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A Holocene record of allochthonous, aeolian mineral grains in an Australian alpine lake; implications for the history of climate change in southeastern Australia

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Abstract

A radiocarbon-dated core, NC, taken in the alpine Blue Lake in the Snowy Mountains of southeastern Australia provides a Holocene record of sedimentation that consists mainly of organic clays. Two types of quartz grains are recovered from 81 samples from the core. One type consists of angular grains, with frequently shattered faces, which originates from granitic lithologies present within the small catchment area of the lake. The other type is characteristically rounded to subrounded, often textured with frequent silica coating and is considered to have been deposited within the lake and its catchment by aeolian processes. These aeolian grains are thought to have been transported along the main dust path that ferries aeolian dust from the Mallee region, west of the Snowy Mountains, as far as the southeastern Tasman Sea. Aeolian grains with the largest size occur over approximately the last 1.6 ka of the Holocene and this indicates an increase of climatic instability, with arid phases that commenced about 3.5 ka. At 2 ka, a wet period in southeastern Australia coincided with low aeolian input at Blue Lake. The period of consistent reduced aeolian activity spans the 7.6 to 5.5 ka interval at Blue Lake.

Introduction

One of the pioneers of Australian geomorphology, Joe Jennings, identified the overall circular pattern of longitudinal dunes in Australia at a continental scale (Jennings, 1968). Based upon this work, Bowler (1976) proposed that during the late Quaternary two major dust paths, marking the route taken by aeolian dust, existed over Australia. Although evidence of both recent (Knight et al., 1995) and palaeo-dust (De Deckker et al., 1991; De Deckker, 2001) transport events outside these paths exists, the prime importance of these paths as routes of dust transport over Australia still holds. The path of interest to the present study is the southeast Australian dust path (Figure 1) which extends over the Australian Highlands and which is believed to have existed since Blue Lake was glacially excavated (*sensu* Hesse, 1994).

The existence of the southeast dust path has been documented at many locations along its course – in soil and on snow in southeastern Australia, in pelagic sediments in the southwest Pacific region and in rain and on snow and glaciers in New Zealand. Studies of the aeolian contribution to soils in Australia have been summarised by Butler and Churchward (1983), although of particular local interest to this study is the work by Walker and Costin (1971) and Johnston (2001) on aeolian dust from snow and soil in the Snowy Mountains region of Australia. Johnston (2001) in particular determined that aeolian dust accession in the region ranged from 0.18–11.3 g/m^2.a. He also determined for the period 1997–99 that the dust collected in snow patches on Mt Twynam (forming part of Blue Lake's catchment) contained a high proportion of fine silt and clay. The evidence of aeolian deposition in the south-

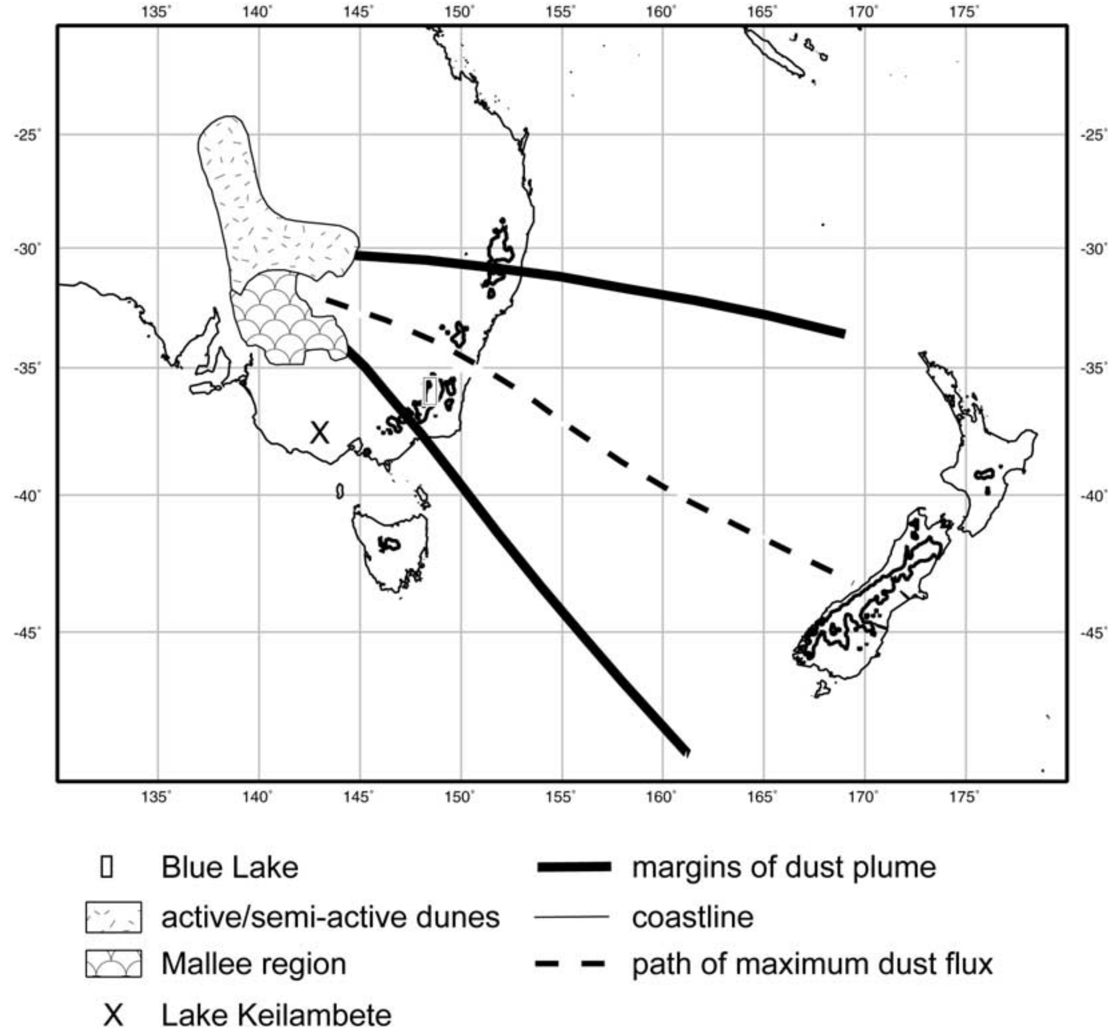

Figure 1. Locality map of southeastern Australia showing the location of Blue Lake, which is situated amidst the path of maximum dust, flux originating from the present-day active dunefield principally from the Mallee region. The contours identify the region above 1,000 m asl. Adapted from Hesse (1993).

