Late Quaternary aridity and dust transport pathways in eastern Australia

Lynda M. Petherick, Hamish A. McGowan, Patrick T. Moss and Balz S. Kamber

Lynda M. Petherick (corresponding author),Hamish A. McGowan, Patrick T. Moss:
School of Geography, Planning & Architecture, University of Queensland,
St. Lucia, Queensland 4072, Australia. E-mail: l.petherick@uq.edu.au
Telephone: +61-7-336-53995 Fax: +61-7-336-56899
Balz S. Kamber: Department of Earth Sciences, Laurentian University, Sudbury, Ontario P3E 2C6, Canada

Abstract

A high-resolution, multiproxy record of palaeoclimatic and palaeoenvironmental variability extending to ca. 42 cal. ka has been constructed from lake sediment from Native Companion Lagoon (NCL), North Stradbroke Island (NSI), Queensland. Aeolian materials extracted from the lake sediment act as a proxy for aridity in eastern Australia. ICP-MS trace element analysis of the aeolian sediment and subsequent provenancing of the far-traveled dust component show variations in dominant dust source areas for NSI, with periods of increased aridity during the late Pleistocene showing increased input into NCL from the Murray-Darling Basin and central South Australia. Conversely, during periods of decreased aridity, dust is transported to NCL from a wide range of source areas, which may reflect increased sediment supply (e.g. due to increased precipitation under a strengthened summer monsoon regime). Variability in the dominance of continental dust source areas for NCL indicates variability in the position and intensity of dust transport pathways to NSI, reflecting major changes in atmospheric circulation patterns over Australia. Palynological and charcoal analyses from the NCL sediment support the record of aeolian sedimentation, providing an indication of local conditions on NSI.

Introduction

In recent times there have been a number of studies into palaeoclimatic and palaeoenvironmental variability in eastern Australia, providing valuable insights into the nature of the late Quaternary. However, there are still only a few long, continuous, high resolution palaeo-records for the region. The Native Companion Lagoon (NCL) record from North Stradbroke Island (NSI) presented here bridges an important spatial gap between the long palaeo-records from the Atherton Tablelands, northern Queensland (Kershaw, 1976, 1994; Haberle, 2005; Turney et al., 2006), Ulungra Springs, New South Wales (Dodson and Wright, 1989) and Barrington Tops, New South Wales (Dodson et al., 1986; Sweller and Martin, 2001). Palaeo-records from subtropical Australia are rare, with the only record comparable to NCL being the 57 ^{14}C kyr Lake Allom record from Fraser Island (Longmore, 1997; Donders et al., 2006). The Lake Allom record provides important insights into subtropical palaeoclimatic variability during the late Quaternary; however, a hiatus in sedimentation 28-10 ^{14}C kyr means that no data for the Last Glacial Maximum (LGM) and deglaciation are available. There are no such hiatuses in the NCL record, meaning that the record is a continuous representation of the past 42 cal. kyr.

In addition to pollen and charcoal, a record of aeolian dust deposition is presented. Despite the fact that Australian dust has been identified in the Tasman Sea (Hesse, 1994), New Zealand (McGowan et al., 2005) and Antarctic ice cores (Revel-Rolland et al., 2006), high resolution, long, terrestrial records of dust deposition available for Australia are scarce. Indeed, the majority of such records for the Southern Hemisphere extending ≥25 kyr come from Antarctica (e.g. Petit et al., 1990; Grousset et al., 1992; Basile et al., 1997, Petit et al., 1999).

In this paper a 42 cal. kyr multiproxy record of palaeoclimatic and palaeoenvironmental variability from subtropical Australia is presented. Using a geochemical "fingerprinting" methodology, aeolian dust is provenanced to continental source area. Knowledge of the varying dominance of source areas through time allows dust transport pathways for eastern Australia to be reconstructed, and atmospheric circulation patterns to be postulated.

Physical Setting: North Stradbroke Island

NSI is a large sand island located in Moreton Bay, southeast Queensland (Figure 1) (Tejan–Kella et al., 1990). Climate on the island is described as 'sub-tropical' under the Köppen classification (Bureau of Meteorology (BOM), 2005), and is characterised by warm, humid summers and relatively mild, dry winters (Clifford and Specht, 1979; Colls and Whitaker, 1990; Thompson, 1992). Annual average rainfall is approximately 1600 mm and the dominant wind direction is southeasterly (Clifford and Specht, 1979; Thompson, 1992).

Situated at the southern end of NSI (Figure 1), NCL is approximately 1 km in length by approximately 0.3 km at an elevation of 20 m a.s..l. NCL is a perched, internally draining lagoon, typical of the majority of freshwater lakes on NSI. As NCL is a closed system, with no fluvial input, it is believed that the only input of sediment is through the deposition of both local and far-traveled materials by wind. The main source of local aeolian sediment is believed to be from the large, parabolic quartz sand dunes that surround NCL.

