

Palaeolimnological evidence for the independent evolution of neighbouring terminal lakes, the Murray Darling Basin, Australia

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Abstract The estuary of the lower River Murray features a complex mosaic of lakes, coastal lagoons and interconnecting channels. The waters of these wetlands are degraded as a result of river regulation, water abstraction, salinisation, sedimentation and the recent constriction of the River mouth. Palaeolimnological analysis of sediment cores in two wetlands reveals that salinity in the large terminal Lake Alexandrina was only moderately influenced by tidal inflow, particularly over the past ca. 2000 years. It is now largely fresh as a result of isolation by a series of barriers completed by 1940 AD. In contrast, the seaward portion of the Coorong, a back barrier coastal lagoon, was determined to be a subsaline estuary strongly influenced by marine inflows. These findings contrast somewhat with the Coorong's current Ramsar

classification as a saline lagoon. Riverine diatoms, typical of the fossil flora of Lake Alexandrina, are rare or absent in the Holocene sediments of the Coorong, other than for a short period in the late Holocene in the northernmost end of the lagoon. The palaeolimnological evidence for independent evolution of these wetlands is consistent with geomorphic evidence of a stranded, last interglacial shoreline that acted as a sill limiting the exchange of flows between Lake Alexandrina and the Coorong lagoon.

Keywords River regulation · Estuaries · Diatoms · Salinisation · Sedimentation · Eutrophication · Ramsar

Introduction

Lake Alexandrina is a broad shallow lake, located at the mouth of the Murray River in South Australia (Fig. 1). It has a surface area of over 660 km² and volume of 1.66×10^6 ML. The Lake is shallow ($Z_{\max} = 4.05$ m; $Z_{\text{mean}} = 2.86$ m) and highly turbid. The Darling River is known to carry a very high-suspended sediment load and this is thought to be the main source of abiogenic turbidity in Lake Alexandrina although Bourman & Barnett (1995) identified considerable erosion of the littoral zone of the Lake over the last century. The Coorong is a large coastal lagoon complex situated between a Holocene beach—dune barrier, the Younghusband Peninsula,

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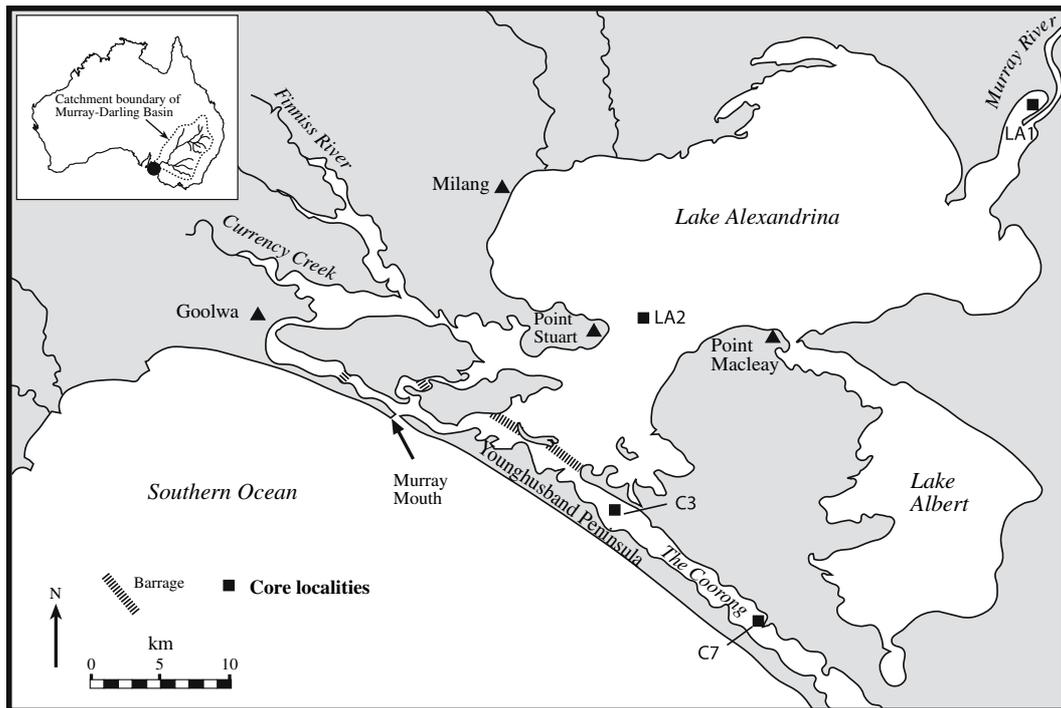


Fig. 1 The location of Lake Alexandrina, the Coorong and the Murray Mouth showing core sites

and, on its north-eastern margin, a fossil shoreline formed during the last interglacial. This former shoreline exists today as a sill of sediments that separates Lakes Alexandrina and Albert from the Coorong and the Murray Mouth. The mouth has rapidly migrated to the north-west since the 1960s (Bourman & Murray-Wallace, 1991) and the sediments in the channel inside the mouth are accreting rapidly (Bourman & Barnett, 1995). Historically, the Goolwa channel carried ~70% of the Murray River flow as it is considerably deeper and less sinuous than the other channels between Lake Alexandrina and the Coorong (Cann et al., 2000).

In the early 1900s controlling tidal flows to the lake system was seen as crucial to the success of river regulation and the maintenance of regional potable water supplies. Consequently, between 1914 and 1940, five barrages, totalling 7.6 km in length, were constructed between Lakes Alexandrina and Albert and the Coorong (Fig. 1). The first completed barrage was constructed of sand bags near the site of the present Mundoo Barrage (Sim & Muller, 2004) in order to maintain water quality at a level suitable for irrigation by reducing the intrusion of tidal marine

water into Lake Alexandrina. These were replaced with a timber barrage in 1919 and the final construction was in place by 1939. The shallow sill of lithified shelly beach facies of the last interglacial shoreline was used as the foundation for the Tauwicheerie, Ewe Island, Mundoo and Boundary Creek Barrages (Bourman et al., 2000), while the Goolwa Barrage, constructed across the main channel, was built on piles driven into non-lithified sediments. The barrages completely separate both lakes from the Coorong, with infrequent fresh water flowing through the barrage gates. As a result, Lake Alexandrina is presently a large, predominantly fresh water system with no salt water input from the Coorong or the Southern Ocean. Conversely, the Coorong presently has only a small estuary and is a predominantly saline—hypersaline system with little inflow of freshwater from the lakes and negligible marine inflow as a result of mouth constriction.

The Coorong, in particular, has been identified as a degraded system (England, 1993) and monitoring has revealed increases in salinity and declines in biological productivity since the 1970s (Geddes, 1984). More broadly, the Murray Darling Basin has been

described as heavily impacted (Norris et al., 2002) and environmental flow scenarios have been generated (Jones et al., 2002) to improve the ecological health of the waterways of the system. The Coorong and Lower Lakes are identified in government initiatives as a “significant ecological icon” deserving of River Murray flows to improve their ecological health (COAG, 2004). This research explores the pre-impact ecological character of Lake Alexandrina and the Coorong to document the water quality changes that have occurred within both systems and to identify the main drivers of those changes. These outcomes will inform the debate on the utility of River Murray environmental flows in re-establishing the ecological character of Lake Alexandrina and the Coorong.

Methods

A diatom based palaeolimnological approach was adopted to investigate the degree of historical connectivity between Lake Alexandrina and the Coorong. Diatoms were chosen as environmental proxies as they are strong salinity indicators (Gasse et al., 1995; Gell, 1997) and were known from previous work (Barnett, 1993; Tucker, 1997; Fluin, 2002; Reid et al., 2002) to be well preserved in the sediments of both environments. Core LA1 was extracted in 1996, close to the entrance of the river channel but sheltered from the effects of tidal inflows, is 85 cm in length and was extracted using a piston coring device. Core LA2 (original core number 22) was also extracted using a piston core in 1989 by Barnett (1993) and is 490 cm in length from the southern section of the main lake between Point Macleay and Point Sturt (Fig. 1). Thirty cores were collected from the Coorong in early 2005. Cores C3 and C7 were selected for comparison with the Lake Alexandrina cores as they are in the northern lagoon and so are remote from the effects of local drainage on the southern lagoon. At Coorong site C3, 10 km south-east of the Tauwitchere Barrage, a 146 cm core was collected with a piston corer. At site C7, a further 20 km to the south-east, a 156 cm core was collected, also with the piston corer.

