Lake George revisited: new evidence for the origin and evolution of a large closed lake, Southern Tablelands, NSW, Australia. 2: earliest Pleistocene (Gelasian) environments

M. Macphail, L. K. Fifield, B. Pillans and G. Hope

ABSTRACT

The three sedimentary units infilling Lake George provide the longest quasi-continuous sedimentary record of any Australian lake basin. A combination of cosmogenic nuclide burial, magnetostratigraphy and biostratigraphic dating techniques previously has shown that the basal (fluvial) unit, the Gearys Gap Formation, began accumulating at ca 4 Ma, in the early Pliocene (Zanclean), and (ii) deposition had ceased by ca 3 Ma, in the mid-late Pliocene (Piacenzian). The same techniques confirm the middle unit, the (fluvo-lacustrine) Ondyong Point Formation began accumulating in the late Pliocene and deposition continued into the earliest Pleistocene (Gelasian) within a shallow but probably laterally extensive freshwater lake extended across the drillhole site. Our data provide a minimum Gelasian age for tectonic blockage of former spillway(s) and formation of paleo-Lake George. Whether this was the earliest lake to form within the basin is unknown, since the dated intervals are separated by a ferric hardpan, interpreted as representing a prolonged period of erosion or non-deposition. Temperate rainforest angiosperms including Nothofagus growing during the late Pliocene had been extirpated or become extinct during this interval, although a number of gymnosperms, now endemic to New Caledonia, New Guinea, New Zealand and Tasmania still survived in the otherwise sclerophyll-dominated vegetation. The succession of plant communities is considered to be due to effectively drier local conditions, which in turn reflect regional aridification during the Plio-Pleistocene transition, despite the formation of a freshwater lake across the basin. The sequence provides a reliable framework for recognising and correlating Plio-Pleistocene deposits elsewhere on the Southern Highlands.

Introduction

This paper is the second in a series evaluating new evidence for Neogene and Quaternary environments in the iconic Lake George basin at 734 m elevation on the Southern Tablelands of New South Wales, ~30 km NE of Canberra (Figure 1). This basin contains the longest known quasi-continuous sedimentary record of any Australian lake basin and, owing to its proximity to Australia’s capital city Canberra, has attracted more than its fair share of urban myths and legends. As for the first paper (Macphail, Fifield, Pillans, Davies, & Hope, 2015), the study is centred on core from BMR Corehole C354, one of several mud-rotary coreholes drilled by the Bureau of Mineral Resources (now Geoscience Australia) in 1982/1983 near the western shoreline of the lake adjacent to the Lake George Range (Figure 1). In this paper, we focus on the middle of the three major sedimentary units infilling the Lake George basin, the Ondyong Formation. Other papers in this series will discuss (a) topographic and seismic evidence for the evolutionary history of the basin and uplift of its associated horst, the Lake George Range, and (b) the early to late Pleistocene environments via geochemical and palynostratigraphic analysis of the youngest unit in the basin, the Bungendore Formation, centred on the recently drilled sonic corehole, Gearys Gap-1.

The first paper established late Pliocene (Piacenzian Stage) age limits for the lowermost of the three major sedimentary units infilling the Lake George basin, the fluvial Gearys Gap Formation (Macphail et al., 2015). Within the differing resolutions achievable by the three dating techniques our results showed that (i) the Gearys Gap Formation began accumulating at ca 4 Ma in the early Pliocene (Zanclean), and (ii) deposition had ceased by ca 3 Ma in the mid-late Pliocene (Piacenzian). During the Piacenzian, the vegetation at the core site was a wetland community dominated by members of the coral fern family Gleicheniaceae, while the surrounding dryland flora was a mix of sclerophyll and temperate rainforest species, with the latter including trees and shrubs now endemic to New Guinea–New Caledonia and Tasmania. Mean annual rainfall and temperatures are inferred to have been...
between ~2000 and 3000 mm, although probably not uniformly distributed throughout the year, and within the mesotherm range (>14°C to <24°C), respectively. However, the available age control did not necessarily confirm an early Pliocene (Zanclean) maximum age for the formation of the lake basin and also left two major geological issues unresolved. These are: (1) Does the Gearys Gap Formation predate uplift of the Lake George Range and therefore provides evidence...
that one of the proposed paleo-spillways of Lake George, that above Geary’s Gap, has been elevated up to 100–200 m by neotectonic activity over the past 4 million years? (2) Did a shallow to deepwater lake exist elsewhere in the lake basin during the Pliocene?

As with the Gearys Gap Formation, the age limits of the fluvio-lacustrine Ondyong Point Formation are based on a combination of cosmogenic nuclide (10Be/26Al), paleomagnetic and palynostratigraphic evidence. Critical sections are (i) quartz-rich gravels at ~89.3–90.45 m depth, located ~16 m above the picked boundary of the Ondyong Point Formation with the underlying Gearys Gap Formation at 106 m depth, and (ii) unweathered carbonaceous silts and clays at ~75.5–87.5 m depth, ~25 m below the boundary of the Ondyong Point Formation with the overlying Bungendore Formation at ~54.3 m depth. These silts and clays were provisionally dated as early Pleistocene by Truswell (1984, 1985), based on trace occurrences of Monotoca. This criterion is now known to be invalid, since the pollen type first appears in the late Miocene–early Pliocene in southeast Australia (Macphail, 1999; Partridge, 1999).

Physical setting

The physical features of the Lake George basin have been described by Abell (1985, 1991) and its regional geological context summarised in Macphail et al. (2015). Lithostratigraphic evidence from coreholes drilled in the basin, including BMR Corehole C354 located on the lake floor ~2 km east of the escarpment of the Lake George Range (Figure 2), have been discussed by Abell (1985, 1991), Singh and Geissler (1985), Singh, Opdyke, and Bowler (1981) and Truswell (1984, 1985).

Key points are: (1) The modern Lake George basin is a hydrologically closed depression whose western margin is formed by the tectonically uplifted Lake George Range, and eastern margin by the line of low hills (Rocky Pic Upland), which form the local watershed of the Great Dividing Range. Streams in the Lake George catchment occupy broad valleys in their upper reaches and meander across the alluvial plains such as the Bungendore Plain before reaching the lake. (2) The steep eastern escarpment of the Lake George Range is mantled by colluvial deposits while Quaternary lacustrine strandlines and eolian deposits line the lake foreshore. Older strandlines up to 37 m above the lake floor reflect much larger variations in lake level during the same period (see Coventry, 1976). (3) Geary’s Gap on the Lake George Range ~30–40 m above the present lake floor, is believed to have been a paleo-spillway connecting the basin to the ancestral Yass River prior to uplift of the Lake George Range (Abell, 1985). Ferruginous, quartz-rich fluvial gravels correlated with the Gearys Gap Formation form the floor in a hollow adjacent to but above Geary’s Gap. (4) The basin is infilled with up to 165 m of sediments comprising

Figure 2. West to east section across Lake George basin (after Abell, 1985).
the lacustrine Bungendore Formation (~0–50 m depth), the Ondyong Point Formation (~50–106 m depth) and Geary Gap Formation (~106–165 m depth).

