

# A high-resolution record of vegetation and climate through the last glacial cycle from Caledonia Fen, southeastern highlands of Australia

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**ABSTRACT:** A blocked tributary has provided a rare site of long-term sediment accumulation in montane southeastern Australia. This site has yielded a continuous, detailed pollen record through the last ca. 140 000 years and revealed marked vegetation and environmental changes at orbital to sub-millennial scales. Radiocarbon and optically stimulated luminescence (OSL, or optical) ages provide some chronological control for the last ca. 70 000 years. Most of the sediment is inorganic but with well preserved pollen that accumulated under unproductive and probably largely ice-covered lake conditions. The lake was surrounded by low-growing plants with an alpine character. Exceptions include three discrete periods of high organic sedimentation in the basin and forest development in the surrounding catchment. The two major periods of forest expansion are related to the last interglacial and the Holocene, with the third, shorter period considered to represent an interstadial in the early part of Marine Isotope Stage (MIS) 3. The latter part of the last glacial period is characterised by abrupt sub-millennial, amelioration events that may relate to documented global oscillations emanating from the North Atlantic. There are systematic changes through the record that can be partly attributed to basin infilling but the progressive reduction and regional extinction of some plant taxa is attributed to a long-term trend towards climatic drying. Copyright © 2007 John Wiley & Sons, Ltd.

  
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**KEYWORDS:** late Quaternary; climate change and variability; vegetation dynamics; optical dating; southeastern Australia.

## Introduction

Southeastern Australia has been a focus for palynological studies that cover at least the last glacial cycle, though a regional picture for comparison with other parts of the world has been difficult to establish. Lake George (Singh *et al.*, 1981;

Singh and Geissler, 1985) provides a general record through the Mid–Late Pleistocene and Holocene, but concerns over continuity of sediment deposition within this large tectonic lake system, variable pollen preservation and limitations of dating, have not allowed detailed comparison with other long terrestrial records or the marine isotope record. The volcanic crater setting of Lake Wangoom appears to provide clear pollen variation on the orbital timescale but uncertainty in the chronology, that has depended largely on uranium/thorium (U/Th) disequilibrium dating, has resulted in debate over whether one or two glacial cycles is represented (Harle *et al.*, 1999, 2002; Kershaw and van der Kaars, 2007). Lake Selina, ‘outside LGM glacier limits’ in western Tasmania, provides evidence of vegetation changes within the most humid part of southeastern Australia (Colhoun *et al.*, 1999, Colhoun, 2000).

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The record is interpreted to cover, and exhibits major changes that may be in phase with, the last glacial cycle as recorded in the marine stratigraphy although the chronology remains uncertain.

The establishment of detailed records with robust chronologies is critical for the understanding of regional influences on global climate change at orbital and sub-orbital scales. Despite the apparent dominance of glacial–interglacial cyclicity in records from the north Atlantic region, there is increasing evidence in the broader Australasian region that regional insolation has directly (e.g. Vandergoes *et al.*, 2005) or indirectly, through the operation of influences such as the El Niño–Southern Oscillation (e.g. Kershaw *et al.*, 2003a) and the northwest Australian monsoon (Kershaw and van der Kaars, 2007), modified or overwhelmed any Northern Hemisphere signal. Furthermore, it has been suggested that sub-orbital variation in northeastern Queensland, although in phase with events in the North Atlantic, has actually resulted from regional ENSO forcing and been transmitted to the Northern Hemisphere rather than being derived from it (Turney *et al.*, 2004).

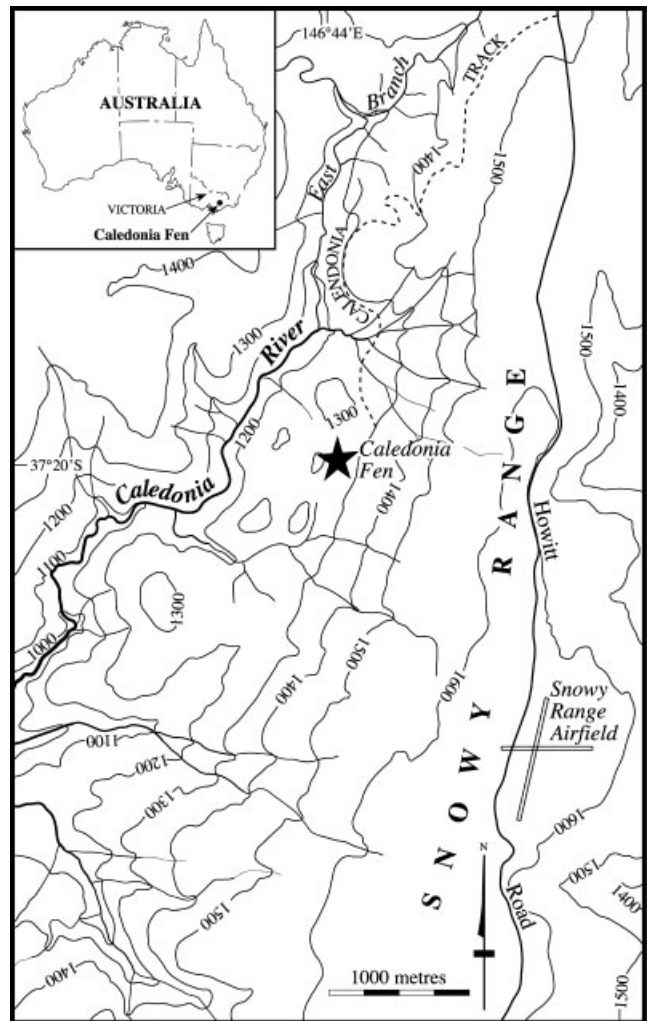
There is also evidence that Australia has experienced a long-term trend towards drier or more variable climatic conditions (Hesse *et al.*, 2004; Kershaw *et al.*, 2003b, 2006) that has not been readily apparent in other parts of the world. It has been suggested that this may relate to Australia's continued northerly movement into Southeast Asia and the impact of this on the Indonesian Throughflow, the Western Pacific Warm Pool and ENSO activity (Kershaw *et al.*, 2003a). The situation is compounded by suggested landscape alteration due to burning by Aboriginal people who were present by at least 45–50 000 years ago (Bowler *et al.*, 2003; Gillespie, 2002; Roberts and Jones, 2001). It has been hypothesised that vegetation communities were sufficiently altered to induce drying through a reduction in monsoon influence through at least the interior of the continent (Miller *et al.*, 2005).

The Caledonia Fen pollen record is well positioned to further our knowledge of Australian, and more specifically south-eastern Australian, climate history and address major issues because of its detailed and continuous nature, the supposed sensitivity of the high-altitude environment to climate change, and the suitability for both accelerator mass spectrometry radiocarbon dating and optical dating. Although the chronology is still less than ideal, it is more secure than other continuous, terrestrial records from the region.

The palynological potential of Caledonia Fen was revealed in 1979 in a record that extended back to an estimated 30 000 years BP (Joyce, 1979; Kershaw *et al.*, 1991); further investigation was limited by the inorganic nature of last glacial sediments that inhibited dating by conventional radiocarbon dating and by the lack of ability to core deeper than 3 m due to the site inaccessibility and lack of appropriate drilling equipment. Overcoming these limitations has resulted in the production of a record that is estimated to continuously cover the period from the end of the penultimate glacial to the present. Detailed pollen analysis of the 19 m core provides an average estimated sampling interval of about 240 years.

## The site and its regional setting

Caledonia Fen (37° 20' S, 146° 44' E: 1280 m a.s.l. (above sea level)) lies in a mountainous tract within the Alpine National Park in the Snowy Plains region of the Australian Alps, between Mt. Howitt (1715 m) to the north and Mt. Wellington (1606 m) to the south, within the catchment of the eastern branch of the



**Figure 1** Location of Caledonia Fen in the southeastern highlands of Victoria. Based on the Tamboritha–Moroka 8223–S.1:50 000 Topographic Map, Survey and Mapping Victoria, 1992

Caledonia River (Fig. 1). The fen is approximately 300 m long and 160 m wide at its widest point and covers an area of about 15 ha. It occupies an unusual position, being perched on the valley side midway between the Caledonia River and the Bennison Plains and is accompanied by a second, similar but dry, depression. It is presently drained by a small, intermittent outlet stream to the south. The landscape is dominated by Upper Devonian and Lower Carboniferous non-marine sediments of siltstone, sandstone, feldspathic sandstone, mudstone and conglomerate of the Snowy Plains Formation which overlie basal Ordovician marine sediments of siltstone, silty shale and feldspathic sandstone. To the north, outside the catchment of the fen, Tertiary basaltic lavas cap peaks in the Snowy Range.

The small elevated depression in which the Fen is located has been eroded into the slopes of the Snowy Range by a trellised tributary of the Caledonia River (Fig. 2). Stereoptic analysis of aerial photographs indicates that the valley is a structural landform controlled by the dipping sedimentary strata of the Snowy Plains Formation. It is a small north–north-east–trending strike valley constrained by a long (750–800 m) and high (1300 to 1570 m a.s.l.) dip slope in the east and a short (approx. 20 m) scarp slope in the west. Strike is NNE. Minor shape variations in the mid to lower slope east of the fen result from erosion of the dip slope less than 30° strata. The short length of the western scarp slope limits the number of exposed sedimentary strata here.



**Figure 2** View north across Caledonia Fen (circled) and the surrounding region. Image was produced using Google Earth™ version 3.0.0762. Digital mapping and image data are provided by Google Earth™ mapping service, Europa Technologies Ltd and TerraMetrics Inc. Reproduced with permission of Google Earth™ mapping service

Reconnaissance field investigation revealed that the lower (southern) end of the fen contains thick mass movement deposits in the tributary depression that are now partly incised by the small outlet stream. These deposits have probably blocked the tributary and led to the sedimentary backfilling in the fen, whereas other strike depressions in the area are predominantly erosional in nature.

The region experiences a temperate climate with winter-dominated rainfall (Bureau of Meteorology, 1989). Although the westerly wind system brings moist and cloudy weather through much of the year, the region also experiences cold air masses emanating from the Southern Ocean close to Antarctica and also moist and warm tropical maritime air from the southern Pacific Ocean (Sturman and Tapper, 2005). The Pacific trade winds may explain the significant influence of ENSO rainfall variability especially in winter and spring (Drosowsky and Williams, 1991). Actual climate data are not available for Caledonia Fen. However, site-specific estimates have been generated by a bioclimatic prediction system (ANUCLIM; Busby, 1991; Houlder *et al.*, 1999). They indicate that the mean annual rainfall is 1530 mm, precipitation of the wettest quarter (winter) is 520 mm, precipitation of the driest quarter (summer) is 238 mm, mean annual temperature is 7.3°C, maximum temperature is 19.1°C and minimum temperature is -1.2°C. Mean monthly temperatures are highest in January and February and lowest in July. In cooler months blizzard conditions may bring subzero maximum daily temperatures for several days at a time and frosts are common

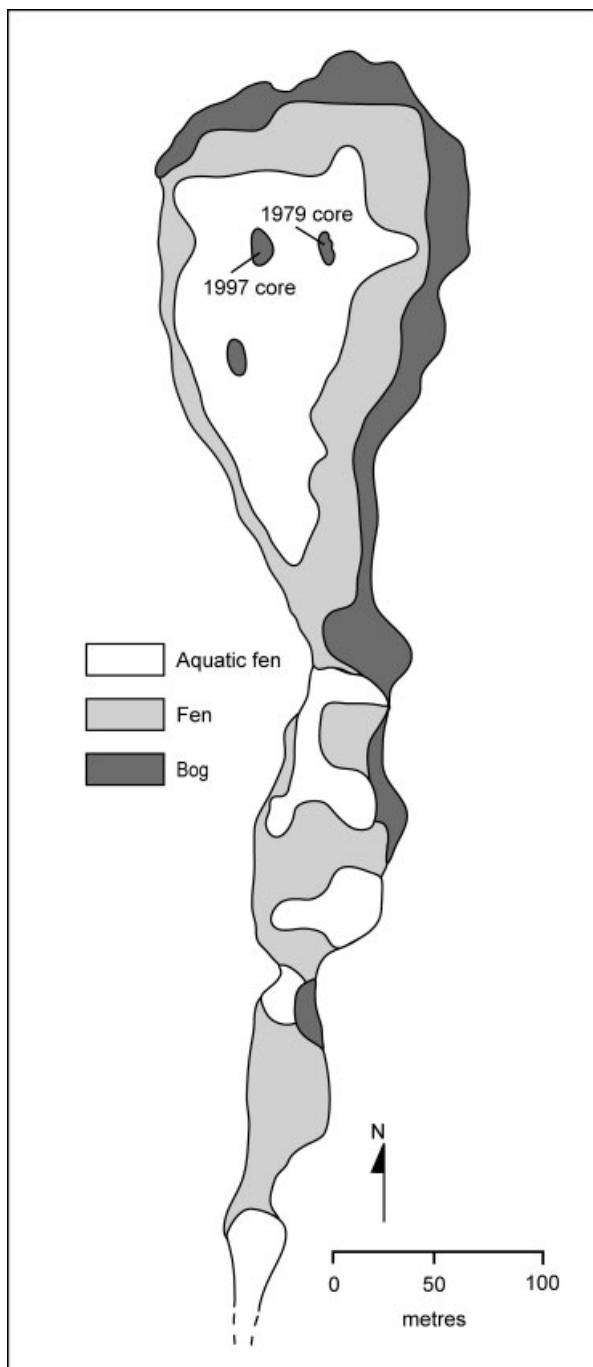
even in the warmest months. At altitudes above 1500 m, winter precipitation is predominantly as snow which accumulates from June until the spring thaw begins in September. As there is no permanent stream flow into the fen, snowmelt is its major source of water. Generally speaking, precipitation in the alpine and sub-alpine regions is often erratic and may occur in the form of rain, mist, snow or hail with low cloud and fog at any time of the year. The unpredictability of precipitation may lead to water stress in summer (Farrell and Ashton, 1973), and especially during El Niño periods.