All cores were dated using conventional and accelerator mass spectroscopy (AMS) ^{14}C (Table 1) techniques and ^{210}Pb geochronology. Radiocarbon

dates were calibrated to calendar years using the southern hemisphere atmospheric calibration data set of McCormac et al. (2004) with Calib 5.0.2. (Stuiver & Reimer, 2005). We took the median of the two sigma of the age range as the calibrated age. Where this range did not include 100% of the age probabilities, we utilised the median of the age range with highest proportion of possible ages as the calibrated age.

The principals of ^{210}Pb geochronology are discussed in detail by Robbins (1978). The ^{210}Pb activities of eleven samples from core LA1 were determined by the Australian Nuclear Science and Technology Organisation (ANSTO). ^{210}Pb measurements were undertaken on core LA2 by Barnett (1993) at 2 cm intervals to a depth of 64 cm. The CSIRO laboratories at Black Mountain, Canberra analysed twelve samples from Coorong cores C3 and C7 for alpha spectrometry and nine for gamma spectrometry to generate a ^{210}Pb decay profile and to gain evidence for ^{137}Cs activity. In the case of the alpha spectrometric analyses, ^{210}Pb was estimated by measurement of its short-lived daughter isotope, ^{210}Po . Excess ^{210}Pb ($^{210}\text{Pb}_{\text{ex}}$) from LA2 was estimated by subtracting the average of the asymptote of the total ^{210}Pb values (25.4 mBq/g), the assumption being that the asymptote represents the contribution of “supported” ^{210}Pb to the total ^{210}Pb activity. Supported ^{210}Pb is usually estimated by the ^{226}Ra activity of the sediment and for all cores other than LA2 $^{210}\text{Pb}_{\text{ex}}$ was determined by direct subtraction of individual ^{226}Ra measurements.

All cores were described (in terms of lithology) their inorganic and organic components were determined, and sediment was subsampled for diatom analysis. Between 300 and 500 diatom valves were identified and enumerated from cores LA1 and LA2, following Battarbee (1986), mostly using an Olympus BH-2 microscope with Normaski Differential Interference Contrast (DIC). At least 200 valves were counted from each sample from cores C3 and C7 using a Nikon E600 with DIC. Diatoms were identified by reference to the primary diatom floras (Krammer & Lange-Bertalot, 1986, 1988, 1991a, b) and Witkowski et al. (2001) as well as Foged (1978), Germain (1981), Archibald (1983), Gasse (1986) and John (1983).

In order to compare the similarity of diatom floras from the four cores, diatom samples were subjected

Table 1 ^{14}C dating results for cores LA1, LA2, C3 and C7

Core LA1	Lab code	^{14}C method	Age	Age range cal yr BP (and proportion of probability that age falls in the range)	Calibrated age (median of 2σ s.d., rounded to nearest 50 years)
40–43		AMS ^a	6644 ± 76	7,325–7,400 (0.083) 7,411–7,595 (0.912) 7,600–7,607 (0.005)	7,500
65–68		AMS ^a	6,499 ± 69	7,179–7,196 (0.011) 7,246–7,491 (0.989)	7,400
82–85		AMS ^a	6,765 ± 76	7,438–7,679 (1.0)	7,600
Core LA2					
50–60		Conventional ^a	Modern		
122–129		Conventional ^a	Modern		
251–259		AMS ^c	2,301 ± 200	1,814–2,756 (1.0)	2,300
251–259		Conventional ^a	1,940 ± 140	1,423–1,431 (0.002) 1,442–1,459 (0.005) 1,515–2,155 (0.986)	1,800
402–410		Conventional ^a	4,940 ± 250	4,965–6,201 (1.0)	5,600
492–494		AMS ^b	7,000 ± 300	7,269–8,374 (1.0)	7,800
Core C3					
80–81	Wk17295	AMS ^a	5,973 ± 40	6,642–6,808 (0.889) 6,811–6,859 (0.102) 6,872–6,880 (0.009)	6,700
143–144	Wk 17294	AMS ^a	6,327 ± 40	7,019–7,123 (0.152) 7,151–7,291 (0.848)	7,200
Core C7					
82–83	Wk17298	AMS ^a	2,381 ± 34	2,164–2,166 (0.002) 2,180–2,241 (0.130) 2,302–2,465 (0.868) 5,470–5,558 (0.534)	2,400 5,500
152–153	Wk17297	AMS ^a	4,886 ± 37	5,568–5,651 (0.466)	

Where multiple possible intersects of the calibration curve occurred, we utilised that age range (shown in bold) with the highest proportion of possible ages

^a ^{14}C age from the University of Waikato Radiocarbon Dating Laboratory

^b AMS ^{14}C age from the Division of Exploration Geoscience, CSIRO, Sydney.

^c AMS ^{14}C age from the department of Nuclear Physics, Australian National University

to unconstrained ordination. Following an initial correspondence analysis in which the sample scores were notably arched, detrended correspondence analysis (DCA) was implemented in CANOCO for Windows 4.02 (ter Braak & Smilauer, 1999). DCA was undertaken on all taxa which occurred $\geq 5\%$ relative abundance in any sample with detrending by segments ($n = 26$) and non-linear re-scaling of axes.

Results

Lithostratigraphy

The lithostratigraphy and organic content of all cores is illustrated in Figs. 3–6.

In LA1, the sediment is predominantly olive grey mud from the sediment surface to 50–60 cm depth.

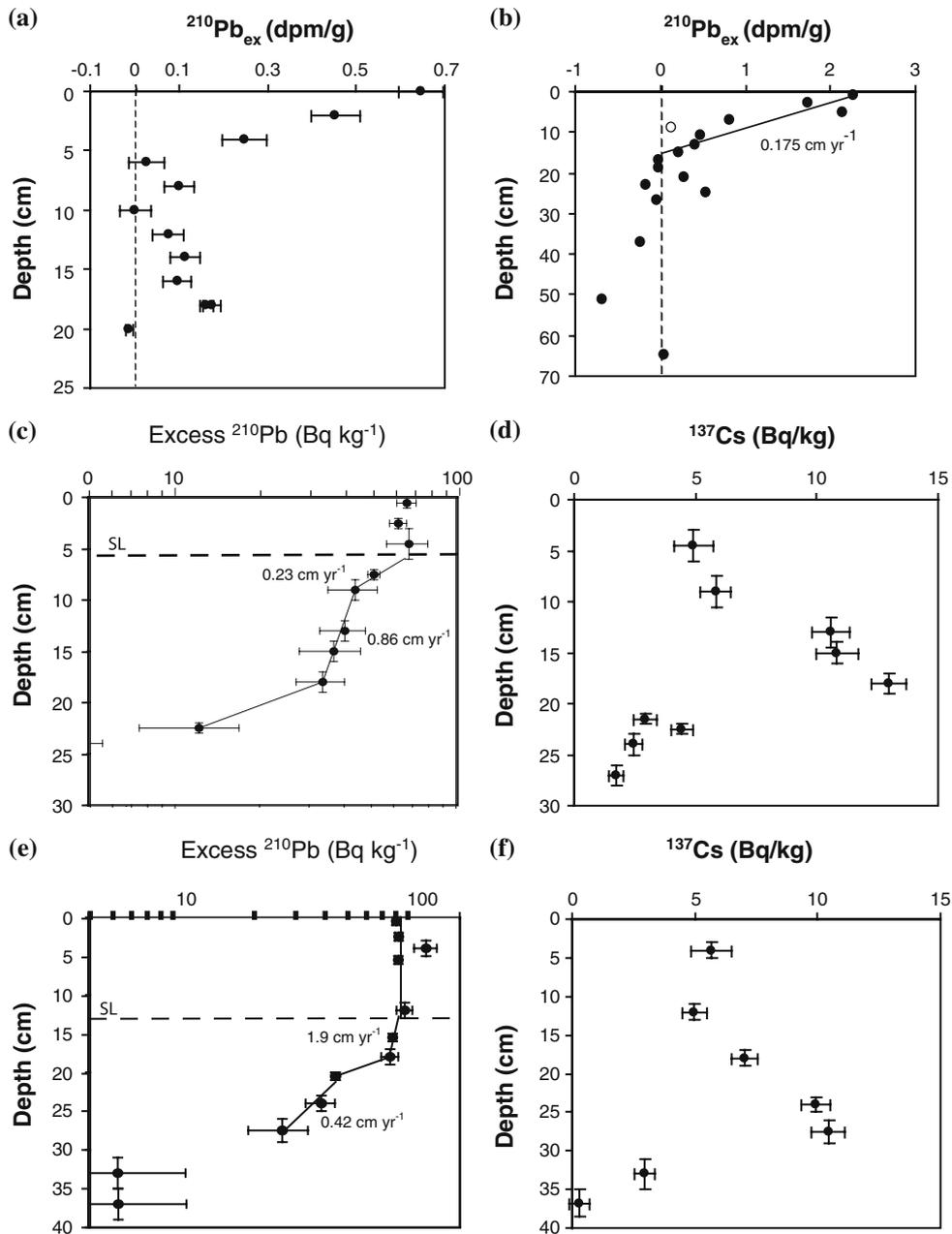


Fig. 2 Excess ^{210}Pb vs depth for cores LA1 (a), LA2 (b), C3 (c), C7 (e). Also shown are ^{137}Cs vs depth for C3 (d) and C7 (f). The line-of-best-fit relationship for 0–17 cm in LA2 excludes data from 9 cm (shown by an unfilled circle)

Below this there is a gradual change between 50 and 60 cm to sandy muds to muddy sands that continue to the base of the core. This layer of sediment is also olive grey although slightly darker than the overlying muds. There are two darker coloured, coarse textured bands present at 55–56 cm, and 78–80 cm. Organic

matter decreases down core with 3.5% at the surface and 0.5% at 85 cm.

