# Sedimentology and geochemistry of an urban coastal lake system: Coombabah Lake Nature Reserve, Gold Coast, Queensland

Tracy D. Frank
*University of Nebraska-Lincoln*, tfrank2@unl.edu

Christopher R. Fielding
*University of Nebraska-Lincoln*, cfielding2@unl.edu

Published in *Australian Journal of Earth Sciences* **51** (2004), pp. 261–271.

Submitted July 18, 2003; accepted March 5, 2004.

# Sedimentology and geochemistry of an urban coastal lake system: Coombabah Lake Nature Reserve, Gold Coast, Queensland

**T. D. Frank and C. R. Fielding**

Department of Geosciences, University of Nebraska–Lincoln, Lincoln, NE 68588–0340, USA.

*Corresponding author* —T. D. Frank, email tfrank2@unl.edu

**Abstract**

A study was initiated to address environmental concerns associated with changes in land use in the catchment area of Coombabah Lake, a brackish coastal lake system located in southeast Queensland. Sedimentological and geochemical data derived from a series of cores that penetrate the *ca.* 0–6000 year-old lacustrine sequence indicate that throughout much of its history, Coombabah Lake has remained a quiet, shallow, water body fed by fine-grained sediment dropped from suspension. Discrete and laterally continuous, shelly horizons form the basis for the stratigraphy developed for the lake sequence. A lithological transition in the upper 50 cm of the sediment column, from mud to shell-rich, sandy mud, suggests that the depositional regime changed ~500 years ago as accommodation space was filled. At this time, the dominant sedimentary processes changed to include reworking, partial bypass of sediment, the intermittent concentration of shell debris by winnowing, and the development of a flood-tidal delta complex in the lower reaches of the lake. Sharp increases in total organic carbon, total nitrogen, and total phosphorus concentrations below the lithological transition at 50 cm depth suggest that the capacity of the system to preserve organic matter and trap nutrients decreased significantly after the transition in depositional regime. Results indicate that current conditions in Lake Coombabah are governed by natural processes associated with the long-term evolution of coastal lake systems, and reveal little to suggest that there were any adverse affects resulting from recent human activities in the surrounding catchment.

**Keywords:** environmental geology, estuarine sediments, geochemistry.

## Introduction

In Australia more than 80% of the population lives within 50 km of the coastline (Australian Bureau of Statistics 1996), with much of the urban development centered on coastal flood plains and along river estuaries. Since World War II, much of the population growth has been focused in southeast Queensland (Figure 1a), an area that stretches northwards from the New South Wales–Queensland border ~220 km to the coastal city of Noosa and westwards from the coast to the Great Dividing Range. The region is experiencing one of the fastest population growth rates (currently 3% per year) of any large city in the developed world, and Brisbane, the urban centre of the region, is the fastest growing capital city in Australia (Skinner *et al*. 1998). Whereas initial settlement of the region in the early to mid-19th century occurred along the shores of the Brisbane River (now Brisbane City), the population has since expanded to the north (Sunshine Coast) and south (Gold Coast) of Brisbane, resulting in high population density throughout most coastal areas of southeast Queensland (Capelin *et al*. 1998).

Because urbanization has led to increases in sewage output, land clearing, and the recreational and commercial use of waterways, coastal and estuarine systems of southeast Queensland are becoming increasingly stressed (Dennison & Abal 1999). To develop effective strategies for environmental management and to prevent further degradation, a series of regional surveys has been launched to gauge the health of coastal and estuarine systems in southeast Queensland (Tibbets *et al*. 1998; Dennison & Abal 1999). Many of these previous investigations emphasized biological and chemical issues, and did not involve an informed analysis of the sedimentary substrate. Previous work in other systems has demonstrated that meaningful results are best achieved by considering the role of the surface and near-surface sediment in chemical and biological processes (Eyre & McConchie 1993).

The present study uses sedimentological and geochemical data derived from a suite of seven cores to examine the long-term history of Coombabah Lake, a brackish coastal lake system located in a heavily urbanized area of the Gold Coast, Queensland. (Figure 1b). Understanding the natural processes involved in the evolution of this and other coastal lakes, including the ability of these systems to maintain a balance between the storage and output of sediment and nutrients that enter the system, is a crucial part of any strategy designed to maintain the integrity of these unique environments.

