erosive event.

The two basal two dates are puzzling, given that they do not conform to the uniform sedimentation rate discussed above. They are within the sand layer, which was carbon poor, and it is possible that groundwater carrying humic acids could have contaminated the sediments with younger organic matter, overwhelming the small quantities of older carbon.

Warrimoo Oval Swamp: A basal sand layer dating to about 4.7 cal ka grades into sandy silt, then another sand layer at about 1.2-1.5 cal ka. The sediments then became increasingly peaty towards the top. Deposition of the basal sand layer probably followed an erosive event, and the sand layer at 50-90 cm probably represents another erosive event. This latter layer may correlate with the basal sand layer in Burralow Creek (from Figs 3 and 5), but this hypothesis requires additional dating control to test it.

Notts Swamp: About 7 cal ka are recorded here (Fig. 7). The basal sandy silt layer is overlain by clay, with peat with roots above it. The profile appears to reflect a low energy depositional environment throughout. The stratigraphy suggests that the lower and upper layers may have accumulated at a somewhat faster rate than the clay in the middle.

Ingar Swamp: This profile also represents about 7 cal ka (Fig. 9). Sandy clay formed the basal sediments, with clay with roots above it, then peat with roots forming the top most layer.

Kings Tableland. Over 10 cal ka, the majority of the Holocene is represented here (Fig. 11). There is a basal sand layer, then a complex stratigraphy of clay, sand, silty peat, sand and sandy peat above it. This suggests that conditions of deposition would have fluctuated, and in which case is unlikely that the sequence is continuous.

Katoomba Swamp. Over 6 cal ka are represented in core 1 and 10-12 cal ka in core 2 (Fig. 13). There are no large sand layers similar to those seen in sediments at some of the other sites, but a complex stratigraphy of finer sediments, often with a sandy component.

Newnes Swamp. About 12 cal ka is recorded here (Fig. 15). The sediments are sand then sandy or silty clay in a complex stratigraphy at the base of the profile. Above this, there is a prominent sand layer, then sandy clay and peat with roots at the top. Superficially, it appears that the sand layer in the middle of the profile accumulated very slowly (Fig. 15), but another interpretation is possible. The date at the top of this sand layer is about 1.3 ka, which approximates the date of the top of the sand layers seen in Warrimoo Oval Swamp and Burralow Creek Swamp. If the sand layer does represent the aftermath of an erosive event, then a section of the sediment profile is likely to have been lost. The roots in the sandy clay at the base of the sand layer may indicate the base of a peat or vegetation layer that was buried by the accumulating sand.

Each swamp thus has its own history of sedimentation. Sandy layers in three of the swamps suggest erosion after disruption of the vegetation, sand deposition, then stabilisation sometime about 1.2-1.6 ka, with subsequent re-establishment of the vegetation and deposition of fine-grained sediments.

If fire was the cause of this erosion, then we could expect evidence of it in the charcoal record, but there is no evidence of increased charcoal at this time. Absence of charcoal cannot be taken as evidence of no fire, as erosion may well have removed the charcoal, along with some of the sediments. Fire is not the only likely cause: as discussed, prolonged drought could also destabilise these systems. Minor tectonics along fault lines in the Blue Mountains (Bembrick et al, 1980) would also accelerate erosion.

The three swamps which have this sand body are Newnes, Burralow Creek and Warrimoo Oval. Newnes and Burralow Creek are the two most northerly swamps and Burralow Creek and Warrimoo Oval are the two most easterly swamps. Whatever the cause of this disturbance, it seems to have come from or been concentrated in the north east (see Fig. 1). That Burralow Creek Swamp has only 1 ka of sediment suggests that it may have suffered the greatest disturbance and erosion.

History of the vegetation

The swamp vegetation. The survey of the vegetation (Chalson and Martin, this volume), shows that species of Restionaceae, Cyperaceae, *Gleichenia*, *Selaginella*, *Baeckea*, *Kunzea* and *Leptospermum* dominate the vegetation cover of these swamps. Many of the common sclerophyllous shrubs have been recorded on the swamps, though not dominant, as well as in the dryland vegetation (Chalson and Martin, this volume). Poaceae has both dryland and swamp species (Sainty and Jacobs, 1981).

In the pollen diagrams, *Gleichenia* and *Selaginella* are found predominantly where the sediments are sandy and Restionaceae is dominant on the clayey sediments. There is very little Cyperaceae here, unlike other sites, e.g Lake Baraba (Black et al., 2007), Dry Lake, (Rose and Martin, 2007), Mountain Lagoon (Robbie and Martin, 2007) and Penrith Lakes (Chalson and Martin, 2008) which have more Cyperaceae than Restionaceae. The swamps of this study, however, are more ephemeral and unlike the others with more Cyperaceae, which are lakes or lagoons where the water would be more permanent. Indeed, there are many species of Cyperaceae that are aquatic (Sainty and Jacobs, 1981) whereas species of Restionaceae are found more in damp and swampy places. Thus Cyperaceae flourishes in the more permanently wet swamps and Restionaceae is more abundant in these swamps subjected to irregular drying. Species of both families may be found in the dryland vegetation but the pollen record is heavily dominated by the wetland species.

Baeckea, Kuzea and *Leptospermum* species are present in the pollen diagrams of the swamps, but mainly towards the top and especially in the European zone. There is very little pollen of these taxa at depths in the profiles. Some *Melaleuca* pollen is present and it shows much the same trends. Although the trend to more of these shrubs started before European settlement, it appears that these woody shrubs, which are often dominant on the swamps today, have probably been further encouraged by European activity, probably by the altered fire regime (Kohen, 1995).

The swamp vegetation thus reflects the sediment substrate and hydrological conditions, with some changes due to European activity.

The dryland vegetation. The sites are examined in a time sequence to determine if there has been any synchronous changes in the vegetation across the Blue Mountains.

Three sites record the early Holocene of 10 ka to 6 ka: Kings Tableland, Katoomba and Newnes Swamps. About 10 cal ka, *Eucalyptus* species were present at all three sites, but there was very little at Kings Tableland. Casuarinaceae, the other group which could be either trees or shrubs was present also. Thus all three sites appear to have been wooded in the early Holocene, with Kings Tableland probably more open than the other sites. By 6-4 cal ka, the mid Holocene, there were virtually no *Eucalyptus* in any of the sites. The vegetation had become more open and probably more of a sclerophyllous shrubland or heath. *Eucalyptus* returned to the Katoomba site about 3 cal ka, but very little is recorded in Newnes and Kings Tableland up to the present. The Katoomba swamp is located in a narrower and steeper valley than the other two sites, and this shelter may have produced better moisture retention and hence tree regeneration. *Melaleuca* became established at Newnes about 1.3 cal ka.

Two sites date from about 6 cal ka, the mid-Holocene: Notts and Ingar Swamps. Species of *Eucalyptus* and *Angophora* were present at both sites, hence they were probably wooded at the time that Kings Tableland, Katoomba and Newnes were dominated by shrubs. Warrimoo Oval dates from about 4 cal ka, and the relatively low frequencies of *Eucalyptus* and *Angophora* indicate it was an open woodland at that time.

In the period 4-2 cal ka, there was little change from the previous period at Notts and Ingar Swamps. At Kings Tableland, Casuarinaceae increased but there was still no *Eucalyptus*. At Katoomba, *Eucalyptus* and *Angophora* species reappeared, as this site probably gained an overstorey of trees again. At Newnes, the 4-2 cal ka period was similar to that before, with very little *Eucalyptus*. Burralow Swamp dated from 1 cal ka was initially very open, with the tree cover increasing about 0.8 cal ka. Except for an increase in *Melaleuca* or *Leptospermum* species in some of the swamps, there was relatively few changes after 2 cal ka until the European period,

In the European zone, there was minimal or no decline in the *Eucalyptus* and *Angophora* content. Casuarinaceae content declined noticeably at all the sites. At Burralow, Warrimoo Oval and Kings Tableland, the woody shrubs *Callistemon, Baeckia, Leptospemum* and *Melaleuca* increased. The Poaceae content remains unchanged in all swamps except for Katoomba, where there is a dramatic increase.

There is thus relatively little change in the palynology after European settlement in all of the sites, except at Katoomba. This perhaps reflects the relatively minor European changes to the sites, with the exception of Katoomba where the swamp itself has a history of use for various urban activities. Agricultural development has been minimal, reflecting the poor soils. The general lack of decline in tree species is unexpected, but European development has largely been confined to the ridgetops and extensive natural vegetation is a feature of the Blue Mountains. The wood of Casuarinaceae was prized by Europeans as the firewood of choice for bakeries and the timber had many uses (Entwisle 2005), hence it may have been sought out more than the *Eucalyptus* species.

Each site has its own distinctive history, as are the dominant *Eucalyptus* species at each site (Chalson and Martin, this volume). There is limited synchronicity of change between the swamps. The three swamps at the highest altitude are the oldest, dating to the beginning of the Holocene. They were wooded in the early Holocene, but became very open or almost treeless by the mid-Holocene. The sites at the lower altitudes, however, were wooded during the mid-Holocene. By the late Holocene, all of the sites had become wooded, although the tree layer may have been very open in some of them. Clearly, the interplay of many environmental factors, not the least of which is altitude, have influenced the vegetation at each site.

Other sites in the Blue Mountains also present unique histories when compared with those of this study. At Mountain Lagoon (Robbie and Martin, 2007), the proportion of Casuarinaceae pollen is substantial at the beginning of the Holocene, then declines throughout the Holocene. *Allocasuarina torulosa* is more common at Mountain Lagoon than at any of the sites of this study. Pollen of swamp plants increase through the Holocene at Mountain Lagoon as the site developed from a lake in the early Holocene to a peat swamp in the mid-late Holocene. The Myrtaceae species identified are mainly different to the species of this study and the proportion of pollen remains much the same throughout the Holocene and only declines after European settlement. The species identified at Mountain Lagoon are often prized for timber (Robbie and Martin, 2007). The physical environment of Mountain Lagoon is totally different to that of the Blue Mountain sites: it is a small basin on Wainamatta Shale, in a particularly sheltered location.

Kings Waterhole, part of the Mellong Swamps in the Wollemi National Park, at 280 m altitude, has a 6 ka history (Black and Mooney, 2007). Myrtaceae (excluding *Melaleuca* spp.) and Casuarinaceae are prominent until about 4-3 ka, when Casuarinaceae begins to deline. At the same time, Restionaceae increases. After 3 ka, there is minimal Casuarinaceae and Restionaceae declines, but *Melaleuca* and Poaceae increase. After 1 ka, Myrtaceae decreases somwhat and Poaceae is prominent (Black and Mooney, 2007). This decline of Casuarinaceae after 3 ka is not seen in any of the sites of this study.

At Gooches Crater Swamp on the Newnes Plateau, between 900 and 1,200 m altitude (Black and Mooney, 2006), there is a 14 ka history of the vegetation. There is a moderate level of variability in the pollen assemblages, and the swamp vegetation varied from a wet heath with semi-permanent to permanent water to a fern swamp. The Myrtaceae and Casuarinaceae content is appreciable and continuously variable. The Asteraceae content is considerable (Black and Mooney, 2006), unlike the sites of this study, although the Newnes site has the greatest Asteraceae content of all the sites of this study.

Penrith Lakes on the Cumberland Plain just east of the Lapstone Monocline has 6 ka of Holocene history. The tree cover was very open in the mid Holocene, becoming somewhat more wooded in the late Holocene (Chalson and Martin, 2008), mirroring the findings of this study.

The rugged terrain of the Blue Mountains would have provided some isolation to each site so that each has its own sedimentary and vegetation history. Any climatic change or other regional event should imprint in these deposits, especially in the more environmentally sensitive sites.

Climatic change

The decline of the trees from the early Holocene to the mid Holocene in the sites at the higher altitudes, *viz*. Newnes, Katoomba and Kings Tableland, suggests that the climate had become drier. A detailed analysis of the climatic requirements of the *Eucalyptus* species also suggests a wetter early Holocene (Chalson, 1991).

Climatic trends in the mid Holocene are uncertain, for while the sites at higher altitudes were not wooded, sites at lower altitudes, i.e. Notts and Ingar Swamps, were wooded at this time. Trees returned to Katoomba about 3k yr, suggesting that the climate had become wetter. As discussed previously, the Katoomba catchment is narrower and steeper-sided, hence the most sheltered of the three higher altitude sites. Newnes and Kings Tableland, however, remained open with few trees, suggesting that if there was an improvement in the rainfall, it had not returned to the early Holocene levels. These uncertain trends continued into the late Holocene. About 2 kyr, there was an increase in the wooded vegetation, with more *Eucalyptus* at Warrimoo, more Casuainaceae at Kings Tableland and more *Melaleuca* at Newnes. The other sites, however, remained much the same. There probably was an increase in rainfall, but it was slight. The detailed analysis by Chalson (1991) came to similar conclusions: climatic changes in the mid and late Holocene are equivocal.

The climatic changes deduced from the this study are in general agreement with other sites in the Blue Mountains. The early Holocene is regarded as a climatic optimum when it was warmer and wetter (Allen and Lindesay, 1998). Evidence for the mid and late Holocene is variable, some indicating wetter, some drier conditions. Evidence suggests that the El Niño-Southern Oscillation (ENSO) phenomenon came into operation about 5 ka, with increasing seasonality. Thus from the mid Holocene, the climate became more like that of today, with more variability (Allen and Lindesay, 1998; Moy et al., 2002; Donders et al., 2007).

Fire history

Charcoal has been found in all of the sites and throughout all of the profiles. In the early Holocene, the charcoal content was low to moderate in Kings Tableland, Katoomba and Newnes. By mid Holocene, the quantity of the charcoal had declined in Katoomba and Newnes: there had been a change in the vegetation from more wooded in the early Holocene to less wooded in the mid Holocene, hence there may have been less fuel to burn.

In the mid Holocene at Notts, Ingar and Warrimoo Swamps, there is very little charcoal. All of the sites would have been wooded to some degree but not as much as in the late Holocene. The charcoal content increases at each site as the tree cover increased. In the late Holocene, charcoal content is variable, but mainly greater than in the mid Holocene. In the European zone, charcoal content is consistently high and the highest for the profile, with the exception of Katoomba. It may be that because of urban use of the swamp at Katoomba, fire was excluded. Within these trends, there may be the occasional single high value, but they do not form any pattern.

The interpretation of a charcoal record is problematical because so many factors are involved, e.g. fire frequency, intensity and transport of charcoal. The results of this study suggest that the greater the biomass, the more fuel there is to burn hence the more charcoal in the sediments.

The higher charcoal content of the European period suggests that fire regimes were changed with settlement. If Aboriginal people regularly burnt off the undergrowth and suppressed the shrubs, then the fuel load would be kept down. With European settlement and the cessation of traditional fire practices, it is possible that the woody shrubs became more common (Kohen, 1995; Ward et al., 2001). Under these conditions, the fuel load would increase. Today, species of *Baeckia, Kunzea* and *Leptospemum* are dominant on all of the swamps (Chalson and Martin, this volume). There is a trend for *Leptospermum* and *Kunzea* species to increase slightly in the late Holocene, with a further increase in the European Zone. These woody species would have had the capacity to produce more charcoal when burnt and be incorporated in the sediments, especially when growing on the swamp, when compared with the smaller sedges and reeds.

At Mountain Lagoon (Robbie and Martin, 2007), fire activity was low through the Holocene, until about 3-2 ka, when it increased. This pattern is similar to those of this study.

At Gooches Crater the charcoal content and hence fire activity fluctuates between 14 ka and 9 ka, then follows a period of low fire activity until about 6 ka, then a period of dramatic increase in fire activity in the late Holocene (Black and Mooney, 2006). Fire activity reaches unprecedented levels in the post-European period (Black and Mooney, 2006). The increase in fire activity in the mid Holocene is attributed to climate, in particular to the greater seasonality associated with the onset of the El Niño-Southern Oscillation (ENSO) phenomenon (Black et al., 2007). This pattern of fire activity is similar to that seen in the sites of this study.

At Kings Waterhole Swamp (Black and Mooney, 2007), the fire activity was low about 6 ka, then increased between 5-3 ka, after which it decreased to low levels to the present. This pattern of fire activity is quite unlike that of this study. It is thought that the decline in fire activity after 3 ka represented an alteration to Aboriginal management strategies associated with increasing population and/or the increased risk of conflagration in an ENSO-dominated climate (Black and Mooney, 2007).

Black et al. (2007) examined the charcoal record together with the archaeological record in an attempt to assess the likely effect of Aboriginal burning on the ecosystem. At Gooches Crater Swamp, the charcoal content appeared to be most influenced by climate, with an abrupt increase in the mid Holocene, perhaps associated with the onset of the modern ENSO-dominated conditions. Kings Waterhole also showed the abrupt increase in the mid Holocene, but there was a marked decrease in charcoal from about 3 ka. Lake Baraba also showed similar low levels of charcoal in the late Holocene. The archaeological records of all three regions showed increased activity/habitation in the late Holocene. It is thus possible that Aborigines strongly influenced fire activity in some places in the Sydney Basin during the late Holocene to prevent the risk of large intense fires as the ENSO-dominated climate became more prevalent (Black et al., 2007)

CONCLUSIONS

Seven swamps were studied and each had its own distinctive history. Where the *Eucalyptus* species were identified, the dominant species were different at each site, as they are today.

Similarities in the histories could be seen between some of the sites and are as follows:

In the early Holocene, the vegetation was more wooded, i.e. woodland or forest, which suggests a warmer wetter climate. Only the three sites at the highest altitudes had sediments of early Holocene age.

In the mid Holocene, the vegetation was less wooded in the three highest sites when the vegetation was probably shrublands and heaths, and this suggests a drier climate. Other sites at lower elevations were wooded in the mid Holocene.

The *Eucalyptus* species return to the less wooded sites towards the late Holocene. There is also a tendency for an increase in *Baeckea, Kunzea,* *Leptospermum* and *Melaleuca*, the woody shrubs. These woody shrubs are dominant on the swamps today.

There is some decline in Casuarinaceae in the European period but the *Eucalyptus* species are maintained at about the same level as in the late Holocene. The woody swamp shrubs increase in the late Holocene and European period.

The charcoal levels suggest that there was moderate fire activity in the early Holocene when the vegetation was more wooded, decreased fire in the mid Holocene when the vegetation was more open, with increased fire in the late Holocene and a further increase in the European period.

It is thought that the altered fire regime under European settlement encouraged the increase in woody shrubs on the swamps (and elsewhere) which in turn produced more charcoal.

These swamps on sandstone are highly erodable and a sand body at about 1.2-1.6 ka in the three most northerly and easterly swamps suggests they may have suffered an erosive event about that time. The destabilising event(s) which triggered this erosion is uncertain.

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APPENDIX A

Pollen type name on the pollen diagrams and the probable source in the vegetation.

Name of pollen type. Major pollen groups (A diagram)	Probable source in the vegetation and ecological inference. From PlantNet (2007)
Podocarpus	Probably *Podocarpus spinulosus*: sclerophyllous shrub/small tree
Pinus	*Pinus* sp(p). Introduced: Pollen input from urban/forestry areas.
Angophora/Corymbia	Species within the two genera: sclerophyll woodland
Eucalyptus/Melaleuca	Species within the two genera sclerophyll woodland/forest
Melaleuca styphelioides	*Melaleuca styphelioides*: moist stream bank habitat
Leptospermum/Baeckea	Species within the two genera: ?mainly swamp communities
Tristaniopsis	*Tristaniopsis* spp : moist habitats in sclerophyll communities
Unidetified Myrtaceae	All pollen types not identifiable further
Casuarinaceae	*Casuarina, Allocasuarina* sp(p): *A. distyla* and *A. nana* in this study
Poaceae	Native and exotic species in the family: open situations, dryland and swamp species
Restionaceae	All species in the family: swamp and dry land species
Cyperaceae	All species in the family: swamp and dry land species
Selaginella	All species in the genus: damp sites, edge of swamp
Gleichenia	*Gleichenia* sp(p): damp sites, edge of swamp
Other fern spores	Other ferns: many possible species
Names of shrubs and herbs (B diagrams)	
Grevillea acanthifolia	Shrub: swampy areas, sand or peat
G. sphacelata	Shrub: heath, dry sclerophyll forest
Grevillea	*Grevillea* sp(p): sclerophyllous understorey
Hakea	*Hakea* sp(p): sclerophyllous understorey
Persoonia pinifolia	Shrub: heath, dry sclerophyll forest
Persoonia	*Persoonia* sp(p): sclerophyllous understorey
Symphionema montanum	Shrub: heath or dry sclerophyll forest, wet or dry situations
Banksia	*Banksia* sp(p): sclerophyllous understorey
Other Proteaceae	Other taxa in the family: sclerophyllous understorey
Acacia	All species in the genus
Styphelia	*Styphelia* sp(p): sclerophyllous understorey
Monotoca	*Monotoca* sp(p): sclerophyllous understorey
Other Ericaceae	Other taxa in the family: sclerophyllous understorey
Rutaceae type	All taxa in the family sclerophyllous understorey
Pimelea	*Pimelea* sp(p): sclerophyllous understorey
Plantago	*Plantago* sp(p): native and introduced herbs
Haloragis	*Haloragis/Gonocarpus* sp(p): Damp sites, sclerophyllous understorey
Other tricolporate grains	Probably shrubs and herbs
Podocarpus	Probably *Podocarpus spinulosus*: sclerophyllous shrub/small tree
Micrantheum	Shrub: heath and dry sclerophyll forest, sandy infertile soils
Myriophyllum	Mainly aquatic herbs, also on damp ground around water bodies
Asteraceae/Liguliflorae	Fenestrate-grained taxa in the subfamily Liguliflorae: herbs
Asteraceae/Tubuliflorae	Echinate-grained taxa in the subfam. Tubuliflorae: shrubs and herbs
Chenopodiaceae	Ruderals, salt tolerant

APPENDIX B

Myrtaceae Pollen type name on the pollen diagrams and the probable source in the vegetation.

Name on the pollen diagrams	Probable source in the vegetation and ecological inference. From PlantNet (2007)
Angophora costata	Deep sandy soils on sandstone
Angophora floribunda	Usually on deep alluvial soils
A. costata x floribunda	-
Angophora	-
Baeckea/Leptospermum	Some species in swamp/moist habitats, also dryland species
Callistemon	Dry sclerophyll communities, some swamp species
Eucalyptus deanei	Tall wet forest, sheltered valleys, deep sandy alluvial soils
E. eugenioides	Dry sclerophyll or grassy forest, on deep soils
E. fibrosa	Wet or dry sclerophyll forest, on shallower, somewhat infertile soils
E. oblonga	Dry sclerophyll woodland, on extremely infertile, sandy soils
E. oreades	Wet or dry scleropnhyll forest, on poor skeletal or sandy soils
E. pauciflora/E. rubida	Grassy or dry sclerophyll woodland, on cold flats.
E. piperita	Dry sclerophyll forest/woodland, moderately fertile, often alluvial sandy soils
E. racemosa	Dry sclerophyll woodland, on shallow infertile soils
Eucalyptus type B	)
Eucalyptus type C	)
Eucalyptus type D	) For definition of Eucalyptus pollen types, see Chalson (1991)
Eucalyptus type K	)
Eucalyptus type M	)
Eucalyptus/Melaleuca	Species within the two genera: sclerophyll woodland/forest
Kunzea	Understorey sclerophyll forest, moist depressions
Leptospermum juniperinum	Swamp, heath and sedgeland, on sandy peat soils
L. polygalifolium	Dryland habitats and moist depressions
Melaleuca ericifolia	Heath and dry sclerophyll forest, streambanks and coastal swamps
M. styphelioides	Moist situations, often stream bank habitats
Melaleuca type B	)
Melaleuca type C	) For definition of pollen type, see Chalson (1991)
Melaleuca	For definition of *Melaleuca* pollen types, see Chalson (1991)
Myrtaceae type C	)
Myrtaceae type D	) For definition of pollen types, see Chalson (1991)
Unidentified Myrtaceae	All myrtaceous pollen types not identifiable further

Modern Pollen Deposition Under Vegetation of the Blue Mountains, New South Wales

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Pollen was extracted from surface samples of swamp sediments and soils under various types of vegetation in the catchments of these swamps. The pollen assemblages in these surface samples were compared with the floristic composition of the vegetation to provide a means of interpreting the assemblages of fossil pollen retrieved from the swamp sediments.

The surface pollen assemblages reflected the local vegetation, indicating more/less tree cover, swamp and/or adjacent dryland environment and local flora diversity. All the evidence pointed to very local deposition and little long distance dispersal of pollen. A number of different units may be defined within the one major vegetation type, dry sclerophyll forest/woodland in this case, but the floristics of the units are too similar to allow discrimination of them from their modern pollen assemblages.

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KEYWORDS: Blue Mountains, local pollen deposition, long distance pollen dispersal, modern pollen deposition, pollen spectra.

INTRODUCTION

Pollen is deposited in sediments by the contemporaneous vegetation, but a number of factors affect the representation of each taxon in the sediments so that it is not possible to relate a fossil pollen assemblage in a deposit directly to the vegetation that produced it. Pollen productivity, dispersal and preservation are the main factors that influence representation of a taxon, and each of these factors are in turn influenced by the local environmental conditions. Pollen deposited from under known plant communities, however, may be used to characterize that community and hence assist in the interpretation of pollen spectra recovered from swamp sediments. The nature of pollen deposition of individual taxa may also be deduced from the surface pollen spectra.

Sites for a study of the history of the vegetation were chosen from swamps in an altitudinal sequence in the Blue Mountains (Fig. 1). These sites are situated on a relatively uniform substrate, sandstone, within dry sclerophyll woodland/open forest. Observations of modern pollen deposition are reported in this paper, and the Holocene history of the vegetation from the swamps is reported in Chalson and Martin (this volume).

THE STUDY SITES

The Blue Mountains are a deeply dissected plateau rising from the Cumberland Plain in the east. The plateau surface is undulating and small creeks form upland valleys. Where the underlying rock type is Hawkesbury Sandstone, the upland valleys become incised and develop into V-shaped gorges. In the west where rock type is Banks Wall sandstone, the valley sides and floors slope gently and the streams flow through a series of swamps (Chalson, 1991).

The swamps chosen for study are as follows (see Fig. 1) and the species found at each site are listed in Appendix 1:

Burralow Creek Swamp, at 33° 32'S, 150° 38'E and 310-330 m altitude, is a narrow swamp that follows the creek for some 3.5 km. The upper end of the swamp is 2 km southeast of Kurrajong Heights. The core site is 1 km downstream from the northern end. There are few cleared areas near the swamp, the nearest being over 2 km away.

The vegetation around Burralow Creek is open forest, woodland and swamps (Keith and Benson,

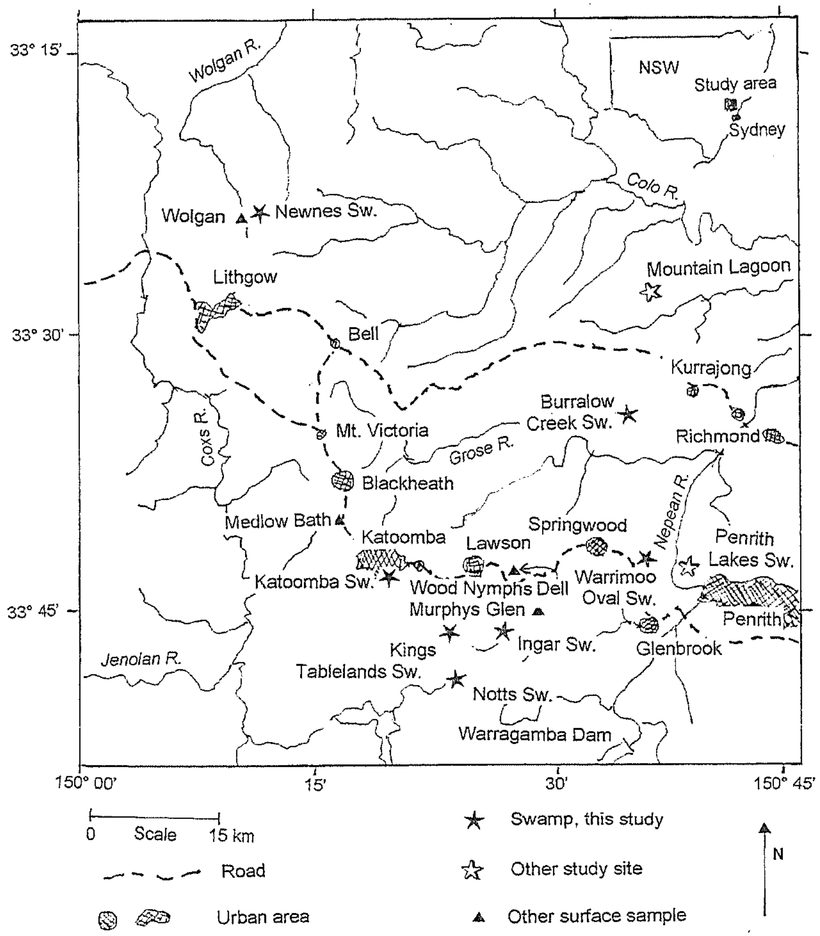

Figure 1. Locality map

1988). *Angophora bakeri, A. costata, Corymbia eximia, Eucalyptus eugenioides, E. multicaulis, E. pauciflora* and *E. radiata* are locally dominant with a few kilometers of the swamp. The surface of the swamp supports an open heathland of *Leptospermum polygalifolium, L. trinervium* and *Eleocharis sphacelata*. Nomenclature follows Harden (1992; 1993; 2000; 2002) and PlantNet (2006)

Warrimoo Oval Swamp, at 33° 43' 21.44"S, 150° 36' 58.35"E and 190-200 m altitude, is approximately 1.5 km east of Warrimoo Post office and 0.4 km south of Warrimoo Oval. There are substantial urban areas within a kilometer of the swamp and weed invasion is considerable.

The vegetation is mainly woodland with some open forest and swamp communities (Keith and Benson, 1988). Locally, *Angophora bakeri, Eucalyptus pauciflora* and *E. radiata* are dominant. The swamp surface supports an open heathland with *Leptospermum* spp.

Notts Swamp, at 33° 48' 35.44" S, 150° 24' 27.66" E and about 682 m altitude is approximately 12 km south-southeast of Wentworth Falls and to the west of Notts Hill. The lower third of the swamp is used as a market garden, but there is no sign of disturbance or weed invasion at the study site. There is no indication of European activities in the catchment upstream of the study site and the nearest settlement is some 7 km to the north-northeast.

The major plant community is open woodland and there is a little open forest and some swamps (Keith and Benson 1988). *Eucalyptus eugenioides, E. multicaulis, E. piperita, E. racemosa* and *E. sieberi* are locally dominant. The swamp supports a closed sedgeland of *Gymnoschoenus sphaerocephalus, Leptospermum trinervium* and *Baloskion australe*.

Ingar Swamp, at 33° 46' 11.65" S, 150° 27' 22.92" E and 584m altitude, is approximately 8 km southeast of Lawson. European settlement is some five km to the northeast, along the highway, and includes some very large, old conifer trees.

The vegetation is mainly woodland with *Corymbia gummifera, Eucalyptus oblongata, E. piperita, E. pauciflora,* and *Angophora costata* dominant locally. Open forest in gorges along the creeks is dominated by *E. eugenioides, E. sclerophylla, Tristania neriifolia* and *Angophora costata*. The swamp community is a closed sedgeland of *Gymnoschoenus sphaerocephalus, Leptocarpus tenax, Baumea* sp., *Chorizandra* sp., *Baloskion australe* and, towards the edge, *Hakea teretifolia, H. dactyloides* and *Leptospermum lanigerum*.

Kings Tablelands, at 33° 45' 47" S, 150° 22' 43" E and about 780-790 m altitude, is located in small valley off Queen Victoria Creek. It is about 0.6 km east of Queen Victoria Memorial Hospital near Wentworth Falls. An urban area is found less than 1 km to the west where exotic conifers have been planted in the gardens.

The vegetation is mainly open forest around the study site, with woodland on the ridges and closed sedgelands in the swamps (Keith and Benson, 1988). Locally, *Eucalyptus dives, E. oreades, E. sieberi* and *E. piperita* are dominant in the open forest and *Corymbia gummifera, E. racemosa* and *E. sieberi* are dominant in the woodland. On the exposed plateau to the northeast, the dominants in an open heathland are *Allocasuarina distyla, E. ligustrina, E. stricta, Banksia serrata* and *Hakea teretifolia*. The dominants on the swamp are *Leptospermum juniperinum* and *L. grandiflorum*.

Katoomba Swamp, at 33° 43' 03" S, 150° 19' 18" E and 950 m altitude, is 1 km east northeast of Katoomba Post Office and 1 km west of Leura Post Office. This swamp is surrounded by urban activity, with drainage ditches and a sealed road running across the swamp. Much of the swamp is (or has been) used for yards for light industry and horse paddocks. Housing extends to the edge of the swamp.

Most of the area around the swamp has been cleared but there are a few remnant pockets of Sandstone Plateau Forest (Keith and Benson, 1988) remaining. *Eucalyptus acmenoides, E. oreades, E. stellulata, E. oblongata* and *E. sieberi* are dominant. The understorey is problematic as the remnant stands are heavily weed infested.

Little remains of the original vegetation over the swamp surface and species of Poaceae are predominant. A small patch of swamp edge vegetation forms a dense thicket of *Leptospermum juniperinum* and *L. scoparium*.

Newnes Swamp, at 33° 22' 57" S,150° 13' 20" E and 1,060 m altitude, is within a forestry area with pine plantations. Regular burning maintains fire breaks.

Woodland communities are found around the swamp (Benson and Keith, 1990) but the shrub layer has been much reduced by frequent burning. Shrubs remaining on the swamp include *Leptospermum trinervium* and *Grevillea acanthifolia*. A ground cover of grasses is found in all but the wettest areas where Juncaceae and Restionaceae are dominant.

METHODS

The vegetation units at each site were determined from maps in Benson (1992), Keith and Benson (1988) and Benson and Keith (1990). Each site was visited, the vegetation checked with the maps and as many species as possible were identified in each of the vegetation units. Since palynology cannot reveal the structure of the vegetation, the focus of survey was on the species list. Dominance was determined subjectively from the abundance of the species

Samples from the surface of the soil, or where possible, from moss polsters, were collected from the centre of the swamp, the swamp edge and the plant communities adjacent or local to, the swamp sites. Samples were taken from at least 100 m away from community boundaries where possible. The sample types and vegetation are listed in Table 1 and the

Table 1 Surface samples used for pollen spectra presented in Figs 2 and 3. Codes for vegetation map units are from Keith and Benson (1988).

Surface sample no.	Vegetation	Vegetation map unit	Sample material
	Burralow Creek		
1	Open sedgeland mid-swamp	28a	Soil
2	Open sedgeland mid-swamp	28a	0 cm core
3	Swamp fringe	28a	Soil
4	Low Woodland	10ar	Soil
5	Open forest	10ag	Soil
	Warrimoo Oval		
6	Closed sedgeland mid-swamp	26a	Soil
7	Closed sedgeland mid-swamp	26a	0 cm core
8	Closed sedgeland swamp fringe	26a	Soil
9	Low woodland	10ar	Soil
	Notts		
10	Closed sedgeland mid-swamp	26a	Soil
11	Closed sedgeland swamp fringe	26a	Soil
	Ingar		
12	Closed sedgeland mid-swamp	26a	Soil
13	Closed sedgeland swamp fringe	26a	Soil
14	Low woodland	10ar	Soil
15	Low woodland	10ar	Soil
	Kings Tableland		
16	Closed sedgeland mid-swamp	26a	0 cm core
17	Closed sedgeland swamp fringe	26a	Soil
18	Low woodland	10ar	Soil
19	Low woodland	10ar	Soil
20	Open forest	9i	Soil
21	Open forest	9i	Soil
22	Open heath	21f	Soil
	Katoomba		
23	Closed sedgeland mid-swamp	26a	Soil
24	Closed sedgeland swamp fringe	26a	Soil
25	Open forest	9i	Soil
26	Open forest	9i	Soil
	Newnes		
27	Closed heath mid-swamp	20a	Moss
28	Closed heath swamp fringe	20a	Moss
29	Woodland	10f/11a	Moss
30	Woodland	10f/11a	Moss
31	Woodland	10f/11a	Soil
32	Woodland	10f/11a	Soil
33	Open heath	21d	Soil
34	Open heath	21c	Soil
35	Forest	10f	Soil
36	Forest	10f	Soil
	Murphys Glen		
37	Tall open forest	6c	Soil
38	Tall open forest	6c	Soil
	Wolgan		
39	Open woodland	11a	Soil
40	Open woodland	11a	Soil
	Wood Nymphs Dell		
41	Open forest	10ag	Soil
	Medlow Bath		
42	Open forest	9i	Soil

study sites are shown in Fig. 1

Six to ten sub-samples were taken from each plant community over a transect of approximately 20 m. The sub-samples were mixed together to reduce the possible over-representation of any one species due to close proximity to an individual plant (Chalson, 1991).

The samples were treated with hydrochloric and hydrofluoric acids to remove siliceous material (Birks and Birks, 1980), oxidised with Schultz solution (a saturated solution of potassium perchlorate in nitric acid), cleared in 10% potassium carbonate and the residue was mounted in glycerine jelly (Brown, 1960).

Pollen was identified by comparing the grains with reference pollen treated with standard acetolysis (Moore et al., 1991). Grains were counted along transects across the slides and tests showed that a count of 140 grains adequately sampled the residues. The counts of each pollen type were presented as percentages of the total count on the pollen diagrams.

RESULTS

Fig. 2 presents the pollen spectra from vegetation on the swamp surface and at the edge of the swamp, and Fig 3. presents spectra from the dry-land communities in the surrounding vegetation. Table 2 presents the name on the pollen diagram, the probable source of the pollen in the vegetation and ecological inference.

Preservation, although adequate, was not good enough for the identification of *Eucalyptus* species beyond broad groups (Chalson and Martin, 1995). The pollen from moss polsters may be better preserved than that from the soil, but moss polsters were not common and usually dried out severely in the forest environment; hence soil samples were usually collected in all but the dampest areas.

Exotic *Pinus* is present in all samples (Figs 2A, 3B) and values are highest at sites near urban areas (Kings Tableland, Katoomba). Surprisingly, *Pinus* values are not high at Newnes, in the forestry area with pine plantations, but the pines were very young at the time of this study.

Angophora/Corymbia and *Eucalyptus/Melaleuca* have been identified in low frequencies in some of the samples which were better preserved. *Melaleuca styphelioides* has been identified in some of the swamp samples (Fig. 2A) where counts may be high. *M. styphelioides* was not found during the survey of the vegetation, but it may be grown in gardens. The highest count at Warimoo Oval Swamp is close to substantial urban areas. *Leptospermum/Baeckea* has been identified from some swamp samples (Fig. 2A) where counts may be considerable. *Leptospermum* spp. are often dominant in the swamp communities (see Appendix 1)

The unidentified Myrtaceae group is larger than the other groups of Mytaceae and counts from the swamp samples are the lowest of all. The woodland or forest samples from the borders of the swamp (Fig. 2A) all have higher counts than the swamp samples. Frequencies in samples from the dry-land vegetation (3A) are much higher than those from swamps. Lack of specific identification was generally due to poor preservation.

Casuarinaceae frequencies are usually low, with a few higher values. The highest value (Fig. 3A) comes from heathland vegetation.

Poaceae frequencies are generally low and the high values are associated with urbanisation and disturbance (Katoomba, Fig. 2A).

Restionaceae frequencies are variable but most of the high values are found in the swamp samples. Cyperaceae has not been recorded from many samples, and where it is present, frequencies are generally low, with the few higher frequencies being found in the swamp samples.

Selaginella is present in a few samples and appreciable frequencies may be recorded in some swamp samples. *Gleichenia* may be present in appreciable frequencies in some swamp samples also. Other fern spores are usually recorded in low frequencies and are more common in the dry-land samples.

Table 2 also lists the likely environmental indication of the pollen groups on the diagrams, but this is difficult, given that a group may include many possible species. For example, the families Restionaceae and Cyperaceae include both swamp and dry-land species, but the species in the vegetation and patterns of high pollen frequencies on the diagrams may indicate the nature of the environment when considered together. Thus the species of Restionaceae and Cyperaceae found in the local vegetation (Appendix 1) are almost entirely species of swamps or damp places (Table 2).

DISCUSSION

There are many indications that the pollen recovered from the surface samples was produced mainly by the local vegetation and thus the pollen spectra can indicate the type of

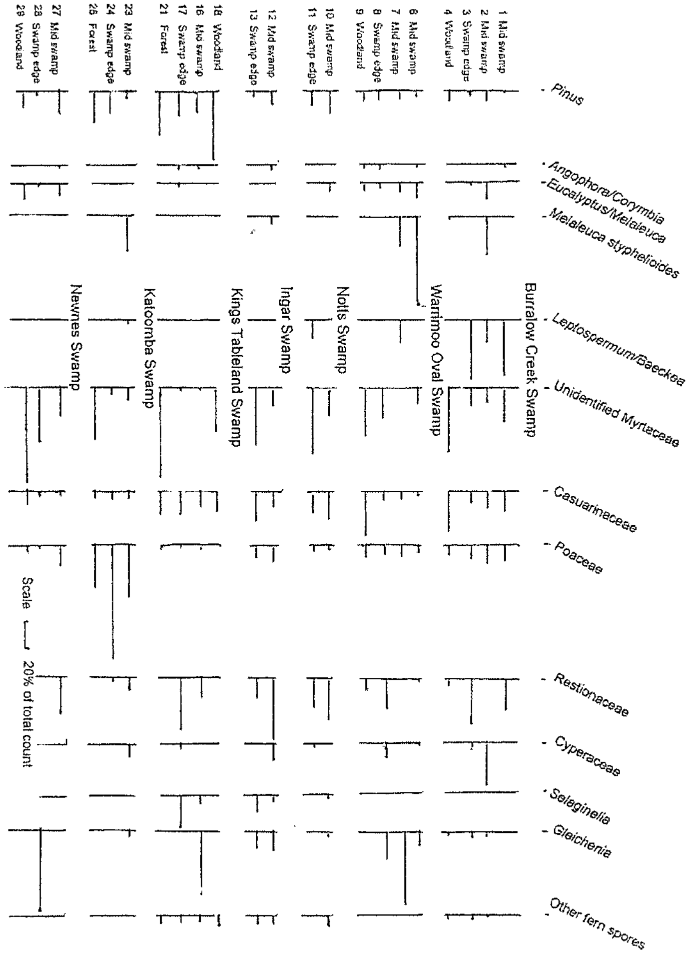

Figure 2A. The pollen spectra from plant communities associated with swamps within major pollen groups. The Sample number (extreme left hand side) refers to the sample in Table 1.

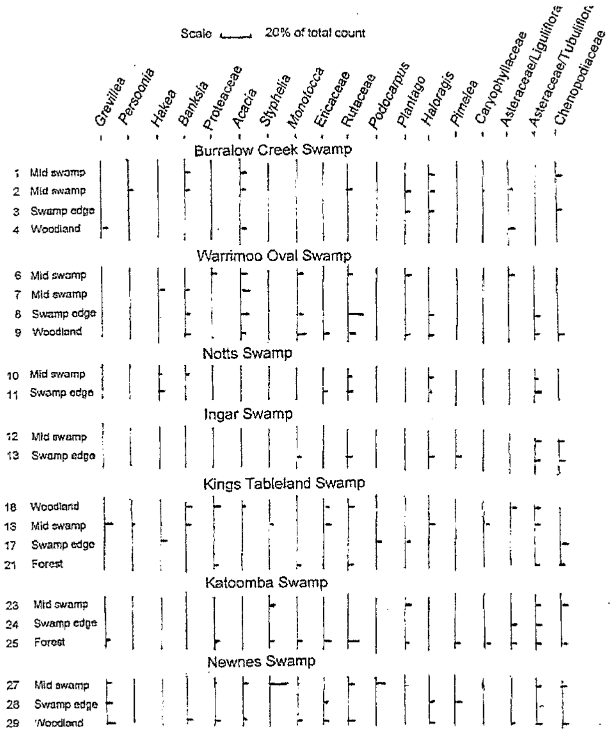

Figure 2B. The pollen spectra from plant communities associated with swamps within low frequency taxa. The Sample number (extreme left hand side) refers to the sample in Table 1

vegetation from which it came. For example, the Myrtaceae pollen content (Figs. 2A, 3A), is lowest from swamp sites, intermediate from the dry-land communities bordering the swamps and highest from the woodland and forest sites away from the swamps, thus inferring a parallel approximate tree cover.

Swamp samples contain much higher pollen frequencies of Restionaceae and/or Cyperaceae than the dry-land sites, although both of these families contain swamp and dry-land species. The species of Restionaceae recorded in the vegetation (Appendix 1) are found on wet and poorly drained soils and in damp to wet heaths (PlantNet, 2007). Most of the species of Cyperaceae, on the other hand, are found in fresh water swamps and swampy areas (Sainty and Jacobs, 1981; PlantNet, 2007), although one dry-land species is also recorded (Appendix 1). Thus high frequencies of Cyperaceae probably indicate swamps which are more permanently waterlogged than swamps with high frequencies of Restionaceae. Both *Selaginella* and *Gleichenia* are found in wet places, on the edge of swamps and streams (PlantNet, 2007).

The pollen of sclerophyllous shrub taxa (Figs 2B, 3B) are usually found sporadically and in very low frequencies, indicating under-representation and very localised distribution.

These findings are in accord with other studies of surface pollen assemblages which indicate very localised distribution of pollen (Dodson, 1983; Kodela, 1990). Kershaw and Strickland (1990) found that, in a 10 year pollen trapping experiment, most pollen came from within 10 m of the trap.