In core LA2, the surface sediments to 64 cm are composed of a light grey to medium dark grey olive mud. From 64 cm to 79 cm there is a light grey to medium dark grey sandy mud to muddy sand. From

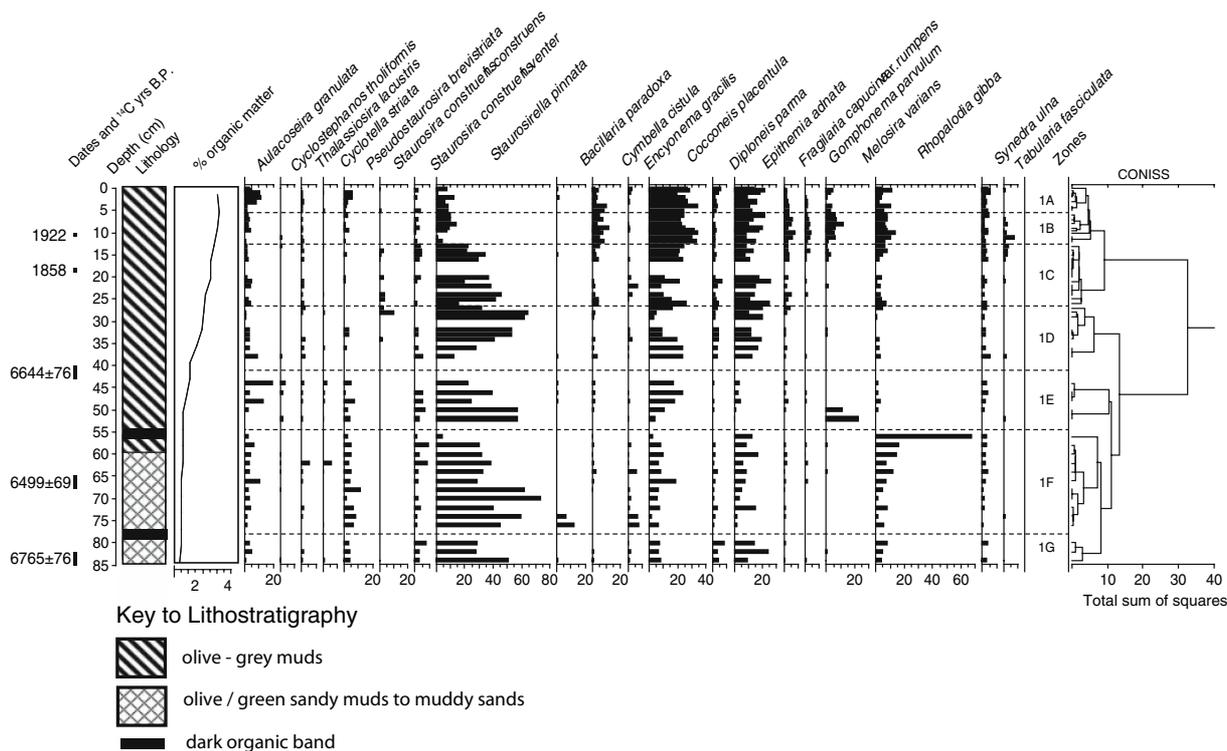


Fig. 3 Summary diatom diagram, CONISS classification and lithostratigraphy from core LA1 from northern Lake Alexandrina

79 cm to 100 cm, the sediment is mostly medium bluish grey to dark greenish grey, with medium dark grey bands at 96–110 cm. Between 110 cm to 123 cm, there is light olive grey to medium dark grey sandy mud to muddy sand, with silt and fine sand irregular bands from 110 cm to 113 cm. Dark greenish grey to olive grey mud is present between 123 cm and 138 cm. From 138 cm to 158 cm, there is light olive grey to darkish greenish grey sandy mud to muddy sand, with irregular bands of silt and fine sands at 146–150 cm. From 158 cm to the base of the core, the sediment is composed of a relatively uniform dark greenish grey, olive grey, and medium light grey to dark grey mud. There are also light greenish grey to olive grey to olive grey bands at 185–190 cm and 214–218 cm; light grey bands at 405–408 cm, dark greenish grey to olive grey fine sand irregular bands at 160–164 cm, olive grey silt rich mud bands at 306, 306.5, 309, 323, 332, and 343 cm, dark grey, striations between 290 cm and 302 cm, crosscutting bands from 306 cm to 350 cm and between 440 cm and 446 cm, and a dark grey mud layer between 310 cm and 321 cm with faint veins included. There

are also *Corbiculina* shells (single valve) present from 160 cm to the bottom of the core, and crustacean (primarily ostracoda) fragments at 256 cm and 462 cm. Organic matter is highest in the surface sediments at 2.15% and then falls to <1.0% downcore.

In core C3, the sediments below 33 cm are comprised of indistinct bands of fine sand and silty clay, all an homogenous grey colour, with one distinct shell band 90–92 cm. The sediments change to fine, grey sandy silt above 33 cm, and to very fine, black silty clay from 21 cm to the top of the core, with a dense band of shells 21–12 cm. Despite three large peaks of organic content (over 40%) in the lower core, the organic content of the core oscillates in values (less than 12%) for most of its length. From 20 cm there is a gradual increase to the top of the core to values more than 16% (Fig. 5).

In core C7, the sediments below 77 cm consist of alternating bands of grey and dark grey sandy clay and shells, with a band of coarser sandy clay and shells 138–147 cm. Those above 77 cm and below 37 cm are comprised of alternating bands of brown or grey sandy clay. There are very dark grey silty clays