## Setting and Sedimentological Context

Coombabah Lake is located 5 km from the coast and ~8.5 km northwest of Southport on the Gold Coast of south-

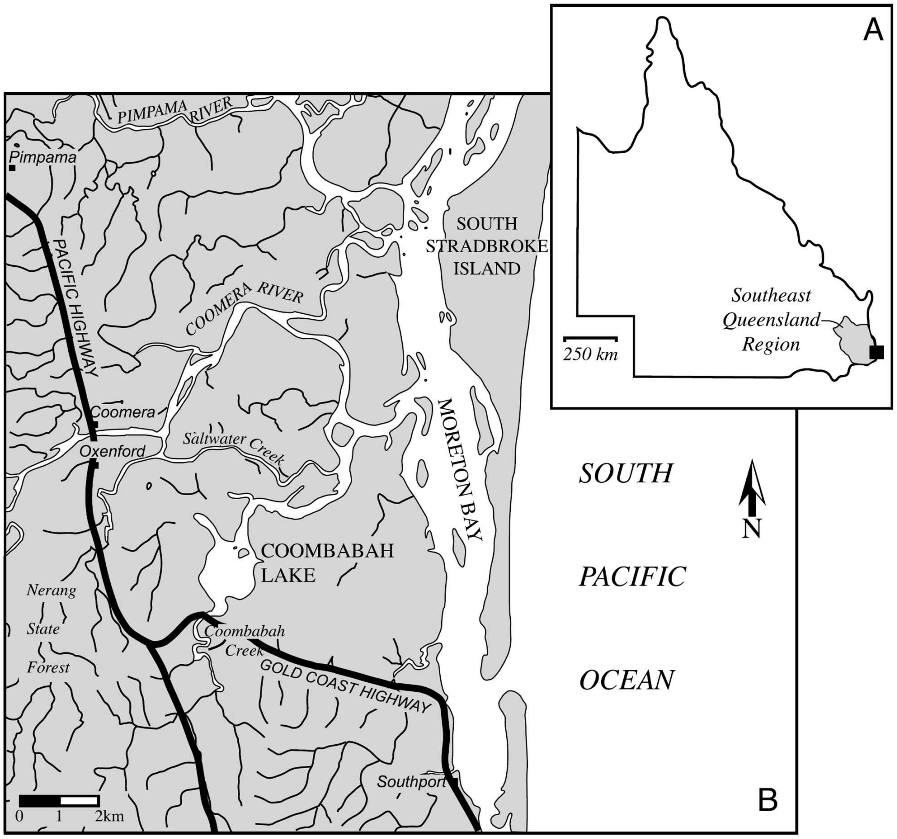


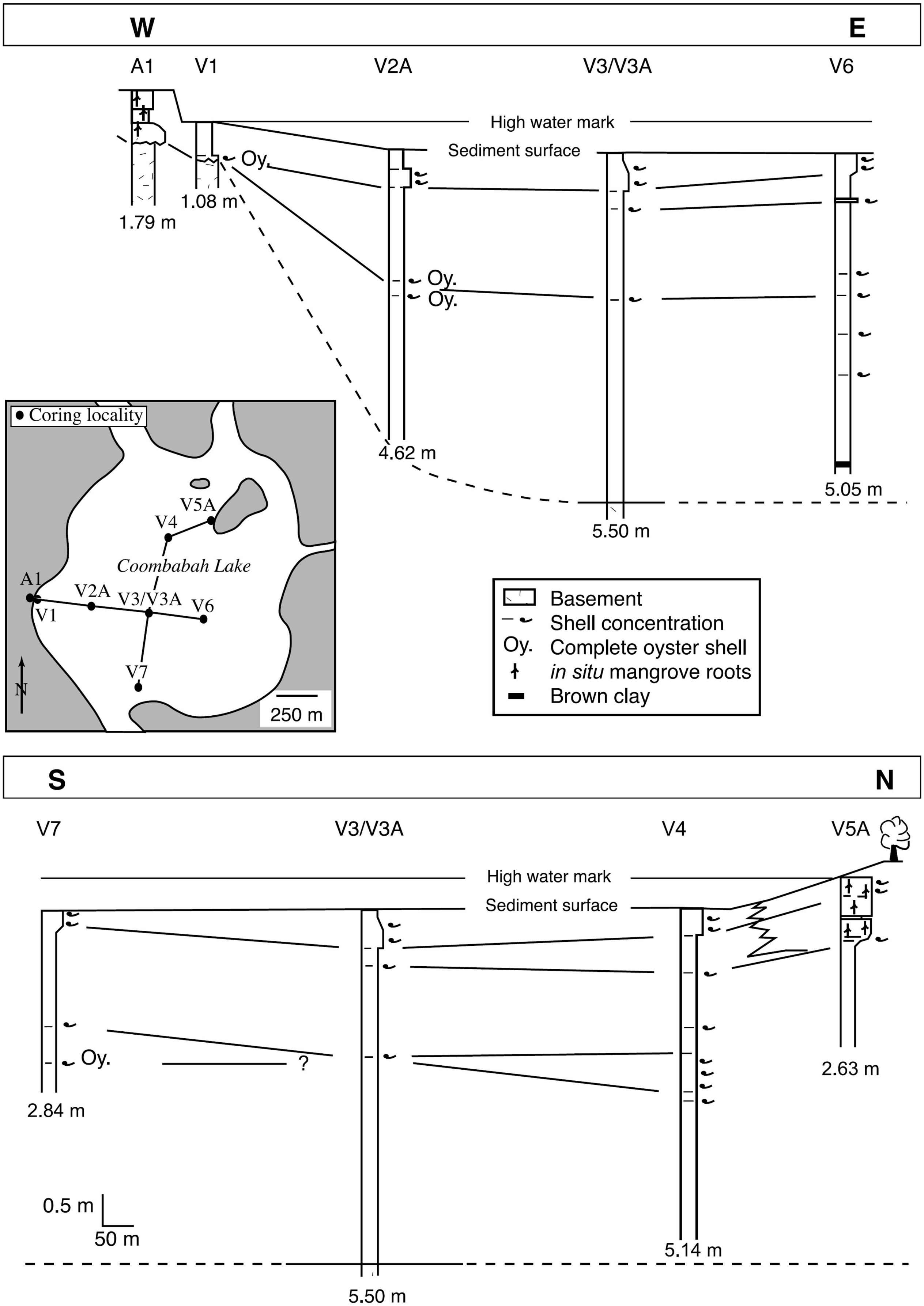

**Figure 1.** (a) Map of Queensland showing extent of southeast Queensland region (stippled) and study region (filled square). (b) Detailed map of study region showing Coombabah Lake, regional drainage systems, and the locations of major cities and roads.

east Queensland (Figure 1). The lake, which comprises the Coombabah Lake Nature Reserve and borders the Ivan Gibbs Wetland Reserve, is classified as a Fish Habitat Area within the Moreton Bay Marine Park and serves as an important wildlife corridor between the Nerang State Forest and the coast. Coombabah Lake is hydrologically open and affected by tidal flux with a tidal range of less than 1 m. The lake is fed from the southwest by Coombabah Creek, which meanders ~15 km from its headwaters in Nerang State Forest, through residential areas, and into Coombabah Lake. The creek exits the lake at its northern end and flows into Saltwater Creek before joining the Coomera River, which discharges into Moreton Bay to the west of South Stradbroke Island. Over the past five decades, human activities in the areas surrounding Coombabah Lake have altered significantly. Major changes included the clearing of the Gaven Forest for a pine plantation in the 1960s, the opening of a road-metal quarry adjacent to the headwaters of Coombabah Creek in Nerang State Forest in the 1980s, and the development of the Helensvale residential estate, which lies along the western margin of Coombabah Lake, in the 1970–1990s. Urban development surrounding the lake included the clearing of land for golf courses and the construction of a sewage treatment plant on the eastern margin of the lake.