These study sites are all contained within small valleys where some barrier impedes drainage of the

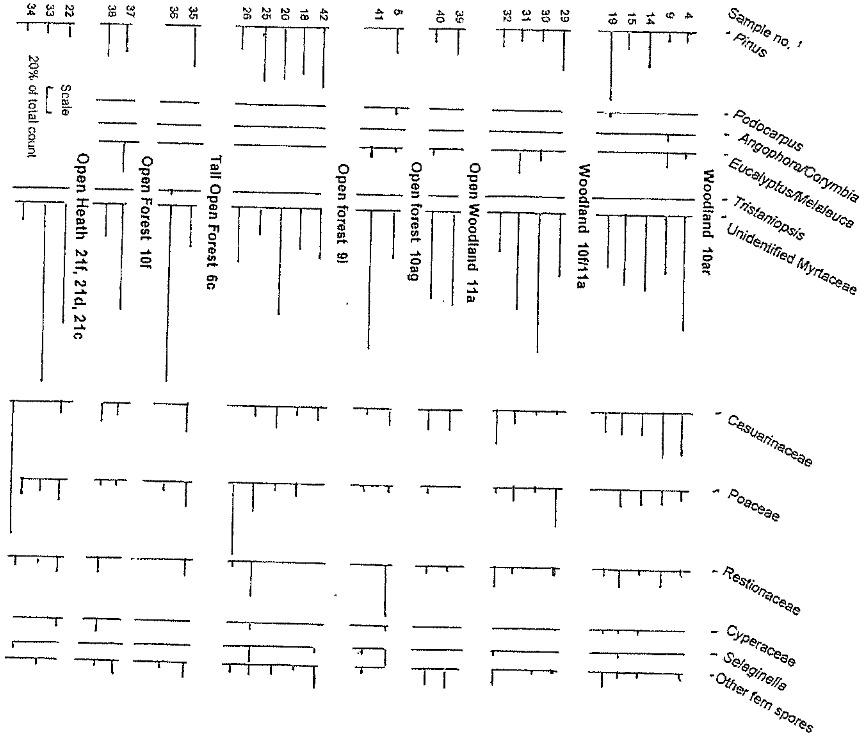

Figure 3A. Pollen spectra associated with dry-land plant communities within major pollen groups. 1 The sample number refers to the sample in Table 1. Codes for the vegetation map units are from Keith and Benson (1988)

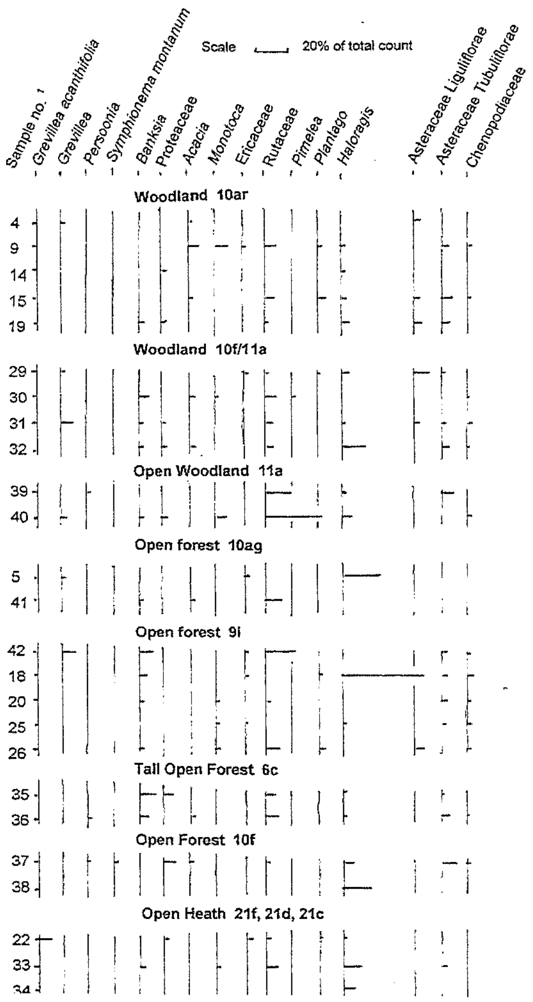

Figure 3B. Pollen spectra associated with dry-land plant communities within low frequency taxa. 1 The sample number refers to the sample in Table 1. Codes for the vegetation map units are from Keith and Benson (1988)

stream and maintains the swamp (for a full description of the sites, see Chalson and Martin, this volume). It may be argued that pollen can be transported a long distance by a stream, to be deposited with the local assemblage. While this may happen, it has been found that very little pollen is transported into the site so that the assemblage truly reflects the local vegetation (Chmura and Liu, 1990).

Table 2. Pollen type name on the pollen diagrams (Figs 2, 3) and the probable source in the vegetation.

Name on the pollen diagrams 2A and 3A	Probable source in the vegetation and ecological inference. From Plantnet (2007)
Podocarpus	Probably *Podocarpus spinulosus*: sclerophyllous shrub/small tree
Pinus	*Pinus* sp(p), Introduced: Pollen input from urban/forestry areas.
Angophora/Corymbia	Species within the two genera: sclerophyll woodland
Eucalyptus/Melaleuca	Species within the two genera : sclerophyll woodland/forest
Melaleuca styphelioides	*Melaleuca styphelioides*: moist stream bank habitat
Leptospermum/Baeckea	Species within the two genera: ?mainly swamp communities
Tristaniopsis	*Tristaniopsis* spp : moist habitats in sclerophyll communities
Unindetified Myrtaceae	All pollen types not identifiable further
Casuarinaceae	*Casuarina, Allocasuarina* sp(p): *A distyla* and *A. nana* in this study
Poaceae	Native and exotic species in the family: open situations, dryland and swamp species
Restionaceae	All species in the family: swamp and dry land species
Cyperaceae	All species in the family: swamp and dry land species
Selaginella	All species in the genus: damp sites, edge of swamp
Gleichenia	*Gleichenia* sp(p): damp sites, edge of swamp
Other fern spores	Other ferns: many possible species
Names on 2B and 3B	
Grevillea acanthifolia	*G. acanthifolia*: sclerophyllous understorey
Grevillea	*Grevillea* sp(p): sclerophyllous understorey
Hakea	*Hakea* sp(p): sclerophyllous understorey
Persoonia	*Persoonia* sp(p): sclerophyllous understorey
Symphionema montanum	*S. montanum*: heath or dry sclerophyll forest
Banksia	*Banksia* sp(p): sclerophyllous understorey
Proteaceae	Other taxa in the family sclerophyllous understorey
Acacia	All species in the genus
Styphelia	*Styphelia* sp(p): sclerophyllous understorey
Monotoca	*Monotoca* sp(p): sclerophyllous understorey
Ericaceae	Other taxa in the family: sclerophyllous understorey
Rutaceae	All taxa in the family: sclerophyllous understorey
Pimelea	*Pimelea* sp(p): sclerophyllous understorey
Plantago	*Plantago* sp(p): native and introduced herbs
Haloragis	*Haloragis/Gonocarpus* sp(p): Damp sites, sclerophyllous understorey
Asteraceae/Liguliflorae	Fenestrate-grained taxa in the subfamily Liguliflorae: herbs
Asteraceae/Tubuliflorae	Echinate-grained taxa in the subfam. Tubuliflorae: shrubs and herbs
Chenopodiaceae	Ruderals, salt tolerant

It is unfortunate that the Myrtaceae species cannot be identified in most cases, since the vegetation units are defined on their species of Myrtaceae. Most Myrtaceae grains are small and thin-walled (Chalson, 1991; Chalson and Martin, 1995) and the preservation may not be good enough to preserve this fine detail which would distinguish the species. The result is that there are large counts of unidentified Myrtaceae. The alternate wetting and drying at the soil surface in these sclerophyll forests are not ideal conditions for pollen preservation.

The forests, woodlands and heaths defined by Benson (1992), Keith and Benson (1988) and Benson and Keith (1990) are structural units within one major vegetation formation and share many species, although the abundance of a particular species may vary. The pollen assemblages cannot denote structure of the vegetation and the floristics of these units are too similar to allow any differentiation, especially as the Myrtaceae pollen is so poorly preserved. For practical purposes, the surface pollen assemblages can denote major vegetation formations (Birks and Birks, 1980; Moore et al., 1991), more/less catchment tree cover, swamp and/or adjacent dry-land environments and local floral diversity.

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APPENDIX. Species found in the vegetation on and around the swamps. Nomenclature follows Harden (1992; 1993; 2000; 2002) and Plantnet (2006). Vegetation map units are from Keith and Benson (1988) D, dominant. *, introduced species.

BURRALOW CREEK SWAMP Species	Open forest 10ar	Wood-land 10ag	Edge swamp 28a	Mid swamp 28a
BRYOPHYTES				
Sphagnaceae				
Sphagnum sp.			+	
PTERIDOPHYTES AND ALLIES				
Adiantaceae				
Adiantum aethiopicum	+	+		
Blechnaceae				
Blechnum ambiguum			+	
B. cartilaginum		+		
Dennstaediaceae				
Pteridium esculentum		+	+	+
Gleicheniaceae				
Gleichenia dicarpa			+	
G. microphylla	+			
Osmundaceae				
Todea barbara		+		
Selaginellaceae				
Selaginella uliginosa			+	
ANGIOSPERMS, DICOTYLEDONS				
Apiaceae				
Platysace ericoides	+			
P. lanceolata				+
P linearifolia	+			+
Xanthosia pilosa	+	+		
Apocynaceae				
Parsonsia straminea	+			
Araliaceae				
Polyscias sambucifolia	+	+		
Asteraceae				
Cassinia aculeata	+			
C. aureonitens	+			
Casuarinaceae				
Allocasuarina nana			+	
Ceratophyllaceae				
Ceratophyllum demersum	+			
Cunoniaceae				
Callicoma serratifolia	+			
Dilleniaceae				
Hibbertia acicularis			+	
H. bracteata		+		
Elaeocarpaceae				
Elaeocarpus reticulatus	+			
Tetratheca thymifolia		+		
Ericaceae				
Epacris paludosa	+			
E. pulchella	+	+		
Leucopogon hookeri	+	+		
Euphorbiaceae				
Ampera xiphoclada	+			
Phyllanthus hirtellus	+			+
Fabaceae, Faboideae				
Bossiaea obcordata	+			
Dillwynia floribunda	+		+	+
D. retorta	+			
Gompholobium huegelii		+	+	
Pultenaea tuberculata	+			
Fabaceae, Mimosoideae				
Acacia falciformis	+			
A. myrtifolia	+			
A. obtusata	+			+
A. ptychoclada			+	+
A. terminalis	+		+	
Goodeniaceae				
Dampiera stricta	+		+	
Goodenia dimorpha			+	
G. heterophylla	+			
G. ovata	+			
Lamiaceae				
Prostanthera violacea		+		
Lauraceae				
Cassytha melantha	+			
Lobeliaceae				
Pratia purpurascens			+	
Loganiaceae				
Mitrasacme pilosa				+
Meliaceae				
**Melia azedarach* var. *australasica*	+			
Menyanthaceae				
Villarsia exaltata				+
Myrsinaceae				
Rapanea howittiana	+	+		
Myrtacae				
Angophora bakeri			D	
A. costata	D			
A. floribunda	+	+		

Baeckea linifolia			+	
Corymbia eximia			D	
Eucalyptus eugenioides			D	
E. multicaulis			D	
E. pauciflora	D	D		
E. radiata		D		
Kunzea capitata	+			D
Leptospermum polygalifolium			+	
L. trinervium				D
Melaleuca linariifolia	D	D		
Tristania neriifolia	D			
Oleaceae				
**Ligustrum sinense*	+			
Notelaea longifolia	+	+		
Pittosporaceae				
Billardiera scandens	+			
Proteaceae				
Banksia ericifolia	+			
B. serrata				+
Hakea teretifolia	+		+	
Lambertia formosa	+	+		
Persoonia laurina			+	
P. levis	+			
P. linearis	+			
P. mollis				+
P. oblongata	+			
Petrophile pulchella		+		
Ranunculaceae				
Clematis aristata		+		
Rhamnaceae				
Cryptandra amara		+		
Rutaceae				
Eriostemon hispidulus	+	+		
Sapindaceae				
Dodonaea pinnata	+			
D. triquetra	+			
Stackhousiaceae				
Stackhousia viminea	+			
Thymelacaceae				
Pimelea ligustrina	+			
Violaceae				
Viola hederacea		+		
ANGIOSPERMS, MONOCOTYLEDONS				
Cyperaceae				
Baumea juncea				+
Baumea sp.			+	+
Chorizandra sp.	+			+
Eleocharis sphacelata		+	+	
Lepidosperma longitudinale			+	
Schoenus sp.			+	
Lomandraceae				
Lomandra glauca		+		
L. longifolia				+
Phormiaceae				
Dianella caerulea	+			
Restionaceae				
Leptocarpus tenax				+
Baloskion fimbriatum		+		
Smilacaceae				
Smilax australis	+			
S. glyciphylla	+			

WARRIMOO OVAL SWAMP Species	Open forest 10ar	Edge swamp 26a	Mid swamp 26a
PTERIDOPHYTES AND ALLIES			
Adiantaceae			
Adiantum diaphanum	+		
Dennstaediaceae			
Pteridium esculentum	+	+	
Gleicheniaceae			
Gleichenia dicarpa		+	+
ANGIOSPERMS, DICOTYLEDONS			
Apiaceae			
Actinotus minor	+		
Platysace lanceolata	+	+	
P linearifolia	+		
Ericaceae			
Brachyloma daphnoides	+		
Dracophyllum secundum		+	
Epacris paludosa	+	+	
Fabaceae, Faboideae			
Bossiaea heterophylla	+	+	
**Cytisus scoparius*	+		
Daviesia ulicifolia	+	+	
Dillwynia phylicoides		+	
Gompholobium huegelii	+	+	
G. latifolium	+		
Hovea linearis		+	

Mirbelia rubifolia	+		
Fabaceae, Mimosoideae			
Acacia falciformis	+		
A. ptychoclada		+	
A. rubida			+
A. terminalis	+		
Goodeniaceae			
Dampiera stricta	+	+	
G. ovata	+		
Lobeliaceae			
Pratia purpurascens	+		
Myrtacae			
Angophora bakeri	D	D	
Baeckea linifolia	+		+
Eucalyptus notabilis		D	
E. pauciflora	D		
E. radiata	D		
Kunzea capitata	+		D
Leptospermum grandifolium			D
L. polygalifolium	+		D
L. trinervium	+	+	
Polygalaceae			
Comesperma defoliatum	+		
C. ericinium	+		
Proteaceae			
Banksia ericifolia	+	+	
B. oblongifolia	+		
B. serrata	+	+	
Grevillea laurifolia	+	+	
G. mucronulata	+		
G. phylicoides	+	+	
Hakea salicifolia	+	+	
Isopogon anethifolius	+	+	
I. prostratus	+	+	
Persoonia laurina	+		
P. myrtilloides	+		
P. pinifolia	+		
Rutaceae			
Boronia microphylla	+	+	
Thymelaeaceae			
Pimelea glauca			+
P. ligustrina	+		
Violaceae			
Viola hederacea			
ANGIOSPERMS, MONOCOTYLEDONS			
Cyperaceae			
Baumea juncea			+
Eleocharis sphacelata			+
Juncaceae			
Juncus remotiflorus			+
Lomandraceae			
Lomandra filiformis ssp *coriacea*		+	
L. longifolia	+		
L. obliqua	+		
Phormiaceae			
Dianella caerulea		+	
Restionaceae			
Leptocarpus tenax	+	+	

NOTTS SWAMP Species	Open forest 10ar	Mid swamp 26a
PTERIDOPHYTES AND ALLIES		
Dennstaediaceae		
Pteridium esculentum	+	
Gleicheniaceae		
Gleichenia dicarpa		+
Selaginellaceae		
Selaginella uliginosa		+
ANGIOSPERMS, DICOTYLEDONS		
Apiaceae		
Actinotus forsythii	+	
Platysace lanceolata	+	
P linearifolia	+	
Ericaceae		
Epacris paludosa	+	
Lissanthe sapida	+	
Euphorbiaceae		
Poranthera microphylla		+
Fabaceae, Faboideae		
Bossiaea heterophylla	+	
Phyllota squarrosa		+
Platylobium formosum		+
Fabaceae, Mimosoideae		
Acacia melanoxylon	+	
A. obtusata	+	
A. obtusifolia		+
A. stricta	+	

Myrtacae		
Eucalyptus aggregata		+
E. dives	D	
E. ligustrina	D	
E. pauciflora	D	
E. piperita	D	
E. sclerophylla	D	
Kunzea capitata		D
Leptospermum juniperinum		+
Proteaceae		
Banksia oblongifolia	+	
B. serrata	+	
Grevillea phylicoides	+	
Hakea teretifolia	+	
Isopogon prostratus	+	
Persoonia laurina	+	
P. linearis	+	
Petrophile pedunculata	+	
Rutaceae		
Boronia microphylla	+	+
ANGIOSPERMS, MONOCOTYLEDONS		
Cyperaceae		
Baumea rubiginosa		+
Carex sp.	+	
Gahnia sp.		D
Iridaceae		
Patersonia sericea	+	
Juncaceae		
Juncus remotiformis		+
Phormiaceae		
Dianella caerulea	+	
Poaceae		
Entolasia marginata	+	
Poa sp.	+	
Restionaceae		
Baloskion australe		+
Leptocarpus tenax (Labill.)		D

INGAR SWAMP Species	Open forest 10ar	Wood-land 10ag	6c Tall open forest	Edge swamp 26a	Mid swamp 26a
PTERIDOPHYTES AND ALLIES					
Adiantaceae					
Adiantum aethiopicum				+	
Dennstaediaceae					
Pteridium esculentum	+		+		
Dicksoniaceae					
Calochlaena dubia			+		
Gleicheniaceae					
Gleichenia dicarpa		+			+
G. microphylla		+			
Osmundaceae					
Todea barbara		+			
Selaginellaceae					
Selaginella uliginosa				+	
ANGIOSPERMS, DICOTYLEDONS					
Apiaceae					
Actinotus forsythii	+			+	
Platysace lanceolata	+	+	+		
P. linearifolia	+			+	
Casuarinaceae					
Allocasuarina distyla		+			
Cunoniaceae					
Bauera rubioides		+			
Callicoma serratifolia		+	+		
Ceratopetalum apetalum		+			
Dilleniaceae					
Hibbertia acicularis	+				
Elaeocarpaceae					
Elaeocarpus reticulatus			+		
Ericaceae					
Brachyloma daphnoides		+			
Dracophyllum secundum				+	
Epacris paludosa	+	+			
Leucopogon esquamatus				+	
L. hookeri		+			
L. lanceolatus		+			
Lissanthe sapida	+				
Euphorbiaceae					
Ampera xiphoclada	+				
Fabaceae, Faboideae					
Bossiaea heterophylla	+				
B. obcordata		+			
Daviesis alata	+	+			
D. ulicifolia	+				
Dillwynia philicoides		+			
D. retorta	+				
Glycine clandestina	+				
Hovea linearis				+	

Phyllota phylicoides	+				
P. squarrosa		+			
Platylobium formosum					+
Pultenaea divaricata		+			
P. flexilis				+	
P. incurvata		+			
P. tuberculata		+	+		
Fabaceae, Mimosoideae					
Acacia echinula	+	+	+		
A. melanoxylon	+				
A. obliquinervia	+				
A. obtusata	+		+		
A. obtusifolia				+	+
A. stricta	+			+	+
A. suaveolens		+	+		
Goodeniaceae					
Dampiera stricta				+	
Goodenia bellidifolia				+	
G. dimorpha				+	
G. ovata				+	
Haloragaceae					
Gonocarpus chinensis ssp *verrucosus*				+	
G. longifolius			+	+	
Myrtacae					
Angophora bakeri	D	D	+		
Backhousia myrtifolia				+	
Baeckea diosmifolia		+			
Corymbia eximia	D				
Eucalyptus agglomerata		D			
E. dalrympleana			D		
E. dives		D			
E. obliqua	D				
E. oreades	D				
E. pauciflora	D	D			
E. radiata		D			
E. sieberi	+				
Kunzea capitata	+	+			
Leptospermum grandifolium			+		
L. juniperinum					D
L. polygalifolium		+			+
L. scoparium			+		
L. trinervium			+		
Melaleuca linariifolia			D		
Syncarpia glomulifera		D			

Proteacceae					
Banksia ericifolia				+	
B. oblongifolia	+	+			
B. serrata	+	+	+		
Grevillea aspleniifolia		+			
G. laurifolia			+		
G. phylicoides	+			D	
Hakea propinqua			+		
H. sericea		+		D	
H. teretifolia	+	+		+	
Isopogon prostratus	+	+			
Lambertia formosa		+			
Lomatia myricoides			+		
Persoonia acerosa		+			
P. laurina	+				
P. levis		+			
P. linearis	+	+	+		
P. pinifolia		+			
Petrophile pedunculata	+				
Ranunculaceae					
Clematis aristata			+		
Rhamnaceae					
Cryptandra amara			+		
Rutaceae					
Boronia microphylla	+				
Thymelaeaceae					
Pimelea ligustrina				+	
ANGIOSPERMS, MONOCOTYLEDONS					
Cyperaceae					
Baumea rubiginosa					D
Carex sp.	+	+			+
Chorizandra cymbaria				D	
Eleocharis sphacelata		+			
Gahnia sieberana		+	+		
Gahnia sp.					D
Gymnoschoenus sphaerocephalus				+	
Lepidosperma longitudinale				D	
Iridaceae					
Patersonia sericea	+				
Juncaceae					
Juncus remotiformis			+		
Luzuriagaceae					
Eustrephus latifolius			+		
Phormiaceae					
Dianella caerulea	+				

Poaceae					
Entolasia marginata	+				
Poa sp.				+	
Restionaceae					
Baloskion australe					+
Empodisma minus				D	
Leptocarpus tenax				D	D
Smilacaceae					
Smilax australis				+	

KINGS TABLELAND SWAMP Species	Wood-land 10ar	Open forest 9i	Open heath 21f	Edge swamp 26a	Mid swamp 26a
PTERIDOPHYTES AND ALLIES					
Dennstaediaceae					
Pteridium esculentum		+			
Gleicheniaceae					
Gleichenia dicarpa					+
GYMNOSPERMS					
Cupressaceae					
Callitris muelleri			+		
ANGIOSPERMS, DICOTYLEDONS					
Apiaceae					
Actinotus forsythii			+		
Platysace lanceolata	+	+	+		
Casuarinaceae					
Allocasuarina distyla		+	D		
Allocasuarina nana			+		
Ericaceae					
Dracophyllum secundum					+
Epacris paludosa			+		
Fabaceae, Faboideae					
Bossiaea heterophylla		+	+		
Daviesia alata	+		+		
D. ulicifolia		+			
Hovea linearis			+		
Phyllota squarrosa	+				
Pultenaea divaricata	+				
Fabaceae, Mimosoideae					
Acacia obtusata		+			
A. stricta		+			
A. suaveolens	+	+			
A. terminalis			+		
Myrtacae					
Corymbia eximia	D				
C. gummifera			D		
Eucalyptus deanei		D			
E. oblonga		D			
E. pauciflora		D			
E. piperita	D				
E. sclerophylla	D	D			
E. stellulata			D		
E. stricta			+		
Kunzea capitata	+	+			
K. ericoides			+		
Leptospermum grandifolium			+		
L. juniperinum					D
L. polygalifolium			+		D
Olacaceae					
Olax stricta			+		
Proteaceae					
Banksia ericifolia	+		+		+
B. oblongifolia		+	D		
B. serrata	+	+	+		
B. spinulosa					+
Grevillea phylicoides	+	+	+		
Hakea dactyloides			+		
H. salicifolia	+	+			
H. sericea			D		+
Isopogon anemonifolius		+			
I. prostratus	+	+	+		
Lomatia silaifolia			+		
Persoonia laurina	+	+			
Petrophile pedunculata	+		+		
Thymelaeaceae					
Pimelea ligustrina					+
ANGIOSPERMS, MONOCOTYLEDONS					
Lomandraceae					
Lomandra glauca		+			

KATOOMBA SWAMP Species	Open forest Upper 9i	Open forest Lower 9i	Edge swamp 26a	Mid swamp 26a
BRYOPHYTES				
Dawsoniineae				
Dawsonia sp.				D

PTERIDOPHYTES AND ALLIES				
Blechnaccae				
Blechnum cartilaginum			+	
Dennstaediaceae				
Pteridium esculentum	+	+		
Gleicheniaceae				
Gleichenia dicarpa			+	
Lycopodiaceae				
Lycopodium deuterodensum	+			
ANGIOSPERMS, DICOTYLEDONS				
Araliaceae				
Polyscias sambucifolia	+	+		
Asteraceae				
Arrhenechthites mixta	+			
Bracteantha bracteata		+		
Cunoniaceae				
Callicoma serratifolia	+			
Ericaceae				
Epacris paludosa		+		
Fabaceae, Faboideae				
Bossiaea rhombifolia	+	+	+	
Daviesia latifolia		+		
Fabaceae, Mimosoideae				
Acacia obtusata	+			
A. suaveolens		+		
Myrtacae				
Callistemon citrinus	D			
Eucalyptus obliqua		D		
E. oblonga	D			
E. sclerophylla		D		
E. squamosa	D			
Kunzea capitata	+	+		
K. ericoides			D	
Leptospermum polygalifolium			D	
L. trinervium		+		
Oleaceae				
**Ligustrum sinense*	+	+		
Polygonaceae				
**Acetosella vulgaris*			+	
**Rumex obtusifolius*			+	
Proteaceae				
Banksia spinulosa			+	
Grevillea mucronata		+		
Isopogon prostratus		+		
Lomatia myricoides		+		
Persoonia laurina		+		
Petrophile pedunculata		+		
Rutaceae				
Boronia microphylla		+		
ANGIOSPERMS, MONOCOTYLEDONS				
Cyperaceae				
Caustis flexuosa				D
Juncaceae				
Juncus remotiformis			+	D
Lomandraceae				
Lomandra obliqua		+		
Phormiaceae				
Dianella caerulea	+			
Poaceae				
Poa sp.			+	

NEWNES SWAMP Species	Open forest 9i	Wood-land 11a	Edge swamp 20a	Mid swamp 2oa
PTERIDOPHYTES AND ALLIES				
Blechnaceae				
Blechnum cartilaginum	+			
Dennstaediaceae				
Pteridium esculentum	+			
Gleicheniaceae				
Gleichenia dicarpa	+		+	
ANGIOSPERMS, DICOTYLEDONS				
Apiaceae				
Platysace lanceolata	+			
Asteraceae				
Arrhenechthites mixta	+			
Helichrysum scorpioides	+	+		
Olearia sp. aff. *chrysophyplla*	+			
Casuarinaceae				
Allocasuarina nana		+		
Dilleniaceae				
Hibbertia dentata	+			
Ericaceae				
Brachyloma daphnoides			+	
Epacris obtusifolia			+	
E. paludosa	+		+	
Lissanthe sapida	+	+		
Monotoca scoparia				+

Euphorbiaceae				
Ampera xiphoclada	+			
Fabaceae, Faboideae				
Daviesis corymbosa	+			
D. ulicifolia	+			
Gompholobium grandiflorum		+		
G. latifolium		+		
Phyllota phylicoides		+		
P. squarrosa	+	+		
Platylobium formosum			+	
Fabaceae, Mimosoideae				
Acacia elata	+			
A. linifolia	+			
A. longifolia		+		
A. melanoxylon		+		
A. suaveolens	+			
Goodeniaceae				
Dampiera stricta	+		+	
Myrtacae				
Baeckea diosmifolia			+	+
Eucalyptus acmenoides		D		
E. aggregata		D		
E. deanei		D		
E. notabilis	D	D		
E. oreades	D	D		
E. racemosa	D			
E. sclerophylla		D		
Kunzea capitata	+		D	
Leptospermum juniperinum			+	+
L. polygalifolium	+			
Proteaceae				
Banksia spinulosa			+	D
Grevillea acanthifolia	+			
G. aspleniifolia	+	+		
G. phylicoides		+		
Hakea salicifolia	+			
H. teretifolia	+			
Petrophile pedunculata	+	+		
Ranunculaceae				
Clematis aristata	+			
Rhamnaceae				
Cryptandra amara		+		
Rutaceae				
Boronia microphylla		+		
Santalaceae				
Exocarpos strictus		+		
Thymelaeaceae				
Pimelea glauca	+			
P. ligustrina	+			
ANGIOSPERMS, MONOCOTYLEDONS				
Cyperaceae				
Lepidosperma laterale	+			+
Iridaceae				
Patersonia sericea	+	+		
Juncaceae				
Juncus remotiformis			+	
Lomandraceae				
Lomandra filiformis ssp *coriacea*	+	+		
L. filiformis ssp *filiformis*		+		
L. glauca Ewart	+			
Phormiaceae				
Dianella caerulea		+		
Poaceae				
Entolasia marginata				+
Poa sp.		+		
Restionaceae				
Empodisma minus				+
Leptocarpus tenax		+	+	

The History of the Vegetation from the Last Glacial Maximum at Mountain Lagoon, Blue Mountains, New South Wales.

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Robbie, A. and Martin, H.A. (2007). The history of the vegetation from the last glacial maximum at Mountain Lagoon, Blue Mountains, New South Wales. *Proceedings of the Linnean Society of New South Wales* **128**, 57-80.

Mountain Lagoon in the Blue Mountains west of Sydney provides a sedimentary record of 23,000 years, thereby including the Last Glacial Maximum. Initially, the site was a lake where clay was being deposited and the vegetation was probably shrubland/herbfields. About 18-19 kyr, the lake became shallow enough for sedgelands and peat formation. At this time, pollen concentrations were high and both Casuarinaceae and Myrtaceae are prominent. In the early Holocene, about 10 kyr, the swamp became a lake again, perhaps because of some minor movement of the fault-line which could have caused a burst of accelerated erosion and clay deposition. The lake surface was re-colonized by the sedgelands again about 7-8 kyr, when the vegetation was woodland/forest.

The vegetation surrounding the site was sclerophyllous throughout the last 23 kyr, as would be expected on these low nutrient soils. In contrast to the likely marked climatic changes during this period, the pollen spectra show remarkably little change in the major taxa. However, variations of some of the Myrtaceae pollen show that there were species changes, although some taxa were present the whole time. Casuarinaceae was prominent throughout and did not decline until European settlement.

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KEYWORDS: Blue Mountains, Holocene, last glacial maximum, Mountain Lagoon, palynology, vegetation history.

INTRODUCTION

Mountain Lagoon (Fig. 1), in a small enclosed basin, was formed following subsidence along the Kurrajong Fault line and the subsequent disruption to the established drainage patterns. The sediments extracted for this study record at least 23,000 years of deposition, which includes the Last Glacial Maximum (LGM) period at about 18,000 years ago. Estimates of the LGM from other records indicate that temperatures were some 4-8°C lower than today and the climate was also more arid (Dodson 1994) with up to 50 % less precipitation (Thom et al. 1994). The site stands at just over 500 m elevation today, but with lowered sea levels during the glacial period, it would have been about 100 m higher in elevation at that time. Hope (1989) estimates that this altitude would have been near or at the treeline during the last glacial period. Studies of the glacial period in southeastern Australia show that the vegetation of the time was more open, with few trees and more grasslands and shrublands (Dodson 1994; Hope 1994), but Pickett et al. (2004) think that xerophytic woods and scrubs were more extensive in south-western and south-eastern Australia.

There are few histories of the vegetation extending back beyond the last glacial period in the Sydney Basin. Chalson (1991) found that the Penrith Lakes Swamp (Fig. 1) provided a 33,000 year record and Black et al. (2006) present a >43,000 year history at Thirlmere Lakes, but these are both lowland sites. At Readhead Lagoon, a coastal site (Fig. 1), Williams et al. (2006) record a history that goes back well before the LGM. Chalson also presents a number of other sites in the Blue Mountains which are all 11,000 years or younger in age and Black and Mooney (2006) present a 14,000 year history of Gooches Crater on the Newnes Plateau. Mountain Lagoon thus provides a record of the changes in the vegetation through the glacial period to the present at a relatively high altitude in the Blue Mountains.

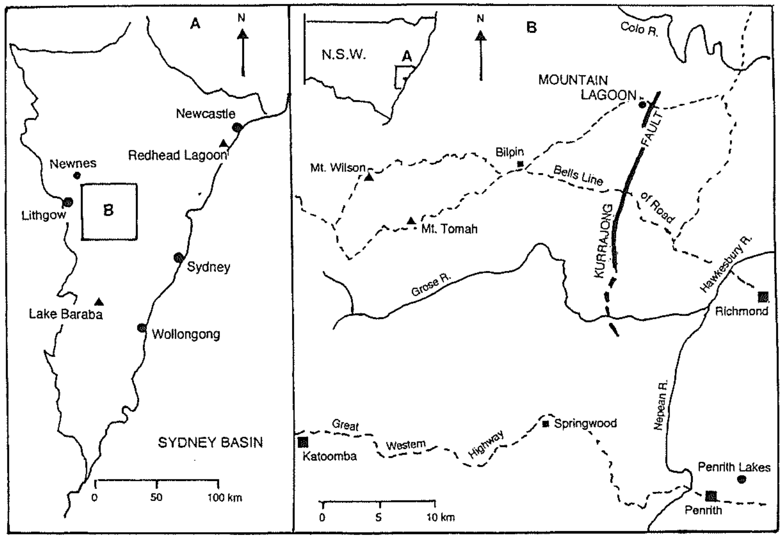

Figure 1. Regional locality map showing study site and place names discussed in text.

THE ENVIRONMENT

Geology

Mountain Lagoon is a shallow, swampy lake in a small basin-shaped valley (Ryan et al. 1996) 14 km north-east of Bilpin in the eastern Blue Mountains (St. Albans G.R. 663966). It was described by Grady and Hogbin (1926) as resembling an 'over-turned saucer", and therefore all sediment within the basin is derived from within its own catchment area which measures approximately 2 km^2. The lagoon lies on top of a small, thin lens of Wainamatta Shale which is underlain by the Triassic Hawkesbury Sandstone (Grady and Hogbin 1926). It is a tectonic lake (Timms 1992) abutting the Kurrajong Block, and was formed following the subsidence of the land to the west of the Kurrajong Fault (David 1902). The Kurrajong Block, which rises some 120 m above Mountain Lagoon on its eastern side and stretches south approximately 25 km to Glenbrook (David 1902), is believed to have impeded the north-eastern progress of a small stream whose waters pooled at this barrier and formed the lagoon (Grady and Hogbin 1926), possibly in the late Tertiary (Branagan 1969).

Climate

Wedged between the coastal ranges, and the Upper Blue Mountains and Great Dividing range, the St Albans region is mostly in a rainshadow and is a relatively dry part of the Hawksbury-Nepean catchment. Rainfall is generally over 900 mm, but Bilpin, some 7-8 km WSW of Mountain Lagoon, seated in front of Mount Wilson, experiences higher orographic rainfall, and receives 1300 mm p.a. (Ryan et al., 1996). Records kept by a landholder at Mountain Lagoon for the period 1952-1994 show an average annual rainfall of 1257 mm, with January-February the wettest months, with an average of 157-181 mm per month, and August-October the driest months, with an average of 51-70 mm per month (Hungerford 1995).

Average maximum temperature for January is 28° C and average minimum temperature for July is 2-3°C (Ryan et al. 1996).

The Vegetation

Prior to historic land clearance for forestry and agriculture, the rich, moist soils of the shale lens supported a tall open forest dominated by *Eucalyptus deanei*, *E. cypellocarpa* and *Syncarpia* *glomulifera*, specimens of which have survived in small patches of forest which remain in the area (Ryan et al. 1996). Two significant species with very restricted distribution are found in these forests, viz. *Acacia pubescens* and *Alania endlicheri*. The lagoon itself supports a freshwater reed swamp dominated by sedges, with a main canopy of *Lepidosperma longitudinale* and a fringing *Melaleuca linariifolia* forest. The sheltered western slope of the Kurrajong Block supports a Sydney Sandstone Gully Forest dominated by *Angophora costata*, *Eucalyptus piperita*, *E. agglomerata* and *Syncarpia glomulifera*. On the exposed ridges at the top of the Kurrajong Block, *Corymbia eximia*, *Angophora bakeri*, *C. gummifera*, *A. costata* and *Eucalyptus punctata* are dominant (Ryan et al. 1996).

Three small patches of basaltic soils at Green Scrub to the south of the lagoon support a warm temperate rainforest (Floyd 1989). Prior to European arrival the forest was most likely dominated by *Dorifera sassafras*, *Acmena smithii*, *Toona ciliata* and *Ceratopetalum* spp., but repeated firing and logging have greatly altered the forest and continue to threaten the floral composition of this forest (Floyd 1989).

Human history and land use

Archaeological evidence tends to suggest that Aboriginal people first settled in the region from 20,000 to14,000 years before the present (BP) and that many sites may have been abandoned at 12,000 years BP, to be followed by 'a more intensive phase of occupation' beginning around 10,000-5,000 years BP (Conyers 1987). Accounts by early European settlers suggest the region was well known to the Dharruk and possibly Wiradjuri groups, who had traditional names for prominent landforms such as Mt. Tomah, and advised on the more accessible routes over the mountains The area is culturally significant to the Dharruk and the raised area to the immediate west of the lagoon was used as a bora ground as late as the 1890s (Hungerford 1995). The region is encircled by sites with rock engravings, cave paintings and axe grinding sites (Stockton 1993).

Europeans such as Mathew Etheringham and the botanist George Caley began exploring the mountains from Kurrajong Heights around the turn of the 19th Century (Hungerford 1995). The existence of Mountain Lagoon was known to Europeans before 1830 and the area was frequented by shooters. Later timber extraction and milling became important in the area with the removal of 'wattle barks, blue-gum and other hardwoods', and it is likely that the lagoon formed part of a stock route linking the Hunter region with Bathurst. The land to the west of the lagoon was first squatted and was later purchased in 1868, and a mixed orchard of oranges, lemons, cherries, and apples was established, along with maize, oats and potatoes. Orchards spread in popularity across the region throughout the 20th century, and strawberries were introduced in the area in the early 1970s. Orchards have largely disappeared from the area since 1975, and the land surrounding the lagoon supports mostly cattle grazing with some citrus and apple growing (Hungerford 1995).

METHODS

Six sites, each within different environments in the vicinity of the lagoon (Fig. 2) were chosen to determine the major variations in vegetation, using aerial photographs and onsite inspections. A full list of species at Site 6 (Green Scrub rainforest) was obtained from P. Hind of the Royal Botanic Gardens, Sydney.

In the latter part of the 1980s the lagoon was greatly modified in the hope that it would become a permanent source of water for cattle. Sediment was excavated from the northeastern end of the lagoon and deposited towards the south-western end (Fig. 3). The results of the excavation were obvious in 1991 when the original core was taken, (Mr. C. Myers, pers. comm. 1996) and an undisturbed site was chosen.

The stratigraphy along two transects at right angles was evaluated using a Hiller corer and the sediments were described using the Troels-Smith method for sediment description (Moore et al. 1991). Two cores for further analysis were taken from a place as close as possible to the original site (cored by C. Myers), using a Livingstone type corer (Livingstone, 1955) with modifications (Neale and Walker 1996).

Two peat sediment samples taken at depths of 33-38 cm and 59-68 cm from the original core were radiocarbon dated by the Beta Analytic Company in 1991 (Table 1). The top 15 cm of the original core was discarded in the belief that this section was disturbed. Two samples from the clay extracted in later cores, at depths of 60-70 cm and 90-100 cm were dated by the Accelerated Mass Spectrometry method at ANTSO (Table 1).

Organic matter was estimated on oven-dried (105°C) samples fired to 550°C, at 10 cm intervals. During ignition, structurally bound water is lost also, but in highly organic sediments, the major loss is from the ignition of organic matter (Bengtsson and Enell 1990).

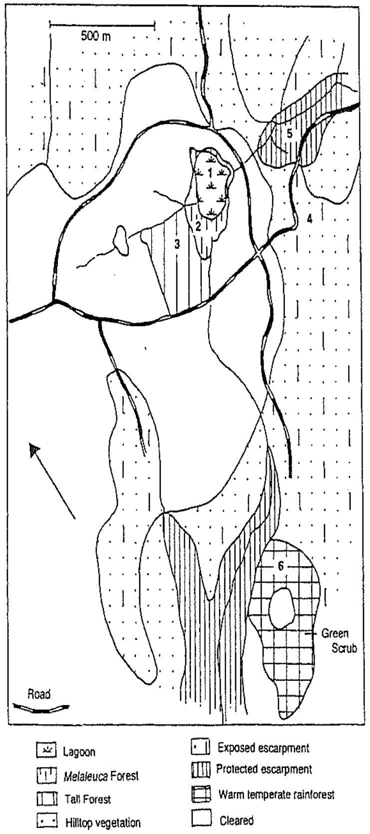

Figure 2. Vegetation survey sites (numbers) and map of the vegetation types.

The saturated isothermal remnant magnetism (SIRM) was measured on sub-samples taken at half centimetre intervals from the original core. The sediment was dried at 50°C, ground and treated in a magnetic field of 1.0 Tesla (Thompson 1990) and measured with a Molspin Magnetometer.

For pollen extraction, sediment samples of 1 cm^3 were taken at 10 cm intervals along the second core and were spiked with an exotic pollen suspension (*Alnus rhombifolia* was used) of known concentration (Birks and Birks 1980). Humic acids were removed with cold 10% potassium hydroxide and mineral matter was removed using hydrochloric and hydrofluoric acids. The residue was treated with acetolysis to clear remaining humic material (Moore et al. 1991). The residues were mounted in glycerine jelly, using No. 0 coverslips.

Pollen was identified by comparison with modern reference pollen. A minimum of 180 pollen grains were counted along traverses on the slides of the fine sediment residues. Where there was insufficient pollen to count 180 grains, those pollen types present were scored as 'present'. The number of the exotic *Alnus* grains encountered along the traverses were counted also, allowing calculation of the pollen concentration. The abundance of each pollen type was expressed as percentages and as pollen concentration. Confidence limits for percentages were calculated following Maher (1972). The amount of charcoal in each preparation was determined as the area of the slide it covered, following the point count method (Clark 1984).

RESULTS

The vegetation

Six vegetation units in the vicinity of the lagoon were defined and a list of species found in each is presented in Appendix 1. The vegetation units are shown in Fig. 2 and were defined as follows:

1. The swamp vegetation of the lagoon itself is a fen which becomes dry periodically. The centre of the lagoon is dominated by *Baumea articulata*, with *Nymphoides geminata* and *Myriophyllum variifolium* at the margins.
2. The lagoon fen is ringed by a *Melaleuca* swamp forest, *c.* 5 m tall, with a 50% cover of *Melaleuca linariifolia* and an understorey of *Leptospermum polygalifolium* and *Acacia filicifolia*. The ground cover consisted of *Lepidosperma longitudinale*, *Sphagnum* sp. and *Viola hederacea*. North-east of the lagoon, the vegetation has largely been cleared for grazing and in this area, small *M. linariifolia* emerge above an understorey of *Acacia longifolia* and *L. polygalifolium*. The ground cover in this area consists of *Gleichenia dicarpa*, *Hypolepis muelleri* and *V. hederacea* on *Sphagnum* peat.

The fen and *Melaleuca* swamp forest together make up the *Lepidosperma longitudinale-Melaleuca linariifolia* Sedgeland (Ryan et al., 1996) which is related to other low nutrient wetlands, such as the Thirlemere Lakes.

Table 1. Radiocarbon dates. Calibrated years has been calculated according to the Radiocarbon Calibrated Program Calib Rev5.0.2 (Stuiver and Reimer, 1986-2005)

Depth (cm)	Sample number	Technique	Age (Radiocarbon years) BP	Calibrated years BP (cal. yr)
33-38	Beta 43680	Standard C^{14}	9,040 ± 90	10,079
59-68	Beta 43681	Standard C^{14}	18,660 ± 150	22,230
60-70	OZD666	AMS C^{14}	19,350 ± 220	23,036
90-100	OZD667	AMS C^{14}	19,700 ± 390	23,484

3. The tall forest has a 60-70% canopy cover of *Eucalyptus deanei* and a sub-canopy of *Syncarpia glomulifera* and *Pittosporum undulatum*. *Leucopogon* spp. and climbers such as *Smilax* form much of the understorey in this forest and a variety of ferns form a thick ground cover. In the cleared areas to the north-east of the lagoon, a few *E. deanei* and some *Eucalyptus piperita* were found on the drier soils near the lagoon. There was no understorey in this area. The ground cover consisted largely of introduced grasses, with *Pteridium esculentum* growing close to the lagoon.
4. On the exposed, rocky escarpment of the Kurrajong Block, the well drained soils support an open woodland dominated by a 40-50% cover of *Eucalyptus piperita*, *Eucalyptus agglomerata* and *Syncarpia glomulifera*. The understorey components are chiefly sclerophyllous species, e.g. *Banksia spinulosa* and *Telopea speciosissima* with *Acacia elata* quite common.
5. The protected gully of Gospers Creek, the outlet of the lagoon, supports a closed Turpentine (*Syncarpia glomulifera*) forest with a canopy cover of greater than 70%. It has both mesic and xeric components and is dominated by *S. glomulifera*, *Angophora costata* and *E. elata*. The understorey is dominated by tall *Banksia serrata* and *Pittosporum revolutum*, with *Lomatia silaifolia*, *Leucopogon juniperinus*, *L. lanceolatus* and *Xanthorrhoea arborea*. The ground cover consists of *Viola hederacea*, *Dianella caerulea* and *Echinopogon ovatus*. See Ryan et al. (1996) for further descriptions of gully forests in the region.
6. Green Scrub, on a small lens of basalt soils in a protected gully south of the lagoon, supports warm temperate rainforest and is dominated by *Doryphora sassafras*, *Acmena smithii* and *Syncarpia glomulifera*. See Appendix 2 for a full list of species.

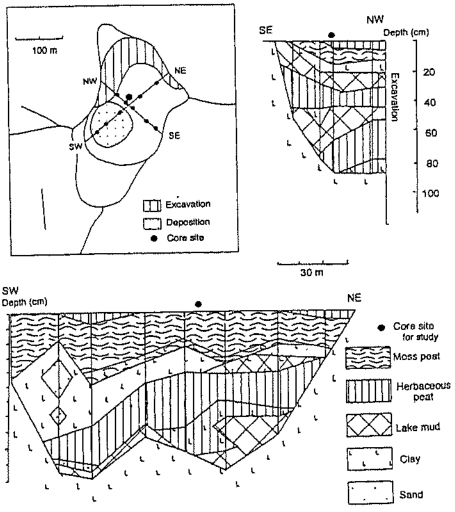

Figure 3. Mountain Lagoon, depicting disturbed sites, stratigraphic transects and the site of the core for this study.

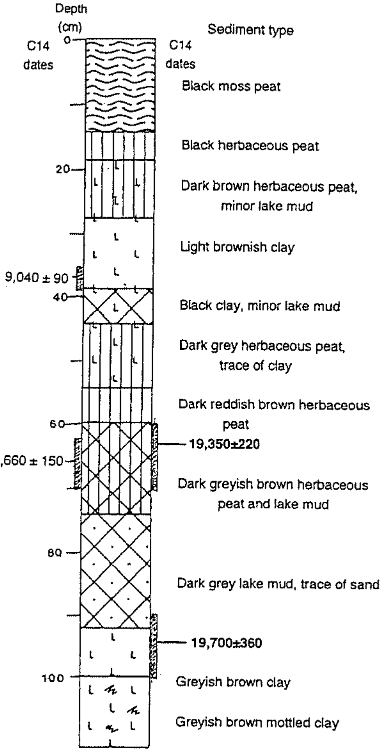

Figure 4. The sedimentary column. Standard C14 dates are on the left and AMS C14 dates are on the right. Dates are given in radiocarbon years. For calibrated ages, see Table 1.

Stratigraphy

The stratigraphic transects and cross sections of the lagoon are shown in Fig. 3. Part of the lagoon in the north has been excavated and the spoil dumped in a patch on the western side. Only the north-western half of the SW-NE cross section of the lagoon is regarded as undisturbed. Sediment descriptions of the core are shown in Fig. 4.

A layer of moss peat covers the lagoon to a depth of about 15 cm in most areas (Fig. 3). There are minor patches of herbaceous peat on top of the moss peat, but they are associated with the disturbed areas. Herbaceous peat underlies the moss peat in the study core (Fig. 4) but it is not evident in the cross sections. A layer of brownish clay is found across the whole of the lagoon, underlain by black clay and/or lake mud over part of the lagoon. A relatively thick layer of herbaceous peat underlies the clay, with a layer of lake mud (very fine organic matter), and at the base, clay. There is some mottling in the deepest layers of the basal clay layer. Traces of sand are found in some of the deeper clays and lake muds.

Table 1 presents the radiocarbon dates. Assuming continuous sedimentation (Fig. 5), the Holocene extends down to about 40 cm in the study core, to the base of the upper clay layer (Fig. 4) and the overall rate of sedimentation approximates 4 cm per k cal. yr. The height of the last glacial period (18 k cal. yr) is recorded at about 60 cm depth, hence during the time from the last glacial maximum to the beginning of the Holocene, the rate of sediment accumulation was about 2.5 cm per k cal. yr. This latter rate continues till about 22 k cal. yr, after which rate of sediment accumulation, was rapid, about 10 cm per k cal. yr.

The SIRM, microscopic and macroscopic charcoal content and carbon content of the sediments is shown on Fig. 6. Peak values for all of these factors are found in the peat and values are lower in the clay.

