# A Holocene palaeoenvironmental reconstruction of Lake Albert, South Australia: an isotopic, geochemical and palynological interpretation

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## Abstract

Lake Albert, situated at the terminus of the River Murray, forms part of the diverse and ecologically important Lower Lakes system of shallow lakes and wetlands. Past and current environmental change within Lake Albert and surrounding areas is currently a topical issue in political and public debate, centering on the heavy regulation of River Murray flows and other anthropogenic impacts, as well as future sustainability and remediation. This study presents the first detailed palaeoenvironmental reconstruction of Lake Albert, based on stable isotope and palynological analysis. Two main cores were analysed, one from the middle of the lake (Site 1) and the other close to the Narrows (Site 2). The sedimentary records from these cores date to 7195 ± 35 yr BP and 7305 ± 35 yr BP respectively, indicating a complete record of lacustrine sedimentation at both sites. Lacustrine clayey-mud facies show an upward decreasing trend in total organic carbon values and increasing carbonate content, indicating general decreases in water depth and productivity with lake evolution, as well as increasing lake isolation. Palynological analysis indicates predominantly freshwater eutrophic conditions, supported by C/N ratios. However, $\delta^{13}C$ concentrations are heavier than typical lake organic matter dominated by algae (range = -18.3 to -26.9‰). This is most likely explained by an increasingly heavy $\delta^{13}C$ composition of dissolved inorganic carbonate input into Lake Albert. Heavy sources of $\delta^{13}C$ in DIC in Lake Albert are most likely as a result of higher input of carbon from remineralised $C_4$ plants, supported by the significant presence of $C_4$ grasses within the lake catchment and little variation in C/N ratios from algal sources. The presence of freshwater pollen and algae, and the absence of dinoflagellates in pollen assemblages indicate that Lake Albert has never been directly connected to the Coorong Lagoon. Major depositional and geochemical changes have occurred within the upper sediments of Lake Albert as a result of anthropogenic impacts, associated with greatly increased sedimentation rates. Increased knowledge in the natural palaeoenvironmental evolution of Lake Albert indicates that, of the three major remediation options proposed by the Federal Senate in 2008, the current remediation program within Lake Albert, which allows it to dry out and become an ephemeral system, is the most sustainable solution currently available.

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## 1. Introduction

Lake systems are sensitive to environmental change, and their sediments provide a record of the evolution of regional climate, vegetation and hydrology (Williamson *et al.* 2008). As such, the study of lake sediments can provide a useful record of past environmental change, particularly in the context of distinguishing long-term natural variability from the more recent influence of human activity. A number of biogeochemical proxies have been utilised to define various palaeoenvironmental parameters within lake systems (Meyers 1997). Of these, variations in $\delta^{13}C$ and $\delta^{15}N$, as well as C/N ratios, have been shown to be useful in determining sources of sedimentary organic matter within aquatic systems (Meyers & Ishiwatari 1993; Meyers 1997; Lamb *et al.* 2006). Palynological analysis has also been established as a useful proxy for palaeovegetation and palaeoenvironmental change (Seppä & Bennett 2003). Used in conjunction, these two complementary methods provide a detailed and comprehensive history of environmental change (Malamud-Roam & Ingram 2004). Within the Lower Murray region, past and current environmental change is currently a topical issue in political and public debate, centering on the heavy abstraction and modification of River Murray flows and other anthropogenic impacts, as well as sustainability and remediation (Senate Committee on Rural and Regional Affairs and Transport 2008).

Lake Albert is situated at the terminus of the River Murray, and with the larger adjacent Lake Alexandrina, forms the Lower Lakes system of shallow lakes and wetlands (Figure 1). The Lower Lakes are a diverse and important ecosystem and, along with the Coorong Lagoon, were recognised as a wetland of international importance by the Ramsar Convention in 1985 (Phillips & Muller 2006). However, the Lower Lakes have been significantly affected by the substantial regulation of the Murray-Darling Basin. Diversions of more than 80% of the mean annual discharge, primarily for irrigation purposes, have resulted in vastly reduced flows reaching the Lower Lakes (Gell *et al.* 2009) and unprecedented drops in lake levels, which are currently at the lowest ever recorded (Senate Committee on Rural and Regional Affairs and Transport 2008). Furthermore, a series of five barrages built between the Lower Lakes and the Coorong in the 1930s (Figure 2), initially installed for navigation purposes, has further altered the lake system, controlling the exchange of water between the Coorong and Lower Lakes, and retaining freshwater within Lakes Albert and Alexandrina (Sim & Muller 2004).

Until recently, research on the Lower Murray area has focussed primarily on the Coorong, and secondarily on Lake Alexandrina. Lake Albert has been regarded only as a smaller analogue. However, Lake Albert's ecosystem is unique because, while Lake Alexandrina is linked to the Coorong, Lake Albert is a terminal lake. Furthermore, studies of the Lower Lakes have primarily addressed the deteriorated state of the lake system. Many studies concentrate on the effects of regulation, such as changes in hydrological inputs to the Lower Lakes (Walker 1985; Walker & Jessup 1992; Webster 2005; Walker 2006) and comparisons of environmental conditions of the Lower Murray region before and after European settlement (Fluin *et al.* 2007; Gell *et al.* 2009; Krull *et al.* 2009). Numerous government reports have also been published detailing the state of the Lower Lakes, and addressing the issue of sustainability and remediation (Department for Environment and Heritage 2000; Department of Water Land and Biodiversity Conservation 2006; Phillips & Muller 2006; Senate Committee on Rural and Regional Affairs and Transport 2008). A 2008 Federal Senate inquiry (Senate Committee on Rural and Regional Affairs and Transport 2008) identified three basic options with which to address the degraded state of the Lower Lakes: increases in freshwater flows; admission of seawater into Lakes Albert and Alexandrina; or allowing Lake Albert to dry out and become an ephemeral system. The latter alternative was adopted in 2009.

However, when addressing the issue of future remediation, it is also important to consider the natural state prior to European impact (Brown 2002). A number of studies have attempted palaeoenvironmental reconstructions of Lake Alexandrina (Barnett 1993, 1994; Fluin *et al.* 2007), as well as identifying more specific changes within the lake, such as changes in the isotopic composition of organic matter (Smith 1996; Herczeg *et al.* 2001), sedimentation (Shuttleworth *et al.* 2005), and salinity and nutrient composition (Williams & Buckney 1976). However, little research has been conducted on Lake Albert (Gloster 1996). This paper aims to present a detailed palaeoenvironmental reconstruction of Lake Albert, based on stable isotope and palynological analysis. Future developments and possible scenarios regarding the deteriorated state of the Lower Murray region will also be discussed in light of these new findings.

## 2. Geological setting

### *2.1. Geology of the Murray-Darling Basin*

The Murray-Darling Basin originated during the early Tertiary, subsequent to the breakup of Australia and Antarctica (Kingham 1998; Walker 2006), and has been subsiding at an average rate of 0.02 mm $yr^{-1}$ (Bourman *et al.* 2000). Neoproterozoic to Cambrian metasediments, Devonian to Late Carboniferous basinal sediments, and Permian glacial deposits underlie the western Murray Basin, including the Lower Lakes region (Brown & Stephenson 1989). Throughout the Tertiary, deposition of sediments within the western Murray Basin was governed by base level changes related to fluctuations in sea-level (Bourman *et al.* 2000). Early Tertiary carbonaceous sand and silt deposits, associated with minor low rank coals, indicate a predominantly paralic depositional setting during the initial stages of basin formation (Firman 1973). Subsequent depositional cycles between marine limestones and marls, and aeolian calcarenites and fluvio-lacustrine carbonaceous sands and silts indicate distinct transgressive-regressive sequences throughout the Tertiary (Barnett 1994; Kingham 1998).

Climatic variations and eustatic fluctuations continued into the Quaternary (Barnett 1994). A transition to predominantly coastal deposits in the late Quaternary coincides with the formation of the Coorong and Lower Lakes and marks the beginning of the current depositional system within the western Murray Basin. This region also records a period of Quaternary intraplate volcanism and magma intrusion in the Mount Burr-Mount Gambier volcanic province (Murray-Wallace *et al.* 2001), resulting in a subsequent period of neotectonism in the western Murray Basin, resulting in long-term uplift rates in the Coorong and Lower Lakes of between 0.07 mm $yr^{-1}$ (Murray-Wallace 2002) and 0.14 mm $yr^{-1}$ (Bourman *et al.* 2000).

### *2.2. Local geology of the Lower Lakes*

In the Lower Lakes region outcropping sediments are primarily bioclastic carbonaceous barrier deposits, aeolian dunes and sandy to muddy lagoonal deposits (Barnett 1994; Murray-Wallace *et al.* 2001). Underlying the Lower Murray area is the Pleistocene Coomandook Formation (Barnett 1994), which comprises shallow marine fossiliferous limestone and calcareous sands (Firman 1973). Overlying the Coomandook Formation are the aeolian bioclastic sands and calcarenites of the Bridgewater Formation (Firman 1973), preserved as calcretised shoreline barrier and dune deposits and associated back-barrier lagoon facies (Bourman *et al.* 2000; Murray-Wallace 2002). The uppermost formation found in the Lower Lakes sequence is the St. Kilda Formation, of which siliceous muds and sands are still being deposited (Barnett 1994). Barnett (1993) documented nine separate sedimentary units within the St. Kilda Formation in a number of cores from Lake Alexandrina. Sedimentation within the Lower Lakes has permanently altered due to river regulation and barrage construction across the Murray Mouth (Barnett 1993; Shuttleworth *et al.* 2005).

Radiocarbon dating indicates the current Lower Murray and Murray Mouth system formed between 8000 and 7000 yr BP (Fluin *et al.* 2007). During the Last Glacial Maximum the region that now comprises the Lower Lakes was located inland as a result of sea-level lowstand (Barnett 1994). Subsequent sea-level rise accompanying deglaciation resulted in northward migration of the Murray Mouth until it stabilised near to its present position *ca*. 7000 yr BP (Barnett 1994; Bourman 1998). Barnett (1994) and Fluin *et al.* (2007) both used palaeolimnological analysis to reconstruct palaeoenvironmental conditions within Lake Alexandrina. From *ca*. 6000 yr BP diatom assemblages indicate a greater freshwater influence in the lakes (Barnett 1994), which may indicate stabilisation of continuous dune barriers forming a system of similar appearance to the contemporary form of Lake Alexandrina. Evidence of fringing, swampy lake flats around Lake Alexandrina may also support the hypothesis that the lake was a more extensive body of water prior to barrier stabilisation (Cann *et al.* 2000). Continual increases in the influence of freshwater flows into Lake Alexandrina are recorded in the diatom fauna (Barnett 1994; Fluin *et al.* 2007). However, the greatest change to the diatom community is recorded in the upper sediments of Lake Alexandrina, coincident with European settlement (Fluin *et al.* 2007). Gloster (1996) attempted an environmental history of Lake Albert based on sedimentology, which indicates the sedimentary history of Lake Albert has been continually governed by fluctuating sea-levels and climate.

## 3. Hydrology

### *3.1. Flow patterns*

The hydrology of the Lower Murray is primarily determined by upstream flows from the Murray-Darling catchment (Walker 2006). The River Murray contributes up to 90% of all discharge (Walker 2006) from inputs of rain and snow in the southern and eastern highlands of Victoria and New South Wales (Newman 1998; Gell *et al.* 2007). The remaining 10% of water discharged to the Lower Murray is contributed by the Darling River (Walker 2006), sourcing surface flows from tropical highlands in NSW and Queensland (Gell *et al.* 2007). The flow regime of the River Murray is naturally variable, due to annually inconsistent system inputs controlled by climatic variations. This variability is compounded by evaporation and the El Niño Southern Oscillation, which affects the Basin (McGlone *et al.* 1992; Newman 1998; Walker 2006). Natural flows to the Murray Mouth peak from late winter and throughout spring; minimum flows occur in late summer (Walker 1985; Newman 1998). It has been estimated that at least half of these flows reached the Murray Mouth under natural conditions, even given substantial losses to seepage and evaporation (Walker 2006). Other inflows to the Lower Lakes include water from tributary streams draining the Mount Lofty Ranges, local rainfall and runoff (Phillips & Muller 2006). Locally, Lake Alexandrina is the primary source of freshwater inflows to Lake Albert. Lake Albert has no flow-through connection to the Coorong or the Southern Ocean (Phillips & Muller 2006).