Present water depths in Coombabah Lake range from 0 to ~1 m in channels at low tide, with large portions of the lake forming exposed mud flats at low tide. Examination of aerial photographs and comparison with similar coastal plain environments in eastern Australia (Roy 1980; Roy & Crawford 1981) suggests that the lake formed following the Holocene (post-glacial) sea-level rise. At the post-glacial sea-level maximum, the broader Coombabah–Helensvale valley was flooded by the sea, forming a drowned valley or ria system similar to many of the estuaries on the east coast of Australia (Roy 1984, 1994). This drowned valley has since been infilled by sediment through a combination of downstream sediment supply, from Coombabah Creek and other watercourses, and backfilling from the coastal zone.

Because the lake is swept by a semidiurnal tide, the water in the lake is turbid and brackish, and supports a mangrove-dominated fringing flora, with *Casuarina* and *Melaleuca* on slightly more protected areas elevated above the high-tide mark. Mangrove roots are abundant over a 10–20 m-wide zone along the outer margin of the lake, and more dispersed across other shallow parts of the basin. Shells of oysters, cockles, mussels, and gastropods are abundant across the lake floor. Few if any living mollusks were encountered at the surface, but articulated, probably extant bivalves were noted in some cores up to 65 cm below the sediment surface. The muds that typically form surface sediment are tinged brown, suggesting some oxidation at the sediment–water interface, whereas subsurface sediments (below ~5 cm) are uniformly medium blue-grey (10BG 4/1) apart from a few, very thin brown horizons, and a strong H 2 S smell was noted during core recovery.