Lithostratigraphy

The Ondyong Point Formation consists of fluvial sand and lacustrine clay and silt disconformably overlying deeply weathered sediments of the Gearys Gap Formation. The overlying Bungendore Formation, which comprises lacustrine clay and silt, was conformably deposited over the Ondyong Point Formation but is separated from it by a laterally persistent layer of sand and silt (Jacobson, Jankowski, & Abell, 1991). The latter two units are the result of sediment deposition in a hydrologically closed drainage basin and variations in the lithofacies are considered to be driven by climatic change. Gypsum occurs in the upper part of the Bungendore Formation and at its lower boundary with the Ondyong Point Formation and traces of halite occur in both the Bungendore Formation and Ondyong Point Formation. Both minerals are considered to be authigenic (Jacobson et al., 1991).

The Ondyong Point Formation is defined from representative sections in drillcore from within the lake basin (see Abell, 1991, table 14) but may extend laterally beneath the alluvial plains on the margins of the lake. The base of the formation in core C354 was arbitrarily placed at 106 m, a depth which corresponds to a change from residual to transported kaolinite and interpreted as a disconformity surface at the top of the Gearys Gap Formation by Abell (1985, 1991). The upper boundary of the Ondyong Point Formation with the overlying Bungendore Formation was picked at the highest, laterally continuous sand at ~54.3 m depth in an overall upward fining sequence of mottled lacustrine clays and fluvial sands (hand-written 1983 geological log for drillhole C354). Reddish-brown ferruginous weathered deposits, representing unconformity surfaces, occur intermittently throughout the sequence. An example of these deposits (a ferric sandstone ‘hardpan’) occurs at 89.1–89.3 m depth in Corehole C354, immediately above the cosmogenic nuclide-dated gravels at 89.3–90.45 m depth, which in turn are located ~16 m above the boundary of the formation with the Gearys Gap Formation. The carbonaceous silts and clays at 75.6–87.7 m depth, dated by McEwen Mason (1991) and Truswell (1984, 1985) using paleomagnetic and palynostratigraphic techniques, respectively, are located ~21–33 m below the upper boundary of the Ondyong Point Formation. Paleomagnetic evidence shows that deposition of Ondyong Point Formation in Corehole C354 ceased sometime during the early Pleistocene (Calabrian Stage) (see below). The age of the boundary with the Bungendore Formation is likely to vary across the basin based on changes in the thickness of the Ondyong Formation within the basin and the transitional nature of the fluviolacustrine environment in which it accumulated.

Methods

The three lines of independent age control used to determine the age limits of particular facies within the Gearys Gap Formation and overlying Ondyong Point Formation in Corehole C354 are described in Macphail et al. (2015). These are (1) cosmogenic nuclide burial age techniques, to date sediments at 89.3–90.45 m depth (Macphail et al., 2015), (2) published paleomagnetic data (McEwen Mason, 1991) and (3) palynostratigraphic data from carbonaceous sediments at 71.16–90.5 m depth (this study). We reiterate that magnetostratigraphy and palynostratigraphy have been widely used to date and correlate Cenozoic sedimentary sequences across Australia for the past 3–4 decades and that the latter technique underpins much of what is currently known about Cenozoic climates (especially precipitation), floras and vegetation across southern Australia (references in Hill, 1994; Macphail, 1997, 2007). The use of cosmogenic nuclides to date pre-Quaternary deposits in Australia is novel and has been successfully applied to date quartz gravels in the Gearys Gap Formation (Macphail et al., 2015).

Cosmogenic nuclide samples

Subangular to subrounded quartz pebbles up to 4 cm in maximum diameter were sampled at 89.3–90.45 m depth (Cores 100–101), ~16 m above the boundary between the Ondyong Point and Gearys Gap Formations. These pebbles were crushed and sieved, and the 250–500 µm fraction was taken for analysis. The quartz was purified, followed by the extraction of the 26Al and 10Be, in the cosmogenic isotope laboratories at the University of Washington (UW) using the methods described on their website http://depts.washington.edu/cosmolab/chem.shtml. Approximately 0.25 mg of the stable beryllium isotope 9Be, was added to each sample as carrier. Since the quartz contained negligible intrinsic beryllium, the 10Be concentration could be deduced from the 10Be/9Be ratio with the assumption that all of the 9Be came from the carrier. In contrast, the purified quartz contained sufficient intrinsic aluminium 27Al so that the addition of the 27Al carrier was not required. In this case, it is, however, necessary to determine the concentration of intrinsic 27Al in the quartz in order to derive an 26Al concentration from the measured 26Al/27Al ratio. The 27Al concentrations were measured using the inductively coupled argon plasma optical emission spectrometer (ICP-OES) at UW. Measurements of the 10Be/Be and 26Al/Al ratios were performed by accelerator mass spectrometry using the 14UD pelletron accelerator of the Heavy Ion Accelerator Facility at the Australian National University and methodologies described by Fifield, Timms, Gladkis, and Morton (2007) and Fifield, Wasson, Pillans, and Stone (2010). Burial ages (Table 1) were calculated from the formulae of Granger and Muzikar (2001), using the reference production rate of 10Be to be 4.96 atoms/g(quartz)/year at sea-level and high latitude, a 26Al/10Be production ratio of 6.1, and an effective attenuation length for production by high-energy spallation in rock of 160 g/cm² (see Balco, Stone, Lifton, & Dunai, 2008). The altitude and latitude scaling scheme of Stone (2000) was employed, and a rock density of 2.6 g/cm³ was assumed.
Burial ages and erosion rates.