The hydraulic behaviour of the Lower Lakes has changed markedly with the introduction of regulation. Water levels within the Murray and Lower Lakes are typically kept relatively static as a result of extensive weirs and barrages. This has disrupted the natural rising and falling cycles and flood pulses within the Murray River system (Walker 2006). The barrages also act to maintain a freshwater environment within the Lower Lakes (Newman 1998). Typically, lake levels of Lake Albert are surcharged to 0.85 m Australian height datum (AHD), allowing for evaporation throughout summer, generally resulting in an average minimum of 0.60 m AHD (Department for Environment and Heritage 2000). These levels are often lower in drought years and currently (Nov, 2009) lake levels are below sea level (Senate Committee on Rural and Regional Affairs and Transport 2008) (Figure 3).

### *3.2. Runoff, groundwater and tidal influences*

Although the Murray River is the major contributor to flows into the Lower Lakes, it is also important to consider runoff, groundwater and tidal influences. The estimated average annual runoff into all rivers within the Murray-Darling Basin is ~23,609 GL or approximately 4% of average annual rainfall. It is thought that over half of this would have reached the Southern Ocean under natural conditions (Walker 2006; Senate Committee on Rural and Regional Affairs and Transport 2008). Furthermore, runoff from the Mount Lofty Ranges is estimated to contribute an average of more than 100 GL in runoff per year (Senate Committee on Rural and Regional Affairs and Transport 2008). There is no major surface runoff contributed directly from regions surrounding the Lower Lakes (Cann *et al.* 2000). In recent times extremely dry conditions associated with ongoing drought have resulted in comparatively low discharge into the Lower Lakes (Senate Committee on Rural and Regional Affairs and Transport 2008).

Groundwater is also an important input into the Coorong and Lower Lakes system, and primarily flows westward from a recharge zone on the Dundas Plateau. Two major aquifer systems have been identified in the region, the shallow unconfined Murray Group Limestone and the deeper confined Renmark Group sands (Taffs 2001; Haese *et al.* 2008). Although a precise value for groundwater discharge into the area is unknown, evidence indicates that groundwater readily discharges into the Lower Lakes and inputs may have been much greater in the past (Haese *et al.* 2008).

Any previous tidal or marine influence within Lakes Albert and Alexandrina ceased with the construction of barrages, although naturally estuarine conditions have been predicted for Lake Alexandrina (Newman 1998). Lake Albert currently has no direct access to the sea. Bourman *et al.* (2000) have proposed the possibility of a previously existing opening between Lake Albert to the Coorong Lagoon, although little evidence is used to support this.

## 4. Holocene climatic variability

Climate is an important driver in the formation and behaviour of lakes and wetlands (Phillips & Muller 2006). Currently, Lake Albert lies just outside the Australian arid zone (Hesse *et al.* 2004) and has a typically Mediterranean climate, with mild, wet winters and warm to hot summers (D'Costa & Kershaw 1997). Climatic fluctuations have persisted throughout the Holocene in southern Australia, although palaeoenvironmental records indicate these changes were of lower magnitude than the larger glacial-interglacial cycles of the late Pleistocene (McGlone *et al.* 1992; Dodson 2001; Wanner *et al.* 2008). Evidence of forest expansion and high lake levels in the early to mid-Holocene indicate regional warming and relatively high rainfall until *ca.*

6000 yr BP (McGlone *et al.* 1992; Mee *et al.* 2007). Holocene marine transgression peaked at *ca*. 6000 yr BP, coinciding with a general shift towards arid conditions (Mee *et al.* 2007). A significant trend towards drier and colder conditions is recorded at *ca*. 5000 yr BP (Hesse *et al.* 2004; Mee *et al.* 2007).

## 5. Methods

### *5.1. Core collection and sampling techniques*

Sediment cores were collected from two sites in Lake Albert, one in the centre of the Lake and another closer to the Narrows (Figure 1). Water depth at both sites was extremely shallow at the time of coring (approximately 40 cm). Two cores were collected from each site. In order to extract a continuous and extensive depositional record, the first was cored until the sediment resisted penetration. The second core was comparatively shorter and used for more detailed analysis of the upper lake sediments. A 298 cm core (LA1) and a 120 cm core (LA1-Pb) were collected from Site 1. Cores from Site 2 measured 667 cm (LA2) and 85 cm (LA2-Pb). Cores LA1 and LA2 were thought to be long enough to document a significant part of Lake Albert's environmental history based on previous studies (Gloster 1996). Cores were collected using a lightweight modified Livingston piston corer with a 50 mm stainless steel core barrel, with the exception of LA1-Pb, which was taken with a plugged 80 mm polyvinyl chloride core barrel (Neale & Walker 1996).

Cores LA1 and LA2 were analysed for sediment characteristics, pollen, total carbon and nitrogen, carbon and nitrogen isotopes, trace element concentrations and diatoms. One cm thick slices were extracted for these analyses at 5 cm intervals for the top 50 cm of both cores and the lowermost 75 cm of LA1. The remaining sections of each core were sampled at 10 cm intervals. Approximately 0.5 g and 5 g of sediment was used for diatom analysis and pollen analysis, respectively, with the remaining sediment used for isotopic and elemental analysis. Organic material from both LA1 and LA2 was also opportunistically sampled and analysed for radiocarbon dates. The upper sections of cores LA1-Pb and LA2-Pb were analysed for $^{210}$Pb and $^{137}$Cs in an attempt to derive a chronology for the more recent sediments. Samples from LA1-Pb were taken as 1 cm slices at 3 cm intervals, while 2 cm thick slices were extracted from LA2-Pb at 4 cm intervals.

### *5.2. Loss on ignition*

Carbonate and total organic content (TOC) was determined using loss on ignition. Samples were initially dried at 100ºC to determine their dry weight, then ignited at 550ºC for two hours to determine TOC and finally combusted at 925ºC for four hours to determine total carbonate content. TOC was calculated as a guide for $\delta^{13}$C analysis. However, final TOC values were measured with a Fisons elemental analyser (EA)

### *5.3. Isotopic and elemental analysis*

Samples collected for isotopic analysis were initially dried at 100ºC, then acidified in 10% HCl for four hours to remove carbonates, and subsequently rinsed and dried. The sediment was then homogenised before being loaded into tin capsules. All samples were analysed in the University of Adelaide Stable Isotope Laboratory by continuous flow on a Fisons Optima gas source mass spectrometer, coupled to a Fisons EA. For $\delta^{13}$C and TOC analyses, approximately 10 mg of sediment was analysed, yielding between 100 and 200 µg of carbon. $\delta^{13}$C values were calibrated with a linear correction using house standards with isotopic compositions bracketing those of the samples. Carbon content was calculated by constructing a calibration curve between peak intensity and total C from standards with variable masses. A quality control standard with similar isotopic values to the samples was run regularly to ensure the reliability of the method. Additionally, every fourth sample was analysed twice in separate runs in order to ensure consistency between runs and establish typical reproducibility.

For $\delta^{15}N$ analyses, approximately 30 mg of sediment was analysed. $\delta^{15}N$ isotope data and total N content (which includes organic nitrogen and a minor fraction from silicate minerals in the sediment, mainly clay) were acquired by similar methods to the $\delta^{13}C$ analyses, except using a logarithmic correction based on at least three calibration standards.

### *5.4. Pollen analysis*

Palynology slides were prepared by Bruce Moffatt at the Santos Palynology Laboratory (Adelaide, SA, Australia). Ten samples were prepared in total, six from LA1 and four from LA2. Samples were chosen based on changes in the lithology of both cores. Samples were initially stored in distilled water to avoid oxidation. Samples were treated with 10% HCl for two hours to dissolve any carbonates and then rinsed through a 10 μm sieve, with the coarser fraction retained. 48% HF was then added to the samples for 30 minutes to remove silicates, which were then rinsed through an 80 μm sieve and a 10 μm sieve. Material ranging in size from 80 to 10 μm was then centrifuged twice, first in a 2.1 specific gravity float (sodium polytungsten) and then in a 1.65 specific gravity float. After the 2.1 organic float, material was washed with hot, cold and RO water through a 10 μm sieve, then dyed red and mounted onto slides. The same process was repeated after the 1.65 float.

Pollen samples were counted at a magnification of 300x on a Nikon Eclipse E600 microscope until a total of at least 100 dryland woody taxa had been identified. Taxa were identified with the assistance of Boyd (1992) and a number of online Australian pollen reference collections (Hopf *et al.* 2005; Haberle *et al.* 2007). Pollen taxa were expressed as relative abundances (percentages) of a pollen "sum" of dryland tree, shrub and herbaceous taxa. The taxa included in the pollen sum are those outlined in D'Costa and Kershaw (1997). These taxa are selected to be representative of regional vegetation patterns and are unlikely to be overrepresented due to their proximity to coring sites, as can occur with aquatic pollen types.

### *5.5. Radiometric dating*

A total of seven samples from LA1-Pb and eight samples from LA2-Pb were submitted to the CSIROs Radionuclide Laboratory (Canberra, ACT, Australia) for gamma spectroscopic $^{210}$Pb and $^{137}$Cs dating. A known weight of dry homogenised sediment was mixed with a polyester resin and formed into a known geometry. The radioactivity of the sample was measured using high-purity Germanium detectors according to the methods outlined in Wallbrink *et al.* (2002).

Two organic samples from LA1 and LA2 were submitted to the University of Waikato Radiocarbon Dating Laboratory (Hamilton, New Zealand) for AMS $^{14}$C radiocarbon dating. Woody material (presumably from terrestrial plants) was selected in preference to aquatic plants or homogenous sediments that are predominantly derived from decomposed aquatic plants, animals and algae. Material dominated by aquatic sources can provide misleading ages due to the "hard water effect" where carbon derived from dissolution of old carbonates of unknown age can be incorporated into the dated material, yielding much older dates (Shotton 1972). Such a problem has been documented in Lake Alexandrina (Fluin *et al.* 2007).

## 6. Lithostratigraphy and chronology

### *6.1. Lithological descriptions*

The lithology of cores LA1 and LA2 comprises a basal well-sorted, rounded sand and olive-grey (5Y 4/1 to 5Y 4/3; Munsell colour chart) clayey mud (Figure 4). The basal unit of core LA1 comprises a very dark greyish brown (10YR 3/2), medium- to coarse-grained, compositionally mature sand, with abundant plant roots. This sand unit abruptly changes colour at 283 cm to a lighter greyish brown (10YR 5/2), although compositionally it is relatively unchanged. There is an abrupt change at the top of the sandy facies (248 cm) to a transitional unit of alternating muddy sand and sandy mud laminae. Olive-grey clayey mud overlies this transitional unit and continues from 238 cm to the top of the core, with abundant dark organic laminations from 115 cm upwards.

Similarly, the basal lithology of core LA2 comprises well-sorted, well-rounded sand. The sand is fine- to medium-grained and contains some woody plant macrofossil material. Composition is nearly pure quartz, with minor feldspar, and appears slightly bimodal. The sandy unit grades to olive-grey mud at 620 cm. The base of the mud unit shows four successive and distinct lightening upwards bands grading from a sharp boundary. Abundant organic laminations occur between 230 and 122 cm. Sparse organic and light laminations also occur, although more sporadically. The uppermost section of core LA2 consists of grey-brown (2.5Y 4/2) clayey mud to silt.