Variations in climate, topography, and soils and their parent materials have resulted in a wide range of plant communities within a few kilometres of Caledonia Fen (Land Conservation Council of Victoria, 1977; Farrell and Ashton, 1973; Walsh *et al.*, 1984) that can be broadly related to altitude. Caledonia Fen lies at the upper limit of montane forest dominated by *Eucalyptus delegatensis* within moister environments with a variety of other eucalypts, including *E. dalrympleana* and *E. rubida* on drier aspects and steeper slopes. These forests have an understorey composed of small trees, woody shrubs, herbs and ferns. On higher slopes these forests give way to open forests and eventually sub-alpine woodland composed of *E. pauciflora*, *E. stellulata* and *E. rubida* with the myrtaceous shrub *Leptospermum grandifolium* and a variable understorey of grasses, scattered shrubs and herbs. A mosaic of treeless communities including dwarf, short and tall herbfield dominated by the Asteraceae, moist and wet heathland, grassland, bog and fen occur within sub-alpine woodland on the Snowy

Range plateau owing to the occurrence of poor and cold air drainage. Dry heathland which forms a floristically and ecologically well-defined closed community exists on rocky exposed ledges or steep gullies. It is characterised by the sole representative of the fire-sensitive, temperate rainforest in southeastern Australia, *Podocarpus lawrencei* (Podocarpaceae). The altitudinal treeline, estimated to be around 1800 m, is not reached within the region.

The vegetation of the fen and its environmental relationships were detailed by Newall (1981). Three major communities are recognised and broadly related to water level, at least in the broader northern part of the fen (Fig. 3). An aquatic fen dominates much of the centre of the basin under a mean water depth of 7 cm at the time of sampling. Dominant species include the emergent *Eleocharis sphacelata* (Cyperaceae) and

*Scirpus crassiusculus* (Cyperaceae) and submerged species *Myriophyllum pedunculatum* and *M. propinquum* (Haloragaceae), commonly with the aquatic moss *Drepanocladus fluitans* (Amblystegiaceae), *Lilaeopsis polyantha* (Apiaceae) *Ranunculus rivularis* (Ranunculaceae) and *Carex gaudichaudiana* (Cyperaceae). This community grades into fen, mainly landwards of aquatic fen where water depth averaged 1 cm. The community is dominated by *Carex gaudichaudiana* and *Sphagnum cristatum* with common *Scirpus crassiusculus* (Cyperaceae). There is a much sharper separation between fen and raised bog, developed above water level, that is dominated by *Sphagnum cristatum*, *Empodisma minus* (Rubiaceae) and *Carex gaudichaudiana* with common *Epacris paludosa* (Epacridaceae or Ericaceae), the moss *Polytrichum commune* (Polytrichaceae) and *Asperula gunnii* (Rubiaceae). Bog forms a narrow band around the site margins, especially on the western side, and grades gradually into dryland vegetation. It also occurs, uncommonly, as discrete patches or hummocks within the centre of the site. The most likely explanation for this mix of bog and fen, if not their distributional patterns, is the prevailing climate. It is found that, at this altitude in the southeastern highlands, raised bog dominates under higher rainfall while in areas drier than this site, fen rather than bog is represented (Kershaw *et al.*, 1997). There is a critical moisture threshold below which raised bog cannot form and the rainfall of Caledonia Fen is around this threshold. Moisture variability is probably also a contributing factor to bog development as well as to maintenance of a continuum between aquatic fen and fen as water levels have been noted to vary by up to 30 cm. The whole system is acidic with water and sediments consistently recording values pH values of 5–6 and 4–5 respectively.



**Figure 3** Vegetation communities of Caledonia Fen (adapted from Newall, 1981) and location of sediment cores in *Sphagnum* hummocks within the fen

## Methods

An 18.5 m sediment core was taken from a *Sphagnum* hummock towards the centre of the north end of the fen using a portable percussion-drilling rig with a petrol-driven jackinghammer in 1997. A further sediment core, collected in 2001 in an attempt to increase the length of the record, was located on a hummock about 30 m to the east. This was the site of the original core analysed by Joyce (1979) and reached a depth of 19.06 m. The two cores were matched stratigraphically and palynologically and combined in the record presented here. Four additional cores, located close to the 1997 core, were collected within 80 mm diameter PVC tubes in 2001. These were 2–4 m in length and designed to provide the bulk of material necessary for recovery of plant and insect macrofossils that could be used for identification and radiocarbon dating. They were matched stratigraphically with each other and with the 1997 core and found to be almost identical.

Sediment samples were taken at 4 cm intervals from the 1997 core and the basal part of the long 2001 core for magnetic susceptibility measurement, sediment analysis and pollen analysis. Mass specific magnetic susceptibility was measured on 10 cm<sup>3</sup> samples at low frequency (0.46 kHz) on a Bartington Instruments MS2B dual-frequency scanner, and later corrected for mass (Dearing, 1999). These samples, except for those in the topmost 40 cm that were almost entirely composed of fibrous organic material, were then used for particle size analysis. They were dispersed in distilled water by boiling for 2 h during which they were shaken every 15 min by cyclonic physical agitation before being measured with a Mastersizer 2600. Particle size classification was to the International Standard (McDonald *et al.*, 1990). Organic content was determined by loss on

ignition (Dean, 1974) on the material remaining from the 1 cm slices extracted for pollen analysis.

Prior to preparation for pollen analysis of 1 cm<sup>3</sup> samples, a tablet of *Lycopodium* marker spores was added to each sample to allow determination of palynomorph and charcoal concentrations. Preparation followed standard chemical treatment (van der Kaars *et al.*, 2001). After treatment, the pollen samples were mounted on microscope slides in glycerol and sealed with paraffin wax. Slides from each level were counted under oil at  $\times 630$  magnification along evenly spaced transects using a Zeiss Axiolab microscope until a minimum of 200 dryland pollen sum grains was recorded. The southeastern, pre-European, Australian pollen sum, consisting of those common native taxa with regional dispersed pollen, i.e. *Nothofagus*, *Podocarpus*, *Elaeocarpus*, *Eucalyptus*, Casuarinaceae, *Pomaderris*, *Acacia*, *Dodonaea*, *Banksia*, Poaceae, *Plantago* (native), Apiaceae (excluding *Hydrocotyle*), *Astelia* and Asteraceae (Tubuliflorae including *Tubuliflorites pleistocenicus*), *Phyllocladus* and *Lagarostrobos* (D'Costa and Kershaw, 1997), was selected in order to facilitate comparison with other southeastern Australian records. All percentage values were calculated relative to the pollen sum. Microscopic charcoal (10–100  $\mu\text{m}$ ) was counted along three evenly spaced transects on each slide. The concentrations per unit volume for both pollen and charcoal were calculated using the dilution of the known volume of *Lycopodium* spores. The programs Tilia and TGView were used for data analysis and pollen diagram construction and a stratigraphically constrained classification of samples, based on percentages of pollen sum taxa, was undertaken using the program CONISS (Grimm, 1987) to assist diagram zonation.

For dating, three samples were initially taken for AMS radiocarbon dating from the upper part of the core, one at the transition between essentially inorganic and organic material at 137 cm depth and two from the underlying inorganics at 239 and 304 cm depth. Samples were prepared in the same manner as for pollen analysis without the acetolysis step that could have introduced modern carbon. Dating was undertaken by the Australian Nuclear Science and Technology Organisation (ANSTO). A reversal in the two older ages prompted the search for alternative material for radiocarbon dating and the collection of wide diameter cores revealed sufficient macro-fossil material in the form of plant remains and charcoal in locations between 249 and 388 cm depth to produce finite ages. Seven ages were determined from five depths with duplicate plant and charcoal ages from two of the depths. These samples were also submitted to ANSTO for dating. The radiocarbon ages were augmented by a single conventional age taken on the original core of Joyce (1979) from the topmost organic layer and its position in this record determined by correlation with the sediment and composition of pollen samples.

The presence of two organic layers at lower depths were considered to have potential for the application of disequilibrium U/Th dating as they were wedged between heavy inorganic sediments that may have prevented escape of the decay product. Four samples for dating were submitted to ANSTO, one from the upper layer (712–715 cm depth) and three from the lower band between 1669 and 1785 cm depth. Methodology is detailed in Heijnis (1992), and Harle *et al.* (2002).

The nature of the inorganic sediments also presented the opportunity to provide the first test of optical dating in Australia on polliniferous sediments. Optical dating provides an estimate of the time elapsed since luminescent minerals, such as quartz, were last exposed to sunlight (Huntley *et al.*, 1985; Aitken, 1998; Lian and Roberts, 2006). Buried grains will accumulate

the effects of the nuclear radiation flux to which they are exposed, and the burial dose (palaeodose) can be measured using the optically stimulated luminescence (OSL) signal. Optical ages are calculated from the palaeodose divided by the dose rate arising from the ionising radiation emitted by the decay of radioactive elements in the minerals and their immediate surroundings, and from cosmic rays.

Samples were analysed from inorganic sediments on either side of the upper organic layer (CF3 and CF4) to provide a comparison with the U/Th age from this layer while one was taken from a depth of 302–308 cm (CF2) to compare with radiocarbon ages. Quartz grains of 90–125  $\mu\text{m}$  diameter were extracted under dim red illumination using standard procedures, including etching by hydrofluoric acid to remove the external alpha-dosed layer and any feldspars (Aitken, 1998). Palaeodoses were estimated from multigrain aliquots composed of  $\sim 8$  grains per aliquot (to check for insufficient bleaching of the quartz grains at deposition; see Olley *et al.*, 1999) using the single-aliquot regenerative-dose (SAR) protocol, experimental apparatus and statistical models described elsewhere (Galbraith *et al.*, 1999; Yoshida *et al.*, 2000). Grains were stimulated for 100 s at 125°C, using  $\sim 25 \text{ mW cm}^{-2}$  of green-plus-blue (420–550 nm) light from a filtered tungsten-halogen lamp. The natural and regenerative doses were preheated at 240°C for 10 s, and the test doses (which are used to correct for any sensitivity changes) were heated to 160°C (but not held at this temperature) before optical stimulation. The ultraviolet OSL emissions were detected using an Electron Tubes Ltd 9235QA photomultiplier tube fitted with a Chance-Pilkington HA-3 filter and 6 mm of Hoya U-340 filter; laboratory doses were given using a calibrated <sup>90</sup>Sr/<sup>90</sup>Y beta source.