Table 1b. Burial ages and erosion rates.

| Sample | Depth (m) | \(^{26}\text{Al}^{10}\text{Be}\) Burial age (Ma) | Erosion rate (m/Ma) |
|--------|-----------|-----------------------------------------------|---------------------|
| 100–101 | 89.3–90.45 | 1.36±0.12, 2.97±0.23, 4.75±0.83 | 1.15–4.98 |
| 159–160 | 163.75–164.6 | 0.87±0.12, 3.93±0.36, 9.7±2.6 | 0.23–4.75 |

Paleomagnetism samples

McEwan Mason’s (1991) magnetostratigraphic analysis of BMR Core C354 was based on 210 samples taken at intervals of less than 1 m along the core, except for 6 intervals of less than 2 m each between 64.9 m and 84.7 m, where core was not recovered or found to be missing. For all measurements, orientation was related to the top and base of each core section, and in the absence of other orientation information only the magnetic inclination was measured. Magnetic remanence directions were measured on a two-axis ScT cryogenic magnetometer at the ANU Black Mountain paleomagnetic laboratory, with samples undergoing stepwise alternating field demagnetisation to isolate their Characteristic Remanent Magnetisations. The magnetic stability of each sample was assessed using demagnetisation curves, orthogonal plots and stereoplots (Zijderveld, 1967).

Palynostratigraphy samples

Three of the 10 samples analysed, at 77.0, 79.5 and 86.5 m depth, were processed by Core Laboratories (Australia) Pty. Ltd. using standard chemical and micro-sieving techniques (see Traverse, 1988). The remaining samples, at 76.16, 84.7, 84.9, 85.9, 86.1, 87.5 and 90.45 m depth, were processed using the same techniques by the Sed-Paly Laboratory at Geoscience Australia, Canberra. Palynostratigraphic criteria used to infer the maximum and minimum age limits are based on time-distribution of fossil pollen and spore species (morphospecies) in the offshore Gippsland Basin and epicontinental Murray Basin in southeastern Australia (Macphail, 1999; Partridge, 1999, 2006). Depositional environments, paleovegetation and paleoclimate are based on the diversity, ecology and relative abundance of these morphospecies and algal cysts preserved in the carbonaceous clay and silt interval. The nearest living relatives (NLRs) of identifiable fossil miospores ecology are given in parentheses when first mentioned in the text and their habit and present-day distribution listed in Table 2.

Results

Age control

Cosmogenic nuclide burial age limits

Quartz clasts in gravels at 89.3–90.45 m depth yielded a \(^{10}\text{Be}/^{26}\text{Al}\) burial age of 2.96 ± 0.23 Ma (Table 1). The burial age demonstrates that the Ondyong Point Formation began accumulating sometime during the Pliocene. In combination with paleomagnetic and palynostratigraphic data, the burial age demonstrates the overlying ferric hardpan at 89.1–89.3 m depth could represent a significant period of erosion or non-deposition at the core site.

Paleomagnetic age limits

Paleomagnetic evidence (McEwen Mason, 1991) demonstrates the carbonaceous clay and silt facies between ~75 and 88 m depth in Corehole C354 were deposited between the Olduvai and Reunion subchron time (Figure 3). Current age limits for the base of the Olduvai Subchron and top of the Reunion Subchron are 1.95 Ma and 2.14 Ma, respectively (Pillans & Gibbard, 2012). This period falls within the earliest Pleistocene Gelasian Stage (2.60–1.81 Ma) following redefinition of the Plio-Pleistocene boundary from 1.81 Ma to 2.59 Ma in 2009 (see discussion in Gradstein, Ogg, Smitz, & Ogg, 2012; Ogg, Ogg, & Gradstein, 2008).

Palynostratigraphic age limits

The stratigraphic distribution and estimated relative abundance data are given in Table 3. These data are given as percentages of the total miospore count excluding algal cysts and fungal spores. Rare taxa (<1%) within the spore-pollen are indicated by ‘+’; very rare taxa recorded outside the spore-pollen count are indicated by ‘.’. Age-diagnostic taxa and a selection of ecologically significant morphospecies and undescribed spore and pollen morphotypes are illustrated in Figure 4 and Figures 5–7, respectively. Many of the rare morphospecies recorded in this study first occur in the late Miocene to early Pliocene sediments in the continental margin basins and most have NLRs in southern Australia. These taxa are of limited biostratigraphic value but provide general support for a Neogene or younger age for the Ondyong Point Formation.

Maximum age limit: The maximum age is earliest Pleistocene (Gelasian Stage), based on (a) Fenestrites, a morphotype whose First Appearance Datum (FAD) occurs within the Pleistocene Tubulifloridites pleistocenicus Zone in the Gippsland Basin; and (b) an aborted (A-type) Epacridaceae tetrad, Monotocidites sp., that closely matches modern pollen of the Leuco-pogon but which has not been recorded in Pliocene or older sediments in southern Australia (M. K. Macphail unpubl. observations). Supporting an earliest Pleistocene (Gelasian) maximum age are frequent to common occurrences of Tubulifloridites pleistocenicus (Cassinia arcuata-type) since this morphospecies first becomes abundant in the Tubulifloridites pleistocenicus Zone in the Gippsland and Murray basins. The absence of Nothofagidites (Nothofagus) spp. is negative evidence for the same maximum age limit (see Macphail, 1997).
Clay at ~90.5 m depth underlying the cosmogenic nuclide-dated gravels at 89.3–90.45 m yielded a long-ranging mor.

Minimum age limit: The minimum age is early Pleistocene, based on Myrtaceidites lipsis (Eucalyptus spatulata), a morphospecies whose Last Appearance Datum (LAD) occurs within the Tubulifloridites pleistocenicus Zone in the Gippsland and Murray basins. Other taxa supporting an early Pleistocene age are (a) the persistent presence of Araucariacites australis, whose NLR is the Bunya Pine genus Araucaria, now restricted to subtropical—tropical vegetation types in northern NSW and Queensland; and (b) Dacrycarpus australiensis (Dacrycarpus), a tall gymnosperm, which now is confined to temperate

Table 2. Taxonomic affinities and ecological data (Southern Tablelands, NSW).