### *6.2. Chronology*

Radiocarbon dating of plant macrofossil material in sediments from both cores LA1 and LA2 indicates that basal sediments at both sites date to the early Holocene, 7195 ± 35 yr BP and 7305 ± 35 yr BP, respectively (Table 1). From this, and disregarding sediment compaction, the average sedimentation rate (without taking into account anthropogenic impacts on sedimentation rates) at Site 2 is ~0.09 cm $yr^{-1}$, approximately double the average sedimentation rate at Site 1 (~0.04 cm $yr^{-1}$).

A $^{210}Pb$ chronology could not be developed for sediments in LA1, a situation not uncommon in riverine wetlands of the region (Gell *et al.* 2005). Excess $^{210}Pb$ is not detectable below 10 cm in LA1 (Figure 5). Furthermore, age estimates could not be derived above this point due to the small number of samples. However, the presence of $^{137}Cs$ in these sediments allows them to be positively identified as being younger than 1955 (corresponding to the first detectable values of the fallout radioisotope $^{137}Cs$ in sediment cores at this latitude) (Leslie & Hancock 2008). Based on the first appearance of $^{137}$Cs in LA2 it is clear that sediments from 12-14 cm were deposited after 1955. Excess $^{210}$Pb was detected below this. However, development of a precise chronology was again not possible due to the relatively small number of samples containing excess $^{210}$Pb. Despite this, the presence of detectable excess $^{210}$Pb (approximately 9 Bq/kg) at 25-26 cm, in combination with the short half life of this isotope (approximately 22.3 years) and its surface concentration of 58 Bq/kg, indicates that these sediments were deposited since 1900 (Appleby & Oldfield 1992; Cook & Gale 2005). Based on these chronological constraints in the upper sediments of LA1 and LA2, the minimum rate of sediment accumulation after European settlement is ~0.19 cm yr$^{-1}$ at Site 1 and ~0.24 cm yr$^{-1}$ at Site 2.

### *6.3. Stratigraphic correlation and depositional setting*

The general lithology at both sites is markedly similar. To improve stratigraphic correlation between cores LA1 and LA2, pollen samples were taken at similar changes in lithology in both cores (Figure 10). In general, pollen samples from the mud lithology show good correlation between Sites 1 and 2. However, samples from the basal sand unit of core LA1 show a markedly different pollen assemblage from a sample taken at the base of the mud lithology in core LA2, initially thought to be loosely correlative. AMS $^{14}$C dates from the basal sand lithologies of both cores indicate contemporaneous deposition (Table 1; Figure 10). Therefore, lithological units at both Sites 1 and 2 can be confidently stratigraphically correlated. Despite this correlation, differing pollen assemblages between the basal sands at Sites 1 and 2, suggest that depositional environments at both sites differed somewhat during the early stages of lake evolution.

Weak bimodality in the basal sand of core LA2, as well as the maturity and sorting of the sand, may indicate a predominantly aeolian origin (Turner & Makhlouf 2005). A similar environment may be inferred for the lighter, greyish brown sand in LA1. The presence of abundant root macrofossils in the underlying very dark greyish brown sand indicates abundance of macrophytes or terrestrial plants. However, despite abundant plant macrofossils, sand from both sites contained very low TOC (Figure 7). This may indicate deposition in an environment proximal to the lake system, possibly an aeolian dune system with plant colonisation (Talbot & Allen 1996; Cohen 2003). The base of the mud facies at both sites most likely corresponds to the final stabilisation of Lake Albert close to its current position. The presence of laminae suggests good preservation of sediments and little bioturbation (Cohen 2003). Coupled with relatively high organic matter in the mud facies (Figure 7), this indicates anoxic conditions for much of the lakes history (Talbot & Allen 1996). The clayey mud to silt lithology at the top of core LA2 may result from changes in sedimentation and sedimentation rates as a result of European settlement, and may be absent at Site 1 due to its distance from the Narrows in comparison to Site 2 (Figure 1).

## 7. Total carbonate, organic carbon and nitrogen contents

### *7.1. Total carbonate profiles*

Total carbonate (%) was calculated from loss on ignition. Taking into account sedimentation rates, the trend in % carbonate at Site 1 mirrors that of Site 2, although the latter shows a more distinct trend (Figure 6). At Site 2 carbonate values coincident with the sandy basal unit are very low (mean = 0.3%). Carbonate values increase to an average 5.9% from 605 to 355 cm, and then increase by another ~2% from 345 to 155 cm, to an average 7.7%. The highest average carbonate contents in the core occur between 145 and 25 cm (mean = 11.1%), above which carbonate values decrease. A similar trend occurs at Site 1, with mean values increasing from 0.3% to 6.7% at 235 cm and again increasing at 155 cm to 9.9%.

### *7.2. Total organic carbon and total nitrogen profiles*

Total organic carbon (TOC %) values are based on the more precise TOC contents calculated from EA analysis, as opposed to TOC calculated from LOI. TOC varies between 0.2 and 3.1% in sediments from Site 1 and 0.05 to 4.6% for Site 2 (Figure 7). Very low TOC values coincide with the sand facies in both cores, with mean TOC = 0.3 (range = 0.18-0.45%) and 0.2% (range = 0.04-0.60%) in LA1 and LA2 respectively. Clayey mud facies generally have higher TOC values, with a mean of 2.2% (range = 1.59-3.14%) in LA1 and 2.5% (range = 0.75-4.62%) in LA2. Site 2 shows a gradual decrease in TOC from the base of the clay facies to the top of the core. Site 1 shows a similar, although less distinct, trend.

At both sites total nitrogen (TN %) concentrations are 5 to 8 times lower than TOC (Figure 7), similar to results from Lake Alexandrina (Herczeg *et al.* 2001) and the Coorong (McKirdy *et al.* 2009). Due to this fact and the very low concentrations of TOC in the sand unit, TN concentrations for the sandy interval at the base of both cores could not be determined. Sites 1 and 2 have mean TN contents of 0.4 (range = 0.28-0.51%) and 0.3% (range = 0.09-0.47%) respectively. In LA2 TN shows a minor decreasing trend to 125 cm and then shows a general increasing trend towards the top of the core. TN contents in LA1 show considerable variability, with a gradually decreasing trend from the base of the core to 75 cm, followed by an increase in TN to a depth of 40 cm and then a general increase in TN to the top of the core. However, poor precision for the samples in LA1 make it difficult to define a clear trend.

### *7.3. Interpretation*

Very low TOC values in the basal facies at both sites indicate the sand units are very lean in organic matter (OM), either due to low OM input at this time or non-preservation. Low amounts of organic matter in this facies as a result of low OM input supports the hypothesis that these basal sands are aeolian sourced. The general decreasing trend of TOC from the base of the mud facies upwards suggests decreasing productivity throughout the history of Lake Albert. Despite very different rates of sediment accumulation, TOC values are similar at Site 1 and 2, indicating higher rates of deposition of OM and nutrients at Site 1. The upper 30 cm of Site 2 shows a change to an increasing TOC trend, most likely as a result of increased OM input corresponding with increased sedimentation rates. This is probably associated with accelerated erosion as a result of anthropogenic disturbances (Meyers 1997; Gell *et al.* 2009). Relatively high OM values in the mud facies supports the hypothesis of anoxic lake conditions (Meyers 1997). As the mud unit is relatively uniform, minor fluctuations in TOC throughout this facies most likely represents fluctuations in aquatic primary productivity (McKirdy *et al.* 2009).

Changes in TN values may indicate fluctuations in abundances of nitrogen-fixing phytoplankton (Howarth *et al.* 1988). However, it is more likely that fluctuations in TN are associated with local changes to runoff or sedimentation, as the primary source of N to most lakes is from N-fixing soil microbes (Meyers 1997). The increasing trend of carbonate values from the base of both cores indicates Lake Albert's chemistry became increasingly basic through its history. A significant decrease in carbonate in the top 25 cm of core LA2, may be consistent with increased sedimentation associated with European settlement or decreased ionic input, possibly associated with decreased groundwater discharge. Increasing isolation through the history of Lake Albert is also suggested by decreasing lake productivity (as indicated by decreasing TOC values) reflective of decreasing external nutrient input.

## 8. Carbon and nitrogen isotopic compositions

### *8.1. Carbon and nitrogen isotopic profiles*

Site 1 shows $\delta^{13}C$ concentrations that range from -18.3 to -23.7‰ (mean = -21.3‰), while values at Site 2 vary between -18.3 to -26.9 (mean = -22.2‰) (Figure 8). In comparison with Site 2, Site 1 is approximately 1‰ more enriched in $^{13}C$. In LA2 $\delta^{13}C$ values decrease from the base of the core to the top of the sand unit, above which $\delta^{13}C$ values gradually increase to a depth of 65 cm. $\delta^{13}C$ values show a ~1‰ decrease between 55 and 65 cm and remain relatively steady for the uppermost section of the core. The overall trend of LA1 also indicates a decrease in $\delta^{13}C$ concentrations at the top of the sandy interval followed by a gradual increase in isotopic values.

$\delta^{15}N$ concentrations range from 3.5 to 7.8‰ (mean = 5.2‰) at Site 1 and 2.5 to 11.2‰ (mean = 6.2‰) at Site 2 (Figure 8). Site 2 is approximately 1‰ more isotopically enriched. Site 1 shows a variable trend in $\delta^{15}N$. $\delta^{15}N$ values at Site 2 show a highly variable, although generally decreasing, trend to a depth of 465 cm and then become isotopically stable (mean = 5.2‰). $\delta^{15}N$ concentrations abruptly increase by ~3‰ at 225 cm and remain relatively stable (between 9.5 and 10.6‰). At a depth of 135 cm $\delta^{15}N$ abruptly decreases by ~3‰ and then shows a gradual increase to the top of the core. The trend between $\delta^{13}C$ and $\delta^{15}N$ is correlative at both sites, although $\delta^{15}N$ values show much larger variation, while comparable changes in $\delta^{13}C$ are more subdued.

### *8.2. C/N ratios*

C/N ratios at Site 1 vary between 3.7 and 9.0%, while C/N ratios at Site 2 range from 1.9 to 21.9% (Figure 8). C/N ratios at both sites show a general decreasing trend, with the exception of C/N ratios between 125 and 75 cm, which show an abrupt 10% increase. There is no distinct divergence in C/N ratios from samples pre-dating European impact to those post-European settlement. Cross plots of $\delta^{13}C$ vs C/N ratios indicate the major source of organic input into the lake system throughout its history has been algae (Figure 9). Samples from both sites typically plot in the marine realm.

### *8.3. Interpretation*

$\delta^{13}C$ values fall within the heavier isotopic range of aquatic sedimentary OM compositional fields (e.g.Lamb *et al.* 2006) and, in conjunction with low C/N ratios, suggest the major source of organic input into the lake system throughout its history has been marine algae (e.g. Meyers, 1999). Site 2 shows some variation from the marine algae field, with samples plotting along the boundary between the marine and freshwater algae fields, and others plotting closer to the $C_3$ and $C_4$ terrestrial plant fields. However, pollen analysis indicates a predominantly freshwater influence in Lake Albert, further supported by the absence of marine dinoflagellates (Figure 10). Furthermore, samples shown to be younger than 1955 (based on excess $^{210}Pb$), also plot within the typical marine realm (Figure 9). These samples are from an unquestionably freshwater environment, as they post-date construction of the barrages along the Murray Mouth, suggesting a more complex isotopic source signature (Meyers & Lallier-Vergès 1999). Nearly all samples from both cores plot within close range of one another, suggesting few major environmental changes since the stabilisation of Lake Albert. Thus, it seems likely that the $\delta^{13}C$ of Lake Albert's dissolved inorganic pool from which algae are obtaining their carbon is lower that than that of typical algae.