Sedimentary history

Initially, Mountain Lagoon was a lake with water too deep for rooted vegetation. Clay is usually an indication of a low energy environment, but at this location, the Wainamatta Shale weathers to produce predominantly clay. Moreover, with the lagoon situated at the base of the escarpment of the Kurrajong Fault, any tectonic movement or vegetation disturbance, even if only slight, could cause instability, and the accelerated erosion may contribute to the deposition of clay in the lagoon. It is thought that some instability of the fault escarpment probably contributed to the rapid rate of clay accumulation at the base of the profile.

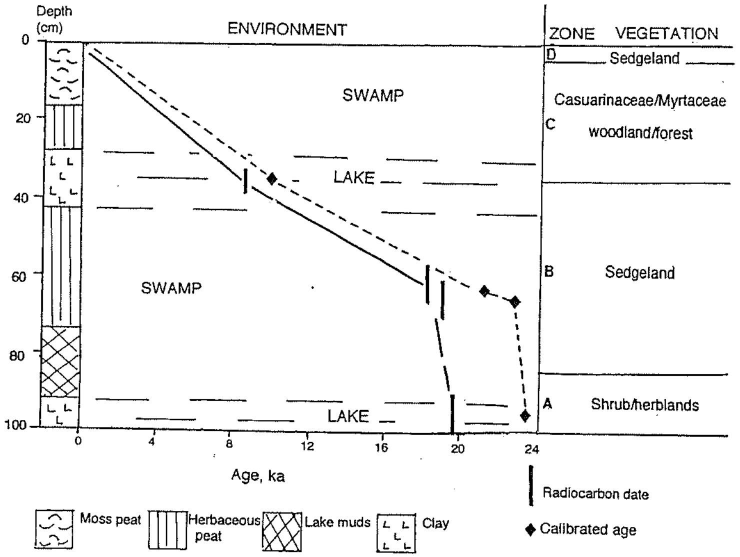

Figure 5. Summary diagram of the history of Mountain Lagoon. This model assumes continuous deposition (see text). For sedimentary symbols, see Figure 4.

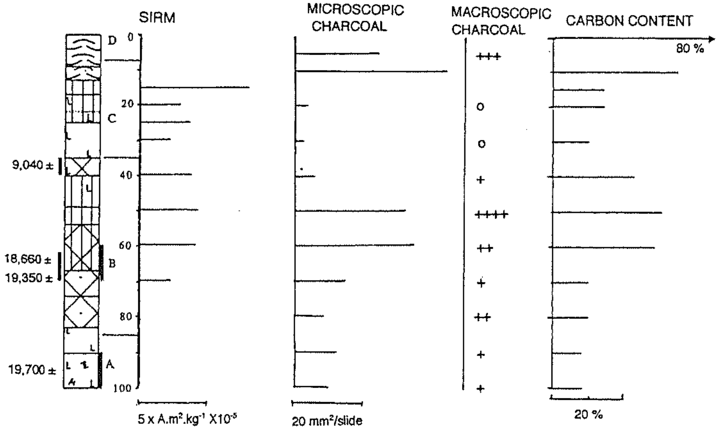

Figure 6. SIRM, microscopic and macroscopic charcoal content and carbon content. For the macroscopic charcoal content, the more '+'s, the more the charcoal. 'o' equals zero macroscopic charcoal. For lithologic symbols, see Fig 4. Dates are given in radiocarbon years. For calibrated ages, see Table 1.

The mottled clay at the base of the profile indicates a fluctuating water table and occasional dry periods in the earlier part of the glacial period. Towards the end of the peak glacial period, the lake became shallow enough to allow rooted vegetation and the production and preservation of peat.

At the beginning of the Holocene, there is a layer of light brown clay, which is unusual when compared to other sites. The colour is also unusual, for if clay is deposited slowly under the anaerobic conditions of a lake or swamp, it would become grey or black. It is possible that some instability of the escarpment may have triggered a short burst of intensified erosion and deposition of this material. With a return to stability, the vegetation recolonized the swamp surface and the deposition of peat continued through the rest of the Holocene.

It has been suggested that the model of continuous deposition adopted above may not apply and the basal clay may have been deposited in the glacial period, with an hiatus from about 17 kyr to the Holocene, when peat deposition commenced. It is difficult to rule out the discontinuous model with only four dates, but it is harder to accommodate the dating into a discontinuous model. The two dates of 18,660 and 19,350 radiocarbon years (22,230 and 23, 036 calibrated years, respectively, see Fig. 4) both come from within the base of the peat/lake muds, which the discontinuous model assumes is Holocene. Further implications of the two models are discussed below.

Table 2. The identification of Myrtaceae pollen in Mountain Lagoon sediments. The unidentified Myrtaceae types are depicted in Fig. 7.

Depth (cm) in profile	5	10	20	50	70
Acmena smithii	5.9	+	4.9	+	
Angophora costata	3.9	+		+	+
Corymbia gummifera	+			+	
Eucalyptus creba	29.4	+	4.9	7.4	4.0
E. punctata	5.9	+		8.8	
E. deanei	7.8	30.3	42.6	36.8	+
E. piperata			16.4		12.0
E. haemostoma		9.1			8.0
Syncarpia glomulifera		+		+	
Leptospermum spp	5.9	6.1	8.2	7.4	16.0
Mytyaceae type I		+			
Mytyaceae type II		6.1			
Mytyaceae type III	13.7	6.1	11.5	14.7	24.0
Myrtaceae type IV		+			
Mytyaceae type V		+			
Unidentified Myrtaceae	21.6	18.2	11.5	19.1	32.0

Charcoal is found in all of the samples, suggesting that burning could have occurred at any time. Charcoal content, however, is higher in the peat, when the vegetation growing on site may have burned and deposited charcoal directly into the sediments. When the lagoon was a lake and depositing clay, charcoal would have to be transported into the site, either by wind or water. The higher macroscopic charcoal content of the peat probably indicates woody shrubs were growing very close to the site of deposition.

The SIRM values of the sediments closely parallel the charcoal input and both are higher in the peat. Commonly, high SIRM values correspond to a high mineral content in the sediment (Thompson and Oldfield 1986) but fire has been found to increase the soil magnetism to some extent (Rummery 1983). In these sediments, fire seems to have had a greater influence on the SIRM values than the mineral content.

Pollen Analysis

In an attempt to identify the myrtaceous pollen, a reference set of eleven species from the study area was examined in detail, using the method outlined by Chalson and Martin (1995). Ten of the species could be identified specifically in the profile (Table 2) but five common types (Fig. 7) found in the profile were not amongst the reference set. Specific identification of fossil grains was often limited by distortion, poor preservation or being obscured by extraneous matter, hence the high proportion of unidentifiable Myrtaceae pollen. Specific identification is time consuming hence only a few levels of the profile have been studied in this detail (Table 2). Appendix 3 presents the name of the pollen type on the pollen diagram and the likely source of the pollen in the vegetation.

The pollen diagram (Fig. 8) shows the percentages of total pollen count, pollen concentrations for the most common specific pollen types and total pollen concentrations. The profile has been divided into four zones based on pollen content and concentrations:

Zone A: 100-85 cm, c. > 23 k cal. yr (see Fig. 5 for approximate dates). Pollen concentration is very low, with a moderate representation of Casuarinaceae and Myrtaceae. *T. pleistocenicus* Martin 1973, a 'spineless' Asteraceae, cf. *Cassinia arcuata*, *Calomeria* and possibly others (Macphail and Martin 1991), has the highest percentage for the profile, which, however, is not much. Other shrubs are restricted to *Monotoca* and *Hakea*, and the herb group is well represented. The aquatic group of Cyperaceae and *Myriophyllum* have low representation.

Zone B: 85-35 cm, c. 23-10 k cal. yr. Pollen concentration is the highest for the profile (except for the very top). Casuarinaceae and Myrtaceae have low percentages but the concentrations are high. Shrubs are well represented in the lower part of the zone and the herb content is slightly higher than the other zones. The aquatic group has high percentages and concentrations. There appears to be a negative correlation between Cyperaceae and *Myriophyllum*.

Zone C: 35-10 cm, c. 10 k cal. yr - ? present. Total pollen concentration is low and percentages for Casuarinaceae and Myrtaceae are high. There is a poor representation of shrubs and aquatic percentages and pollen concentrations are low.

Zone D: 5 cm, ? present. Total pollen concentration is exceptionally high and Casuarinaceae and *Myriophyllum* have the highest concentrations. Shrubs are poorly represented, and herbs are diverse.

From the glacial period to the present, trees would have been almost entirely species of Casuarinaceae and Myrtaceae. Both of these families, however, contain shrubby species and even the same tree species may assume a shrubby habit under harsh conditions, e.g. *Eucalyptus stricta* is a mallee and both *Eucalyptus pulverulenta* and *Corymbia gummifera* may be a tree or mallee in the Blue Mountains today (Plantnet 2006). The habit of the species cannot be determined from the pollen, but since Mountain Lagoon is likely to have been at or above the treeline during the glacial period (Hope 1989), shrubby species are a possibility. By the time of the Holocene, when the climate was more like that of today, they were probably trees.

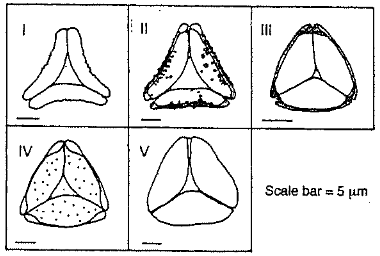

Figure 7. Common, unidentified Myrtaceae pollen types.

Taxa within the family Casuarinaceae are generally not identifiable from their pollen. Casuarinaceae was not found in the survey of the vegetation (Appendix 1), but the pollen is wind distributed and some of it may travel a long way. Today, *Allocasuarina torulosa* is most likely in this region (Ryan et al. 1996). Casuarinaceae pollen is present throughout the profile, with higher percentages in the Holocene.

Percentages of Myrtaceae pollen in Zone B, the period between the glacial maximum and the Holocene, are moderate, increasing in the Holocene, and decreasing to the present. Concentrations in Zone B, however, are very high, and during this time, *Eucalyptus deanei*, *E. piperita* and Myrtaceae type III were prominent in the vegetation. In the Holocene, *E. deanei* was still the most prominent, but *Eucalyptus creba* is the most common in the top of the profile. Pollen of *Melaleuca linariifolia* was not identified in this study, but Rose and Martin (this volume) found that it was indistinguishable from pollen of *Leptospermum* spp. and >15 % in surface samples was recorded where *M. linairifolia* was dominant in the vegetation. In this study, *M. linairifolia* and *Leptospermum* spp. are included in the Myrtaceae group.

Shrub taxa are most diverse in the lower part of zone B, and being low pollen producers, only their presence is recorded for most of them. *T. pleistocenicus*, (*Cassinia arcuata*, *Calomeria* and probably others) is found throughout the profile and it may be common in some glacial and older sediments (Martin 1973; Edney et al. 1990; Macphail and Martin 1991). Today, *Cassinia arcuata* may be common on disturbed mineral soils (Macphai and Martin 1991) and *Calomeria* is found along streams and may be abundant after fire (Botanic Garden Trust 2005).

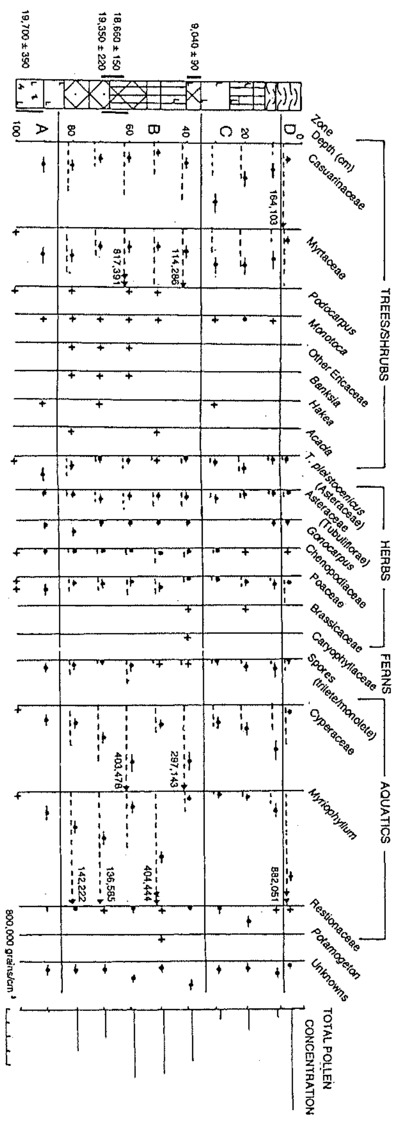

Figure 8 Pollen diagram showing percentages of total pollen count, pollen concentrations for the most common pollen types and total pollen concentrations. For lithologic symbols, see Fig 4. For species included in the pollen type name on the diagram, see Appendix 3. Dates are given in radiocarbon years. For calibrated ages, see Table 1.

The herbaceous taxa are present throughout the profile and concentrations are higher in B Zone. Asteraceae (Tubuliflorae), *Gonocarpus*, Chenopodiaceae and Poaceae are the main taxa, but individually, are only present in low abundance.

The aquatics Cyperaceae and *Myriophyllum* indicate the extent of the sedgeland vegetation. They are low in Zone A (glacial period) and the lower levels of Zone C (early Holocene) in the clay sediments. At these times, the lagoon would have been more of a lake with a fringing sedgeland. Zone B (post-glacial, pre-Holocene) has high percentages of Cyperaceae and *Myriophyllum*, where the sediments are almost entirely organic, when the sedgeland would have covered most of the lake. The inverse relationship between Cyperaceae and *Myriophyllum* probably reflects subtle changes in the water depth and the vegetation mosaic.

The high pollen concentrations in Zone B are found in the lake muds, very finely divided organic matter. In the lake muds, the plant fragments of the peat have been mostly broken down, probably compacting the original peat and at the same time, concentrating the pollen content. Percentages suggest that the pollen content of Casuarinaceae and Myrtaceae decrease in Zone B, but concentrations show that this was not so: in fact the pollen concentrations have increased considerably. The better representation of shrubs and the increase in the herbs and considerable increase in aquatic pollen would mean that proportionately, other groups are less well represented (in terms of percentages). The low pollen concentration of aquatics in Zone C, the early Holocene, is probably the result of the change of habitat caused by the clay deposition, making it unsuitable for aquatics. Towards the present, the sedgeland vegetation was re-established.

Freshwater algal spores of species of Zygnemataceae were found in the sediments and *Debarya* sp., cf. *Mougetia viridis*, cf. *M. elegatula*, *Spyrogyra* sp. and *Zygnema* sp. were identified. *Botryococcus braunii* and spores of Cyanobacteria (Churchill 1960) were also present. Characeae oospores were found at 5 cm in sieved material, before treatment with acids. An unidentified dinoflagellate was also common in the sediments.

In the clay of Zone A, algal spores were moderately represented. *Botryococcus*, cf. *Mougetia viridis* and cf. *M. elegantula* were common in the shallower margins of the lake. In Zone B, all of the algal types increased at 70 cm depth, where *Zygnema* and *Debarya* were at their most abundant. Very few algal spores were found at 60 cm, and *Debarya* and *Spirogyra* were not found in this zone above 60 cm. The remaining Zygnemataceae and the unknown dinoflagellate increased in abundance at 40 cm. *Botryococcus* remained abundant throughout Zone B with high amounts at 50 cm. Cyanobacteria were abundant at 70 cm and 40 cm.

In Zone C, Zygnemataceae spores were low at 30 cm, in the clay, increasing to high levels at 20 cm, with the exception of *Debarya*. *Zygnema* was particularly high in abundance at 20 cm, and high amounts of this alga were maintained into Zone D. *Botryococcus* was present in very high amounts at 30 cm and amounts remained relatively high to the top of the core. The abundance of Cyanobacteria was moderate at 30 cm, increasing to a peak at 20 cm and remaining high to the top of the of the core. Oospores of Characeae were common in Zone D.

History of the Vegetation

During the late glacial period, the vegetation was probably a shrubland with a diversity of species. When clay was being deposited and the lagoon was a lake, the sedgeland would have been confined to a fringe around the lake. When the water depth became shallow enough, the sedgelands encroached on the surface of the lake. Peat was forming at 23-22 k cal. yr, prior to the height of the glacial period, hence the lake had become shallow enough for a sedgeland at this time (Fig. 5).

During the period preceding the Holocene, the sedgeland flourished and it was probably comparable with the sedgeland there today. Myrtaceae was also abundant, and it may have been similar to the *Melaleuca* and *Leptospermum* swamp forest seen there today. Herbs were well represented also. In the early Holocene, the lagoon reverted to a lake and the sedgelands were once again restricted in extent, but they returned later in the Holocene. Casuarinaceae and Myrtaceae were relatively the most abundant and they were probably trees.

Algal spores are present through the profile and are abundant at some levels. Zygnemetaceae are found in oligotrophic waters, and shallow, stagnant pools of mesotrophic waters, less than half a metre deep, induce spore formation in spring (Van Geel 1978; van Geel and Grenfell 1996). Of the Characeae, *Chara* is typically found in hard waters, and secretes lime, but *Nitella* grows in soft water (Pentecost 1984). These water conditions could occur, even if for only a short time, given the right combination of fresh water input and evaporation.

At this level of identification of the pollen, there appears relatively little change in the taxa present, but where a more precise identification is possible, e.g. with some Myrtaceae grains, changes at the species level were detected. Some species of *Eucalyptus* have been present the whole time. The major dryland vegetation type, viz. sclerophyllous shrublands/ woodlands/ forests, with both Casuarinaceae and Myrtaceae prominent, seem to have occupied the site for the whole of the time recorded here. On these poor nutrient soils, substantial grasslands are unlikely, even with climatic change.

Climatic Implications

A climatic interpretation for the changes at Mountain Lagoon is somewhat uncertain. A lake implies water too deep for rooted swamp plants. It is estimated that rainfall would have been up to half of the present values during the last glacial period (Thom et al. 1994; Allan and Lindsay 1998) and the warmest month was up to 9 °C less than today, (Galloway 1965; Allan and Lindsay 1998). With a lower rainfall and less evaporation, and if the dominants were shrubs, evapotranspiration would be less also, then free water may have been available for the lake. Mottling indicates a fluctuating water table and there were probably dry spells when the lake dried up, but probably not long enough for sedgelands to become established. Perhaps water balance was too variable for the development of sedgelands. However, sedgelands colonized the lagoon surface during the glacial period, inferring that the water balance had become favourable or stable enough for rooted vegetation, at a time that other sites record dry and cold conditions for southern Australia. Moreover, the sedgelands may have persisted from the height of the glacial period to the beginning of the Holocene, and the pollen concentration and amount of organic matter suggest a quite productive ecosystem.

The climatic tolerances of most of the myrtaceous species identified are presented in Table 3 and it can be seen that the ranges of mean annual precipitation under which these species are found is quite large. If the rainfall of Mountain Lagoon is halved, as would have been likely during the glacial maximum, then the site would have been at or close to the lower limits for all of the *Angophora/Corymbia/Eucalyptus* species. Consequently, all of these species could have been present throughout the glacial period. Unfortunately, temperature data are not available for a similar analysis since the closest meteorological stations are at such different altitudes.

In reviewing the studies of dune building in southeastern Australia, Thom et al. (1994) found that extensive aeolian deposits in the Shoalhaven River Catchment were dated to two periods of dune building between 19,000-6,000 yr BP, with a period of stability between 18,000 and 14,000 yr BP. This evidence implies an increase in vegetation cover during this period, and there may have been fluctuations in climate within the overall general trends. Mountain Lagoon data would support this view.

DISCUSSION

There are three other sites in the Sydney Basin with a vegetation history going back to the last glacial period. Lake Baraba, one of the Thirlmere Lakes (Fig. 1), is an upland fluviatile system contained in an entrenched meander (Timms 1992). Here, Casuarinaceae was dominant from >34 kyr to the Holocene, when the sediments were clay. Myrtaceae became co-dominant about 8 kyr, when peat formation began (Black et al. 2006). In contrast, both Casuarinaceae and Myrtaceae are prominent through the glacial period and the whole of the time at Mountain Lagoon. Sclerophyll communities with minimal Poaceae were present at Lake Baraba the whole time, just as they are at Mountain Lagoon.

The second site, Penrith Lakes (Fig.1), was an abandoned meander in the flood plain of the Nepean River (Chalson 1991). Clay was deposited from >33 kyr, changing to peat only about 3 kyr. During the glacial period, there were minimal Myrtaceae and Casuarinaceae, some Poaceae and relatively abundant *T. pleistocenicus*, the *Cassinia arcuata* type. The shrubby *C. arcuata* may become abundant on disturbed mineral soils, and this habitat was probably common on the floodplain, which would have been a shrubland at the time of the glacial period. Some

Table 3. Climatic tolerances of Myrtaceous species identified in sediments from Mountain Lagoon (Boland et al. 2002) and climatic data for the closest meteorological stations. Richmond (average of University of Western Sydney and RAAF base), Katoomba (BoM 2006) and Mountain Lagoon (Hungerford 1995. The altitude for the meteorological stations is included.

Species	Mean max. hottest month (°C)	Mean min. coldest month (°C)	Max. frost days/year	Mean annual ppt (mm)
Acmena smithii	26-32	5-15	few	1000-2000
Angophora costata	25-35	0-8	0-50	600-1200
Corymbia gummifera	24-32	1-8	0-30	700-1800
Eucalyptus creba	26-36	0-17	0-50	550-2000
E. punctata	26-33	1-6	0-40	700-1200
E. deanei	25-30	0-5	0-50	750-1500
Richmond, alt. ~ 20 m	24	10-11		800-810
Mt. Lagoon, alt ~ 500 m				1257
Katoomba, alt. ~ 1040 m	16.6	7.9		1400

Myrtaceae and Casuarinaceae are found during the upper Holocene, and Poaceae became prominent, unlike Mountain Lagoon.

The third site, Redhead Lagoon (Fig.1), a now near-coastal site south of Newcastle (Williams et al. 2006) has a long record. During the height of the glacial period, there was a very high Casuarinaceae pollen content with lesser amounts of *Angophora/ Corymbia*, and *Eucalyptus*. The environment was not treeless, although it is possible that the Casuarinaceae may have been small trees or shrubs. It is thought that local conditions may have enhanced the moisture relationships (Williams et al. 2006).

The rapid rate of clay deposition during the glacial period at Mountain Lagoon is an unusual feature, but it is recorded in at least one other site. Burraga Swamp on the Barrington Tops (Sweller and Martin 2001) is situated at the base of Mount Lumeah hence has a topographically similar situation to Mountain Lagoon. There, from from 38-21,000 years BP., the rate of sedimentation was low. Then followed a much higher rate of sedimentation during the height of the glacial period, attributed to catchment instability caused by periglacial activity. Mountain Lagoon was probably at or above the treeline during the glacial period (Hope 1989) and if the vegetation cover was disrupted by the harsh climate of the glacial period, it may have caused some instability of the easily eroded Wainamatta Shale escarpment, with a consequent higher rate of sedimentation in the lake. Movement along the Kurrajong Fault line, even if slight, would be another cause of instability that could occur at any time and contribute to an increased rate of sedimentation.

The deposition of peat during the glacial period is also unusual. As discussed previously, clay was being deposited at both Penrith Lakes (Chalson 1991), and Thirlmere Lakes (Black et al. 2006), and silt at Redhead Lagoon (Williams et al. 2006), the only other sites in the Sydney Basin with records going back to the last glacial maximum. Further afield, at Lake George (Singh and Geissler 1985) and Burraga Swamp on the Barrington Tops (Sweller and Martin 2001), inorganic sediments were being deposited during the last glacial period. On the Barrington Tops, the change from inorganic to peat sedimentation occurred at least close to or during the Holocene (Dodson 1987). Mountain Lagoon must have been particularly favourable for plant growth during the glacial period. Perhaps its location on the western side of the Kurrajong block, which may have provided some protection, was advantageous. The lagoon would have received run-off from the surrounding slopes, and the warming of the Block by the afternoon sun may have meant that temperatures were less extreme. In any case, a comparison of the range of precipitation where the dominant species are found today and the probable precipitation during the glacial period show that they could have been present at Mountain Lagoon through the height of the glacial period, albeit at the lower end of their range. The shrubs and herbaceous species found at Mountain Lagoon are mainly widespread taxa and the results of this study would suggest that they too existed at the site through the glacial maximum.

A decline in Casuarinaceae and its replacement with Myrtaceae about mid Holocene time may be found in a number of sites, and likely causes for this feature have been suggested, as discussed in Rose and Martin (this volume). Mountain Lagoon does not show any decline in Casuarinaceae and both Casuarinaceae and Myrtaceae were well represented the whole time. Casurinceae was not found in the survey of the vegetation for this study, hence its only decline would have been the result of logging by European settlers. The wood of Casuarinaceae was prized by Europeans for firewood, building and tool making (Entwisle 2005).

The history of the vegetation at Mountain Lagoon suggests very little change in the vegetation from the glacial period to the present and even some to the *Eucalyptus* species are found throughout the profile. Unfortunately, the palynology cannot determine if a species assumed a different lifeform during the glacial period. The only change in the vegetation is associated with the change from lake to sedgelands (Fig. 5), controlled by hydrological changes. Even these changes do not fit the traditional view of a harsh glacial climate, slowly improving to a climate like the present about the time of the Holocene. Mountain Lagoon may either have been a refugium or there was more variation in the vegetation during the last glacial period than previously thought. As discussed previously, evidence from 'coastal' dunes during the last glacial period (Thom et al. 1994) suggested that there was a '...greater concentration of forests in more discrete, protected sites along the eastern escarpment than was previously considered by palaeoecologists', and this view may be applicable to other regions such as the Blue Mountains.

In a study of aeolian dunes on the Newnes Plateau in the Blue Mountains (altitude 1000 m), Hesse et al. (2003) came to the conclusion that unrealistically drier conditions were necessary to allow wind transport at this site. They have suggested that it would require additional impediments to plant growth, such as lower temperatures and lower atmospheric carbon dioxide concentrations during the height of the glacial period to disrupt the sparse vegetation and allow the necessary conditions for dune formation. This interpretation is at odds with the story from Mountain Lagoon. Today, periodic drought will disrupt the vegetation and allow inactive dunes to become mobile, and this could have happened during the height of the glacial period also. The two sites are not comparable: palynology requires sites which remain permanently wet and are thus probably the most hydrologically favourable in the landscape, in contrast to sites that allow aeolian transport, such as an exposed plateau. There must have been a mosaic of environments during the glacial period, just as there is today and these two studies have sampled different environmental settings.

CONCLUSIONS

The rapid accumulation of clay in the lake at 22-23 k cal. yr is thought to have been caused by vegetation and soil instability, the result of the harsh climate at the height of the glacial maximum.

Sedgelands colonized the lake surface about 22 k cal. yr and then followed peat deposition from what must have been a productive ecosystem, comparable to today, until the Holocene.

The Lagoon reverted to a lake and clay deposition, c. 10-8 k cal. yr, probably because of slight instability of the fault-line and a burst of accelerated erosion.

Sedgelands re-colonized the lake surface again and remained to the present day.

The dryland vegetation appears remarkably similar through the whole time: it was sclerophyllous shrubland/woodland/forest.

When Myrtaceae grains are identified to species, they show that there has been change in the species, but some species have been present the whole time.

The species found in the locality today could have been present through the glacial period, albeit at the lower end of their range of precipitaiton.

Both Casuarinaceae and Myrtaceae are prominent the whole time, and Casuarinaceae only declines with European settlement.

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APPENDIX 1.

Mountain Lagoon species lists obtained from the vegetation survey. Sites: 1, Lagoon. 2, Melaleuca forest. 3, Tall forest. 4, Exposed escarpment (full species list not obtained and omitted here. For vegetation description, see text). 5, Protected escarpment. For site 6, the Green Scrub rainforest, see Appendix 2. For a full list of species in the region, see Ryan et al. (1996). Nomenclature follows Harden (1992; 1993; 2000:; 2002) and Plantnet (2005). *Indicates introduced species.

Species	Site 1	Site 2	Site 3	Site 4	Site 5
BRYOPHYTA					
Sphagnum sp.		+			
FERNS/FERN ALLIES					
Adiantaceae					
Adiantum aethiopicum L.			+		
Blechnaceae					
Blechnum cartilagineum Sw.		+			
Dennstaedtiaceae					
Hypolepis meulleri N.A. Wakef.		+	+		
Pteridium esculentum (Forst. f.) Cockayne		+	+		+
Gleicheniaceae					
Gleichenia dicarpa R.br.		+			
Pteridaceae					
Pteris tremula R. Br			+		+
Schizaeaceae					
Schizaea dichotoma Sm.					+
DICOTYLEDONS					
Apiaceae					
Hydrocotyle peduncularis A. Rich.			+		
Araliaceae					
Polyscias sambucifolia Harms			+		
Apocynaceae					
Tylophora barbata R. Br.			+		
Convolvulaceae					
Cuscuta australia R. Br.					+
Cunoniaceae					
Ceratopetalum apetalum D. Don		+	+		
Dilleniaceae					
Hibbertia dentata DC.			+		

H. hermanniifolia DC.					+
Elaeocarpaceae					
Tetratheca ciliata Lindl.			+		+
Ericaceae					
Leucopogon ericoides R. Br.			+		
L. juniperinus R. Br.			+		+
L. lanceolatus (Sm.) R. Br.		+	+		+
Fabaceae - faboideae					
Dillwynia retorta Druce					+
Gompholobium latifolium Sm.					+
Pultenaea flexilis Sm.			+		
P. linophylla Schrad. and J.C. Wendl.					+
Fabaceae - mimosoideaea					
Acacia elata Benth.				+	+
A. filicifolia M.B. Welch, Coombs & McGlynn		+			
A. longifolia (Andrews) Willd.		+			
Haloragaceae					
Myriophyllum latifolium F. Muell.	+				
Myriophyllum cf *M. variifolium* Hook. f.	+				
Menyanthaceae					
Nymphoides geminata (R. Br.) Kuntze	+				
Myrtaceae					
Angophora costata Britten					+
Eucalyptus agglomerata Maiden				+	
E. deanei Maiden			+		
E. elata Dehnh.					+
E. piperita Sm.			+	+	
E. saligna Sm.		+			
Leptospermum polygalifolia Salib.		+	+		
Melaleuca linariifolia Sm.		+			
Syncarpia glomulifera (Sm.) Nied.			+	+	+
Pittosporaceae					
Billardiera scandens Sm.					+
Pittosporum revolutum Dryand.					+
P. undulatum Vent.			+		
Proteaceae					
Banksia serrata L. f.					+

B. spinulosa Sm.				+	
Lomatia silaifolia (Sm.) R. Br.			+		
Persoonia laurina Pers.					+
Telopea speciosissima R. Br.				+	
Santalaceae					
Exocarpus strictus R. Br.					+
Sapindaceae					
Dodonaea triquetra J.C. Wendl.		+	+		
Violaceae					
Viola hederaceae Labill.	+	+			+
MONOCOTYLEDONS					
Alismataceae					
Alisma plantago-aquatica L.		+			
Damasonium minus Buchenau	+	+			
Cyperaceae					
Baumea articulata (Nees) Broeck.	+				
Lepidosperma laterale R. Br.		+			
L. longitudinale Labill.			+		
Schoenus melanostachys R. Br.		+			
Juncaceae					
Juncus usitatus L.A.S. Johnson		+			
Lomandraceae					
Lomandra longifolia Labill.			+		
Luzuriagnaceae					
Eustrephus latifolius Ker Gawl.			+		
Phormiaceae					
Dianella longifolia R. Br.		+	+		
D. caerulea Sims					+
Poaceae					
**Echinopogon caespitosus* C.E. Hubb.			+		+
**E. ovatus* (G. Forst.) P. Beauv.		+			+
Entolasia marginata (R. Br.) Hughs		+			
Microlaena stipoides (Labill.) R. Br.		+			
**Paspalum distichum* L.		+			
Smilacaceae					
Smilax austalis R. Br.			+		

S. glyciphylla Sm.	+	
Xanthorrhoeaceae		
Xanthorrhoea arborea R. Br.		+

APPENDIX 2

Species found in Green Scrub Rainforest, Site 6 (P. Hind, pers. comm.). Nomenclature follows Harden (1992; 1993; 2000:; 2002) and Plantnet (2005). * denotes an introduced species.

FERNS/FERN ALLIES
Adiantaceae
Adiantum aethiopicum L.
A. diaphanum Blume
A. formosum R. Br.
A. hispidulum Sw.
A. silvaticum Tindale (R. Br.) F, e
Pellaea falcata (R. Br.) Fée
P. nana (Hook) Bostock

Aspleniaceae
Asplenium attenuatum R. Br.
A. australasicum (J. Sm.) Hook.
A. flabelllifolium Cav.

Athyriaceae
Diplazium australe (R. Br.) N.A. Wakef.

Blechnaceae
Blechnum ambiguum (C. Presl.) Kaulf. ex C. Chr.
B. cartilagineum Sw.
B. nudum (Labill.) Mett. ex Luerss.
B. patersonii (R. Br.) Mett.
B. wattsii Tindale
Doodia aspera R. Br.

Cyatheaceae
Cyathea australis (R. Br.) Domin.
C. leichhardtiana (F. Muell.) Copel.

Davalliaceae
Arthropteris tenella (G. Forst.) J. Sm. ex Hook. f.

Dennstaedtiaceae
Dennstaedtia davallioides (R. Br.) T. Moore
Histiopteris incisa (Thunb.) J. sm.
Pteridium esculentum (G. Forst.) Cockayne

Dicksoniaceae
Calochlaena dubia (R. Br.) M.D. Turner& R.A. White

Dryopteridaceae
Lastreopsis acuminata (Houlston) C.V. Morton
L. decomposita (R. Br.) Tindale
L. microsora (Engl.) Tindale
Polystichum australiense Tindale

Gleicheniaceae
Sticherus flabellatus (R. Br.) H. St John

Grammitaceae
Grammitis billardieri Willd.

Hymenophyllaceae
Hymenophyllum australe Willd.
H. cupressiforme Labill.

Lindsaeaceae
Lindsaea microphylla Sw.

Osmundaceae
Leptopteris fraseri (Hook. & Grev.) C. Presl.
Todea Barbata (L.) T. Moore

Polypodiaceae
Platycerium bifurcatum (Cav.) C. Chr.
Pyrrosia rupestris (R. Br.) Ching

Pteridaceae
Pteris tremula R. Br.
P. umbrosa R. Br.

Schizaeaceae
Cheilanthes distans (R. Br.) Mett.
C. sieberi Kunze

Tmesipteridaceae
Tmesipteris truncata (R. Br.) Desv.

DICOTYLEDONS
Amaranthaceae
Deeringia amaranthoides (Lam.) Merr.

Aphanopetalaceae
Aphanopetalum resinosum Endl.

Apocynaceae
Melodinus australis (F. Muell.) Pierre
Marsdenia flavescens A. Cunn. ex Hook.
Parsonsia straminea Pichon
Tylophora barbata R. Br.

Araliaceae
Astrotricha latifolia Benth.

Polyscias murayi (F. Muell.) Harms.

Asteraceae
**Conza albida* Willd. ex Sprengl.
Olearia tomentosa (J.C. Wendl.) Benth.
Senecio linearifolius A. Rich.

Bignoniaceae
Pandorea pandorana (Andrews) Steenis

Boraginaceae
Ehretia acuminata R. Br.
Austrocynoglossum latifolium (R. Br.) R. Mill.

Caprifoliaceae
Sambucus australasicus (Lindl.) Fritsch

Caryophyllaceae
Stellaria flaccida Hook.

Chenopodiaceae
Einadia hastata (R. Br.) J. Scott

Convolvulaceae
Calystegia marginata R. Br.
Dichondra repens J. Forst. & G. Forst.

Cunoniaceae
Callicoma serratifolia Andrews
Ceratophyllum apetalum D. Don
C gummiferum Sm.
Schizomeria ovata D. Don

Dilleniaceae
Hibbertia dentata R. Br. ex D.C.
Hibbertia sp.

Ebenaceae
Diospyros australis (R. Br.) Hiern

Elaeocarpaceae
Elaeocarpus reticulatus Sm.

Ericaceae
Acrotriche divaricata R. Br.
Trococarpa laurina R. Br.

Euphorbiaceae
Breynia oblongifolia F. Muell.
Claoxylon australis Baill.
Omalanthus populifolius Graham

Eupomatiaceae
Eupomatia laurina R. Br.

Fabaceae
Desmodium varians (Labill.) C. Don
Glycine clandestina J.C. Wendl.
Indigofera australis Willd.
Kennedia rubicunda Vent.
Pultenaea flexilis Sm.

Gesneriaceae
Fieldia australis A. Cunn.

Geraniaceae
Geranium homeanum Turcz.

Goodeniaceae
Goodenia ovata Sm.

Lamiaceae
Chloanthes stoechadis R. Br.
Plectranthus parviflorus Willd.
Prostranthera rhombea R. Br.
Teucrium corymbosum R. Br.

Malvaceae
Abutilon oxycarpum (F. Muell.) F. Muell. ex Benth.
Howittia trilocularis F. Muell.

Meliaceae
Toona ciliata (F. Muell.) Harms

Menispermaceae
Sarcopetalum harveyanum F. Muell.
Stephania japonica (Thunb.) Miers var. *discolor* (Blume) Forman

Mimosaceae
Acacia elata Benth.
A. implexa Benth.
A. maidenii F. Muell.
A. oxycedrus Dieber ex DC.
A. parramattensis Tindale
A. saliciformis Tindale

Monimiaceae
Doryphora sassafras Endl.
Hedycarya angustifolia A. Cunn.
Palmeria scandens F. Muell.
Wilkiea huegeliana (Tul.) A. DC.

Moraceae
Ficus coronata Spin
F. rubiginosa Desf. ex Vent.

Myrsinaceae
Rapanea howittiana Mez.
R. variabilis (R. Br.) Mez.

Myrtaceae
Acmena smithii (Poir.) Merr. & L.M. Perry
Angophora costata Britten
Backhousia myrtifolia Hook. & Harv.
Eucalyptus agglomerata Maiden
E. piperata Sm.
E. saligna Sm.
Rhodamnia rubescens (Benth.) Miq.
Syncarpia glomulifera (Sm.) Nied.
Tristaniopsis laurina (Sm.) Peter G. Wilson & J.T. Waterh.

Oleaceae
Notolea ovata R. Br.
N. venosa F.Muell.

Passifloraceae
Passiflora cinnabarina Lindl.
P. herbertiana Ker. Gawl.
**P. subpeltata* Ortega

Pittosporaceae
Bursaria spinosa Cav.
Pittosporum multiflorum (A. Cunn. ex Loudon) L. Cayzer, Crisp & I. Telford
P. revolutum Dryand.
P. undulatum Vent.

Plantaginaceae
Plantago debilis R. Br.

Proteaceae
Persoonia levis (Cav) Domin.
P. linearis Andrews
P. pinifolia R. Br
Stenocarpus salignus R. Br

Ranunculaceae
Clematis aristida R. Br ex Ker. Gawl.

Rhamnaceae
Alphitonia excelsa (Fenzl.) Benth.

Rosaceae
Rubus moluccanus L. var. *trilobatus* A.R. Bean
R.rosifolius sm.
Rubus sp. aff. *R. moorei* F. Mull.

Rubiaceae
Galium binifolium N.A. Wakef.
G. propinquum A. Cunn.
Morinda jasminoides A. Cunn.
Psychotria loniceroides Sieber ex DC.

Rutaceae
Melicope micrococca (F. Muell.) T.G. Hartley

Sapindaceae
Guioa semiglauca R. Br.

Scrophulariaceae
Veronica plebeia R. Br.

Solanaceae
Solanum aviculare G. Forst.
S. americanum Miller
S. stelligerum Sm.
Solanum sp.

Thymelaeaceae
Pimelea latifolia R. Br. var. *hirsuta* (Meissner) Threlfall

Ulmaceae
Trema aspera (Brongn.) Blume

Verbenaceae
Clerodendrum tomentosum R. Br.

Violaceae
Hymenanthera dentata R. Br. ex DC.
Viola hederacea Labill.

Vitaceae
Cayratia clematidea (F. Muell.) Domin
Cissus antarctica Vent.
C. hypoglauca A. Gray

Winteraceae
Tasmannia insipida R. Br. ex DC.

MONOCOTYLEDONS
Araceae
Gymnostachys anceps R. Br.

Arecaceae
Livistonia australia (R. Br.) Mart.

Asteliaceae
Cordyline stricta (Sims) Endl.

Commelinaceae
Commelina cyanea R. Br.

Cyperaceae
Carex appressa R. Br.
Cyperus imbicillis R. Br.
Gahnia aspera (R. Br.) Spreng.
G. melanocarpa R. Br.
G. sieberiana Kunth.
Gymnoschoenus sphaerocephalus (R. Br.) Hook. f.
Lepidosperma laterale R. Br.
L. urophorum N.A. Wakef.

Lomandraceae
Lomandra longifolia Labill.
L. montana (R. Br.) L.R. Frazer & Vickery

Luzuriagaceae
Eustrephus latifolius Ker. Gawl.
Geitonoplesium cymosum R. Br.

Orchidaceae
Bulbophyllum shepherdii (F. Muell.) F. Muell
B. exiguum F. Muell.
Cymbidiium suave R. Br.
Dendrobium aemulum R. Br.
D. pugioniforme A. Cunn.
D. speciosum Sm.
D. striolatum Rchb. f.
D. teretifolium R. Br.
Liparis reflexa (R. Br.) Lindl.
Plectorrhiza tridentata (Lindl.) Dockrill
Pterostylis curta R. Br.
P. grandiflora R. Br.
P. longifolia R. Br.
P. nutans R. Br.
P. obtusa R. Br.
P. pedunculata R. Br.
Sarcochilus falcatus R. Br.
S. hillii (F. Muell) F. Muell.
S. olivaceus Lindl.

Phormiaceae
Dianella caerulea Sims

Poaceae
**Echinopogon ovatus* (G. Forst. P. Beau.
Entolasia stricta (R. Br.) Hughes
Imperata cylindrica var *major* S.W.L. Jacobs & C.A. Wall
Oplismenus aemulus (R. Br.) Roem. & Schult.
O. imbecillis (R. Br.) Roem. & Schult.
Microlaena stipoides (Labill.) R. Br.
Panicum pygmaeum R. Br.

Ripogonaceae
Ripogonum album R. Br.

Smilacaceae
Smilax australis R. Br.

Appendix 3

Pollen type name on pollen diagram (Fig. 8) and probable source in the vegetation, taken from the vegetation survey and Ryan et al. (1996).

Pollen type on pollen diagram	Probable source in the vegetation
TREES AND SHRUBS	
Casuarinaceae	*Casuarina* and *Allocasuarina*. *A. torulosa* most likely
Myrtaceae	All species in the family. For identifications and proportions, see Table 2
Podocarpus	Probably *Podocarpus spinulosus*
Monotoca	Probably *Monotoca scoparia*
Other Ericaceae	Other species in the family
Banksia	All species in the genus
Hakea	All species in the genus
Acacia	All species in the genus
Asteraceae *T. pleistocenicus*	A 'spineless' Asterceae, thought to be a *Cassinia*
HERBS	
Asteraceae (Tubuliflorae)	All species in the Tubuliflorae
Gonocarpus	*Gonocarpus/Haloragis*
Chenopodiaceae	All species in the family
Poaceae	All species in the family
Brassicaceae	All species in the family
Caryophyllaceae	All species in the family
AQUATICS	
Cyperaceae	All species in the family
Myriophyllum	All species in the genus
Restionaceae	All species in the family
Potamogeton	All species in the genus
?Convolvulaceae	?Convolvulaceae
FERNS AND ALLIES	
Trilete/monolete spores	All ferns and their allies
Unknowns	Unidentified pollen types

DAYS 5, 6

Information on Hawks Nest is found at:
http://www.teagardenshawksnest.com/

Myall Lakes National Park is described at:
http://www.environment.nsw.gov.au/NationalParks/parkHome.aspx?id=N0026

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Routledge
Taylor & Francis Group

The Response of Aboriginal Burning Practices to Population Levels and El Niño–Southern Oscillation Events during the mid- to late-Holocene: a case study from the Sydney Basin using charcoal and pollen analysis

MANU P. BLACK & SCOTT D. MOONEY, *University of New South Wales, Australia*

ABSTRACT *Pollen and macroscopic charcoal have been analysed from a sedimentary sequence representing approximately 6100 years from a site within Wollemi National Park. This is located to the north-west of Sydney and forms a part of the Greater Blue Mountains World Heritage Area. The overall aim of the work was to examine the prehistoric interrelationships between vegetation, fire and human activity. There were relatively minor changes in the vegetation over the last ~6000 years, perhaps reflecting the climate- and fire-resilient nature of the sclerophyllous vegetation found on Hawkesbury Sandstone throughout the Sydney Basin. Casuarinaceae declined in the late Holocene, a trend that has been detected in numerous palaeoecological studies throughout south-eastern Australia. This decline was unrelated to fire, which has been a persistent feature at the site over the entire analysed sequence. The fire regime at the site changed from 5.7 ka, which is interpreted as reflecting the onset of increased climatic variability associated with El Niño-Southern Oscillation (ENSO) events. Another dramatic change in the fire regime occurred at 3 ka, which was coeval with archaeological changes in the region. It is possible that the change in fire activity from 3 ka represented an alteration to Aboriginal management strategies associated with an increasing population and/or the increased risk of conflagrations in an ENSO-dominated climate.*

KEY WORDS *Fire history; Holocene; Sydney Basin; charcoal; palynology; impacts of Aborigines.*

Introduction

The Holocene environmental history of the Wollemi region and elsewhere in the Sydney Basin is poorly understood, although a number of studies provide

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comparative records which have offered some insights into the Holocene vegetation history. Selected studies from the Sydney region are listed in Table 1 and their locations are shown in Figure 1. Kodela and Dodson (1988) suggest that the sclerophyllous vegetation that grows on Sydney sandstone lithology is relatively resilient to climate change, fire and other disturbances.

The fire history of the Sydney Basin is unclear, with questions concerning the importance of human activity and climatic changes on fire activity. Aboriginal people utilised fire for a number of purposes, including hunting, but the ecological impacts and effects on vegetational patterns of this use of fire are uncertain. Martin (1994) suggests that human occupation over the past 5 ka at Kurnell Peninsula had little impact on the vegetation composition, through their use of fire, but cautions that the concept of Aboriginal people as 'careful custodians of the land' may have to be re-evaluated and suggests that low population numbers have been 'more important than care' (Martin 1994). Fire was a persistent feature over the past ~6 ka although there was a decline in fire activity, indicated by a decline in charcoal, over the past 200 years at Ku-ring-gai Chase National Park, and this was attributed to the arrival of Europeans and the displacement of Aboriginal people and their burning practices (Kodela & Dodson 1988). Johnson (1994) attributes most of the variations in microscopic charcoal concentrations to changes in Aboriginal people's use of fire during the late Holocene at the Kurnell Peninsula. Mooney *et al*. (2001) found consistently low levels of macroscopic charcoal during the Aboriginal (or pre-European) period, with only one large conflagration occurring during the analysed 1600 years. They suggest that it may have been unnecessary for the coastal Aboriginal groups that occupied the site to burn the catchment, considering the abundance of marine resources.