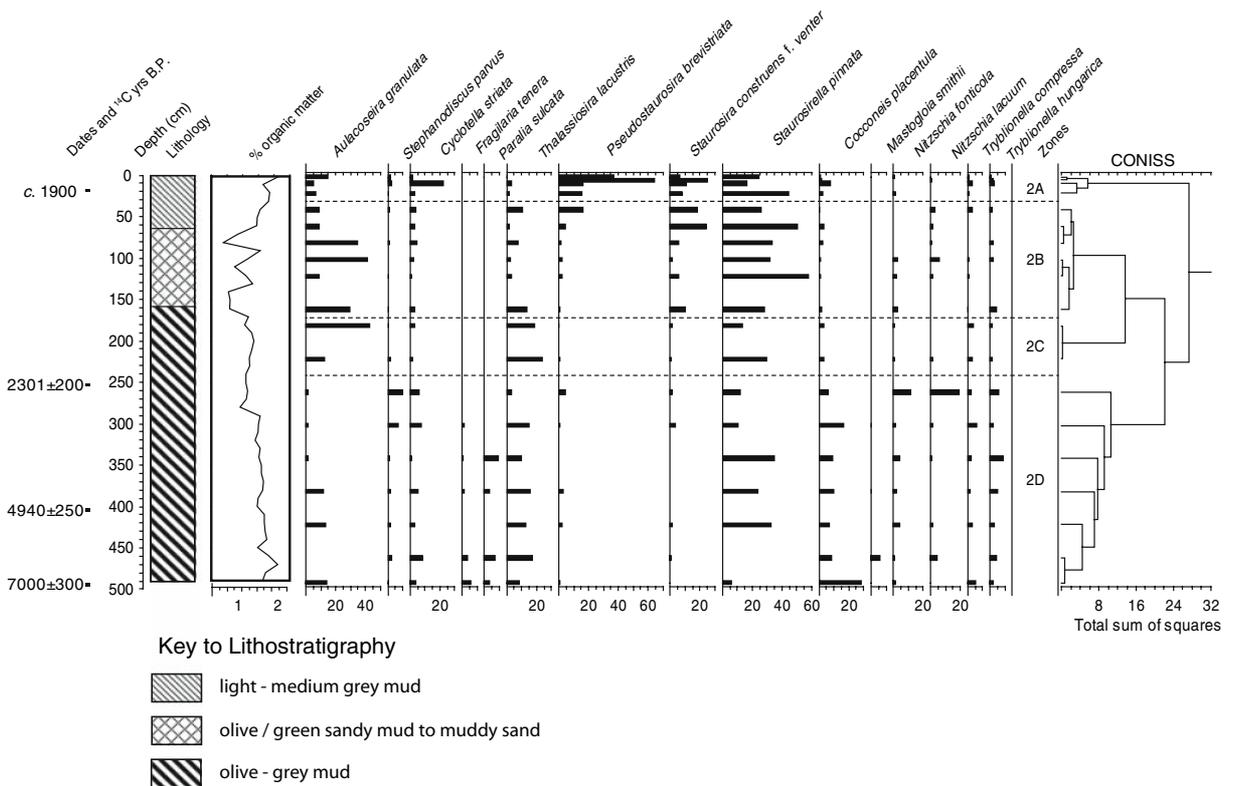


Fig. 4 Summary diatom diagram, CONISS classification and lithostratigraphy from core LA2 from southern Lake Alexandrina

between 37 cm and 14 cm, and very fine, black silty clay from 14 cm to the top of the core. Below 115 cm, the relative proportions of organic and inorganic matter are stable, after which they oscillate to 51 cm, where the organic percentage shows a dramatic increase to more than 50% for 10 cm. From 40 cm to the top of the core, the relative proportion of organic matter shows a slight overall increase, but averages less than 14% (Fig. 6).

Chronology

The results of the ^{14}C analyses for all cores are provided in Table 1 while Fig. 2 illustrates the ^{210}Pb and ^{137}Cs data. The basal ages of all cores are early to mid-Holocene. The ^{14}C ages for LA2 and C7 indicate steady sediment accumulation, however mid-core ages for the other cores are older than would be predicted by a steady sedimentation rate. The depth of detectable $^{210}\text{Pb}_{\text{ex}}$ ranges from 19 cm (LA1) to 29 cm (C7) with C3 (23 cm) and LA2 (25 cm)

intermediate between these. In the Lake Alexandrina cores $^{210}\text{Pb}_{\text{ex}}$ generally declines steadily with depth to 11 cm and 18 cm in LA1 and LA2. Between this point and the limit of detection $^{210}\text{Pb}_{\text{ex}}$ values are generally suppressed but variable. In the Coorong cores, $^{210}\text{Pb}_{\text{ex}}$ concentrations are relatively constant with respect to depth to 6 cm in C3 and up to 19 cm in C7. Below this point $^{210}\text{Pb}_{\text{ex}}$ concentrations decline with depth in a linear fashion until a stepped decline below 19 cm in C3 and 29 cm in C7. ^{137}Cs is detectable (defined as concentration greater than two standard deviations above zero) from 26 cm to 28 cm (the basal sample in which it was measured) in Coorong C3 and in C7 to a depth of 31–35 cm, but absent in the C7 sample from 35 cm to 38.5 cm.

Diatom analysis

Lake Alexandrina core LA1

The most common groups of diatom species in core LA1 are littoral and facultative planktonic (Fig. 3). The most

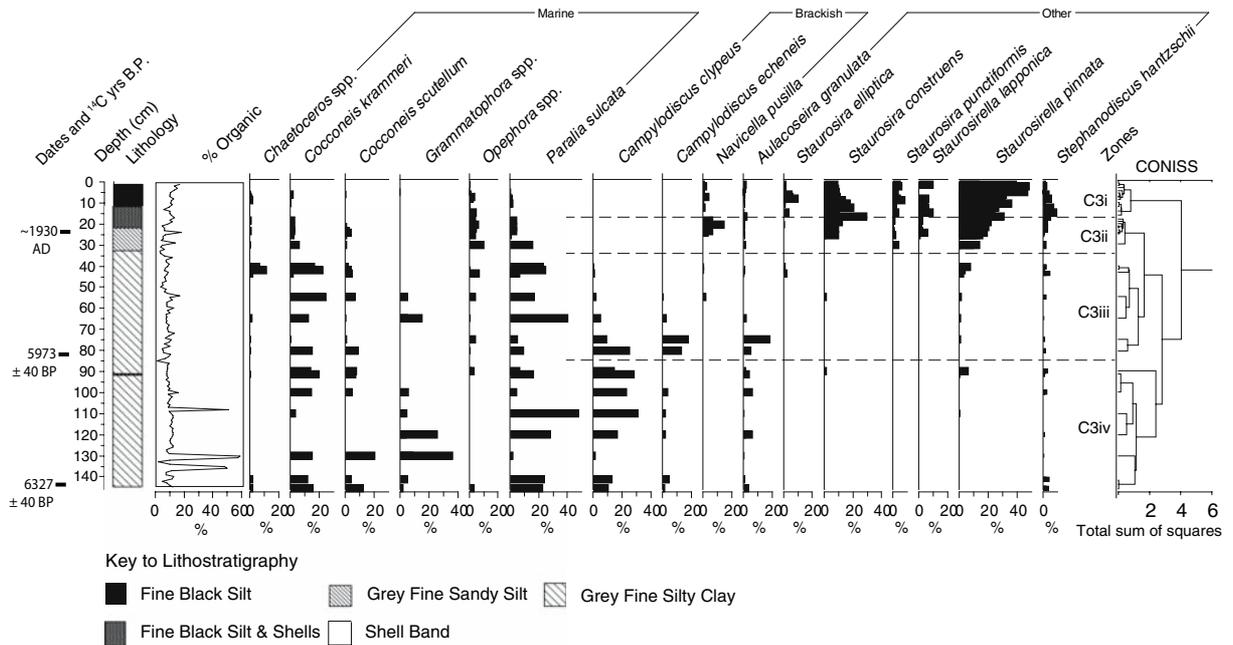


Fig. 5 Summary diatom diagram, CONISS classification and lithostratigraphy from Coorong core site C3

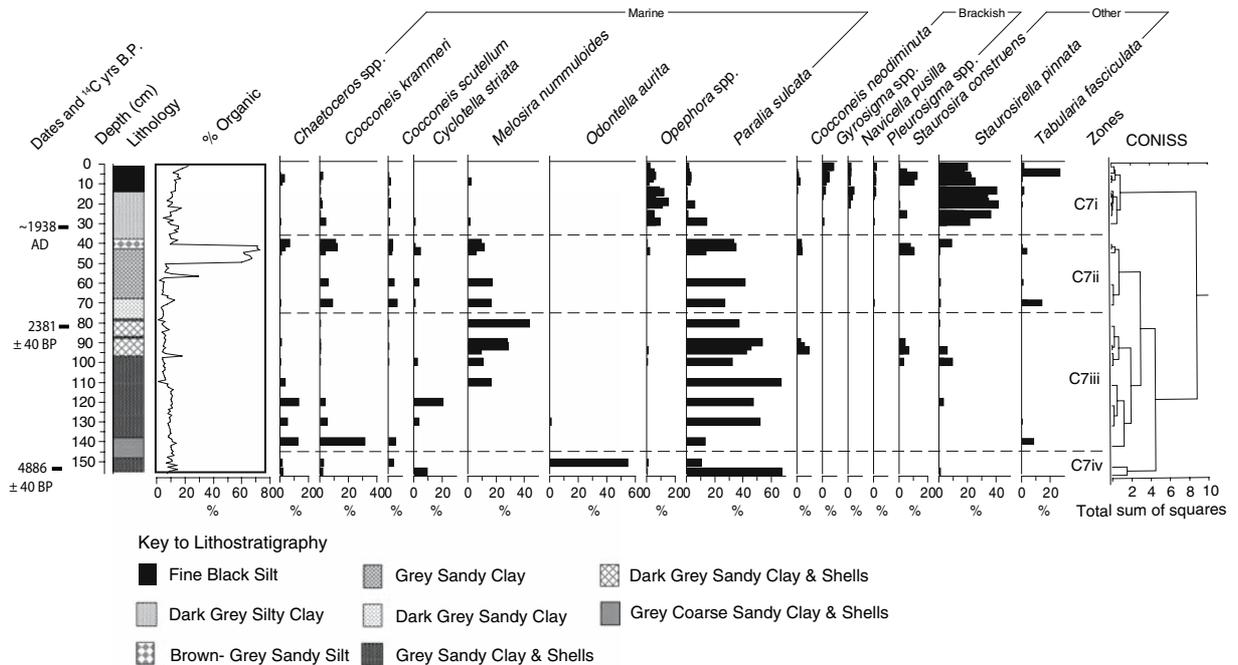


Fig. 6 Summary diatom diagram, CONISS classification and lithostratigraphy from Coorong core site C7

abundant diatom species are *Cocconeis placentula*, *Epithemia adnata* and *Staurosirella pinnata*. Diatom valves were not preserved in five sections of core LA1 (17–20 cm, 39–44 cm, 53–55 cm, 77–80 cm, and 85–100 cm). Seven zones of distinctive diatom flora were determined and are used to describe the record.