| Morphospecies | Nlr | Common name | Ecology/distribution |
|---------------|-----|-------------|---------------------|
| Gymnosperms   | Araucariacites australis | Araucaria | Subtropical—tropical dry rainforest |
| | Dacrycarpus australiensis | Dacrycarpus | Temperate—montane rainforest [NZ, SE Asia] |
| | Pinus pollenites | Pinus (exotic contaminant) | Widely planted for timber and as windbreaks |
| | Dacrydium florinii | Dacrydium | Temperate—montane rainforest [NZ, SE Asia] |
| | Microcladites paleogenicus | Microcladites | Temperate rainforest [Tasmania, NZ, SE Asia] |
| | Podocarpites spp. | Podocarpus | Wet habitats coastal to alpine |
| Herbs         | Cyperaceae | Cyperaceae | Sedges |
| | Drosera | Drosera | Sun-dew |
| | Fenestraria spe. | Fenestraria (Microseris-type) | Native dandelion |
| | Glencopspos omatus | Polygonum | Knotweed |
| | Graminidites spp. | Poaceae | Grasses |
| | Haloragacites haloragoides | Haloragis/Gonocarpos | Raspwort |
| | Haloragacites myriophylloides | Myriophyllum | Water-milfoil |
| | Liliacites spp. | Liliaceae | Lilies |
| | Lymingtonia | Neopaxia-type | Neopaxia |
| | Milliforia hypoleaenae | Restionaceae | Cord-rushes |
| | Periparopollites (Plantago) | Plantago | Native plantain |
| | Polyporina granulata | Stelevaria | Starwort |
| | Polyporina reticulata | Silene | Silene |
| | Sparganiaceepollenites sp. | Typhaeae? | Brultsh |
| | Strianscopites laxus | Villarsia (Liparophyllum) | Marsh-flower |
| | stephanoporate sp. (Wahlenbergia) | Wahlenbergia | Widespread, especially in open habitats |
| | Tetracolpales (Rumex) | Rumex | Dock |
| | Tricolpites podocarpiodes | Stylidium | Trigger-plant |
| | Tricolpites pelargoniioides | Brassicaceae | Crucifer |
| | Tricolpites pelargoniioides | Pelargonium | Pelargonium |
| | Tricolpites (Apiceae) | Apio-type | Native celery |
| | Ferns and fern allies | Azolla | Azolla |
| | Cyathaea paleopora | Cyathaea | Incl. rough tree-fern |
| | Cyathidites australi/minor | Selaginella uliginos | Swamp selaginella |
| | Densiosporites impexus | Densiosporites | Coral ferns |
| | Gleicheniadiites spp. | Gleicheniaceae | Damp to wet substrates, shaded to open |
| | Herkosporites eliotii | Lycopodium deuterodensum | Bushy club-moss |
| | Ischyosporites lachlanensis | Dicksoniae | Quillworts |
| | Isotes | Isotes | Quillworts |
| | Loeagiosporites ovatus/omajor | Blechnaceae | Various |
| | Matisnospores morphomorphs | Dicksonia antarctica-type | Soft tree-fern |
| | Pilularia-type | Pilularia | Austral pillwort |
| | Ophioglossiopsis spp. | Phyllophagium-type | Pygmy club-moss |
| | Permonolites balcutus | Blechnaceae | Widespread in dry to damp habitats |
| | Podocarpidites sp. | Pteris | Tender brake |
| | Podopollides histiopteroides | Histioptes incisa | Rainforest and rocky substrates |
| | Podopollides spe. | Bats-wing fern | Wet gullies, creek banks damp rocks |
| | Retiniflorites cf. austroclavatidites | Davallioaceae, Polypodiaceae | Rockry creek banks, epiphytic on trees |
| | Rugulastepites pollatus | Lycopodium fugitatum-type | Open wet situations at high elevations |
| | Hornworts, liverworts, mosses | Liparophyllum | Rainbow fern |
| | Cingulatisporites spp. | Calochlaena | Sheltered open forests and rainforest |
| | Riccialesporites | Phaeoceros-type | (Hornwort) |
| | Riccialesporites | (Lerviron) | Epiphyte on damp substrates |
| | Rudolphisporus rudolfi | Anthoceros-type | (Hornwort) |
| | Stereisporites sp. | Sphagnum | (Hornwort) |
| | Algae | Botryococcus | Botryococcus | ±Stagnant freshwater |
| | Chara | Chara | Chara | Slow-moving freshwater |
| | Circulispis parvus | Zygmenitaceae | N/A | Freshwater |
| | Debanya sp. | Zygmenitaceae | N/A | Freshwater to soil interstices |
| | Pediastrum | Pediacium | N/A | ±Stagnant freshwater |
| | Tetraporina sp. | Zygmenitaceae | N/A | Freshwater to soil interstices |
| | Zygmena | Zygmenitaceae | N/A | Freshwater to soil interstices |
| | cf. Coloboceridium | Dinophyceae | N/A | Brackish water |
rainforest in New Zealand and analogous montane communities in New Caledonia and New Guinea (cf. Kershaw, McKenzie, & McMinn, 1993, Wagstaff, Kershaw, O’Sullivan, Harle, & Edwards, 2001). We note that *Dacrycarpus* survived until at least 1.5 Ma (Calabrian) in the Stony Creek Basin at Daylesford in the Central Highlands of Victoria (K. Sniderman pers. comm.) and at high elevations in northeastern Queensland up to ca 930 ka (references in Kershaw et al., 1993).

**Depositional environments, paleovegetation, wildfire and paleoclimate**

**Depositional environment**

All samples yielded low to abundant numbers of the freshwater algae *Botryococcus* and/or (*79.50 m) abundant *Pediasstrum*. These are associated with a diverse population of Zygernataceae, amorphous and thick-walled algal cysts that are assumed to represent aquatic species, and infrequent to common miospores of aquatic and semi-aquatic cryptogams and herbs such as *Isoetes drummondii*-type, *Haloragacites myriophylloides* (*Myriophyllum*), *Milfordia hypolaenoides* (Restionaceae) and *Cyperaceaepollis* (Cyperaceae). Salt-tolerant taxa are rare, e.g. *Chenopodipollis chenopodiaceoides* (*Chenopodiaceae*). These taxa and the organic-rich lithology is unequivocal evidence that a shallow freshwater lake extended across the core site at the time of deposition (cf. Singh & Geissler, 1985). The decrease upsection in the relative abundance of the quillwort *Isoetes* and water-milfoil *Myriophyllum* may be evidence for minor shallowing of the lake during the period of record. The dryland component is dominated by morphospecies whose NLRs produce/disperse their pollen in large numbers over long distances by wind and/or water, e.g. tree-ferns *Cyathea* (fossil equivalent *Cyathidites*) and *Dicksonia* (*Matonisporites ornamentalis*), the mostly tall-tree gymnosperm families Araucariaceae and Podocarpaceae, and most of the common to rare angiosperms, including *Haloragacites harrisii* (*Allocasuarina/Casuarina*), *Chenopodipollis chenopodiaceoides*, *Monotocidites galeatus* (*Monotoca*), *Gyropollis psilatus* (Gyrostemonaceae) and *Graminidites* (Poaceae). This phenomenon (strong Neves Effect: see Traverse, 1988, p. 413) is circumstantial evidence that, as now, the core site was located a significant distance from the paleoshoreline and that the lake was laterally extensive.