TABLE 1. The key palaeoenvironmental records of the Sydney Basin

Author	Type of record	Time span[a]	Location
Chalson (1983)	Pollen	4500 years BP	Jibbon Swamp, Royal National Park
Kodela and Dodson (1988)	Pollen and charcoal	5000–6000 years BP	Ku-ring-gai Chase National Park
Chalson (1991)	Pollen	32 000 years BP	Blue Mountains (eight sites)
Dodson and Thom (1992)	Pollen and charcoal	9.1 ka	Hawkesbury Valley
Johnson (1994)	Pollen and charcoal	2.4 ka	Kurnell Peninsula
Martin (1994)	Pollen and charcoal	8 ka	Kurnell Peninsula
Johnson (2000)	Pollen and charcoal	0.82 ka	Hawkesbury Valley
Mooney *et al*. (2001)	Pollen and charcoal	1.6 ka	Jibbon Swamp, Royal National Park
Black and Mooney (2006)	Pollen and charcoal	14 ka	Gooches Swamp, Blue Mountains
Black *et al*. (2006)	Pollen and charcoal	>43 000 BP	Lake Baraba, Thirlmere Lakes National Park

Note:
[a] years BP = uncalibrated years before present; ka = calibrated thousand years before present; BP = radiocarbon years before present.

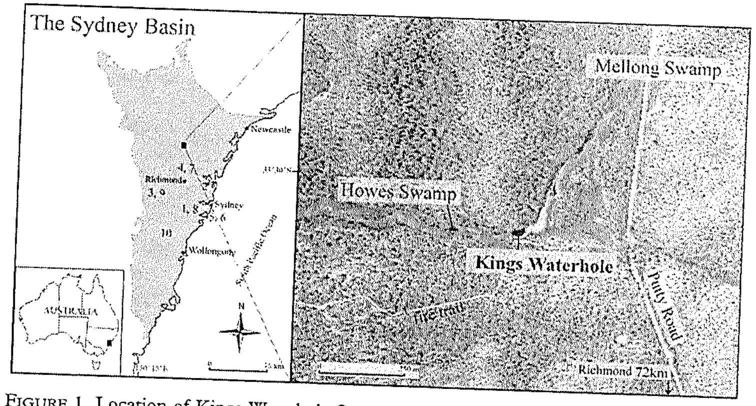

FIGURE 1. Location of Kings Waterhole Swamp, Mellong Swamp, Wollemi National Park. The location of the key palaeoecological sites of the Sydney Basin are numbered (1 = Chalson (1983); 2 = Kodela and Dodson (1988); 3 = Chalson (1991); 4 = Dodson and Thom (1992); 5 = Johnson (1994); 6 = Martin (1994); 7 = Johnson (2000); 8 = Mooney *et al*. (2001); 9 = Black and Mooney (2006); 10 = Black *et al*. (2006)).

The Wollemi National Park region of New South Wales has recently become the focus of archaeological research with the finding of new rock art sites within Wollemi National Park. Prior to these finds only 120 Aboriginal sites had been recorded within Wollemi National Park (NPWS 2001). The park has an area of over 487 000 ha and hence the area was not thought to have supported an intensive or permanent human population. It is now thought that the Wollemi region became a 'wilderness', void of people, only after the arrival of Europeans (Taçon 2005; Taçon *et al*. 2005). This may be evidenced by changes in fire and plant responses.

This study presents a record extending beyond 6000 years of vegetation change and one of the few contiguous fire records from the Sydney Basin region. The site, Kings Waterhole Swamp, is found within Wollemi National Park, which protects the largest wilderness area remaining in New South Wales (NPWS 2001) and forms a part of the Greater Blue Mountains World Heritage Area. The Holocene fire history of the Wollemi region has repercussions for present-day management of the area since an understanding of how climate and humans have affected fire in the past can give insights into how to manage for the future. The vegetation and fire record of the site was investigated to provide some insight into how to appropriately manage the poorly conserved Mellong Swamp plant communities of which Kings Waterhole Swamp is a part. The ecological importance of applying appropriate fire regimes to Sydney sandstone communities has been well documented (e.g. Clark 1988; Cary & Morrison 1995; Conroy 1996). Furthermore the NSW National Parks and Wildlife Service (NPWS 2001) has expressed concern that the recent high frequency of fire may impact on the long-term biodiversity of Wollemi National Park.

Site description

Kings Waterhole Swamp (33° 1' S, 150° 40' E, 280 m asl) is an occasionally flooded graminoid fen that extends along Mellong Creek. The site, located 100 km north-west of Sydney (see Figure 1), is on the eastern boundary of Wollemi National Park which forms the northern and western edge of the Sydney Basin. Kings Waterhole is one of several large swamps, known as the Mellong Swamps (Ryan *et al*. 1996), and is approximately 51 ha in area. Mellong Creek has a catchment area of approximately 50 km^2, and drains into the Colo River via Wollemi Creek.

The landscape surrounding Kings Waterhole is dominated by Hawkesbury Sandstone, which forms the ridges and the plateaux, but valleys are formed on the Narrabeen Group sandstones and shales (Ryan *et al*. 1996). Quaternary deposits of sand, clays and peats have infilled many of these shallow valleys. Kings Waterhole is one such example of a low relief valley that has been infilled with Quaternary alluvial deposits and peat. A geophysical survey of the Mellong area by Riley and Henry (1987) describes late Holocene valley development on the Mellong Plateau as one of aggradation combined with colluvial and alluvial deposition.

Kings Waterhole is located in a slight rain-shadow between the Great Dividing Range and the upper Blue Mountains to the west and the ranges towards the coast (Ryan *et al*. 1996). The nearest climate station to the site, Richmond (33° 36' S, 150° 47' E), is approximately 70 km south and probably receives slightly more rainfall than Kings Waterhole. At Richmond the mean annual rainfall is 810 mm with a distinctly summer-dominated rainfall, meaning that February is the wettest month (105.6 mm) and July the driest month (35.9 mm) (BoM 2005). Richmond is warm and temperate with an average maximum temperature range of 29.6°C in January to 17.2°C in July, and average minima of 17.4°C and 5°C in January and July, respectively (BoM 2005).

At Kings Waterhole, the fire season extends from late spring to late summer when low relative humidity and high temperatures occur. Although the highest rainfall occurs during summer, high evaporation at this time results in reduced water availability (NPWS 2001). Documentation of fires for the Mellong Swamps area began in 1943 and since this time there have been 14 bushfires that have affected the area, averaging one every 4 years (NPWS 2001).

Ryan *et al*. (1996) describe four major vegetation communities in the study area. Mellong Woodlands are found on a range of poorly- to well-drained soils on the plateau, Mellong Swamps are found in waterlogged soils, Sydney Sandstone Ridgetop Woodlands occur on the northern facing slopes of Hawkesbury Sandstone and the Sydney Sandstone Gully Forests are found on southern-facing slopes and gullies (Ryan *et al*. 1996). The woodland communities are dominated by *Corymbia/Eucalyptus* (e.g. *Corymbia gummifera* (redblood), *Corymbia eximia* (yellowblood), *Eucalyptus sclerophylla* (scribbly gum)), *Angophora bakeri* (narrow-leaved apple) and *Allocasuarina torulosa* (forest oak). The major species on the swamp surface include *Lepyrodia scariosa* (sedge), *Schoenus brevifolius* (bog-rush), *Carex appressa* (tall sedge), *Gonocarpus micranthus* (creeping raspwort), *Goodenia paniculate* (branched goodenia), *Persicaria decipiens* (slender knotweed), *Dichondra repens* (kidney weed), *Triglochin procera* (water ribbons) and *Selaginella uliginosa* (swamp selaginella). In wetter patches *Triglochin procera* is dominant and *Eleocharis sphacelata* (tall spike rush) surrounds the open water of Kings Waterhole. Stands of

Callistemon citrinus (crimson bottlebrush), *Melaleuca linariifolia* (flaxleaf paperbark) and *Acacia retinoides* (swamp wattle) surround the swamp.

Moore (1981) suggests that Aborigines have been using Wollemi National Park from ~12 000 years BP, with others suggesting establishment of habitation from 10 000 to 5000 years BP. The remoteness and ruggedness of Wollemi National Park has, until recently, prevented much archaeological investigation of the region. Recent discoveries of rock art sites have led to renewed speculation on the intensity and antiquity of Aboriginal occupation within the region. Attenbrow (2003) suggests that the region may have belonged to a range of bands associated with the Darginung language group. The Windradyne, Wanaruah, Darkinjung and Dharug Aboriginal Land Councils are currently involved in the management of the Aboriginal heritage within Wollemi National Park (NPWS 2001).

Methods

A 5.55 m sediment core was extracted from Kings Waterhole in October 2003 using a Russian D-section corer (Jowsey 1966). This core was recovered 16.0 m upstream from the open water of the actual Kings Waterhole, in the centre of the infilled valley. The stratigraphy of the core was examined using a modified version of the Troels-Smith method (Kershaw 1997) and was photographed. Two samples of organic sediment and one wood sample from three sections of the core (147–154, 348–353 and 547–553 cm) were submitted for radiocarbon dating to Beta Analytic, Florida, USA. These sections were chosen for dating because they are from roughly regular intervals along the core and more likely to provide an accurate age–depth curve. The organic sediment and wood were pre-treated with acid washes and acid/alkali/acid (AAA) washes. The radiocarbon ages were calibrated using the SHcal04.14C data set (McCormac *et al.* 2004) in CALIB v5 (Stuiver *et al.* 2005).

Macroscopic charcoal was analysed using image analysis (Mooney & Black 2003). Volumetric sub-samples (2 cm^3) from 2.5 cm contiguous intervals were taken from the core and dispersed for 24 hours in dilute (~6%) sodium hypochlorite (bleach) to remove the pigment from organic matter and hence aid in the identification of charcoal. The material was then washed through a 250 μm sieve with the aim of collecting macroscopic charcoal >250 μm in size. Digital images of the collected material were obtained using a 4 megapixel Nikon Coolpix 4500 digital camera and these images were analysed with image analysis software (Scion Image Beta 4.02 for Windows) to calculate the area of charcoal in each sample. Charcoal was expressed as a concentration (mm^2/cm^3); given the near-linear rate of sedimentation these data were not re-expressed as an influx (per unit area per unit time).

Pollen samples were prepared using standard palynological techniques (Faegri & Iverson 1975). Sediment samples were taken from 1 cm depth increments every 10 cm along the core, giving a total of 56 samples. The samples were deflocculated with hot 10% NaOH to remove organic acids and then sieved through a 150 μm mesh. Silicates were removed using heavy liquid (i.e. $ZnBr_2$(aq.)) separation and organic matter with acetolysis. Samples were mounted in silicon oil and the palynomorphs were counted at 400× magnification until 200 grains were identified. Nineteen different palynomorphs were quantified, chosen to represent the major taxa currently growing on or around the site. Pollen of *Melaleuca* spp. was separated out from other members of the family Myrtaceae. The pollen counts were expressed as percentages, with all grains contributing to the pollen sum. The pollen data were stratigraphically grouped into different zones using the CONISS cluster analysis feature of Tilia Graph (Grimm 1992).

Results

Stratigraphy and dating

The stratigraphy of the core revealed that peat and clays have been deposited for the majority of the time period represented by the sampled sediment core, although occasional bands of sand suggest periods of higher energy. The upper 70 cm of the core consisted of peat with fibrous roots. *Pinus* pollen was found to a depth of 20 cm and this was interpreted as the time of the first pine plantations in the region from ~AD 1920.

The results of the radiocarbon dating are shown in Table 2. The calibrated ^{14}C ages were used to formulate a linear age–depth curve (calibrated age in years BP = $10.87x+100$, where x = depth in cm, $R^2=0.9785$). This relationship was used to estimate the age of various features in the following discussion. Extrapolation of the age–depth curve suggests that the basal age of the analysed core was approximately 6.1 ka. This is slightly less than, but not widely different from, the calibrated basal date in Table 2 (i.e. 6250±240 cal. years BP).

Palynology

Figure 2 shows the results of the palynological analysis of Kings Waterhole Swamp. The cluster analysis revealed four major pollen zones labelled as KW1 (555–360 cm), KW2 (360–180 cm), KW3 (180–80 cm) and KW4 (80–0 cm) on the pollen diagram. Although there were statistically significant changes throughout the pollen spectra, all major pollen taxa persisted throughout the entire analysed sedimentary sequence. Of the pollen types analysed only Myrtaceae (including *Melaleuca* spp.), Casuarinaceae, Restionaceae, Haloragaceae, Poaceae and *Dodonaea* spp. changed significantly.

Zone KW1 (555–360 cm, ~6.1-4.0 ka)

This zone was dominated by approximately equal proportions of Myrtaceae (~31% of total pollen sum) and Casuarinaceae pollen (~28%). Restionaceae (~9%), Poaceae (~9%), Haloragaceae (~7%) and *Dodonaea* spp. (~2%) were the next best represented pollen types. There were low levels of ferns and mosses,

TABLE 2. Radiocarbon dates and calibration for Kings Waterhole Swamp. Calibration results from CALIB v5 (Stuiver *et al.* 2005). The mid-points of calibrated year ranges are used in age–depth model calculations. BP: before present (i.e. from AD 1950)

Depth (cm)	^{14}C date BP (1s error)	Cal. years BP (2s error)	Lab code
147–154	2220±60	2165±160	β 186146
348–353	3280±70	3450±180	β 186147
547–553	5560±90	6250±240	β 186148

Banksia spp. and *Melaleuca* spp. and only traces of *Pteridium* spp., *Acacia* spp., Chenopodiaceae and Asteraceae (tub.). Cyperaceae, Proteaceae, Asteraceae (fen.) and Juncaginaceae were not identified within this zone.

Zone KW2 (360–180 cm, ~4.0–2.1 ka)

Myrtaceae was the most well-represented pollen type in this zone with levels similar to that of the preceding zone (~32%). There was a decrease in Casuarinaceae pollen (~19%) but an increased proportion of Restionaceae pollen (~16%). Poaceae pollen representation remained stable at ~9%. Chenopodiaceae and Haloragaceae were present throughout this zone, although at low levels. There were very low levels of *Dodonaea* spp., Asteraceae (tub.), Juncaginaceae, *Banksia* spp., *Pteridium* spp., Epacridaceae, Cyperaceae, ferns and mosses. Asteraceae (fen.), Proteaceae and *Acacia* spp. were not identified within this zone. *Melaleuca* spp. pollen increased towards the top of this zone.

Zone KW3 (180–80 cm, ~2.1–1.0 ka)

Myrtaceae (~40%) continued to be the dominant pollen type represented in this zone, followed by Poaceae which increased to ~14% of the total pollen sum. *Melaleuca* spp. and *Pteridium* spp. increased in this zone. There was a major decrease in Casuarinaceae pollen (~4%) and also a decrease in Restionaceae (~6%) and Haloragaceae (~1.5%). There were low levels of ferns/mosses, *Banksia* spp. and Chenopodiaceae. There were very low or trace levels of Epacridaceae, Juncaginaceae, Proteaceae, Asteraceae (tub.), *Dodonaea* spp. and Cyperaceae (although there was one significant peak of Cyperaceae at 150 cm depth with ~41% of the total pollen sum). *Acacia* spp., Asteraceae (fen.) and Epacridaceae were not identified in this zone.

Zone KW4 (80–0 cm, ~1.0 ka to present)

This zone is characterised by high levels of Poaceae, with ~24% of the total pollen sum. Myrtaceae decreased slightly to an average of ~28%. Casuarinaceae remained low with the exception of a peak of ~25% at 20 cm. There were low levels of Restionaceae, Haloragaceae, ferns/mosses, *Pteridium* spp. and Asteraceae (tub.). There were trace levels of Epacridaceae, *Banksia* spp., *Acacia* spp., Juncaginaceae, Chenopodiaceae, Proteaceae, Asteraceae (fen.) and *Dodonaea* spp. There were very low levels of Cyperaceae, with the exception of the surface sample that had ~45% of the total pollen sum. The first appearance of *Pinus* sp. pollen was at 20 cm.

Macroscopic charcoal

Macroscopic charcoal was present throughout the entire sedimentary sequence of Kings Waterhole Swamp, although the concentrations of charcoal did vary considerably (see Figure 3). Charcoal was initially low between 555 and 515 cm (~6.1 and 5.7 ka) and subsequently increased dramatically. Charcoal generally remained high and variable between 515 and 265 cm (~5.7 and 3 ka) with the exception of low charcoal levels of deposition between 470 and 430 cm (~5.2 and 4.8 ka). Charcoal decreased rapidly at 265 cm (~3 ka) and remained generally low from this time to the present. Charcoal deposition for the top 80 cm (thought to represent the past ~1 ka) was especially low, although this may be associated with the 'dilution' of the charcoal concentration due to very high levels of organic matter deposition.

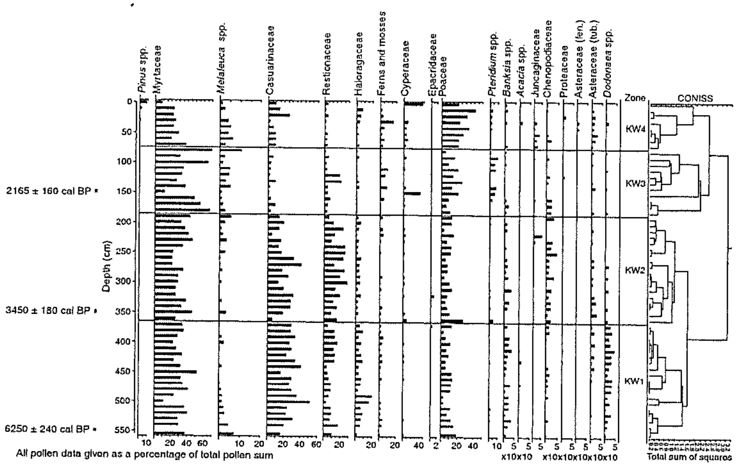

FIGURE 2. Results of the palynological analysis of Kings Waterhole Swamp.

Discussion

Vegetation history and climatic implications

The mixed *Eucalyptus–Casuarina* woodland, with a sclerophyllous shrubby understorey, which currently surrounds Kings Waterhole, is believed to have existed for the entire analysed sequence (the past ~6.1 ka), although there have been changes in the ratio of these dominant woody taxa. Myrtaceae and Casuarinaceae had approximately equal representation between ~6.1 and 2.1 ka with ~32% and ~24% of the total pollen sum, respectively. At ~2.1 ka there was a dramatic decline in Casuarinaceae and levels remained generally low to the present. Myrtaceae decreased only slightly in the past ~1 ka. The relatively small shifts in the flora over the past ~6 ka at Kings Waterhole indicate that there was little climate change or that the sclerophyllous vegetation that occupies the site is relatively resilient to environmental changes.

The representation of swamp indicators (Restionaceae, Cyperaceae and Haloragaceae) in the vegetation was highest between 5 and 2.1 ka and this may reflect a period of high moisture and perhaps a larger swamp. The past ~2.1 ka saw a decrease in swamp indicators Restionaceae and Haloragaceae and an increase in grasses (Poaceae) (especially in the past 1000 years), paperbarks (*Melaleuca* spp.) and bracken (*Pteridium* spp.). The increase in Poaceae and *Melaleuca* spp. from 2.1 ka may be representative of grasses and paperbarks, respectively, encroaching on

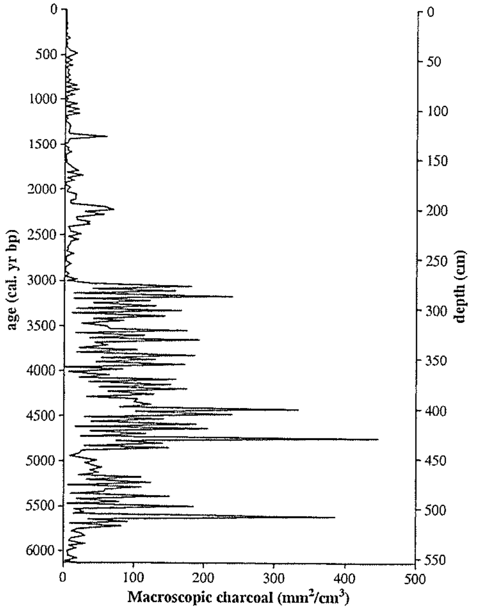

FIGURE 3. Results of the macroscopic charcoal (>250 μm in size) analysis from Kings Waterhole Swamp.

the swamp surface during times of periodic drought. Distinct changes to the vegetation of the swamp surface have been witnessed during the 2001–05 drought (pers. observation) and this has included increased colonisation of the swamp surface by Cyperaceae and grass species. The swamp taxa, such as Restionaceae and Haloragaceae, had a reduced representation during the past ~2.2 ka which further supports the interpretation of a relatively drier period. A grassy understorey, represented by high concentrations of Poaceae, increased from ~2.2 ka and there was a decrease in woody taxa (Myrtaceae) from ~1.1 ka. The surface sample at Kings Waterhole is characterised by very high levels of Cyperaceae (~45%) and Poaceae (~21%). This is most likely associated with the encroachment of this vegetation onto the swamp surface during the recent severe droughts experienced at the site.

Comparisons with other sites

The vegetation surrounding Kings Waterhole Swamp did not change greatly over the past ~6.1 ka and this is supportive of Kershaw's (1995) and Pickett *et al.*'s (2004) suggestion that most of the characteristics of south-eastern Australia's vegetation were established by ~6 ka. Furthermore, Dodson and Thom (1992) suggest that there have been no significant responses within the Sydney sandstone flora since the climatic shift of the Holocene Climatic Optimum between 7 and 5 ka (Kershaw 1995).

Kershaw (1995) suggests that during the late Holocene there was an opening up of forest canopies throughout south-eastern Australia and attributes this to climatic variability or the intensification of prehistoric human populations. At Kings Waterhole Swamp a grassy understorey increased from ~2.1 ka and there was a decrease in woody taxa (Myrtaceae) from ~1 ka. These trends are suggestive of the opening up of the canopy, although attributing a cause is difficult. Kodela and Dodson (1988) also describe a decline in *Eucalyptus* in the late Holocene. Chalson (1983) attributes a similar late Holocene decline in *Eucalyptus* at Jibbon Swamp to hydrological evolution and ecological succession. The vegetational changes witnessed in the late Holocene at Kings Waterhole Swamp may be related to hydrological and successional changes associated with the infilling of the swamp with sediment, but this is unlikely considering the physical setting of the site.

Chalson (1991) identifies an approximately coeval wet period from 5.5 to 2.5 ka from the nearby Blue Mountains. Chalson (1991) and Kodela and Dodson (1988) identify the past 2000 years as a period of generally drier climate in the Sydney region. Kershaw *et al.* (2002), however, suggest that south-eastern Australia was relatively dry and cool between 4 and 2 ka and the past 2000 years saw the return to wetter climatic conditions. This contradiction could perhaps reflect real spatial differences across south-eastern Australia during the past 2000 years, with a concurrent wetter southern and a drier northern section. These conditions could result, for example, from the southward deflection of the cold fronts that are often associated with precipitation in south-eastern Australia.

Kodela and Dodson (1988) recorded no major changes over the past ~6000 years in the vegetation from Ku-ring-gai Chase National Park, some 80 km south-east of Kings Waterhole Swamp. Notably their site was also surrounded by Sydney Sandstone Complex vegetation and dominated by Hawkesbury Sandstone. Kodela and Dodson (1988) suggest that the sclerophyllous vegetation that dominates Hawkesbury Sandstone is resilient to fire and that low-nutrient sandy soils, exposure to high insolation and drought means that the vegetation was probably insensitive to minor environmental changes. Black *et al.* (2006) also suggest that the sandstone vegetation surrounding Lake Baraba was resilient to climatic change based on relatively little change in the palynology over the last >43 ka, a period which notably includes the last glacial maximum.

The decline in Casuarinaceae during the Holocene, as found at Kings Waterhole, has been widely reported throughout south-eastern Australia and is often associated with an increase in *Eucalyptus* (e.g. Ladd *et al.* 1992; Gale and Pisanu 2001). At Kurnell Peninsula, a coastal site just south of Sydney, *Casuarina* woodland was established by 8 ka, but *Eucalyptus* increased and by 5.3 ka *Eucalyptus* exceeded *Casuarina* as the dominant vegetation at the site (Martin 1994). Dodson and Thom (1992) describe a general trend of increasing *Eucalyptus* and decreasing *Casuarina* throughout the Holocene from Mill Creek on the Hawkesbury River, approximately 40 km south-east of Kings Waterhole Swamp, and attribute this change to a decline in upper saltmarsh communities and increasing sclerophyll and woodland cover.

At Kings Waterhole Swamp, Myrtaceae remained relatively constant and hence *Eucalyptus* is unlikely to be associated with the decline in Casuarinaceae at this site. The substantial decline is coincident with the dry period inferred from the reduced swamp cover and possible encroachment of grass onto the swamp surface. This suggests that the decline in Casuarinaceae at Kings Waterhole Swamp reflects either climatically or edaphically driven hydrological changes at the site.

Fire history of Kings Waterhole Swamp

The analysis of charcoal at Kings Waterhole Swamp suggests that fire was a persistent feature of the local landscape throughout the past 6.1 ka and that there were some major changes in fire activity. Charcoal deposition was initially low between ~6.1 and 5.7 ka and then increased markedly at ~5.7 ka to remain high and variable until 3 ka, with the exception of a low period between ~5.2 and 4.8 ka. At 3 ka charcoal concentrations decreased abruptly in the absence of any major changes in the sediment or rate of sedimentation. It is likely that climates in south-eastern Australia became more variable from the mid-Holocene, as numerous studies have dated the onset of 'modern' El Niño–Southern Oscillation (ENSO) events to this time (e.g. Shulmeister 1999; Rodbell *et al.* 1999; Sandweiss *et al.* 2001; Moy *et al.* 2002). The onset of climatic variability and times of vegetational change have been linked to increases in charcoal quantity due to more frequent or intense fire activity (e.g. Edney *et al.* 1990; Haberle *et al.* 2001; Kershaw *et al.* 2002; Black & Mooney 2006). Since the Kings Waterhole Swamp record does not extend past ~6.1 ka it is not known whether the increase in charcoal at 5.7 ka marks the end of an early Holocene period of low charcoal accumulation.

Notably, Black and Mooney (2006) also found a rapid increase in fire activity at ~5.7 ka from Gooches Swamp in the nearby Blue Mountains. They suggest that increased climatic variability associated with the onset of 'modern' ENSO events (e.g. Moy *et al.* 2002) resulted in a distinctly different fire regime compared to that of the early to mid-Holocene. Significant increases in burning after 5 ka in all vegetation types across Australia (except the wet forests) have been associated with climate change (Kershaw *et al.* 2002). The accumulation of larger charcoal particles is often associated with high-intensity fires (Ward & Hardy 1991). We suggest that an ENSO-dominated climate resulted in an increased frequency of intense fires at Kings Waterhole Swamp between ~5.7 and 3 ka and perhaps large intense fires encroached onto the swamp surface and deposited charcoal *in situ*. At Kings Waterhole there was a marked decline in charcoal from ~3 ka, and after this time charcoal remained relatively low.

Attenbrow (2003) examined the past habitation and land-use patterns of Aborigines in the Upper Mangrove Creek catchment, which is approximately 30 km east of Kings Waterhole Swamp. Attenbrow (2003) analysed 30 excavated archaeological deposits from rockshelters in the region and presented several indices including rate of habitation establishment and number of habitations used per millennium to quantify how use of the catchment changed over time. The results of this study suggest that habitation patterns and subsistence organisation changed over the past 11 ka, including an unprecedented level of change occurring from 3 ka with a substantial increase in base camps. Attenbrow (2003) hypothesises that the changing habitation distribution patterns reflect 'a re-organisation of mobility patterns ... relating to camp life and subsistence activities took place in the catchment at frequent intervals and even more frequently and dynamically in the last four thousand years' (2003, p. 29).

Comparison of the archaeological data from the Upper Mangrove Creek and the Kings Waterhole Swamp charcoal curve (see Figure 4) suggests that the reduced charcoal concentration from 3 ka at Kings Waterhole Swamp is perhaps associated with human activity in the region. The fire regime of Aborigines is generally associated with resource manipulation and is described as being frequent but of low intensity (e.g. Jones 1969; Kohen & Lampert 1987; Gott 2005). Aborigines may have manipulated fire and/or fuel loads in the Kings Waterhole Swamp landscape in various ways which resulted in lower concentrations of charcoal in the sediment after 3 ka. Whitlock and Larsen (2001) suggest that fire regimes characterised by 'frequent and efficient ground fires' do not produce much charcoal. This could imply a change from high-intensity natural fire to more frequent, low-intensity anthropogenic fire from ~3 ka. We suggest that Aborigines may have begun intensively managing fire during the late Holocene to reduce fuel loads, in response to the risks associated with living in a fire-prone environment under an ENSO-dominated climate.

In their study in the nearby Hawkesbury Valley, Dodson and Thom (1992) suggest that lower charcoal input to the sediment could have resulted from a more frequent but a lower intensity burning regime. Other studies have also attributed changes in charcoal to the fire intensity (e.g. Singh *et al.* 1981; Hope 1999). Previous studies in the Sydney Basin have found various changes to charcoal during the European period, with some sites recording increases in quantity (e.g. Johnson 2000; Mooney *et al.* 2001) and others showing a decrease (e.g. Kodela & Dodson

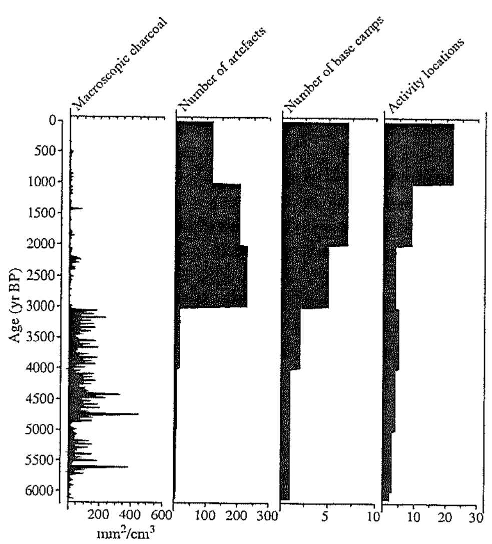

FIGURE 4. A comparison of the Upper Mangrove archaeological data (Attenbrow 2003, 2004) and the Kings Waterhole Swamp charcoal curve.

1988). Very low quantities of charcoal were found in the sediments of the European period at Kings Waterhole Swamp, which is surprising considering the relatively high frequency of intense bushfires that have occurred in the landscape in recent times. The unexpected lack of charcoal in the European period may be attributed to the very high levels of organic matter accumulation in the recent sediments at Kings Waterhole Swamp, such as living roots from the swamp vegetation, diluting the charcoal concentrations. A detailed chronology (e.g. using ^{137}Cs or ^{210}Pb) could resolve the matter of the influx of charcoal during this European period.

Comparison of charcoal and pollen data

Statistically significant changes in vegetation occurred at 4, 2.1 and 1 ka based on the cluster analysis of the pollen data. These changes did not correspond to any major fluctuations in the charcoal record. This suggests that changes in fire activity at Kings Waterhole Swamp did not have a significant impact on the overall vegetation composition at the site. This does not preclude, however, vegetational changes at the species level which are not visible in the results due to the broad classification of the palynomorphs (i.e. pollen types were chosen at either the 'family' or 'genus' level).

Although there appears to be no relationship between the overall vegetational changes of the site and fire activity when individual pollen curves are examined, there are some broad relationships. Hopbush (*Dodonaea* spp.) often becomes more abundant during periods of high fire activity (Wilson & Scott 2002). This vegetational response is evident at Kings Waterhole Swamp with higher concentrations of *Dodonaea* pollen between 5.7 and 3 ka when charcoal accumulation was high. In this setting, *Dodonaea* spp. appears to be a good indicator of disturbance associated, perhaps, with intense fire activity. The representation of bracken (*Pteridium esculentum*), which also thrives on the disturbance following a fire (Benson 1992), does not appear to be related to charcoal abundance. In fact, during periods of high charcoal concentrations there were very low concentrations of bracken pollen whilst during the last 3 ka, when charcoal was low, there were higher levels of bracken. The proportion of *Dodonaea* spp., Asteraceae, *Banksia* spp. and Haloragaceae declined, whilst Poaceae and *Juncus* spp. increased, at 3 ka when charcoal declined substantially.

Dodson (1986) had previously noted little association between pollen and charcoal curves and suggested that either: (1) fire had no impact at the level of pollen identification; (2) there were significant differences between the spatial sources of the pollen and charcoal; or (3) the fire-sensitive species had already been eliminated from the environment by the time the site started recording the environmental history and that a fire–vegetation equilibrium had already been established.

Conclusions

There have been only slight changes in the vegetation composition during the past ~6.1 ka from Kings Waterhole. The mixed *Eucalyptus–Casuarina* woodland with a shrubby sclerophyll understorey, which currently surrounds the swamp, is believed to have existed for the entire sequence. Kershaw (1995) and Pickett *et al.* (2004) have previously suggested that most of the characteristics of south-eastern Australia's vegetation were established by ~6 ka. Furthermore, the resilient nature of the Sydney Sandstone flora may mean that it is relatively insensitive to minor climatic changes.

The record displays a decreased representation of Casuarinaceae throughout the mid- to late-Holocene and this decrease has been described from several studies in south-eastern Australia (e.g. Ladd *et al.* 1992; Gale & Pisanu 2001). Macroscopic charcoal abundance increased abruptly at 5.7 ka at Kings Waterhole Swamp and this is likely to be associated with the onset of an ENSO-dominated climate when more intense natural fires became a feature of the landscape. At 3 ka there was a major decrease in charcoal abundance, which corresponds with archaeological information suggesting altered Aboriginal activity in the region. It is therefore likely that from 3 ka low-intensity anthropogenic fires were a feature of the landscape.

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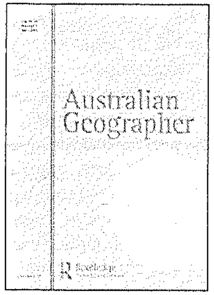

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A Comparison of Charcoal and Archaeological Information to Address the Influences on Holocene Fire Activity in the Sydney Basin

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ABSTRACT *The influence of Aboriginal people on fire activity and hence the vegetation of Australia has long been debated. This study aimed to document the local fire activity of the Holocene in the catchment of a small freshwater reed swamp located in the Sydney Basin and to compare this with nearby archaeological evidence; including artefact discard rates and the number of base camps and activity locations used through time. This archaeological evidence was used as an index of human activity through time to assess anthropogenic influences on fire activity. Charcoal (>250 μm) was quantified in a radiocarbon-dated sediment core from Griffith Swamp covering ~6000 calibrated years BP. A substantial increase in fire activity was found from ~3000 years BP and a lesser increase approximately 700 years ago. The change in fire activity at ~3000 years BP was approximately coeval with changes in archaeological evidence from Upper Mangrove Creek, suggesting either greater human presence in the landscape or altered subsistence and land-use strategies. Fire frequency in the catchment of Griffith Swamp peaked at about eight episodes per century, perhaps in response to environmental change that promoted both increased human activity and a higher natural fire frequency. This study provides an extended temporal perspective on fire and humans in this landscape, demonstrating how palaeoecology can provide practical information for the contemporary management of such fire-prone ecosystems.*

KEY WORDS *Holocene fire activity; Sydney; charcoal and archaeological evidence; Aboriginal activity.*

Introduction

Knowledge of past fire regimes is critical to successful natural resource management and for meeting the ideals of conservation of biodiversity and sustainability. It is especially important in temperate Australia where many native species are reliant upon fire for regeneration and/or germination (Gill 1981). European explorers

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often noted Aboriginal people using fire or connected smoke with them: this ethnographic record has led many to argue that Aboriginal people regularly burnt much of the Australian landscape (Jones 1969; Flannery 1992; Kohen 1996; Gott 2005). Some doubt has been cast on these ideas, however, with Benson and Redpath (1997) presenting arguments of selective and biased quoting of the ethnographic record. Gill (1977, p. 24) had also previously suggested that the observations of explorers 'perhaps influenced Aboriginal behaviour' and that more recent Aboriginal practices were 'perhaps influenced by European customs'.

The debate concerning prehistoric fire in Australia is also confused by the interpretation of an increase in charcoal in sediments as evidence for the ingress of Aboriginal people into naïve Australian ecosystems (e.g. Singh *et al.* 1981; Kershaw 1986; Turney *et al.* 2001). Further, at ~50 000 years BP, the confluence of several contentious but approximately coeval events have added momentum to the idea of significant Aboriginal impacts on the Australian environment. These 'events' have included the arrival of Aboriginal people, as determined by re-dating of the Mungo human remains (Bowler *et al.* 2003), vegetation change (Turney *et al.* 2001), extinction events (Miller *et al.* 1999; Roberts *et al.* 2001) and postulated climatic responses to anthropogenic fire-induced vegetation changes (Miller *et al.* 2005).

Perhaps the most widely cited author to question paradigms concerning Aboriginal influences on the Australian landscape is Horton (1982, p. 237) who argued that Aboriginal people 'observed and made use of an existing natural fire regime in Australia, they did not attempt to develop a new one'.

In Australia it is likely that the use of broad-acre fire by Aboriginal people would have varied across almost all spatial scales, with some ecosystems being more favoured for utilisation and others more resilient (Clark 1983; Clark & McLoughlin 1986; Head 1989; Bowman 1998). The use of fire may also have changed through time, with shifts in climate, vegetation and population and with changes in technology and other cultural factors (Clark 1983; Head 1989).

Previous palaeoecological investigation at Royal National Park (Mooney *et al.* 2001) and Myall Lakes National Park (Mooney & Maltby 2006), both coastal locations of south-eastern Australia, found little evidence of regular landscape fire as one would expect from 'fire-stick farming' (Jones 1969). While this may be related to the availability of resources associated with nearby marine or coastal ecosystems in these study areas, it also brings into question some of the central tenets of the paradigm of Aboriginal use of fire in the landscape. In the Blue Mountains, to the west of Sydney, Black and Mooney (2006) have also recently argued that Holocene fire activity primarily reflected climatic rather than anthropogenic controls.

The history of fire in the humid environments of south-eastern Australia has significant implications for the contemporary management of these landscapes. Recent conflagrations (e.g. Sydney in 2002; Canberra and ACT in 2003) have often resulted in demands for increased prescribed fires for fuel management and hazard reduction (e.g. the House of Representatives Select Committee on the Recent Australian Bushfires, CoA, 2003). The underlying assumption is that high-frequency prescribed fire reintroduces prehistoric regimes. Generalisations about Aboriginal use of fire are also interwoven with the debate concerning contemporary land clearing in NSW, with some arguing that clearing represents removal of regrowth associated with the cessation of Aboriginal fire (e.g. Ryan *et al.* 1995). The prehistoric use of fire by Aboriginal people also has socio-political ramifications (Head 1989): active management of land by Aboriginal people through the use of fire is a challenge to the notion of *Terra nullius* and thereby influences the debate about Aboriginal land rights.

Bowman (1998) emphasises that in order to advance our understanding of Aboriginal landscape burning the coupling of archaeological research with palaeoenvironmental analyses must be undertaken. This project thus aimed to compare changes in Holocene archaeological sequences against a palaeoecological record of fire activity from a site in the Sydney Basin, with a view to examining the controls on fire activity.

The archaeological literature of the Sydney Basin was reviewed to determine which studies were sufficiently detailed to be compared with potential palaeoecological work. Upper Mangrove Creek has been surveyed extensively by Attenbrow (1982a, b, 2003, 2004) and is one of the most detailed archaeological records in south-eastern Australia. Based on 30 excavated archaeological deposits, all in rockshelters, Attenbrow (2003, 2004) describes four indices of habitation site abundance and artefact numbers: rates of habitation establishment per millennium; numbers of habitations used per millennium; artefact accumulation rates for individual deposits/habitations; and artefact accumulation rates for the upper Mangrove Creek catchment as a whole. Attenbrow (2003, pp. 21–2) proposes that the habitation and artefact indices reflect 'how use of the catchment changed over time'.

Topographic maps were examined for sedimentary deposits (namely lakes or swamps) in the vicinity of the Upper Mangrove Creek archaeological sites. This was constrained to locations that would have been within a day's walking distance of the archaeological sites. Potential palaeoecological sites were examined in greater detail using aerial photographs, and reconnaissance trips investigated the most promising sites. Eventually, Griffith Swamp was selected to be compared to Upper Mangrove Creek, as shown in Figure 1.

The environmental setting

Griffith Swamp is located on Wellums Creek, a tributary of the Macdonald River, at 33° 17′ S, 150° 60′ E, and approximately 15 m above sea level. Wellums Creek drains a catchment of 43 km^2 (Korup & Busche 2000) and the swamp surface covers an area of ~0.25 km^2, as shown in Figure 1. In wet years (e.g. 1992) surface water covers at least half the swamp surface; however, at the time of coring (2004) only a small pond covered the southern end of the swamp. Griffith Swamp is close to Yengo National Park and approximately 20 km from the archaeological sites of the Upper Mangrove Creek.

Griffith Swamp is located on a floodplain consisting of Quaternary alluvium, gravel, sand, silt and clay (Department of Mines 1966). Jones and Dodson (1997) describe the stratigraphy of the nearby Wrights Creek valley as consisting of an uppermost unit of approximately 50 cm of silty organic sediments overlying a silty clay to a depth of at least 2.5 m. Radiocarbon dating, palynology and comparison with other Hawkesbury-Colo sites suggests that the lower clayey unit represents the gradual replacement of saline conditions, perhaps after a mid-Holocene higher sea level, until freshwater communities dominated since about 3350 BP. The slopes surrounding the floodplain consist of the Triassic Narrabeen Group, while the

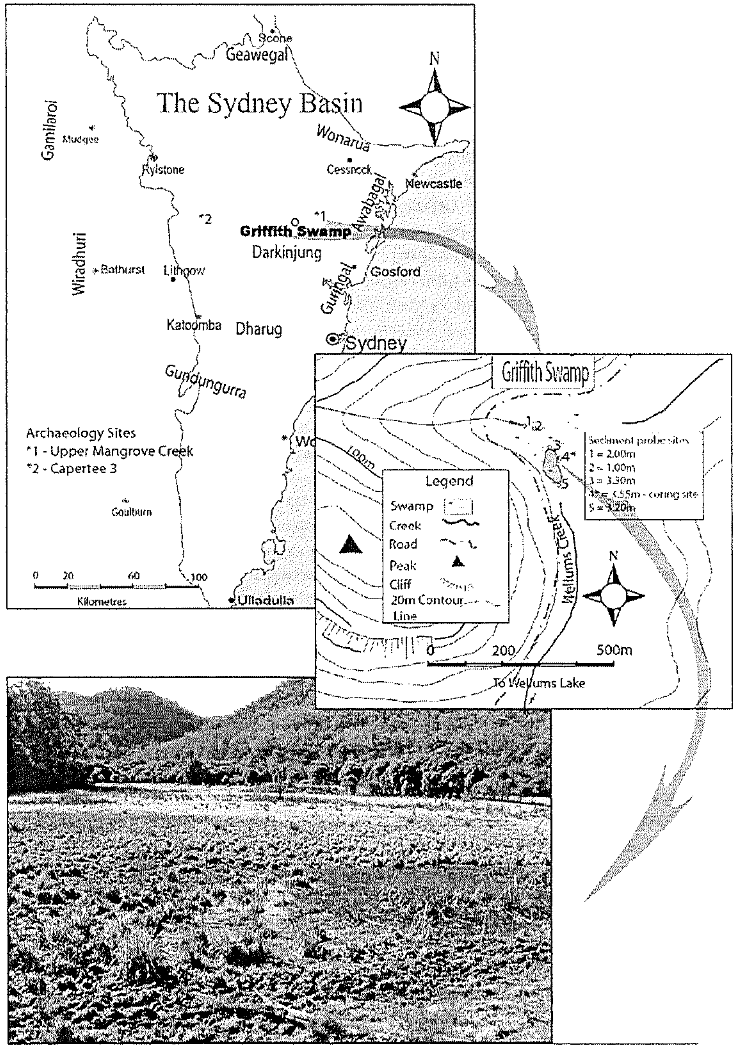

FIGURE 1. Sydney Basin map showing swamp site locations, archaeology site locations, Aboriginal territories, major rivers and cities.

ridges, forming a part of the Hornsby Plateau, are dominated by Triassic Hawkesbury Sandstone.

The palaeoecological site, Griffith Swamp, is a complex of freshwater reed swamp and open-sedgeland dominated by *Eleocharis sphacelata*, *Juncus usitatus* and *Persicaria hydropiper*. The surrounding slopes are vegetated with Sydney Sandstone Ridgetop Woodland or low open woodland (Ryan *et al.* 1996), dominated by *Corymbia eximia*, *C. gummifera*, *Angophora bakeri*, *A. costata* and *Eucalyptus punctata*. The floodplain has largely been cleared and currently supports pasture grasses and cattle grazing. At the time of coring, the surface of the swamp was unfenced and cattle had disturbed the site to a depth of ~15 cm.

The Holocene is generally portrayed as a period of relatively stable climate. Sclerophyll vegetation in eastern Australia was largely established by the early Holocene and palynological studies in the Sydney Basin (e.g. Kodela & Dodson 1988; Jones & Dodson 1997) have found relatively little vegetation change during the last 6000 years. How relative sea level has behaved during the Holocene is a contentious issue; however, Baker *et al.* (2001) describe a mid-to-late Holocene high stand of approximately +1.7 m from 4300 to 2800 years BP and of about + 1.0 m from 2800 to 1500 years BP (both periods are corrected for marine reservoir effects).

This part of the Macdonald River Valley has a slight summer maximum in rainfall and on average receives ~900 mm of rainfall per annum (Bureau of Meteorology 2004). The low rainfall and high temperatures of spring and early summer make this the most fire-prone period for the region (NPWS 1999).

At the time of first British settlement, the Macdonald River area and Upper Mangrove Creek were part of the territory of a language group now known as the Darginung (also written Darkinjung, Darkinjang and Darkinung). Darginung territory covered an area extending south from the watershed of the Hunter River, including portions of the Macdonald and Colo Rivers and lower Hawkesbury River at Wisemans Ferry (Mathews, 1897, p. 1; Tindale 1974, p. 193; Dharug and Lower Hawkesbury Historical Society 1988, p. 4; Attenbrow 2003, 2004). Thus both Griffith Swamp and the Upper Mangrove Creek archaeological sites were in Darginung country. On the basis of the archaeological and historical evidence, Attenbrow (2004) proposes that these people were relatively mobile hunter-gatherers, who used several base camps as well as many activity locations (e.g. sites for hunting and gathering, tool maintenance, etc.) and transit or short-term camps within their country.

European settlers began moving into the lower Hawkesbury in ad 1794, and by 1796 settlers were established in the Macdonald River Valley (Dharug and Lower Hawkesbury Historical Society 1988). Sim (1969) provides a more conservative estimate, reporting that the larger valleys of the Macdonald and its tributaries were settled by approximately 1840.

The recent fire history of the region surrounding Griffith Swamp was obtained from a GIS database maintained by the National Parks and Wildlife Service (NPWS). This database stretches back to 1964, during which time four fires have been recorded in the Wellums Creek catchment: these were 2002–03 (burning 248.8 km^2), 1997–98 (3.23 km^2), 1990–91 (10.32 km^2) and 1990–91 (7 km^2). At least two of these fires (1990–91, 2002–03) burnt on or around Griffith Swamp and a fire in 1997/98 burnt the upper reaches of the Wellums Creek catchment (NPWS 2004).

Methods

Preliminary exploration of both the depth and sediment type of the swamp was used to identify the most organic and deepest part of the swamp, which was then selected as the coring site. Coring was undertaken using a Russian D-section corer (Jowsey 1966) to a depth of 355 cm and the sediment was immediately wrapped, secured in a cradle and transported to the lab. The cores were immediately photographed and described using Kershaw's (1997) modification of the Troels-Smith (1955) method, and then refrigerated (at 4°C). Following usual procedure, one of these cores was selected for detailed analysis.

The charcoal content of the Griffith Swamp sediment core was initially analysed at 5 cm intervals. To better define the record, the upper 250 cm was subsequently contiguously sub-sampled using 1 cm increments. This resulted in the analysis of charcoal in 271 sub-samples of sediment.