**Figure 2. (opposite, p. 263)** Stratigraphic profiles across west to east (top) and south to north (bottom) transects drilled in Coombabah Lake, showing relative locations and major features of cores COO-A1, -V1, -V2A, -V3A, -V4, -V5A, -V6, and -V7. Vertical scale relates to penetrated depths. Inset map shows coring sites and transect traces.


W
E
A1
V1
V2A
V3/V3A
V6
High water mark
Sediment surface
Oy.
1.79 m
1.08 m
Oy.
Oy.
4.62 m
5.05 m
5.50 m
Coring locality
V5A
V4
Coombabah Lake
A1
V2A
V3/V3A
V6
V1
V7
N
250 m
Basement
Shell concentration
Oy. Complete oyster shell
in situ mangrove roots
Brown clay
S
N
V7
V3/V3A
V4
V5A
High water mark
Sediment surface
Oy.
?
2.84 m
2.63 m
0.5 m
50 m
5.14 m
5.50 m

An anastomosing network of shallow channels cuts the floor of the lake, much of which is exposed at low tide. The channels are typically 20–50 m wide and over most of the lake they are <1 m deep at low tide. These channels become deeper and focused into a single channel thread where Coombabah Creek enters and exits the lake. Elsewhere, the lake floor comprises muddy shoals and flats that display an undulating topography of <1 m. Near the northern (outlet) end of the lake, the sediment surface has been locally elevated to ~0.3 m above high-tide level to form two islands, the larger one approximately 300 m long and 100 m wide. These islands are densely vegetated by mangroves and halophytic grasses.

## Methods

### *Core recovery*

The nature and thickness of subsurface sediment in Coombabah Lake were addressed by acquiring a series of cores in a pattern along two transects, one orientated north–south and the other east–west across the lake (Figure 2). The common site on both transects, the location of core COO-V3A, was used as a focus for geochronological analysis (see below). The sedimentary section on the western shore of the lake was tested by means of a hand auger (hole COO-A1, which penetrated to 179 cm). The remaining cores (COO-V1 to V7) were captured inside aluminum pipes (70 mm irrigation pipe), which were either pushed manually into the subsurface (to as much as 5.5 m below surface) or power-assisted by a vibrocore device comprising a vibrating steel head clamped to the pipe and attached by hydraulic hose to a portable generator unit. At most sites the fine-grained sediments were unavoidably compacted by 30–55% during the coring process (see Table 1 for penetrated and recovered depths for each site).

### *Geochemistry*

A suite of samples was analyzed geochemically to evaluate the nature of material sourced from the catchment and/or produced *in situ* (minerals and organic matter) and stored in the sedimentary record of Coombabah Lake. Sediment samples (~20 cm 3 ) were collected from regularly spaced intervals in cores COO-V1, COO-V2A and COO-V3A. To minimize contamination from the drill pipe, the outer ~2 cm of the core was avoided during sample collection. Samples were dried overnight in an oven at 50 °C and ground to a fine, homogeneous powder using a mortar and pestle. Samples were analyzed for total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC), and concentrations of $SiO_2$ , $Al_2O_3$ , and $Fe_2O_3$. The TN was analyzed by combustion on a LECO CNS 2000 combustion analyzer set at 1100 °C. The TOC was measured using a UIC Carbon Analyser, which measures all of the $CO_2$ that is liberated by either acidifying samples (total inorganic carbon: TIC) or heating samples to 1000 °C (total carbon: TC), and backtitrating to a coulometric end-point. The TOC was calculated as the difference between concentrations of TC and TIC. The TP, Si, Al, and Fe concentrations were analyzed by inductively coupled plasma atomic emission spectrometry (ICP-AES). Samples analyzed for TP were digested with HCl, $HNO_3$ and HF in a CEM MSP1000 microwave digester. The remaining samples were prepared using the lithium metaborate fusion method and Lu was used as an internal standard. Geochemical data from the present study are supplemented by data from Gallagher (2001) and presented in Table 2.

To assess the average sedimentation rate in Coombabah Lake, samples (~50 $cm^3$ ) were taken from regularly spaced intervals in core COO-V3A, chosen for its location in the lake's depocenter. Samples were dried thoroughly in an oven at 50 °C, powdered, and sent to the Australian Nuclear Science and Technology Organisation (ANSTO) for $^{210}Pb$ dating using the alpha method.