Relatively heavy $\delta^{13}C$ compositions are coincident with low TOC values in the basal sands at both sites, indicating higher dominance of terrestrial $C_4$ OM within these sediments. An abrupt decrease at the base of the mud lithology indicates a change to more eutrophic conditions, which is probably coincident with stabilisation of Lake Albert. A subsequent upwards increasing trend suggests an increasingly heavy $\delta^{13}C$ composition of dissolved inorganic carbon (DIC) input to Lake Albert. One possibility is an increase in dissolved carbonate from inflow of groundwater, which is reasonable considering the regional watershed composed of predominantly Pleistocene limestone (Firman 1973; Barnett 1994; Kingham 1998). However, the typically light $\delta^{13}C$ values of lacustrine algae are a result of the important contribution of carbon derived from the decay of soil organic matter to groundwater. Typically, this carbon is derived largely from $C_3$ plants, but in the Lower Lakes region, $C_4$ plants are an important source of OM, thus resulting in heavier $\delta^{13}C$ values. Heavier average $\delta^{13}C$ concentrations at Site 2 may indicate that terrestrial OM input into Lake Albert is partly sourced from inflows from Lake Alexandrina and the River Murray, as it is situated closer to the Narrows, in which it would reflect a higher input of $C_4$ organic matter.

The $\delta^{15}N$ ranges for Sites 1 and 2 coincide with both those of marine algae (3-13%) and terrestrial plants (-5-15%) (McKirdy *et al.* 2009). High $\delta^{15}N$ values between 225 and 135 cm in core LA2 may indicate increased algal productivity (Herczeg *et al.* 2001). The lowering of lake levels has also been associated with shifts towards higher $\delta^{15}N$ values, reduced input of $C_3$ terrestrial plant detritus, or reduced fluvial input of dissolved nitrate, resulting in higher algal uptake of $^{15}N$ (Meyers 1997; Meyers & Lallier-Vergès 1999). Subsequent declines in $\delta^{15}N$ may result from increasing nutrient enrichment in Lake Albert (Brenner *et al.* 1999), possibly associated with the closed hydrology of the lake. Increases in $\delta^{15}N$ at the top of the cores, particularly in core LA2, is most likely a result of increased input of nutrients from agricultural runoff.

## 9. Palynological analysis

### *9.1. Pollen diagrams*

Pollen analysis of all samples from Sites 1 and 2 indicates dominance by Casuarinaceae (Figure 10). Other woody taxa, such as *Eucalyptus*, occur sparsely and display no clear trend. Chenopodiaceae, Asteraceae and Cyperaceae are moderately represented throughout the cores. However, LA1 has higher relative abundances of Chenopodiaceae representation towards the base of the core, while LA2 shows an inverse trend. Poaceae abundance shows a similar inverse trend, with Poaceae values decreasing towards the base of LA1 and increasing towards the base of LA2. In both cores, all aquatic pollen is from freshwater taxa, although, generally, there is a low representation of aquatic pollen.

Large numbers of algal taxa *Pediastrum* and *Botryococcus* are also present in all samples apart from the uppermost in LA1 and lowermost sample in LA2. The lowermost sample in LA2 shows a ten-fold increase in spores and fern spores, and a five-fold increase in fungal spores, relative to other LA2 samples. The two lowermost samples of LA1 were taken from the dark brown sandy unit. Correspondingly, the lowermost sample of LA2 is taken just above the sand interval. However, these samples show greatly varying pollen assemblages between sand units.

### *9.2. Interpretation*

Palynological analysis of Lake Albert indicates a predominantly freshwater history for the system. All aquatic pollen recorded in Lake Albert is derived from freshwater taxa, although there is a low representation of aquatic pollen. Absence of dinoflagellates within the samples is also a useful indication of low marine input (Head 1996). This is further supported by the presence of algal taxa *Pediastrum* and *Botryococcus*, both indicators of freshwater to brackish conditions (Guy-Ohlson 1992; Batten 1996; Jankovská & Komárek 2000). The quantity of these algal taxa present in the samples far outweighs pollen, indicating predominantly eutrophic conditions (Dodson & Wilson 1975). Good preservation of *Botryococcus* also indicates deposition in undisturbed shallow waters (Guy-Ohlson 1992).

The absence of *Pediastrum* and *Botryococcus* in the uppermost sample of LA1 may indicate an increase in salinity or a decrease in water depth, resulting in increased breakage and negligible preservation. However, the absence of both taxa in the lowermost sample of LA2 may be evidence of an environment antecedent to the freshwater lake. This is further supported by a large percentage of spores in the lowermost LA2 sample. A higher number of spores establishes an increased presence of non-vascular plants and ferns, indicating a higher density of terrestrial plants. Ferns grow in the riparian zone and generally have poor dispersal, although they can be over-represented in lakes with significant river inputs (Wilmshurst & McGlone 2005). This indicates that sediments at Site 2 formed part of the riparian zone at this time and are evidence of a still-developing lake. Increased fern spores at the base of core LA2 may also indicate a more significant river connection between Lake Albert and Lake Alexandrina, and the River Murray during the preliminary stages of lake development, although this is not well-supported by the isotopic composition of the sediments.

The majority of taxa recorded throughout both cores are indicative of dry, arid conditions. Chenopodiaceae, Casuarinaceae and Haloragaceae are characteristic of arid environments (D'Costa & Kershaw 1997). Total aquatic taxa slightly decrease throughout both cores, which may indicate a general decline in water depth throughout time (Edney *et al.* 1990) and/or a gradual change to more eutrophic conditions (Reid *et al.* 2007).

## 10. Discussion

### *10.1. Lithology, radiometric dating and regional comparisons*

The lithological units described in cores LA1 and LA2 are consistent with the description of the St. Kilda Formation documented throughout the western Murray Basin (Barnett 1994). The basal sand lithology is most likely correlative with the dark grey, grey or black sand (Unit D) described in Lake Albert by Gloster (1996), while mud units correspond to the dark grey to green grey diatom rich mud (Unit F). Many cores from this earlier study intersected sapropelic sediments between Units D and F, although this unit was not present in either core from Site 1 or 2. Similar depositional facies, dominated by sand and mud units, are documented throughout the Lower Lakes area (Barnett 1993; Fluin *et al.* 2007). The commencement of deposition of the mud facies has been correlated to marine transgression and the final stabilisation of the Lower Lakes, whereas deposition of the underlying sands is attributed to pre-transgressional depositional conditions (Barnett 1994; Gloster 1996; Bourman 1998; Cann *et al.* 2000).

There is considerable correspondence between radiocarbon dates from Lake Albert and those of other Lower Murray sites. Sediments in Lake Albert, dated by Gloster (1996), show slightly younger radiocarbon ages (6650 yr BP at 265 cm and 6740 yr BP at 345 cm respectively) than this study. These ages are dated using sapropel material and support the older ages in this study, dated from macrofossil material in the underlying sand unit. Radiocarbon dates from Lake Alexandrina indicate basal core ages dating from the early- to mid-Holocene, with a maximum age of 7800 yr BP (Fluin *et al.* 2007). Radiocarbon dates from the Coorong also indicate similar ages (Fluin *et al.* 2007). AMS $^{14}C$ dates from this study support the currently accepted hypothesis that the Lower Lakes formed and stabilised in the early Holocene, between 8000 and 7000 yr BP, with Lake Albert closer to 7000 yr BP.

Sedimentation rates are based on limited AMS $^{14}C$ dates and the first appearance of excess $^{210}Pb$ and $^{137}Cs$ in the cores. Average sedimentation rates from these values have been calculated to compare generalised sedimentation rates between sites and rate changes associated with European settlement. However, sedimentation rates and the depositional history of Lake Albert would not have been as constant as suggested, nor do these estimates take into account compaction. Despite this, it is clear that sedimentation rates at Site 2 greatly exceeded those of Site 1, most likely due to closer proximity to the Narrows. It must also be noted that comparison between radiocarbon dates and the $^{210}Pb$ record involves comparisons across significantly different time intervals. As such, changes in sedimentation rates based on $^{14}C$ and $^{210}Pb$ may result from discrepancies between short- and long-term depositional events or from differences between the individual dating techniques (Sadler 1981). Despite this, increases in sedimentation associated with European settlement have been extensively documented along the River Murray (Barnett 1994; Leahy *et al.* 2005; Fluin *et al.* 2007; Gell *et al.* 2009). Therefore, it is likely that increased sedimentation rates at the top of cores LA1 and LA2 are, at least partially, a result of anthropogenically associated increases in erosion and sedimentation.

### *10.2. Reliability of pollen vs. carbon and nitrogen isotopic compositions*

Based solely on $\delta^{13}C$ vs. C/N ratio cross plots, the dominant source of OM input into Lake Albert appears to be marine algae. However, pollen analysis indicates this to be misleading, as pollen within the sediments reveals a predominantly freshwater history for Lake Albert, posing a major discrepancy between the two data sets. Therefore, it is important to assess the reliability of C and N isotopic compositions in Lake Albert, as well as pollen analysis of the lake sediments.

Pollen interpretation in Lake Albert must be treated with some precaution as the site has a connection with the River Murray (D'Costa & Kershaw 1997). However, evidence of increasing isolation of Lake Albert and its connection to Lake Alexandrina via a narrow channel suggests that a large proportion of the pollen is locally sourced. Furthermore, it has been shown that small lakes have a smaller pollen source area than larger ones (Seppä & Bennett 2003). Therefore, it can be assumed that pollen samples from Lake Albert are mostly representative of the vegetation within the lake and from its immediate watershed. Lake Albert can, therefore, be described as preserving a generally freshwater history, despite isotopically heavy $\delta\ ^{13}C$. This is further supported by the placement of known freshwater samples within the marine compositional field of $\delta^{13}C$ vs. C/N ratio cross plots, indicating $\delta^{13}C$ values in Lake Albert are complex and not representative of the major OM source.

There are a number of environmental factors that may affect the reliability of $\delta^{13}C$ and C/N as accurate recorders of the source OM in sediments. $\delta^{13}C$ values in Lake Albert are heavier than typical lake OM dominated by algae. A similar discrepancy has been recorded in other lake systems, including Swan Lake, Nebraska (Hassan *et al.* 1997) and a number of lakes in Florida (Brenner *et al.* 1999). As previously mentioned, this discrepancy can be attributed to a number of factors, such as increased $\delta^{13}C$ composition of the DIC pool as a result of higher input of carbon from remineralisation of $C_4$ plants or dissolved carbonate, or from higher input of detrital $C_4$ organic matter (Brenner *et al.* 1999; Meyers & Lallier-Vergès 1999). Heavy $\delta^{13}C$ values can also result from high export production of organic matter within the lake (Meyers & Ishiwatari 1993), although decreasing TOC and increasing carbonate in Lake Albert indicate that this is unlikely. The most likely source of heavy $\delta^{13}C$ in Lake Albert is increased $\delta^{13}C$

of the DIC pool, indicated by little variation in C/N ratios, which would be expected if a higher input of $C_4$ terrestrial organic matter was the cause. It has also been argued that C/N values are an unreliable source indicator at low TOC values (Sampei & Matsumoto 2001). However, Lake Albert sediments have a relatively high TOC content indicating C/N ratios can be considered reliable. Limited enrichment in $\delta^{15}N$ values indicates that alteration of $\delta^{13}C$ and $\delta^{15}N$ due to diagenesis of sediments is unlikely (Hassan *et al.* 1997), and $\delta^{15}N$ values in lake sediments are generally accepted as reliable indicators of OM sources (Meyers & Lallier-Vergès 1999).

### *10.3. Changes in source organic matter*

Organic matter in lake sediments is derived from a combination of autochthonous and allochthonous sources. Autochthonous organic matter is lake-derived, as a result of photosynthesis in phytoplankton and macrophytes and subsequent burial of these organisms and bacteria. Allochthonous OM is sourced from the surrounding catchment and includes soil organic matter and degraded terrestrial plant matter, such as leaves and grass (Herczeg *et al.* 2001; Lamb *et al.* 2006). Generally, the four main contributors of particulate and dissolved C and N within coastal lakes are marine algae, freshwater algae, and $C_3$ and $C_4$ plants (Meyers 1994; Lamb *et al.* 2006). The relative abundances of each of these OM sources and overall changes in their deposition determine variations in $\delta^{13}C$ and $\delta^{15}N$.