The macroscopic (>250 μm) charcoal content of the sediment was analysed using a modification of the 'Oregon Sieving Method' (Millspaugh & Whitlock 1995; Long *et al.* 1998; Gardner & Whitlock 2001). This method consists of dispersing sub-samples of sediment of known volume and mass in bleach (6.5%) for 19 hours. The sediment was then washed through a 250 μm sieve and the captured material was transferred into a Petri dish and a high-resolution (4 megapixel) digital image captured. The area and number of charcoal particles in each image was determined using the Scion Image program (Mooney & Radford 2001; Mooney & Black 2003).

Bulk sediment samples (120–130, 200–210, 320–330 cm) from Griffith Swamp were radiocarbon dated at Beta Analytic Radiocarbon Laboratory, Florida, USA, after a pre-treatment consisting of acid washes. The conventional radiocarbon ages were subsequently calibrated to calendar years using the INTCAL98 database (Stuiver *et al.* 1998). To supplement the ^{14}C determinations, exotic pollen present in the sediment core was used to estimate the depth at which European influences began at the site. Pollen slides were initially prepared at 10 cm intervals and then further samples were taken at 2 cm increments to find the deepest record of exotic pollen.

Pollen preparation procedures were undertaken as outlined in many standard texts (e.g. Birks & Birks 1980; Faegri & Iversen 1975). This consisted of an alkali treatment (using 10% NaOH in a water bath), sieving (150 μm) to remove coarse material, acetolysis to hydrolyse the cellulose, and mounting of the material on microscope slides in silicon oil. Transects of the pollen slides where then undertaken in search of exotic pollen.

Fire activity in the catchment of Griffith Swamp was better characterised by converting the concentration of charcoal in the sediment sub-samples to a charcoal accumulation rate (CHAR). CHAR was calculated using the average rate of sediment deposition which was derived from the radiocarbon dates. The Charcoal Analysis Programs (CHAPS) of Long *et al.* (1998) were used to interpolate from the raw data a set of values regularly spaced in time and to divide the CHAR record into two components, namely a low-frequency background component and a higher frequency peak component. The former represents secondary charcoal which may be introduced into a deposit over a period of years after a fire (Whitlock & Millspaugh 1996) and the latter is a better record of fire episodes (Long *et al.* 1998).

The CHAPS program decomposes the raw time series by using a locally weighted (moving) average to define the background component and assigns a threshold to separate the background from the peak component (Long *et al.* 1998). The width of the averaging window controls the smoothness of the resulting background component and can be selected by visually comparing the resulting background component with the CHAR time series (Long *et al.* 1998). The CHAR threshold can also be calibrated using the historical record to specify at what level a peak is indicative of a fire (Hallett & Walker 2000).

The CHAPS programs are designed for contiguously sampled data and high-resolution analysis (Carcaillet *et al.* 2002). Hence, only the contiguous 1 cm charcoal data from the uppermost 250 cm from Griffith Swamp was analysed with CHAPS. A threshold value of 1.1 was used, as it closely resembles the peak to mean ratios of previous studies using CHAPS.

Results

Figure 2 depicts the sediment profile from Griffith Swamp, revealing the clayey nature of the analysed sediments. The results of radiocarbon analyses from Griffith Swamp are presented in Table 1. Exotic pollen was scarce in the prepared slides but *Pinus* pollen was found to a depth of 26 cm. These data resulted in a chronology of sedimentation for the core site. A highly significant ($r^2 = 0.996$) second-order polynomial, used to describe this age–depth relationship as shown in Figure 3, justified interpolation between these dates.

The primary data provided charcoal concentrations, either as a count (no. of charcoal particles greater than 250 μm/cm^3) or as an area (mm^2/cm^3) against depth in the core, as displayed in Figure 4. This figure also shows the influx of charcoal (CHAR) for Griffith Swamp, using the deposition time calculated using the rate of sediment accumulation (Figure 3).

The record at Griffith Swamp reveals a high influx of charcoal from ~6300 to 5200 cal. years BP and a low influx from 5200 to 2500 cal. years BP. This period of low charcoal is especially apparent between 4000 and 2500 cal. years BP. A substantial increase in charcoal influx occurred at ~2500 cal. years BP, and from this time until 500 cal. years BP the charcoal influx was generally high. During this period the highest influxes of charcoal were centred on ~700 cal. years BP. The charcoal influx remained low in the last 500 years. No evidence of the recent fires for the area surrounding Griffith Swamp were obvious in the charcoal record of the uppermost sediments, although a small peak estimated to have occurred ~25 years ago may represent the 1990/91 fires.

Matching charcoal peaks to historical fires is a useful method for the selection of criteria within CHAPS, including the window width for the weighted mean calculations and the peak to mean ratios (e.g. Hallett & Walker 2000). As it was not possible to match individual charcoal peaks to historical fires in this study, the data were analysed using a variety of window widths (see Figure 5). As noted, only the uppermost 250 cm of the Griffith Swamp core was analysed contiguously; however, this spans the last ~4000 cal. years BP (see Figure 3), which is the period of most recorded archaeological change in the Yengo National Park region (e.g. Attenbrow 2003, 2004). The varying window widths resulted in similar trends, with the frequency of fire episodes increasing substantially at approximately 2500 cal. years BP.

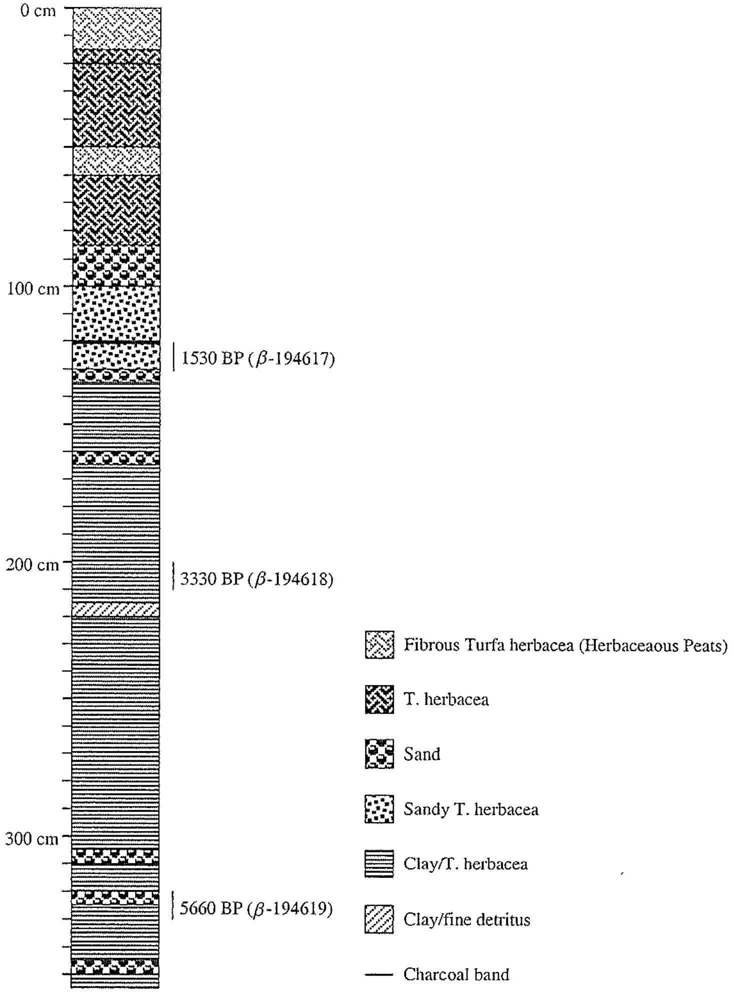

FIGURE 2. Griffith Swamp sediment profile with ^{14}C dates calibrated to years BP.

Discussion

Attenbrow's (2003, 2004) archaeological investigations in Upper Mangrove Creek indicate significant changes in land-use patterns during the late Holocene, including reorganisation of habitation, subsistence and manufacturing activities. For her study Attenbrow calculated the number of habitations that were established and used in each millennium over the 11 000 years for which archaeological evidence was recovered. To document changing use of the landscape, she also divided the catchment into topographic zones (based on valley bottoms, slopes and ridgetops). The habitation sites were divided into base camps (with a greater amount and range of archaeological materials) and activity locations or transit camps (with a much smaller amount and range of archaeological material).

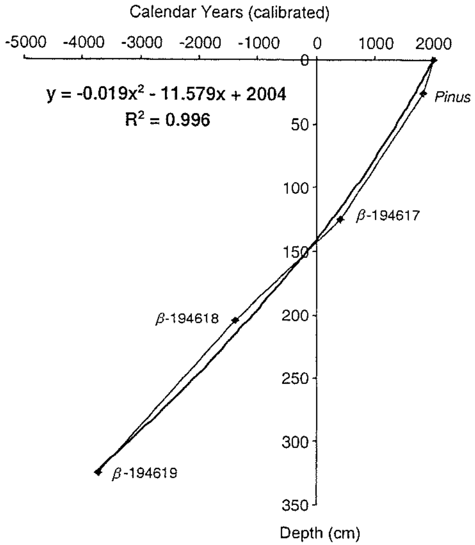

FIGURE 3. Age–depth relationship for Griffith Swamp sediment core.

In summary, Attenbrow (2003, p. 27) proposes 'that the number of activity locations/transit camps used in the catchment gradually increased until 3000 BP and then, after 2000 BP, there was a dramatic increase in number associated with the use of topographic zones not previously or only infrequently used'. Base camps were first established in the 11th millennium BP, but the number did not increase until the 4th millennium BP, with the greatest increase occurring in the 3rd millennium BP. Artefact production rates also increased dramatically in the 3rd

TABLE 1. Radiocarbon ages and calibrated years before present (BP) for the dated sediment samples from Griffith Swamp

Depth (cm)	Measured ^{14}C age (years BP)	2σ calibrated years (BP)	Intercept of ^{14}C age with calibration curve (years BP)	Laboratory number
120–130	1620±60	1660–1690	1530	β-194617
200–210	3080±60	3140–3400	3330	β-194618
320–330	4960±60	5800–5890	5660	β-194619

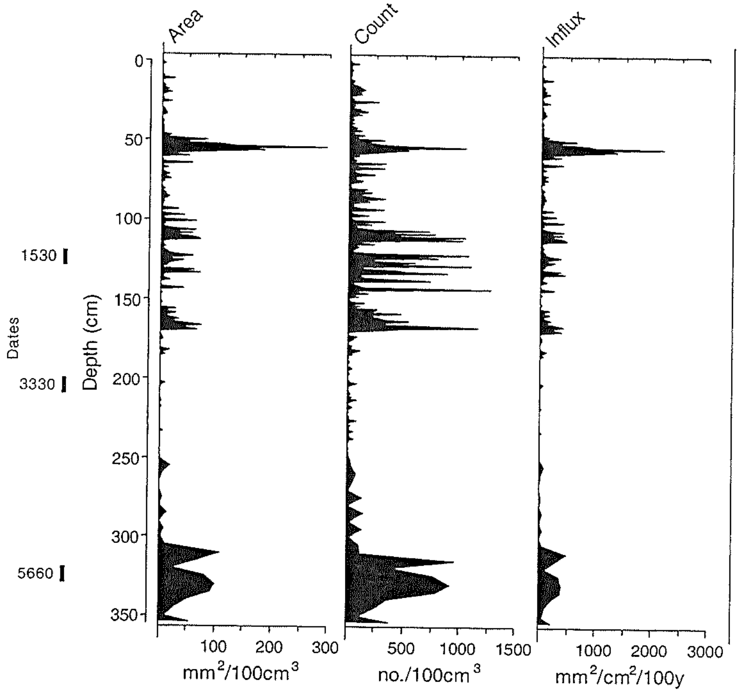

FIGURE 4. Griffith Swamp charcoal data, graphed against depth.

millennium BP (Attenbrow 2004). These changes in the 3rd millennium BP were of an unprecedented scale and nature in the 11 000 year record of Upper Mangrove Creek (Attenbrow 2003, p. 26).

In Figure 6 the Upper Mangrove Creek archaeological data are compared against the influx of charcoal at Griffith Swamp over the last 6500 years. The late Holocene increase in charcoal from ~2500 cal. years BP can seemingly be related to increased human intensity of land use. Similarly, the decreased artefact accumulation rates demonstrated at many individual sites in the last millennium, and in the catchment as a whole, apparently corresponds with reduced charcoal influx over the last 500 years, although from the CHAPS analysis the frequency of fires does not also decrease.

This is the second use of CHAPS on Australian charcoal data (cf. Mooney & Maltby 2006). It should be emphasised that CHAPS were developed for analysing North American charcoal records where fire frequencies are naturally much lower than those supported by many Australian environments. A review of four recent North American studies (Long *et al.* 1998; Hallett & Walker 2000; Millspaugh *et al.* 2000; Hallett *et al.* 2003) found that the inferred fire frequencies of the

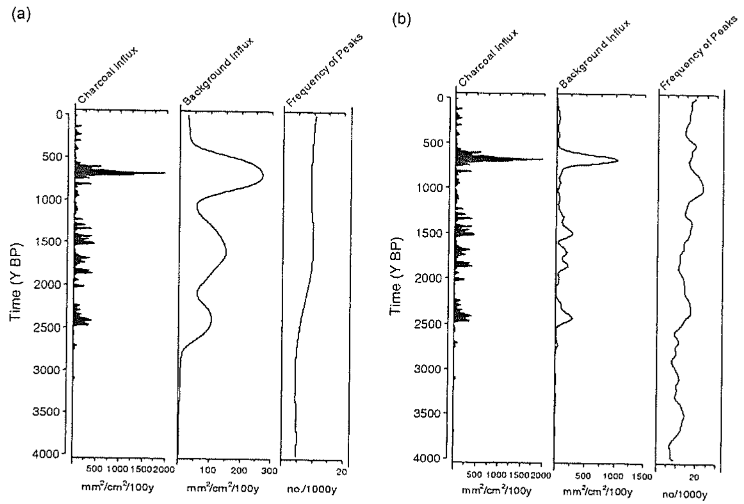

FIGURE 5. Results of the CHAPS analysis of the Griffith Swamp charcoal data. (a) Results of using long window widths (the locally weighted mean window width for calculating the background influx was 750 years and the locally weighted window width for calculating peak frequency was 2000 years). (b) Results of using short window widths (with a background influx window width of 140 years, and peak frequency window width of 375 years).

studied sites never exceeded 15 fires per 1000 years and rarely rose above 10. In these North American studies peaks in the charcoal influx also often matched recorded historical fires, suggesting that the sub-sampling frequency was high enough to record each fire as a distinctive charcoal peak. The fire frequency of the recent historic period at Griffith Swamp greatly exceeds any of these examples: To separate peaks into individual fires at this site would require sub-sampling at unrealistically fine depth increments. These caveats demand some caution; however, the *relative* changes in the frequency of fire episodes can be considered as an index of fire activity through time.

Increases in the influx of charcoal and presumably fire activity near the base of the analysed record at Griffith Swamp, representing ~6500 to ~5200 cal. years BP, does not correspond to any archaeological changes in the Upper Mangrove Creek catchment (see Figure 6). However, two excavated sites in the Macdonald River catchment, Mt Yengo shelter (McDonald 1992) and Macdonald River MR/1 near St Albans (Moore 1981), both have initial occupation dated to around 6000 years BP. This may indicate an increased use of the valley at this time; however, the absence of any systematic survey and excavation in the Macdonald River catchment does not allow any certain conclusions.

Palaeoenvironmental analyses from Indonesia and Papua New Guinea (Haberle & David 2004) and from Gooches Crater in the Blue Mountains (Black & Mooney 2006) have described increases in fire activity after approximately 5000 years BP. This has been linked to the initiation of modern periodicities and amplitudes of

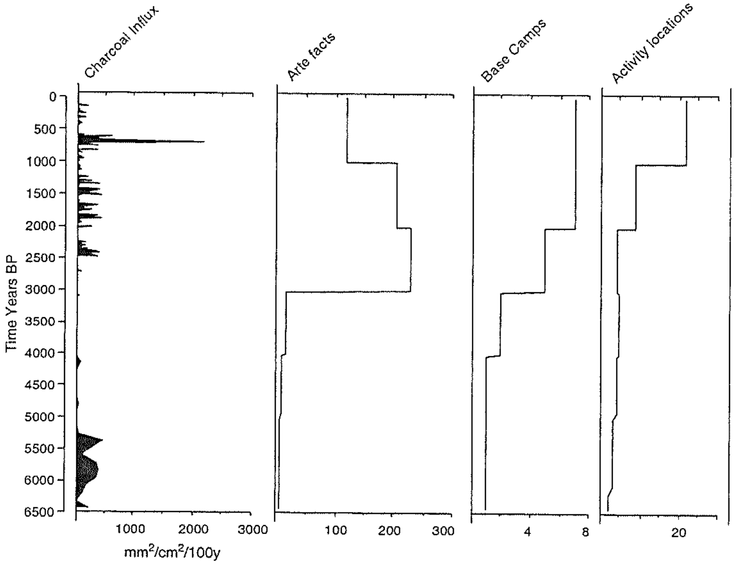

FIGURE 6. Charcoal influx from Griffith Swamp and archaeological data from Attenbrow (2003), summarising the Upper Mangrove Creek sites.

ENSO (El Niño–Southern Oscillation) phenomena (e.g. Gagan *et al.* 2004; Rodbell *et al.* 1999; Shulmeister 1999). This shift perhaps simultaneously allowed the accumulation of greater fuel loads (La Niña) and periodic drought (El Niño) or influenced some other climatic control of fire such as the increased frequency of lightning strikes. Haberle and Ledru (2001) suggest that this climatic reorganisation may also have stimulated agricultural intensification.

By 5000 cal. years BP fire activity decreased substantially at Griffith Swamp, although it should be noted that, despite this reduction, fire appears to have been a persistent feature in the landscape. This period of lower fire activity at Griffith Swamp spans ~5200 to 2500 years BP, and overlaps a suggested period of colder climates and drier summers in Australasia from 5000 to 3000 years BP (McGlone *et al.* 1992). CHAPS analysis revealed very low fire frequencies (between 5 and 10 fires per millennium) in the period between 4000 and 2500 years BP. This result is at odds with variation in the Gooches Crater Right charcoal at this time (Black & Mooney 2006); however, the Griffith Swamp record receives broad support from Jones and Dodson (1997).

Differences between palaeoecological sites within the Sydney Basin could be explained by site-specific influences or perhaps to the anthropogenic influences of different Aboriginal groups or practices. Notably, at Griffith Swamp, the charcoal data follow changes in the sedimentology of the core, with lower charcoal found in the peaty clay from about 300 to 160 cm. This section of the core corresponds well with the period of higher relative sea level from about 4300 to 2800 years BP (corrected for marine reservoir effects) surmised by Baker *et al.* (2001). Jones and Dodson (1997) describe how estuarine mud dominated the Wrights Creek valley prior to about 4000 years ago, with increasing freshwater deposits after this time. It is possible that the changing depositional environment and/or trap efficiency of the deposit, associated with changes in the relative sea level, have influenced charcoal concentration at the site; however, this seems unlikely in the quiet depositional environment as indicated by the clay content.

At Griffith Swamp a relatively abrupt increase in fire activity is found at ~2500 cal. years BP. One possible explanation for these changes is a relatively abrupt increase in the frequency and magnitude of ENSO described at ~3000 years BP (Clement *et al.* 2000; Sandweiss *et al.* 2001; Riedinger *et al.* 2002; Gagan *et al.* 2004). This implies that increased fire activity at Griffith Swamp may have been a result of increased climate variability.

This abrupt increase in fire activity at Griffith Swamp is also approximately coeval with a sudden increase in artefact number, which occurred between 2000 and 3000 years BP and continued until ~1000 years BP in Upper Mangrove Creek (Attenbrow 2003, 2004). Simultaneously Attenbrow (2003) describes the largest increase in base camps in the record and a slight reduction in the number of activity locations used. Attenbrow (2004) argues that relating these archaeological indices to population changes is not straightforward and instead she proposes that some other change took place in the culture, technology or socio-economics of the people.

Attenbrow (2004) links the changes in artefacts to changes in faunal assemblages and proposes that they were, in part, a response to variations in subsistence risks, linked to climate changes through changes in vegetation and thus macropods. Notably, while Jones and Dodson (1997) describe changes in the abundance of rainforest elements through the mid- to late Holocene in the nearby Wrights Creek valley, they found a general decrease in rainforest and expansion of sclerophyll communities from about 4000 years ago, pre-dating these archaeological changes. Greater chronological control in these studies is needed to explore these relationships fully.

The highest influx of charcoal at Griffith Swamp occurs at ~700 cal. years BP, which is approximately coeval with the Medieval Warm Period (MWP). While the geographic extent and cause of the MWP is controversial (e.g. Bradley *et al.* 2003; Broecker 2001) recent evidence increasingly supports a global warm period followed by a cooler phase, the Little Ice Age (LIA), over the last 1000 years (e.g. Moberg *et al.* 2005). These climatic oscillations appear to be reflected in fire activity of the Griffith Swamp catchment, with increased fire activity during the MWP and then reduced fire activity during the LIA. It is possible that climate change may have altered vegetation or resources, thereby requiring different strategies of fire use by Aboriginal people.

The period of high fire activity at Griffith Swamp at ~700 cal. years BP also corresponds to reduced artefact numbers and substantially increased numbers of activity locations for the last millennium in Upper Mangrove Creek (see Figure 6). The relationship between archaeology and fire in this period is the reverse of that of 2500 years BP, where high fire frequency is apparently linked with increased artefact numbers and slightly reduced activity locations. This lack of correlation may be due to the relatively low resolution of the archaeological data for the Upper

Mangrove Creek catchment as a whole, which cannot resolve relatively short-duration environmental changes like the MWP and LIA.

It should be noted that the archaeological changes evident in Upper Mangrove Creek are often represented in sites across the Sydney Basin. As an example, Hiscock and Attenbrow (2004, 2005) describe changes in artefact production rates at the Capertee 3 archaeological site (location indicated in Figure 1) during the Holocene that are similar to those from Upper Mangrove Creek. Similarly, at the Springwood Creek site a substantial increase in artefact density found from ~2500 years BP (Attenbrow 2004, p. 362) mirrors the charcoal record from Griffith Swamp. Similar archaeological changes are known from other Blue Mountains sites including Shaws Creek and Capertee 3. It therefore seems likely that these changes occurred at a regional scale. While this could perhaps be used to support a climatic influence, it could also be argued that ideas, cultural changes or technological developments spread rapidly between Aboriginal groups.

Conclusions

The fire regimes of Griffith Swamp changed dramatically throughout the mid- to late Holocene. This is at odds with generalised depictions of one pre-European fire regime (e.g. Pyne 1991). The findings from this palaeoenvironmental study suggest that changes in fire activity coincided with regional (or larger spatial scale) climate changes but that some of the changes were also approximately coeval with archaeological changes.

Tension between behavioural explanations (e.g. Lourandos 1983) and 'environmental determinism' (e.g. Rowland 1999; Hiscock 2002; Attenbrow 2004) has been a persistent feature of archaeological discourse: nonetheless, it is likely that environmental change provided a series of options from which people made choices. This potentially reflects a complex nexus between climate, people and fire in the landscape. Given the limitations of the palaeoecological and archaeological records it is unlikely that these components can be further disentangled without finer resolution analyses and well-structured experimental design allowing the two hypotheses (climate and people) to be tested independently.

Previous palaeoenvironmental studies (Kershaw *et al.* 2002; Genever *et al.* 2003; Black & Mooney 2006) have argued that changes in fire activity during the Holocene in humid Australian environments appear to be related to climatic controls. This study suggests that increased fire activity could be linked either to climate or human behavioural change and the most parsimonious explanation is that Aboriginal people burnt the landscape but did so in response to the prevailing climate.

The ethnographic record suggests Aboriginal people used fire at the very least on some areas of the landscape (Nicholson 1981; Kohen 1993). This study, however, provides no evidence to support the central tenets of the fire-stick farming hypothesis at this site beyond 2500–3000 years BP and even within this timeframe the reconstructed fire frequencies are lower than commonly hypothesised and fire activity appears to have varied through time. It should also be emphasised that at Griffith Swamp the fire frequency of the recent post-European period is higher than at any time in the past ~6500 years.

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A palynological reconstruction of pre-European riparian vegetation at Wollombi, New South Wales and its application to stream bank management and revegetation

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Summary A palynological investigation was conducted on sediments from three small floodplain swamps on upper Wollombi Brook in the Hunter Valley NSW in order to reconstruct pre-European riparian vegetation composition and community structure. Pre-European riparian plant communities on upper Wollombi Brook were characterized by wet sclerophyll forest associations with rainforest elements (most likely close to the channel). Major changes in both the nature and extent of riparian vegetation have been associated with European settlement. The pre-European pollen spectra assists the identification of a suite of native taxa potentially suitable for use in riparian revegetation operations, particularly in highly cleared streambank sites where protection of water quality and aquatic habitat is an important goal but where insufficient local remnants are available to indicate pre-existing plant species. The research emphasizes the use of palaeoenvironmental evidence as a tool for contemporary environmental management.

Key words *Hunter Valley, NSW, palynology, revegetation, riparian, streambank stabilization.*

Introduction

The arrival of Europeans into Australia saw vast areas cleared by the settlers to make way for pasture and crops and to provide timber for building and fuel (Adamson & Fox 1982; AUSTLIG 1990; Kirkpatrick 1994). This clearing, combined with poor land management practices and the introduction of domestic animals, caused major changes to the flow regimes, water quality and geomorphology of many rivers in agricultural areas (e.g. Warner 1991). In particular, the destruction of riparian plant communities to increase pasture area, facilitate crop production and to allow stock access to water has contributed to major problems; notably bank erosion, siltation and, in many cases, a subsequent reduction in stream productivity and general river and catchment health.

Gregory *et al.* (1991; p.540) defined the riparian zone as 'the interface between terrestrial and aquatic ecosystems'. Riparian zones represent a critical linkage between streams and the catchments they drain and the important ecological roles of plants in this terrestrial/aquatic interface (e.g. streambank stabilization; contribution to aquatic habitat) are well documented (Likens & Bormann 1974; Peterjohn & Correll 1984; Bunn 1986, 1993; Gregory *et al.* 1991; Jackson 1993). The protection of in-stream values, including the maintenance of water quality and a habitat for aquatic biota, undoubtedly hinges on the protection of riparian zones.

The rehabilitation of degraded riparian zones represents a major challenge. A starting point in any vegetative rehabilitation strategy should be the establishment of a baseline, which approximates the original vegetation community (Benson & Howell 1993). Benson and Howell (1993) extrapolated information from existing remnant plant communities to formulate a strategy for the rehabilitation of the riparian vegetation of the Hawkesbury-Nepean River, New South Wales. An alternative method is the use of various historical records and accounts that describe the vegetation of an area before European impact (Jeans 1978; Benson & Howell 1993; Davis & Finlayson 1999; Starr 1999).

Palaeoecological studies are another source of information applicable to the rehabilitation of human altered systems, by defining the predisruption conditions of the area or ecosystem. A considerable body of literature has expounded the benefits of applying information from palaeoecological studies to present day management issues (e.g. Wasson & Clark 1985; De Deckker *et al.* 1988; D'Costa *et al.* 1989; Clark 1990; Birks 1993; Davis 1994; Huntley 1996). Palynological studies, which are primarily aimed at the reconstruction of past plant communities (Faegri & Iverson 1975), offer considerable scope to revegetation programmes, but this potential has largely been unfulfilled. As an example we are aware of four Australian studies: D'Costa *et al.* (1989); Kelly (1984); Kenyon *et al.* (1996) and Kenyon and Rutherford (1999).

Aims and objectives

The present study aims to reconstruct the pre-European riparian and floodplain vegetation for three sites on upper Wollombi Brook using palynology. This reconstruction aims to contribute to revegetation strategies by making inferences about species composition and community structure of the pre-European vegetation. Furthermore, the study allows documentation of the changes in riparian and floodplain vegetation on upper Wollombi Brook from prehistorical to historical times, to fill in gaps from available historical information.

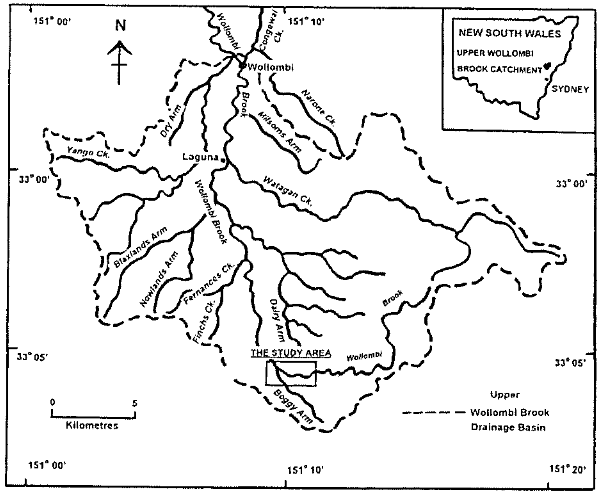

Figure 1. The Hunter River catchment, showing the location of the Upper Wollombi Brook.

The study region

Wollombi Brook is located in central eastern NSW in the southern region of the Hunter catchment, as shown in Fig. 1. Wollombi Brook is the main southern tributary of the Hunter River and its catchment area of approximately 2000 km^2 includes the relatively steep topography that forms the southern rim of the Hunter River catchment.

Upstream of Wollombi township the Brook is referred to as the upper Wollombi Brook and the particular section examined in this study, known as 'Murrays Run', extends upstream from the Fernances Creek Junction (Fig. 2). The Brook originates to the south in an area of relatively high relief on the border of the Hunter and Hawkesbury-Nepean catchments, and is a well-defined channel before 'Will-O-Wyn' (Fig. 2).

The Brook occupies a relatively narrow valley, which contains sediments derived mainly from the Triassic sandstones and occasional shales that characterize the geology of the region (Hanlon *et al.* 1953; Nashar 1964). The mean annual rainfall of upper Wollombi Brook is approximately 900 mm, with precipitation decreasing in an east to west gradient across the catchment (Erskine 1986).

The upper Wollombi Brook floodplain is now largely vegetated with introduced agricultural grasses such as Couch (*Cynodon dactylon*) and Kikuyu (*Pennisetum clandestinum*). Most trees now growing on the banks of Murrays Run are exotic species such as willows (*Salix* spp.) and poplars (*Populus* spp.) or species such as wattles (*Acacia* spp.) characteris-

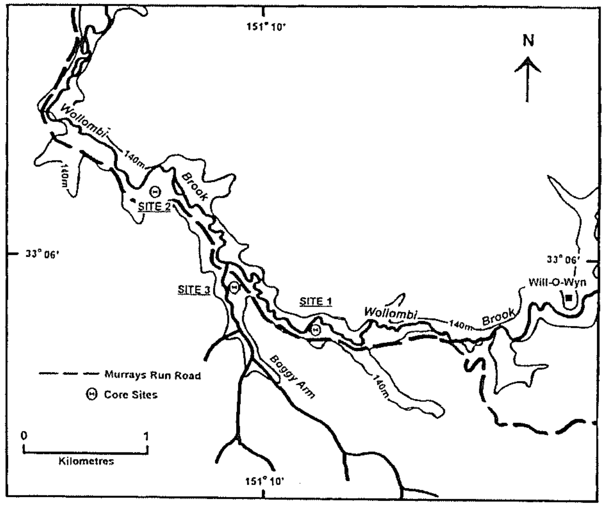

Figure 2. Study sites on the upper Wollombi Brook.

tic of disturbed sites (Story 1963). Continued grazing is preventing any significant natural regeneration. Little has been deciphered from historical records of the pre-European riparian vegetation communities of upper Wollombi Brook.

Vernon (1994) carried out a vegetation survey of remnant riparian vegetation in the Wollombi valley. Remnant vegetation occurs mainly as small, isolated patches on the occasional rocky banks of some parts of Wollombi Brook. The species composition of these sites is not likely to be representative of the deep alluvial soils of the stream bank and floodplain. Some significant remnant vegetation has been identified in the upper Wollombi system, especially in the upper reaches of tributaries, such as Watagan Creek and Dairy Arm. Some sections of Watagan Creek are vegetated with likely approximations of the original riparian associations: these are dominated by Water Gum (*Tristaniopsis laurina*) and Lilly Pilly (*Acmena smithii*), although they have been invaded by introduced species such as Blackberry (*Rubus* spp.).

The history of European settlement and land use in the Wollombi Valley

The completion of the Great North Road between Sydney and Maitland in 1830 stimulated the rapid settlement of the Wollombi Valley in the 1830s (Walker 1910). Initial land use concentrated on wheat production, with supplementary income derived from tobacco and vegetable crops (Parkes 1979). In the late 1860s, fungal diseases forced the virtual abandonment of wheat production in the area (Rees 1994) and the increasing domination of dairy farming. Although dairy farming is still employed on sections of the Brook, the importance of the valley as an agricultural centre has greatly diminished and 'hobby farms' now dominate. Grazing is, however, still commonplace.

Stream bank stabilization and native revegetation on Wollombi Brook

In early land surveys Wollombi Brook is depicted as a small, sinuous stream with occasional large pools (Mitchell 1829 as cited in Erskine 1986). The situation today along most of the lower Brook is markedly different, with extensive bank erosion and channel widening. Sections of the upper Brook have also been significantly degraded. Apart from the loss of the majority of the native riparian vegetation, a large incised channel exists upstream of Wollombi township (Erskine 1986). This incised reach extends from Fernances Creek upstream to Hungry Creek and a downstream depositional zone stretches from Fernances Creek to the Watagan Creek junction at Laguna (Erskine 1986). The section of the Brook examined in this study just upstream of Hungry Creek is still relatively geomorphically intact. Although the riparian vegetation has been removed, the channel in this location is generally not incised (Erskine 1986) and recent observation from the authors has confirmed that bank erosion and geomorphic disturbance is minimal.

Stream bank revegetation on Wollombi Brook and the larger Hunter Valley has until recently involved the planting of willows and poplars, both exotic genera. Responding to an increased interest in the use of native vegetation in stream bank revegetation the (now) Department of Land and Water Conservation established a trial planting site on Wollombi Brook, at Broke, approximately 20 km downstream from Wollombi township. Only three of the nine species trialled were indigenous to the area. Both Price (1997) and Webb (1997) have investigated the success of trial plantings in the Hunter Valley with Webb (1997) reporting that a trial at Broke was characterized by poor survival rates attributed to poor species selection and inadequate planting strategies. This failure highlights the need for greater consideration of restoration goals and species selection.

Methods

In any palaeoecological study, site selection is critical to provide the best data to answer the aim of the research (Jacobson & Bradshaw 1981). The aim of the present study required sites accumulating sediment close to the river channel. Kenyon and Rutherford (1999) have emphasized that pollen records from floodplains are unlike those from lacustrine settings in that they directly reflect floodplain vegetation rather than regional vegetation.

Investigation of maps and aerial photographs and a subsequent field inspection identified a number of floodplain swamps along the section of upper Wollombi Brook. The three sites chosen are shown in Fig. 2. All were relatively small floodplain swamps located within 25 m of the current channel with fringing vegetation consisting of Bull-rush (*Typha orientalis*), Smartweeds (*Persicaria* spp.) and Juncaceae and Cyperaceae species.

A Russian D-section corer (Jowsey 1966) was used to sample the sediment from the centre of the three floodplain swamps studied. An overlapping sequence of cores, including replicates, were taken from each of the sites, with the final depth reached dependent on the difficulty of penetration into the stiff, heavy clays. In the laboratory, the sediment cores were photographed and fully described using basic field observations and the Troels-Smith (1955) method of description of unconsolidated sediment.

The cores were subsampled at 5 cm intervals. Standard pollen preparation techniques, as described by Faegri and Iverson (1975) and Moore and Webb (1978) were used.

Pollen counts were undertaken at a magnification of ×400. A minimum of 200 grains were counted per slide (with an average of 220 grains), using a method of random transects across the slide. Target taxa were established during the early stages of counting in order to highlight changes in the major components of the vegetation through time. The pollen types targeted and counted are listed in Appendix I along with other related information such as the likely species represented by these taxa at the sites, their life form and their typical habitat and ecology. The pollen counts were expressed as percentages of total pollen and spores in separate percentage pollen diagrams for each of the three sites.

The first appearance of pollen from introduced taxa in the pollen record has been used to approximate the boundary between historical and prehistorical sediments.

A number of palynological slides were examined in detail from depths representative of the undisturbed vegetation in an attempt to better characterize the numerous Myrtaceae pollen grains to a genus or species level. Reference slides from the pollen herbarium at the University of New South Wales and published accounts of Myrtaceae pollen morphology (Pike 1955; Gadek & Martin 1981; Chalson 1991; Chalson & Martin 1995) were used to confirm identifications. An examination of current riparian plant communities on the upper Wollombi Brook and its tributaries (including possible remnants) and research into the species of Myrtaceae that could have been present at the sites before European settlement (based on physiographic and environmental characteristics) allowed elimination of possibilities and thus assisted in identification.

Nomenclature in the present paper follows Harden (1990–1993).

Results

Descriptions of the sediment from sites Wollombi 1, Wollombi 2 and Wollombi 3 are presented in Fig. 3. The upper 30 cm of the deposit at Wollombi 3 was unrecoverable, due to a dense herbaceous root mat.

The results of the pollen analysis are expressed in separate percentage pollen diagrams for each of the three sites (Fig. 4a–c). The presence of *Pinus* pollen is traditionally used to separate historical and prehistorical sediments in Australian palynology (Kodela & Mackillop 1988; Dodson *et al.* 1994a, 1994b, 1994c, 1995; Mooney *et al.* 1997). *Pinus*, however, was extremely rare in the pollen record at all three sites. Thus, the boundary between the historical and prehistorical zones was approximated using the first appearance of pollen from other introduced taxa (e.g. Lamb's Tongue, *Plantago lanceolata*). This also indicates differing rates of sedimentation between the three swamps.

The pre-European record at all three of the Wollombi sites is characterized by an extremely high representation of Myrtaceae pollen. Myrtaceae undergoes a sharp and substantial decline at the boundary between the prehistorical and historical sediments and, at the same time, a dramatic increase in Poaceae is evident. Poaceae constituted only 2–5% of the total pollen sum in the prehistorical period, yet its representation rises to over 20% in the historical period.

The focused analysis of the pre-European pollen identified that, on average, approximately 80–85% of the total Myrtaceae count was *Eucalyptus*-type pollen. The remainder of the Myrtaceae pollen consisted of *Angophora* type, *Melaleuca* type, *Tristaniopsis* type, *Acmena* type and *Syncarpia* type. A small number of *Leptospermum*-type pollen grains were also observed.

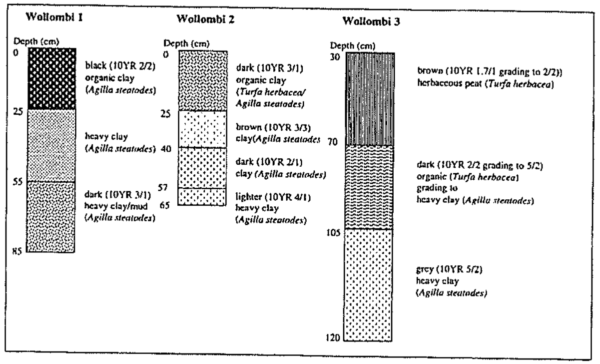

Figure 3. Sediment description of the analysed cores from the upper Wollombi Brook.

All of the sites also display a pronounced decrease in the representation of *Casuarina* from the prehistorical to the historical period; however, *Casuarina* then remains relatively stable in the historical period. *Acacia* pollen is more abundant in the historical zone at all three sites. At both Wollombi 2 and 3 the increase in the representation of *Acacia* seems to slightly predate the approximated boundary of this period.

At Wollombi 1 (Fig. 4a) the representation of Lauraceae is relatively consistent in the prehistorical zone but generally decreases in the historical pollen record at all three sites. The record of Lauraceae at Wollombi 3 is similar to that of Wollombi 1; however, it is also represented in the historical record (poorly).

At Wollombi 1 and 3 the prehistorical period is characterized by a relatively higher representation of fern spores (both monolete and trilete). *Pteridium*, however, appears to follow an opposite trend, with a slightly higher representation in the historical period. Although Wollombi 2 has the highest representation of fern spores in the earliest analysed prehistorical period, in contrast to the other sites, a general increase in fern spores is observed in the historical period. As with the other sites, however, *Pteridium* is poorly represented in the prehistorical period.

At all the investigated sites Chenopodiaceae exhibits a similar pattern of occurrence, with an irregular representation most evident in the historical period. Similarly, a substantial increase in Cyperaceae is evident at all three sites in the historical period.

Changes in the herbaceous taxa at Wollombi 1 are not as marked as those exhibited by the tree/shrub and grass taxa. Above a depth of 20 cm the pollen of introduced taxa all display an increase into the historical period. With the exception of Poaceae, at Wollombi 2 the pollen of herbaceous taxa is dominated by Asteraceae (Tub.), which increases substantially in the historical period. In the historical period at Wollombi 2 (Fig. 4b) pollen from the introduced taxa display an initial

A palynological reconstruction of pre-European riparian vegetation at Wollombi, New South Wales and its application to stream bank management and revegetation

By P. Bennett and S. D. Mooney

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Summary A palynological investigation was conducted on sediments from three small floodplain swamps on upper Wollombi Brook in the Hunter Valley NSW in order to reconstruct pre-European riparian vegetation composition and community structure. Pre-European riparian plant communities on upper Wollombi Brook were characterized by wet sclerophyll forest associations with rainforest elements (most likely close to the channel). Major changes in both the nature and extent of riparian vegetation have been associated with European settlement. The pre-European pollen spectra assists the identification of a suite of native taxa potentially suitable for use in riparian revegetation operations, particularly in highly cleared streambank sites where protection of water quality and aquatic habitat is an important goal but where insufficient local remnants are available to indicate pre-existing plant species. The research emphasizes the use of palaeoenvironmental evidence as a tool for contemporary environmental management.

Key words *Hunter Valley, NSW, palynology, revegetation, riparian, streambank stabilization.*

Introduction

The arrival of Europeans into Australia saw vast areas cleared by the settlers to make way for pasture and crops and to provide timber for building and fuel (Adamson & Fox 1982; AUSTLIG 1990; Kirkpatrick 1994). This clearing, combined with poor land management practices and the introduction of domestic animals, caused major changes to the flow regimes, water quality and geomorphology of many rivers in agricultural areas (e.g. Warner 1991). In particular, the destruction of riparian plant communities to increase pasture area, facilitate crop production and to allow stock access to water has contributed to major problems; notably bank erosion, siltation and, in many cases, a subsequent reduction in stream productivity and general river and catchment health.

Gregory *et al.* (1991; p.540) defined the riparian zone as 'the interface between terrestrial and aquatic ecosystems'. Riparian zones represent a critical linkage between streams and the catchments they drain and the important ecological roles of plants in this terrestrial/aquatic interface (e.g. streambank stabilization; contribution to aquatic habitat) are well documented (Likens & Bormann 1974; Peterjohn & Correll 1984; Bunn 1986, 1993; Gregory *et al.* 1991; Jackson 1993). The protection of in-stream values, including the maintenance of water quality and a habitat for aquatic biota, undoubtedly hinges on the protection of riparian zones.

The rehabilitation of degraded riparian zones represents a major challenge. A starting point in any vegetative rehabilitation strategy should be the establishment of a baseline, which approximates the original vegetation community (Benson & Howell 1993). Benson and Howell (1993) extrapolated information from existing remnant plant communities to formulate a strategy for the rehabilitation of the riparian vegetation of the Hawkesbury-Nepean River, New South Wales. An alternative method is the use of various historical records and accounts that describe the vegetation of an area before European impact (Jeans 1978; Benson & Howell 1993; Davis & Finlayson 1999; Starr 1999).

Palaeoecological studies are another source of information applicable to the rehabilitation of human altered systems, by defining the predisruption conditions of the area or ecosystem. A considerable body of literature has expounded the benefits of applying information from palaeoecological studies to present day management issues (e.g. Wasson & Clark 1985; De Deckker *et al.* 1988; D'Costa *et al.* 1989; Clark 1990; Birks 1993; Davis 1994; Huntley 1996). Palynological studies, which are primarily aimed at the reconstruction of past plant communities (Faegri & Iverson 1975), offer considerable scope to revegetation programmes, but this potential has largely been unfulfilled. As an example we are aware of four Australian studies: D'Costa *et al.* (1989); Kelly (1984); Kenyon *et al.* (1996) and Kenyon and Rutherford (1999).

Aims and objectives

The present study aims to reconstruct the pre-European riparian and floodplain vegetation for three sites on upper Wollombi Brook using palynology. This reconstruction aims to contribute to revegetation strategies by making inferences about species composition and community structure of the pre-European vegetation. Furthermore, the study allows documentation of the changes in riparian and floodplain vegetation on upper Wollombi Brook from prehistorical to historical times, to fill in gaps from available historical information.

The study region

Wollombi Brook is located in central eastern NSW in the southern region of the Hunter catchment, as shown in Fig. 1. Wollombi Brook is the main southern tributary of the Hunter River and its catchment area of approximately 2000 km^2 includes the relatively steep topography that forms the southern rim of the Hunter River catchment.

Upstream of Wollombi township the Brook is referred to as the upper Wollombi Brook and the particular section examined in this study, known as 'Murrays Run', extends upstream from the Fernances Creek Junction (Fig. 2). The Brook originates to the south in an area of relatively high relief on the border of the Hunter and Hawkesbury-Nepean catchments, and is a well-defined channel before 'Will-O-Wyn' (Fig. 2).

The Brook occupies a relatively narrow valley, which contains sediments derived mainly from the Triassic sandstones and occasional shales that characterize the geology of the region (Hanlon *et al.* 1953; Nashar 1964). The mean annual rainfall of upper Wollombi Brook is approximately 900 mm, with precipitation decreasing in an east to west gradient across the catchment (Erskine 1986).

The upper Wollombi Brook floodplain is now largely vegetated with introduced agricultural grasses such as Couch (*Cynodon dactylon*) and Kikuyu (*Pennisetum clandestinum*). Most trees now growing on the banks of Murrays Run are exotic species such as willows (*Salix* spp.) and poplars (*Populus* spp.) or species such as wattles (*Acacia* spp.) characteris-

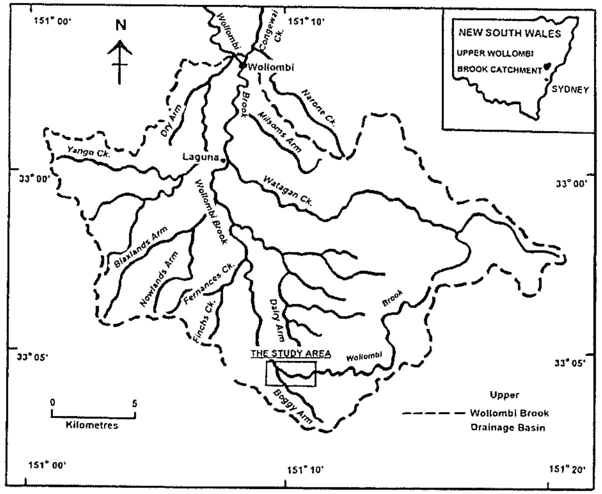


Figure 1. The Hunter River catchment, showing the location of the Upper Wollombi Brook.