ern Pacific Ocean comes from the interpretation of maps of the distribution of quartz (Thiede, 1979) and clays (Griffin et al., 1968 for kaolinite, illite and chlorite and Goldberg & Griffin, 1970 for illite and chlorite) in oceanic sediments. Studies on the accumulation of trace metals in pelagic sediments in the western Pacific Ocean (Windom, 1970) concur by finding that aeolian dust was a contributing factor. In New Zealand, occurrences of 'red rain' and the sightings of red dust found in snow and on glaciers have been attributed to dust originating from Australian dunefields. The published instances of dust observations in New Zealand have been summarised in McTainsh (1989) with later publications including those by Knight et al. (1995). Evidence of dust accumulation in lake sediments in Australia has been restricted to the work of De Deckker et al. (1991) and De Deckker (2001) at the palaeo-Lake Carpentaria, outside the two recognised dust paths.

The aim of this study is to identify whether the accumulation of aeolian particles into a closed basin lake, such as Blue Lake that occurs below the broad path of aeolian dust transport for southeast Australia, can adequately record significant arid events in the dust source region. Many studies of environmental change in Australia, summarised by Wasson and Clark (1988), including those of δ^{18}O from deep-sea cores, fluvial sedimentation and periods of dune building tend to provide large-scale information. The record of Blue

Lake has the potential to provide, for the first time, a better resolution of aeolian activity because of the high sedimentation rate in the lake (1 cm ≈ 25 yrs) compared to lower sedimentation rates in deep-sea cores in the Tasman Sea (Hesse, 1994) and inadequate chronology for the Australian dune fields.

Setting

Blue Lake

Blue Lake is situated in the rather small alpine region of southeastern Australia and is one of the few mainland glacial lakes in Australia that are permanently filled with water. It occurs on the eastern side of the main range of peaks that constitutes the high country of Australia and is the largest and deepest of the mainland Australian glacial lakes. The onset of widespread cooling in the southeast Australian region commenced around 40 ka[1] with glaciation reaching a maximum at around 25–19 ka (Costin, 1972; Bowler et al., 1976). Blue Lake was excavated by glacial action at this time, possibly at the point of convergence of three valley glaciers (Dulhunty, 1945). Deglaciation was completed in the Kosciuszko region after 16.8 ± 1.4 ka, when the last moraine was formed (Barrows et al., 2001), although periglacial conditions continued locally until about 10 ka (Costin, 1972; Bowler et al., 1976), with renewed periglacial activity between 3.2 and 1.05 ka (Costin, 1972). Sediment accumulated in the lake after the last moraine was formed with the oldest date so far obtained from bottom bulk sediments from a Blue Lake core giving an age of 15.4 ka (Shakau, unpublished, SUA2601; sample submitted to Sydney University Radiocarbon Laboratory by P. De Deckker & B. Shakau).

Blue Lake is approximately trapezoidal in shape being 540 m long and 360 metres wide (Raine, 1974) and sits in a small catchment about 1.9 km^2. The lake is dammed in part by the terminal moraine that is located at its eastern end (Dulhunty, 1945). The bathymetry of the lake (Figure 2) is uneven with a series of parallel moraine ridges extending into the lake from its eastern end (Dulhunty, 1945). The lake floor comprises two main basins with depths at just over 26 and 28 m situated near the centre of the lake and close to the outlet respectively (Figure 2 and Raine, 1974).

Blue Lake is noted for being the only dimictic lake in mainland Australia, as it undergoes temperature stratification during the summer (Burgess et al., 1988). The intensity of the stratification appears to vary according to windiness and the total radiation receipt for the area (Burgess et al., 1988) as the occurrence of both intense (Raine, 1982) and less intense (Balmaks, 1984) periods of stratification has been noted. The lake water is characteristically very dilute and with very low turbidity readings combined with low conductivity and neutral pH values (Balmaks, 1984). Other studies at Blue Lake have dealt with the recovery of zooplankton (Bayly, 1970) and phytoplankton (Powling, 1970), actuopalynology (Raine, 1974) and water chemistry (Williams et al., 1970) and benthos analysis (Timms, 1980) of the present lake. Palaeopalynological (Raine, 1974), palaeomagnetic (Barton, unpublished) as well as palaeoentomological (Shakau B, unpublished) studies have also been performed on cores from the lake, but these all remain unpublished. Most recently, a number of dating methods have been applied to several cores from the lake have highlighted the post-European increase of sedimentation into the lake due to inadequate land management practices until the area became a national park (De Deckker et al., submitted).

The geology of the Kosciuszko area was recently reexamined by Wyborn et al. (1990); it is dominated by granitic plutons intruding Ordovician metamorphosed deep-sea sediments consisting of silicifed shales. Within the Blue Lake catchment, two granite plutons and metasediments outcrop and form bands that run NNE-SSW across the catchment. Rock outcrops are predominant within the catchment and only sparse areas are covered with a thin veneer of peaty sediments.