**Paleovegetation**

Some 25 spore-, 5 gymnosperm- and 65 angiosperm morphospecies can be identified to a living genus or family (Table 2). However, reconstructing the dryland vegetation is more difficult, partly because of the low taxonomic resolution of most morphospecies, and partly because many of the parent taxa...
Table 3. Relative abundance data, 76.16–90.5 m depth, BMR Corehole C354. For samples yielding 250 specimens, these data are given as percentages of the total miospore count excluding algal cysts and fungal spores. Rare taxa (<1%) within the spore-pollen are indicated by ‘C’; very rare taxa recorded outside the spore-pollen count are indicated by ‘x.’

| Morphospecies | Depth (m) | 76.16 | 77.00 | 79.50 | 84.70 | 84.90 | 85.90 | 86.14 | 86.50 | 87.50 |
|---------------|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| **Gymnosperms** |          |       |       |       |       |       |       |       |       |       |
| Araucariacites australis | 1% | + | + | + | + | + | + | + | + | + |
| Dacrycypites australiensis | x | x | x | x | x | x | x | x | x | x |
| Dacrydiumites florinii | x | + | + | + | + | + | + | + | + | + |
| Microalatidites palaeogenicus | x | x | x | x | x | x | x | x | x | x |
| Podocarpidites spp. | 1% | + | 1% | 3% | 3% | + | 2% | 2% | + | + |
| Cypereceopolis | 12% | 10% | 9% | 1% | 1% | 14% | 11% | 12% | 9% | + |
| Droseridites sp. | + | + | + | + | + | + | + | + | + | + |
| Glencopollis ornatus | + | + | + | + | + | + | + | + | + | + |
| Graminidites spp. | 8% | 9% | 11% | 16% | 8% | 16% | 12% | 10% | 20% | + |
| Halaragacidites haloragoides | 4% | 2% | 3% | 7% | 3% | 2% | 3% | 6% | 4% | + |
| Haloragacidites myriophylloides | + | 2% | + | 1% | 2% | 4% | 4% | 4% | + | + |
| Liliacidites spp. | + | + | + | + | + | + | + | + | + | + |
| Luminidites sp. | x | + | + | 1% | x | + | + | + | + | + |
| Lymnionta | x | + | + | + | + | + | + | + | + | + |
| Milfordia hypolaenoides | 2% | 5% | 3% | + | + | 2% | 2% | 3% | + | + |
| **Angiosperms (trees/shrubs)** |          |       |       |       |       |       |       |       |       |       |
| Acaciapollenites myriosporites | + | + | 2% | + | 1% | + | x | + | x | + |
| Acaciapollenites weissi | x | x | x | x | x | x | x | x | x | x |
| Banksiae oligophloios | + | + | + | + | + | + | + | + | + | + |
| Banksiae cf. Banksia serrata | + | + | + | + | + | + | + | + | + | + |
| Crotonipollis spp. | x | x | x | x | x | x | x | x | x | x |
| Dodonaea viscosa-type | x | + | + | + | + | + | + | + | + | + |
| Ericipites spp. | 4% | 1% | + | + | + | + | + | 1% | + | + |
| Ericipites cf. Sprengelia | x | + | + | + | + | + | + | + | + | + |
| Gothanipollis cf. bassensis | x | + | + | + | + | + | + | + | + | + |
| Gyropollis pristis | x | x | x | x | x | x | x | x | x | x |
| Hakeidites spp. | x | + | + | + | 1% | 2% | 1% | 1% | + | 1% |
| Haloragacidites harissii | 26% | 40% | 32% | 35% | 38% | 25% | 18% | 25% | 15% | + |
| Malvacipollis regattaeensis | x | + | + | + | + | + | + | + | + | + |
| Malvacipollis spinyspora | 6% | 2% | 4% | + | + | + | + | + | + | 2% |
| Malvacipollis sp. | x | x | x | x | x | x | x | x | x | x |
| Margocarpidites vanjihii | x | + | + | + | + | + | + | + | + | + |
| Monotocidites galeatus | + | + | + | + | + | + | + | + | + | + |
| Monotocidites sp. [Leucopogon] | x | + | + | + | + | + | + | + | + | + |
| Myrtaceidites eucalyptoides | 1% | + | + | + | 1% | x | + | + | + | + |
| Myrtaceidites leptospermoides | x | x | + | + | + | + | + | + | + | + |
| Myrtaceidites lispis | x | x | + | + | + | + | + | + | + | + |
| Myrtaceidites spp. | + | + | + | + | + | + | + | + | + | + |
| Palaeocoprosmadites zelandiae | + | + | + | + | + | + | + | + | + | + |
| Proteacidites personioides | + | + | + | + | + | + | + | + | + | + |
| Proteacidites cf. pseudomoides | x | + | + | + | + | + | + | + | + | + |
| Proteacidites cf. differentipolpis | x | + | + | + | + | + | + | + | + | + |
| Proteacidites cf. truncatus | x | + | + | + | + | + | + | + | + | + |
| Pseudowinterapolpis calathus | x | + | + | + | + | + | + | + | + | + |
| Rhipoecarpites ampereoliformis | x | x | x | x | x | x | x | x | x | x |
| Rhipoecarpites muehlenbeckiaformis | x | + | + | + | + | + | + | + | + | + |
| Stephanocarpites oblatus | + | + | + | + | 1% | + | x | + | x | + |
| Tetracolporites sp. | x | + | + | + | x | x | x | x | x | x |
| Thymeleaepollis sp. | x | + | + | x | x | + | + | + | + | + |
| Tricolporites (Myoporum) sp. | x | + | + | + | x | x | x | x | x | x |
| Tricolporites (Rhamnaceae) sp. | x | x | x | x | x | x | x | x | x | x |
| Tubulifloridites pleistocenicus | 7% | + | 3% | 1% | 7% | 5% | 16% | 4% | + | + |
| Tubulifloridites cf. pleistocenicus | + | 3% | 5% | + | 1% | 2% | 3% | 2% | + | + |
| **Angiosperms (herbs)** |          |       |       |       |       |       |       |       |       |       |
| Cypereceopolis | 12% | 15% | 10% | 9% | 1% | 14% | 11% | 12% | 9% | + |
| Draseridites sp. | + | + | + | + | + | + | + | + | + | + |
| Fenestrites sp. | + | + | + | + | + | + | + | + | + | + |

(continued)
include both tree- and shrub-sized genera. Examples are *Allocasuarina/Casuarina* and *Asteraceae*. Individual morpho-genera may occupy habitats as diverse as dry hillsides and mires. Using water transport, the miospores could have come from plants growing around the shoreline or upstream within the catchment and/or (wind-pollinated trees, shrubs and ferns) in the regional vegetation (see Macphail, Alley, Truswell, & Sluiter, 1994). For example, the presence of *Tubulifloridites pleistocenicus* (*Cassinia arcuata*-type) is consistent with eroding soils (see Macphail & Martin, 1991) whether or not this is related to tectonic activity.