Such dunes are typical of NSI and are usually vegetated by *Eucalyptus* forest with *Banksia* and *Casuarina* also present. The dunes on NSI were formed over a number of dune-building phases from Marine Isotope Stage 12 (486 – 430 ka) through to the Holocene (Kelley and Baker, 1984; Ward, 2006). The podzol nature of the dunes (i.e. highly porous with low organic and clay content (Consolidated Rutile Limited, 2005)) suggests that overland flow into NCL is rare. Deposition by aeolian processes of local sediments (e.g. from the sand dunes surrounding NCL) is believed to be restricted to the margins of the lake bed. Even when NCL is dry, such as at the time of core extraction, sand transport onto the lake bed is retarded by its peaty nature and rapid colonisation by plants.

Methodology

3.1 CORE EXTRACTION, ASHING & DATING

Using a Russian D-section corer, a 3.8 m organic-rich sediment core was extracted from NCL. The presence of a sand layer at 3.8 m indicates that this is the maximum depth of lake sediment. The core was sampled at 5 mm intervals and dried at 65°C for 65 hours to remove moisture. The dried NCL samples were ashed in a high-temperature furnace at 490°C for 12 hours to remove organic material, retaining the inorganic, aeolian fraction.

Nineteen dried sediment samples (Table 1) for the 3.8 m core were sent to the University of Waikato radiocarbon laboratory, New Zealand, for AMS radiocarbon dating to establish age control (http://www.radiocarbondating.com). The samples were organic-rich lake sediment, with varying concentrations of quartz sand. Samples NC-1-567 and NC-1-677 returned ages close to the limit of radiocarbon dating (Table 1) (Allen and Holdaway, 1995; Fifield et al., 2001), and so should be treated with some degree of caution. In addition, 2 dates (NC-1-270: 13570 ±100 ^{14}C yr. and NC-1-312: 13534 ± 99 ^{14}C yr.) returned age reversals (Table 1). However, the age of NC-1-270 is within the error margins of the radiocarbon dating, and so was considered suitable for describing the age-depth chronology of the record. Even with the inclusion of NC-1-312, the radiocarbon age-depth relationship could be described by the cubic polynomial $y = -2E\text{-}07x3 + 0.001x2 + 9.1343x$, which estimated 98% of the variance. The radiocarbon dates were converted to calendar years using the Hughen et al. (2006) Cariaco Basin chronology (Petherick et al., accepted – a).

3.2 POLLEN AND CHARCOAL ANALYSES

The methodology of van der Kaars (1991) was employed to analyse pollen and charcoal in 66 NCL sediment samples, providing a temporal resolution of ca. 500 years. After the addition of lycopod spores (to assist in the calculation of pollen and charcoal concentrations), sodium pyrophosphate was used to deflocculate the samples. Sodium polytungstate, a heavy liquid solution with a specific gravity of 2.0, was then used to separate the organic fraction (including pollen and charcoal) from the lithogenic fraction. Finally, the pollen grains were stained by acetolysis before being placed onto slides in glycerol for analysis at X 650

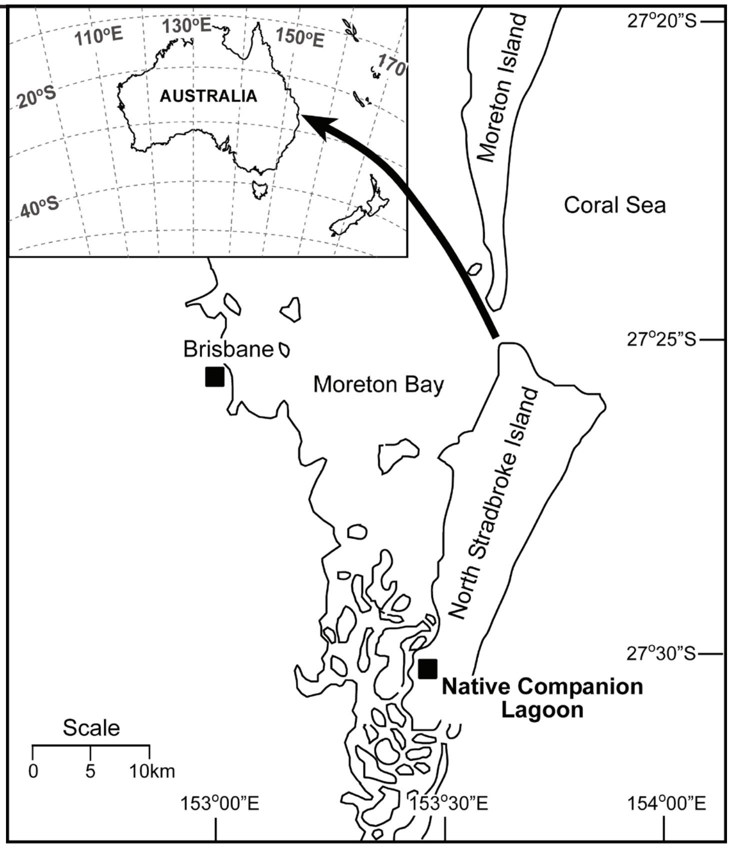

Figure 1: The study site: North Stradbroke Island.

magnification under a light microscope. A minimum of 100 identifiable pollen grains were counted for each NCL sample. Charcoal was identified as black angular particles with a diameter >10 μm. At least 200 charcoal points per NCL sample were counted using the point count method of Clark (1982).

3.3 ICP-MS TRACE ELEMENT ANALYSIS

3.3.1 Sample preparation and analytical techniques

One hundred and thirty-one ashed NCL sediment samples were selected to undergo ICP-MS trace element analysis. In addition, 2 samples from the quartz sand dunes were analysed in order to determine the chemistry of the local aeolian component.