The dominant source of OM to sediments in Lake Albert appears to be freshwater algae. This has not changed significantly throughout the lakes history. Very high percentages of freshwater algae in pollen samples from cores LA1 and LA2 support this, as do C/N ratios of the sediments. Relatively heavy $\delta^{13}C$ values also indicate the importance of inputs of relatively heavier sources of DIC, most likely from remineralised $C_4$ terrestrial OM as opposed to marine algae. This is supported by pollen assemblages within Lake Albert, which indicate significant deposition of $C_4$ grasses (Chenopodiaceae, Poaceae) from the lake catchment and demonstrate a distinct absence of marine-sourced dinoflagellates. C/N ratios indicate no significant deviations from a eutrophic freshwater environment during lake evolution. This supports the hypothesis that Lake Albert has been relatively isolated throughout its history, as autochthonous sources tend to dominate lakes that are not regularly flushed by fresh or marine water (Lamb *et al.* 2006).

Studies of sediments from Lake Alexandrina (Herczeg *et al.* 2001) indicate a predominantly aquatic plant OM source. Heavy $\delta^{13}C$ values have also been derived from Lake Alexandrina, similar to those in Lake Albert, which has been attributed to increasing seawater intrusion and resultant increases in marine DIC ($\delta^{13}C = \sim 0‰$) (Herczeg *et al.* 2001). Palaeolimnological evidence from Lake Alexandrina also suggests estuarine conditions with a minor marine influence within the system, although overall conditions were predominantly freshwater (Barnett 1994; Fluin *et al.* 2007). This suggests that Lake Albert may have been relatively isolated from Lake Alexandrina throughout its history. The hydrology of Lake Albert may also be more significantly influenced by groundwater flows and runoff than first estimated, as lake conditions have remained relatively fresh, even during brackish periods in Lake Alexandrina. Furthermore, it is unlikely that a connection has ever existed between Lake Albert and the Coorong and Southern Ocean, as there is no evidence of significant marine incursions. This supports the hypothesis that the Lower Lakes system has evolved in isolation to the Coorong (Fluin *et al.* 2007).

### *10.4. Changes in geochemical character*

Overall, total carbonate, TOC, TN, and $\delta^{13}C$ and $\delta^{15}N$ show systematic and consistent trends throughout the history of Lake Albert. Decreasing TOC and increasing carbonate values show a general decrease in lake levels since the stabilisation of Lake Albert. This would result in associated decreases in primary productivity as a result of a less productive water column (Fluin *et al.* 2007). A minor decrease in the dominance of freshwater algae is also indicated by increasing $\delta^{13}C$ values, indicating a gradually increasing input of terrestrial $C_4$ plant matter. However, primary productivity within the lake is likely to have fluctuated within this general trend. High $\delta^{15}N$ values, associated with a distinct increase between 225 and 135 cm in core LA2, may indicate an increase in productivity possibly associated with the mid-Holocene wet phase described by Stanley and De Deckker (2002) and Fluin *et al.* (2007), although pollen assemblages in Lake Albert show little evidence of major climatic fluctuations.

Isotopic variation at the top of cores LA1 and LA2 may indicate changes in organic matter input, nutrient input and/or C and N cycling as a result of changes in land-use associated with European settlement. Decreases in $\delta^{13}C$ at the top of the cores, particularly evident at Site 2, may result from reduced input of $C_4$ organic matter as a result of heavy river regulation (Gell *et al.* 2007). Increases in TN in the upper sediments of Lake Albert correspond with recent large increases in net sedimentation rates documented in the Lower Lakes region (Barnett 1994). These higher nutrient inputs can be attributed to human-induced factors such as increased catchment surface erosion, river bank erosion and collapse, and soil surface sodicity (Walker 1985; Gell *et al.* 2009). Decreases in water quality and increased deposition of stored salts, associated with high sedimentation rates, are also evidenced by the absence of freshwater algae in the uppermost sediments at Site 1.

### *10.5. Pollen assemblages and regional comparisons*

The current vegetation surrounding Lake Albert is characterised by woodland to open forest, dominated by *Casuarina stricta* with a herbaceous understorey, and low shrubland dominated by Chenopodiaceous shrubs (Specht 1972). Submerged vegetation within Lake Albert is dominated by freshwater aquatic plants, including Cyperaceae and *Typha*, while semi-emergent vegetation includes Haloragaceae and Potamogetonaceae (Ganf 1998). The pollen record of Lake Albert indicates that surrounding vegetation has not significantly changed throughout the history of the lake. This suggests that dry, arid climatic conditions (indicated by dominant pollen taxa) have remained relatively stable throughout Lake Albert's evolution. The presence of taxa such as Chenopodiaceae and Poaceae indicate a significant presence of $C_4$ plants within Lake Albert's catchment area. Inverse trends in the abundance of these two taxa may be explained by the fact that both taxa are predominantly wind dispersed (Jongejans & Schippers 1999) and have experienced varied dispersal and deposition within Lake Albert.

Similar pollen taxa are recorded at other palynological sites throughout southeastern Australia (Kershaw & Bulman 1996; D'Costa & Kershaw 1997; Kershaw *et al.* 2004). However, trends in pollen assemblages at both sites in Lake Albert are somewhat unusual in that very high Casuarinaceae numbers and low *Eucalyptus* numbers are recorded in all samples throughout both cores. Conversely, a large number of palynological sites in southeast Australia show a clear change in sclerophyll vegetation during the Holocene from Casuarinaceae- to *Eucalyptus*-dominance (Crowley 1994a), including sites at the nearby Coorong (Black 2007). Declining Casuarinaceae numbers are also associated with an increase in Chenopodiaceae to more than 5% of the pollen sum (Crowley 1994b), a trend that is not reflected in the pollen record of Lake Albert. Crowley (1994a, b) suggests the decreasing Casuarinaceae trend may be a result of rising groundwater levels and increased soil salinisation. This may indicate that the proximate area around Lake Albert has not experienced significant increases in groundwater and soil salinity throughout the Holocene. The significant presence of salt-tolerant Chenopodiaceae pollen in Lake Albert may result from pollen dispersal from the saline Coorong. Conversely, similarly high Casuarinaceae and Chenopodiaceae numbers may indicate increased freshwater surface flow through the Lower Lakes and surrounding wetlands, similar to surface flow patterns documented by Taffs (2001) to the south of Lake Albert.

### *10.6. Palaeoenvironmental reconstruction of Lake Albert*

Combining lithological, chronological, geochemical and palynological data a palaeoenvironmental reconstruction of Lake Albert can be inferred. Prior to final development and stabilisation of Lake Albert, the area experienced deposition of sandy, aeolian sediments, which were colonised by macrophytes and/or terrestrial plants. The presence of freshwater pollen indicates that a connection to the River Murray and the precursor Lake Alexandrina was already established at this time. The presence of fern spores at Site 2 suggests this area may have formed part of the riparian zone during initial development of the lake, while freshwater algae recorded in the sand facies at Site 2 indicates the presence of freshwater. Therefore, it is likely that smaller, shallow bodies of freshwater existed between aeolian dunes.

Stabilisation of Lake Albert close to its present position occurred ~7000 yr BP. It was at this time that freshwater lacustrine conditions and deposition of the clayey-mud facies commenced. Geochemical evidence indicates generally decreasing water depths and increasing isolation of Lake Albert throughout time, resulting, at least in part, in declining lake productivity. However, periods of increases in algal productivity are indicated by jumps in $\delta^{15}N$, although other geochemical indicators show more subdued trends. Lake Albert has remained freshwater throughout its history. Therefore, there has never been a connection between Lake Albert, and the Coorong and Southern Ocean. While the dominant source of OM within Lake Albert has been freshwater algae, $\delta^{13}C$ and pollen data also record an increasingly significant input of remineralised terrestrial $C_4$ plant matter. Despite the shallow nature of Lake Albert, turbidity and wind currents do not seem to have significantly affected the water column, which was most likely stratified with basal anoxic conditions, as evidenced by abundant laminations and high TOC in the mud lithology.

The first evidence of European impact occurs at 10 cm at Site 1 and 26 cm at Site 2. The major changes to Lake Albert seem to be associated with increased sedimentation rates as a result of anthropogenically-induced changes in land-use and associated increases in erosion. Water diversions and irrigation have resulted in lowering lake levels, although do not seem to have significantly affected the lake chemistry (Herczeg *et al.* 2001).

### *10.7. Future remediation within Lake Albert*

When addressing the issue of future remediation, it is important to consider the natural state of the lake prior to European impact in order to implement the most sustainable and ecologically sensitive solution (Brown 2002; Gell *et al.* 2007). Therefore, the freshwater history of Lake Albert is an important consideration when assessing remediation options. Currently the government has adopted the policy of decommissioning Lake Albert by allowing it to dry out and become an ephemeral system. The two other options proposed to address the degraded state of the Lower Lakes are increases in freshwater flows or the admission of seawater into Lakes Albert and Alexandrina (Senate Committee on Rural and Regional Affairs and Transport 2008). Although significantly increasing freshwater flows is the most ecologically sound solution, this is unlikely, given the position of the NSW and Victorian governments, who dispute South Australia's right to an increase in allocated freshwater flows (Walker 2009). Considering Lake Albert's freshwater history, allowing seawater to inundate the Lower Lakes would have disastrous impacts on the current ecology and biodiversity within Lake Albert (Nielsen *et al.* 2003). Decommissioning Lake Albert also has associated problems with acid sulphate soils beneath Lake Albert posing a serious environmental issue, because the sulphuric acid that is generated as it dries may contaminate drainage and floodwaters (Dent & Pons 1995; Fitzpatrick *et al.* 2008). Bioremediation, including mulching and planting acid tolerant vegetation, or the application of lime to the soils are possible means of neutralisation and remediation of Lake Albert acid sulphate soils (Senate Committee on Rural and Regional Affairs and Transport 2008). Although there is no evidence that Lake Albert has acted as an ephemeral lake system, based on environmental factors alone the current remediation scheme is probably the most sustainable solution that is currently available and will result in substantial decreases in water lost to evaporation.

## 11. Conclusion

Although unexpectedly heavy $\delta^{13}C$ values initially suggest a marine source of OM within Lake Albert, palynological analysis and corresponding C/N ratios suggest a predominantly freshwater history for Lake Albert since its final stabilisation ~7000 yr BP. The dominant source of OM to sediments in Lake Albert is freshwater algae, with significant contributions of heavier sources of DIC, most likely from remineralised $C_4$ terrestrial OM. There has been no significant connection between Lake Albert, and the Coorong and Southern Ocean, throughout the lake's history, and may even have had limited hydrological interaction with Lake Alexandrina in the past, as brackish periods recorded within Lake Alexandrina are not recorded in Lake Albert. Groundwater discharge into Lake Albert may have played an important role in the lake hydrology and may have been higher than present. Geochemical and isotopic evidence indicates generally decreasing water depths, increasing lake isolation and associated declining primary productivity as the lake evolved. Major depositional and geochemical changes have occurred within the upper sediments of Lake Albert as a result of European settlement, particularly associated with increased erosion and sedimentation rates. Increased knowledge in the natural palaeoenvironmental evolution of Lake Albert indicates that based on environmental factors alone, of the three major remediation options proposed by the Federal Senate in 2008, the current remediation program within Lake Albert, which allows it to dry out and become an ephemeral system, is the most sustainable solution currently available.

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## 14. Figure captions

*Figure 1.* Location map of Lake Albert, South Australia, and core sampling sites. Four cores were collected from a total of two sampling locations (35º34.272’S 139º17.241’E and 35º38.473’S 139º18.257’E).

*Figure 2.* Location of barrages separating the Lower Lakes from the Coorong and Murray Mouth (Department for Environment and Heritage 2000). A series of five barrages were built between the Lower Lakes and the Coorong in the 1930s, resulting in maintenance of freshwater conditions in both Lakes Alexandrina and Albert. When sufficient water is available, the barrages act to keep lake levels surcharged to a maximum 0.85 m AHD.