Quartz grain morphologies

Quartz grains have been used as the proxy to determine the occurrence of aeolian material within the sediment from Blue Lake; as such grains are morphologically distinctive, as discussed below. The different mineralised siliceous inputs deposited on the lake floor include: (1) locally derived quartz, that originates from the mechanical and chemical weathering of rocks from within the catchment area of the lake; (2) aeolian quartz, that has been transported at some stage via the atmosphere and dropped within the lake catchment or directly into the lake; and (3) biogenic silica, this comprises the remains of siliceous organisms including sponge spicules, frustules of diatoms and chrysophyte cysts that

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[1] All dates discussed below are in calibrated years B.P.

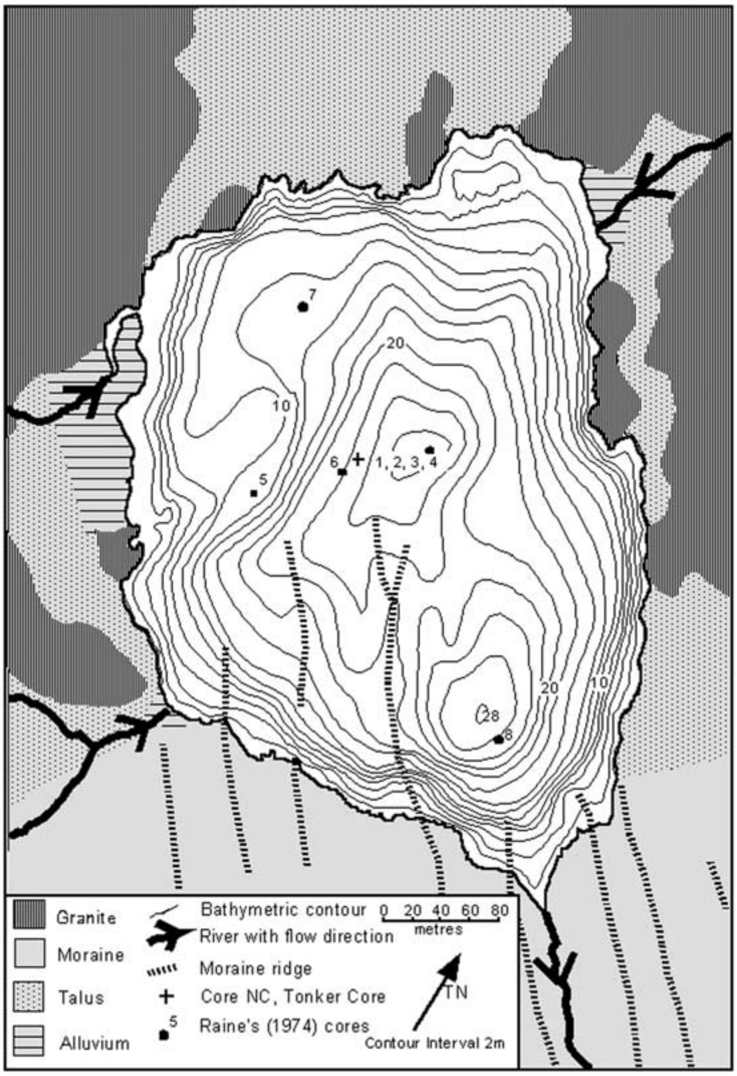

Figure 2. Map of Blue Lake showing the lake bathymetry, local geology, and the location of the cores discussed in the text. Map adapted from Raine (1974).

were formed within the lake. No search for phytoliths was made.

Quartz grains recovered from the cores within the lake are primarily the residuals of the weathering of the lithologies within the catchment area. Any other quartz grains that occur within the lake must therefore be aeolian of origin, and the most likely source for these grains being a dunefield, all of which are quite distant from the Snowy Mountains. The closest supply of quartz sand would be the source-bordering dunes along the ancestral rivers of the Riverine Plain to the west of the Mountains (Bowler, 1967). The dunes would supply grains with morphological characteristics significantly different to those attained from cool climate weathering processes.

Weathered quartz grains can include a variety of mechanically and chemically produced micromorphological features. The amount and intensity of chemical features are dependant upon whether grain faces have been exposed and the length of this exposure (Krinsley & Doornkamp, 1973). The amount and intensity of mechanically produced features is dependent upon the number of grain interactions that occur. Grain rounding is a very slow process (Pettijohn et al., 1987) and requires periods of fluvial or aeolian activity. Locally derived quartz grains tend to exhibit conchoidal fractures and flat cleavage surfaces (Krinsley & Doornkamp, 1973; Krinsley & Smalley, 1973). Therefore, we conclude that the quartz grains that have been weathered out of local lithologies would not possess the same features as grains that have undergone aeolian activity.

There have been numerous studies on the morphological characteristics of quartz grains of an aeolian origin. Krinsley and Doornkamp (1973) reviewed all the work to that time and later works by Krinsley et al. (1976), Krinsley and McCoy (1978) and Krinsley and Trusty (1985) extend this review. Krinsley and Trusty (1985) list five common characteristics of aeolian quartz grains: (1) grain rounding – this can range from a well rounded to somewhat angular grain, and occurs due to collision between grains; (2) 'upturned plates' – these appear as parallel ridges on quartz grains and can occur due to the collision of grains or are due to subsequent silica precipitation; (3) equidimensional or elongate depressions – these are caused by the development of conchoidal fractures that result when grains directly hit each other; (4) smooth surfaces – these are caused by the dissolution of silica on grains that are too small to be affected by abrasion; and (5) arcuate, circular or polygonal fractures – these may be caused as a result of physical or chemical weathering.