Palaeodoses were determined from the first 5 s of OSL, using the final 20 s as background. Dose–response curves were fitted using a saturating-exponential-plus-linear function, and the palaeodoses (and their measurement uncertainties) were calculated using the procedures described by Yoshida *et al.* (2000: Appendix A). The suitability of these experimental and analytical conditions was confirmed using a 'preheat plateau' test on 12 natural aliquots of sample CF2, which showed no dependence of palaeodose on preheat temperatures of 160–280°C (held for 10 s). SAR protocol performance was also validated using a second set of 12 aliquots that been bleached and then given a known dose. These yielded the correct dose estimates (ratio of measured/given doses of  $0.99 \pm 0.03$ ) and negligible thermally transferred signals at zero applied dose (<1% of the natural OSL).

The total dose rates were calculated as the sum of the beta and gamma dose rates due to <sup>238</sup>U, <sup>235</sup>U, <sup>232</sup>Th (and their decay products) and <sup>40</sup>K. The radionuclide activities were measured by high-resolution gamma-ray spectrometry, using the same equipment and calibration standards as Olley *et al.* (1996). These values were converted to dose rates (using the conversion factors given in Olley *et al.*, 1996), making allowance for beta-dose attenuation (after Mejdahl, 1979) and sample water content (after Aitken, 1985). Account was also taken of the cosmic-ray contribution (adjusted for site altitude, geomagnetic latitude, and thickness and water content of sediment overburden), following Readhead (1987) and Prescott and Hutton (1994). A value of  $0.03 \text{ Gy ka}^{-1}$  was included for the effective internal alpha dose rate, based on measurements made previously on quartz grains from southeastern Australia (Bowler *et al.*, 2003).

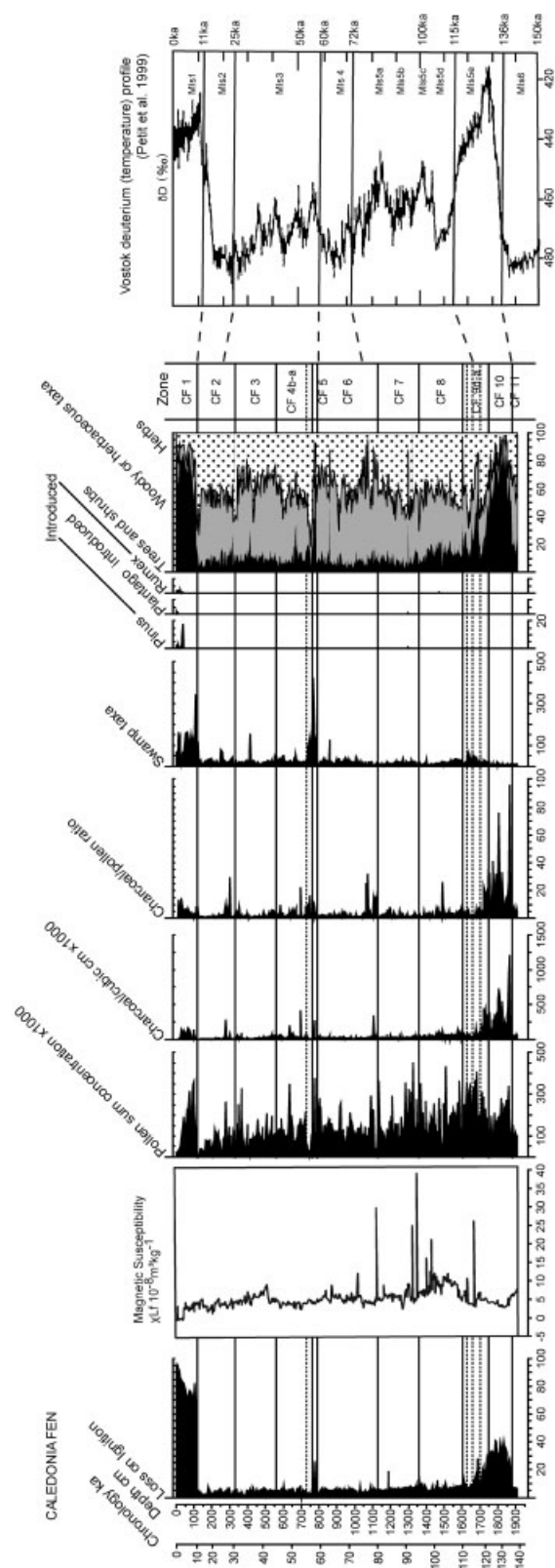
The water content of Caledonia Fen sediments was generally higher than in well-drained deposits, and fluctuated about a value of  $42 \pm 10\%$  over the depth interval of interest for the OSL samples (80–800 cm). Here, the water contents are expressed as

percentage of dry mass of sample, where the uncertainty is the standard deviation of 180 measurements made on consecutive 4 cm thick increments. We used these modern-day water contents to adjust the beta, gamma and cosmic-ray dose rates, and assigned uncertainties of  $\pm 10\%$  to accommodate variations over time. The modern-day variability partly reflects differences in the sedimentary composition of the deposit with depth, so we adjusted the dry beta, gamma and cosmic-ray dose rates differently for water content. The latter were adjusted using the average water content for the full thickness of sediment overlying each OSL sample; beta dose rates were corrected using only the water content over the depth intervals from which the OSL samples were collected; and gamma dose rates were corrected using the water content in the deposits above and below the OSL samples to a distance of 30 cm (the maximum travel distance of most gamma rays through soil and rock)

Samples CF3 and CF4 were collected from a part of the sedimentary sequence composed mostly of silts and clays, so we measured the radionuclide activities in samples of sediment collected from 30 cm above to 30 cm below the depth of each OSL sample. By contrast, sample CF2 was collected from the centre of a sandy layer, overlain and underlain by silts and clays, so we measured the radionuclide activities in the different layers (Table 2). The beta dose rate was calculated using the values for the sandy layer, while the gamma dose rate was calculated using both datasets, taking into account the fractional contributions from the different layers (following Aitken, 1985: Table H.1). Table 2 also lists the effective water content for each sample. This can be thought of as the 'average' modern-day value, where the water contents specific to the beta, gamma, and cosmic-ray dose rates are multiplied by their fractional contributions to the total dose rate, and then summed. Additional optical ages are in the process of production, but saturation of the sediments with respect to absorbed dose is likely to prevent application to the lower part of the core.

## Establishment of a chronology

The nature of the sediments provided some basis for selection of samples for dating and, subsequently, has been important in the establishment of an age structure for the record. Only those features, i.e. loss on ignition and magnetic susceptibility, that have been analysed from similar depths as those for pollen, are considered here and these are included on Fig. 4. Variation within inorganic sediments is also excluded because of its complexity but will be detailed elsewhere (Brown, in preparation). Overall, apart from organic bands, the sediments are dominated by clays and fine silts with infrequent bands of coarser material. The clays and silts (predominantly  $< 20 \mu\text{m}$ ) are representative of low energy (suspension settling) deposition in a basin with minimal outflow. There is evidence of banding of sediments through parts of the sequence, although the timescales represented by the bands are uncertain. Periods of higher energy water flow into the fen are indicated by well-sorted coarser grain sands. Some of these sediments contain a significant fine fraction, indicating mixing with previously deposited sediment, as well as minimal sediment outflow. Others contain only the coarse fraction, representing periods when there was significant outflow from the fen, carrying finer sediments. Infrequently in the sequence, sediments with broad particle size ranges and minimal sorting were found. The distribution of these sediments is similar to those on the surrounding slope, providing evidence



**Figure 4** Summary diagram with loss on ignition, magnetic susceptibility, charcoal particles per cubic centimetre, charcoal/pollen sum ratio and summary statistics for pollen including pollen sum concentrations, the total percentage of aquatic pollen and introduced taxa, in relation to the Vostok temperature record (Pettit *et al.*, 1999)

**Table 1** Radiocarbon and uranium/thorium ages for sediment samples from Caledonia Fen. The radiocarbon ages are calibrated to calendar ages using the Cologne Radiocarbon and Palaeoclimate Research Package CalPal 2005 SFCP. Radiocarbon ages are expressed with an uncertainty of  $\pm 2$  standard deviations

Dating method	Laboratory code	Depth (cm)	Sample material	$^{14}\text{C}$ age (BP) 2 SD	Calendric age (cal. BP)
Radiocarbon	GX6515	90	Organic sediment	8495 $\pm$ 460	9514 $\pm$ 590
Radiocarbon	OZ 493	137	Organic clay/silt	10 300 $\pm$ 280	12 001 $\pm$ 483
Radiocarbon	OZ 494	239	Organic clay/silt	20 900 $\pm$ 420	24 246 $\pm$ 570
Radiocarbon	OZ 495	304	Organic clay/silt	18 350 $\pm$ 1220	21 442 $\pm$ 1300
Radiocarbon	OZ 792	249	Plant remains	22 110 $\pm$ 220	25 728 $\pm$ 417
Radiocarbon	OZ 793	284	Plant remains	23 460 $\pm$ 260	27 292 $\pm$ 452
Radiocarbon	OZ 794	328	Plant remains	36 540 $\pm$ 780	41 015 $\pm$ 308
Radiocarbon	OZ 795	356	Plant remains	40 900 $\pm$ 1200	42 991 $\pm$ 833
Radiocarbon	OZ 797	388	Plant remains	48 600 $\pm$ 3200	49 193 $\pm$ 3162
Radiocarbon	OZ 796	356	Charcoal	43 100 $\pm$ 1800	44 905 $\pm$ 1836
Radiocarbon	OZ 798	388	Charcoal	46 200 $\pm$ 2400	47 127 $\pm$ 2281

Dating method	Laboratory code	Depth (cm)	Sample material	Uranium/thorium age
Uranium/thorium	LH 7704–LH 7706	712, 713, 715	Organic sediment	60 + 10–5 ka
Uranium/thorium	LH 7707–LH 7709	1669, 1676, 1684	Organic sediment	60 $\pm$ 5 ka
Uranium/thorium	LH 7713–LH 7715	1759, 1760, 1761	Organic sediment	>350 ka
Uranium/thorium	LH 7710–LH 7712	1783, 1784, 1785	Organic sediment	Undateable—during to poor isochron spread

of mass movement on the slopes during periods when the fen was shallow.

Although a magnetic susceptibility curve is included on Fig. 4, the relatively low values of susceptibility meant that frequency-dependent susceptibility (f<sub>ds</sub>) could not be determined. There is evidence within the sequence of vivianite (Fe<sub>3</sub> + 3(PO<sub>4</sub>)<sub>2</sub>H<sub>2</sub>O), which can be produced after biogenic reduction of magnetite (Dong *et al.*, 2000), and the curve does little to inform on sediment depositional conditions. The sediment susceptibility is far less than that recorded in soils surrounding the fen, supporting the proposal of dissolution of the primary minerals found in the catchment soils. Details of mineral magnetic investigations will be presented elsewhere (Brown, in preparation).