Palynological dominance is mostly shared between four taxa, *Allocasuarina/Casuarina*, *Asteraceae* (*Tubulifloridites* spp.), *Poaceae* and *Cyperaceae*. A plausible reconstruction of the Gelasian dryland vegetation is that *Allocasuarina/Casuarina* sclerophyll woodland was growing on dry hill slopes or lined the banks of inflowing streams, while shrubs and herbs colonised rocky and/or sandy outcrops around the shoreline. What is certain is that the earliest Pleistocene sclerophyll vegetation differed from modern forests and woodlands on the Southern Tableland in that eucalypts (*Eucalyptus sensu lato*) were extremely rare (cf. Keith, 2004). Most of the angiosperms represented by fossil pollen still grow on the Southern Tablelands or conceivably could have done so in the geologically very recent past. However, reinforcing the difference between the earliest Pleistocene and modern highland vegetation, are

| Morphospecies | 76.16 | 77.00 | 79.50 | 84.70 | 84.90 | 85.90 | 86.14 | 86.50 | 87.50 |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| *Glencopollis ornatus* | 8% | 9% | 11% | 16% | 8% | 16% | 12% | 10% | 20% |
| *Graminidites* spp. | + | + | + | 1% | + | + | + | + | + |
| *Haloragacidites haloragoides* | 4% | 2% | 3% | 7% | 3% | 2% | 3% | 6% | 4% |
| *Haloragacidites myriophylloides* | + | 2% | + | 1% | 2% | 2% | 4% | 4% | 4% | + |
| *Liilacidites* spp. | + | x | x | + | x | x | + | x | + |
| *Luminidites* sp. | x | x | x | + | + | + | + | + | + |
| *Miltiorhiza hypolaenoides* | 2% | 5% | 3% | + | + | 2% | 2% | 3% | + |
| *Mulsipollis* sp. | x | x | + | + | + | + | + | + | + |
| *Periporopollenites* (Plantago) | + | + | + | + | + | + | + | + | + |
| *Polyporina granulata* | x | + | + | + | x | x | x | + | + |
| *Polyporina reticulata* | x | + | + | + | x | x | + | + | + |
| *Sparganiumepollenites* sp. | + | + | + | + | + | + | + | + | + |
| *Strasyncoptites lasus* | + | x | x | + | x | + | + | + | + |
| *Stephanoporate* sp. (Wahlenber gia) | + | + | + | + | + | + | + | + | + |
| *Tetracolpites* (Rumex) sp. | x | + | x | + | x | + | x | + | + |
| *Tricloptes* stilidioides | + | + | + | + | x | x | + | + | + |
| *Tricloptes* (Brassicaceae) spp. | x | x | + | + | + | + | + | + | + |
| *Tricloptes* (Euphorbiaceae-type) | x | + | + | + | x | x | + | + | + |
| *Tricloporites* (Apiaceae) sp. | x | x | + | x | + | + | + | + | + |
| *Tetraporopollenites* (Plantago) | + | + | + | + | + | + | + | + | + |
| *Tricloporites* (Euphorbiaceae) spp. | x | x | + | + | x | + | + | + | + |
| *Tricloporites* (Brassicaceae) spp. | x | x | + | + | + | + | + | + | + |
| *Tetraconapollenites* (Plantago) | + | + | + | + | + | + | + | + | + |
| *Tetraporopollenites* (Plantago) | x | x | + | + | x | + | + | + | + |
| *Tetraporopollenites* (Plantago) | + | + | + | + | + | + | + | + | + |
| *Tetraporopollenites* (Plantago) | x | x | + | + | x | + | + | + | + |
| *Tetraporopollenites* (Plantago) | x | x | + | + | x | + | + | + | + |
| *Tricloporites* (Euphorbiaceae) spp. | + | + | + | + | x | x | + | + | + |
| *Tricloporites* (Euphorbiaceae) spp. | + | + | + | + | x | x | + | + | + |
| *Triporopollenites* (Plantago) | x | x | + | + | x | + | + | + | + |
| *Triporopollenites* (Plantago) | x | x | + | + | x | + | + | + | + |
| *Triporopollenites* (Plantago) | x | x | + | + | x | + | + | + | + |
| *Unidentified pollen* | 2% | 3% | + | + | + | + | + | + | + |

**Ferns and fern allies**

| Azolla | + | + | + | + | + | + | + | + | + |
| Baculatisporites spp. | + | x | + | x | + | + | + | + | + |
| Cyathidites australis/minor | x | x | x | + | + | 1% | + | 1% | + | + |
| Densoisporites implexus | + | + | + | x | + | + | x | + | + |
| Foveotriletes cf. crater | x | x | x | + | + | 1% | 2% | + | + | + |
| Foveotriletes cf. lacunosus | x | x | x | + | + | 1% | 2% | + | + | + |
| Gleechnidites spp. | x | x | x | + | + | 1% | 2% | + | + | + |
| Herkanopteris elliotii | x | x | x | + | + | 1% | 2% | + | + | + |
| Isoetes drummondii-type | + | + | + | 2% | + | 2% | 4% | + | + | + |
| Laoegatosporites ovatus/major | + | + | + | + | + | + | + | + | + |
| Matonisporites ornamentalis | x | x | x | x | x | + | + | + | + |
| Ophioglissosporites spp. | x | x | + | + | + | + | + | + | + |
| Peromonolites baculatus ms | + | + | + | + | + | 2% | 1% | + | + | + |
| Pilularia-type | x | + | + | x | x | + | + | 2% | 1% | + |
| Polydiosporeaferrisporites cf. reticulatus | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |
| Polydiosporeaferrisporites histioteroides | x | x | x | + | + | + | + | + | + | + |