Zone 1G (85–78 cm): Littoral and facultative planktonic taxa are present in equal abundances in this zone (combined average >46%), with a minor presence of planktonic taxa (7%). The dominant taxon is *Staurosirella pinnata*, which has an average abundance of 36%. The littoral taxa *Epithemia adnata* and *Cocconeis placentula* are the next most abundant with averages of 16% and 7% respectively. Minor taxa, including *Pseudostaurosira brevistriata*, *Rhopalodia gibba* and *Staurosira construens* forma *venter* are also consistently present.

Zone 1F (78–55 cm): Littoral taxa decrease to an average of 39.1% in this zone (from 46.3% in Zone 1G), resulting mainly from a decrease in *Epithemia adnata* from an average of 16% in zone 1G to 9.5% in this zone. *Rhopalodia gibba* gradually increases towards the top of the zone, reaching its maximum abundance for the core of 68% at 56 cm. An increase in *Staurosirella pinnata* from an average of 36% in zone 1G to 44% in this zone, contributes to an overall increase in facultative planktonic taxa. *Staurosirella pinnata* abundance is highly variable within the zone, varying from 44% at 76 cm to 73% at 70 cm, then decreasing to 8% at 56 cm. There is little change in the percentage of planktonic taxa between this and the previous zone.

Zone 1E (55–42 cm): Littoral taxa continue to decline through this zone, accounting for an average of 28.8% of valves (cf. 39.1% in Zone 1F). This is despite an increase in *Cocconeis placentula* from 7% in zone 1F to 18% in this zone. The decrease is largely due to a declining abundance of *Epithemia adnata*, that falls to only 2% in this zone, and of *Rhopalodia gibba* that declines from an average of 29% to 1%. The littoral taxa are replaced by higher values in planktonic taxa, mostly attributable to an increase in *Aulacoseira granulata* but also in other, previously absent, centric taxa including *Cyclotella striata*, *Cyclostephanos tholiformis*, and *Thalassiosira lacustris*.

Zone 1D (42–27 cm): This zone is characterised by a substantial increase in littoral taxa (from 28.8% to 42.3%), and decreases in both facultative

planktonic and planktonic taxa. The increase in littoral taxa, however, is not uniform across all species, with *Cocconeis placentula* decreasing and *Epithemia adnata* increasing in average abundance. Numbers of *Staurosirella pinnata* vary but remain at ~40% of valves. Both *Staurosira construens* forma *venter* and *Pseudostaurosira brevistriata* decrease in this zone. Conversely, *Staurosira construens* var. *construens* makes its first appearance here with an average of 2% but peak of 11%. Planktonic taxa decrease in abundance due to the loss of the minor planktonic taxa of zone 1E, but also a decrease in *Aulacoseira granulata* from 7% to 3%.

Zone 1C (27–13 cm): Littoral taxa increase again in this zone (to 56%) with a corresponding decrease in facultative planktonic taxa (down to 39%). At the base of the zone several of the minor littoral taxa (*Cymbella cistula*, *Gomphonema parvulum*, *Melosira varians* and *Tabularia fasciculata*) occur consistently in higher values than elsewhere. The main change within the facultative planktonic taxa is a decrease in *Staurosirella pinnata* from a peak of 65% near the top of the previous zone. The planktonic taxa remain largely unchanged in abundance at <5.0%.

Zone 1B (13–6 cm): Littoral taxa increase further in this zone reaching an average of 74.1% of valves mainly attributable to small increases in both *Cocconeis placentula* and *Epithemia adnata* and continuing increases in the aforementioned minor littoral taxa, *Cymbella cistula* (increases to an average of 8%), *Melosira varians* (6%), *Tabularia fasciculata* (7%) and, to a lesser extent, *Gomphonema parvulum* (2%). Facultative planktonic taxa decrease in abundance markedly, from ~39% in zone 1C to 16.7% here, mostly due to an abrupt decrease in *Staurosirella pinnata*. Planktonic taxa increase from 4.6% to an average of 9.1% in this zone mainly due to a sustained increase in minor taxa (<5%, not graphed), including *Cyclotella striata* and *Cyclostephanos tholiformis*.

Zone 1A (6–0 cm): Littoral diatoms account for over 72% of all the taxa in this uppermost zone of the core. The abundance of the three dominant taxa, *Cocconeis placentula*, *Epithemia adnata* and *Staurosirella pinnata*, remain relatively unchanged from the previous zone. *Pseudostaurosira brevistriata* increases slightly from 1% to 3%, while *Rhopalodia gibba* decreases. The minor littoral taxa common in zone 1B all decrease. The planktonic *Aulacoseira*

granulata increases to an average of 8% in this zone, with a peak of 11% at 2–3 cm.

Lake Alexandrina core LA2

Core LA2 is dominated primarily by planktonic and facultative planktonic taxa (Fig. 4). The major planktonic taxa present are *Aulacoseira granulata*, *Cyclotella striata*, and *Thalassiosira lacustris*. The major facultative planktonic taxa present are *Staurosirella pinnata*, *Pseudostaurosira brevistriata* and *Staurosira construens* forma *venter*. With the aid of CONISS, four zones were identified.

Zone 2D (490–240 cm): The degree of dissimilarity between most samples, combined with the high level chaining, indicates that this is a very variable zone, but one which is not easy to subdivide without separation of individual samples. With the exception of the bottom sample, dominated by *Cocconeis placentula* (28.6%), the major taxon in this zone is *Staurosirella pinnata* (average of 17%). The next most common taxon is the planktonic *Thalassiosira lacustris*, which has an average abundance of >11%. Three other minor planktonic taxa are present; *Aulacoseira granulata*, *Cyclotella striata* and *Stephanodiscus parvus*. *Aulacoseira granulata* has its highest abundances at 490 cm, 420 cm, and 380 cm (all >11%), and lowest values of <2% at depths of 340 cm, 300 cm, and 260 cm. *Cyclotella striata* has an average abundance of 5% throughout the zone, peaking at 8% at 460 cm. *Stephanodiscus parvus* has an average abundance of <3%, increasing in abundance towards the top of the zone. Littoral taxa are prevalent in this zone, particularly *Cocconeis placentula*, *Paralia sulcata*, *Nitzschia fonticola* and *Nitzschia lacuum*. After peaking in the bottom sample, *Cocconeis placentula* remains relatively constant in abundance, averaging 10%. *Paralia sulcata* does not display any particular patterns and is present at <10% in all samples. Both *Nitzschia fonticola* and *Nitzschia lacuum* peak in abundance at the top of the zone, accounting for 11.7% and 18.8%, respectively.

Zone 2C (240–170 cm): This zone consists of two samples only, at 220 cm and 180 cm depth. It appears that CONISS clusters this section of the core as a distinct zone because of an increase in the abundance

of *Thalassiosira lacustris*, which accounts for 24% of the diatom assemblage at 220 cm and 18% at 180 cm, and also *Aulacoseira granulata* that increases to 12% and 43%, respectively. The other common planktonic taxon, *Cyclotella striata*, decreases in this zone, however, averaging <3%. *Cocconeis placentula* also decreases in abundance in this zone, averaging <3%. There is little change in *Staurosirella pinnata* from its abundance in zone 2D. *Paralia sulcata* is absent from this zone, while *Nitzschia fonticola* and *Nitzschia lacuum* decrease to an average of <1% abundance.

Zone 2B (170–30 cm): This zone consists of 6 samples: 160, 120, 100, 80, 60 and 40 cm. The most abundant taxon from zone 2C, *Aulacoseira granulata*, decreases in abundance at 120 cm (to 9%), increases again to >35% at 100 cm and 80 cm depths, before decreasing at 60 cm and 40 cm depth to <9%. *Thalassiosira lacustris* declines considerably in this zone, falling to <2% at 60 cm. However, it should be noted that at 80 cm and 40 cm this taxon increases to 8% and 11% respectively. *Staurosirella pinnata* peaks in abundance at 120 cm accounting for 51% of the total assemblage, with the average abundance increasing to 38% (from 24% in zone 2C and 17% in zone 2D). *Staurosira construens* forma *venter* increases in abundance in this zone, with highest representation in the top 2 samples, while *Pseudostaurosira brevistriata* has low but consistent representation until a sharp increase to 16% in the top sample of the zone.