Preparation of the samples for ICP-MS was conducted using the well-established beaker hotplate approach (e.g. Marx et al., 2005). The highly static nature of the samples meant that there was a chance that sediment may stick to the glassware and potentially be lost. To minimise this risk, after weighing the samples were transferred into beakers and suspended in dilute nitric acid (HNO_3). Hydrofluoric acid was used to digest the sediment samples on a hotplate at 100°C overnight. Post-acid digestion, the samples were 2000X diluted and centrifuged. An aliquot of each sample was added to a test tube containing 0.18 g standard solution, which contained known quantities of elements such as rhodium, rhenium and indium which are unlikely to be present in the samples. Sample weight was brought to approximately 12 g with HNO_3 before the samples were centrifuged again. Blank samples went through

Sample ID	Average depth (mm)	Description	Age (^{14}C yr.)	Error (^{14}C yr.)	Age (cal. yr. BP)	Error (cal. yr.)
NC-1-001	5	Organic-rich sediment	540	± 36	544	± 30
NC-1-028	197.5	Organic-rich sediment	1745	± 37	1657	± 52
NC-1-069	395	Organic-rich sediment	6353	± 50	7279	± 50
NC-1-081	455	Organic-rich sediment	6176	± 47	7074	± 78
NC-1-149	792.5	Organic-rich sediment	9222	± 65	10381	± 103
NC-1-177	935	Organic-rich sediment	10130	± 73	11764	± 171
NC-1-207	1090.5	Organic-rich sediment	11478	± 79	13336	± 98
NC-1-224	1172.5	Organic-rich sediment	12714	± 90	14811	± 136
NC-1-256	1334.5	Organic-rich sediment	13467	± 98	15678	± 155
NC-1-270	1403	Organic-rich sediment	13570	± 100	15796	± 157
NC-1-279	1450	Organic-rich sediment	13586	± 100	15814	±158
NC-1-301	1567	Organic-rich sediment	14762	± 116	17629	± 269
NC-1-335	1737.5	Organic-rich sediment	15999	± 132	19140	± 141
NC-1-394	1982	Organic-rich sediment	19311	± 157	22961	± 244
NC-1-528	2667.5	Organic-rich sediment	28684	± 456	34080	± 496
NC-1-567	2862.5	Organic-rich sediment	33187	± 816	38573	± 822
NC-1-677	3482.5	Organic-rich sediment	35757	± 1147	41018	± 1060

Table 1: Results of radiocarbon dating and subsequent calibration of19 NCL samples.

	Average NCL	NC-Q-01	NC-Q-02
Li	6,915	4,876	4,851
Be	1,486	41	49
Sc	17,564	123	217
Ti	12,797,730	328,776	587,765
V	294,299	886	2,093
Cr	108,063	468	1,075
Mn	180,223	4,120	9,954
Co	12,875	94	203
Ni	32,423	123	234
Cu	73,918	393	587
Zn	31,351	803	1,288
Ga	20,808	62	166
As	15,628	97	220
Rb	13,793	277	560
Sr	391,125	1,249	5,786
Y	31,973	659	606
Zr	175,525	7,721	5,818
Nb	18,567	340	776
Mo	6,092	24	43
Cd	337	3	5
Sn	4,127	59	118
Sb	719	87	107
Cs	901	62	67
Ba	179,399	5,158	7,216
La	57,921	529	902
Ce	120,836	1,110	1,816
Pr	14,277	128	212
Nd	53,775	478	773
Sm	10,146	96	148
Eu	1,869	16	22
Gd	2,962	90	121
Tb	6,348	16	19
Dy	6,457	109	113
Ho	1,277	24	23
Er	3,466	73	66
Tm	515	12	11
Yb	3,301	83	73
Lu	485	13	11
Hf	4,895	225	166
Ta	1,361	23	49
W	1,663	34	61
Tl	109	3	5
Pb	46,606	457	1,680
Th	20,495	272	373
U	4,409	98	94

Table 2: Trace element composition of averaged NCL samples and 2 local dune sand samples (NC-Q-01 and NC-Q-02)

the same procedures to provide controls. The samples underwent trace element analysis on the Thermo Electron X Series ICP-MS at the ACQUIRE laboratory, the University of Queensland, following the method of Eggins et al. (1997).

3.3.2 Source area samples

In order to determine continental source area chemistries, 149 samples were collected from across eastern Australia, from regions known to be, or have been, active dust source areas (Figure 2) (e.g. Middleton, 1984; McTainsh et al., 1998; 2005; Bullard and McTainsh, 2003). Dust storms are accountable for the removal of large amounts of soil in semi-arid regions (McTainsh et al., 1998), and as such, surface sediment samples were collected from regions identified as having high frequency of dust storms. For example, recent major dust storm events have occurred in the Simpson Desert/Channel Country (December 1987: Knight et al., 1995), Eyre Peninsula (May 1994: Butler et al., 1995) and western Queensland/Murray Darling Basin (October 2002: McTainsh et al., 2002). Surface sediment samples were collected from sites (e.g. floodplains, dunes, dry lake surfaces, riverbanks) in regions such as these, and underwent identical preparation and ICP-MS analysis as the NCL samples.