Radiocarbon and U/Th results are listed in Table 1 and optical dating results are presented in Table 2. Only radiocarbon and optical ages from the top 8 m of sediment were

considered for contribution to the establishment of a timescale. U/Th results were excluded because of specific problems with U/Th ages from the basal organic layer and, more generally, because of concerns over the reliability of ages obtained from long pollen sequences in Australia, of which those from Lake Wangoom have already been noted (Kershaw and van der Kaars, 2007). Contributing age determinations are plotted on Fig. 5. Apart from the age from pollen preparation of 21 442  $\pm$  1300 cal. yr BP, all radiocarbon ages fall into an age–depth sequence. The validity of these ages is supported by the topmost age of 12 001  $\pm$  483 cal. yr BP that is taken from the boundary between inorganic sediments and the topmost organic section which realistically represents the Holocene period and at the older end where the calibrated ages from paired macrofossil plants and charcoal overlap at single standard deviations. The ages suggest variation in sediment accumulation with a possible reduction in rate between about

**Table 2** Dose rate data, palaeodoses and optical ages for sediment samples from Caledonia Fen

Sample code	Sample depth (cm)	Radionuclide activities <sup>a</sup> (Bq kg <sup>-1</sup> )						Cosmic-ray dose rate <sup>b</sup> (Gy ka <sup>-1</sup> )	Total dose rate <sup>c,d</sup> (Gy ka <sup>-1</sup> )	Palaeodose <sup>c,e</sup> (Gy)	Optical age <sup>c</sup> (ka)	
		<sup>238</sup> U	<sup>226</sup> Ra	<sup>210</sup> Pb	<sup>228</sup> Ra	<sup>228</sup> Th	<sup>40</sup> K					
CF2	302–308	(a)	23 $\pm$ 7	34.7 $\pm$ 1.4	41 $\pm$ 7	47 $\pm$ 3	47.7 $\pm$ 1.4	290 $\pm$ 16	0.13	2.27 $\pm$ 0.19 (33)	47 $\pm$ 5 (19 $\pm$ 7)	21 $\pm$ 3
		(b)	51 $\pm$ 7	46.3 $\pm$ 1.7	51 $\pm$ 6	71 $\pm$ 4	67.6 $\pm$ 1.5					
CF4	748–755		38 $\pm$ 6	44.3 $\pm$ 1.2	34 $\pm$ 6	63 $\pm$ 3	65.6 $\pm$ 1.4	460 $\pm$ 15	0.10	2.50 $\pm$ 0.18 (32)	166 $\pm$ 17 (28 $\pm$ 7)	66 $\pm$ 8
CF3	776–783		46 $\pm$ 6	46.5 $\pm$ 1.6	53 $\pm$ 6	73 $\pm$ 3	72.3 $\pm$ 1.5	591 $\pm$ 21	0.10	2.39 $\pm$ 0.15 (66)	163 $\pm$ 17 (27 $\pm$ 7)	68 $\pm$ 8

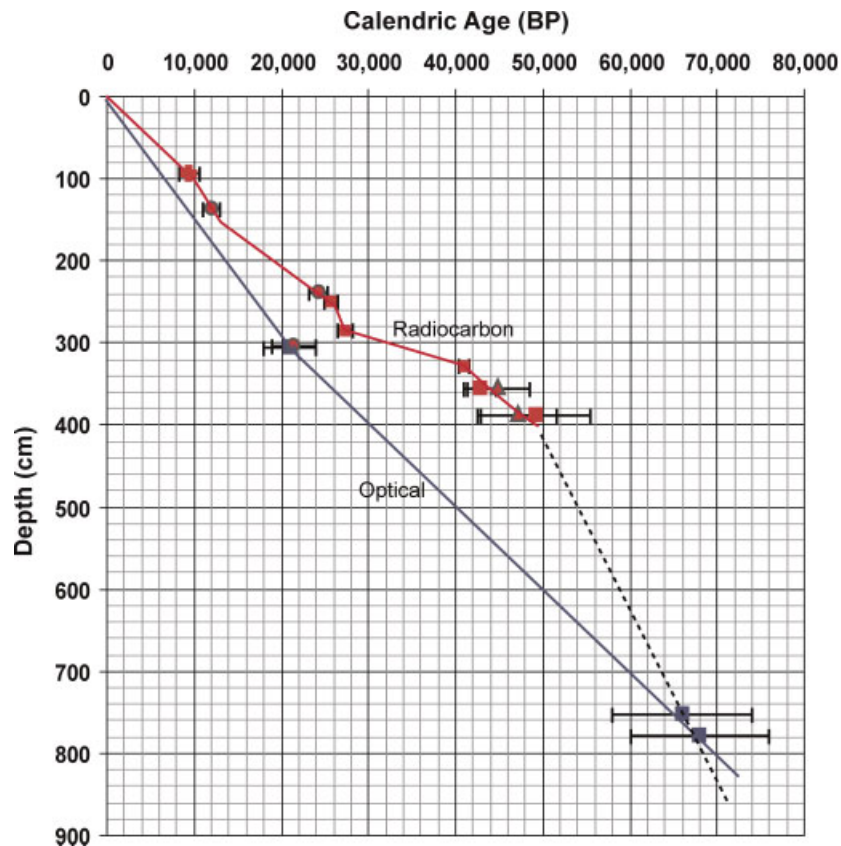
<sup>a</sup> Measurements made on dried and powdered samples by high-resolution gamma-ray spectrometry. These values were converted to dose rates (Olley *et al.*, 1996), making adjustments for beta-dose attenuation (Mejdahl, 1979) and for the measured (field) water contents of the samples and the deposits surrounding them to a distance of 30 cm (Aitken, 1985). The two sets of data for CF2 were obtained from (a) the sandy layer from which the OSL sample was collected, and (b) the silt/clay layers up to 30 cm above and below the sandy layer. The beta dose rate was calculated using dataset (a), and the gamma dose rate was calculated from datasets (a) and (b) as the sum of their fractional contributions (0.2 and 0.8, respectively; Aitken, 1985: Table H.1).

<sup>b</sup> Adjusted for site altitude, geomagnetic latitude, and thickness and water content of sediment overburden over the period of sample burial (Prescott and Hutton, 1994; Readhead, 1987), and assigned a relative uncertainty of  $\pm 20\%$ .

<sup>c</sup> Mean  $\pm$  total uncertainty (68% confidence interval), calculated as the quadratic sum of the random and systematic uncertainties.

<sup>d</sup> Sum of beta, gamma and cosmic-ray dose rates, plus an assumed internal alpha dose rate of 0.03 Gy ka<sup>-1</sup> (with a relative uncertainty of  $\pm 20\%$ ). The numbers in parentheses are the effective field water contents, expressed as percentage of dry mass of sample and assigned relative uncertainties of  $\pm 10\%$ .

<sup>e</sup> Estimated using the central age model (Galbraith *et al.*, 1999). The numbers in parentheses are the over-dispersion values (relative standard deviations, in per cent) of the palaeodose distributions after allowing for measurement uncertainties (Galbraith *et al.*, 2005). The over-dispersion is taken into account in the random uncertainty on the sample palaeodose, and the total uncertainty includes a systematic component of  $\pm 2\%$  associated with laboratory beta-source calibration.



**Figure 5** Graph of AMS radiocarbon ages of pollen, plant and charcoal, and optical ages of sediment plotted against depth of sediment in the Caledonia Fen core (with radiocarbon ages, squares are for AMS on plant fragments; triangles are for AMS on charcoal; circles are for AMS on pollen preparations; cross is for conventional radiocarbon). This figure is available in colour online at [www.interscience.wiley.com/journal/jqs](http://www.interscience.wiley.com/journal/jqs)

40 000 and 30 000 years ago, although the accuracy and calibration of ages greater than 20 000 yr BP is open to question. Optical ages also fall into an age–depth sequence suggesting a generally higher and more linear sediment accumulation rate through the last 60 000–70 000 years with the uppermost optical age being almost identical to the radiocarbon age outlier of  $21\,442 \pm 1300$  cal. yr BP.

Several lines of evidence provide confidence in the optical ages. In terms of dose rate, the present-day activities of the radionuclides in the  $^{238}\text{U}$  and  $^{232}\text{Th}$  decay series are consistent with a condition of secular equilibrium; none of the  $^{238}\text{U}/^{226}\text{Ra}$ ,  $^{210}\text{Pb}/^{226}\text{Ra}$  or  $^{228}\text{Th}/^{228}\text{Ra}$  ratios differ significantly from unity at the 95% confidence interval (for the uranium-series ratios) or the 68% confidence interval (for the thorium-series ratio). This suggests that there has been no recent ingress or loss of mobile radionuclides, so we calculated the optical ages under the assumption that the measured radionuclide activities have prevailed throughout the period of sample burial. Even under conditions of moderate disequilibrium, this approach will not compromise the accuracy of the dose rate by more than a few per cent (Olley *et al.*, 1996).

The greatest source of unknown error for the dose rate is past changes in water content. For the Caledonia Fen samples, the total dose rates will decrease (and the optical ages will increase) by 0.5–1% for each 1% increase in water content. To illustrate how the ages may be affected by large and sustained changes in water content, the optical age for sample CF4 would shift to ca. 60 ka or ca. 70 ka if water contents of 20% or 40%, respectively, had persisted over the *entire* period of sample burial. These ages are similar to our best estimate of the age of this sample ( $66 \pm 8$  ka), so the OSL chronology for Caledonia Fen is unlikely to be seriously distorted by complications due to past variations in water content.

In terms of sample palaeodose, we used aliquots composed of only  $\sim 8$  grains so that the properties of the palaeodose distributions could be examined for any evidence that the sediments had been incompletely bleached by sunlight at the time of deposition (e.g. Olley *et al.*, 2004a, 2004b). No such signs were detected, and any residual dose due to incomplete bleaching at deposition is apt to be a small fraction of the  $\sim 165$  Gy burial doses of samples CF3 and CF4. After taking measurement errors into account, the remaining spread ('overdispersion') in the palaeodose distribution of sample CF2 ( $19 \pm 7\%$ ) is consistent with the values reported for other quartz samples that had been well-bleached at deposition (Galbraith *et al.*, 2005; Lian and Roberts, 2006). The overdispersion values for the two older samples are slightly higher (CF3:  $27 \pm 7\%$ ; CF4:  $28 \pm 7\%$ ), but not significantly so. Some of this extra overdispersion may be due to additional uncertainties associated with reconstruction of the OSL dose–response curve at high doses.

We therefore consider the Caledonia Fen sediments to have been satisfactorily bleached when deposited, and have accordingly calculated the weighted mean palaeodose for each sample using the 'central age model' of Galbraith *et al.* (1999), which takes the overdispersion into account in the estimation of the associated error term. The corresponding optical ages are in correct stratigraphic order, and those for samples CF3 and CF4 are statistically indistinguishable ( $68 \pm 8$  and  $66 \pm 8$  ka, respectively). As regards the latter, if this part of the sedimentary sequence accumulated rapidly, then it would be appropriate to use the weighted mean age ( $67 \pm 6$  ka) as the two samples are effectively contemporaneous. However, if the two samples are not coeval (i.e. sediment accumulated at a slow but steady rate), then their individual ages should not be combined. We cannot distinguish between these two possibi-



lities solely on the basis of the optical ages, which have total relative uncertainties of ~12%.

Application of lines and curves of best fit to the radiocarbon and optical ages individually produces a range of ages for the base of the sequence, of which the youngest estimate (from extrapolation of the optical ages) is about 160 ka.

An alternative or additional approach to establishment of a timescale, required from a consideration of the lack of agreement between the radiocarbon and optical age estimates of rates of sediment accumulation and the fact that they cover only the top part of the record, is comparison with the marine isotope stratigraphy (Martinson *et al.*, 1987). This is shown in relation to the Vostok temperature curve of Pettit *et al.* (1999) on Fig. 4. This curve is most appropriate for comparison because of the strong temperature influence on the Caledonia Fen record and its Southern Hemisphere location. From the dated top section of the Caledonia Fen record it is clear that the latest part of the last glacial period was much cooler than the Holocene as determined from the sediment type and pollen content. The last time that global temperatures achieved anything like those at present was during the last interglacial period, Marine Isotope Stage (MIS) 5e. This period could be equated with peaks in organic sediment between about 780 and 800 cm or 1880 to 1750 cm depth. The latter period is preferred because it appears to be of similar duration to the Holocene whereas the former period is too short and, from the OSL age of  $67 \pm 6$  ka, it most likely represents a major interstadial within the last glacial period.

From the Vostok curve the most prominent temperature peak during the last glacial period is that corresponding with MIS 5a, around 85 ka. However, this is substantially older than the optical ages enveloping this period and cannot be supported by sediment depth which is too close to that of the inferred interglacial or because pollen concentrations indicate little overall change in the sedimentation rate. A more likely match is with the peak at beginning of MIS 3, around 58 ka, which, although rather young, is more consistent with the optical ages, and with a more constant sedimentation rate. In fact, there is a near-overlap between the combined optical ages and MIS 3. Although this correlation still implies a decrease in the rate of sedimentation through time, such a decrease may result from the shallowing and broadening of the fen basin as a result of infilling through time, a feature suggested from the proposed valley origin of the site and perhaps also the generally increased magnetic susceptibility values with depth. Slope inwash as well as pollen focusing within a steep-sided, largely unvegetated lake may explain why pollen concentrations in the lower part are equal to or exceed those in the upper part of the record.

Using the Vostok timescale of Pettit *et al.* (1999), the sediment core covers about the last 140 ka, only slightly younger than the 160 ka determined from the linear extrapolation from the optical ages. Tentative correlations between the pollen stratigraphy and the Vostok temperature record are indicated on Fig. 4 with ages on the core interpolated between each of the tie points MIS 6/5e, MIS 5e/5d, MIS 4/3, MIS 3/2, MIS 2/1 and MIS 1/present using the Vostok ages for the earlier boundaries and radiocarbon dates for MIS 2 and MIS 1.