Zone 2A (30–0 cm): This zone is comprised of four samples, at 0, 4, 8 and 20 cm, with most diatoms being facultative planktonic (average of 69.4%) in nature. Of these facultative planktonic taxa, *Pseudostaurosira brevistriata* is the most abundant, accounting for 36.6% of the total count at the surface, 64.4% at 4 cm, 16.4% at 8 cm and 15.8% at 20 cm. *Staurosirella pinnata* reaches a maximum of 44.8% at 20 cm, while *Staurosira construens* forma *venter* reaches a maximum of 24.8% at 4 cm. Of the planktonic taxa, *Aulacoseira granulata* occurs at an average of 6.5% throughout the zone (lower than its average abundance from zone 2) and *Cyclotella striata* occurs at <5% at all depths with the exception of 8 cm depth where it is peaks at 22.2%. *Thalassiosira lacustris* is also present at <5%, consistently lower than in earlier zones.

The Coorong

Coorong core C3

The greatest diatom assemblage change, as demonstrated by the CONISS dendrogram, occurs at 18 cm (Fig. 5). This occurs just above the reduced clay surficial layer at 21 cm. Other major changes are at 85 cm and 35 cm producing four zones.

Zone C3iv (146–85 cm): The flora of this zone is dominated by the marine tychopelagic diatom *Paralia sulcata*, a species with marine affinities (Witkowski et al., 2001); marine benthic forms *Cocconeis krammeri*, *Cocconeis scutellum*, *Grammatophora* spp. (which comprises *G. oceanica* and *G. macilenta*), and the brackish water, benthic taxon, *Campylodiscus clypeus*.

Zone C3iii (85–35 cm): In the lower samples in this zone *Paralia sulcata* is largely replaced by *Campylodiscus echineis*, *Campylodiscus clypeus* and the river plankton *Aulacoseira granulata*. The flora then returns to that of zone C3iv other than increases in *Chaetoceros muelleri*.

Zone C3ii (35–18 cm): This zone is marked by an abrupt replacement of marine taxa with small Fragilariaceae, including the marine genus *Opephora*. *Opephora* spp., *Staurosira punctiformis* and *Staurosirella pinnata* increase at 30 cm to be joined by *Staurosira construens* and *Staurosira lapponica* at 24 cm. The brackish form *Navicella pusilla* peaks at the top of this zone and the planktonic *Stephanodiscus hantzschii*, appears at 28 cm.

Zone C3i (18–0 cm): The upper sediments are dominated by *Staurosirella pinnata*, *Staurosira construens*, *Staurosira punctiformis* and *Staurosirella lapponica*. *Stephanodiscus hantzschii* exceeds 10% of valves at 15 cm and is well represented through the zone. The river plankton *Aulacoseira granulata* is consistently present but in low numbers (<2%). Marine taxa are in the lowest proportions for the record.

Coorong core C7

The greatest change in the diatom flora, as demonstrated by the CONISS diagram (Fig. 6), occurs at 35 cm, well below the reduced clay layer at 14 cm. Other major changes occur at 75 and 145 cm, producing four zones.

Zone C7iv (156–145 cm): This zone is represented by two samples dominated by the marine tychopelagic species *Paralia sulcata* and, to a lesser extent, *Cyclotella striata* at 155 cm, and the marine (benthic) form *Odontella aurita* at 150 cm.

Zone C7iii (145–75 cm): The flora of this zone is dominated by *Paralia sulcata*, with representations from marine planktonic forms, including *Aulacoseira lacustris*, *Cyclotella striata*, and *Melosira nummuloides*, at selected levels. Marine benthic taxa (e.g., *Cocconeis krammeri*) are also well represented at selected levels, suggesting low turbidity. The brackish plankter *Chaetoceros muelleri* is well represented at the base of the zone.

Zone C7ii (75–35 cm): Marine taxa *Paralia sulcata*, *Melosira nummuloides* and *Cocconeis krammeri* dominate this part of the record. The upper part of the zone is marked by appearances of small Fragilariaceae, the benthic taxon *Cocconeis neodiminuta* and the brackish plankter *Chaetoceros muelleri*.

Zone C7i (35–0 cm): The transition to this zone is marked by a decline in marine taxa and the predominance of small Fragilariaceae *Staurosirella pinnata*, including the marine variety *Opephora* spp. True brackish-saline taxa (*Gyrosigma*, *Pleurosigma*) appear above 20 cm, and *Staurosira construens* appears after 15 cm. There is also an increase in *Tabularia fasciculata*, representing more than 20% of the assemblages 2–3 cm.

Discussion

Chronology

The ^{14}C ages derived for the core materials indicates that the wetland complex of Lake Alexandrina and the Coorong originated within the millennium after 8,000 yr B.P. This is supported by ages of $6,765 \pm 76$ (7,600 cal. yr B.P.) at the base of core LA1, $7,000 \pm 300$ (7,800 cal. yr B.P.) at the base of core LA2 and $6,327 \pm 40$ (7,200 cal. yr B.P.) at the base of core C3. The age of $4,886 \pm 37$ (5,500 cal. yr B.P.) at 152 cm for the piston core at C7 is not for the basal sediments as a Russian core extended to 235 cm. The ages of $2,381 \pm 34$ (2,400 cal. yr B.P.) at 82–83 cm in core C7, and $4,940 \pm 250$ (5,600 cal. yr B.P.) (402–410 cm) and $2,301 \pm 200$ (2,300 cal. yr B.P.)

(251–259) cm in core LA2, suggest steady sedimentation rates through the Holocene. By contrast, the mid-core ages from cores LA1 and C3 are apparently of similar age (>7,000 cal. yr BP) to that of the basal sediments. On face value, these dates suggest that the lower half the cores were deposited in a century or two and the remaining sediments in 7000 years. There is no stratigraphic or diatom density evidence to support this interpretation and so it is more likely that, given the very small quantities of organic carbon in the sediment (typically <1% of the sediment weight), the ages are suspect (Figs. 3 and 5). Rather, at these sites, it would appear that the ^{14}C analysis was probably affected by the hard—water effect (Shotton, 1972), where sediment is contaminated with older carbon. This process, which can occur when aquatic plants take up aqueous bicarbonate derived from old, inert sources, is common in wetlands set in calcareous environments (Roberts, 1998) such as the lower River Murray.

The construction of precise age-depth relationships for post-European sediments in these cores is somewhat problematic as a result of a number of factors including the variable concentrations of ^{210}Pb in the sediments, inconsistencies between age estimates derived from ^{210}Pb data and ^{137}Cs data in Coorong cores and the absence of ^{137}Cs determinations on Lake Alexandrina cores. Despite this, the chronologies established have sufficient precision to assess the degree of recent change.

Despite the shallow, wind stressed nature of Lake Alexandrina, excess ^{210}Pb ($^{210}\text{Pb}_{\text{ex}}$) concentrations in LA1 and LA2 decay steadily from the surface, with little evidence of a mixed layer. In core LA1, if the 6–7 cm sample is disregarded as an outlier, five $^{210}\text{Pb}_{\text{ex}}$ values essentially lie on a straight line between the surface and 11 cm. Using the constant initial concentration algorithm (CIC, Appleby and Oldfield, 1992), the 12–13 cm section is estimated to be approximately 78 years old (ca. 1919 AD). In the absence of other evidence (e.g., ^{137}Cs activities) it is difficult to further evaluate the 20th century chronology. However, the three samples from 12 cm to 19 cm inclusive have essentially the same ^{210}Pb concentrations, with the sample from 18 cm to 19 cm recording slightly higher values. Such data are likely to represent rapid accumulations of sediment. At 20 cm ^{210}Pb is not detected and indicates a CIC-age

greater than four ^{210}Pb half-lives (>90 years, or pre-1915 AD). In other localities within the Murray Basin (Gell et al., 2005), and indeed in other Australian lowland river systems (Leahy et al., 2005), these rapid accretions of sediment signal the commencement of European settlement. These data, taken together, suggest that the first evidence for European impact is registered at approximately 19 cm and that a late 19th Century or early 20th century age for the sediments below 19 cm appears probable.