Pell and Chivas (1994) studied sand-sized quartz grain morphologies from the dunefield regions of Australia. They found variations in the morphology of quartz grains across the four dunefield regions. The northwestern, northeastern and southern dunefields contained quartz grains that are poorly rounded and that are dominated by dissolution and/or precipitation features. The quartz grain morphologies from the southeastern dunefields, comprising the Mallee region, are dependant upon the original formations that supplied them, these being the Woorinen Formation and the Lowan Sand (Pell & Chivas, 1994). Quartz grains from the Woorinen Formation are moderately rounded and have flat faces (Pell & Chivas, 1994). In addition, the same authors found that precipitation of silica had formed 'raindrop' solution with minor amounts of precipitated plates, polygonal cracks and craters in rare grain depressions. The Lowan Sand, on the other hand, contains irregular-shaped quartz grains with abraded edges, and the grains contain equidimensional or elongate depressions with minor amounts of precipitated sheets and 'raindrop' solution evident on a limited number of grains (Pell & Chivas, 1994).

Methods

Sample preparation

Core NC, studied here, measures 436 cm and was collected from the lake in March 1977, along with six other cores, by Charles Barton. The core was retrieved using a Mackereth corer and the upper part of the sediment in the core was disturbed and subsequently not retained (Barton, personal communication, 1997). The core was subsequently cut, with 8 cm of sediment being lost where the core was cut at mid-length (Barton, personal communication, 1997). These 8 cm, which consisted of dark brown organic clay similar to that on either side (Barton, personal communication, 1997), have been accounted for when presenting core depths and respective ages.

Samples of 2 cm^3 each were taken from the core at 5 cm intervals for portions of the core with apparent uniformity, being usually dark brown organic clay. Other samples were taken where a distinct sedimentary layer occurred and sample volumes varied depending upon the thickness of the layer. The samples were oven dried, then immersed in a solution of 1.3 L of distillate deionised water to which were added 42 g of anhydrous tetrasodium pyrophosphate ($Na_4P_2O_7$) and 0.87 L of hydrogen peroxide at 35% concentration was added to remove any organic matter present. The samples remained in solution until the reaction ceased, up to 65 days, and then the supernatant was decanted. The mineral fraction left in the containers could then be pipetted out for microscopic examination.

Quartz grain observations

A small amount of sample was analysed using transmitted light microscopy to identify its mineral content as well as the dominant features and sizes of any quartz grains present. The roundness and sphericity of quartz grains were classified following Powers' (1953) procedures. Apart from quartz grains the mineralogical fraction of the samples consisted of felspars, mica and clays; biotite and apatite were recognised in some samples. Numerous core samples were chosen for further study by scanning electron microscopy (SEM) based upon their representativeness of quartz features down the core as recognised through transmitted light microscopy. Two main types of grains were found: (1) textured grains – grains which commonly ranged from being rounded to subangular with some instances of angular grains;

and (2) non-textured grains – which constantly ranged from being subangular to very angular, with some occurrences of subrounded grains. Another procedure involved measuring the largest textured grain in its longest orientation.

Particle size analysis

A GALAI Computerised Inspection System 100 (CIS-100) was used for particle size analysis of the whole mineral fraction of samples. This procedure uses a laser-based optical analysis channel employing a He-Ne laser beam that functions on the time of transition theory, the apparatus outputs values by grain size in relative percentages based upon the number of laser-grain interactions (GALAI, 1994). Comparative studies of an earlier version of this apparatus, the CIS-1, with other particle size analysis equipment were performed by Syvitski et al. (1991) who found the GALAI apparatus to be imprecise. Thus, to remedy this problem and to account for the fact that the GALAI apparatus assumes that grains are spherical in shape, samples were run a number of times until the mean diameter output was within 1.5 μm for any two given runs.

AMS radiocarbon sample preparation

Five bulk samples were taken from core NC for AMS dating. A further sample was taken from a Tonker core extracted from Blue Lake and discussed further in De Deckker et al. (submitted). Samples were pre-treated before being converted to CO_2. First, samples were sieved to eliminate any potential large fractions such as leaves and pieces of wood. The samples were then milled to homogenise them prior to undergoing the standard chemical Acid-Alkali-Acid treatment as specified in Hua et al. (2001). This was done at the ANTARES AMS Centre at the Australian Nuclear Science and Technology Organisation in Menai, NSW. The pre-treated samples were converted to CO_2 by combustion using the scaled-tube technique of Vandeputte et al. (1996) – see Hua et al. (2000) for more details. The AMS targets were prepared as graphite using the technique detailed in Jacobsen et al. (1997).

Results

Core stratigraphy

Core NC could easily be compared with the broad stratigraphic description (units A to E) made by Raine (1974) for his cores. An abridged log of core NC is provided in Figure 4. Some minor differences were noted – in particular the occurrence of small granitic pebbles and sand were found in unit A by Raine (1974), not recognised in core NC. Because of this, the units from core NC are referred to here as units I to V, colours given are for moist samples classified using the Munsell colour chart. Units I and III consist of olive black to black organic-rich muds with an absence of stratification. Woody fragments and laminae of fibrous material occur commonly within unit I. Unit II consists of layers of greyish olive and olive black organic muds; mica grains and coarse grains were visible within the unit, the base of which consists a layer of grains up to 4 mm. Unit IV consists of layers of olive black and olive grey mud; mica grains are present throughout the unit with a mica-rich band visible at the base of the unit. Unit V consists of alternating layers of greyish olive and brownish black muds. Core NC did not penetrate the lower units identified by Raine (1974) which consist of pale grey, organic-poor horizons. A correlation of unit thicknesses between core NC and those studied by Raine (1974) is given in Table 1 and the locations of all cores are shown in Figure 2.

Microscopic observations

Several SEM photomicrographs (Figure 3) are used to represent the major different types of quartz grain morphologies recognised in the core. Only limited SEM observations could be made, but these were used to confirm the exhaustive observations made through transmitted light microscopy. Of note, SEM photography confirmed that the texturing of quartz grains was not formed through diagenesis within the lake sediments. This was confirmed by the fact that pristine diatom frustules and chrysophyte cysts were ubiquitous throughout the entire core. Any slight diagenesis of siliceous material would have affected the diatoms first.