3.4 SEPARATION OF LOCAL AND FAR-TRAVELED AEOLIAN COMPONENTS

The NCL sediment samples had a distinct local aeolian component, which needed to be distinguished in order to provenance only the 'foreign' far-traveled dust component. The local component was predominantly quartz sand, with a biogenic silica content of <1% (Moss et al., 2006) and as such had very low concentrations of trace elements (Table 2). Conversely, the far-traveled dust was trace element-rich, characterised by elements associated with clays, believed to be sourced solely from the Australian mainland. Four elements (Ga, Ni, Tl and Sc) were used as proxies for far-traveled materials such as clays and goethite allowing local and far-traveled components to be separated by geochemistry (Petherick et al., accepted – b).

3.5 PROVENANCING THE FAR-TRAVELED DUST

Using a geochemical "fingerprinting" technique (Marx et al., 2005; Petherick et al., accepted – b), the far-traveled dust component was provenanced to continental source area(s). The technique involves the statistical comparison of the trace element chemistry of each NCL sample with that of the 149 source area samples in order to find the most likely match. Although 44 trace elements were analysed by ICP-MS, only elements that were conservative (i.e. immobile) through the sediment core were suitable for use in provenancing. As such, elements susceptible to loss through weathering (e.g. alkali earth elements), loss through mineral sorting (e.g. zirconium, hafnium) or high solubility in water (e.g. barium, strontium) were rejected. The concentrations of elements whose behaviour was unknown were plotted against elements known to be conservative in terrestrial environments (e.g. thorium, rare earth elements) (Kamber et al., 2005). Strong linear relationships indicated that the element with previously unknown behaviour was also immobile through the core, and could thus be used to provenance the dust. Eventually, of the 44 elements, we deemed 16 to be immobile through the core, and therefore useful for provenancing.

The chemistry of each NCL sample was compared with potential source area samples using a ternary mixing model (Petherick et al., accepted – b). This statistical comparison was used to establish the contribution of material into NCL from the 3 most likely source areas: comprised of a southeast Queensland source area and 2 continental source areas (Petherick et al., accepted – b). Although 149 samples were taken from regions either currently active or known to be active in the past as dust source areas, it should be noted that there is a possibility that an un-sampled source area contributed to the NCL record.

4.0 Results: The 42 kyr NCL record

4.1 THE NATURE OF THE NCL RECORD

The NCL core was characterised by organic-rich sediment with macrofossils and quartz present in varying concentrations (Figure 3). The record of total (i.e. combined local and far-traveled) aeolian flux shows a series of peaks and troughs for the past 42 kyr and does not appear to be random or noisy (Figure 3). Total aeolian sediment flux ranges from 0.32 g m^{-2} $yr.^{-1}$ to 28.88 g m^{-2} yr^{-1}.

4.2 POLLEN AND CHARCOAL ANALYSES

The NCL pollen record indicates that the vegetation surrounding NCL for the past 42 kyr has been dominated by sclerophyll woodland, predominantly Casuarinaceae (Figure 3). The pollen record correlates well with the record of aeolian sedimentation, with changes in sedimentation corresponding with changes in vegetation around NCL. The NCL charcoal record is also consistent with the record of sedimentation, with periods of increased charcoal corresponding with periods of increased aeolian sediment flux (Figure 3).

4.3 PROVENANCE OF THE FAR-TRAVELED DUST

NCL sediment sample chemistries for the entire record are presented in Table 2 (NB: previous elemental data published by Petherick et al. (accepted – b) represented only 0 – 25 cal. ka, and as such differs slightly from the data presented here).

The results of the dust provenancing identified the continental source areas whose chemistry most closely matches that of the NCL samples. A potential limitation of this geochemical "fingerprinting" method (and inherent in most provenancing studies) is the possibility that all dust source areas in eastern Australia have not been sampled. So, it should be kept in mind that there may be dust transport from source areas that have not been sampled. However, as discussed in Section 3.5, surface sediment samples were collected from regions that are, or have been, dominant dust source areas for eastern Australia (Figure 2), minimizing the likelihood of major input from another region.

Comparison of the geochemistry of the far-traveled dust fraction with that of potential continental dust source area indicated that overall the MDB has been the most dominant dust source area for eastern Australian