## The pollen diagrams

Figures 6(a), 6(b) and 6(c) detail the percentage values for individual taxa relative to the southeast Australian pollen sum (D'Costa and Kershaw, 1997), and are divided into the major groups of trees and shrubs (Fig. 6(a)), taxa that can be derived

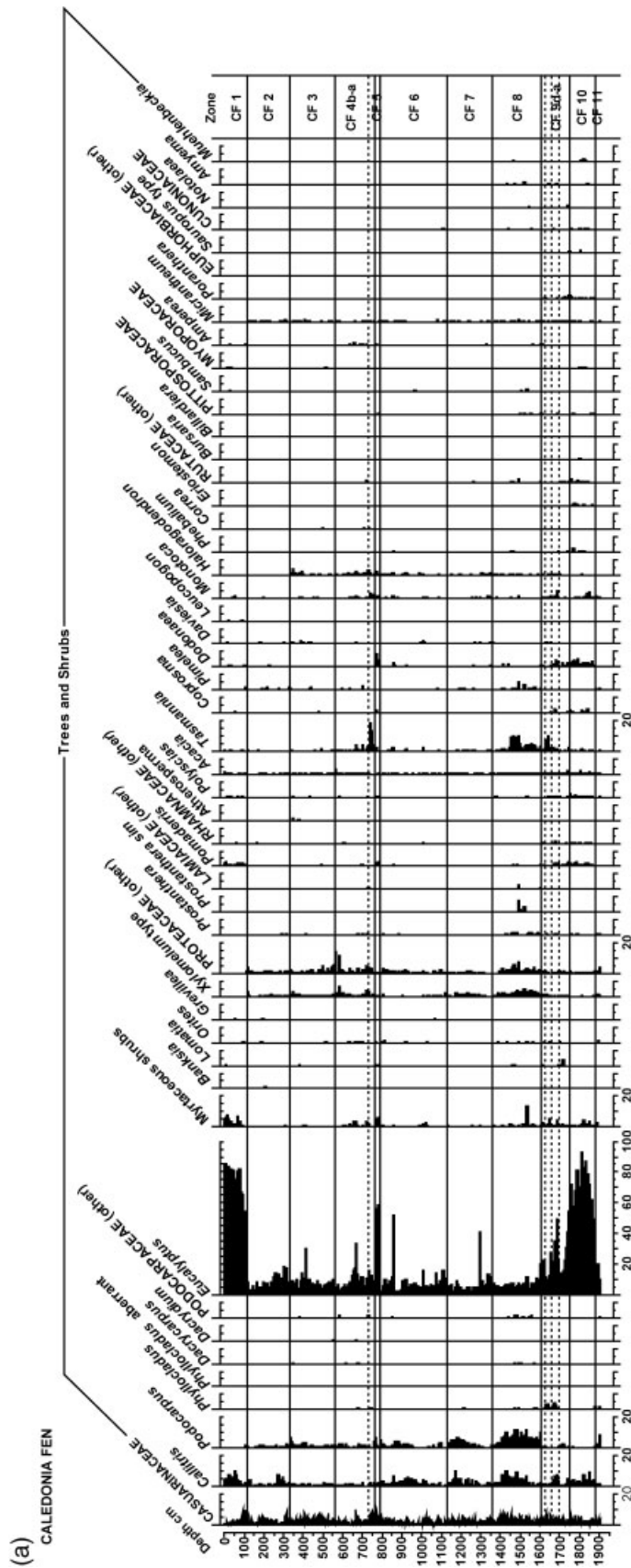
from either woody or herbaceous taxa, herbs and introduced taxa (Fig. 6(b)) and aquatic pollen taxa as well as pteridophyte and bryophyte spores and selected algal spores (Fig. 6(c)). The distinction between some dry land and aquatic taxa is often blurred in relatively moist, high-altitude environments and a decision to include pollen of major representatives of both environments, Ranunculaceae, Restionaceae and Epacridaceae, within the aquatic diagram is based on the fact that pollen dispersal is limited. This decision is supported by the high-value variability of the taxa, indicative of a very local source. It is acknowledged that the Australian Epacridaceae have now been included in the Ericaceae (Kron *et al.*, 2002) but the term Epacridaceae is retained because the change has not yet been registered in Australian floras. The CONISS dendrogram is shown on Fig. 6(b). Figure 4 contains charcoal measures and summary statistics for the pollen including pollen sum concentrations, relative proportions of the major dryland pollen groups and total percentages of aquatic pollen as well as previously mentioned organic content and magnetic susceptibility values and suggested correlations between zone boundaries and the Vostok temperature record.

*Zone CF 11 (1906–1880 cm depth; ca. 140–136 ka)* is dominated by pollen of herbs and woody or herbaceous plants of which Poaceae and Asteraceae Tubuliflorae are by far the most abundant, while *Tubulifloridites pleistocenicus* (whose present-day affinity has not been firmly established (Macphail and Martin, 1991)), Chenopodiaceae, *Plantago*, *Chionogentias*, *Aciphylla*, *Pratia*, *Pimelea* and Liliaceae have notable representation. Trees and shrubs have low values with only *Eucalyptus*, *Podocarpus*, *Phyllocladus*, some Proteaceae, Casuarinaceae, *Callitris* and *Prostanthera* represented. Pteridophyte and bryophyte spores are virtually absent. Few aquatic taxa are recorded with only Cyperaceae and Epacridaceae having a consistent presence while algal spores are absent. The sediment is predominantly inorganic and charcoal values as well as pollen concentrations are low.

*Zone CF 10 (1880–1740 cm depth; ca. 136–122 ka)*. The pollen flora changes sharply and substantially at the zone CF 11/10 boundary to become dominated by *Eucalyptus*. There is increased representation of a number of other tree or shrub taxa including *Callitris*, *Pomaderris*, *Polyscias*, *Acacia*, *Coprosma*, *Phebalium* and *Eriostemon* as well as ferns including the tree ferns *Dicksonia* and *Cyathea*. Conversely, the importance of Poaceae and Asteraceae types is much reduced with Asteraceae Liguliflorae and *Tubulifloridites pleistocenicus* almost disappearing from the record. Reductions are also recorded in other herb taxa including *Plantago* and *Aciphylla* as well as some woody taxa, most notably Proteaceae, *Podocarpus* and *Phyllocladus*. The percentages of Casuarinaceae and Chenopodiaceae do not change. Swamp pollen taxon values remain low with Cyperaceae and Restionaceae maintaining their low percentages and *Myriophyllum* is consistently present. However, algal spores achieve high values in a number of spectra, almost all relatable to *Botryococcus*. Charcoal values, although variable, are the highest for the record while loss on ignition values are distinctively and consistently high. Pollen concentrations have increased though they become gradually reduced through the zone.

*Zone CF 9 (1740–1650 cm depth; ca. 122–111 ka)*, covers a period of rapid changes that is clearly divisible into four subzones based largely on the relative proportions of *Eucalyptus* and Poaceae. The other major pollen type, Asteraceae, shows relatively little variation. There is an overall reduction in representation of woody plants through the zone.

*Subzone CF 9d (1740–1700 cm depth; ca. 122–118 ka)* is marked by a reversion towards the pollen assemblage of zone



**Figure 6(a)** Pollen diagram showing the relative proportions of individual tree and shrub taxa. All percentages of individual taxa are based on the southeastern Australian pollen sum (D'Costa and Kershaw, 1997)

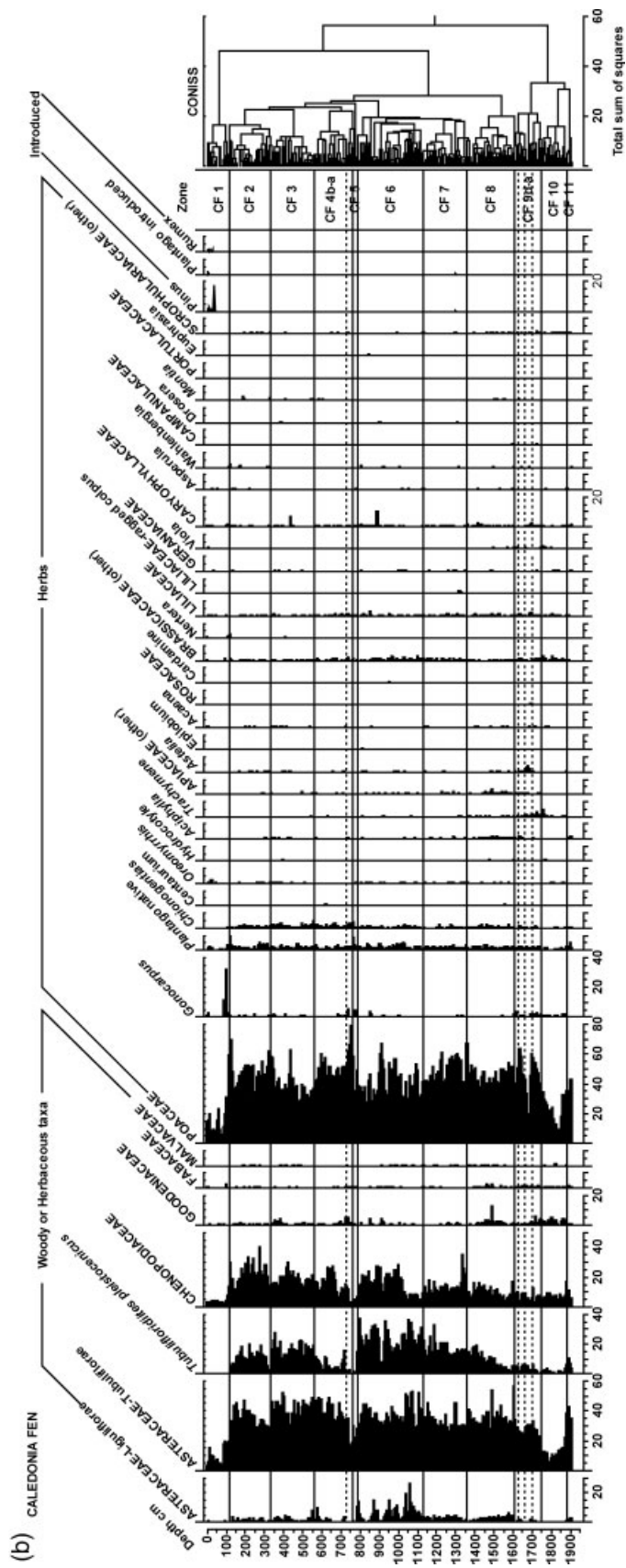
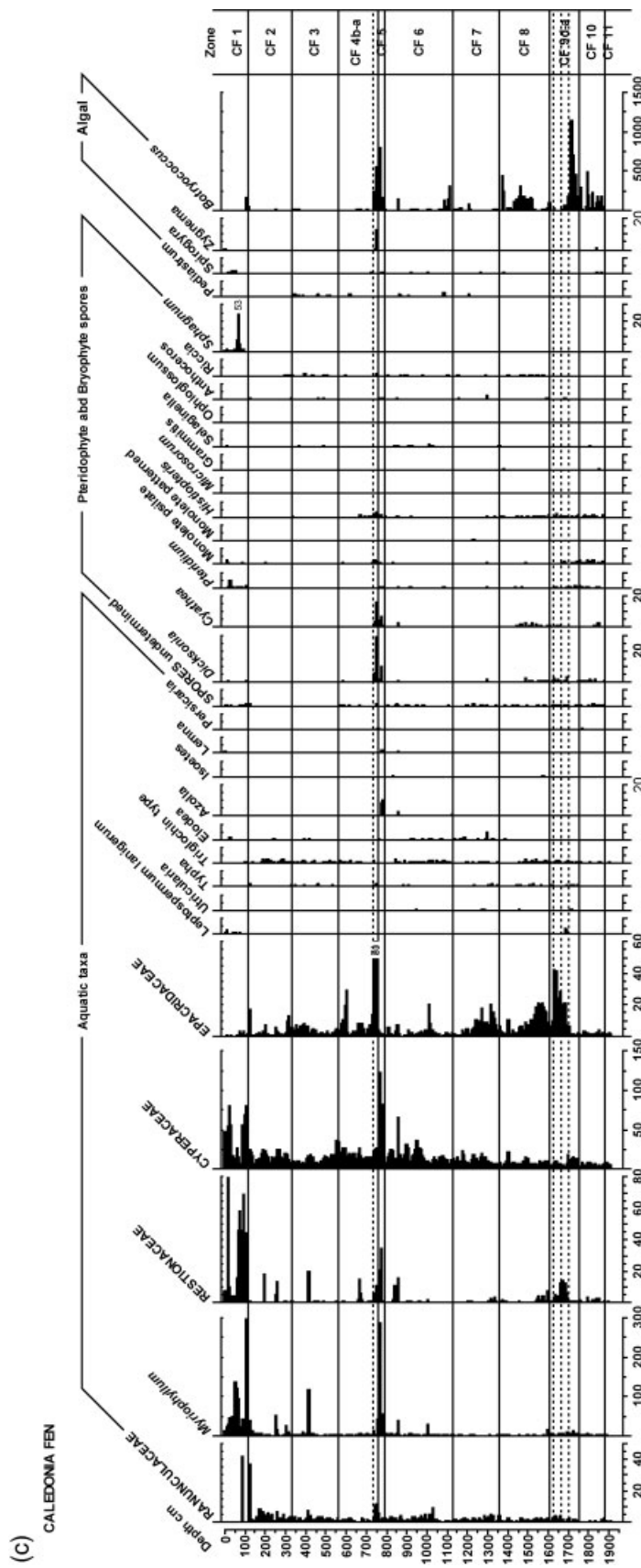