In many ways the excess ^{210}Pb profile for LA2 is similar to that from LA1. The fitting of a linear line of best fit between the surface and the 17–18 cm sample (with the 8–9 cm sample excluded) determines a CIC sedimentation rate for these sediments of 0.175 cm/yr. These data suggest that sediments from 18 cm were laid down at approximately the turn of the twentieth century. However, as is the case with LA1, higher excess ^{210}Pb values are recorded from 24 cm to 25 cm. Certainly, it appears that these sediments are post-European in age, although a precise age estimate remains elusive.

The relatively constant $^{210}\text{Pb}_{\text{ex}}$ activities near the surface of the Coorong cores suggest changing sedimentation rates, changes in the source of sediment, or mixing. For Coorong core C3, a 2-layer CIC model (Robbins, 1978) was applied from the base of the constant-activity surface layer at 6 cm. Below this the log-linear plot of the $^{210}\text{Pb}_{\text{ex}}$ profile shows periods of constant accumulation rate to a depth of 23 cm, as indicated by the linear regressions in Fig. 2. The mean accumulation rate to a depth of 23 cm is 0.35 cm/yr and the segment with the highest rate lies in the 8–19 cm depth interval (0.86 cm/yr). The accumulation rate appears lower below this depth, with the excess ^{210}Pb activity at the 22–23 interval indicating an age of around 50 years. ^{137}Cs is still detectable at 28 cm. If the date of first detection of ^{137}Cs in Australian sediments is taken as 1955 (Leslie & Hancock, in press) this gives a minimum accumulation rate of 0.44 cm/yr (22 cm/50 years). The presence of ^{137}Cs at 26–28 cm is inconsistent with $^{210}\text{Pb}_{\text{ex}}$ which is essentially non-detectable at this depth indicating an age older than ~60–70 years (three ^{210}Pb half-lives). ^{137}Cs mobility may be responsible, or else sediment accumulation accelerated during the 1950s leading to variable ^{210}Pb

activities in the sediment. It is also worth noting the shape of the ^{137}Cs profile in both C3 and C7 (discussed below). Although other explanations are possible, the distinctive ^{137}Cs activity peak seen in both cores suggests a correlation with global ^{137}Cs fallout activity which is recorded to have peaked in 1964. Using the 2-layer CIC model the $^{210}\text{Pb}_{\text{ex}}$ chronology indicates an age of 22–28 years for ^{137}Cs peak at 17–19 cm (1977–1983 AD). Again this analysis indicates a discrepancy between the ^{210}Pb profile (as modelled by CIC) and the ^{137}Cs profile, although in this case the CIC age is too young. Whilst the detailed chronology of the C3 record is the subject of further analysis, it is clear that, at a minimum, the upper 23 cm accumulated in the latter half of the 20th Century.

In Coorong core C7 the 2-layer CIC model was applied from the base of the surface layer at 13 cm. Below this linear regressions on the log-linear $^{210}\text{Pb}_{\text{ex}}$ plot indicate accumulation rates of 1.9 cm/yr and 0.4 cm/yr, with a slow period between 18 cm and 22 cm. The mean accumulation rate to 29 cm depth is 0.43 cm/yr, similar to C3. ^{137}Cs is seen at 35 cm, a depth not consistent with the $^{210}\text{Pb}_{\text{ex}}$ CIC model age at this depth (>70 years). However for this core the CIC age corresponding to the peak ^{137}Cs activity at 26–29 cm corresponds reasonably well with the expected age (37 ± 4 years corresponding to 1963–1971 AD). Once again, although the ^{210}Pb – ^{137}Cs discrepancies are not resolved it is clear that all or the bulk of the upper 30 cm of C7 was deposited in the second half of the 20th Century. In summary, ^{210}Pb and ^{137}Cs chronometers indicate that for both Coorong cores the sediment accumulation rate over the last 50 years lies in the range 0.35–0.45 cm/yr.

Although defining the precise pre and post-European boundary in our records is difficult since the ^{210}Pb chronologies do not extend to the point of settlement, it is clear that sedimentation rates have increased many-fold in the terminal wetlands of the Murray Basin. At all sites, the ^{210}Pb -derived sediment accumulation rates for recent sediments, ranging from 0.18 cm/yr in LA2 to ~ 0.4 cm/yr in the Coorong cores are much higher than their pre-European counterparts (e.g., 0.05 cm/yr between ca. 7,000 and 2,000 years BP in LA2 and 0.03 cm/yr ca. 5,000 and 2,000 years BP at C3).

Diatom analysis

Lake Alexandrina

Despite the site of core LA1 being at least 500 m from the shores of Lake Alexandrina (Fig. 1), the diatom record is strongly dominated by littoral (primarily epiphytic) and facultative planktonic taxa. This flora is typical of very shallow (<1 m) lake sites where either the lake area was very small or the core was taken close (<50 m) to the shore, or where there was enough light penetration to allow growth on the benthos (see Bennion et al., 2000). These, and not euplanktonic taxa, dominate in this northern part of Lake Alexandrina as the site is close to a littoral zone with a 5 m wide band of fringing *Phragmites* and *Typha* and protected from the influence of the River Murray by a silt barrier. Wind stress and subsequent turbulence would readily entrain these taxa into the water column before being deposited into the sediment. Additionally, these facultative planktonic diatoms (the small *Staurosira* spp., *Staurosirella* spp. and *Pseudostaurosira* spp.) live in the water column in Lake Alexandrina (Fluin, 2002).

The base of core LA1 is dominated by *Staurosirella pinnata*, *Epithemia adnata* and *Cocconeis placentula*, indicating a shallow, meso-eutrophic, reed fringed environment with fresh to brackish water in a pH range of 8.0–9.0. The diatom assemblage from 77 cm is dominated by *Staurosirella pinnata* that peaks at 70 cm (78%) and then decreases to <10% at the top of the zone, being replaced by a range of benthic and epiphytic taxa. *Staurosirella pinnata* is gradually replaced by *Epithemia adnata* and *Rhopalodia gibba*—these two taxa accounting for >70% of the total assemblage at 56 cm. This most likely reflects an increase in alkalinity and a reduction in water level. At 56 cm pH values probably exceeded 9.0, with high pH being conducive to valve dissolution, accounting for the diatom barren zone at 54 cm. Through this early phase the river potamoplankton *Aulacoseira granulata* is regularly present, and, apart from a peak at 63 cm, thalassic forms (e.g., *Thalassiosira lacustris*) are absent.

Towards the middle of the core *Staurosirella pinnata* returns to dominance with *Melosira varians*, suggesting a deepening of lake waters. The peaks in *Aulacoseira granulata* suggest that this water is

derived from river rather than tidal inflow. The flora is dominated by *Stausirella pinnata* at 29 cm, after which this taxon declines to the top of the core. This decline marks a point of greatest change in the diatom community and represents the estimated time boundary of the onset of non-indigenous settlement. The epiphyte *Cocconeis placentula* replaces the facultative planktonic *Stausirella pinnata* reflecting modification of diatom habitat availability, most likely an increase in abundance of aquatic plants (submerged and/or fringing). Additionally, the increase in abundance of some of the minor littoral taxa indicative of eutrophic to hypertrophic conditions (*Cymbella cistula*, *Gomphonema parvulum*, *Melosira varians*, *Rhopalodia gibba* and *Tabularia fasciculata*) reveals an increase in nutrient concentrations within the lake, probably by the late 1800s, most likely arising from human settlement. *Tabularia fasciculata* also reflects high lake water salinities, perhaps reflecting seepage from elevated saline water tables that occurred due to extensive vegetation clearance soon after non-indigenous settlement (Menzies, 1983). The peak in *Tabularia fasciculata* and the absence of *Aulacoseira granulata* at 11 cm is dated by ^{210}Pb to possibly occur early as the 1900s and so may correlate with the severe drought in south eastern Australia between 1914 and 1915 where river conductivity at Morgan measured 10,000 EC (Eastburn, 1990). The eutrophic littoral taxa that increased in abundance in the early 1900s decrease in the most upper sections of the core. The other major changes in the recent past are an increase in *Aulacoseira granulata* and *Pseudostaurosira brevistriata* numbers, which are both still indicative of high nutrient concentrations. The decrease in littoral taxa may represent an improvement in trophic status, but the concurrent increases in eutrophic planktonic and facultative planktonic taxa indicate that nutrient concentrations remain high. Without further information (i.e., comparison with other biological fossil indicators), interpretation of the recent past from this site remains speculative.