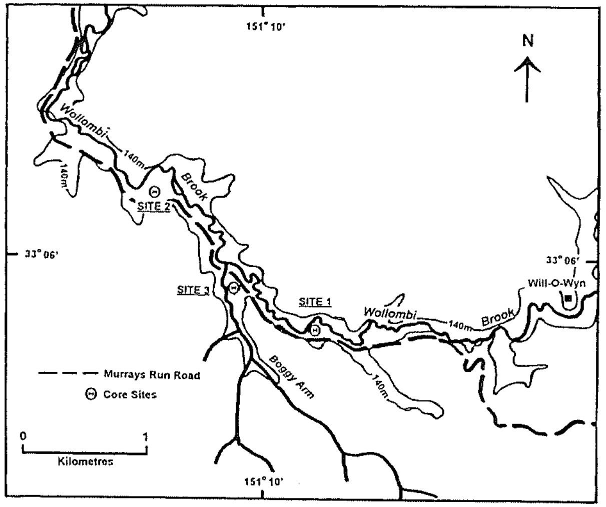


Figure 2. Study sites on the upper Wollombi Brook.

tic of disturbed sites (Story 1963). Continued grazing is preventing any significant natural regeneration. Little has been deciphered from historical records of the pre-European riparian vegetation communities of upper Wollombi Brook.

Vernon (1994) carried out a vegetation survey of remnant riparian vegetation in the Wollombi valley. Remnant vegetation occurs mainly as small, isolated patches on the occasional rocky banks of some parts of Wollombi Brook. The species composition of these sites is not likely to be representative of the deep alluvial soils of the stream bank and floodplain. Some significant remnant vegetation has been identified in the upper Wollombi system, especially in the upper reaches of tributaries, such as Watagan Creek and Dairy Arm. Some sections of Watagan Creek are vegetated with likely approximations of the original riparian associations: these are dominated by Water Gum (*Tristaniopsis laurina*) and Lilly Pilly (*Acmena smithii*), although they have been invaded by introduced species such as Blackberry (*Rubus* spp.).

The history of European settlement and land use in the Wollombi Valley

The completion of the Great North Road between Sydney and Maitland in 1830 stimulated the rapid settlement of the Wollombi Valley in the 1830s (Walker 1910). Initial land use concentrated on wheat production, with supplementary income derived from tobacco and vegetable crops (Parkes 1979). In the late 1860s, fungal diseases forced the virtual abandonment of wheat production in the area (Rees 1994) and the increasing domination of dairy farming. Although dairy farming is still employed on sections of the Brook, the importance of the valley as an agricultural centre has greatly diminished and 'hobby farms' now dominate. Grazing is, however, still commonplace.

Stream bank stabilization and native revegetation on Wollombi Brook

In early land surveys Wollombi Brook is depicted as a small, sinuous stream with occasional large pools (Mitchell 1829 as cited in Erskine 1986). The situation today along most of the lower Brook is markedly different, with extensive bank erosion and channel widening. Sections of the upper Brook have also been significantly degraded. Apart from the loss of the majority of the native riparian vegetation, a large incised channel exists upstream of Wollombi township (Erskine 1986). This incised reach extends from Fernances Creek upstream to Hungry Creek and a downstream depositional zone stretches from Fernances Creek to the Watagan Creek junction at Laguna (Erskine 1986). The section of the Brook examined in this study just upstream of Hungry Creek is still relatively geomorphically intact. Although the riparian vegetation has been removed, the channel in this location is generally not incised (Erskine 1986) and recent observation from the authors has confirmed that bank erosion and geomorphic disturbance is minimal.

Stream bank revegetation on Wollombi Brook and the larger Hunter Valley has until recently involved the planting of willows and poplars, both exotic genera. Responding to an increased interest in the use of native vegetation in stream bank revegetation the (now) Department of Land and Water Conservation established a trial planting site on Wollombi Brook, at Broke, approximately 20 km downstream from Wollombi township. Only three of the nine species trialled were indigenous to the area. Both Price (1997) and Webb (1997) have investigated the success of trial plantings in the Hunter Valley with Webb (1997) reporting that a trial at Broke was characterized by poor survival rates attributed to poor species selection and inadequate planting strategies. This failure highlights the need for greater consideration of restoration goals and species selection.

Methods

In any palaeoecological study, site selection is critical to provide the best data to answer the aim of the research (Jacobson & Bradshaw 1981). The aim of the present study required sites accumulating sediment close to the river channel. Kenyon and Rutherford (1999) have emphasized that pollen records from floodplains are unlike those from lacustrine settings in that they directly reflect floodplain vegetation rather than regional vegetation.

Investigation of maps and aerial photographs and a subsequent field inspection identified a number of floodplain swamps along the section of upper Wollombi Brook. The three sites chosen are shown in Fig. 2. All were relatively small floodplain swamps located within 25 m of the current channel with fringing vegetation consisting of Bull-rush (*Typha orientalis*), Smartweeds (*Persicaria* spp.) and Juncaceae and Cyperaceae species.

A Russian D-section corer (Jowsey 1966) was used to sample the sediment from the centre of the three floodplain swamps studied. An overlapping sequence of cores, including replicates, were taken from each of the sites, with the final depth reached dependent on the difficulty of penetration into the stiff, heavy clays. In the laboratory, the sediment cores were photographed and fully described using basic field observations and the Troels-Smith (1955) method of description of unconsolidated sediment.

The cores were subsampled at 5 cm intervals. Standard pollen preparation techniques, as described by Faegri and Iverson (1975) and Moore and Webb (1978) were used.

Pollen counts were undertaken at a magnification of ×400. A minimum of 200 grains were counted per slide (with an average of 220 grains), using a method of random transects across the slide. Target taxa were established during the early stages of counting in order to highlight changes in the major components of the vegetation through time. The pollen types targeted and counted are listed in Appendix I along with other related information such as the likely species represented by these taxa at the sites, their life form and their typical habitat and ecology. The pollen counts were expressed as percentages of total pollen and spores in separate percentage pollen diagrams for each of the three sites.

The first appearance of pollen from introduced taxa in the pollen record has been used to approximate the boundary

between historical and prehistorical sediments.

A number of palynological slides were examined in detail from depths representative of the undisturbed vegetation in an attempt to better characterize the numerous Myrtaceae pollen grains to a genus or species level. Reference slides from the pollen herbarium at the University of New South Wales and published accounts of Myrtaceae pollen morphology (Pike 1955; Gadek & Martin 1981; Chalson 1991; Chalson & Martin 1995) were used to confirm identifications. An examination of current riparian plant communities on the upper Wollombi Brook and its tributaries (including possible remnants) and research into the species of Myrtaceae that could have been present at the sites before European settlement (based on physiographic and environmental characteristics) allowed elimination of possibilities and thus assisted in identification.

Nomenclature in the present paper follows Harden (1990–1993).

Results

Descriptions of the sediment from sites Wollombi 1, Wollombi 2 and Wollombi 3 are presented in Fig. 3. The upper 30 cm of the deposit at Wollombi 3 was unrecoverable, due to a dense herbaceous root mat.

The results of the pollen analysis are expressed in separate percentage pollen diagrams for each of the three sites (Fig. 4a–c). The presence of *Pinus* pollen is traditionally used to separate historical and prehistorical sediments in Australian palynology (Kodela & Mackillop 1988; Dodson *et al.* 1994a, 1994b, 1994c, 1995; Mooney *et al.* 1997). *Pinus*, however, was extremely rare in the pollen record at all three sites. Thus, the boundary between the historical and prehistorical zones was approximated using the first appearance of pollen from other introduced taxa (e.g. Lamb's Tongue, *Plantago lanceolata*). This also indicates differing rates of sedimentation between the three swamps.

The pre-European record at all three of the Wollombi sites is characterized by an extremely high representation of Myrtaceae pollen. Myrtaceae undergoes a sharp and substantial decline at the boundary between the prehistorical and historical sediments and, at the same time, a dramatic increase in Poaceae is evident. Poaceae constituted only 2–5% of the total pollen sum in the prehistorical period, yet its representation rises to over 20% in the historical period.

The focused analysis of the pre-European pollen identified that, on average, approximately 80–85% of the total Myrtaceae count was *Eucalyptus*-type pollen. The remainder of the Myrtaceae pollen consisted of *Angophora* type, *Melaleuca* type, *Tristaniopsis* type, *Acmena* type and *Syncarpia* type. A small number of *Leptospermum*-type pollen grains were also observed.

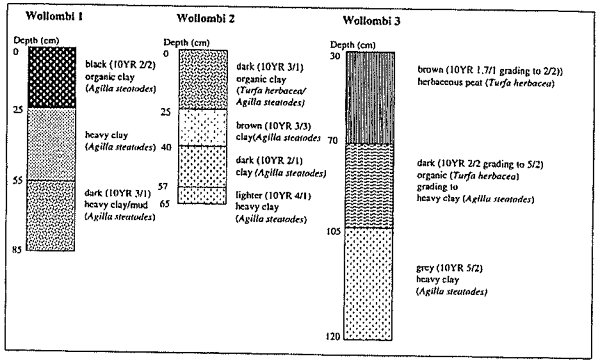


Figure 3. Sediment description of the analysed cores from the upper Wollombi Brook.

All of the sites also display a pronounced decrease in the representation of *Casuarina* from the prehistorical to the historical period; however, *Casuarina* then remains relatively stable in the historical period. *Acacia* pollen is more abundant in the historical zone at all three sites. At both Wollombi 2 and 3 the increase in the representation of *Acacia* seems to slightly predate the approximated boundary of this period.

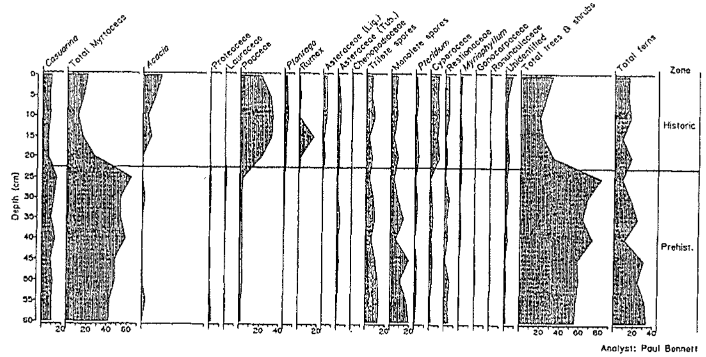
At Wollombi 1 (Fig. 4a) the representation of Lauraceae is relatively consistent in the prehistorical zone but generally decreases in the historical pollen record at all three sites. The record of Lauraceae at Wollombi 3 is similar to that of Wollombi 1; however, it is also represented in the historical record (poorly).

At Wollombi 1 and 3 the prehistorical period is characterized by a relatively higher representation of fern spores (both monolete and trilete). *Pteridium*, however, appears to follow an opposite trend, with a slightly higher representation in the historical period. Although Wollombi 2 has the highest representation of fern spores in the earliest analysed prehistorical period, in contrast to the other sites, a general increase in fern spores is observed in the historical period. As with the other sites, however, *Pteridium* is poorly represented in the prehistorical period.

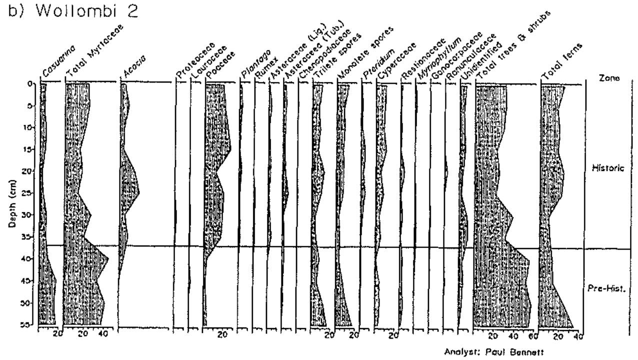
At all the investigated sites Chenopodiaceae exhibits a similar pattern of occurrence, with an irregular representation most evident in the historical period. Similarly, a substantial increase in Cyperaceae is evident at all three sites in the historical period.

Changes in the herbaceous taxa at Wollombi 1 are not as marked as those exhibited by the tree/shrub and grass taxa. Above a depth of 20 cm the pollen of introduced taxa all display an increase into the historical period. With the exception of Poaceae, at Wollombi 2 the pollen of herbaceous taxa is dominated by Asteraceae (Tub.), which increases substantially in the historical period. In the historical period at Wollombi 2 (Fig. 4b) pollen from the introduced taxa display an initial

a) Wollombi 1



b) Wollombi 2



c) Wollombi 3

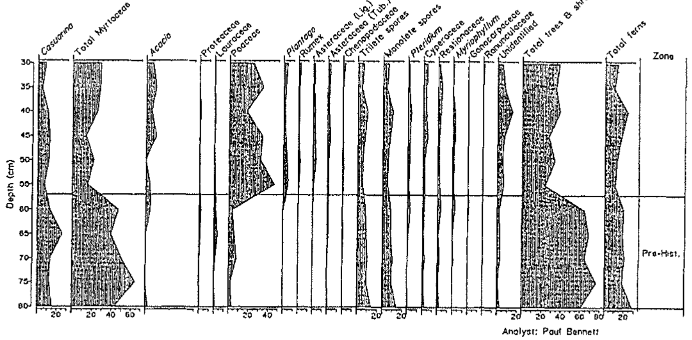


Figure 4. (a–c) Results of the palynology from the three sites.

increase in the historical period after which *Rumex* and Asteraceae (Lig.) stabilize; in contrast, *Plantago* generally continues to increase.

Herbaceous taxa are poorly represented throughout the Wollombi 3 record. Asteraceae (Tub.) and Chenopodiaceae are generally higher in the historical period. *Ranunculus* was absent up until the top 5 cm of the record and *Gonocarpus* was only recorded in the historical period. Counts for these pollen types were very low, due to the dominance of Myrtaceae and *Casuarina* in the prehistorical period and Poaceae in the historical period. *Myriophyllum* also generally increases in the historical period.

In summary, the results of the pollen analysis show major changes in the types and relative proportions of pollen taxa between the prehistorical and historical periods. A number of important similarities are exhibited by the three pollen diagrams including a major decline in Myrtaceae and *Casuarina* in the historical period and a decline in total fern spores. In contrast to the prehistorical zone Lauraceae is largely absent in the historical period at the three sites. A number of taxa generally increase in the historical period, the most obvious being Poaceae and the recognized introduced taxa. *Acacia*, Asteraceae (Tub.), Cyperaceae, *Pteridium*, Chenopodiaceae, unidentified pollen grains and, to a lesser degree, *Myriophyllum* also follow this trend.

Discussion

An important consideration in the interpretation of palynological records is the source area of the pollen (Jacobson & Bradshaw 1981; Sugita 1993). It is evident that the pollen of the majority of Australia's taxa has relatively poor dispersal capabilities (Dodson 1977, 1983, 1988; Dodson & Myers 1986). It has also been found that pollen deposited within forest stands is generally highly local (Tauber 1967; Dodson 1983; Kodela 1990a). The size of the sedimentary deposit from which a record is derived can also determine the source area of the pollen, with smaller basins containing largely local pollen types (Dodson 1977, 1988; Jacobson & Bradshaw 1981; Prentice 1985; Sugita 1993).

The study sites used in the present study were small swampy depressions, implying that the majority of pollen falling onto the swamps would be derived from local sources (i.e. riparian and floodplain vegetation), particularly as the results indicate that forest stands were present. In historical times, the upper catchment and up-slope vegetation of Wollombi Brook has suffered far less disturbance compared to the valley floor: the marked historical changes in the pollen diagrams, therefore, suggest that the majority of pollen is derived from the vegetation of the valley floor. Nonetheless, there is undoubtedly representation of some non-riparian species in the pollen spectra.

The palynological investigation of Wollombi 1 suggests that the pre-European riparian/floodplain vegetation surrounding this site was characterized by a wet sclerophyll forest association with a significant rainforest element characterized by Water Gum, Lilly Pilly, Lauraceae species and ferns. Water Gum and Lilly Pilly are commonly found growing in association on stream banks (Melick 1990a, 1990b).

The floodplain vegetation is likely to have been dominated by *Eucalyptus* spp., Paperbarks (*Melaleuca* spp.) and Rough-barked Apple (*Angophora floribunda*) further away from the channel. Rough-barked Apple, Prickly leaved Tea Tree (*Melaleuca styphelioides*) and *Melaleuca linariifolia* still occur on scattered sections of upper Wollombi Brook, with the latter occupying poorly drained sites. The pollen record also indicates that *Casuarina* was represented in the community, with River Oak (*C. cunninghamiana*) probably occupying the banks and the immediate floodplain.

The palynological results also provide evidence that the natural vegetation of the upper Wollombi Valley has been greatly modified since European settlement. Little of the original vegetation remains, particularly on the floodplain, as a result of early clearing for agriculture. Associated with the clearing of the floodplain vegetation, the European period has witnessed the almost complete removal of River Oak from the banks of the upper Wollombi Brook. Large quantities of River Oak needles have been observed in sediments from a 1949 cut-off on Murrays Run (Wayne D. Erskine, pers. comm., 1994), further suggesting the importance of this particular species in past riparian plant communities on upper Wollombi Brook.

Turpentine (*Syncarpia glomulifera*), was also likely to have been present in the overstorey, although its representation in the pollen record was poor. This species is commonly found in places transitional between *Eucalyptus* forest and rainforest (Robinson 1991). It probably grew further away from the banks as it is generally associated with valley sides in the Wollombi area (Good 1953).

The pollen record shows the past presence of both *Tristaniopsis laurina* and, to a lesser extent, Lilly Pilly. Water Gum is still present on upper Wollombi Brook, in the reaches above 'Will-O-Wyn' and just below the Watagan Creek junction. Lilly Pilly was not recorded on Wollombi Brook by Vernon (1994); however, it is present on nearby Watagan Creek. These two species are characteristically riparian (usually in closed forest associations) and they are often co-dominant on riverbanks (Melick 1990a, 1990b). Their low representation in the pollen record does not necessarily reflect a low representation in the pre-European riparian plant community, as Kodela (1990a, 1990b) has found that *Acmena* is generally poorly represented in modern pollen spectra. Water Gum is also likely to be a low pollen producer, due to a predilection for vegetative reproduction as exemplified by their growth form, characterized by multiple coppicing stems.

Species from the family Lauraceae, probably Jackwood (*Cryptocarya glaucescens*) and possibly *Endiandra* spp., were also likely to have been present in the riparian vegetation community at Wollombi 1. Vernon (1994) identified Jackwood growing on nearby Congewai Creek. Typically a rainforest family, the counts of Lauraceae pollen grains were very low, but again, this probably does not indicate that they were uncommon in the community. Numerous modern pollen rain studies (Kershaw & Hyland 1975; Ladd 1978, 1979a, 1979b; Dodson 1983; Kodela 1990a, 1990b; Dodson & Thom 1992) have emphasized that pollen production from rainforest species is very low compared to sclerophyll vegetation. Furthermore, pollen production and effective dispersal from *Eucalyptus* spp. can result in the overrepresentation of this genus in pollen records from communities with a rainforest element (Kodela 1990a, 1990b). Together, this means that even a slight presence of rainforest pollen in the record can indicate a significant rainforest component.

High representation of monolete and trilete fern spores at Wollombi 1 in the pre-European period suggests a significant fern component in the understorey. This suggests moist conditions and is usually indicative of wet sclerophyll forest (Dodson 1983; Dodson & Thom 1992), as the closed canopy creates a more humid microclimate conducive to mesic vegetation. The consistent levels of monolete and trilete spores recorded into the historical period may be due to the fact that a dominant overstorey is not present allowing the ferns surrounding the swamps to be overrepresented in the pollen record.

Poaceae and herbaceous taxa such as Asteraceae (Tub.) are likely to have been present as ground cover in the pre-European period; however, their significance in the pollen record was low. This low significance may have also been the result of high *Eucalyptus*, *Casuarina* and fern representation suppressing the herbaceous component in the percentage pollen diagrams.

The palynological results from Wollombi 2 and 3 (Fig. 4b,c) are similar and, hence, the sites will be discussed together. The prehistorical riparian vegetation at Wollombi 2 and 3 appears to resemble the reconstruction for Wollombi 1; however, the abundance of the various taxa appears to be slightly different. *Casuarina* pollen, likely to represent River Oak growing close to the Brook, had a greater representation at these sites compared to Wollombi 1. Pre-European representation of Poaceae and herbaceous taxa such as Asteraceae (Tub.) appears to have been higher at these sites suggesting perhaps a slightly more open canopy compared to the Wollombi 1 site.

Poor representation of Water Gum and Lilly Pilly at Wollombi 2 and 3 suggests that these species were not as significant in this vicinity, compared to Wollombi 1. At both sites, however, and particularly at Wollombi 3, the inclusion of Lauraceae pollen, likely to be significant given that they are generally underrepresented in pollen records, suggests that rainforest species were present at these sites.

Native revegetation on Wollombi Brook and other management issues

The palynological investigation of upper Wollombi Brook not only allows the reconstruction of the pre-European vegetation communities and documents the changes associated with European transhumance, but can be used for identifying a suite of native taxa with potential for local stream bank revegetation operations. Table 1 is a summary of the taxa recommended for trialling based on both the pollen records described and some subsequent field investigation of scattered remnant patches of native vegetation present on the Brook. Trial planting operations using local propagules (Benson & Howell 1993; Daniell 1993) and an effective monitoring programme should be used to test the viability of these particular species for stream bank revegetation.

The present study also emphasizes the variable nature of plant communities over relatively short distances. The pre-European vegetation at Wollombi 1 appeared to be slightly different from the other two sites located only 2–3 km further downstream. Changes in environmental variables, such as rainfall, soil substrate and valley width, vary significantly with distance along the Brook (Erskine 1986) and these are major controls on vegetation type. Thus, the results of this study are most applicable to the upper Wollombi Brook. Furthermore, many of the species recommended from the pollen record are rainforest species. However, there is considerable scope for applying palynological investigations elsewhere if conditions have allowed the preservation of pollen in sediments.

Table 1. Summary of the species suggested for inclusion in trial plantings on upper Wollombi Brook, grouped in terms of the landscape position

Landscape position	Species suggested
On the bank toe and slope	*Acmena smithii*
	Casuarina cunninghamiana
	Leptospermum polygalifolium
	Melaleuca linariifolia
	M. styphelioides
	Tristaniopsis laurina
On the top of banks and immediate floodplain	*Acacia decurrens*
	A. floribunda
	A. parramattensis
	Angophora floribunda
	Casuarina cunninghamiana
	Eucalyptus agglomerata
	E. deanei
	E. maculata
	E. saligna
	E. tereticornis
	E. viminalis
	Melaleuca linariifolia
	M. styphelioides
	Syncarpia glomulifera
At the terrestrial/aquatic interface	*Carex appressa*
	Eleocharis sphacelata
	Juncus prismatocarpus
	Juncus usitatus
	Lepidosperma limicola
	Lomandra longifolia
	Paspalum distichum
	Phragmites australis
	Schoenoplectus validus
	Typha orientalis

Conclusion

The present study demonstrates the potential application of palaeoenvironmental information to present day environmental rehabilitation projects. The analysis of pollen and spores preserved in sediments from three floodplain swamps on upper Wollombi Brook has provided an insight into the pre-European riparian vegetation communities, apparently characterized by moist, largely closed, eucalypt forest associations, with some rainforest elements.

The study depicts major changes in both the nature and extent of riparian vegetation communities associated with European settlement and identifies a suite of native species with potential for local riparian revegetation projects. It is recognized that hydrological and geomorphic conditions have been drastically altered on eroding sections of upper Wollombi Brook, placing some doubt on the viability of pre-European riparian vegetation associations under present day conditions in these areas. However, the sections of the Brook examined in this study are not yet incised and erosion is minimal. Therefore, in these areas, the inclusion and evaluation of the recommended species from the original vegetation community in trial planting operations will advance stream bank revegetation projects on upper Wollombi Brook.

Furthermore, this study provides a method applicable to the wider field of vegetation restoration. In most situations, practitioners use remnant species within an area or adjacent undisturbed catchments for species selection or to set the goals of any restoration. The use of palynological techniques may, however, find its greatest application in more degraded landscapes where remnants are not available.

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Appendix I. Taxa recorded in the palynology of the upper Wollombi Brook and their likely taxonomy, life form and habitat

Taxa recorded	Family	Likely species	Life form	Likely habitat and ecology
Acacia	Mimosaceae	*A. decurrens*	Small tree	Open forest
		A. floribunda	Tree	Open or closed forest. Mainly on rivers.
		A. parramettensis	Shrub	Woodland
Acmena	Myrtaceae	*Acmena smithii*	Tree	Closed forest/rainforest, usually in sheltered gullies and along watercourses.
Angophora	Myrtaceae	*Angophora floribunda*	Tree	Open or closed forests. Alluvial flats.
Asteraceae (lig.)	Asteraceae	Many species*	Forbs	Common in disturbed areas, especially agricultural areas.
Asteraceae (tub.)	Asteraceae	Many species	Forbs	Wide habitat
Casuarina	Casuarinaceae	*Casuarina cunninghamiana*	Tree	Common on riverbanks
Chenopodiaceae	Chenopodiaceae	*Einadia* spp.	Herbs	Open forest and rainforest gullies
Cyathea	Cyatheaceae	*Cyathea australis*	Treefern	Gullies, in closed forest and rainforest
		Cyathea cooperi		
Cyperaceae	Cyperaceae	Many species	Sedges and rushes	Marshy ground. Associated with swamps and watercourses.
Eucalyptus type	Myrtaceae	Many species	Trees	Forest and woodland
Gonocarpaceae	Haloragaceae	*Gonocarpus micranthus*	Forb	Marshy areas
		G. teucrioides	Forb	Marshy areas and closed forest
Lauraceae	Lauraceae	*Cryptocarya glaucescens*	Tree	Rainforest and sandstone gullies
		Endiandra spp.	Trees	Rainforest and wet, closed forest
Leptospermum	Myrtaceae	*Leptospermum phylicoides*	Shrub	Open forest and along streams
		L. polygalifolium	Shrub	Moist woodland and along streams
		L. lanigerum	Shrub	Closed scrub along streams and marshes
		L. brevipes	Shrub	Open forest and along streams
		L. emarginatum	Shrub	Always near streams
Melaleuca	Myrtaceae	*Melaleuca linariifolia*	Tree	Open and closed forest. Marshy areas
		M. styphelioides	Tree	Swampy places, near creeks
Monolete spores	Fern families	Many species	Ferns	Generally associated with moist areas
Myriophyllum	Haloragaceae	*Myriophyllum aquaticum**	Aquatic herbs	Swamps and water edges
		M. variifolium		
Plantago	Plantaginaceae	*Plantago lanceolata**	Forb	Moist forest, grassland and usually many other species associated with agricultural pasture
Poaceae	Poaceae	Many species	Grasses	Wide habitat
Pteridium	Dennstaedtiaceae	*Pteridium esculentum*	Fern	Invasive, wide habitat, often colonizing disturbed sites
Ranunculaceae	Ranunculaceae	*Ranunculus plebeius*	Forb	Damp, marshy environments
		R. lappaceus	Forb	Damp, marshy environments
		R. inundatus	Forb	Aquatic
		*R. repens**	Forb	Marshy environments
Restionaceae	Restionaceae	Many species	Rushes	Wet places, usually associated with swamps and riverbanks
Rumex	Polygonaceae	Many species*	Herb	Swamps or dry land
Syncarpia	Myrtaceae	*Syncarpia glomulifera*	Tree	Moist forest, particularly in transition zone between Eucalypt forest and rainforest.
Trilete spores	Fern families	Many species	Ferns	Mostly associated with moisture
Tristaniopsis	Myrtaceae	*Tristaniopsis laurina*	Tree	Riverbanks. Often with *Acmena smithii*

*Indicates that the species in question is introduced.

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Two proxy records revealing the late Holocene fire history at a site on the central coast of New South Wales, Australia

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Abstract: The local fire history of a coastal swamp catchment in New South Wales was reconstructed using two proxy records of fire: sedimentary macroscopic charcoal and fire-scar analyses of *Xanthorrhoea johnsonii*. The charcoal analysis provided a record of fire activity spanning the last 2800 years, while the *Xanthorrhoea* record covered the last approx. 300 years. The ability of each method to accurately record fire events was verified by cross referencing against the recent (post 1968) historic fire record. Fire history was then extrapolated beyond the historic record, to reveal an unprecedented level of fire activity in the last 35 years, which coincides with increased human activity in the area. In the prehistoric period charcoal and fire scars are comparatively rare, which is most parsimoniously ascribed to little fire activity, but perhaps represents skilful fire manipulation, as is often attributed to Aboriginal people. The comparatively minor fluctuations in macroscopic charcoal during the prehistoric period were approximately coeval with previous evidence of late Holocene environmental change in south-eastern Australia, suggesting that fire frequency at the site responded to climatic variability. The longer temporal perspective of this palaeoenvironmental approach provides information for the contemporary management of fire in this conservation reserve.

Key words: charcoal, coastal New South Wales, fire history, fire-scar analysis, Holocene.

INTRODUCTION

Altered fire regimes are one of a multitude of adverse environmental impacts associated with European settlement (Adamson & Fox 1982) and fire is a fundamental tool of conservation and management in the *Eucalyptus*-dominated vegetation communities of south-eastern Australia. The management of fire is also one of the most contentious environmental issues in Australia, with conflict stemming from perceptions of the history and role of anthropogenic fire in Australia, and the divergent objectives of conservation and risk minimization through hazard reduction burning (Morrison *et al.* 1996).

It is widely believed that Aboriginal people frequently used small, low-intensity fires within a defined fire season in south-eastern Australia (Jones 1969; Recher & Christensen 1981; Horton 1982; Clark & McLoughlin 1986; Pyne 1991; Kohen 1996; Bowman 1998; Gott 2005). The 'fire-stick farming' thesis developed by Jones (1969) described that broadcast fire was primarily used to increase the availability of resources, either by manipulating vegetation or as an aid for hunting animals (Nicholson 1981). Whether the use of fire by Aboriginal people resulted in lasting vegetation change is a contentious issue (Bowman 1998).

Fire-stick farming is a popular, but largely untested, paradigm. Gill (1977) cautioned that the idea that Aboriginal people used fire frequently 'should not be generalized over the whole continent'. Horton (1982) also questioned whether fire does in fact increase resources in many Australian ecosystems. Benson and Redpath (1997) argued that perceptions concerning Aboriginal burning practices are inaccurately based on extrapolated and biased evidence. Others have emphasized that Aboriginal activities operated within the wider contexts of climate change, other environmental constraints and varied due to changes in population density and technology (Clark 1983; Head 1989; Williams & Gill 1995; Black & Mooney 2006).

Ideas about prehistoric anthropogenic fire in Australia have also permeated natural resource management with suggestions that high-frequency fires are required to *re-create* grassy, open-woodland vegetation communities that they propose were widespread in humid Australia prior to European settlement (Flannery 1994; Ryan *et al.* 1995; Jurkis 2000). This argument has also been subsequently applied by land managers to support claims for land-clearing (Henderson 1999; National Association of Forest Industries 2003).

The Australian flora has developed a wide range of responses to fire over evolutionary time periods such that fire is essential for regeneration and germination for many Australian species (Gill 1981; Hodgkinson *et al.* 1984; Keith 1992; Bradstock *et al.* 2002). Gill (1977) first proposed that vegetation is not simply adapted to fire, but rather is adapted to a specific fire regime, consisting of the type (peat or above-ground), intensity, frequency and season of occurrence of fire. The post-fire response of a community is determined by the cumulative effects of the interdependent components of a fire regime (Bradstock *et al.* 1995, 1998; Keith 1996; Morrison *et al.* 1996). Observations suggest that a heterogeneous fire regime at the landscape scale is optimal for the conservation of species and community diversity (Gill & Nicholls 1989; Bradstock *et al.* 1997).

Fire ecology studies are fundamental to the development of appropriate fire regimes, but as they are limited to observational and short-term experimentation, their contribution to understanding pre-European fire regimes, variability and long-term change are limited. A longer temporal perspective is most commonly achieved by either tree-ring analyses or, more commonly in Australia, by way of charcoal analyses of lake and swamp sediment cores (Kershaw *et al.* 2002). Whereas previous reviews have highlighted ambiguities (Bowman 1998), advances in methods and statistical procedures have significantly enhanced the information derived from the analysis of sedimentary charcoal (Clark & Royall 1995; Whitlock & Millspaugh 1996; Long *et al.* 1998; Rhodes 1998; Millspaugh *et al.* 2000; Carcaillet *et al.* 2001; Gardner & Whitlock 2001; Hallett *et al.* 2003).

Despite several limitations to the use of dendrochronology for the elucidation of fire history in Australia (Ogden 1978) studies using members of the family Xanthorrhoeaceae suggest considerable potential. *Xanthorrhoea* is a monocot genus with some arborescent species. They are often common across Australia, considered fire tolerant and resprout after fire (Gill 1981; Bradstock *et al.* 1997). Using a known preponderance to flower after fire, Lamont and Downes (1979) and Bulow-Olsen *et al.* (1982) reconstructed fire histories from patterns of flower scars on the caudex of *Xanthorrhoea preissii* and *Xanthorrhoea johnsonii*, respectively. Ward *et al.* (2001) and Colangelo *et al.* (2002) extended this usefulness by describing the preservation of black bands (hereafter 'fire scars') associated with the passage of fire in populations of *X. preissii* in south-western Australia.

This study investigated the late Holocene fire history of a catchment on the central NSW coast. Two methods were investigated, the quantification of charcoal in a dune swamp and the detection of fire-induced scars on *Xanthorrhoea* in the catchment of this swamp. To test these methods, the results were compared with the known fire history of the area. The overall objective was to examine the recent history of fire against a longer temporal perspective.

SITE DESCRIPTION

Myall Lakes National Park (MLNP) is located on the central coast of NSW, approximately 230 km north of Sydney (Fig. 1). The study site, located at 32°31′S, 152°20′E, is a previously unnamed perched dune swamp and its catchment, herein referred to as Worimi Swamp, named after the original inhabitants of the area. It is found at 377 033 on the Bombah Point 1:25 000 Topographic mapsheet at approximately 8 m a.s.l. (LPI 2001).

This section of the NSW coastline is characterized by Pleistocene (Inner) and Holocene (Outer) age sand barriers, associated with sea level rises during the Last Interglacial and Post-glacial Marine Transgression, respectively (Thom *et al.* 1981, 1992). Worimi Swamp is located at the eastern edge of the Pleistocene inner barrier of the Eurunderee coastal embayment.

Vegetation on the sands of the inner barrier is controlled by edaphic conditions, influenced by age, mode of origin and topography, drainage, nutrient status and degree of podzolization (Myerscough & Carolin 1986; Thom *et al.* 1992). Drier *Angophora*/Eucalypt-dominated forest occurs on the better-drained sands of the ridge crests, and swamp forest and wet heath frequently occur in swales and flatter areas. The vegetation communities covering over 60% of MLNP are highly pyrogenic (National Parks and Wildlife Service (NPWS) 2002a) and fire regimes influence community structure, floristic composition and species richness (Fox & Fox 1986; Myerscough & Carolin 1986; Fox 1988; Hunter 2000).

Worimi Swamp occupies a deflation hollow and is a permanently waterlogged *Lepironia* swamp, fringed with *Melaleuca quinquenervia*. Its catchment is small (approx. 0.5 km^2) and the low-relief, leached dunes are vegetated with sclerophyll open forest dominated by *Angophora costata*, *Eucalyptus gummifiera*, *Eucalyptus pilularis* and *Eucalyptus robusta* (Timms 1982; Myerscough & Carolin 1986; Thom *et al.* 1992). *Xanthorrhoea johnsonii* (Lee 1966) (possible hybrid with *Xanthorrhoea latifolia*) occurs as scattered individuals in the catchment.

MLNP has a humid temperate climate. Although more than 70% of all recorded bushfires have occurred in spring, the fire season may extend to March depending on rainfall. The most extreme fire weather occurs from August to October, when strong westerly winds correspond with the driest time of the year (NPWS 2002a). MLNP occurs in Fire Region 11, which has a fire interval of 5–15 years. Inappropriate fire regimes and high fire frequency have been identified as significant threats to biodiversity in the area to the east of Myall Lake, which encompasses Worimi Swamp and its catchment (NPWS 2002b).

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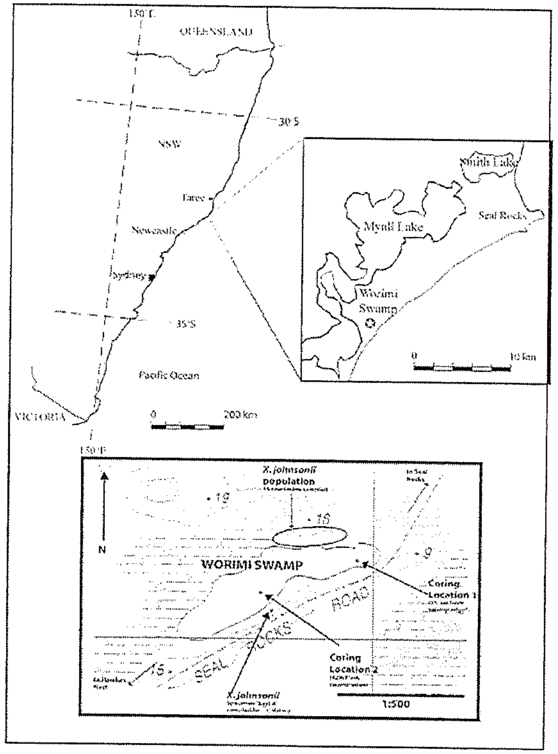

Fig. 1. The location of Worimi Swamp and the study sites at Myall Lakes National Park.

The Worimi people were the original inhabitants of the MLNP region (Garland & Wheeler 1982). Abundant natural resources, a favourable climate and permanent freshwater probably supported a relatively large Aboriginal community (Garland & Wheeler 1982; Hunter 2000; NPWS 2001). Abundant evidence of their occupation includes campsites, ceremonial sites, middens, canoe trees, stone arrangements, several wells, a fish trap, rock carving and quarries (NPWS 2002b).

The use of fire has been suggested to be a fundamental aspect of the Worimi people's lifestyle (Hunter 2000; NPWS 2002b) and the MLNP Plan of Management states that the Worimi 'altered their natural environment through the use of fire' (NPWS 2002b). Hunter (2000) suggested that their intermittent firing of the landscape increased the abundance of several species of grasses. This is a common interpretation of Aboriginal fire management and subsequent vegetation change but in reality the nature and consequences of their management of fire is poorly known. Our understanding of Worimi culture is primarily based on early European ethnographic records, which occurred during a period of significant disruption.

The first Europeans in the MLNP region were escaped convicts and timber getters, the latter arriving from Newcastle in 1816 (Garland & Wheeler 1982). By the 1820s the extraction of commercial timbers was causing significant vegetation change (Wright 1991; NPWS 2002b). The population of Gloucester Shire doubled during the 1830s and at about the same time the traditional lifestyle of the Worimi people ended in

what is now the southern section of MLNP (Garland & Wheeler 1982; NPWS 2002b).

Timber milling, fishing, boat building and small scale farming continued in the region from the 19th and into the 20th century. Sand mining operations began in 1957 on the barrier system east of Myall Lake (NPWS 2002b) and coupled with the earlier timber gathering led to a network of unofficial tracks and roads in MLNP (York 1989; Wright 1991; Hunter 2000). The ecological, scientific and recreational value of the Myall Lakes region were officially recognized in 1972 when 15 000 ha on the eastern side of the Myall Lake (encompassing Worimi Swamp) was gazetted as National Park. Mining operations ceased entirely in 1986 and subsequent land acquisitions have added to the still expanding National Park (NPWS 2002b).

METHODS

Worimi Swamp and its catchment are suitable for the purposes of this study as it was inhabited by a relatively large Aboriginal population and has not witnessed significant disturbance in the post-European period. Furthermore, the catchment is small, no watercourses flow into or out of the site, and the vegetation is primarily composed of shallow rooted sedges. These factors suggest that the swamp's sedimentary profile should primarily reflect changing land management practices from the Aboriginal to European periods. As *Xanthorrhoea* are also located in the catchment, the site provided an opportunity to compare the results of a fire-scar analysis with the sediment record, without compounding influences caused by distance.

Several short sediment cores of less than 1 m were extracted using a Russian D-section corer (Jowsey 1966) from two locations on the swamp (Location 1 (L1) and Location 2 (L2) on Fig. 1). Each core was described (Kershaw 1997) and digitally photographed. Two depth intervals, 31–36 and 60–65 cm, from the L1 site, were submitted for radiocarbon dating and the results were used to estimate the rate of sediment accumulation.

The organic proportion of continuous 1-cm intervals of a core from site L2 was quantified using loss-on-ignition (LOI) as outlined in Bengtsson and Enell (1986). Variations in the organic *versus* inorganic proportion of sediment at Worimi Swamp generally reflects stability or disturbance of the catchment (Mackereth 1965, 1966) with the organic fraction a measure of autochthonous primary productivity and the inorganic material resultant from wind or water transported sand. Subsamples were oven-dried (at 105°C for 24 h), then placed in a muffle furnace (at 550°C for 2 h) and LOI calculated as grams of organic content lost per gram of oven-dried sediment (g g^{-1}).

The abundance of sand in the sediment at site L2 was also estimated using an ordinal scale.

Charcoal analyses, using a modified Oregon Sieving Method (Long *et al.* 1998; Mooney & Radford 2001; Mooney & Black 2003) were conducted using contiguous 1 cm subsamples of sediment from both site L1 and L2 on Worimi Swamp. Volumetric subsamples from site L1 were placed in a 12% solution of bleach for 18 h and those from L2 were similarly treated with 6% bleach (following Rhodes 1998; Carcaillet *et al.* 2001). The samples were then wet-sieved using a 250-µm mesh and high-resolution digital images of the collected material taken. The abundance (no. cm^{-3}), area (mm^2 cm^{-3}) and maximum area (mm^2) of charcoal in each sample were calculated using Scion Image (Mooney & Black 2003). As only core L1 was (radiocarbon) dated, charcoal accumulation rates (cm^2 cm^{-2} $year^{-1}$) were calculated for that core.

The Charcoal Analysis Program (CHAPS), described by Long *et al.* (1998), was used to estimate fire frequency through time. CHAPS uses charcoal influx from evenly spaced time intervals (CHAR) and identifies catchment fires as peaks above a threshold. CHAR below this threshold does not reflect specific fire events but is washed into a sedimentary profile with other allochthonous material. Details of the historic fire record, obtained from the NPWS GIS database for MLNP, were used to calibrate peaks in the charcoal influx data with actual fire events, a method based on Hallet and Walker (2000). A locally weighted mean width of 3 × 25 years was selected for calculating the background component of the charcoal accumulation data and a threshold of 1.1 was selected for determining influx peaks. This meant that any 3-year average influx value that exceeded the 75-year background influx by more than 1.1 was identified as a fire event.

The *Xanthorrhoea* fire-scar analysis was undertaken on 14 individual specimens in the northern part of the Worimi Swamp catchment (Fig. 1). These were chosen on the basis of single, relatively straight caudexes. Using methods described by Bulow-Olsen *et al.* (1982) and Ward *et al.* (2001), the outer caudex was cleaned to expose a series of dark bands identified as 'fire scars' and reddish, resin-filled areas identified as 'flower scars'. These were measured on each *Xanthorrhoea* specimen as distance down from the base of the living leaves at the crown as this represented a common age among the analysed specimens.

From the field measurements, scar graphs were produced for all 14 specimens, depicting the location and width of all identified fire and flower scars. The fire and flower scar data for the entire sampled population were then collated onto a master diagram. To reduce the potential influence of differing growth rates between individuals, these population data were combined into (fire and flower) scar frequency over contiguous 3-cm height intervals and then expressed as a percentage of the total number of specimens. This method accounts for the fact that as distance from the crown increased the number of specimens decreased (i.e. tall specimens were relatively rare). Where the frequency of fire scars across the population was high, this was more confidently interpreted as a fire-event. Bivariate correlations using Spearman's rho correlation coefficient were calculated using the statistical package SPSS (Version 11.0 for Windows, SPSS Inc., Chicago, IL, USA), to better characterize the relationship between distance from the crown and the frequency of scars (fire, flower and combined).

In *Xanthorrhoea*, height is a function of age (Gill & Ingwersen 1976), and hence to provide an estimate of the age (and frequency) of past fire-scaring events it was necessary to develop an age–height relationship. Six samples for Accelerator Mass Spectrometry (AMS) radiocarbon analyses were extracted from two specimens from known distances down the caudexes. Three samples were taken from Specimen *East A* at 48–51, 83–85 and 116.8–118.8 cm and three samples from Specimen *West 15* at 251–253, 315–318 and 370–372 cm. These samples were submitted to the Australian Nuclear Science and Technology Organization (ANSTO) Environment Laboratory in Sydney for AMS radiocarbon dating.

The ANSTO ^{14}C results, in radiocarbon years BP, were subsequently calibrated to calendar years using the INTCAL 98 calibration program (Stuiver *et al.* 1998). When graphed, a relationship was derived for the age–height data. This method assumes a constant growth rate within and between the 14 individuals which is unlikely to be entirely valid, suggesting some caution in assigning ages to individual fire scars.

RESULTS

Recent (historic) fire records

Since 1968, bushfires have occurred within MLNP every fire season with an average of 6.4 fires burning on average 1691 ha each year (NPWS 2002b). Arson and unknown causes accounted for 81% of ignition for non-prescribed fires. Prior to 1984, landholders, graziers, timber-getters and fishers deliberately lit fires in the area (NPWS 2001). Since then the NPWS have conducted 32 controlled burns mainly in autumn (NPWS 2002a).

Ten fires have occurred within a 1-km radius of the catchment of Worimi Swamp in the last 36 years (Table 1), seven of which have burnt within the catchment, and the *X. johnsonii* population has burnt at least five, possibly six times over this time period. The catchment scale fire interval of this historic period ranges from 3 to 10 years, with an average frequency of 5 years.

Table 1. The recent (1946–present) historic fire record for Worimi Swamp and its catchment as recorded on the National Parks and Wildlife Service (NPWS) fire database (NPWS 2003)

Fire Season	Area burnt[†] (ha)	Location and comments
1968–69	10 809	A wildfire that burnt the entire Barrier System[‡] on the eastern side of Myall Lake from Bombah Broadwater to Seal Rocks. This fire burnt in the catchment of Worimi Swamp and should have impacted upon the sampled *Xanthorrhoea*.
1974–75	3039	A wildfire that burnt from northern perimeter of Worimi Swamp to Seal Rocks. This fire did not directly impact on the catchment of Worimi Swamp.
1977–78	279 and 293	These two wildfires burnt near Worimi Swamp, however, while fire probably occurred in the catchment, the sampled *Xanthorrhoea* population may have been unaffected.
1980–81	566	This wildfire burnt the Worimi Swamp catchment and the sampled *Xanthorrhoea* population.
1981–82	313	This wildfire burnt an area to the north-east of Worimi Swamp and so did not directly impact the study area.
1985	52	This was a prescribed fire located to the east of Seal Rocks Road, approximately 1 km north of Worimi Swamp.
1987	778	A wildfire that burnt to the north-east of Worimi Swamp on the eastern side of Seal Rocks Road.
1990	1472	Wildfires burnt the Barrier System west of Seal Rocks Road and other areas of the park. This fire burnt in the catchment of Worimi Swamp and the sampled *Xanthorrhoea*.
1994	1743	Extensive wildfire on the Barrier System from Mungo Brush west to Bombah Point and north to Palmers Bay. This fire burnt both the catchment of Worimi Swamp and the sampled *Xanthorrhoea*.
1997	4176	Extensive wildfire that consumed the vegetation of the entire Barrier System, including the catchment of Worimi Swamp and the sampled *Xanthorrhoea*.

[†] 'Area burnt' refers to the burn areas affecting Worimi Swamp and its catchment. The area of coincident burns in the Park are not reported here.

[‡] 'Barrier System' refers to the Dual Barrier System Geomorphology Unit on the eastern side of Myall Lake (Thom *et al.* 1992).