| pollen sum | 393 | 377 | 363 | 336 | 404 | 400 | 535 | 335 | 337 |
Figure 4. Age-diagnostic and rainforest morphotaxa. (a) *Fenestrites* sp. (Asteraceae: Liguliﬂorae), (b) *Monotocidites* sp. (Epacridaceae: Leucopogon), (c) *Myrtaceidites lipsis* (Myrtaceae: Eucalyptus spathulata-type), (d) *Cyathidites australis* (Cyatheaceae), (e) *Matonisporites ornamentalis* (Dicksoniaceae: Dicksonia antarctica), (f) *Polypodiaceoisporites cf. retirugatus* (Adiantaceae: Pteris), (g) *Araucariocites australis* (Araucariaceae: Araucaria), (h) *Araucariocites australis* var. (Araucariaceae: Araucaria), (i) *Dacrycarpites australiensis* (Podocarpaceae: Dacrycarpus), (j) *Dacrydiumites florinii* (Podocarpaceae: Dacrydium), (k) *Microalatidites palaeogenicus* (Podocarpaceae: Phyllocladus) and (l) *Podocarpidites* sp. tetrad (Podocarpaceae: Podocarpus – Prumnopitys).
Figure 5. Lacustrine and wetland morphotaxa. (a) *Botryococcus* (Botryococcaceae: *Botryococcus*), (b) *Pediastrum* (Hydrodictyaceae: *Pediastrum*), (c) cf. *Cobricoperidinium* (Dinophyaceae), (d) *Isoetes drummondi*-type (Isoetaceae: *Isoetes*), (e) *Pilularia*-type (Marsileaceae: *Pilularia*), (f) *Ophioglossisporites* sp. (Huperziaceae: *Phylloglossum drummondii*), (g) *Densoisporites impexus* (Selaginellaceae: *Selaginella uliginosa*), (h) *Cyperaceaepollis neogenicus* (Cyperaceae), (i) *Droseridites* (Droseraceae: *Drosera*), (j) *Milfordia hypolaenoides* (Restionaceae), (k) *Haloragacidites myriophylloides* (Haloragaceae: *Myriophyllum*) and (l) *Striasyncolpites laxus* (Menyanthaceae: *Villarsia*-type).
Figure 6. Sclerophyll tree and shrub morphotaxa. (a) Acaciapollenites weissii (Mimosaceae: Acacia), (b) Banksieaeidites sp. (Proteaceae: Banksia cf. serrata), (c) Banksieaeidites elongatus (Proteaceae: Banksia), (d) Gyropollis psilatus (Gyrostromonaceae), (e) Hakeidites sp. (Proteaceae: Grevillea/Hakea), (f) Myrtacridites cf. leptospermoides (Myrtaceae: Leptospermae), (g) Malvacipollis cf. spinyspora (Malvaceae: Gymnoca), (h) Malvacipollis cf. subtilis (Euphorbiaceae: Austrobusus), (i) Malvacipollis spinyspora (Euphorbiaceae: Micrantheum), (j) Monotocidites galeatus (Epacridaceae: Monotoca), (k) Poluspissusites novae-zelandiae (Rubiaceae: Coprosma-type) and (l) Poluspissusites zelandiae (Goodeniaceae).
Figure 7. Sclerophyll shrub, climber & herbaceous morphotaxa. (a) Stephanocolpites oblatus (Haloragaceae: Haloragodendron-type), (b) Thymelaepollis sp. (Thymelea-ceae: Pimelea), (c) Tubulifloridites pleistocenicus (Asteraceae: Cassinia arcuata-type), (d) Gothanipollis cf. bassensis (Loranthaceae), (e) pericolpate sp. (Ranunculaceae: Ranunculus-type), (f) Perforoticolpites digitatus (Convolvulaceae: Polygonia-type), (g) Tricolpites pelargonioides (Geraniaceae: Pelargonium), (h) Polyporina granulata (Caryophyllaceae: Stellaria-type), (i) Polyponira sp. (Caryophyllaceae?), (j) Polyporina relictula (Caryophyllaceae: Silene), (k) stephanoporate sp. (Campanulaceae: Wahlenbergia) and (l) Tricolporites sp. cf. Apium (Apiaceae: Apium-type).
the presence of (i) now regionally extinct rainforest gymnosperms such as *Dacrycarpites australiensis*, (*Dacrycarpus*), *Dacrydiumites florini* (*Dacrydium*) and *Microalatidites palaeogenicus* (*Phyllocladus*); (ii) a eucalypt Myrtaceidites lipis whose NLR (*Eucalyptus spathulata*) is confined to semiarid habitats in southwest Western Australia, such as saline depressions, and the margins of salt lakes (see [https://florbase.dpaw.wa.gov.au/browse/map/5775](https://florbase.dpaw.wa.gov.au/browse/map/5775), Martin & Gadek, 1988); and (iii) treeferns that now are restricted to sheltered gullies on the southeastern Highlands, e.g. *Cystidites* (*Cyathea*) and *Matonisporites ornatamentalis* (*Dicksonia antarctica*).

**Wildfires**

As for the Piacenzian interval in core C354, the organic matrix (palynodebris) of which pollen and spores comprise a minor fraction, are dominated by mid-brown particles in which the cell walls are well-preserved, and very dark brown particles in which all traces of the cellular structure have been lost (see Macphail et al., 2015). Whether the latter are carbonised particles owing to wildfires or the result of natural oxidative processes is less certain without independent evidence for burning, e.g. the presence of biomarkers such as levoglucosan (see dos Santos et al., 2013). We note the elimination of fire-intolerant *Nothofagus* spp. and expansion of sclerophyll species is consistent with both aridification and wildfires becoming prevalent in the catchment (cf. McLaren & Wallace, 2010).

**Paleoclimate**

A detailed reconstruction of climates prevailing during the Gelasian is precluded by the low taxonomic resolution of most morphospecies and the wide-ranging of environments inhabited by their NLRs. For example, *Striasyncopites laxus* could represent the very widely distributed species *Villarsia exaltata*, the semi-aquatic species *V. reniformis*, which grows in stationary or slow-flowing shallow water, in swamps and in ephemeral pools along the NSW coast and on the Southern Tablelands, or a cold climate species *Liparophyllum gunnii*, now restricted to the margins of mountain lakes and glacial tarns in Tasmania. In other instances, the distribution of the NLR is likely to be a poor guide to the ecology of the fossil taxon. An example is *Myrtaceidites lipis* since the morphospecies might represent an extinct ectype of *Eucalyptus spatulata* or an extinct species, which produced essentially the same pollen type.