Two main types of quartz grains were recognised. One is derived from the granitic lithologies with the lake's catchment and ended up in the lake as a result of rock weathering or rock shattering due to cold temperatures, mostly in winter, but frequently at night as subzero temperatures are recorded today in this alpine region. These grains of local granitic origin are typically angular (Figure 3E) and would have travelled very little since being 'dislocated' from the original granites. The other type of grains can either be rounded, 'smoothed', by impact against other grains (Figure 3A) or will also show an external coating (Figures 3B–3D)

Table 1. Stratigraphic correlation for all cores studied from Blue Lake

Unit	Core 3	Core 2	Core 6	Core NC	Core 7	Core NC unit
A	0–524	0–516	0–(459)	0–355.1	0–272	I
B	524–526	516–526		355.1–362.7	272–364	II
C	526–550	526–(538)		362.7–398.1	364–380	III
D	550–565			398.1–416.9	380–(440)	IV
E	565–595			416.9–(436)		V
F	595–615					
G	615–642					
H	642–(674)					

Core NC is compared with cores 2, 3, 6 and 7 of Raine (1974). Core details in columns from left to right denote cores taken from progressively closer to shore in the lake environment as determined by stratigraphy and core location. For location of cores refer to Figure 2.

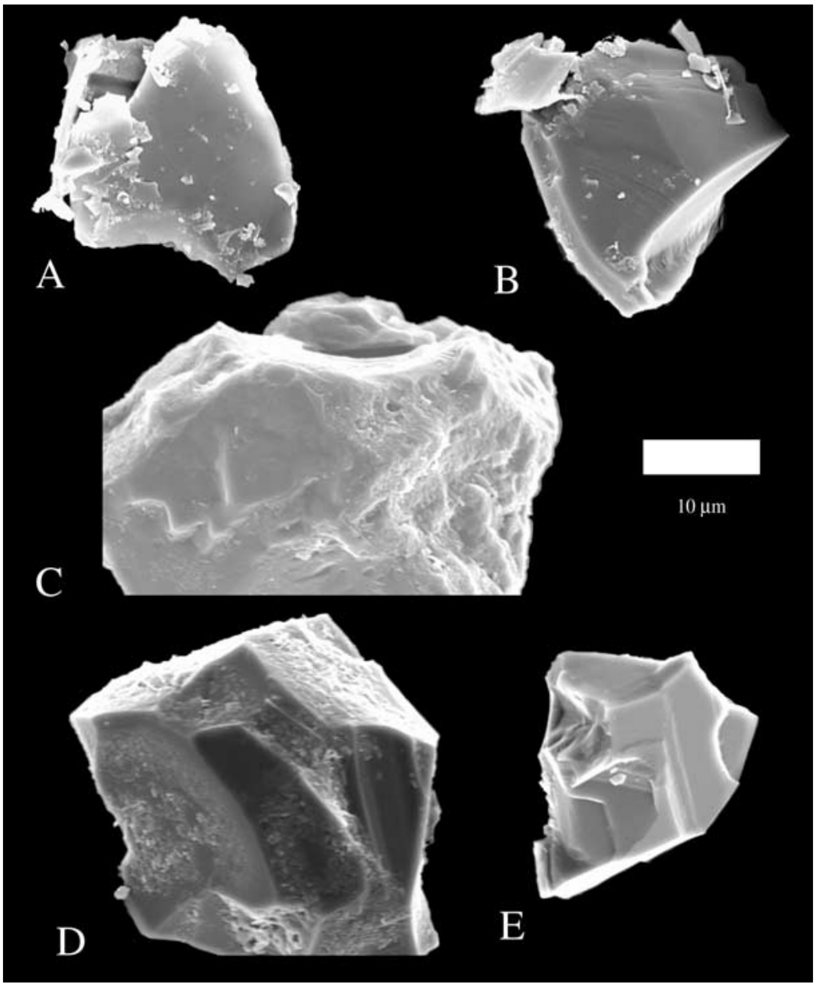

Figure 3. SEM photomicrographs of quartz grains recovered from core NC: (A) an aeolian quartz grain at 278 cm. The grain has undergone extensive silica reprecipitation as evidenced by its very smooth surface. (B) a locally derived quartz grain at 278 cm. (C) an aeolian quartz grain at 413 cm. This grain has undergone extensive chemical dissolution and reprecipitation as evidenced by the uneven grain surfaces. (D) an aeolian quartz grain at 432.5 cm. This grain is angular, although the occurrence of several micromorphological features including ‘up-turned plates’ on the grain faces that would have formed due to the precipitation of silica identifies this grain as aeolian in origin. (E) a locally derived quartz grain at 432.5 cm. This grain and the one photographed in 3B show examples of angularity to sub-angularity, which do not exhibit any identifiable degree of texturing.

of silica having been redeposited after considerable time while part of the regolith. Such a degree of silica reprecipitation could not have occurred within the lake sediment for reasons explained before. These grains are considered to have been aerially transported to Blue Lake and its catchment.

Observations were also made on grains washed from weathered samples of shale and granite outcrops in the lake's catchment, and these confirmed that those grains were predominantly angular to very angular with no texturing present.