Figure 6(b) Pollen diagram showing the relative proportions of woody or herbaceous taxa, herb taxa, introduced taxa and the CONISS dendrogram. All percentages of individual taxa are based on the southeastern Australian pollen sum (D’Costa and Kershaw, 1997)



**Figure 6(c)** Pollen diagram showing the relative proportions of swamp taxa, pteridophyte and bryophyte taxa and algal taxa. All percentages of individual taxa are based on the southeastern Australian pollen sum (D'Costa and Kershaw, 1997)

CF 11 in that there are major decreases in *Eucalyptus* and *Callitris*, woody understorey taxa and ferns in association with substantial increases in Asteraceae Tubuliflorae, Poaceae and *Podocarpus*. There are also increases in the Proteaceae, *Podocarpus* and *Trachymene*. *Pomaderris* is still recorded and *Tubulifloridites pleistocenicus* values remain low while *Phyllocladus* is absent.

A similar picture is painted by the evidence for aquatic environments with a reduction in organic sediment content to zone CF11 levels by the end of the subzone but the achievement of highest values of *Botryococcus* for the diagram. There is a return of Ranunculaceae combined with the first notable representation of *Myriophyllum* and slight increase in Cyperaceae. Despite the reduction in forest vegetation, charcoal values indicate that conditions remained suitable for the support of fires.

*Subzone CF 9c (1700–1660 cm depth; ca. 118–115 ka)* displays some recovery in eucalypt percentages and a concomitant decrease in Poaceae. Only minor changes are recorded in other dryland taxa although *Callitris* values recover to zone CF10 levels, Asteraceae tubuliflorae values are slightly higher, percentages of *Phyllocladus* and *Astela*, although low, are about the highest for the diagram, while *Podocarpus* is absent. Swamp taxa have their first notable representation, due to increases in Epacridaceae and Restionaceae, while Cyperaceae percentages are lower. *Botryococcus* spores are reduced to low levels. There is a partial recovery in organic values, but charcoal values are low and pollen concentrations become very variable, a feature that characterises much of the remainder of the record.

*Subzone CF 9b (1660–1625 cm depth; ca. 115–113 ka)* marks another sharp reversal in representation of *Eucalyptus* and Poaceae. Despite the reduction in *Eucalyptus* along with *Callitris* and woody understorey taxa such as *Pomaderris*, *Dodonaea* and *Coprosma*, *Tasmannia* reaches its highest values to date while *Phyllocladus* values are maintained. The tree ferns *Dicksonia* and *Cyathea* maintain or slightly increase their representation although values are consistently low. Within the swamp taxon group, Epacridaceae has a high peak but the alga *Botryococcus* is absent. Charcoal values are low as are loss on ignition values while magnetic susceptibility exhibits the first of several sharp peaks.

*Subzone CF 9a (1625–1605 cm depth; ca. 113–111 ka)* shows a brief resurgence of *Eucalyptus* values but to lower levels than those of subzone CF 9c and zone CF 10, while Poaceae records a concomitant dip in values. Despite the peak in *Eucalyptus*, there is no similar response in other woody taxa with *Phyllocladus*, *Callitris* and *Tasmannia* being conspicuously absent. There is a similar reduction in the major swamp taxa, a result of temporary dips in values of Restionaceae and Epacridaceae. Loss on ignition values show a small rise while charcoal measures remain low.

*Zone CF 8 (1605–1360 cm depth; ca. 111–95 ka)* shows a return to low percentages of *Eucalyptus*, with dominant Poaceae and Asteraceae Tubuliflorae, the latter displaying a couple of short peaks. In contrast to the previous subzone, woody taxa other than *Eucalyptus* and, in particular, *Callitris*, *Podocarpus*, the Proteaceae and *Tasmannia* are relatively well represented. They generally increase at the base and then decrease towards the end of the zone, a pattern also noted in Asteraceae Tubuliflorae and Goodeniaceae but inverse to the curve in Poaceae. Both *Tubulifloridites pleistocenicus* and Chenopodiaceae generally increase through the zone, the latter dramatically so. One feature of the zone is the attainment of highest conifer values for the record. Although mainly the result of *Podocarpus* representation, *Phyllocladus*, *Dacrycarpus* and other Podocarpaceae are also present. The swamp taxa

Epacridaceae and Restionaceae initially recover at the base of the zone and then decline, while Cyperaceae maintains low and fairly consistent percentages. Peaks in *Botryococcus* are recorded. Loss on ignition values are consistently low though magnetic susceptibility values are, on average, the highest for the record. With the exception of a single sample peak in the charcoal/pollen ratio, charcoal levels remain low.

*Zone CF 7 (1360–1130 cm depth; ca. 95–81 ka)*. There is a great deal of similarity between this and the previous zone with generally low representation of woody plants and high percentages of woody and herbaceous plants and herbs. There is, however, an early dip in Asteraceae Tubuliflorae values and a rise in Poaceae early in the zone with reversals towards the top. *Tubulifloridites pleistocenicus* values continue to rise and Chenopodiaceae maintains relatively constant values. There are generally lower values for woody plants although *Eucalyptus* exhibits a minor peak at the base of the zone, followed by a single high value. A number of taxa including *Callitris* and *Podocarpus*, and Proteaceae, composed almost entirely of *Xylomelum* type, show similar patterns to those in the previous zone but with less amplitude in most cases and they peak generally higher within the zone. Within the aquatic component, there are some similarities with the previous zone in that Epacridaceae shows an early peak with a subsequent decline to very low values while Restionaceae pollen is almost restricted to the base of the zone. Cyperaceae values are generally slightly higher while there are no notable occurrences of *Botryococcus*. Loss on ignition and charcoal values remain low and magnetic susceptibility values, although generally lower, include high values at the base of the zone.

*Zone CF 6 (1136–790 cm depth; ca. 81–60 ka)*. Poaceae and Asteraceae continue to dominate, with high percentages of Asteraceae Liguliflorae for the only time in the record. Notable abrupt events include an early lowering of Asteraceae Tubuliflorae values, several peaks and troughs in *Tubulifloridites pleistocenicus*, Asteraceae Liguliflorae and Poaceae, and a reduction to lowest levels in the diagram for *Eucalyptus* towards the top of the zone. The trough in *Eucalyptus* is followed by a single very high value that is accompanied by similar spikes in the aquatic taxa Cyperaceae, *Myriophyllum* and *Botryococcus* and a slightly more sustained peak in Restionaceae.

The pattern evident in *Callitris*, *Podocarpus* and Proteaceae (in this zone without *Xylomelum* type) within the previous two zones continues with peaks towards its top although their amplitude is further reduced. The situation is similar with Epacridaceae that again has a peak preceding those of the other taxa. Major and largely sustained changes within the record are evident in the lower part of the zone around 1000 cm depth. There is little recognition in the CONISS diagram because, apart from *Plantago*, the contributing taxa are excluded from the pollen sum. The most substantial change is an increase in Chenopodiaceae. Other changes are in aquatic taxa, particularly Cyperaceae and, slightly before this time, Ranunculaceae, while *Myriophyllum* attains occasional high values. Loss on ignition values are consistently low while the zone records the last isolated peaks on magnetic susceptibility in the record. Charcoal values continue to be low except for peaks, especially in the charcoal/pollen ration, at the base of the zone.

*Zone CF 5 (790–760 cm depth; ca. 60–58 ka)*. This narrow zone is marked by a major peak of approximately 60% in *Eucalyptus* and corresponding peaks in many understorey taxa including myrtaceous shrubs, *Pomaderris*, *Polyscias*, *Coprosma*, *Dodonaea* and *Haloragodendron* as well as ferns, mainly *Dicksonia* and *Cyathea*. Casuarinaceae, *Podocarpus*, *Plantago* (native) and Gentianaceae have high values in the topmost sample of the zone. Asteraceae, Chenopodiaceae and

Poaceae values are very low. Swamp taxa *Myriophyllum*, Restionaceae and Cyperaceae as well as *Botryococcus*, and spores and pollen of the floating plants *Azolla* and *Lemna*, respectively, are mainly restricted to this zone. Loss on ignition, charcoal and pollen concentration also increase with pollen concentration approaching its highest value in the record. Charcoal and charcoal/pollen values show higher values.

Zone CF 4 (760–560 cm depth; ca. 58–45 ka) is distinguished by a return to low eucalypt pollen percentages and by an associated decrease in organic content of the sediment, as well as of generally low percentages of *Tubulifloridites pleistocenicus*. Two subzones are identified, the first, subzone CF 4b displaying a combination of some distinctive features as well as a continuation of some characteristics of the previous zone.

Subzone CF 4b (760–730 cm depth; ca. 58–56 ka) shows a sharp reversion in *Eucalyptus* to low values and many other regional woody taxa, including *Podocarpus*, *Pomaderris* and *Dodonaea*, have very low percentages or are not recorded. By contrast *Phyllocladus* is present after being absent in the previous two zones, Proteaceae, *Monotoca* and *Haloragodendron* have their highest values while *Tasmannia* peaks for the record. All three Asteraceae taxa as well as Chenopodiaceae and most herb taxa remain low, but Poaceae and the ferns *Dicksonia*, *Cyathea* and *Histiopteris* achieve their highest values. Within the basin, organic matter is reduced to minimal values but swamp taxon values, largely due to Ranunculaceae, Restionaceae and Epacridaceae, and lake algae including the only occurrence of *Zygnema* in the record as well as *Botryococcus*, remain high. Moderate charcoal/pollen ratio values are maintained from the previous zone but charcoal concentrations are very low suggesting that the ratios are simply an artefact of pollen concentrations which are the lowest within the record.

Subzone CF 4a (730–560 cm depth; ca. 56–45 ka) displays a return to an assemblage similar to those recorded in zones CF7 and CF8 that are dominated by Asteraceae Tubuliflorae and Poaceae although there is little evidence of the systematic variation that was evident in *Callitris*, *Podocarpus* and Proteaceae in the early period. Both *Callitris* and *Podocarpus* have consistently low values while the Proteaceae have relatively high but variable representation. Ferns have virtually disappeared. Some of the features of the previous subzone continue into this one. Chenopodiaceae and *Tubulifloridites pleistocenicus* maintain generally lower values while *Chionogentias* maintains the increased presentation achieved in zone CF5. Within the Podocarpaceae, the regionally extinct taxa *Phyllocladus*, *Dacrycarpus* and *Dacrydium*, as well as indeterminate Podocarpaceae, have an occasional presence. Aquatic pollen is poorly represented apart from Cyperaceae and Epacridaceae that peak towards the top of the zone and there is a sharp peak in Restionaceae that corresponds with a similar high value of *Eucalyptus*. Loss on ignition and magnetic susceptibility values are consistently low but charcoal values are generally higher with occasional moderate peaks.