**Precipitation:** Whether or not wildfires were prevalent in the catchment, the extinction of *Nothofagus* (*Brassospora*) spp. by the earliest Pleistocene is reliable evidence that precipitation on the Lake George Range had fallen below 1200–1300 mm pa and/or rainfall received during the summer quarter had fallen below the ecologically critical amount of ~200 mm (references in Veblen, Hill, & Read, 1996). Mean minimum precipitation is less certain but conditions around the basin remained sufficiently humid to support temperate rainforest gymnosperms as well as a shallow freshwater lake. Accordingly, we propose that the replacement of *Nothofagus* rainforest by sclerophyll-dominated vegetation types in the Lake George basin ecologically is consistent with effectively drier conditions, probably associated with increasing climatic variability, on the highlands. Atmosphere–ocean general circulation models predict mean annual precipitation rates decreased by 30% over most parts of the continent during Plio-Pleistocene aridification of Australia (Krebs, Park, & Schneider, 2011). A significant proportion of the annual rainfall appears to have come from weather systems moving inland from the Tasman Sea since *Nothofagus* (*Brassospora*) communities on the western slopes of the Southern Tablelands had been extirpated some 2–8 million years earlier than at Lake George (compare Macphail et al., 2015; Martin, 1991, 2006).

**Temperature:** Assuming the inferred reduction in mean and/or seasonal rainfall receipts is correct, the presence of a shallow lake at the core site is persuasive evidence that evaporation had also decreased during the Gelasian. One possible cause is an effective reduction in mean air temperatures enhanced by an increased cloud cover during summer months. It is possible that more precise estimates can be made if morphospecies, such as *Polypora reticulata* and *Ophioglossisporites* spp., can be demonstrated to represent herbs such as *Silene* and *Phylloglossum drummondii*, respectively. In the interim, the strongest indication that mean annual temperatures were within the upper microtherm to lower mesotherm range (~10°C to ~20°C) of Nix (1982) during the Gelasian is negative evidence, viz, the absence of warm temperate indicators such as *Cupaniederites orthoteichus* (Anisopodaceae tribe Cupanieae) in the dryland vegetation and absence of cool climate indicators such as *Astelia* in the wetland vegetation. We note that pollen of the latter herb (pine-apple grass) is recorded in Quaternary glacial stage microflora in the Lake George basin (cf. Singh & Geissler, 1985).

**Discussion**

Our data support Abell’s (1991, p. 58) interpretation of the Ondyon Formation as a ‘transitional fluvo-lacustrine sequence’ that accumulated under a ‘fluctuating wet and dry climate.’ An example of deposits forming during dry conditions is likely to be the ferric sandstone at 89.1–89.3 m depth. However, the combined chronostratigraphic evidence emphatically do not support Abell’s (1991) qualified interpretations that the Ondyon Formation dates to the *Triporopollenites bellus* Zone, whose current age limits are inferred to be 11.6–16.0 Ma (Partridge, 2006), and is a correlative of ‘rainforest-dominated intervals’ recorded in the Lachlan River Valley to the west of Lake George (references in Martin, 1991).

Notwithstanding current uncertainties regarding the timing of uplift leading to the formation of the Lake George Range, our data provide a minimum Gelasian age for blockage of the former spillway(s) to the Yass River or other drainage systems and for the formation of paleo-Lake George. Whether or not the Lake George basin was ‘dry’ during the ferruginisation ‘event’ at 89.1–89.3 m depth, we consider it improbable that the freshwater lake recorded at 76.16–87.50 m depth was the first to extend across this area.
of the basin. This conclusion is supported by paleomagnetically dated evidence from a second hole, ANU Corehole LG4, drilled in the embayment forming the northern end of Lake George, where the 2.588 Ma Matuyama/Gauss magnetic polarity chron appears to coincide with the deposition of deep water clay facies after a period when colluvium was being transported onto the dry lake floor (Abell, 1985; McLaren & Wallace, 1991).

The microflora provide compelling evidence that sclerophyll-dominated plant communities growing in the Lake George basin during the Gelasian differed significantly from the mosaic of temperate rainforest and sclerophyll communities present in the basin during the late Pliocene (Macphail et al., 2015). Environmental factors leading to the extinction of *Nothofagus* affected both the subgenus *Brassospora*, now endemic to New Guinea and New Caledonia, and also the subgenera *Lophozonia*, species of which survive in Tasmania, Victoria, and northeast highlands in NSW and southern Queensland, and *Fuscospora*, now represented by the deciduous beech *N. gunnii* in montane-alpine Tasmania. These extinctions/extirpations appear to have been regional during the late Pliocene (*Nothofagus* (Brassospora) species and *Symlocos* survived into the early Pleistocene (Calabrian Stage) at ~610 m elevation on the Central Highlands in Victoria (Macphail et al., 2015; Sniderman, 2011).

The extinction of *Nothofagus* recorded in Corehole C354 during the Plio-Pleistocene transition period is inconsistent with Singh and Geissler’s (1985) records of *Nothofagus* (Brassospora) pollen in other corehole samples representing the period from ca 0.78 Ma (Matuyama-Brunhes Chron paleomagnetic boundary) to just before the Last Glacial Maximum at ca 25 ka. Other anomalous records include *Nothofagidites brachyspinulosus* (*Nothofagus* (Fuscospora)), *Dacrydiumites florinii*, *Microalatidites palaeogenicus* and *Microcachryidites antarcticus* (*Microcachryis*). Most of these records comprise one to several grains only and we suggest are due to reworking of Neogene microflora into middle–late Pleistocene (Bungendore Formation) sediments. If correct, it is highly improbable that ‘cool temperate rainforest’ survived in the catchment during the Quaternary as inferred by Singh and Geissler (1985, p. 416).

Conclusions

Despite the sporadic preservation, unweathered carbonaceous sediments in the Lake George basin provide an unusually detailed record of environmental changes that both complements and sharpens records of environmental change elsewhere in Australia during the Plio-Pleistocene transition period (references in Fujioka & Chappell, 2010; Martin, 2006; McLaren & Wallace, 2010): we have no doubt that sedimentological and microfossil evidence preserved in the Gearys Gap and Ondyong Point formations reflect changes in global climate during the Plio-Pleistocene transition despite the impacts of local tectonism and differences in the timing of extinctions/extirpations compared with other regions in southern Australia (compare Dodson & Macphail, 2004; Martin, 1991; Sniderman, 2011). The critical requirement in unraveling local factors from regional events in the Lake George basin has been the ability to date the sedimentary sequence using different forms of age control. For the same reason, geographic variations in extinction times in southeastern Australia emphasise that caution is needed when using the ‘reference’ Gippsland or Murray basin palynostratigraphies to date geologically recent sediments outside these basins unless independent age control is available (cf. Macphail & Gibson, 2014). Nevertheless, the sequence of local extinctions forced by climate change at Lake George does appear to provide a cost-effective, moderately reliable framework for recognising and correlating Plio-Pleistocene deposits on the Southern Highlands (including Blue Mountains) in New South Wales.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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