The base of the core LA2 is dominated by *Cocconeis placentula* and *Aulacoseira granulata*, and to a lesser extent, *Thalassiosira lacustris*. The presence of *Thalassiosira lacustris*, *Cyclotella striata* and *Paralia sulcata* indicate marine influence at this time. At 420 cm, *Stausirella pinnata* increases abruptly to nearly 40% at the expense of littoral, rather than planktonic, taxa. High values of

Stausirella pinnata are sustained through to the top of the core, other than at 260–300 cm depth, where they are briefly replaced by littoral taxa. *Aulacoseira granulata* also decreases between 380 cm and 220 cm, in part replaced by *Stephanodiscus parvus*. *Paralia sulcata* is absent above 340 cm and *Thalassiosira lacustris* has lower values at 260 cm, replaced briefly by littoral taxa, although the thalassic planktonic taxon, *Cyclotella striata*, remains common. This change in diatom community is likely to represent a decrease in lake level and increased penetration of seawater, possibly associated with the variable, dry climate phase after the mid-Holocene wet phase as identified by Stanley & De Deckker (2002), Bowler (1981), and others. This would then lead to lower abundance of riverine/fresh lake planktonic diatoms and an increase in littoral taxa, particularly benthic taxa, and a mixing or incursion of more brackish to marine planktonic taxa from areas closer to the river mouth.

The planktonic taxa *Aulacoseira granulata* and *Thalassiosira lacustris* increase at 220 cm, at the expense of the estuarine diatom *Cyclotella striata*, marking a strong river input to the estuary. The decline in *Thalassiosira lacustris* above 160 cm marks a further increase in freshwater river input conditions, perhaps influenced by the increases in precipitation witnessed in lake records in western Victoria (De Deckker, 1981). The subsequent decrease in *Aulacoseira granulata* from 80 cm, combined with the increase in *Stausira construens* forma *venter*, indicates reduced lake levels and river input. The greatest change to the diatom flora is again near the surface, at 30 cm, mostly attributable to a strong increase in *Pseudostaurosira brevistriata* coinciding with the estimated time boundary for the onset of river regulation. This increase is associated with a small decrease in *Stausirella pinnata* that may be attributable to the barrages controlling tidal flux to the Lake favouring *Pseudostaurosira brevistriata*, which has a lower salinity tolerance than *Stausirella pinnata* (Gell, 1997; Fluin, 2002).

Coorong

Prior to European settlement the northern Coorong (as represented by cores C3 and C7) was characterised by a high proportion of marine and/or estuarine

taxa. These are mostly planktonic forms such as *Cyclotella striata*, *Paralia sulcata* and *Melosira nummuloides*, but also benthic taxa such as *Cocconeis* spp. and *Grammatophora oceanica*. The continued dominance of marine-estuarine taxa demonstrates a predominantly tidal, rather than continental, source for the waters of the Coorong before European settlement. The paucity of true saline lake taxa (*Amphora coffeaeformis*, *Gyrosigma attenuatum*) suggests that salinities were mostly below seawater. The abundance of *Campylodiscus clypeus* suggests that conductivities as low as 5–10000 EC were possible at site C3. At site C7 the rarity of such brackish taxa suggests that salinities were mostly high, and historically, consistently higher than those at site C3.

Low values of *Aulacoseira granulata* and *Aulacoseira ambigua* in core C3 suggest minimal river input, mostly around 75 cm. These taxa are not represented in the sediments of core C7, suggesting that pre-regulation riverine input to the Coorong was spatially limited to the uppermost northern reach. Other taxa which are commonly found in Lake Alexandrina plankton surveys, such as *Cyclotella* spp., *Synedra ulna*, *Staurosirella pinnata* and *Melosira varians* are absent throughout the entire Coorong records, with only *Staurosirella pinnata* present in the post-regulation period.

All marine indicators decline in both cores after European settlement and the diatom assemblages become dominated by members of the Fragilariaceae (*Fragilaria*, *Staurosira*, *Staurosirella*). These taxa are typical of both inland and coastal waters and appear to exploit disturbed or variable systems where there is a paucity of habitats for specialist taxa (Espinosa, 1994; Fluin, 2002; Bennion et al., 2004; Mackay et al., 2005; Weckström & Juggins, 2006). The Coorong post-European period is therefore more difficult to characterise due to the cosmopolitan nature of the taxa present. What is known, however, is that due to massive extractions from the river system followed by the barrage separation of the lake and Coorong, availability of freshwater to enter the Coorong must have been minimal during this time period. Therefore, these taxa are likely to be autochthonous, rather than being fluvially transported from Lake Alexandrina. If these taxa were present in the pre-regulation phase of the fossil record, then the argument of minimal connection between the two

systems becomes ambiguous. However, this is clearly not the case, with the majority of pre-regulation taxa between the two systems showing little similarity. This hypothesis is investigated further in ordination of the four core assemblages.

Ordination of the core records

Detrended correspondence analysis indicates that in the pre-European period, the diatom flora from all core sites was for the most part distinct, with only two samples from Coorong core 7 overlapping with samples from Coorong core 3. Assemblages from the two Coorong cores were differentiated on axis 2, while those from Lake Alexandrina were located on different parts of axis 1. In the latter part of the Coorong records, samples from C3i-ii and C7i converge, and to some extent, overlap in ordination space with samples from Lake Alexandrina core 2 (although notably more so with older samples from A2b-d than with those from A2a). By contrast to the upper sediments from the Coorong, samples from Lake Alexandrina core 1 are distinct from both the other Lake Alexandrina and samples from the Coorong, plotting instead high on axis 1 (Fig. 7).

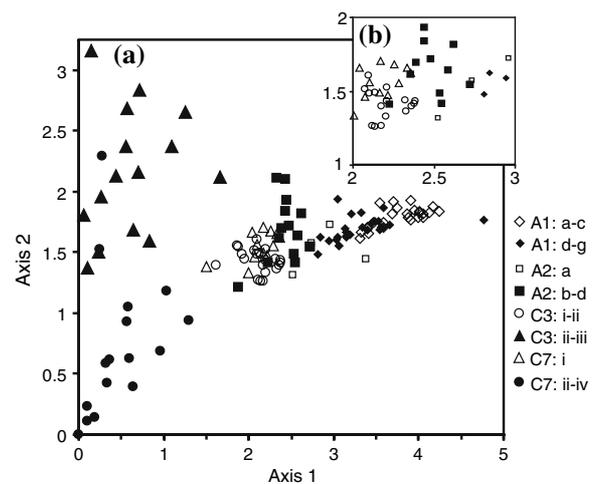


Fig. 7 a. Detrended Correspondence Analysis of fossil diatom assemblages from Lake Alexandrina and The Coorong. b. Enlargement of (axis 1 2–3 and axis 2, 1–2)

Conclusion

The Holocene diatom assemblages of Lake Alexandrina reflect relatively freshwater conditions with longstanding and major inputs from the River Murray, particularly after ca. 2,000 years b.p. at site LA2. In the protected site LA1, the freshwater flora is dominated by fresh to oligosaline littoral and facultative planktonic taxa. Marine water indicators were never dominant in Lake Alexandrina. The pre-European flora of the Coorong reveals a prevailing marine influence with salinity levels varying within the subsaline range. River flora made a notable contribution to the fossil assemblage at the northernmost site C3 during the mid-Holocene but have been uncommon since. Other than this episode, for much of the last 4,000–5,000 years, river flora have been essentially absent from the Coorong sediments and the dominant Coorong species have been absent or in very low abundances from Lake Alexandrina. For the entire Late Holocene, the diatom evidence suggests the two coastal lake systems evolved in relative isolation.

In all cores (Lake Alexandrina and Coorong) the greatest changes to the diatom flora occurred at, or after, European settlement. In Lake Alexandrina the post-impact condition is dominated by taxa with high nutrient and pH tolerances and low salinity tolerances. The impact of human activity in the Coorong is also obvious with typical marine flora being rapidly replaced by species with wide environmental tolerances. The presence of these taxa, and the absence of other supporting taxa, means that the water quality in the Coorong post-European period is more difficult to evaluate than that in Lake Alexandrina. Although establishing connectivity between the two systems during the post-European is problematic, the most critical phase, in terms of management, is the pre-impact condition, and the taxa in all four records strongly suggest marginal levels of connectivity.

The provision of environmental flows from the River Murray has been identified as an important management measure to restore the ecological character of the Coorong. This evidence shows that the ecological character of the Coorong was, for most of its existence, a coastal lagoon strongly influenced by tidal water, presumably through the Murray Mouth. Also, the character of the Coorong

changed early in the European period so that by the time of its listing as a Ramsar site in 1985, it was already substantially modified. Finally, owing to the independent evolution of the Coorong and Lake Alexandrina, efforts to restore the ecological health of the Coorong should focus on re-establishing its link to marine waters via the Murray Mouth. It would seem that the role of the Murray River is more important for the opening of the Murray Mouth and maintaining an estuary, than directly making changes to the water balance in the Coorong.

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