Sediment analysis and chronology

The sediment cores used in this study had a similar composition. They were relatively homogenous with diffuse boundaries and little stratification. The surface of the sediment from L1 contained fine root and other organic material and visible charcoal bands at 3–4 and 4.5–5.5 cm. Fine organic material was present throughout each core but decreased with depth as the bulk density, humification and sand content increased (Fig. 2).

The results of the ^{14}C dating analyses (Table 2) were used to construct the age–depth relationship of the sediment (Fig. 3). Where ages are reported in the text they are based on a quadratic polynomial fitted through these data and the surface of the sediment. This age–depth model suggests that the 95 cm analysed in core L1 represents approx. 2816 calibrated ^{14}C years. The age–depth model implies that the accumulation rate of the sediment increased from 0.017 cm year^{-1} at the base of the core (approx. 95 cm) to approx. 6.8 cm year^{-1} at the surface, meaning that the temporal resolution of the analyses increased markedly towards the surface of the sediment. For example, the depth 94–95 cm represented 60 years of sedimentation, 44–45 cm represented 28 years and 1–2 cm represented 0.8 year of sediment accumulation.

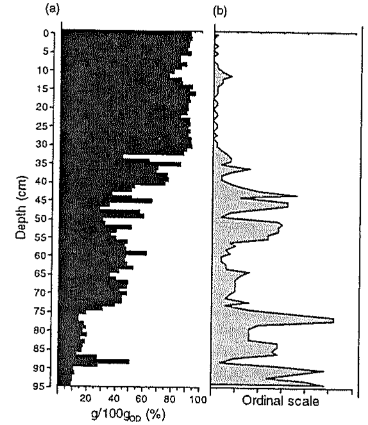

Fig. 2. The loss-on-ignition (a) and the sand content of core L2 (b) from Worimi Swamp. The material lost on ignition approximates the organic content of the sediment.

Charcoal analyses

The trends in the concentration of charcoal (expressed as mm^2 cm^{-3}) for the cores extracted from different locations on the swamp were similar although differences in abundance were apparent (Fig. 4a,b). At Worimi Swamp the changing sedimentation rate meant that charcoal was best expressed as an accumulation.

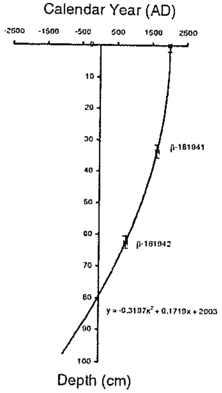

Fig. 3. The age–depth relationship of the sediment at Worimi Swamp.

Table 2. The results of the ^{14}C dating analyses of the sediment from Worimi Swamp

Depth (cm)	Radiocarbon years (±SE) BP	Intercept of ^{14}C age with calibration curve (1σ calibrated results)[†]	Laboratory no.
31–36	260 (±60)	AD 1650 (AD 1525–60, 1630–65)	β-181941
60–65	1260 (±50)	AD 765 (AD 685–795)	β-181942

[†] Samples were calibrated to calendar years using Stuiver *et al.* (1998).

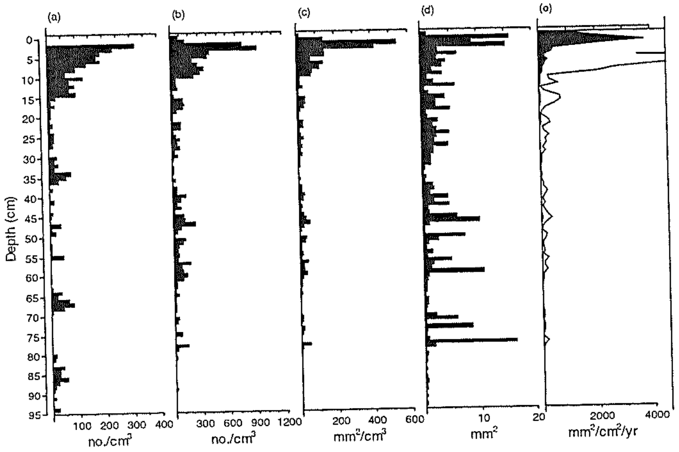

Fig. 4. Various measures of the fire history of the Worimi Swamp catchment: (a) Charcoal expressed as a concentration (using no. cm^{-3}) from core L2 prepared using 6% bleach; (b) charcoal expressed as a concentration (using no. cm^{-3}) from core L1 prepared using 12% bleach; (c) the concentration of charcoal in core L1, expressed as an area (mm^2 cm^{-3}); (d) the maximum particle area of charcoal (mm^2) for core L1; and (e) charcoal expressed as a rate of accumulation (mm cm^{-2} $year^{-1}$) for core L1. The line shows the same data with a 20× exaggeration.

The influx of charcoal was generally low in the core with the exception of the uppermost 11 cm (Fig. 4e), which represented the period since AD 1966 (Fig. 3). Although charcoal influx was relatively low below a depth of 11 cm, it was slightly elevated in the core between 37 and 61 cm and above 30 cm (Fig. 4e), representing *c.* AD 825–1570 (380–1125 calibrated years BP) and after *c.* AD 1720, respectively (Fig. 3).

When the inferred fire frequency was calculated using the CHAPS program for core L1 the resulting frequency covering the last 35 years exceeded six fires per 99 years (Fig. 5) which is less than, but not strongly divergent from the known frequency (NPWS 2003). Notably, the inferred fire frequency of the period post-dating *c.* AD 1970 exceeded any other period of the analysed approx. 2800 years (Fig. 5). Other periods of higher fire frequency were inferred between about AD 1500 and 1600, AD 1113–1213, AD 798–898, AD 204–304 and in the first century AD. Where the fire frequency was zero, between AD 404 and 746 and in the analysed BC period (1–866 BC), fire-free periods were inferred.

Xanthorrhoea age and fire-scar analysis

The AMS dating of the *X. johnsonii* caudexes confirmed that the Worimi Swamp population is long-lived (Table 3). As conversion of these ages to calendar years resulted in multiple intercepts with the radiocarbon calibration curve, we used the principle of superposition (greater distances down the caudexes must have been older) and previous estimates of *Xanthorrhoea* growth rates (Gill & Ingwersen 1976; Lamont & Downes 1979; Bulow-Olsen *et al.* 1982) to determine which were probable.

As the growth rate of *Xanthorrhoea* is likely to vary over time in response to fires and flower production, the relationship between height and age was described using a polynomial (Fig. 6). Given the relatively large errors associated with the dating results (Table 3), this method provides only a coarse estimate of the age at any distance down the caudexes. Based on the height–age relationship the tallest specimen analysed (292 cm) was approx. 304 years old.

The cleaned *Xanthorrhoea* caudexes revealed numerous fire scars, usually of approx. 1 cm, which became more obvious with some minor enhancement of the digital images. Flower scars were also obvious, varied between 1 and 5 cm in width and were often located below a bend in the caudex. A high proportion of fire scars (44 of 118, or 37%) was found within 40 cm of the crown (representing the last approx. 40 years) with the majority of the analysed specimens recording few scars in the lowermost 40 cm (Fig. 7). Very few fire or flower scars were recorded below 2 m; however, it should be noted that only five of the 14 specimens attained this height. The lower sections of these taller specimens were often weathered and furrowed making identification of scars difficult.

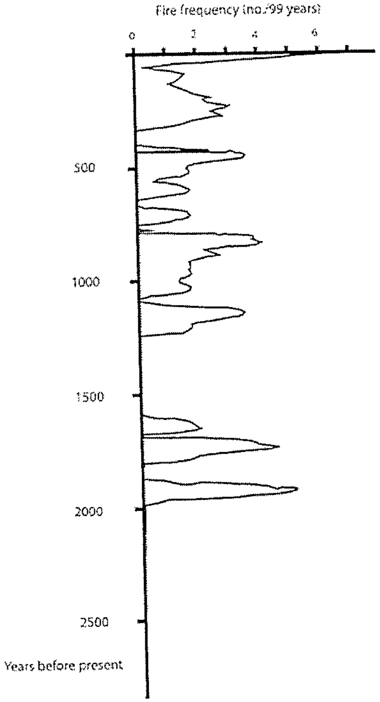

Fig. 5. The inferred frequency of fire through time.

Higher incidences of fire scars occurred at 12–30 cm (about 1973–91), 39–42 cm (about 1961–64), 48–57 cm (about 1946–55), 60–63 cm (about 1940–43), 69–72 cm (about 1931–34), 75–78 cm (about 1926–29) and 114–116 cm (about 1844–48) (Fig. 7). The pattern of scarring on individual specimens between 12 and 30 cm and 48–63 cm suggested multiple fires in those corresponding time periods. Flower scars were more frequent at 39–42 cm (about 1961–64), 51–54 cm (about 1949–52), 66–69 cm (about 1934–37), 81–84 cm (about 1920–23), 99–102 cm (about 1902–05), 114–117 cm (about 1844–48), 126–132 cm (about 1827–34), 168–171 cm (about 1788–90) and 213–216 cm (about 1748–51).

Although there was a weak correlation between the incidence of fire and flower scars along the caudex ($r_s = 0.147$, $P \leq 0.01$), the patterns of fire and flower

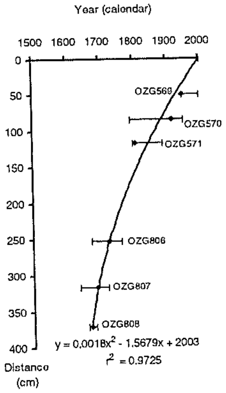

Fig. 6. The age–height relationship in the sampled population of *Xanthorrhoea*. The *y*-axis ('Distance') represents the distance down the caudex from the lowest green leaf.

Table 3. The results of the ^{14}C Accelerator Mass Spectrometry (AMS) dating analysis of the samples from the *Xanthorrhoea* caudexes

Specimen ID	Distance down caudex (cm)	Radiocarbon years (BP) (±SE)	Calibrated calendar years (1σ)†	Laboratory code
East A	48–51	Modern	Post 1950	OZG569
East A	83–85	125 (±40)	1920 (1872–1953)	OZG570
East A	116.8–118.8	130 (±40)	1810 (1802–1891)	OZG571
West 15	251–253	130 (±40)	1729 (1676– 1764)	OZG806
West 15	315–318	125 (±40)	1728 (1677–1760)	OZG807
West 15	370–372	180 (±40)	1673 (1662–1685)	OZG808

†Samples were AMS radiocarbon dated at Australian Nuclear Science and Technology Organization Laboratories in Sydney (see Lawson *et al.* 2000) and calibrated using Stuiver *et al.* (1998).

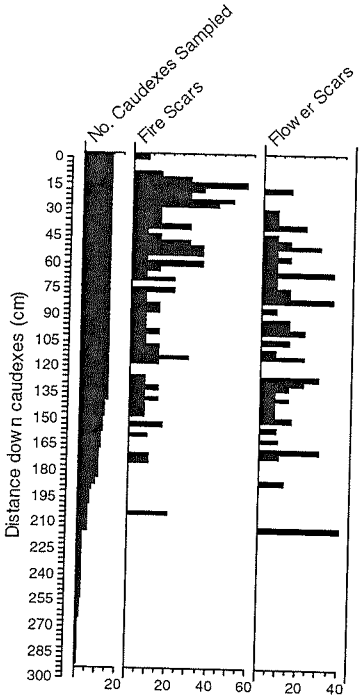

Fig. 7. The cumulative incidence of fire and flower scars in the sampled *Xanthorrhoea*.

scars were often not synchronous (Fig. 7). For example, the high frequency of flower scars at 81–84 cm and 126–132 cm were not associated with fire scars, but between AD 1844–48, 1949–52 and 1961–64 fire scars corresponded with flower scars. Of particular note, the upper sections of the analysed caudexes revealed very few flower scars, despite numerous fire scars. As an example, 37 fire scars were found in the upper 30 cm (since *c.* 1973) of all specimens, but only two flower scars were revealed over the same section (Fig. 7).

DISCUSSION

In this study two methods were employed to reconstruct fire history in the catchment of Worimi Swamp: (i) quantification of macroscopic charcoal from a sediment core extending back approx. 2800 years; and (ii) analysis of fire and flower scars on the caudexes of *X. johnsonii* adjacent to the swamp spanning approximately 300 years.

Verification of the charcoal and *Xanthorrhoea* records

Comparing recent historic fires with the proxies derived from the sedimentary charcoal and the *Xanthorrhoea* fire scars allowed verification of the methods and facilitates interpretation beyond the historic record (Edwards & Whittington 2000). This was hampered, however, by the short interfire intervals of the historic record (Table 1) and the resolution of the analysis.

Nonetheless, the recent charcoal accumulation in the sediment of Worimi Swamp and the frequency of fire scars in the *Xanthorrhoea* population of the catchment shared a distinct overall pattern. In the period since about AD 1970 fire appears to have increased in frequency. The dramatic increase in charcoal accumulation from a depth of 11 cm in core L1 also corresponded well with the fire of 1968–69. The fire-free period of the 1980s was also associated with a dip in the accumulation of charcoal (centred on approx. 6 cm) and the most recent fires (1990–91, 1994–95 and 1997–98) corresponded to extremely high maximum charcoal particle areas and the highest charcoal accumulation, evident between 2 and 5 cm in core L1.

The peaks in the *Xanthorrhoea* fire-scar data were also associated with historic fires. As an example, the peak in fire scars at 39–41 cm corresponded to 1961–64 using the height–age model and so may have represented the 1968 catchment fire. The decrease in fire scars between 30 and 39 cm correlated well with the recorded 10-year fire-free period between 1968 and 1977 (NPWS 2003) and subsequent fire-scar peaks fitted the 1977–78 (27–30 cm), 1980–81 (24–27 cm), 1990–91 (18–21 cm), 1994–95 (15–18 cm) and 1997–98 (12–15 cm) fires. This suggested that the height–age model used overestimated the age at any height in the recent past by 5 or 6 years.

These results suggested that both the fire-scar analysis of *X. johnsonii* and the sediment charcoal record accurately revealed recent fire events at Worimi Swamp.

The late Holocene fire history at Worimi Swamp

During the prehistoric period fire activity in the Worimi Swamp catchment appeared to be relatively low, with fire frequencies rarely greater than four events per century. Furthermore, this fire may not reflect anthropogenic activity, as two fires have been attributed to lightning in MLNP since 1968 (NPWS 2002a), suggesting that lightning alone could explain the prehistoric fire frequency.

As the rationale for the use of broadcast fire by Aboriginal people is most often ascribed to the manipulation of resources, the characteristics of these at a site are of paramount importance. Broadcast fire is most commonly associated with the hunting of larger animals such as macropods or emus (Flood 1987) although Gott (1982, 2005) also highlighted the use of fire to encourage the growth of various plant resources. At Worimi Swamp it is possible that the infrequent burning regime of the Aboriginal period may reflect the abundant marine and freshwater food resources from the nearby lakes and coastal areas. This suggestion was also forwarded by Mooney *et al.* (2001) when discussing the relative rarity of fire in the prehistoric period at a coastal location in Royal National Park to the south of Sydney.

It is also plausible that the low influx of charcoal to Worimi Swamp during the prehistoric period may have resulted from Aboriginal cultural practices such that fire may have been confined to relatively small patches within the catchment at any one time or even to individual *Xanthorrhoea*. In this case the charcoal record may reflect the spatial extent of fire, with 'mosaic' or 'patch' fires represented by little charcoal accumulation in the prehistoric period and large conflagrations in the historic period represented by much greater charcoal accumulation. It should be emphasized, however, that only charcoal larger than 250 μm was quantified herein which should predominantly reflect fire at small spatial scales. Several overseas studies have related the size of charcoal particles (but not the quantity) to the distance between the fire and the deposition site (Clark & Royall 1995; Millspaugh & Whitlock 1995; Carcaillet *et al.* 2001). Nonetheless, this hypothesis warrants further testing in Australian settings.

Although the accumulation of charcoal was low during the prehistoric period, there was more fire activity in the early AD period, and in the eighth, 12th and early 16th centuries AD. More frequent or intense fire may reflect climatic instability (Green 1982; Edney *et al.* 1990; Jenkins & Kershaw 1997; Haberle *et al.* 2001), or changes in Aboriginal population density, technology or their land management practices near Worimi Swamp. As a further complication, changes in fire activity may also have been a *response* from the Aboriginal population to any climatic change, reflecting, for example, vegetation change and hence changed resource availability or flammability.

At Worimi Swamp there was evidence for a period of increased fire activity between the very late BC period and *c.* AD 450, seen most clearly in the maximum particle area between 70 and 80 cm (Fig. 4d) and the peak in fire frequency (Fig. 5). Environmental change between approx. 2000 and 1700 BP has been suggested in previous palaeoecological studies in south-eastern Australia, including from Tasmania (Cook *et al.* 2000), Victoria (Dodson 1974; De Deckker 1982; D'Costa *et al.* 1989; McKenzie & Kershaw 1997; Mooney 1997), Barrington Tops in the northern tablelands of NSW (Dodson *et al.* 1986) and from Sydney (Kodela & Dodson 1989).

It is also of interest to note that fire activity in the Worimi Swamp catchment was generally high in the 10–15th centuries followed by low fire activity from the 15th to early 18th centuries. This change is reminiscent of the general temperature trends of temperate regions during the last 1000 years, with a warmer first half followed by more frequent below average values after AD 1520 (Hughes & Diaz 1994).

Fire activity in the Worimi Swamp catchment was generally higher in the period *c.* AD 785–1500, which is approximately coeval with above average temperatures identified in a Huon Pine dendroclimatological sequence from Tasmania (Cook *et al.* 2000). Furthermore, fire activity at Worimi Swamp was highest in the AD 12th century during the most favourable climates of the Medieval Warm Period (MWP) (Williams & Wigley 1983; Grove 1988). Evidence for a global MWP is equivocal (e.g. Grove 1988; Bradley & Jones 1993; Hughes & Diaz 1994; Jones *et al.* 1998); however, environmental change has been described during this time period in Australasia by Cook *et al.* (1991, 1992, 2000, 2002) and Mooney (1997).

At Worimi Swamp a period of relatively low fire activity was found between *c.* AD 1570 and 1720, which is a period that overlaps with the Little Ice Age (LIA). Like the MWP, the temporal and spatial extent of the LIA on a global scale is debated (Williams & Wigley 1983; Bradley & Jones 1993; Grove & Switsur 1994; Hughes & Diaz 1994; Jones *et al.* 1998) but it has been reported in the Southern Hemisphere in Peru (Thompson *et al.* 1986), New Zealand (Salinger 1976), the western Pacific (Nunn 1998; Hendy *et al.* 2002) and in Africa (Stager *et al.* 1997; Holmgren *et al.* 1999). Equivocal results regarding the LIA have been recorded in Antarctic $\delta^{18}O$ ice-core records (Mosley-Thompson 1996) and although Cook *et al.* (2000) found little dendroclimatological evidence for the LIA in Tasmania, they did find 'reduced multidecadal variability' in the period AD 1500–1900.

These results tend to support the view that the prehistoric fire activity at Worimi Swamp was climatically controlled, with periods of warmer temperatures associated with increased fire frequency and colder and perhaps more climatically stable intervals associated with lower fire activity.

Fire in the post-European period (after AD 1820)

The first fire recorded in the database for MLNP was in 1968 (NPWS 2003). The fire-scar analysis of the

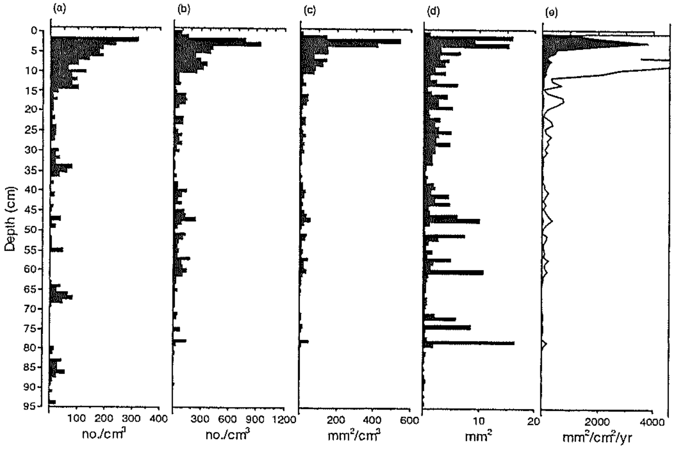

Fig. 4. Various measures of the fire history of the Worimi Swamp catchment: (a) Charcoal expressed as a concentration (using no. cm^{-3}) from core L2 prepared using 6% bleach; (b) charcoal expressed as a concentration (using no. cm^{-3}) from core L1 prepared using 12% bleach; (c) the concentration of charcoal in core L1, expressed as an area (mm^2 cm^{-3}); (d) the maximum particle area of charcoal (mm^2) for core L1; and (e) charcoal expressed as a rate of accumulation (mm cm^{-2} $year^{-1}$) for core L1. The line shows the same data with a 20× exaggeration.

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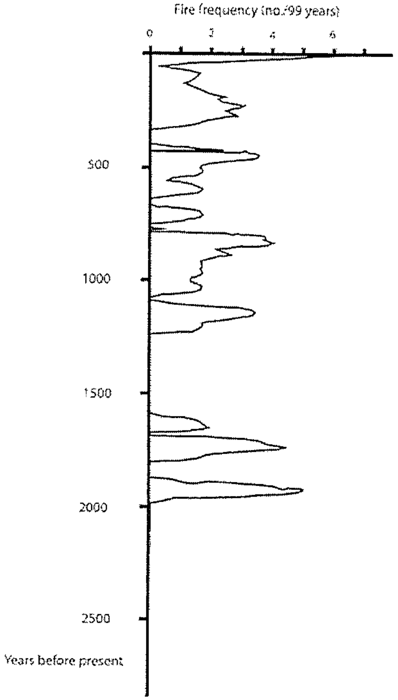

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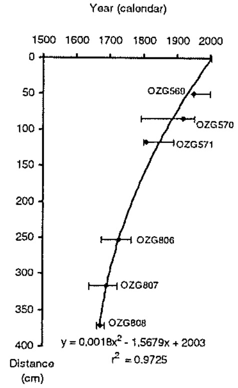

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West 15	251–253	130 (±40)	1729 (1676– 1764)	OZG806
West 15	315–318	125 (±40)	1728 (1677–1760)	OZG807
West 15	370–372	180 (±40)	1673 (1662–1685)	OZG808

†Samples were AMS radiocarbon dated at Australian Nuclear Science and Technology Organization Laboratories in Sydney (see Lawson *et al.* 2000) and calibrated using Stuiver *et al.* (1998).

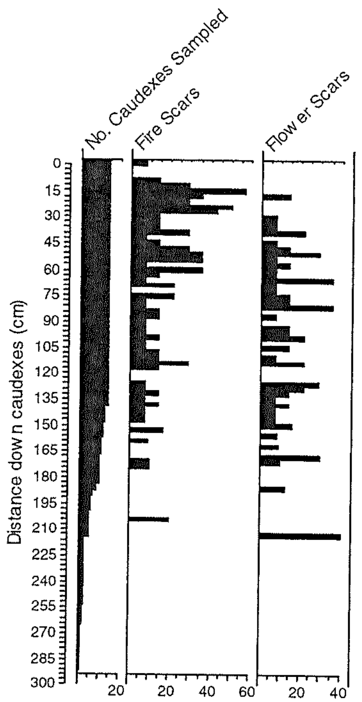

Fig. 7. The cumulative incidence of fire and flower scars in the sampled *Xanthorrhoea*.

scars were often not synchronous (Fig. 7). For example, the high frequency of flower scars at 81–84 cm and 126–132 cm were not associated with fire scars, but between AD 1844–48, 1949–52 and 1961–64 fire scars corresponded with flower scars. Of particular note, the upper sections of the analysed caudexes revealed very few flower scars, despite numerous fire scars. As an example, 37 fire scars were found in the upper 30 cm (since *c.* 1973) of all specimens, but only two flower scars were revealed over the same section (Fig. 7).

DISCUSSION

In this study two methods were employed to reconstruct fire history in the catchment of Worimi Swamp: (i) quantification of macroscopic charcoal from a sediment core extending back approx. 2800 years; and (ii) analysis of fire and flower scars on the caudexes of *X. johnsonii* adjacent to the swamp spanning approximately 300 years.

Verification of the charcoal and *Xanthorrhoea* records

Comparing recent historic fires with the proxies derived from the sedimentary charcoal and the *Xanthorrhoea* fire scars allowed verification of the methods and facilitates interpretation beyond the historic record (Edwards & Whittington 2000). This was hampered, however, by the short interfire intervals of the historic record (Table 1) and the resolution of the analysis.

Nonetheless, the recent charcoal accumulation in the sediment of Worimi Swamp and the frequency of fire scars in the *Xanthorrhoea* population of the catchment shared a distinct overall pattern. In the period since about AD 1970 fire appears to have increased in frequency. The dramatic increase in charcoal accumulation from a depth of 11 cm in core L1 also corresponded well with the fire of 1968–69. The fire-free period of the 1980s was also associated with a dip in the accumulation of charcoal (centred on approx. 6 cm) and the most recent fires (1990–91, 1994–95 and 1997–98) corresponded to extremely high maximum charcoal particle areas and the highest charcoal accumulation, evident between 2 and 5 cm in core L1.

The peaks in the *Xanthorrhoea* fire-scar data were also associated with historic fires. As an example, the peak in fire scars at 39–41 cm corresponded to 1961–64 using the height–age model and so may have represented the 1968 catchment fire. The decrease in fire scars between 30 and 39 cm correlated well with the recorded 10-year fire-free period between 1968 and 1977 (NPWS 2003) and subsequent fire-scar peaks fitted the 1977–78 (27–30 cm), 1980–81 (24–27 cm), 1990–91 (18–21 cm), 1994–95 (15–18 cm) and 1997–98 (12–15 cm) fires. This suggested that the height–age model used overestimated the age at any height in the recent past by 5 or 6 years.

These results suggested that both the fire-scar analysis of *X. johnsonii* and the sediment charcoal record accurately revealed recent fire events at Worimi Swamp.

The late Holocene fire history at Worimi Swamp

During the prehistoric period fire activity in the Worimi Swamp catchment appeared to be relatively low, with fire frequencies rarely greater than four events per century. Furthermore, this fire may not reflect anthropogenic activity, as two fires have been attributed to lightning in MLNP since 1968 (NPWS

2002a), suggesting that lightning alone could explain the prehistoric fire frequency.

As the rationale for the use of broadcast fire by Aboriginal people is most often ascribed to the manipulation of resources, the characteristics of these at a site are of paramount importance. Broadcast fire is most commonly associated with the hunting of larger animals such as macropods or emus (Flood 1987) although Gott (1982, 2005) also highlighted the use of fire to encourage the growth of various plant resources. At Worimi Swamp it is possible that the infrequent burning regime of the Aboriginal period may reflect the abundant marine and freshwater food resources from the nearby lakes and coastal areas. This suggestion was also forwarded by Mooney *et al.* (2001) when discussing the relative rarity of fire in the prehistoric period at a coastal location in Royal National Park to the south of Sydney.

It is also plausible that the low influx of charcoal to Worimi Swamp during the prehistoric period may have resulted from Aboriginal cultural practices such that fire may have been confined to relatively small patches within the catchment at any one time or even to individual *Xanthorrhoea*. In this case the charcoal record may reflect the spatial extent of fire, with 'mosaic' or 'patch' fires represented by little charcoal accumulation in the prehistoric period and large conflagrations in the historic period represented by much greater charcoal accumulation. It should be emphasized, however, that only charcoal larger than 250 μm was quantified herein which should predominantly reflect fire at small spatial scales. Several overseas studies have related the size of charcoal particles (but not the quantity) to the distance between the fire and the deposition site (Clark & Royall 1995; Millspaugh & Whitlock 1995; Carcaillet *et al.* 2001). Nonetheless, this hypothesis warrants further testing in Australian settings.

Although the accumulation of charcoal was low during the prehistoric period, there was more fire activity in the early AD period, and in the eighth, 12th and early 16th centuries AD. More frequent or intense fire may reflect climatic instability (Green 1982; Edney *et al.* 1990; Jenkins & Kershaw 1997; Haberle *et al.* 2001), or changes in Aboriginal population density, technology or their land management practices near Worimi Swamp. As a further complication, changes in fire activity may also have been a *response* from the Aboriginal population to any climatic change, reflecting, for example, vegetation change and hence changed resource availability or flammability.

At Worimi Swamp there was evidence for a period of increased fire activity between the very late BC period and *c.* AD 450, seen most clearly in the maximum particle area between 70 and 80 cm (Fig. 4d) and the peak in fire frequency (Fig. 5). Environmental change between approx. 2000 and 1700 BP has been suggested in previous palaeoecological studies in south-eastern Australia, including from Tasmania (Cook *et al.* 2000), Victoria (Dodson 1974; De Deckker 1982; D'Costa *et al.* 1989; McKenzie & Kershaw 1997; Mooney 1997), Barrington Tops in the northern tablelands of NSW (Dodson *et al.* 1986) and from Sydney (Kodela & Dodson 1989).

It is also of interest to note that fire activity in the Worimi Swamp catchment was generally high in the 10–15th centuries followed by low fire activity from the 15th to early 18th centuries. This change is reminiscent of the general temperature trends of temperate regions during the last 1000 years, with a warmer first half followed by more frequent below average values after AD 1520 (Hughes & Diaz 1994).

Fire activity in the Worimi Swamp catchment was generally higher in the period *c.* AD 785–1500, which is approximately coeval with above average temperatures identified in a Huon Pine dendroclimatological sequence from Tasmania (Cook *et al.* 2000). Furthermore, fire activity at Worimi Swamp was highest in the AD 12th century during the most favourable climates of the Medieval Warm Period (MWP) (Williams & Wigley 1983; Grove 1988). Evidence for a global MWP is equivocal (e.g. Grove 1988; Bradley & Jones 1993; Hughes & Diaz 1994; Jones *et al.* 1998); however, environmental change has been described during this time period in Australasia by Cook *et al.* (1991, 1992, 2000, 2002) and Mooney (1997).

At Worimi Swamp a period of relatively low fire activity was found between *c.* AD 1570 and 1720, which is a period that overlaps with the Little Ice Age (LIA). Like the MWP, the temporal and spatial extent of the LIA on a global scale is debated (Williams & Wigley 1983; Bradley & Jones 1993; Grove & Switsur 1994; Hughes & Diaz 1994; Jones *et al.* 1998) but it has been reported in the Southern Hemisphere in Peru (Thompson *et al.* 1986), New Zealand (Salinger 1976), the western Pacific (Nunn 1998; Hendy *et al.* 2002) and in Africa (Stager *et al.* 1997; Holmgren *et al.* 1999). Equivocal results regarding the LIA have been recorded in Antarctic δ^{18}O ice-core records (Mosley-Thompson 1996) and although Cook *et al.* (2000) found little dendroclimatological evidence for the LIA in Tasmania, they did find 'reduced multidecadal variability' in the period AD 1500–1900.

These results tend to support the view that the prehistoric fire activity at Worimi Swamp was climatically controlled, with periods of warmer temperatures associated with increased fire frequency and colder and perhaps more climatically stable intervals associated with lower fire activity.

Fire in the post-European period (after AD 1820)

The first fire recorded in the database for MLNP was in 1968 (NPWS 2003). The fire-scar analysis of the

Xanthorrhoea population at Worimi Swamp suggests that fire events also occurred in *c.* 1845, in the late 1920s, in the early 1930s, at about 1942 and between 1946 and 1955. Fire scars also occur between these times, although in relatively low frequencies. The analysis of the Worimi Swamp sediment revealed a slight increase in the influx of charcoal after *c.* AD 1890, another slight increase between 1943 and 1951, and a dramatic increase in the period since AD 1966.

European presence in the Myall Lakes region began in approximately AD 1820 with the initiation of timber getting, minor agricultural activity and settlement (Garland & Wheeler 1982). At Worimi Swamp the charcoal record of the 19th century implies that the prehistoric fire regime did not undergo significant change until approximately AD 1890. This suggestion is collaborated by a higher incidence of fire scars at *c.* AD 1893 in the *Xanthorrhoea* record.

Both the analysed proxies depict a marked increase in fire activity at Worimi Swamp since the late 1960s and the maximum fire frequency over the last 2800 years is inferred during this time. This increase in fire activity occurs at a later date than in other south-eastern Australian studies (e.g. Boon & Dodson 1992; Gell *et al.* 1993; Mooney *et al.* 2001) and represents arson by locals and increased human presence as tourism has increased since the 1960s.

Fire and flowering of *Xanthorrhoea* at Worimi Swamp

Prolific flowering after fire has been documented for many species of *Xanthorrhoea*, yet fire does not necessarily stimulate flowering. Flowering may also occur in the absence of fire, in response to cryptic aspects of a fire regime (such as seasonality, intensity, flame heights, fire interval), or may be related to smoke or the reproductive stage of the plant (Gill & Ingwersen 1976; Gill 1977; Lamont & Downes 1979; Bulow-Olsen *et al.* 1982; Curtis 1996; Taylor *et al.* 1998; Lamont *et al.* 2000).

These observations help explain the weak correlation ($r_s = 0.147$, $P \leq 0.01$) between the incidence of fire and flower scars along the caudexes of the sampled *Xanthorrhoea* in the Worimi catchment. This relationship between fire and flower scars is weakest in the uppermost 30 cm of the caudexes, representing the time since *c.* AD 1970 when four or five fires have burnt in the catchment. Although the primary juvenile period in *Xanthorrhoea* is short (Gill 1977), there is evidence to suggest that the time required by an adult plant to achieve the first post-fire reproduction (*viz.* the secondary juvenile period) is substantially longer, for example, up to 30 years in *Xanthorrhoea resinifera* (Keith 1996). Hence, it is possible that the recent fire regime has affected the reproductive capacity of the studied *Xanthorrhoea* population.

CONCLUSIONS

1. Cross-referencing sedimentary macroscopic charcoal and fire scars in *X. johnsonii* demonstrated that both proxies reveal fire activity at the site, although limitations were identified for each. The proxies used in this study probably best reveal large and intense fires.
2. The use of fire scars on *Xanthorrhoea* appears to provide an important proxy of past fire frequency, but detecting fire scars in older sections of the caudexes proved to be difficult due to their weathered nature and secondary growth. This means that it is probably limited to the last few hundred years, which nonetheless allows examination of the late prehistoric and historic periods in Australia. Importantly, the method may provide a proxy of past fire frequency in drier environments where sediment-based records do not exist.
3. The macroscopic charcoal and *Xanthorrhoea* analyses revealed that a substantial shift in the nature of the fire regime has occurred at Worimi Swamp but only during the 20th century. Rates of charcoal accumulation since about the mid- to late 1960s are unprecedented in the late Holocene.
4. In the prehistoric period at Worimi Swamp the paucity of evidence for past fires indicated either little activity or the skilful use of fire, such that charcoal was not delivered to the lake sediments and fire scars were not formed. These alternatives need to be evaluated using carefully crafted experiments in south-eastern Australia.
5. Increased fire activity in the prehistoric period at Worimi Swamp appears to be related to periods of warmer climates and cooler or less variable times with less fire. This implied that prehistoric fire regimes were climatically controlled, although whether human activity was also involved remains speculative. If climate was the dominant control on fire activity this has implications for the future under probable anthropogenic climate change.

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The vegetation history of the last glacial–interglacial cycle in eastern New South Wales, Australia

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ABSTRACT: We present a reconstruction of the vegetation history of the last glacial–interglacial cycle (ca. 75 k cal. yr BP–present) at Redhead Lagoon, an enclosed lake basin in coastal, eastern New South Wales, Australia. The sequence of vegetation change at the site is broadly comparable with the pattern of climatically induced changes observed in many other pollen records in southeast Australia. Open woodland–herbland and woodland–forest communities correspond with glacial and interglacial periods respectively, with an additional change towards a more open understorey vegetation assemblage over the last 40 000 yr. The driest conditions appear to have occurred during the height of the last glacial (some time between 30 and 20 k cal. yr BP). This is consistent with other records from southeast Australia, and provides support for a poleward shift in the subtropical anticyclone belt and, less certainly, for the thesis that the Southern Hemisphere westerlies intensified during this period. In marked contrast to most sites in southeast Australia, Casuarinaceae dominates the pollen record through the height of the last glacial period and into the Holocene. The postglacial climatic amelioration is accompanied by the general reappearance of tree pollen in the record, by the disappearance of several open and disturbed environment indicator taxa, by increases in organic sediment deposition and pollen taxon diversity, and by higher water balances. While climate appears to have been the major control on patterns of vegetation change at this site throughout most of the last glacial–interglacial cycle, changes in depositional environment and hydrology have also played a role. Significantly, substantial increases in the rate and magnitude of many indicators of environmental disturbance since European settlement suggest that humans are now the most important mechanism for environmental change. Copyright © 2006 John Wiley & Sons, Ltd.

KEYWORDS: Australia; late Quaternary; lake sediments; pollen analysis; human impact; climate change

Introduction

Many of the driving mechanisms of global environmental change are located in the Southern Hemisphere. Yet little is known of the long-term operation of these factors or their impact on the environment. This is largely due to the paucity of environmental sequences that span the last glacial–interglacial cycle, coupled with a lack of chronological resolution for many records.

Australia is of particular significance in this context since very few sites across the continent are capable of preserving long and detailed records of environmental change. The limited number of continuous and well-dated sequences has resulted in an incomplete understanding of the environmental response to changes in climate and human activities through a full glacial–interglacial cycle.

As well as being limited temporally, there are large gaps in the spatial record of the Australian Quaternary. Apart from Lake George, for example, there is no published sequence from New South Wales that spans the entire last glacial cycle. Moreover, despite its significance, the Lake George record contains significant hiatuses (Singh *et al.*, 1981), and both the causes attributed to the palaeoecological changes recorded at the site and their chronological interpretation have been the subject of criticism (Horton, 1982; Wright, 1986; McEwan Mason, 1991). Yet regional studies are crucial to understanding the nature of environmental change. Low spatial resolution data tend to encourage oversimplified interpretations of the nature and mechanisms of environmental change and, as Croke *et al.* (1996) have argued, the precise relationship between environmental shifts and climatic forcing mechanisms is often obscured at large scales of interpretation. For example, evidence for a poleward shift in the subtropical anticyclone belt and a possible strengthening of the Southern Hemisphere westerlies during the last glacial maximum is based on a sparse set of records from Australia and New Zealand (Harrison and Dodson, 1993; Shulmeister *et al.*, 2004). Filling the spatial gaps in this dataset is of critical importance in efforts to confirm and refine this model.

This paper outlines a reconstruction of the vegetation history of the last glacial–interglacial cycle at Redhead Lagoon, an enclosed lake basin in coastal, eastern New South Wales, Australia. This record is uniquely placed to contribute to our understanding of past climatic change and the impact it has had on the Australian environment. It not only fills an important temporal gap, by providing a record of environmental change through the last glacial period, but also a vital spatial gap through its location on the central region of coastal eastern Australia.

Site description

Internally-draining lake basins, often known locally as lagoons, represent one of the few geomorphic features found in Australia in which sediments of Quaternary age may be trapped and preserved. Redhead Lagoon (32° 59′ S, 151° 43′ E), located to the northeast of Lake Macquarie in coastal, eastern New South Wales, lies approximately 66 m above sea level in a depression on a coastal headland (Figs 1 and 2). The lake covers an area of 0.11 km², with a catchment of 0.59 km². Lake levels have varied by at least 2 m over the last 10 years. Under dry conditions, the shallower northern basin of the lake is transformed to a swamp. From our observations over the last decade and from the evidence of aerial photographs dating back to 1940, however, the southern basin appears to support permanent open water.

The northern part of the catchment is underlain by Permo-Triassic sandstones and conglomerates. These form steep slopes reaching elevations of up to 128 m AHD (Australian Height Datum). The southern section of the catchment is of lower relief and lower altitude, with vegetated, deeply leached, aeolian sand dunes blanketing the bedrock surface (Timms, 1976). Although most of the northern catchment is urbanised and has been cleared of native vegetation, much of the southern part is covered by dry sclerophyll woodland. *Melaleuca quinquenervia* and *Eucalyptus robusta* form a narrow fringe around most of the perimeter of the lagoon; the shallower, northern part of the lake supports sedgelands of *Eleocharis* sp., *Juncus* sp. and *Typha* sp.

The basin appears to be a sandstone karst feature (e.g. Jennings, 1983; Young and Wray, 2000) developed by the seepage of surface waters into the underlying aquifer. The focussing of chemical activity along fractures would have opened the depression and the fall in sea levels during Quaternary cold stages would have lowered water tables and enhanced vertical seepage. Support for this thesis is provided by the close match between the lake's morphology and the disposition of faults and dykes in the sandstone.

Redhead Lagoon experiences a humid, subtropical climate, with moist, warm to hot summers and cool to mild winters. It has a mean annual precipitation of 1142 mm, predominantly occurring between March and June. The annual mean daily maximum temperature is 21.3°C and the mean daily minimum temperature is 14.3°C (Bureau of Meteorology, 1995).

Land use in the catchment has changed dramatically through time. The site was originally a camping ground for the Awabakal Aborigines (Dyall, 1972). Following European settlement in the 1860s, vegetation was cleared for agricultural activities such as market gardening and the cultivation of orchards. A coal mine was established in the northwest of the catchment in the late

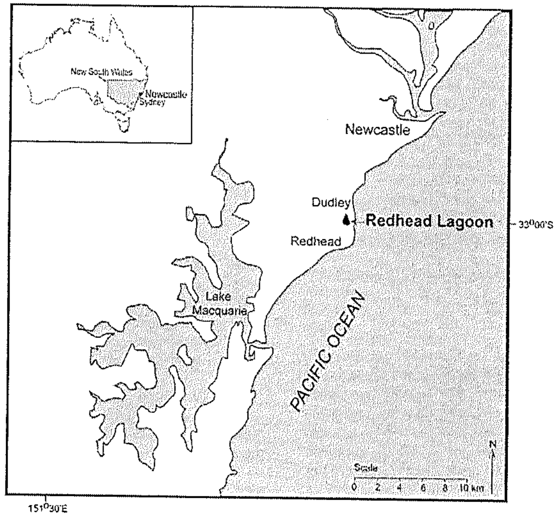

Figure 1 The location of Redhead Lagoon in coastal, eastern New South Wales, Australia

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1880s, leading to the rapid growth of the mining village of Dudley along the northern margins of the basin. Although the mine closed in 1939, Dudley has continued to expand and now functions largely as a suburb of the city of Newcastle.

Methods

In order to establish the detailed pattern of sedimentation in the lake basin, cores were taken from 43 stations across Redhead Lagoon, with up to three cores (coded a, b and c) recovered from several of the sites. Sampling was based on a 50-m grid aligned along the main axis of the lake (Fig. 2(b)). With two exceptions, all the cores were taken using 56 mm or 89 mm external diameter polyvinyl chloride tubing. The remaining two cores (E12b and E12c) were recovered using a 51 mm external diameter barrel vibrocorer, with the cores extruded into plastic sleeving on-site. The use of plastic liners allowed downcore variations in volume-specific magnetic susceptibility to be measured without extruding the cores from their sleeves. Measurements were taken at 20-mm intervals along each core following procedures similar to those described by Gale and Hoare (1991).

The downcore measurements of magnetic susceptibility were used to trace stratigraphic features from core to core to provide an understanding of patterns of sedimentation across the entire lake basin. On this basis, three cores were selected for detailed study. Core F4c was chosen to provide a detailed record of the middle and late Holocene and, particularly, the period since European contact. Core E12b was investigated to extend the record back into the Pleistocene. Core E12c was taken from within 2 m of E12b to supplement and check the E12b record and to extend the sequence as far back as available coring techniques allowed.

Cores E12b (5.80 m) and F4c (2.66 m) were carefully removed from their plastic sleeves and sliced into a series of cylinders, each 40 mm thick. Core E12c (7.30 m) was subsampled by extracting 1000 mm^3 cylinders of sediment at 25-mm intervals between 1.470 and 1.745 m, and at 30-mm intervals between 1.84 and 2.14 m. The cores were logged to provide a record of bed thickness, bed contacts, texture, organic content, colour, weathering phenomena, and sedimentary and pedogenic structures.

Subsamples (of 0.5–1.0 g dry mass) from cores E12b, E12c and F4c were prepared for pollen analysis using the standard methods of potassium hydroxide digestion, hydrofluoric acid treatment and acetolysis (Faegri *et al.*, 1989). A known quantity of *Lycopodium* spores was added to each sample prior to processing to enable the estimation of absolute abundances of pollen, expressed as grains per gram of dry sediment. Every 40 mm subsample from core E12b was processed down to a depth of 1.20 m; alternate subsamples were taken between 1.20 and 4.20 m; and every fourth sample was analysed between 4.20 m and the base of the core. This gave a total of 77 samples. Twenty-two samples from between 1.47 and 2.14 m in core E12c and 18 samples from between 0.30 and 2.60 m in core F4c were prepared for analysis. Palynological residues were mounted on microscope slides in silicon oil and counted using a transmitted light microscope under ×400 and ×600 magnifications. Where possible, a minimum of 200 dryland pollen grains per sample was counted. In some instances, extremely low pollen concentrations and poor preservation prevented this target from being achieved.

Identification of pollen grains was carried out using local reference material, Australian reference collections, image databases and a range of taxonomic texts (Boyd, 1992; Chalson and Martin, 1995; Pickett and Newsome, 1997; Shimeld *et al.*, 2000; Hopf *et al.*, 2001; Macphail and Hope, 2003). Nine types of Myrtaceae were identified using the classifications of Pike (1956) and Chalson and Martin (1995). These included *Acmena*, *Angophora*/Bloodwood eucalypts, *Baeckea*, *Callistemon*, *Calytrix*, *Eucalyptus*, *Eucalyptus*/*Melaleuca* type, *Leptospermum* and *Melaleuca*. Three morphological classes of Asteraceae were recognised—a fenestrate type (Asteraceae tribe Liguliflorae), and two Asteraceae tribe Tubuliflorae types (A and B). Asteraceae type B has a distinct blunted to spineless pollen morphology that is common in many Australian Pleistocene assemblages and has been interpreted as an indicator of glacial conditions (Edney *et al.*, 1990; Kershaw *et al.*, 1991; Harle, 1998). Two size classes of Casuarinaceae (<23 μm and >23 μm) were distinguished based on the diameters of the individual grains (Kershaw, 1970; Dodson, 1975, 1977a).

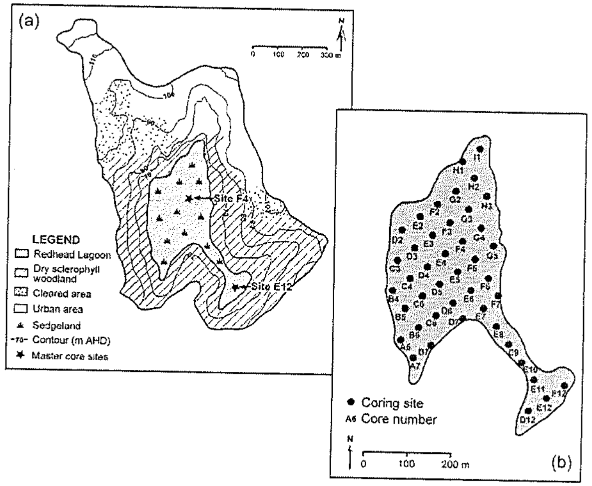


Figure 2 (a) The catchment of Redhead Lagoon in coastal, eastern New South Wales, Australia, (b) The pattern of coring sites in Redhead Lagoon

The taxa identified were classified into the following broad vegetation categories: rainforest trees and tree ferns, other trees, small trees and shrubs, woody and herbaceous taxa, herbaceous taxa, ground ferns, aquatic taxa and sedges, and exotic and unknown taxa.