AMS radiocarbon dates

The ages determined from AMS are presented in Table 2 for five horizons from core NC. De Deckker et al. (submitted) studied 3 cores of some of the youngest material recovered from Blue Lake and used 3 techniques in an attempt to date the sediments. They compared AMS-radiocarbon-dated samples against the optically stimulated luminescence technique of quartz grains and the occurrence of *Pinus* pollen in the sediment. (The pine pollen would have originated from pine trees planted in the area at lower latitudes). Their study positively identified that 'old' carbon is present in the upper parts of the sediment sequence in Blue Lake and that the radiocarbon dates are consistently 900 years too old (De Deckker et al., submitted). This approach is taken into account with 900 years being systematically subtracted from four of the five AMS dates for core NC (see Table 2), the oldest sample was not corrected as it is believed to have been deposited when there was little or no 'old' carbon in the catchment which was previously 'cleared' by glacial activity and little arboreal vegetation. The 900 year correction was done after the dates were calibrated using the following polynomial provided by Bard et al. (1998): calendar year age in cal-yr-BP = $158.5 + 0.44247x + 3.1455 \times 10^{-4}x^2 - 4.9893 \times 10^{-8}x^3 + 2.8872 \times 10^{-12}x^4 - 3.6582 \times 10^{-14}x^5$ with x being the C^{14} age in year BP measured here by AMS. The age for the lowermost dated sample (OZD736) remained unchanged (i.e. 900 yrs was not subtracted) as this sample was taken from below the layer consisting of tiny pebbles that is considered to indicate a slump in the lake. Of importance here is that, once the 900 year effect is taken from the samples above the slump layer, sedimentation (~ 40 cm/kyr) for the last ~ 9 ka was fairly constant.

History of sedimentation

Several inferences on the sedimentary history of Blue Lake can be made, and are based on the correlation of all cores (Table 1) studied earlier. In core NC, unit I is noted to thicken from 272 to 524 cm at the centre of the northern depression of the lake basin. This unit is marked by high organic matter content. Costin (1972) proposed that Blue Lake is protected from sedimentation by the upper cirque, and that, at present, sedimentation would consist not only of organic matter produced in the lake but fine sediment carried in suspension including coarser sediments that are trapped in the upper cirque. This phenomenon typifies the sedimentation environment of unit I. Unit III, which appears to be of a variable thickness across the lake, is otherwise similar to unit I, except that it contains lower levels of organic matter (Raine, 1974), and was therefore possibly formed under less vegetated, but broadly similar, circumstances.

Initially, unit II thins rapidly towards the northern depression of the lake from 92 cm within core 7 and 57 cm in core 8 to 7.6 cm within core NC, and from

Table 2. AMS and calibrated ages determined for core samples

Sample no.	Core depth – Core NC (cm)	Core depth – Tonker core (cm)	AMS radiocarbon age	1 σ error	Calibrated age	Best age estimate
OZD730		35–36	1090	60	960–1040	60–140
OZD732	30–31		1660	50	1555	655
OZD733	120–121		3150	60	3150	2250
OZD734	185–186		3880	70	4070	3170
OZD735	263–264		5470	80	6076	5176
OZD736	368–369		9530	80	10507	10507

Sample OZD730 taken from frozen finger core taken from lake by De Deckker et al. (submitted), other samples taken from core NC. Age calibration was done using Bard et al. (1998)'s polynomial (see text for more details). The best age estimate was calculated for the top four samples by subtracting 900 years (due to the inclusion of 'old' carbon – see De Deckker et al., submitted) from the calibrated ages. The bottom sample was deposited at a time when the lake started to accumulate organic mud at the bottom but we assume that little 'old' carbon was available in the catchment at the time.

here it continues to thin, less rapidly, down to 2 cm at core 3. Raine (1974) described this unit as consisting of silt and very fine to medium sand with the base of the unit consisting of pebbles in core 7. This unit represents a thinning turbidite sequence possibly formed by multiple slumping events given the greater thickness of the unit at both ends of the lake. The basal section of the turbidite, which consists of pebbles, does not reach the northern depression of the lake, although it is noted to occur at the base of unit B in core 8 from the southeastern end of the lake. The occurrence of mica grains in unit IV may denote a similar turbiditic origin for this unit, although any such events were not as extreme as the ones that formed unit II as no pebbles occur within unit IV.

Units F to H of Raine (1974) were not collected in core NC, and unit V does not exist in its entirety, therefore inferences on this part of the sedimentation history of Blue Lake cannot be readily drawn. They will not be discussed any further.

A record of Holocene aeolian activity

Observations of rounded to subrounded quartz grains from all the samples identified that, although the amount of textured grains when present varied throughout the core, grains < 30 µm were ubiquitous (Figure 4); this value of 37.5 µm represents the 'mode'. It is therefore considered that grains below that size were transported to Blue Lake under 'average/normal' wind conditions and that the source area did not change significantly. Values above the 37.5 µm mode would therefore indicate aeolian conditions 'above the norm', very likely implying stronger storms that would carry larger grains. Thus, the size of the largest textured grain measured in its longest orientation provides a pattern worthy of consideration (Figure 5) because of the accepted correlation between wind strength and grain size. Although dust flux and grain size are known to vary independently (Rea, 1994), the line of maximum dust flux that is situated today above southeastern Australia (Figure 1) coincides with maximum wind erosion (Hesse, 1993). Given the assumptions made above, and accepting Parkin and Shackleton's (1973) idea that the occurrence of large aeolian grains can be interpreted to be indicative of stronger winds, a series of trends become apparent. Figure 5 shows that larger aeolian grains were transported into the lake during the last 5.5 ka compared to the previous 6.5 ka, which we interpret as indicating either greater wind strength or stronger storms during this period. In addition, the period spanning the interval of 7.6 to 5.5 ka registered the smallest grain size; consistently well below 30 µm, thus indicating reduced wind strength or fewer storms. In addition, the periods of enhanced wind strength occurred in between intervals of reduced activity during the last 1.6 ka. We assume, therefore, that this represents a period of climatic instability, but which is characteristically the one with the most enhanced level of wind strength/activity. This period of the late Holocene 'instability' could coincide with what is so characteristic of Australia today, a continent affected by strong ENSO variations, fluctuating between extreme wet and dry periods.