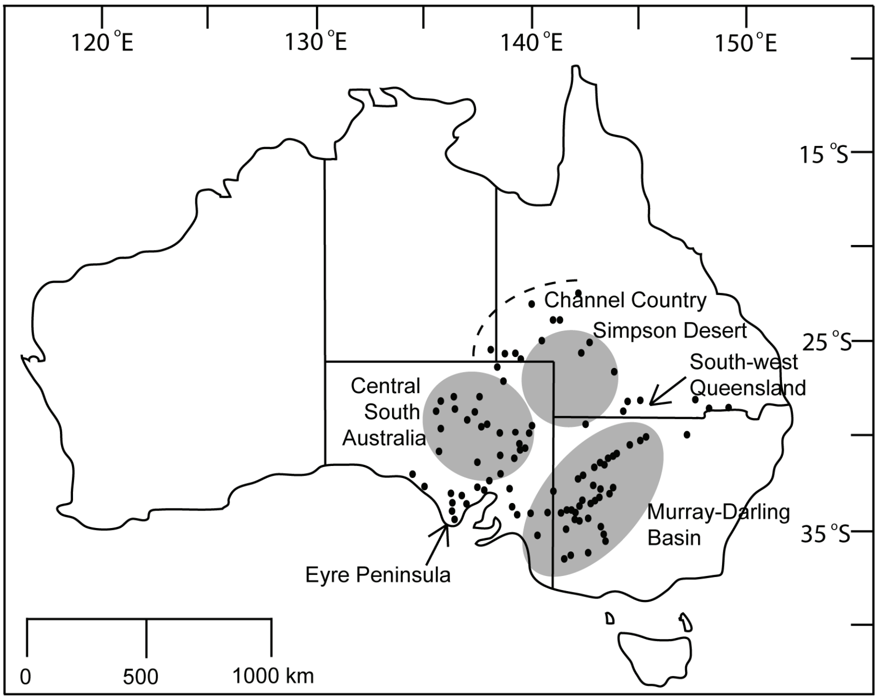

Figure 2: Map showing potential dust source areas for which surface chemistries were established in relation to the location of North Stradbroke Island.

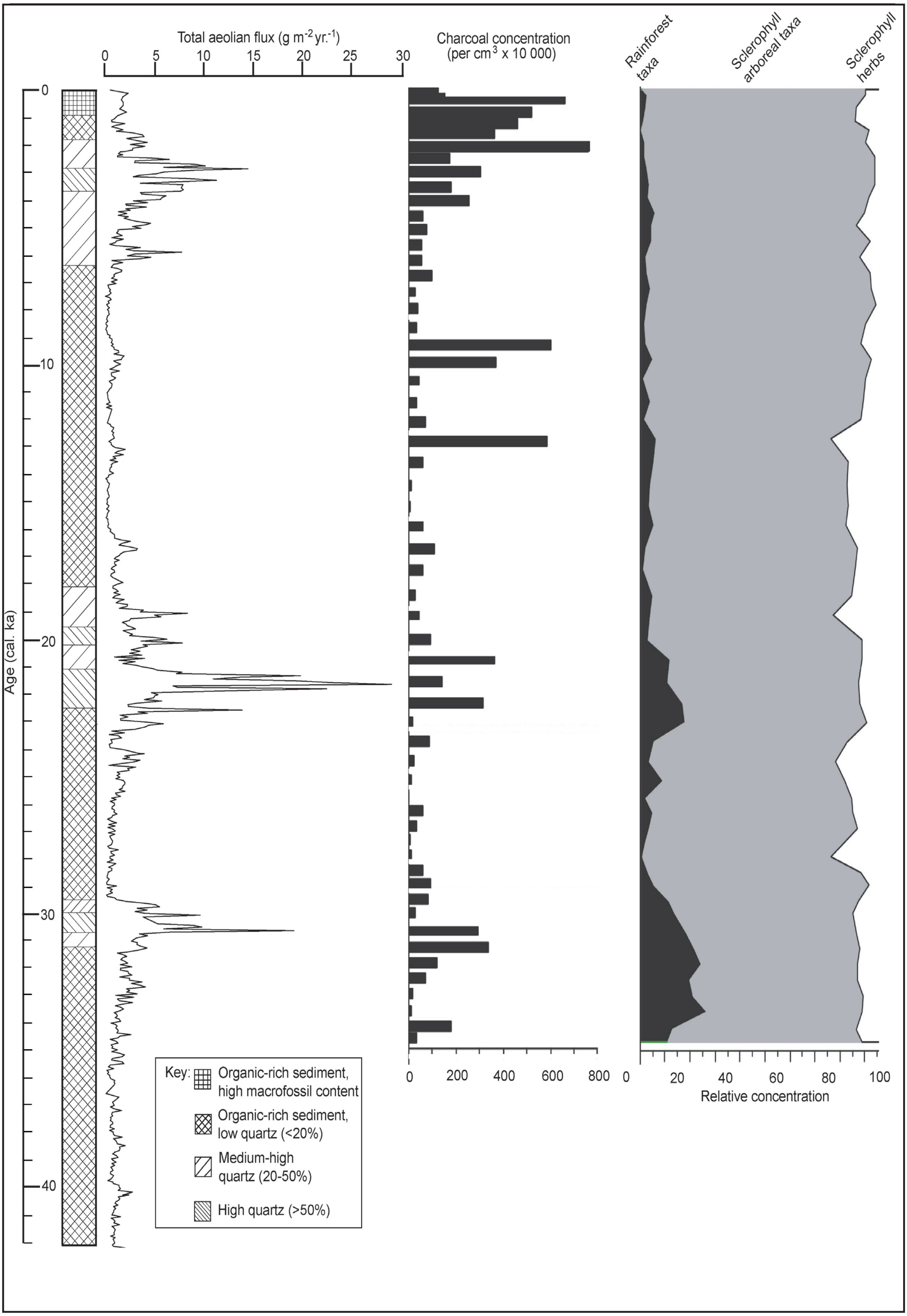

Figure 3: The 42 kyr record from NCL showing core lithology, total aeolian sediment flux, charcoal and pollen.

during the past 42 kyr. Periods of increased aeolian sedimentation in the NCL record are characterised by dust input from the MDB and central South Australia. Periods of decreased aeolian sedimentation are characterised by dust input from a wide range of continental source areas, such as the Channel Country, Eyre Peninsula, southwestern Queensland and the northern MDB.