Zone CF 3 (560–330 cm depth; ca. 45–31 ka). Asteraceae values, including *Tubulifloridites pleistocenicus* as well as Asteraceae Tubuliflorae, are high in this zone, Poaceae values are reduced while eucalypt values generally remain low. *Callitris* values also remain low and those of Proteaceae are reduced. *Podocarpus* has a small peak at the top of the zone accompanied by the last appearances of *Phyllocladus* and *Dacrycarpus*. *Haloragodendron* achieves highest values before disappearing from the record at the zone CF3/2 boundary. Within the aquatics, Cyperaceae and Epacridaceae remain the best represented taxa with consistent values of Ranunculaceae and obligate aquatics, with the exception of occasional occurrences of *Pediastrum*, are virtually absent. An isolated

peak of *Eucalyptus* is matched by associated peaks in *Myriophyllum* and Restionaceae. There is no change in loss on ignition levels but magnetic susceptibility values are higher in the middle of the zone and charcoal values are consistently low.

Zone CF 2 (330–118 cm depth; ca. 31–11 ka). The zone CF3-2 boundary is marked by sharp reductions in Asteraceae and *Tubulifloridites pleistocenicus* and, although these do recover, Poaceae, that had a concomitant increase around the boundary, remains the dominant pollen type throughout the zone with a major, sharp peak at the top of the zone. Chenopodiaceae achieves its highest percentages for the diagram. No other dryland taxa, apart from Casuarinaceae, *Callitris*, Proteaceae, *Plantago* and *Chionogentias*, have consistent representation and diversity is low. Within the aquatic taxa, Cyperaceae and Ranunculaceae increase their representation slightly, but Epacridaceae percentages are reduced and few other aquatic are recorded. *Myriophyllum* and Restionaceae have occasional high values although, unlike previous events, are not accompanied by similar high values of *Eucalyptus*. Loss on ignition values remain low and drop even further towards the top of the zone. There are progressive reductions in both magnetic susceptibility values and pollen concentrations through the zone with the latter losing the degree of variability that characterises much of the record, Charcoal values peak only at the base of the zone.

Zone CF 1 (118–0 cm depth; ca. 11–0 ka). The change at the base of this zone appears to be sharpest and most extreme in the record with *Eucalyptus* values rising from about 5% to 60% and then increasing to 85% at the surface. The rise is largely at the expense of Poaceae that experiences an equally devastating decline. Asteraceae Tubuliflorae and Chenopodiaceae also show substantial reductions, and *Tubulifloridites pleistocenicus* almost disappears. Casuarinaceae has a minor peak at the base of the zone and *Callitris* increases to achieve its highest level of the record, while *Pomaderris* is the only regional understorey taxon to have consistent representation. Taxa that are abundant in alpine assemblages including Proteaceae, *Pimelea*, *Micrantheum* and *Chionogentias* disappear at the base of the zone while *Plantago* is reduced to occasional representation. *Pteridium* has its best representation in the record, and is one of few fern spore taxa recorded. There are also substantial changes in the basin with aquatic pollen and loss on ignition values increasing sharply at the zone CF 2/1 boundary and achieving highest values for the record. *Botryococcus*, *Myriophyllum*, Ranunculaceae, Restionaceae and Cyperaceae values are highest at the base with *Myriophyllum* peaking again in the middle of the zone and Cyperaceae and Restionaceae peaking again at the top. The zone records the only occurrence of *Sphagnum* in the record with a high value mid-zone. Charcoal values generally increase through the zone while magnetic susceptibility predictably decreases with the very high organic component of the sediment at the top of zone.

## Discussion

The detailed record of Caledonia Fen reveals substantial variation in local and regional vegetation and environmental change through the last glacial–interglacial cycle on a number of scales varying from long-term trends, through orbital cyclicity to millennial and sub-millennial events. It is to be expected that the sensitivity of the site to each of these influences will vary depending on such factors as the stage of

basin development and threshold values for vegetation and hydrosere change.

### Orbital scale variation

The most distinctive feature of the record is the difference between glacial and interglacial environments. The Holocene and at least the height of the last interglacial (zone CF 10) are marked by dominance of *Eucalyptus* pollen that demonstrates the existence of forest around the site under temperature and precipitation levels, almost certainly, broadly similar to those of today. The presence of the understorey taxon, *Pomaderris*, indicates that wet sclerophyll forest was regionally widespread even if not in the local vicinity, while low values for predominantly low shrub or herbaceous taxa, particularly Asteraceae and Poaceae, suggest that communities dominated by these taxa were very restricted in their distribution. The assemblages within the two periods also show the low but consistent presence of two other major dominants of sclerophyll vegetation, Casuarinaceae and *Callitris*. However, similar percentages for Casuarinaceae through the whole of the record suggest that this is a long-distance pollen component and, as today, has never been a significant part of the regional vegetation. The situation appears somewhat different for *Callitris* that has much more variable representation through the record. It likely reflects a changing abundance in drier valleys within the region.

Differences between the two periods include a greater range and abundance of sclerophyll understorey taxa during the last interglacial. These taxa include the angiosperms *Polyscias*, *Coprosma*, *Phebalium* and *Eriostemon* as well as ferns including the tree ferns *Dicksonia* and *Cyathea*, which are found most commonly in wet sclerophyll forest and could suggest that this period was wetter than the Holocene. However, the high values for the drier sclerophyll forest taxon *Dodonaea* could indicate the opposite. Differences may relate to different basin characteristics. The high organic content of the last interglacial sediments is composed of lake mud that in combination with low levels of swamp pollen and high values for algal spores indicates a relatively deep lake environment within a stable catchment. It is likely that, without a vegetation cover, pollen could have been washed off the surrounding slopes and focused within the basin. By contrast, the predominantly peat sediment combined with high values for local aquatic pollen indicate the consistent presence of fen or bog vegetation that would have inhibited representation of pollen from plants with poor aerial dispersal, that includes many of the wet sclerophyll understorey species.

At this scale of analysis, there is little indication of patterns of variation in dryland vegetation that allows assessment of climate or other environmental change within the interglacial periods, although conditions appear to have been more constant during the last interglacial. It is interesting though that both *Callitris* and myrtaceous shrubs do show opposing representation. It may be suggested that higher values in the later part of the Holocene indicate slightly drier conditions, regionally in the case of *Callitris* and more locally in the case of myrtaceous shrubs that have limited pollen dispersal. Conversely, drier conditions may have characterised the early part of the last interglacial. However, marked changes of climatic significance are evident in the aquatic vegetation of the Holocene. The earliest Holocene spectra include peaks in *Botryococcus*, *Myriophyllum* and Ranunculaceae that indicate conditions suitable for the establishment of largely submerged vegetation. There is then evidence of succession through a

swamp or fen stage with high Cyperaceae to bog dominated by Restionaceae. Although it could be expected that *Sphagnum* would have been an integral part of this succession, it is not recorded until a late stage. It has been considered that *Sphagnum* seldom spores at high altitudes and when the vegetation is under stress (Kershaw *et al.*, 1997). Consequently the high values of *Sphagnum* spores may represent drying and/or a peak in temperature within the zone. There is then evidence for a second successional sequence with *Myriophyllum* replaced by Cyperaceae which in turn gave way to Restionaceae, presumably under a subsequent increase in effective precipitation. This sequence is similar to that represented spatially by aquatic fen, fen and bog communities with a reduction in water depth today on the fen. Notably, there is no evidence of *Sphagnum* spores within this sequence despite the frequency of the bryophyte in the present vegetation.

Almost all dryland assemblages of the inferred glacial periods, MIS 6 and 5d to 2, are dominated by pollen of herbs and woody or herbaceous plants of which Poaceae, Asteraceae and generally Chenopodiaceae are by far the most abundant. The presence of taxa such as *Plantago*, *Chionogentias*, *Aciphylla*, *Pratia*, *Pimelea* and Proteaceae suggest that the dominant vegetation was probably alpine in character indicating a significant reduction in temperature. However, because of the broad ecological ranges of most of these taxa, specific vegetation and climatic estimates are difficult to postulate. In the first place, alpine vegetation is very restricted in its distribution at the present day so that modern pollen assemblages are dominated by pollen of plants from surrounding woodland and forest that have high pollen production and dispersal capabilities (D'Costa and Kershaw, 1997). Consequently, the value of comparisons is limited. Secondly, the glacial assemblages generally contain a high proportion of blunt-spined Asteraceae (*Tubulifloridites pleistocenicus*) whose present-day affinity has not been firmly established (Macphail and Martin, 1991), providing a non-analogue situation. Through the Quaternary period, it is clearly associated with glacial periods. It is most likely that the fen was above the altitudinal treeline during a large part of glacial period, suggesting a minimum decline of 3°C in the temperature of the warmest month, and was probably much colder during the glacial maxima judging from estimates of the past extent of periglacial activity in montane Australia generally (Barrows *et al.*, 2001). The pollen assemblage itself is uninformative in this regard.

However, there is some suggestion, from initial examination and bioclimatic analysis of macrofossils from the wide diameter cores, that temperature lowering was, at times during MIS 3, insufficient to cause a depression of treeline below the level of the site, although full analysis of these data have yet to be completed (Porch, in preparation). The significance of the position of the treeline at Caledonia Fen has also to be examined in relation to evidence from other pollen records in southeastern Australia, and these indicate that predominantly treeless conditions extended to sea level during much of the last glacial period (Hope, 1989; Kershaw *et al.*, 1991; Kershaw, 1998) supporting the idea that summer temperature was not the limiting factor to tree growth. Indeed, the continuous representation of *Eucalyptus*, occasionally with high values, suggests survival, perhaps in shrub form, at least within small, sheltered patches not too distant from the fen. Factors responsible for this limited distribution may have included higher wind speeds and incursions of cold polar air (McGlone, 1988) especially with a more northward positioning of the polar easterlies and westerly wind belt. However, the extent and direction of latitudinal pressure belt movements, as well as

changing intensities of atmospheric circulation systems, are still vigorously debated (Shulmeister *et al.*, 2004).

Another factor possibly influencing tree growth is precipitation and it has generally been considered to have contributed to glacial treelessness. Certainly, high values of Chenopodiaceae, in particular, could suggest substantially drier conditions. However, Chenopodiaceae percentages do not conform well to glacial–interglacial cyclicity suggesting that aridity was not a consistent feature of glacials. For example, values at the end of the penultimate glacial period are little different than those of the last interglacial suggesting little effective moisture change. These values are little higher than background values recorded today throughout eastern Victoria and presumably the pollen was derived from extensive semi-arid chenopodiaceous shrublands. Modern background values extend throughout the Holocene in the Caledonia Fen record, and may provide additional support for the option that this period was wetter than the last interglacial. However, there is a marked increase in Chenopodiaceae within zone CF 6, which is suggested on Fig. 4 to represent the MIS 5/4 boundary. The exclusion of Chenopodiaceae from the pollen sum, due to its over-representation in saline water bodies within the western part of the southeast Australian region (D'Costa and Kershaw, 1997), has prevented the detection of this boundary in the CONISS classification. High values are largely maintained through to the end of the Pleistocene, suggesting that the main part of the last glacial period experienced relatively dry conditions. The lack of a Chenopodiaceae response in MIS 6 could be due to the limited record that picks up only the glacial–interglacial transition.

Chenopodiaceae values are highest towards the end of the glacial period (zone CF 2; ca. 31 ka) suggesting lowest precipitation levels of the last glacial–interglacial cycle. Whether this period corresponds with MIS 2 is uncertain and depends, to some degree, on whether the majority of radiocarbon ages or the optical age is accepted. The suggestion from the radiocarbon ages that the Last Glacial Maximum may have begun earlier in the mid-latitudes of the Southern Hemisphere supports the proposition of Vandergoes *et al.* (2005) from analysis of a pollen record from New Zealand, who attribute this feature to a minimum in regional insolation. It may also be consistent with a marked fall in temperatures in the Vostok record, dated to about 34 ka.

The local basin record suggests also, from the apparent continuity of its record and preservation of pollen, that conditions were never very dry. The predominantly inorganic sediments are relatively homogeneous and reflect a low productivity system both within the basin and in the surrounding catchment. An open lake is suggested at times by high values of *Botryococcus* and there is some suggestion of a vegetated fringe with the consistent presence of Cyperaceae and perhaps times of marginal bog supporting Epacridaceae and Restionaceae. However, there is no clear hydroseral succession evident through most of glacial period, and this could indicate rapidly fluctuating lake levels. Conversely, or in addition, succession may have been inhibited by a cover of ice through much of the year.