Through examination of the volume of particles within the range 0–150 µm, as determined by the CIS-100 (Figure 4) it is apparent that, before ~ 10 ka the volume of grains > 30 µm was very erratic in deposition but, after this time, the volume became fairly constant, except for near the top of the core when a decrease became evident at ~ 0.87 ka. The cause of this decrease remains unexplained. This pattern in particle volume is taken as further proof that periglacial conditions, which directly affected the local vegetation and also sediment input into the lake, continued in the Blue Lake area until ~ 10 ka. The persistence in the volume of grains after that time is taken to represent a time when the Blue Lake catchment was well vegetated and with the vegetation itself controlling the sediment input into the lake. This assumption that the Blue Lake catchment became well vegetated ~ 10 ka relies on Raine's (1974) pollen study of several cores.

Conclusion

The textured grains, and their respective maximum grain size, recovered from Blue lake sediments permitted us to identify a variation in aeolian activity above Blue Lake during the last 12 ka. Of significance is that the last 1.6 ka registered the strongest fluctuations in aeolian activity interrupted quite frequently by interval of reduced activity, but still above the norm for the entire Holocene. We could interpret this record as indicating that storminess was more predominant during the last 1.6 ka, with stronger storms carrying larger aeolian grains. In addition, it appears that the last 5.5 ka of the record saw a progressively increasing intensity of aeolian activity. The period of 'below norm' aeolian activity spans the 7.6 to 5.5 ka period, which coincides with the time when lakes in southeastern Australia reg-

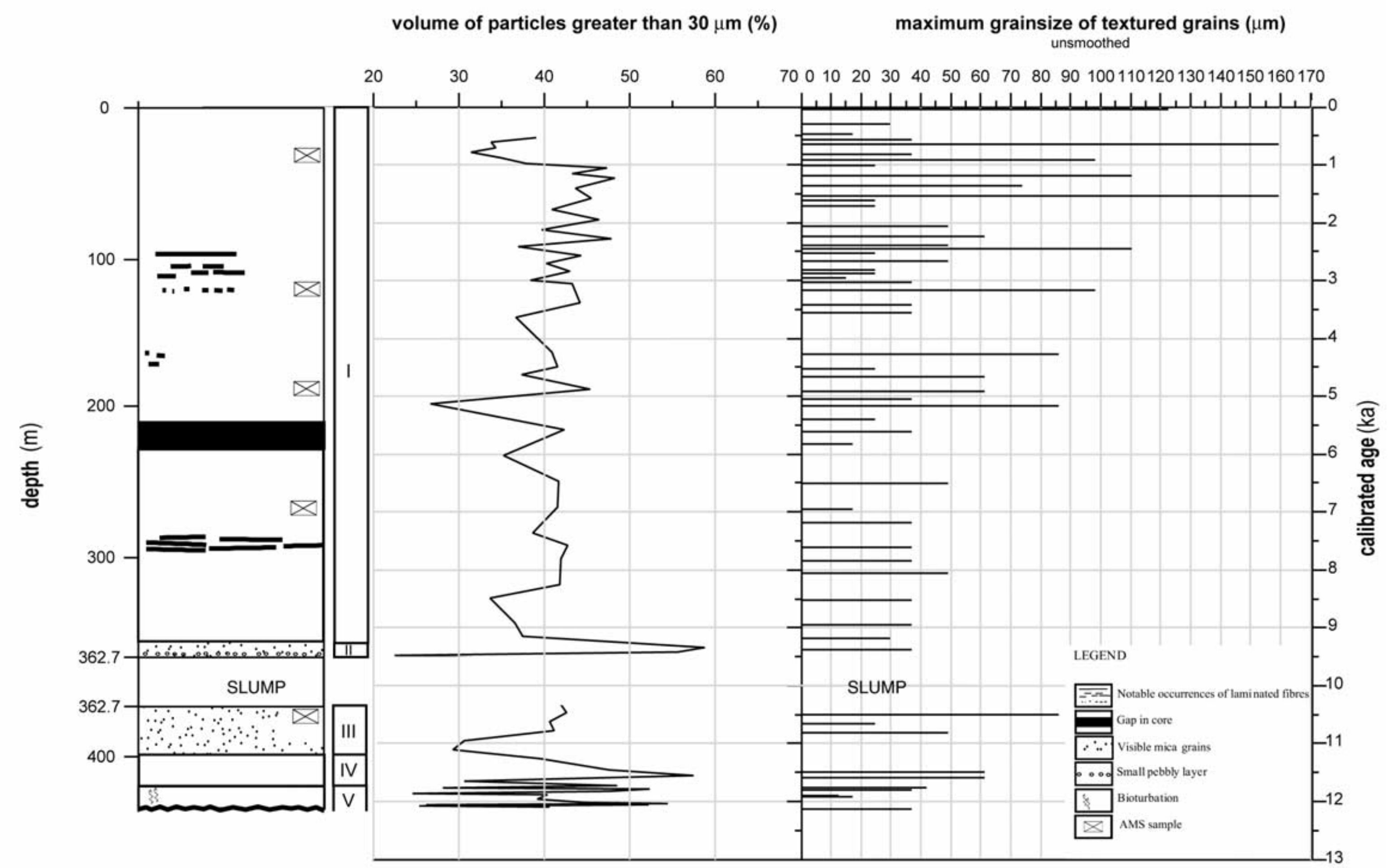

Figure 4. Abridged log of Blue Lake core NC showing also the 5 different zones (I–V) discussed in the text. The volume of particles greater than 30 µm as recognised in all samples from core NC (data obtained from the GALAI apparatus) is presented in the middle column and shows fluctuations but overall a mean range between 40 and 50 µm. The largest grain size of aeolian origin measured under a binocular microscope; (unsmoothed data) versus age is presented in the right hand column.