*Figure 3.* Photographs from Lake Albert taken during core collection, 9 April 2009. Water depth was approximately 40 cm at the time of core collection. (a) Lake Albert jetty. (b) Sediment disturbance caused by boat propeller.

*Figure 4.* Lithostratigraphic logs of cores LA1 and LA2, Lake Albert.

*Figure 5.* $^{137}$Cs and $^{210}$Pb profiles from the upper sections of cores LA1-Pb and LA2-Pb, Lake Albert. The first appearance of the fallout radioisotope $^{137}$Cs results from weapons testing and is used to indicate sediment younger than 1955. The presence of excess $^{210}$Pb in these profiles corresponds to ~1900 or later.

*Figure 6.* Depth profile of total carbonate (%) from cores LA1 and LA2, Lake Albert.

*Figure 7.* Depth profiles of TOC (%) and TN (%) from cores LA1 and LA2, Lake Albert.

*Figure 8.* Depth profiles of $\delta^{13}$C, $\delta^{15}$N and C/N (%) ratios from cores LA1 and LA2, Lake Albert.

*Figure 9.* Cross plot of $\delta^{13}$C versus C/N (%) ratios from cores (a) LA1 and (b) LA2, Lake Albert, indicating potential sources of sedimentary organic matter and demonstrating the relationship between sedimentary organic matter deposited before

and after European settlement. Post-European settlement samples are defined based on presence of $^{137}$Cs and $^{210}$Pb. Samples that did not distinctly show excess $^{137}$Cs and $^{210}$Pb were placed in the pre-European category. Generalised compositional fields are modified from Lamb *et al.* (2006).

*Figure 10.* Pollen diagrams from cores (a) LA1 and (b) LA2, Lake Albert. Note variable scale. All taxa are expressed as percentages of the dryland pollen sum for each sample. AMS $^{14}$C dates are shown in uncalibrated year BP. $\delta^{13}$C and $\delta^{15}$N isotopic compositions, total organic carbon and total carbonates are also shown for comparison.

## 15. Table captions

*Table 1.* AMS $^{14}$C radiocarbon dates determined from woody macrofossil material from cores LA1 and LA2. Samples were dated at the University of Waikato Radiocarbon Dating Laboratory (Hamilton, New Zealand).

## 16. Figures

Figure 1

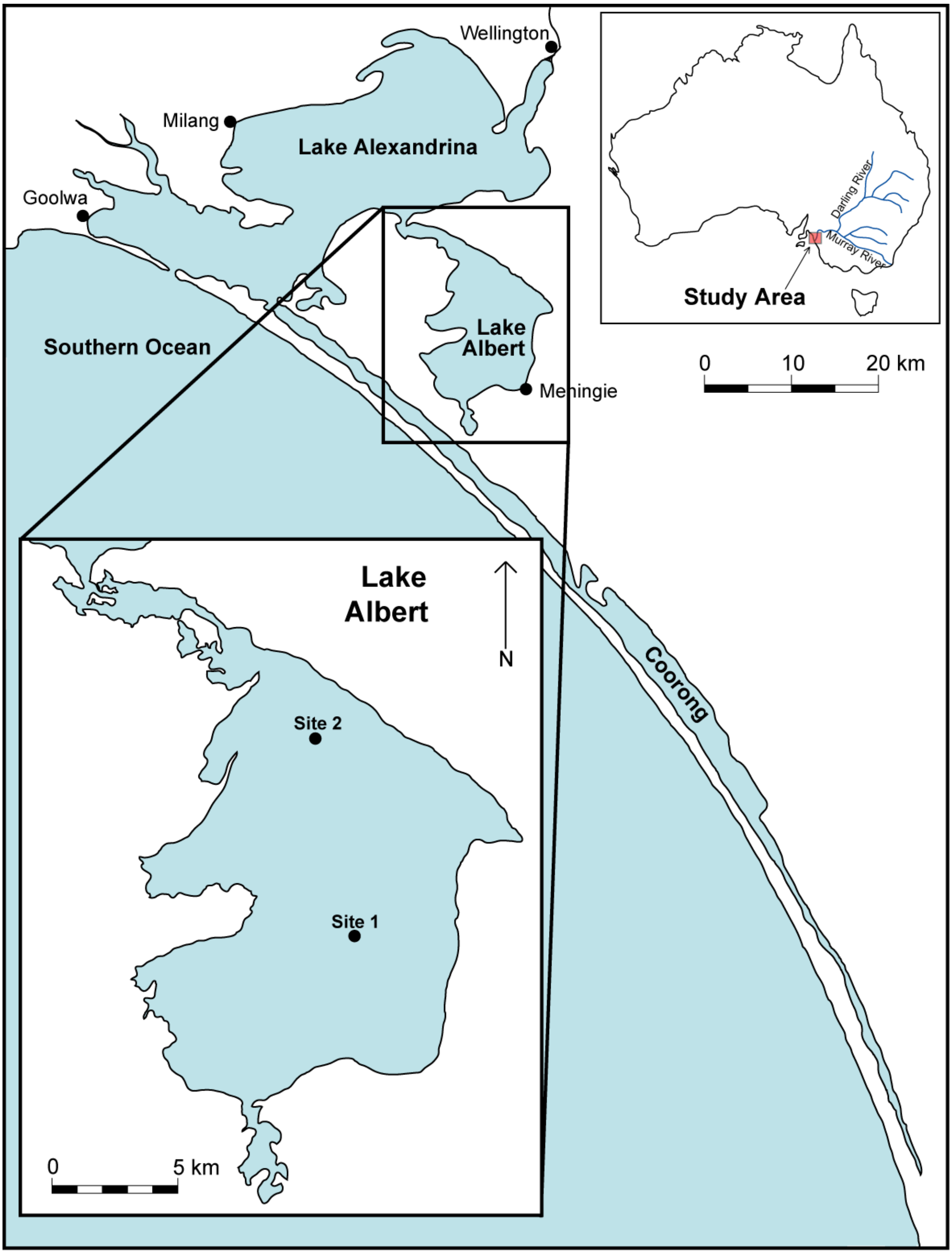


Figure 2

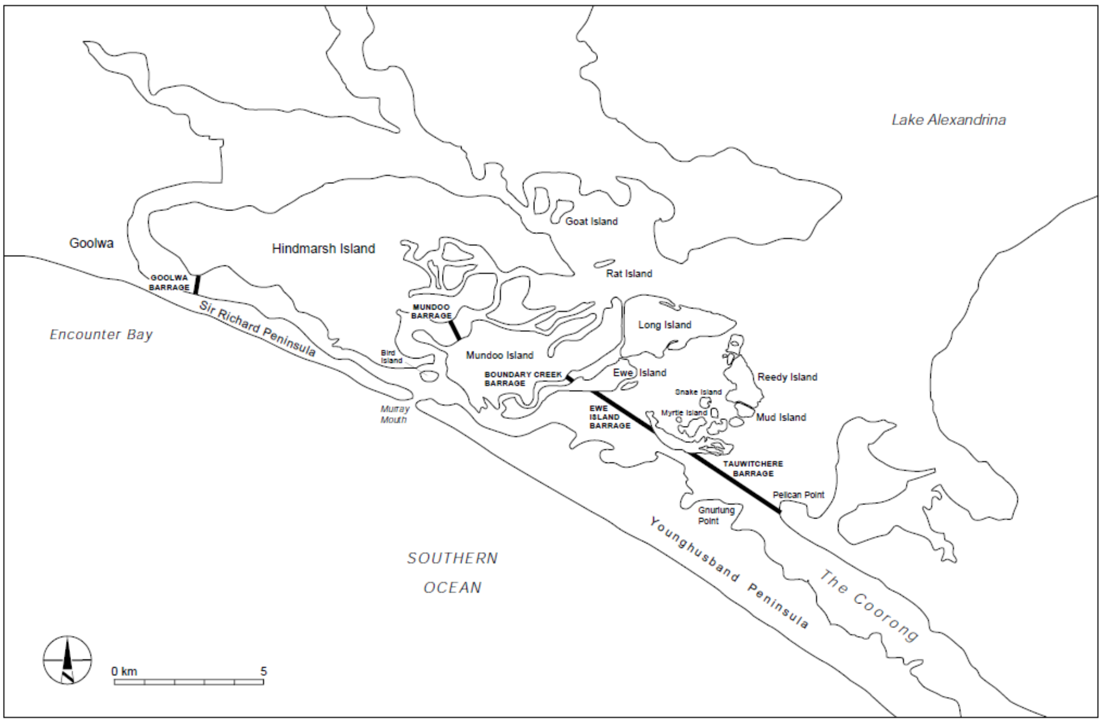


Figure 3

(a)

(b)

Figure 4

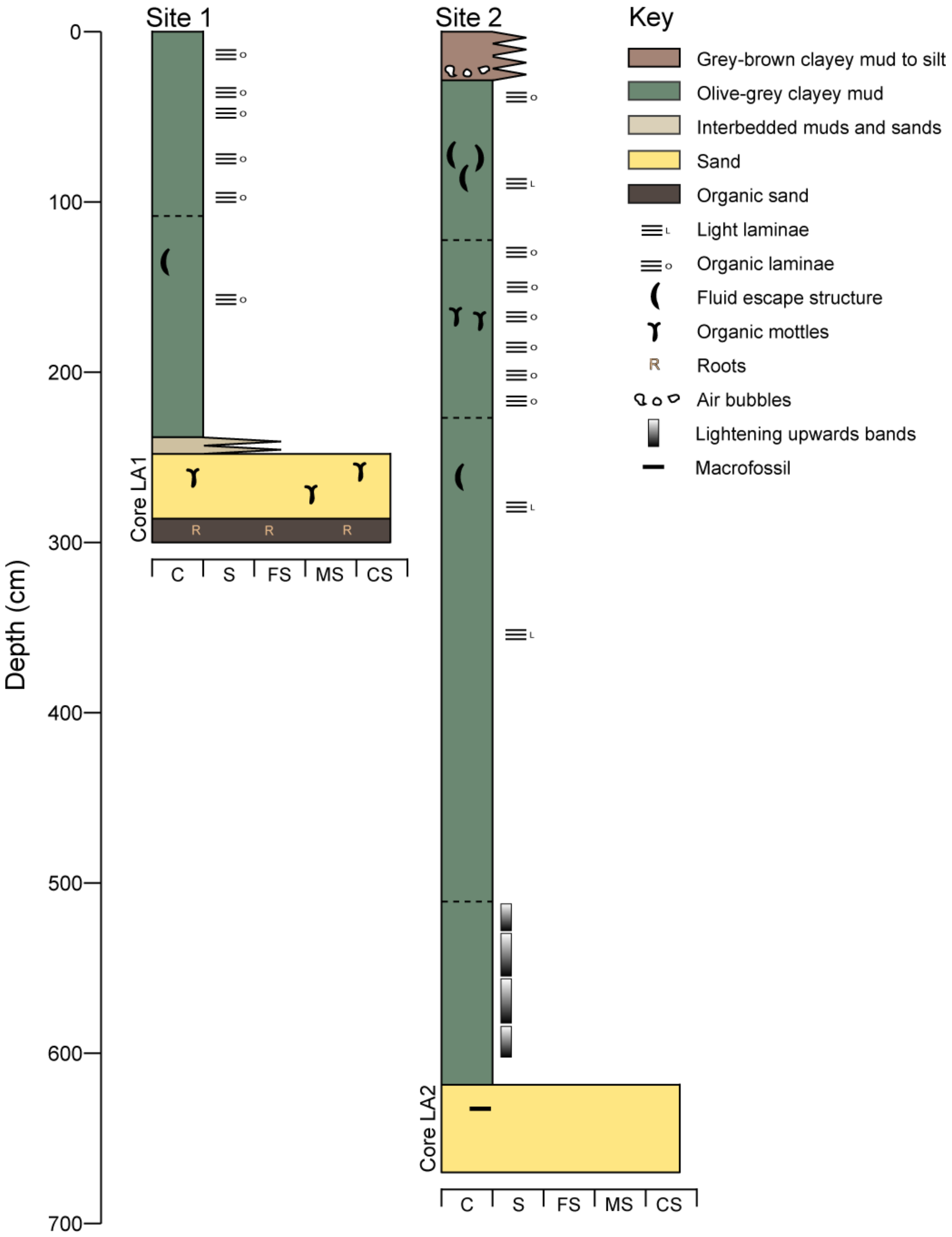
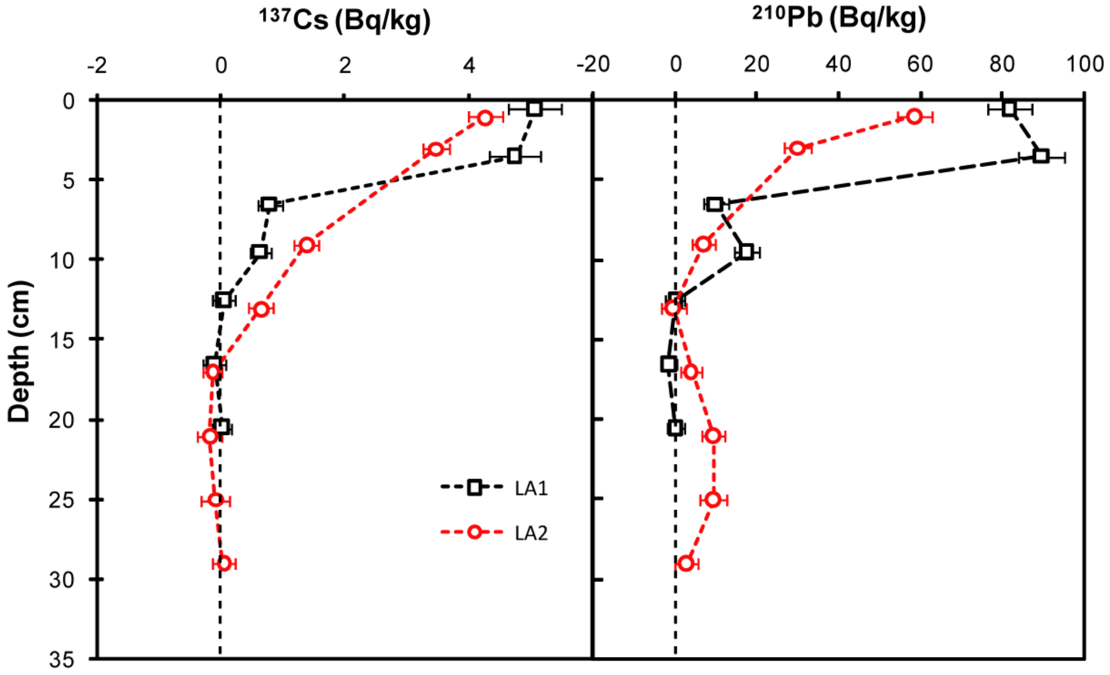