5.0 Palaeodust transport pathways and aridity in eastern Australia through the late Quaternary

Periods of increased aeolian sedimentation in the NCL record indicate increased dust transport from both local and continental dust source areas. Intensified dust transport indicates increased surface susceptibility to wind erosion, associated with decreased soil moisture and reduced vegetation cover (McTainsh et al., 1998). Such conditions are associated with reduced effective precipitation (defined here as precipitation minus evaporation) and increased aridity. Conversely, periods of decreased aeolian sedimentation suggest a stabilised landscape due to increased effective precipitation.

Three interrelated variables influence the transport of dust from mainland Australia to NSI: aridity and sediment supply in the source area, and atmospheric circulation patterns. Periods of increased aridity in mainland Australia would have been associated with reduced effective precipitation leading to decreased soil moisture and reduced vegetation cover. The extent and type of vegetation cover plays a significant role in the susceptibility of a surface to erosion by the wind (McTainsh et al., 1989; Shao, 2000; Day et al., 2003). As such, sources of moisture such as groundwater supply (a critical factor for vegetation) are also important (Coughlan, 2003).

With the exception of longitudinal dunes, in order for a region (e.g. playas, floodplains) to act continuously as a dust source area, it must have a replenishable supply of sediment (e.g. through fluvial or colluvial deposition) for deflation (McTainsh et al., 1989; 1998; Bullard and McTainsh, 2003). However, even if local conditions are suitable in a potential source area, dust transport to NSI is dependent on favourable weather patterns for dust transport.

5.1 LATE QUATERNARY PALAEOCLIMATES OF EASTERN AUSTRALIA

5.1.1 Pre-Last Glacial Maximum: 42 – 24 ka

The period prior to the Last Glacial Maximum (LGM) is characterised by relatively low aeolian sediment flux, with the exception of a peak centered on ca. 30.8 ka. Vegetation around NCL appears to have been dominated by mixed Eucalypt/*Casuarina* forest. There is also a significant presence of rainforest and relatively high representation of aquatics and ferns. Overall, this indicates that climate on NSI pre-LGM was characterised by increased effective precipitation, leading to a stabilized landscape not susceptible to wind erosion. Charcoal values during this period are high, which is probably a reflection of increased biomass (i.e. *Eucalyptus*) available for burning. However, conditions coeval with the 30.8 ka peak in aeolian sedimentation appear to have been characterised by an increased representation of *Casuarina*, suggesting a drier climate.

The pre-LGM 30.8 ka peak in aeolian sedimentation, indicating increased aridity in eastern Australia, corresponds well with other records emerging from the Southern Hemisphere. For example, records of glacial advance in New Zealand (Suggate, 1990; Suggate and Almond, 2005) and Chile (Denton et al., 1999), New Zealand maar lake records (Alloway et al., 2007), the Taylor Dome (Steig et al., 2000) and Dome C nss-Ca^{+2} (Röthlisberger et al., 2002) records and the EPICA Dronning Maud Land ^{18}O record (EPICA community members, 2006) provide evidence for a period prior to the LGM during which environmental conditions were similar to those during the LGM.

5.1.2 Last Glacial Maximum: 24 – 21 ka

The LGM is shown as the period of maximum aeolian sedimentation in the 42 ka NCL record, which is in agreement with well-established assertion that the LGM was a period of characterised by increased aridity and atmospheric dust concentrations both globally and in Australia (e.g. Bowler, 1976; Jouzel et al., 1995; De Deckker, 2001). Increased dune activity on NSI during the LGM is indicated by the significant input of local sand and dust into the NCL sediment, probably due to decreased vegetation cover associated with decreased effective precipitation and increased landscape susceptibility to fire.

Increased aeolian sedimentation in the NCL record, peaking at ca. 21.9 ka, corresponds with an increased representation of *Casuarina* in the pollen record, indicating similar environmental conditions as during the 30.8 ka peak. Rainforest and eucalypt presence during these periods decreased, suggesting a drier climate.

5.1.3 Last Termination: 21 – 12 ka

The Last Termination is characterised by a generally decreasing trend in aeolian sedimentation, indicating decreased aridity. However, there are several reversals (ca. 20.2 ka, 19.2 ka and 16.8 ka) to what appear to be near-glacial conditions during the termination, which is possibly a reflection of instability in the climate system. Vegetation around NCL during this period was dominated by *Casuarina*, with low representation of rainforest and eucalypts, suggesting conditions were still fairly dry. However, the lower (500 yr.) resolution of the pollen may have just picked out the reversals, and not the overall trend of decreasing aridity.

5.1.4 The Holocene: 12 – 0 ka

The early to mid Holocene (12 – 7 ka) in the NCL record is characterised by comparatively low aeolian sedimentation, indicating decreased aridity.
The dominant vegetation during this period was Casuarinaceae forest, although there was also an increased presence of eucalypts and rainforest. The early Holocene peak in aquatics may indicate 'swampy' conditions at NCL. The early Holocene marks the onset of the presence of *Banksia*, which may be a reflection of the development of 'Wallum' heath which occurs throughout the Holocene period.