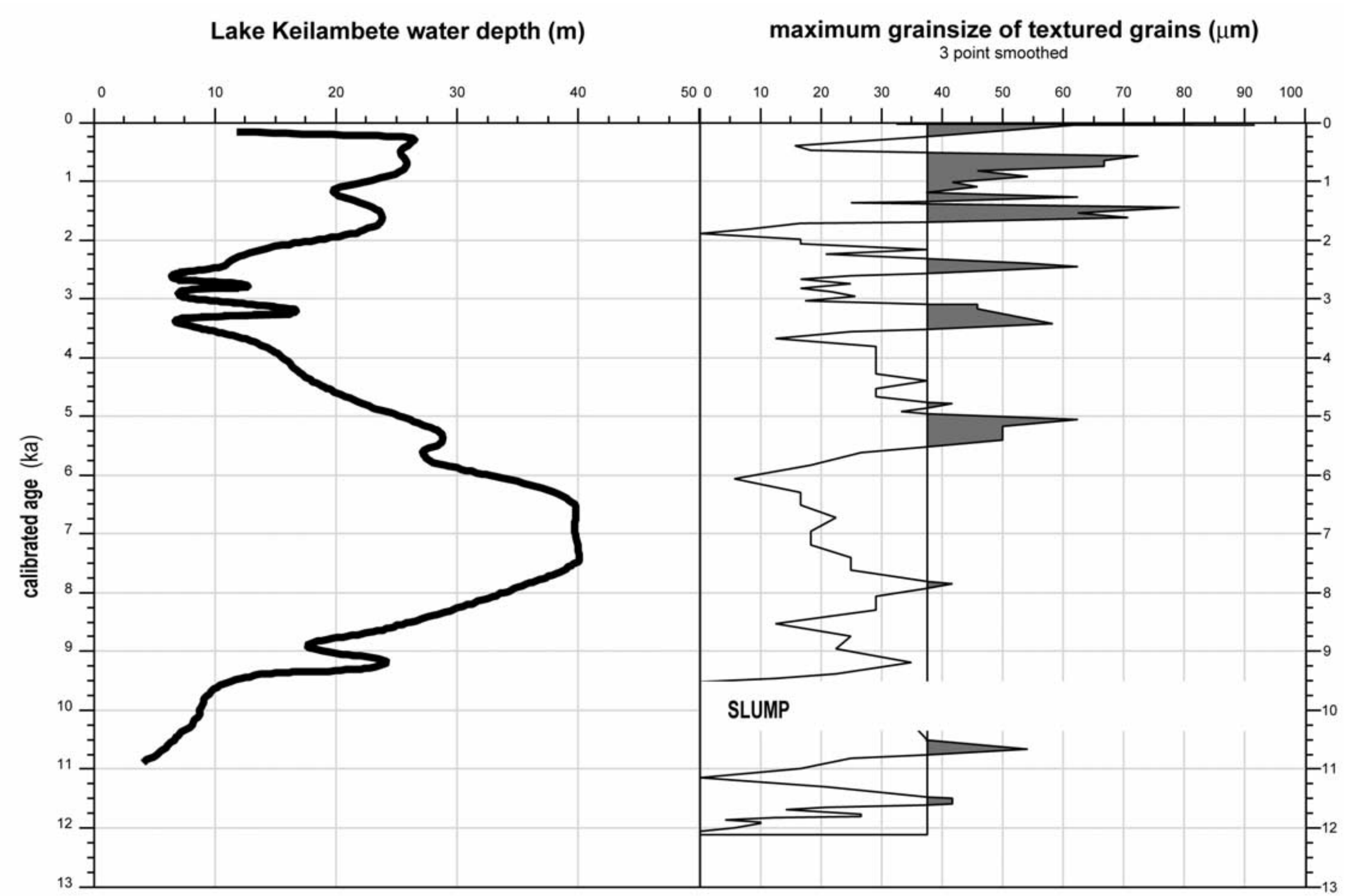

Figure 5. The largest size of aeolian grains recognised microscopically in all 81 samples from Blue Lake core NC (3 point smoothed data) are compared against Lake Keilambete level curve vs. age in calendar yrs B.P. taken and modified from Bowler (1981). In the right hand column the recognised mean grain size value of 37.5 μm (vertical line) helps showing departure trends such as the overall drop in maximum grain size when Lake Keilambete was at its fullest (7.5 to 5.5 ka), and the increase in maximum grain size for the latter part of the Holocene.

istered their highest levels, with the best example from Lake Keilambete (Bowler, 1981; De Deckker, 1981; Chivas et al., 1993). Thus, we believe that the trend recognised in the Blue Lake core is representative of climatic conditions that occurred during the Holocene, at least for southeastern Australia. Closer examination of the maximum grain size of textured grains record shifted significantly to very low values around 2 ka. This coincides with the drowning of trees in three crater lakes in western Victoria at the time (Bullenmerri, Gnotuk and Keilambete), (Bowler, 1981; De Deckker, 1982, and unpublished). Once again, this increase of rainfall, coinciding with the occurrence of smaller aeolian grains being deposited into Blue Lake, is a result of a broad regional trend.

It is noteworthy that at a time of significant and rapid water level fluctuation at Lake Keilambete (Figure 5), between 3.5 and 2.5 ka; rapid, significant as well as contrasting periods of aeolian activity were registered in the Blue Lake record. This must therefore indicate a broad regional trend for southeastern Australia at least.

We interpret this change of climatic conditions for the latter part of the Holocene as a ‘downgrading’ of climatic stability with the predominance of wet and dry periods such as we know them today and that are strongly influences by the El Nino Southern Oscillation (ENSO). The latter seems to have been less effective prior to 5.5 ka.

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