In order to reconstruct changes in regional vegetation patterns and to allow comparison with similar studies elsewhere in Australia, the pollen sum used in this study consists of pollen taxa known to have region-wide dispersal; that is, all dryland types with the exception of those taxa such as *Melaleuca*, *Acacia*, *Leptospermum*, Chenopodiaceae and ground ferns, whose pollen is only locally dispersed (Dodson, 1977b, 1983; Macphail, 1979; Kodela, 1990a, 1990b, 1996; Kershaw *et al.*, 1994).

Pollen incidences were calculated and pollen diagrams were prepared using Tilia and TGView (Grimm, 1991) respectively. The pollen data are displayed as both percentages of the pollen sum and as absolute values of individual pollen taxa (Figs 3–6). Pollen zonation is based on a stratigraphically constrained cluster analytical procedure using the program CONISS (Grimm, 1987) and employing only the taxa selected for the pollen sum.

Results and interpretation

Chronostratigraphy and lithostratigraphy

A chronology of deposition in Redhead Lagoon extending back approximately 75 000 yr has been established on the basis of 20 radiocarbon ages and four optically stimulated luminescence (OSL) ages (Table 1). Lithostratigraphic and magnetostratigraphic linkages between individual cores have been employed to construct a composite stratigraphy and a composite chronology for the lake sediments, allowing the results of analyses from the various cores to be placed in a single stratigraphic and chronological sequence. The depths are normalised to the stratigraphy recorded at site E12 (Williams, 2005).

The composite lithostratigraphy is made up of three primary lithological units (Figs 3–7). The basal unit (6.13–4.33 m) consists of gray (10YR 6/1) to very dark gray (10YR 3/1) moderately sorted silty sands composed mainly of quartzose medium sand. This displays a sharp contact with the overlying sequence of black (10YR 2/1) to very dark gray (10YR 3/1) coarse silts (4.33–3.33 m). These contain rare quartz sands and fragments of charcoal and plant organic matter, whose incidence increases up the sequence. The upper unit (3.33–0.00 m), which exhibits a gradational contact with the underlying bed, consists predominantly of black (10YR 2/1) plant organic-rich silt, with occasional to common fragments of charcoal and plant organic matter.

The pollen record

Over 80 different taxa were identified in the Redhead Lagoon pollen record. Percentage and absolute pollen diagrams for the composite sequence are presented in Figs 3 and 4. Five distinct pollen assemblage zones were distinguished in the composite record. In stratigraphic order, these are RH5 (6.13–4.33 m), RH4 (4.33–1.69 m), RH3 (1.69–1.25 m), RH2 (1.25–0.82 m) and RH1 (0.82–0.00 m). RH1 has been further divided into subzones RH1c (0.82–0.54 m), RH1b (0.54–0.24 m) and RH1a (0.24–0.00 m). Pollen subzone RH1a was analysed in particular detail and the percentage and absolute diagrams corresponding to this section of the sequence have been reproduced in Figs 5 and 6 for greater clarity.

Pollen zone RH5 (early glacial: ca. 75 k cal. yr BP)

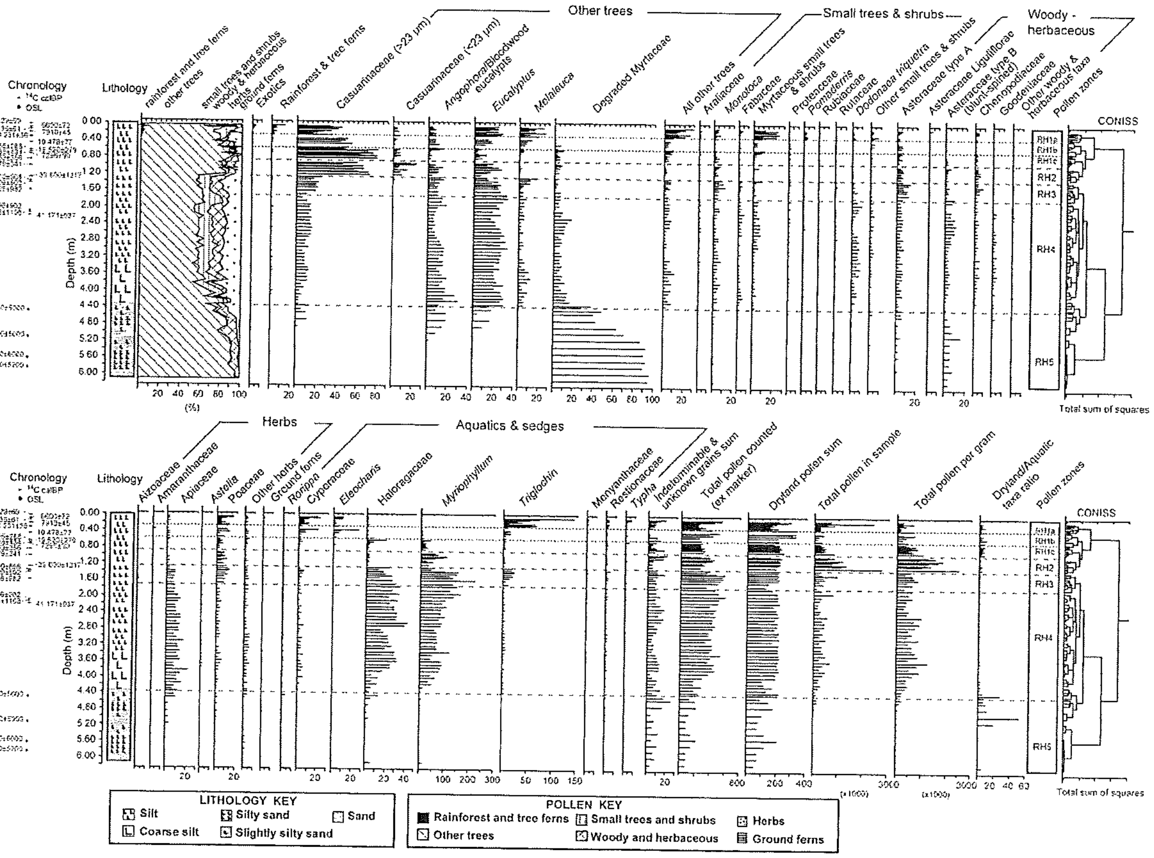
This pollen assemblage zone lies within the basal sand unit of the lake sediment stratigraphy and is characterised by extremely low pollen concentrations and low levels of taxonomic diversity. Most of the pollen in the zone is heavily degraded. The low pollen concentrations are probably the result of a combination of poor preservation conditions (the sands were deposited as aeolian dunes characterised by aerobic conditions deleterious to pollen) and high sedimentation rates. It is thus likely that the pollen assemblage is biased to those pollen types that were either originally present in large numbers or were sufficiently robust to resist destruction. Little can be said, therefore, of the nature of the regional or local vegetation at this time. That fossil pollen that has been preserved, however, indicates the presence of an open woodland–herbland vegetation association, with myrtaceous types and the glacial indicator taxon Asteraceae type B dominating the assemblage.

The highest ratios of dryland to aquatic taxa in the entire core are attained in zone RH5 at around 75 k cal. yr BP. A high proportion of dryland to aquatic taxa indicates either open water or, far more likely in this part of the core, an absence of water. A high level of aquatic taxa, by contrast, is generally indicative of closed (or shallow) water conditions (Kershaw, 1979). During the early part of the glacial period, it appears that Redhead Lagoon was devoid of aquatic taxa, and small amounts of *Rorippa*, Haloragaceae, *Myriophyllum* and Restionaceae pollen begin to appear only towards the top of the sand unit. This is interpreted as indicating an absence of permanent water in the basin until relatively shallow water conditions were initiated with the start of organic-rich silt deposition in pollen zone RH4.

Pollen zone RH4 (early to middle glacial:
ca. 75–40 k cal. yr BP)

Pollen zone RH4 reveals a dramatic change in the pollen assemblage. Pollen concentrations and taxonomic diversity increase significantly, while the relative incidence of degraded pollen decreases. These changes are probably the result of a shift in the nature of the depositional environment to more favourable pollen preservation conditions associated with the switch from sand to organic-rich silts. Casuarinaceae (>23 μm), *Angophora*/Bloodwood eucalypts and *Eucalyptus* are the predominant taxa throughout this zone, although the degraded Myrtaceae that dominated the previous pollen zone continues to persist throughout this zone. Small trees and shrubs, and woody and herbaceous types expand to their greatest levels in the sequence within this zone. Apiaceae, in particular, reaches

Figure 3 The composite chronostratigraphy, lithostratigraphy and selected percentage pollen incidence of the sediments of Redhead Lagoon, coastal, eastern New South Wales, Australia. The depths are normalised to the stratigraphy recorded at site E12



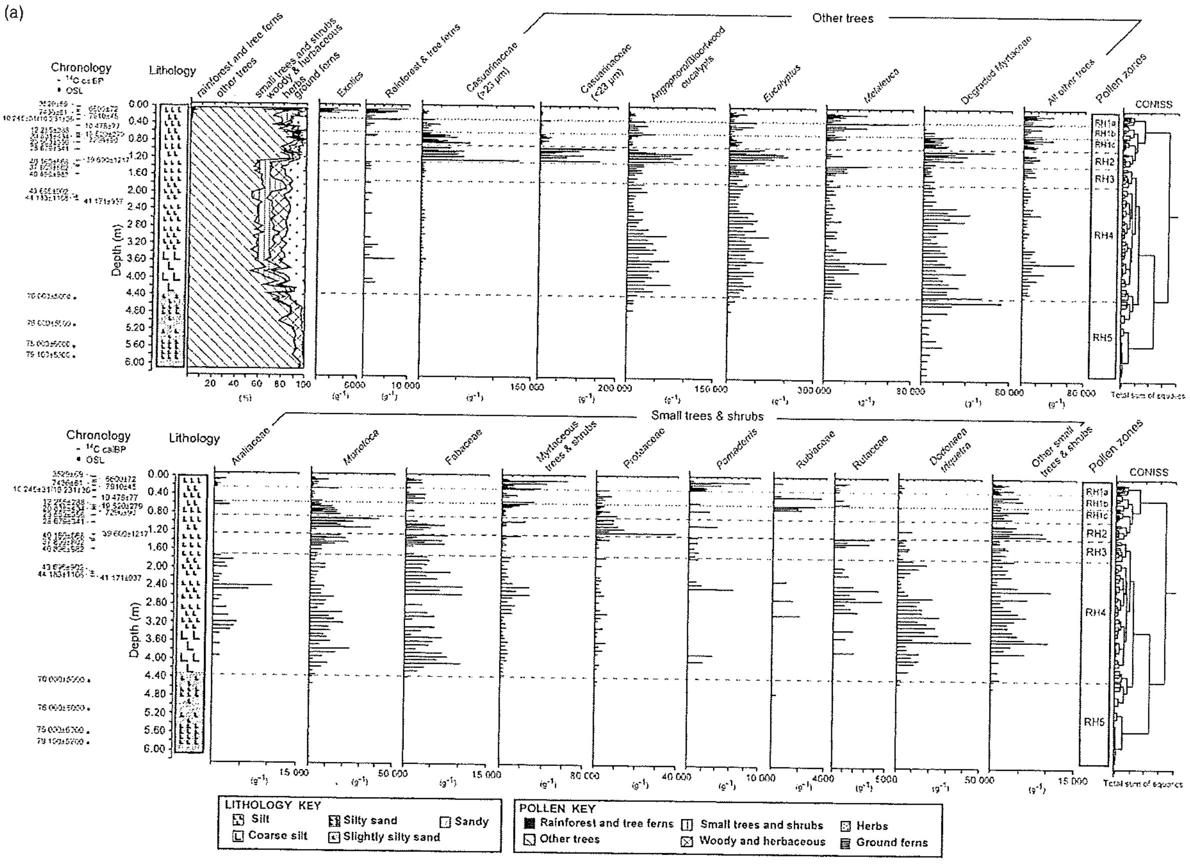


Figure 4 (Continued)

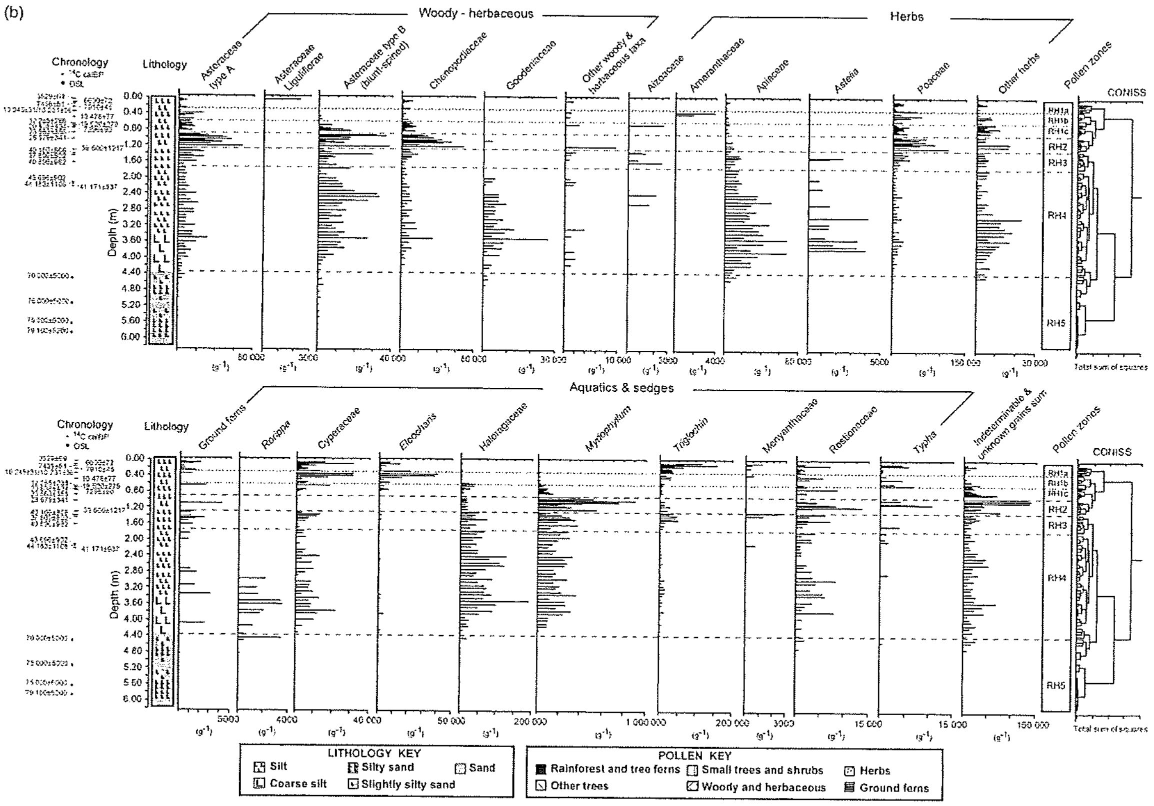


Figure 4 (a)The composite chronostratigraphy, lithostratigraphy and selected absolute pollen incidence of the sediments of Redhead Lagoon, coastal, eastern New South Wales, Australia. The depths are normalised to the stratigraphy recorded at site E12. Other trees, small trees and shrubs. (b) The composite chronostratigraphy, lithostratigraphy and selected absolute pollen incidence of the sediments of Redhead Lagoon, coastal, eastern New South Wales, Australia. The depths are normalised to the stratigraphy recorded at site E12. Woody and herbaceous taxa, herbs, aquatic taxa and sedges

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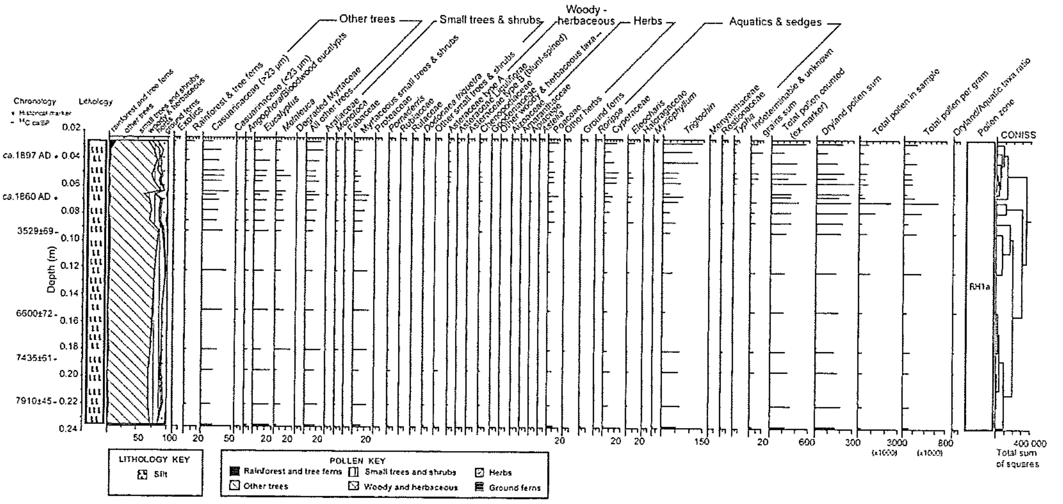

Figure 5 The composite chronostratigraphy, lithostratigraphy and selected percentage pollen incidence of the sediments of pollen subzone RH1a, Redhead Lagoon, coastal, eastern New South Wales, Australia. The depths are normalised to the stratigraphy recorded at site E12

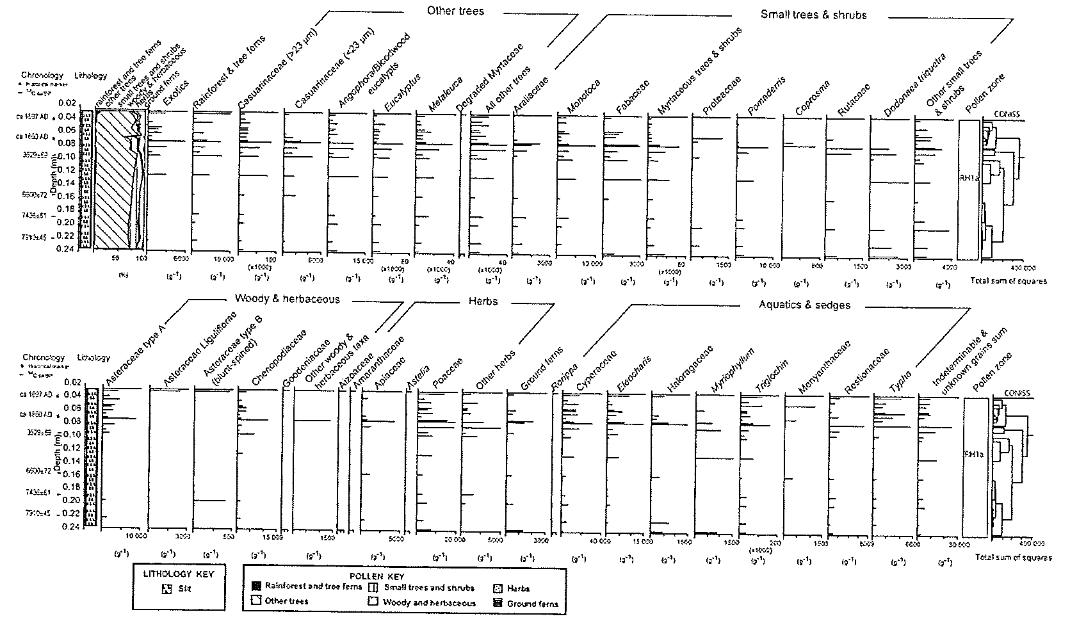

Figure 6 The composite chronostratigraphy, lithostratigraphy and selected absolute pollen incidence of the sediments of pollen subzone RH1a, Redhead Lagoon, coastal, eastern New South Wales, Australia. The depths are normalised to the stratigraphy recorded at site E12

Table 1 The composite chronostratigraphy of the sediments of Redhead Lagoon, coastal, eastern New South Wales, Australia. The depths are normalised to the stratigraphy recorded at site E12. Depth ranges represent the thickness of each sample. The radiocarbon ages are calibrated to calendar ages using the Cologne Radiocarbon Calibration and Paleoclimate Research Package CalPal 2005 SFCP. Ages are expressed with an uncertainty of ±1 standard deviation

Core	Dating method	Laboratory code	Mean normalised depth (m)	Sample material	$\delta^{13}C$ (‰)	Modern carbon (%)	^{14}C age (BP)	Calendar age (cal. BP)
F4c	Radiocarbon	Wk-8572	0.094 ± 0.002	Macroscopic charcoal	−27.6 ± 0.2	66.4 ± 0.5	3290 ± 60	3529 ± 69
	Radiocarbon	OZE080	0.156 ± 0.002	Macroscopic charcoal	−27.57	48.57 ± 0.31	5800 ± 60	6600 ± 72
	Radiocarbon	OZE081	0.188 ± 0.002	Macroscopic charcoal	−27.21	44.34 ± 0.31	6530 ± 60	7436 ± 61
E12b	Radiocarbon	OZG350	0.220 ± 0.020	Macroscopic charcoal	−25.0[a]	41.42 ± 0.22	7080 ± 50	7910 ± 45
	Radiocarbon	OZG777	0.380 ± 0.020	Microscopic organic matter	−24.4	32.38 ± 0.22	9060 ± 60	10 231 ± 36
	Radiocarbon	OZG352	0.380 ± 0.020	Macroscopic charcoal	−25.0[a]	32.28 ± 0.17	9080 ± 50	10 245 ± 31
E12c	Radiocarbon	OZG349	0.536	Macroscopic charcoal	−25.0[a]	31.47 ± 0.17	9290 ± 50	10 478 ± 77
	Radiocarbon	OZG786	0.706	Microscopic organic matter	−25.0[a]	27.37 ± 0.53	10 410 ± 160	12 255 ± 288
D3	Radiocarbon	OZG783	0.742 ± 0.020	Microscopic organic matter	−27.10	13.17 ± 0.19	16 280 ± 120	19 520 ± 279
E12c	Radiocarbon	OZG787	0.786	Microscopic organic matter	−25.5	11.65 ± 0.14	17 270 ± 100	20 838 ± 434
D3	Radiocarbon	OZG784	0.791 ± 0.020	Microscopic organic matter	−25.0[a]	45.33 ± 0.44	6360 ± 80	7296 ± 90
E12c	Radiocarbon	OZG348	0.906	Macroscopic charcoal	−25.0[a]	8.57 ± 0.10	19 740 ± 100	23 563 ± 356
	Radiocarbon	OZG788	1.066	Microscopic organic matter	−31.3	5.20 ± 0.09	23 750 ± 140	28 679 ± 341
E12b	Radiocarbon	OZG351	1.354 ± 0.020	Macroscopic charcoal	−25.0[a]	1.50 ± 0.06	33 750 ± 320	39 600 ± 1217
	Radiocarbon	Wk-8571	1.434 ± 0.020	Macroscopic charcoal	−24.2 ± 0.2	1.4 ± 0.1	34 020 ± 340	40 160 ± 868
	Radiocarbon	Wk-8574	1.474 ± 0.020	Macroscopic charcoal	−25.8 ± 0.2	1.8 ± 0.1	32 350 ± 280	37 809 ± 802
	Radiocarbon	Wk-7702	1.634 ± 0.020	Macroscopic charcoal	−25.1 ± 0.2	1.2 ± 0.1	35 660 ± 790	40 896 ± 982
	Radiocarbon	Wk-7703	2.154 ± 0.020	Macroscopic charcoal	−24.5 ± 0.2	0.7 ± 0.1	39 530 ± 1320	43 696 ± 902
	Radiocarbon	Wk-7704	2.194 ± 0.020	Macroscopic charcoal	−25.6 ± 0.2	0.7 ± 0.1	40 200 ± 1450	44 183 ± 1108
	Radiocarbon	Wk-7705	2.234 ± 0.020	Macroscopic charcoal	−26.3 ± 0.2	1.1 ± 0.1	36 060 ± 830	41 171 ± 937
Core	Dating method	Laboratory code	Mean normalised depth (m)	Sample material	Total dose rate (Gy ka^{-1})	Equivalent dose (Gy)	Luminescence age (a)	
E12b	OSL	GL02096	4.534 ± 0.120	Sand (quartz grains)	0.88 ± 0.05	61.7 ± 2.6	70 000 ± 5000	
	OSL	GL02097	5.174 ± 0.120	Sand (quartz grains)	0.75 ± 0.04	57.5 ± 2.4	76 000 ± 5000	
	OSL	GL02098	5.654 ± 0.120	Sand (quartz grains)	0.87 ± 0.05	66.0 ± 3.5	75 000 ± 6000	
E12c	OSL	WLL264	5.890 ± 0.110	Sand (quartz grains)	0.70 ± 0.04	55.1 ± 1.1	79 100 ± 5200	

[a] These values of $\delta^{13}C$ are assumed.

levels of over 20% in the lower part of this zone. Elsewhere in southeast Australia, the presence of Apiaceae has been interpreted as indicating annual mean temperatures at least 6°C lower than those of today (Kershaw and Bulman, 1996). Traces of the alpine herb *Astelia* in this zone also indicate a cool climate. The other herbaceous types present (for example, Goodeniaceae, Chenopodiaceae and Aizoaceae) all generally prefer well-drained and open situations. The increase in these and other non-arboreal taxa, and the relatively low dryland taxon diversity suggest the presence of an open woodland–herbland landscape existing under cool and possibly dry climatic conditions throughout the early to middle last glacial period. However, traces of *Pomaderris*, Rutaceae, *Melaleuca*, ground ferns such as *Calochlaena (Culcita)* and rainforest pollen such as *Acmena* in this zone indicate the existence of sheltered, moist places in woodland and periods of improved water balance.

The aquatic taxon record suggests shallow and possibly fluctuating water levels and an abundance of colonising aquatic taxa, with Haloragaceae (probably *Haloragis*) and *Myriophyllum* dominating the aquatic vegetation throughout this period. *Haloragis* is often found in moist swampy ground and *Myriophyllum* is an aquatic genus consisting of generally submerged aquatic plants, usually found in fresh to slightly brackish water up to a metre deep (Sainty and Jacobs, 1994). Some species of *Myriophyllum* flower in response to falling water levels (Orchard, 1985). An increase in this taxon may thus represent a decrease in water levels during its summer florescence (Gell *et al.*, 1993).

Pollen zones RH3–RH2 (middle glacial: ca. 40–20 k cal. yr BP)

Zone RH3 marks the start of a significant increase in both absolute and relative values of Poaceae, along with declines in absolute values of woody and herbaceous taxa such as Apiaceae, *Dodonaea triquetra*, Goodeniaceae and *Astelia*. These trends imply a shift from an open woodland–herbland to a grassland-dominated environment heading into the latter stages of the last glacial period. Within the upper part of zone RH3 there are increases in *Melaleuca*, Cyperaceae and *Triglochin*, suggesting water levels in the lake basin became more variable from around 40 k cal. yr in association with increasing aridity.

Zone RH2 spans the height of the last glacial period and is marked by high total pollen levels and a dominance of Casuarinaceae, which makes up over 70% of the pollen sum. The rainforest taxa of the early glacial are absent, suggesting the onset of drier conditions. Other taxa present during this period include *Angophora*/Bloodwood eucalypts, *Eucalyptus*, Asteraceae (types A and B), Chenopodiaceae and Poaceae. A decline in *Melaleuca*, Cyperaceae and *Triglochin*, along with an increase in *Myriophyllum*, may indicate shallow water levels and hence increased aridity during this period.

Pollen subzone RH1c (late glacial: ca. 20–10 k cal. yr BP)

Casuarinaceae (>23 μm) is overwhelmingly the dominant taxon in RH1c, both relatively and absolutely, reaching values of around 80% of the pollen sum through most of the subzone. The low percentage representation of many of the other taxa in this subzone is not replicated in the absolute diagram and is probably an artefact of the high Casuarinaceae values.

There are increases in the absolute numbers of Casuarinaceae, *Monotoca*, Proteaceae, Asteraceae type B and Chenopodiaceae in the initial part of this subzone. Both *Melaleuca* and rainforest taxa are absent for most of this period. The environment appears to have been characterised by Casuarinaceae-dominated open woodland, with a Poaceae and Asteraceae understorey.

The Casuarinaceae pollen that dominates subzone RH1c is largely made up of grains >23 μm in diameter. The only Casuarinaceae species currently found within the catchment of Redhead Lagoon, *Allocasuarina littoralis* and *A. torulosa*, both have pollen >23 μm. However, a significant number of aberrant Casuarinaceae grains was found in this subzone. Grains were classed as 'aberrant' if they possessed either two or four or more apertures, rather than the usual three. Kershaw (1970) recognised that a particular group (the *Casuarina distyla* group) was characterised by high variation in pore number. He suggested that this variation may be the result of polyploidy (the possession of multiple sets of chromosomes), as species known to contain polyploid members show wide variation in pore numbers. One member of this polyploid Casuarinaceae group is *A. littoralis*. It seems likely, therefore, that this species was present in the region during this period. The occurrence of normal grains in this part of the sequence and the overlap in the size ranges of *A. littoralis* and *A. torulosa* mean that the presence of *A. torulosa* cannot be ruled out. Nevertheless, the large number of aberrant grains in this zone indicates that the majority of Casuarinaceae pollen was derived from *A. littoralis* and that the contribution of *A. torulosa* is likely to be minor. *Allocasuarina torulosa* usually takes the form of a small tree and grows in moister situations than *A. littoralis* (Robinson, 1994). *Allocasuarina littoralis* has a range of forms (tree, small tree or shrub) depending on habitat. The majority of the increase in Casuarinaceae at this time may therefore represent small tree or shrub forms of *A. littoralis* that were able to find a source of water around the lake basin.

The aquatic vegetation during this period consisted predominantly of *Myriophyllum*, suggesting shallow and possibly fluctuating water levels at this time. The pollen assemblage as a whole is indicative of a harsh, dry environment, characterised by less complex vegetation communities than those of today.

Pollen subzone RH1b (early interglacial: ca. 10–8 k cal. yr BP)

Taxa from the 'other trees' category dominate the pollen assemblage throughout this subzone, attaining combined values of over 80% of the pollen sum. Although still the dominant individual taxon, Casuarinaceae percentages fall to around 50% from a maximum of close to 80% through most of the previous subzone. Absolute values of Casuarinaceae are also significantly less than in RH1c. There are increases throughout this subzone in the absolute incidence of several 'other tree' taxa, such as *Angophora*/Bloodwood eucalypts, *Eucalyptus* and *Melaleuca*. Poaceae attains its highest absolute representation in the record and Amaranthaceae makes its first and only appearance in the sequence within this subzone. Significantly, subzone RH1b marks the end of the abundance of Asteraceae type B, with only rare traces of this type found above the base of this unit. In addition, there is a significant decrease in Chenopodiaceae following elevated levels in the previous two zones. The total number of indeterminable and unknown grains also decreases dramatically through this subzone, to its lowest level in the entire sequence.

Subzone RH1b marks the end of the primacy of Haloragaceae and *Myriophyllum*, the dominant aquatic taxa in all the preceding zones. Their role is taken instead by Cyperaceae (including *Eleocharis*), with support from *Triglochin*, Restionaceae and *Typha*. This may reflect hydroseral succession processes, including the development of a fringing Cyperaceae-dominated community around the lake edges.

Moist environment indicators such as *Pomaderris* and Rutaceae are either absent or near-absent during the early Holocene. This, in conjunction with a general decrease in the relative abundance of aquatic taxa for most of this period, may reflect lake shallowing, possibly a result of increased sedimentation and lower water balances. The deteriorating water balance may have been caused by an increase in evapotranspiration as a result of rising temperatures during this period of rapid climatic amelioration.

Pollen subzone RH1a (middle to late interglacial: ca. 8 k cal. yr BP–present)

The middle Holocene is characterised by highly organic deposition, and by increases in pollen diversity and in the overall abundance of small trees and shrubs, woody and herbaceous taxa, and rainforest types. Trees such as Casuarinaceae, *Angophora*/Bloodwood eucalypts, *Eucalyptus* and *Melaleuca* are dominant throughout most of this subzone, although there is a decrease in the relative abundance of Casuarinaceae, apparently a result of the concurrent rise in absolute values of taxa such as *Eucalyptus* and *Melaleuca*. *Melaleuca quinquenervia* was separately identified within the *Melaleuca* pollen count. This species reaches its highest levels in the entire sequence during the middle to late interglacial, culminating in the current dominance of this swamp- and marsh-loving taxon along the lake margin.

The rainforest taxa identified within this subzone include trees and ferns such as *Cyathea, Elaeocarpus, Nothofagus moorei* and *Acmena*. Increases in these rainforest and tree fern taxa, along with increases in Rutaceae, fern spores, and the wet sclerophyll forest indicator, *Pomaderris*, point to the development of more sheltered, moist conditions in the middle Holocene. The dryland pollen counts are thus indicative of open woodland and wet sclerophyll forest coexisting with a grassland understorey, with taxa such as Casuarinaceae, *Eucalyptus, Melaleuca* and small myrtaceous trees and shrubs dominating the pollen spectra.

The aquatic taxon *Hydrocotle* (within the Apiaceae family) reappears in this period after its absence at the height of the last glacial, indicating a return to more permanent freshwater conditions (Sainty and Jacobs, 1994). *Triglochin*, Restionaceae and *Typha* reach their maximum or near-maximum abundance in the middle to late Holocene. Increases in these taxa suggest more open (possibly deeper), stable and freshwater conditions in the lake basin during the late Holocene.

Exotic indicator species (such as *Plantago lanceolata, Pinus* and cultivated Poaceae grains with diameters >50 μm) all appear for the first time during the upper part of this subzone, signalling the start of European settlement at the site. European contact is also marked by sharp decreases in a number of taxa from the other trees, and small trees and shrubs categories, with a concurrent increase in several woody and herbaceous types of taxa, including Asteraceae and Poaceae. These changes in the pollen record may reflect land clearance and the increasing fragmentation of forest communities after European settlers arrived in the catchment.

There are significant increases in both the absolute and percentage abundance of *Typha* in the post-contact part of the sequence. *Typha* grows vigorously and may dominate and outcompete other aquatic plants in shallow areas receiving nutrient-rich runoff (SWC Consultancy, 1998). The increase in *Typha* in the European period may therefore be a response to elevated levels of nutrients as a result of agricultural and urban activities in the catchment. This explanation has been advanced to explain post-contact increases in *Typha* at other sites in New South Wales, including Trenerry Reserve (Dodson *et al.*, 1995) and Wingecarribee Swamp (Kodela, 1996).

Environmental change through the last glacial–interglacial cycle

Early last glacial (ca. 75–40 k cal. yr BP)

The poor pollen preservation and low pollen concentration of the lower part of the sequence leave the reliability of the vegetation reconstruction at Redhead Lagoon around 75 k cal. yr BP open to question. Nevertheless, the dryland pollen that has been preserved is indicative of an open woodland–herbland vegetation association, with myrtaceous types and the glacial indicator taxon, Asteraceae type B. These results accord with other studies that have suggested that greater continentality and seasonality, and reduced atmospheric carbon dioxide levels during this period may have militated against extensive tree survival over much of southern Australia, producing erodible landscapes and facilitating aeolian activity (Kershaw, 1995; Hesse *et al.*, 2004).

The incidence of herbaceous and generally hardy taxa increases upsequence, with higher values of the cold or glacial taxa, Asteraceae type B and Apiaceae. The increase in these and other non-arboreal taxa, along with moderate pollen concentrations and a relatively low dryland taxon diversity, suggests the presence of open woodland–herbland under cool and possibly dry climatic conditions for most of the early glacial period.

The complete absence of aquatic taxa and the deposition of wind-blown sands in the lake basin are indicative of very dry conditions around 75 k cal. yr BP. The evidence of dust deposition at this time across the North and South Island of New Zealand (Shulmeister *et al.*, 2004) and, less certainly, in the Tasman Sea (Hesse, 1994; Kawahata, 2002) suggests that these conditions may have been experienced widely across the region. For the remainder of the early glacial, water levels remained shallow and possibly fluctuating. Colonising taxa such as Haloragaceae (probably *Haloragis*) and *Myriophyllum* dominated the aquatic vegetation during this time. Sea levels would have varied between approximately −35 and −90 m MSL during this period (Chappell *et al.*, 1996). This would have exposed the continental shelf and left the site between perhaps 5 and 15 km from the coast (Thom *et al.*, 1992). The resultant reduction in precipitation may help to explain the presence of open woodland–herbland vegetation at the site for most of this period.

Middle to late last glacial (ca. 40–10 k cal. yr BP)

Around 40 k cal. yr BP, the pollen record indicates a notable shift from open woodland–herbland to a grassland-dominated environment. Poaceae, Chenopodiaceae, Asteraceae type A and the glacial indicator, Asteraceae type B, all peak in this period. This change occurs within the subpluvial episode that has been identified between ca. 55 and 30 k cal. yr BP at a range of sites throughout eastern Australia (e.g. Bowler, 1981, 1986; Nanson *et al.*, 1992; Page *et al.*, 1996). The subpluvial may itself have been the product of snowmelt associated with the period of cold climates that gave rise to the Headley Tarn Advance glaciation of the Snowy Mountains (Barrows *et al.*, 2001) and with evidence of sustained aridity between 40 and 30 k cal. yr BP from southwest New South Wales (Bowler *et al.*, 2003).

The occurrence of cold climates during this period is supported by the peak in representation of the glacial indicator, Asteraceae type B, and the occurrence of other cold climate taxa, such as

Apiaceae. The driest period appears to have occurred in the latter part of this period, probably between 30 and 20 k cal. yr BP, when rainforest taxa were absent. Taxonomic diversity also appears to have been reduced during this period.

Increases in *Melaleuca*, Cyperaceae, *Myriophyllum* and *Triglochin* from around 40 k cal. yr BP are consistent with water levels becoming lower and more variable in association with increasing aridity. During the latter part of this period, the reduction in the incidence of these taxa and the high values of Chenopodiaceae accord with evidence for increased salinity and the existence of the lowest water levels in the record.

Numerous other sites throughout southeast Australia preserve evidence of similar conditions between ca. 25 000 and 11 000 ^{14}C yr ago. These include Lake Leake (Dodson, 1975), Wyrie Swamp (Dodson, 1977a), Lake Bullenmerri (Dodson, 1979), Pulbeena Swamp (Colhoun *et al.*, 1982), Lake Wangoom (Edney *et al.*, 1990) and Burraga Swamp (Sweller and Martin, 2001). Although climatic factors, such as lower temperatures and steeper pressure gradients, are likely to have been the major cause of the extremely dry and possibly cold conditions experienced during this period, the reduction in maritime influence associated with the increased distance to the coastline may also have been significant. Given sea levels of between approximately −65 and −120 m MSL (Chappell *et al.*, 1996), the coast would have lain between perhaps 5 and 20 km east of its present location (Thom *et al.*, 1992). A change in atmospheric circulation is also likely to have played a role, with evidence from sites in Australia and New Zealand suggesting a poleward displacement of the subtropical high-pressure belt and enhancement of the Southern Hemisphere westerlies during the last glacial period (Shulmeister *et al.*, 2004). This in turn would have contributed to drier conditions in southern and southeast coastal regions of Australia (Harrison and Dodson, 1993).

Relatively few records preserve evidence of vegetation during the height of the last glacial period in Australia. Those from southeast Australia point to treeless conditions dominated by Poaceae and Asteraceae (Hope, 1994). Kershaw (1995) has calculated the average percentages of the major taxa from 11 southeast mainland Australian pollen datasets for this period. Poaceae and Asteraceae in combination recorded an average of 79%, whereas the mean incidence of Casuarinaceae was only 3%. Although the results from Redhead Lagoon support the picture of elevated levels of Poaceae and Asteraceae, the environment of the site was not treeless. Indeed, the extremely high proportion of Casuarinaceae (around 80%) at this time is in sharp contrast to most southeast Australian pollen records. This may reflect in part the northerly location of Redhead Lagoon by comparison with Kershaw's (1995) reference sites, which lie almost without exception in Victoria. It may also reflect the fact that, unlike most other southeast Australian sites, locally moist conditions were maintained throughout the height of the last glacial period at Redhead, allowing the survival of Casuarinaceae. Although it is possible that the Casuarinaceae present at this time may have been small trees or shrubs, Redhead Lagoon provides one of the few records of the presence of arboreal pollen during the height of the last glacial in Australia. The existence of this glacial refugium has important implications for our understanding of the processes of postglacial vegetational recolonisation.

The Holocene (ca. 10 k cal. yr BP–present)

The early interglacial was a period of major environmental change at Redhead Lagoon. Significantly, this period marks the end of the dominance of the glacial indicator taxon, Asteraceae type B. The disappearance or decline of Asteraceae type B during the Holocene has also been noted at several western Victorian sites, including Tower Hill (D'Costa *et al.*, 1989), Lake Wangoom (Edney *et al.*, 1990; Harle *et al.*, 1999) and Lake Terang (D'Costa and Kershaw, 1995).

Moist environment indicators such as *Pomaderris* and Rutaceae are either absent or near-absent during the transition to the early interglacial. This, in conjunction with a general decrease in the relative abundance of aquatic taxa for most of this period, may reflect lake shallowing, possibly a result of increased sedimentation and lower water balances. The deteriorating water balance may have been caused by an increase in evapotranspiration as a result of rising temperatures during this period of rapid climatic amelioration. This response is very similar to that of other lakes throughout southeast Australia, which display generally low water levels during the Pleistocene–Holocene transition (Harrison and Dodson, 1993).

The early interglacial was also marked by a decrease in the proportion of Casuarinaceae, which had dominated the open woodland vegetation at the site since the start of subzone RH1c. This appears to be a consequence of rises in the absolute incidence of taxa such as *Eucalyptus* and *Melaleuca*. The pattern of an initial increase of Casuarinaceae in the early Holocene, followed by a decline in relation to *Eucalyptus* in the middle to late Holocene is evident in a number of sequences from southeast Australia (D'Costa *et al.*, 1989; Harle *et al.*, 2004). This has been attributed to various causes, including increases in burning, soil salinisation and improvements in water balances. The same pattern is observed at Redhead Lagoon, although the timing of the Casuarinaceae expansion and the decline relative to *Eucalyptus* is earlier at this site. The microscopic charcoal record from Redhead Lagoon indicates that the relative decline in Casuarinaceae throughout the Holocene cannot be attributed to increased burning (Williams, 2005). However, the Chenopodiaceae/Casuarinaceae ratio, an indicator of salt-tolerance (Crowley, 1994a, b), suggests that soil salinisation may have contributed to the changing representation of Casuarinaceae and *Eucalyptus* over the last glacial period (Fig. 7). While reduced moisture availability may have facilitated the expansion of Casuarinaceae relative to *Eucalyptus* in the late glacial period, the restriction of Casuarinaceae representation during earlier arid periods indicates that this cannot have been the sole factor at work (Fig. 7).

As the Holocene progressed, there is evidence of wetter conditions in southeast Australia (Harrison and Dodson, 1993; Hope *et al.*, 2004). This trend is also seen at Redhead Lagoon, as the middle Holocene signals the start of highly organic deposition, an increase in pollen diversity and the development of woodland and forest communities, including wet sclerophyll forest. There is also some evidence for the re-emergence of rainforest elements. The Redhead Lagoon sequence suggests climates were relatively stable between 8 and 3.5 k cal. yr BP, although the rather coarse resolution of the record (Figs 5 and 6) hampers a more exact reconstruction.

Finally, the arrival of Europeans at the site marked the start of major modification of the catchment surface. This involved land clearance, small-scale cultivation, and grazing, mining and urbanisation. The consequences included significant increases in sediment accumulation rates (Gale, 2003), firing of the catchment (Williams, 2005) and elevated levels of nutrients (Franklin, 1997). These changes have been identified in many post-contact sequences in southeast Australia (Dodson and Mooney, 2002). Declines in some tree and rainforest taxa with concurrent increases in several woody and herbaceous taxa may reflect land-clearing practices and the increasing

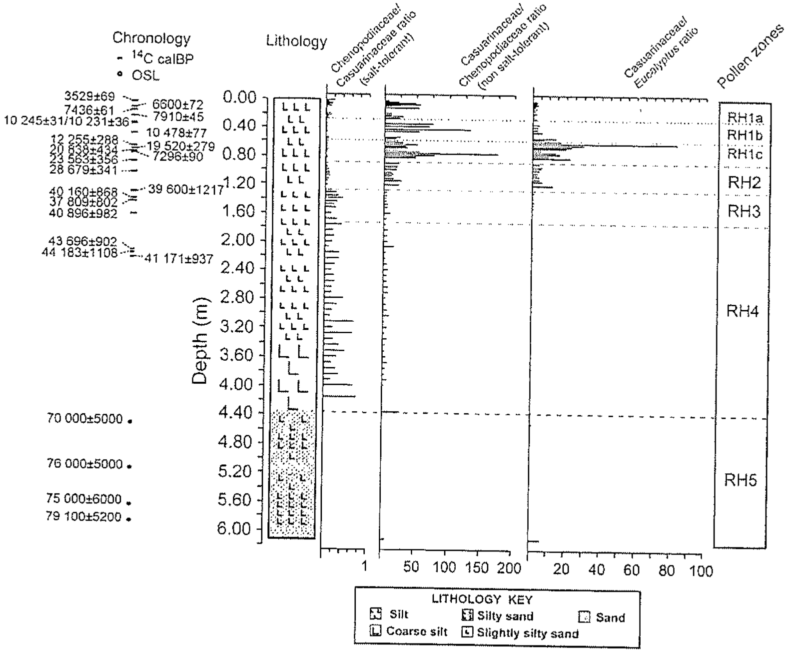

Figure 7 The composite chronostratigraphy, lithostratigraphy and selected pollen ratios (Chenopodiaceae/Casuarinaceae, Casuarinaceae/Chenopodiaceae and Casuarinaceae/*Eucalyptus*) of the sediments of Redhead Lagoon, coastal, eastern New South Wales, Australia. The depths are normalised to the stratigraphy recorded at site E12

fragmentation of forest communities after European settlers arrived in the catchment.

Conclusions

Redhead Lagoon possesses one of the best-dated records of environmental change through the last full glacial–interglacial cycle so far available in Australia. The lake provides much-needed information on the vegetation history of eastern Australia from a location part way between the large number of sites that have been investigated in Victoria and the cluster of records from northeast Queensland.

The near-continuous sequence of deposits at Redhead Lagoon has provided a high-resolution record of vegetational change. The broad picture is one of alternating open woodland–herbland and woodland–forest communities, corresponding with glacial and interglacial periods respectively. However, along with climate, variations in depositional environment, hydrological changes and human activities have all played a role in determining vegetational change throughout this period.

Redhead Lagoon provides one of the few records of trees during the height of the last glacial period in Australia. Noteworthy too is the dominance of Casuarinaceae at the site through the end of the last glacial and into the Holocene. This is in marked contrast with the generally low values of Casuarinaceae at most sites in southeast Australia at this time. This may reflect in part the northerly location of Redhead Lagoon by comparison with other sites that preserve records during this period. It may also reflect the fact that, unlike most other southeast Australian sites, locally moist conditions were maintained throughout the height of the last glacial period at Redhead, allowing the survival of Casuarinaceae.

The evidence from the Redhead Lagoon record is indicative of alternations in the intensity of cool climates during the last glacial. This may accord with evidence from alpine mainland Australia for several ice advances during this time. The driest conditions, however, appear to have occurred during the height of the last glacial (some time between 30 and 20 k cal. yr BP). This is consistent with other records from southeast Australia, and provides support for the model of a poleward shift in the subtropical anticyclone belt and a possible intensification of the Southern Hemisphere westerlies during this period.

Finally, the vegetation record provides evidence of increasing fragmentation of forest communities over the last 150 years. This is likely to be a result of the intensification of land use since European settlement in the region. Indeed, the arrival of Europeans at the site may have had as much impact on the landscape as any of the climatic changes of the previous 75 000 yr.

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