Very low aeolian sediment flux (≥ 0.32 g m^{-2} $yr.^{-1}$) during the early Holocene coincides well with a period of humid climate recognised in a number of Australian palaeo-records (e.g. Luly, 1993; Nott and Price, 1994;

Kershaw, 1995; Dodson and Ono, 1997; Dodson, 1998). Under conditions of increased effective precipitation, soil moisture and vegetation cover are likely to have increased leading to reduced susceptibility of surface sediments to wind erosion. The lowest aeolian sediment flux (0.14 g m^{-2} $yr.^{-1}$) in the entire record occurs at 7.6 ka, which may indicate a Holocene climatic optimum characterised by increased effective precipitation. Peaks in rainforest and ferns during this period provide supporting evidence for a phase of increased effective precipitation in eastern Australia.

From ca. 7 ka aeolian sediment flux increases, peaking at 14.43 g m^{-2} $yr.^{-1}$ at ca. 2.9 ka, indicating a period of climatic deterioration. This period of increased aridity may represent a late Holocene dry phase (McGowan et al., 2007), which has been found across eastern Australia as a period of decreased effective precipitation, increased windiness and increased fire frequency (e.g. Bowler et al., 1976; Wasson, 1976; Wasson, 1979; Ross et al., 1992; Harrison, 1993; Luly, 1993; Magee et al., 1995; Shulmeister and Lees, 1995; Ahmad, 1996; Longmore, 1998). Increased terrigenous kaolinite in marine sediments off the coast of southern Australia indicates intensified aeolian activity from 5 ka (Gingele et al., 2007), which is in agreement with the NCL record.

The presence of mangroves in the NCL pollen record during this period suggests higher sea levels, as reported by various authors (e.g. Nanson et al., 1992). Shoreline erosion by transgressing seas and subsequent transport of loose sands by onshore winds is likely to have led to intensified dune building on NSI, which is supported by the increase in sedimentation seen in the NCL record. Stronger onshore winds are also possibly the mechanism by which mangrove pollens were transported to NCL.

Increased charcoal values in the NCL record occur from 2 ka, which may be a reflection of sustained burning associated with intensified Aboriginal occupation of the region. Aeolian sedimentation decreases from ca. 2.5 ka, indicating decreased aridity and the onset of modern climatic conditions. Vegetation around NCL was dominated by Casuarinaceae forest, with an increased representation of grasses possibly indicating a more open understorey. The decreased aridity inferred from the NCL record disagrees with the trend towards drier climatic conditions indicated by several records (e.g. Bowler, 1976; Nott and Price, 1994; Martin, 1999; Hesse et al., 2004). Other records, however, indicate increased effective precipitation in the late Holocene (e.g. Wasson, 1976; Dodson et al., 1986; Mooney, 1997; Sweller and Martin, 2001). These discrepancies may be an indication of increased seasonality, variability and/or instability in the climate system (Kershaw, 1995; Donders et al., 2006), possibly as a result of an increasingly variable ENSO (Stanley and De Deckker, 2001). The late Holocene weakening of the Australian summer monsoon (Wyrwoll and Miller, 2001) was possibly influenced by an intensified ENSO (Moy et al., 2002), and may have resulted in the reduction and subsequent exhaustion of sediment supply in dust source areas.

5.2 DUST TRANSPORT PATHWAYS AND PALAEOCLIMATE

Comparison of the results of the dust provenancing with the multiproxy NCL record indicate that periods of increased aridity are characterised by dust input from source areas distinct from those dominant during periods of decreased aridity (Figure 4). As such, dust transport pathways to NSI are different during periods of increased aridity compared with periods of decreased aridity, indicating that atmospheric circulation patterns for dust transport are also different.

5.2.1 Periods of increased aridity

The record of aeolian sedimentation indicates several periods of increased aridity during the past 42 kyr, such as pre-LGM (ca. 32 – 30 ka), the LGM (ca. 24 – 21 ka) and the late Holocene (ca. 7 – 2.5 ka). During these periods, dust input to NSI appears to be predominantly from the floodplains of the Darling and Murray Rivers and the palaeo-dunes of the MDB (Figure 4 (a)). The influence of dust from the MDB from 25 ka is supported by evidence for the drying out of lakes, waterways and adjacent landscapes in the Basin (e.g. Bowler et al., 1976; Harrison, 1993, Field et al., 2002), providing sediment suitable for deflation. Bullard and McTainsh (2003) propose that the MDB was the dominant dust source area for eastern Australia during the LGM, supported by evidence of increased dune building in the Basin 35 – 10 ka (Lomax et al., 2007).

The late Holocene arid phase is also characterised by dust input from the Darling River floodplains, with some input from the playa lakes (e.g. Lake Frome) of central South Australia. The input of dust from Lake Frome from ca. 5 ka corresponds well with a coeval phase of dune building in the Strzelecki Desert (Lomax et al., 2003).