The major exception to this glacial landscape is the interstadial of early MIS 3. Both dryland and aquatic data indicate greater similarity to interglacial than glacial conditions during zone CF 5, although the phase appears to have lasted only about 2000 years. Deposition of organic sediments indicates a much more productive environment while aquatic vegetation development suggests that temperatures increased sufficiently to eliminate ice cover as a significant environmental factor. There is some evidence for hydroseral succession with initial responses from the open water or swamp taxa

*Botryococcus*, *Myriophyllum*, *Azolla* and Cyperaceae followed by the bog taxon Restionaceae to form a vegetation cover similar to that of today but with a greater open water component. Variation in abundance of the different taxa through the zone suggests that climate variation may have influenced the changing composition of the vegetation as much as succession and the demonstrated rapidity of change supports the proposed fundamental climate control over aquatic variation noted within the much longer Holocene period. Within dryland vegetation, a number of forest understorey taxa accompany the peak in *Eucalyptus*. Of note are the tree ferns *Dicksonia* and *Cyathea* which have higher values than present, or at any other time within the record, perhaps suggesting either higher rainfall or more effective rainfall due to a feature such as lower summer temperatures, greater summer rainfall or increased cloud cover.

Although most features of the record revert to the glacial norm after the period represented by zone CF 5, high values for tree ferns persist into subzone CF 4b and are joined by highest values in the record for the wet shrub taxa Epacridaceae and *Tasmannia*, suggesting some continuity of moist or equable conditions, although temperatures most likely decreased. Conditions remained generally unsuitable for *Tubulifloridites pleistocenicus*, which had also decreased abruptly at the zone CF 6/5 boundary, until the end of the period represented by CF zone 4. Although these conditions are not known they do suggest an extension of some aspects of the early MIS 3 environment.

There is little evidence globally for such a distinctive MIS 3 climate but this period is very marked, at least by peaks in effective precipitation, in many Australian Quaternary records from inland lake and fluvial environments (Bowler *et al.*, 2001; Kershaw and Nanson, 1993; Magee *et al.*, 2004) and often more so than the Holocene, while similar ameliorations are either inconsistently recorded or not apparent in MIS 5 interstadials. A similar strong amelioration in early MIS 3 may be postulated for the Lake Wangoom pollen record (Kershaw and van der Kaars, 2007). At Caledonia Fen it is suggested that a less seasonal climate may have existed. Such a climate may have incorporated increased summer rainfall consistent with a proposed stronger monsoon influence over much of Australia than today during this period (Miller *et al.*, 2005).

The early part of the glacial period, embracing the period covered by subzones MIS 5d–a that shows prominent precessional variation in the marine isotope stratigraphy and in the temperature record of the Vostok core, lacks substantial variation in the Caledonia Fen record. However, there is some indication of this scale of cyclicity, best indicated by in phase changes in representation of the dryland taxa *Callitris* and *Podocarpus* but also present in the aquatic pollen record by peaks in Ranunculaceae and Epacridaceae alternating with those in *Botryococcus*, neither of which are in phase with those of the dryland taxa. These cycles decrease in amplitude through the period. Likely climatic controls are difficult to determine, especially as both *Callitris* and *Podocarpus* are considered to be represented by remnant populations in the area today, but probably involve subtle changes in both precipitation and temperature. Stratigraphically, peaks in *Callitris* and *Podocarpus* correspond most closely with stadials, with the peaks appearing to occur within MIS 5d, MIS 5b and MIS 4. These muted signals may result from competing hemispheric precessional forces emanating from the North Atlantic and southern mid-latitudes. The subsequent loss of this cyclicity in the later part of the glacial period may then be attributed to a reduction in the amplitude of precessional insolation variation generally after about 60 ka BP (Berger and Loutre, 2002).



## Abrupt events

The resolution of the Caledonia Fen record allows examination of millennial to sub-millennial variation. A number of millennial-scale events are suggested by independent variations in major taxa but are generally difficult to relate to each other and to explain. Perhaps the most notable features of the record are the abrupt events that are represented by peaks in both dryland (especially *Eucalyptus*) and aquatic taxa and which, apart from that correlated with early MIS3 (zone CF5), appear to have lasted for a few centuries at a maximum. As they indicate responses in both aquatic and dryland environments, they must have had a regional trigger, most probably a sharp increase in temperature. The events are concentrated within the period inferred to cover MIS4–2. Although this concentration may be attributed, at least in part, to the sensitivity of the site in relation to stage of basin development, there is a general relationship with the pattern of abrupt interstadial Dansgaard–Oeschger (D-O) events, originally determined and best expressed in the Greenland ice cores (Johnsen *et al.*, 2001; North Greenland Ice-Core Project (NorthGRIP Members, 2004)). The chronology of the Caledonia Fen record is too uncertain to allow detailed correlations with the ice record. However the representation of about six events, defined on the co-occurrence of peaks in *Eucalyptus* and at least one aquatic taxon, would correspond reasonably well with the 20 identified events in ice cores, when the fact that only one in four centimetres of the Caledonia Fen core has been analysed is taken into account. It has been proposed that the much less abrupt peaks in the Vostok record are in antiphase with D-O events as a result of a 'bipolar seesaw' (Broecker, 1998) whereby warm conditions in the Northern Hemisphere are matched to cool conditions in the Southern Hemisphere and vice versa as a result of global atmospheric or oceanic connections (Broecker, 2003). Consequently, the events recorded in Caledonia Fen may relate to either phase. Although, their abrupt nature has more in common with the Northern Hemisphere signal, the suggestion that they indicate warming is more consistent with a Southern Hemisphere forcing.

Abrupt events, most marked by peaks in *Eucalyptus* also characterise what is considered to represent the termination of the Last Interglacial (inferred MIS 5e extending into MIS 5d: subzones CF 9d and 9a), a period of considerable interest for future climate change if the present interglacial is, in fact, in its termination phase (Berger and Loutre, 2002). There have been few parallels of abrupt coolings in other records although one event around the MIS 5e-d boundary is widely recorded from marine and terrestrial records in the Northern Hemisphere (e.g. McManus *et al.*, 1994). Recently, however, more frequent (1–3 ka) climatic oscillations have been detected after the interglacial peak in oxygen and carbon isotope records and pollen records from the mid-latitude North Atlantic region (Oppo *et al.*, 2001; Heusser and Oppo, 2003; Sprovieri *et al.*, 2006). Consequently, these may be widespread features.

## Environmental and vegetational trends

A number of systematic changes in the record can be attributed to the evolution of the basin from what was originally a relatively deep and narrow valley depression capable of containing a deep lake to the present situation where sediment has accumulated to the outflow. Although it has been proposed that this may have had some influence on differences in the composition of dryland assemblages from the last interglacial

and the Holocene, largely through the degree of inwash of pollen into the centre of the basin, differential pollen representation within glacial periods, when the basin lake is likely to have been predominantly frozen inhibiting local vegetation development, is likely to have been minimal. However, the higher degree of systematic variation in representation of aquatic vegetation, most evident in the alternation of open water as indicated by *Botryococcus* and bog as suggested by Epacridaceae, in the lower half of the sequence may have been as much a result of the stage of evolution of the site as of external precessionally controlled climate influences.

One feature that cannot be attributed to basin development is the loss of a number of taxa, mainly southern conifer Podocarpaceae (*Phyllocladus*, *Dacrycarpus* and *Dacrydium*) but including the angiosperm *Haloragodendron*, a member of the Haloragidaceae.

All the Podocarpaceae that disappear from the record were common components of the rainforest vegetation that dominated Australian vegetation within the Tertiary period (Martin, 1994) and were still well represented in the Early Pleistocene, at least in places (Sniderman *et al.*, 2007). Survival through the Middle Pleistocene in southeastern mainland Australia is suggested by occasional representation in volcanic crater records from the western plains of Victoria (Wagstaff *et al.*, 2001; Harle *et al.*, 2004). These records are, however, complicated by the presence of Tertiary sediments that may have resulted in contamination and by the relatively open nature of the vegetation that would have assisted long-distance representation. The continued representation of *Phyllocladus* into the Holocene within these crater sediments has been attributed to long-distance transport from Tasmania where the taxon still survives (Head, 1985). The last definite presence of *Phyllocladus* on the mainland is from the Otway Ranges, some 300 km west of Caledonia Fen, aged to sometime before 40 000 years ago (McKenzie and Kershaw, 2000). Both *Dacrydium* and *Dacrycarpus* have been recorded at the base of a Holocene sequence in the Otways and, although it was suggested that the basal samples may have related to an earlier period, a relatively late Pleistocene survival is suggested (McKenzie and Kershaw, 2004).

The small tree or shrub taxon *Haloragodendron* differs from the Podocarpaceae in being a component of the now-dominant sclerophyll vegetation, possessing a regional rather than continental decline, and in the abrupt nature of its demise. However, the genus displays some similar characteristics to the Podocarpaceae in being restricted to small isolated patches in habitats that offer some protection from fire and also having a long history in Australia (Tibby, 1995). The pollen can be equated with the form taxon *Stephanocolpites oblatus* which is first recorded in the early Tertiary and, although its pollen is best represented towards the end of the Tertiary period when conditions were becoming drier, has had very limited representation in the Quaternary (Martin, 1973). The most likely source of the pollen here is from *Haloragodendron bauerlenii*, the only Victorian representative and classified as rare (Briggs and Leigh, 1988). It has highly specific habitats and is largely confined to elevated dry rocky spurs (Jeanes, 1996).

The general decline in *Phyllocladus* in the Caledonia Fen record suggests increasingly unfavourable climatic conditions for its survival either during peak occurrences or between these peaks. This may be indicative of a general trend towards drier or more variable conditions as suggested from long records elsewhere (Kershaw *et al.*, 2006). Such a trend may be supported by the fact that the latter part of the last glacial period appears to have been drier than that of MIS 6 and that forest development may have been greater during MIS 5e than in the Holocene. However, as previously mentioned, comparison of

the Caledonia Fen record with the Vostok record suggest that temperatures may have already increased from glacial maximum levels at the beginning of the Caledonia Fen record.

An alternative or additional explanation for taxon disappearance is that there was a critical event around the zone CF3/2 boundary, estimated, from the radiocarbon ages, to have been around 31 ka BP that witnessed the last occurrences of the extinct Podocarpaceae and the abrupt disappearance of *Haloragodendron*. The event does mark a change to apparently drier conditions for the record and could have tipped the balance towards extinction or marked range contraction. It might suggest the most extreme conditions experienced during the Quaternary period. However, it is known that indigenous people were present in Australia at this time and, although it is at least 10 ka after the most substantial, suggested impact on the vegetation through the agent of fire (Kershaw *et al.*, 2006), some lag in colonisation might be expected because of the relatively hostile landscape of the southeastern highlands. The advocacy of a possible burning cause demands some examination of the charcoal record. This record suggests that fire was most frequent or more intense during interglacial periods, probably owing to greater fuel availability within a forested catchment. The higher values during the last interglacial than the Holocene can be most readily explained by the closer proximity of forest vegetation to the coring site with a more restricted basin area and the presence of a lake rather than swamp surface that allowed inwash of charcoal from the surrounding slope. Apart from isolated peaks, charcoal concentrations during glacial periods are low, presumably due to a lack of a woody charcoal source and perhaps also a more open structure to the vegetation. Additional peaks in the charcoal/pollen ratio possibly reflect the contribution of old soil surface charcoal in the absence of significant flowering events. There is no indication of higher burning levels or of a change in fire regime at the zone CF 3/2 boundary. Consequently, despite the relative sensitivity to burning of these ancient taxa, there seems to be no positive evidence to implicate either natural or anthropogenically induced fire in this extirpation event.

## Conclusions

Detailed palynological analysis of the sediment core from Caledonia Fen provides what is considered to be a continuous record of at least 140 000 years, i.e. the last glacial–interglacial cycle. Although the chronology relies heavily on comparison with temperature variation evident in the Vostok ice core and on the marine isotope stratigraphy, confidence in ages is provided by the first OSL determinations from a terrestrial lake record in Australia. Temperature appears to provide a major control over vegetation development within the basin and regionally, although other factors need to be invoked to explain the degree of variation recorded. Contrary to interpretations from other records, there is little evidence for aridity, although conditions are considered to have been regionally drier in the record between about 30 000 and 11 000 years ago. The disappearance of a number of taxa, that have had much more extensive distributions on the continent within the Tertiary period and earlier part of the Quaternary period, at this time, suggests a culmination of a long-term trend towards drier conditions. The high-resolution record has allowed investigation of millennial and sub-millennial variation within the record and speculation about the end of an interglacial and possible relationships with abrupt events recorded in the North Atlantic region.

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