Site 1
Site 2
Key
Grey-brown clayey mud to silt
Olive-grey clayey mud
Interbedded muds and sands
Sand
Organic sand
Light laminae
Organic laminae
Fluid escape structure
Organic mottles
Roots
Air bubbles
Lightening upwards bands
Macrofossil
Depth (cm)
0
100
200
300
400
500
600
700
Core LA1
Core LA2
C
S
FS
MS
CS
R

Figure 5



$^{137}$Cs (Bq/kg)
$^{210}$Pb (Bq/kg)
-2
0
2
4
-20
0
20
40
60
80
100
0
5
10
15
20
25
30
35
Depth (cm)
LA1
LA2

Figure 6

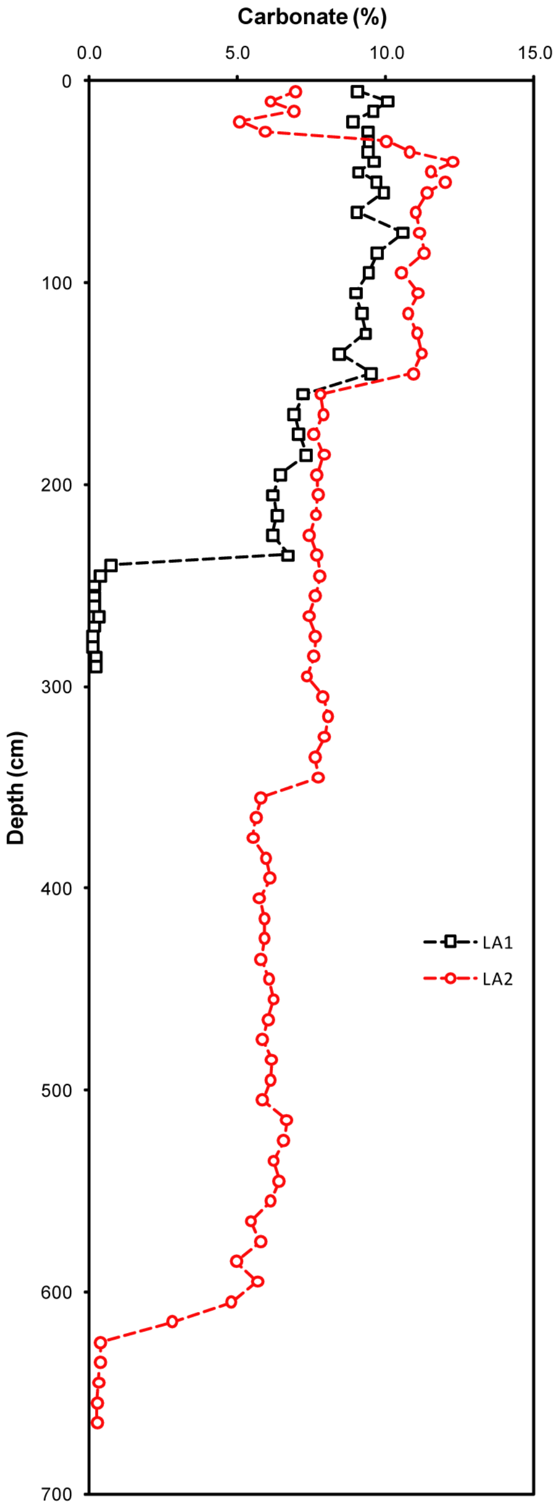

Carbonate (%)
0.0
5.0
10.0
15.0
0
100
200
300
400
500
600
700
Depth (cm)
LA1
LA2

Figure 7

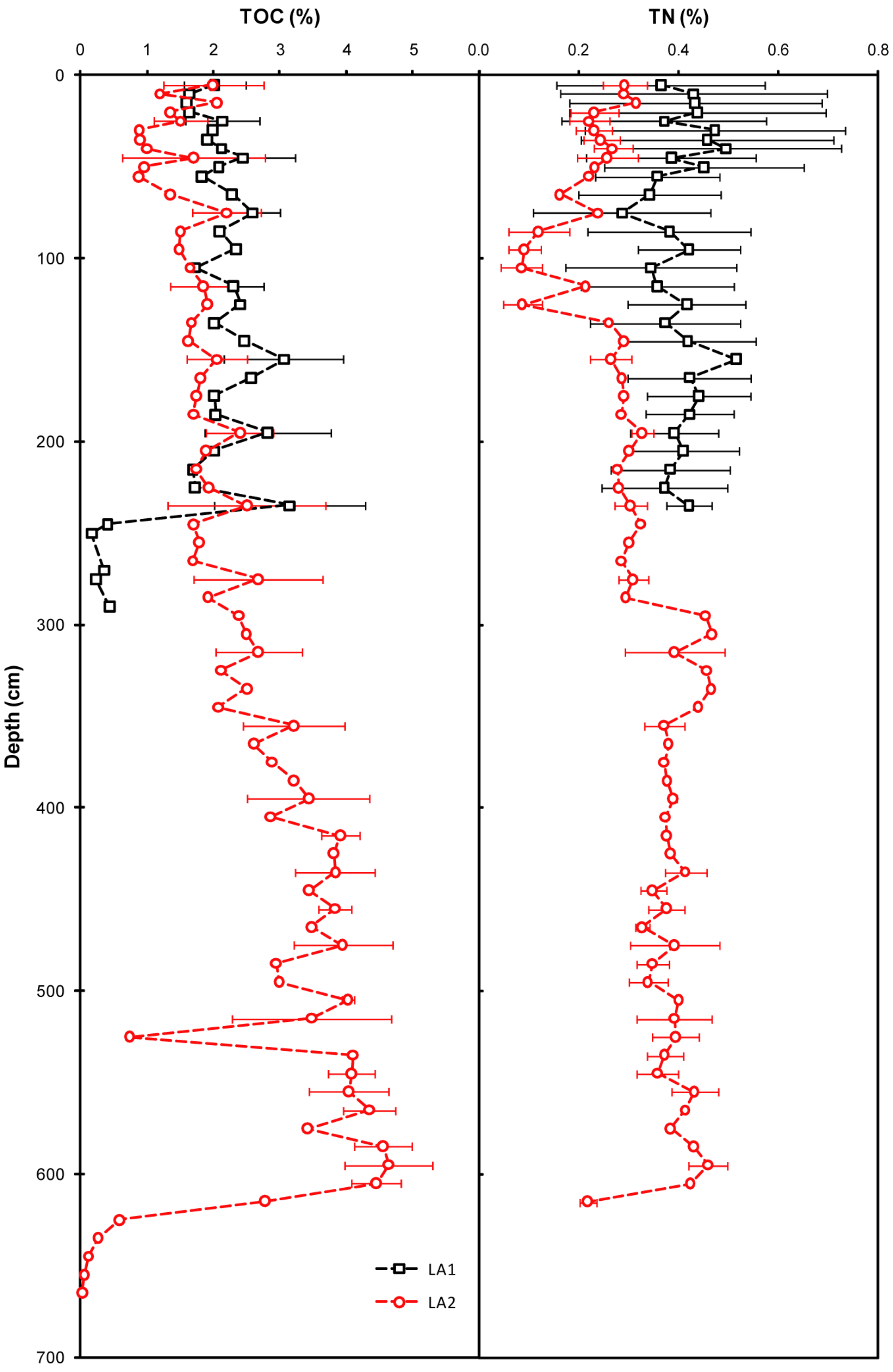

TOC (%)
0
1
2
3
4
5
TN (%)
0.0
0.2
0.4
0.6
0.8
Depth (cm)
0
100
200
300
400
500
600
700
LA1
LA2