The dominance of these continental source areas during periods of increased aridity may indicate enhanced meridional southwesterly winds transporting dust to NSI. Although this contrasts the theory of intensified westerly winds during the LGM (e.g. Thiede, 1979; Shulmeister et al., 2004), high concentrations of kaolinite off the east coast of Australia between 0 – 30°S (Griffin et al., 1968) supports our interpretation. This proposed dominance of meridional winds may be due to an equator-ward movement of Rossby Waves, resulting in the penetration of low pressure systems and associated cold fronts further north into the Australian continent (Hurrell et al., 1998).

5.2.2 Periods of decreased aridity

During periods of decreased aridity (as indicated by the record of aeolian sedimentation), such as 42 – 32 ka, 30 – 24 ka, 21 – 7 ka and 2.5 – 0 ka, the playa surface of Lake Frome and the river floodplains of central South Australia appear to have been the dominant dust source areas for NSI (Figure 4 (b)). The dominance of dust from Lake Frome during these periods corresponds well with interpreted increased aridity, aeolian activity and dune building in the region (Fitzsimmons et al., 2007).

Unlike during phases of increased aridity, a wide range of secondary source areas appear to have been active, including the Diamantina River floodplains of the Channel Country, Lake Eyre, the dunes of the Strzelecki Desert, the floodplains of the MDB, the palaeo-dunes of Eyre Peninsula and the Paroo River floodplains of southwest Queensland. The extensive range of influential dust source areas may be a function of increased effective precipitation leading to increased sediment supply for subsequent deflation and transport by the wind.

The dominance of more northern source areas, such as the Channel Country and southwest Queensland, suggests that dust transport in eastern Australia during periods of decreased aridity occurred under a regime of an intensified zonal westerly circulation. However, the humid conditions locally on NSI, inferred from the pollen record, indicates that the southeasterly winds coming off the Tasman Sea were more influential on the coastal climate than the zonal westerly winds.

6.0 Conclusions

The multiproxy record from NCL presented here provides the first high resolution record of aeolian dust deposition for Australia. In addition to a record of palaeoclimatic and palaeoenvironmental variability for the past 42 kyr, dust transport pathways for eastern Australia have been reconstructed using ICP-MS trace element analysis and dust provenancing.

There is a clear distinction in atmospheric circulation patterns between periods of increased aridity and periods of decreased aridity in eastern Australia. Periods of increased aridity are characterised by dust input from the floodplains of the MDB and central South Australia, which is interpreted as signifying an intensification of meridional southwesterly winds. Such conditions may be a result of an equator-ward shift in the position of the Rossby Waves, allowing low pressure systems and associated cold fronts to have greater influence over the Australian continent.

Conversely, periods of decreased dust deposition in the NCL record are thought to signify decreased aridity in eastern Australia. Dominant dust source areas during these periods are Lake Frome and central South Australia, with input from a wide range of secondary source areas including the Channel Country and southwest Queensland. Dust input to NSI from these more northern source areas suggests an intensification of zonal westerly winds, although evidence for humid conditions on NSI indicates that moist southeasterly winds coming off the Tasman Sea had greater influence on the climate of coastal southeast Queensland.

Overall, it appears that organic-rich lake sediments provide an excellent archive of aeolian dust deposits, pollen and charcoal, allowing high resolution multiproxy records of palaeoclimatic and palaeoenvironmental variability to be reconstructed.

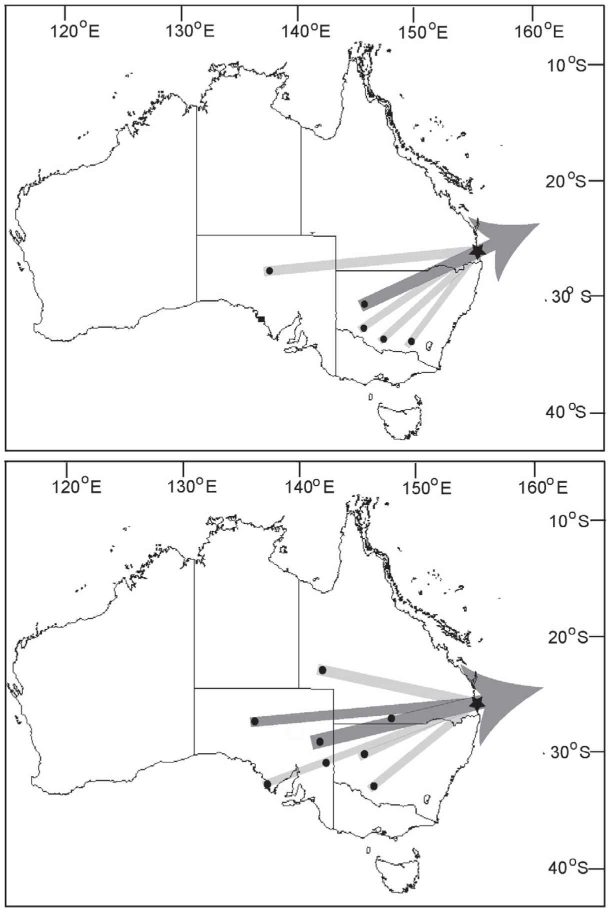

Figure 4: Dust transport pathway models for NSI during periods of (a) increased aridity (32 – 30 ka, 24 – 21 ka and 7 – 2.5 ka), and (b) decreased aridity (42 – 32 ka, 30 – 24 ka, 21 – 7 ka and 2.5 – 0 ka). Location of NSI represented by the star symbol.

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