Figure 8

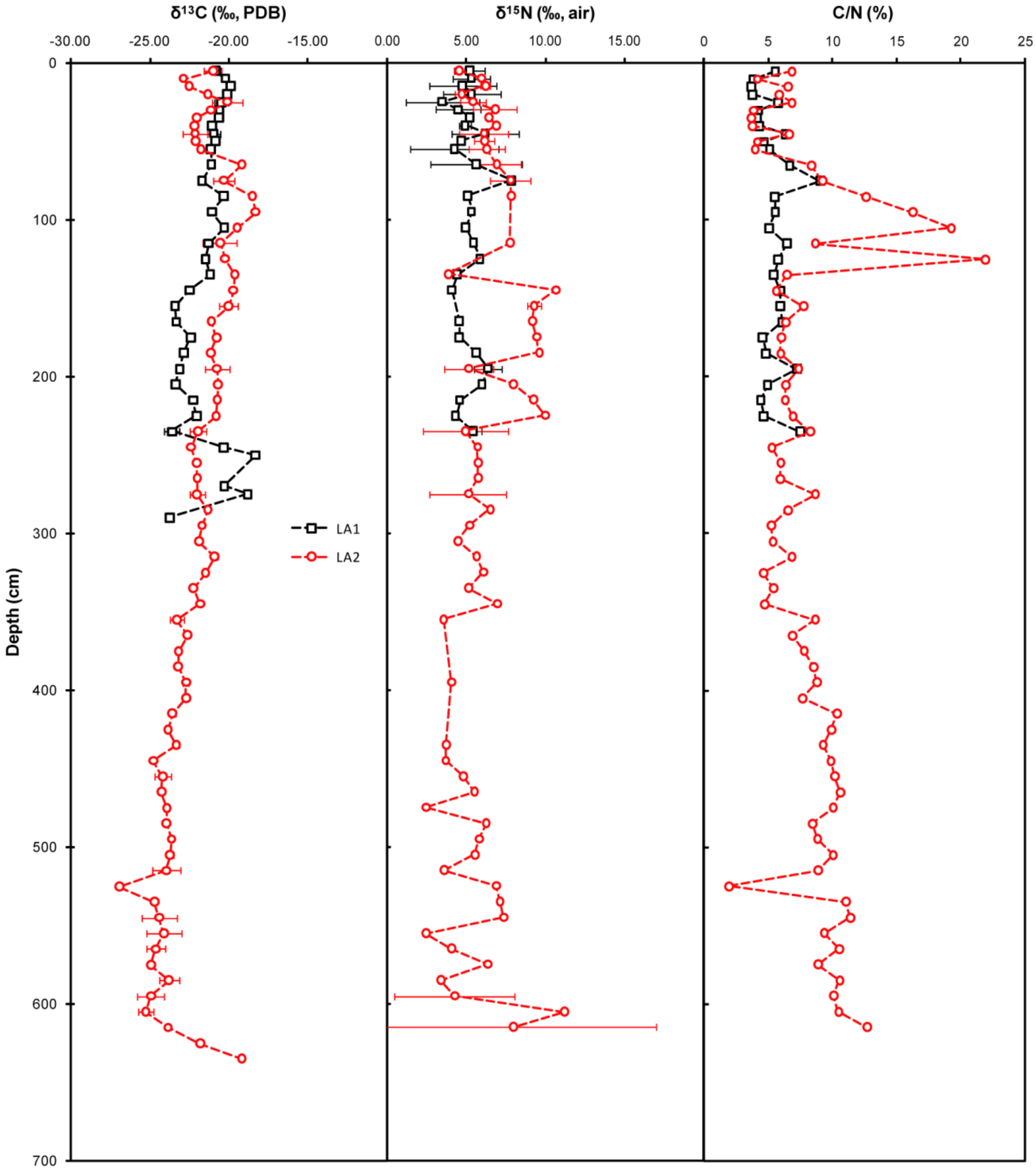

δ¹³C (‰, PDB)
-30.00
-25.00
-20.00
-15.00
0.00
δ¹⁵N (‰, air)
5.00
10.00
15.00
C/N (%)
0
5
10
15
20
25
Depth (cm)
0
100
200
300
400
500
600
700
LA1
LA2

Figure 9

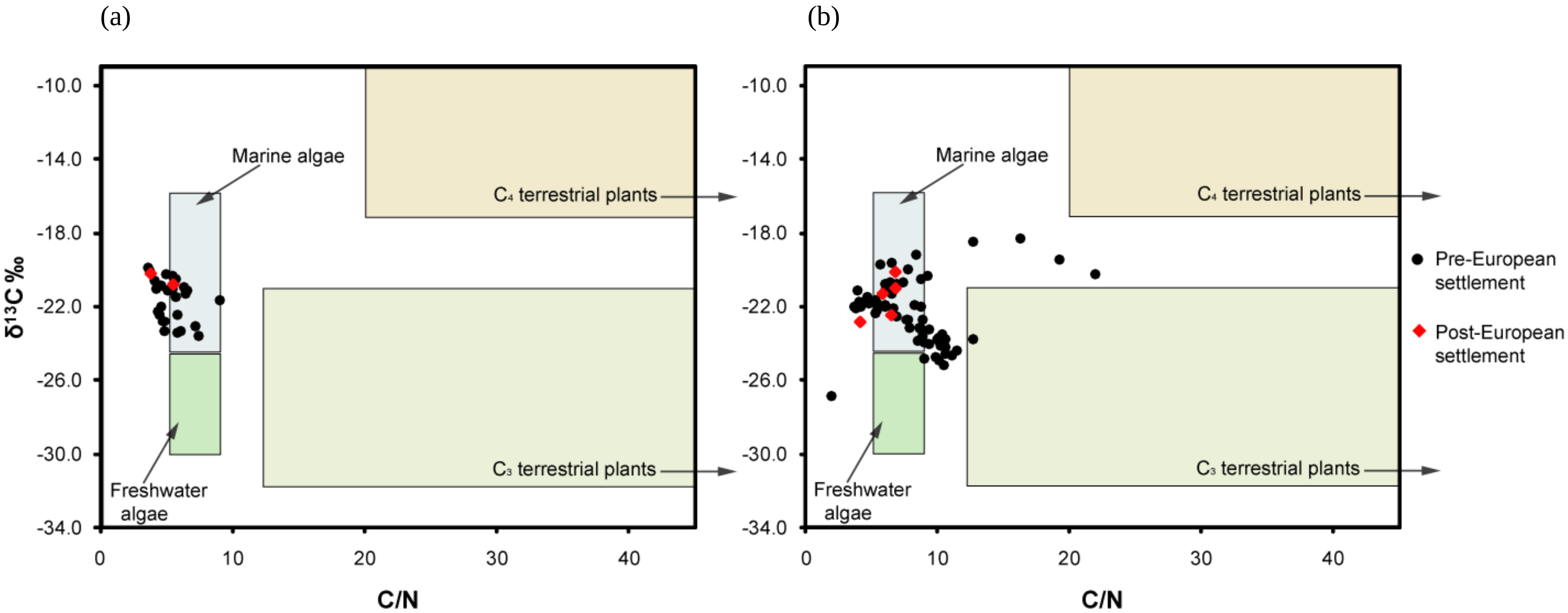
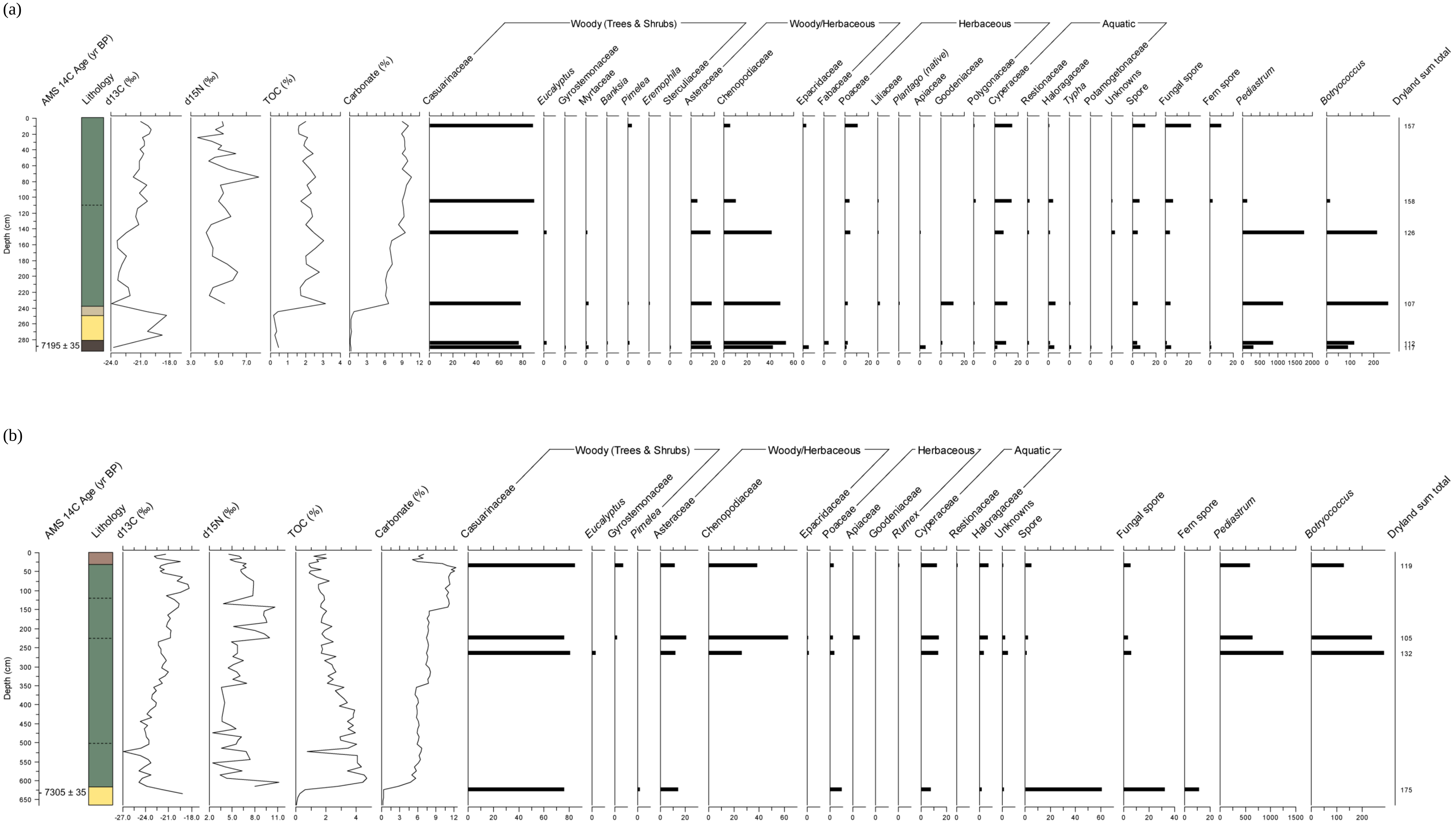

(a)
(b)
-10.0
-14.0
-18.0
-22.0
-26.0
-30.0
-34.0
δ13C ‰
Marine algae
C4 terrestrial plants
C3 terrestrial plants
Freshwater algae
0
10
20
30
40
C/N
● Pre-European settlement
◆ Post-European settlement

Figure 10


(a)
Woody (Trees & Shrubs)
Woody/Herbaceous
Herbaceous
Aquatic
AMS 14C Age (yr BP)
Lithology
d13C (‰)
d15N (‰)
TOC (%)
Carbonate (%)
Casuarinaceae
Eucalyptus
Gyrostemonaceae
Myrtaceae
Banksia
Pimelea
Eremophila
Sterculiaceae
Asteraceae
Chenopodiaceae
Epacridaceae
Fabaceae
Poaceae
Liliaceae
Plantago (native)
Apiaceae
Goodeniaceae
Polygonaceae
Cyperaceae
Restionaceae
Haloragaceae
Typha
Potamogetonaceae
Unknowns
Spore
Fungal spore
Fern spore
Pediastrum
Botryococcus
Dryland sum total
Depth (cm)
7195 ± 35
157
158
126
107
112
117
(b)
Woody (Trees & Shrubs)
Woody/Herbaceous
Herbaceous
Aquatic
AMS 14C Age (yr BP)
Lithology
d13C (‰)
d15N (‰)
TOC (%)
Carbonate (%)
Casuarinaceae
Eucalyptus
Gyrostemonaceae
Pimelea
Asteraceae
Chenopodiaceae
Epacridaceae
Poaceae
Apiaceae
Goodeniaceae
Rumex
Cyperaceae
Restionaceae
Haloragaceae
Unknowns
Spore
Fungal spore
Fern spore
Pediastrum
Botryococcus
Dryland sum total
Depth (cm)
7305 ± 35
119
105
132
175

## 17. Tables

Table 1

| Core | Depth (cm) | Sample type | Code | AMS 14C uncalibrated yr BP |
|---|---|---|---|---|
| LA1 | 285-287 | Plant roots | Wk-25854 | 7195 ± 35 |
| LA2 | 629 | Woody macrofossil | Wk-25855 | 7305 ± 35 |