## Results

### *Core description*

Auger hole COO-A1, on the western edge of the lake (Figure 2), encountered a short interval of sandy clay overlying a blue-grey clay interval of similar appearance to sediments from the lake, and all were penetrated by live plant roots. Beneath the clay was a fining-upward bed of gravelly sandy clay to sandy clay, which abruptly overlayed intensely weathered, stiff white clay with iron oxide concretions and mottles, and which passed gradationally downward to weathered, quartz-veined quartzite at the base of the hole. The top layer of sandy clay constituted the present (supratidal) soil horizon, whereas the underlying blue-grey clay was interpreted as recording deposition in the lake. This suggests that the lateral margins of the lake may have prograded slightly in a lakeward direction since the post-glacial

**Table 1.** Core recovery.

| Core | Penetrated depth (cm) | Recovered thickness (cm) | Compaction (%)[a] | GPS coordinates [b] Easting | Northing |
|---|---|---|---|---|---|
| COO-A1[c] | 179 | 179 | 0 | 5 336 84 | 69 126 55 |
| COO-V1 | 108 | 50 | 54 | 5 337 00 | 69 126 35 |
| COO-V2A | 462 | 300 | 35 | 5 340 03 | 69 126 05 |
| COO-V3/V3A | 505 | 300 | 41 | 5 342 95 | 69 125 78 |
| COO-V4 | 514 | 283 | 45 | 5 344 34 | 69 129 83 |
| COO-V5A | 263 | 180 | 32 | 5 346 86 | 69 130 80 |
| COO-V6 | 505 | 281 | 44 | 5 346 20 | 69 125 38 |
| COO-V7 | 284 | 149 | 48 | 5 342 70 | 69 121 52 |

[a] Compaction due to drilling process; [b] AMG Grid Zone 56J; [c] Auger hole.

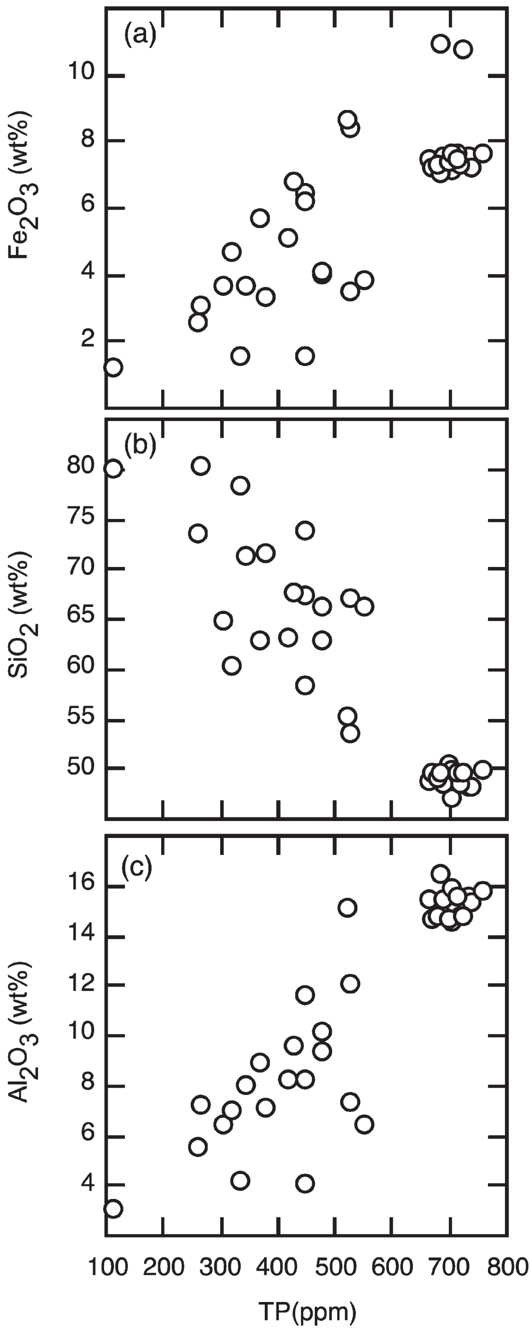



**Figure 3.** Concentrations of $Fe_2O_3$ (top), $SiO_2$ (middle), and $Al_2O_3$ (bottom) *vs* total phosphorus (TP) in Coombabah Lake sediments.

sea-level maximum. The fining-upward, gravelly bed is interpreted as a lake-marginal lag deposit developed over the strongly decomposed basement of Upper Devonian–Lower Carboniferous Neranleigh–Fernvale beds quartzites. The important outcomes from this hole are the presence of strongly weathered basement at shallow depth, and the occurrence of lacustrine muds beneath what is now a stabilized, supratidal surface.

Site COO-V1 (50 cm recovered, 108 cm penetrated) penetrated a short interval of shelly, silty clay abruptly overlying strongly weathered clay with iron oxide mottles and concretions. The basal portion of the silty clay was essentially a muddy shell hash, with abundant shells and fragments of cockles, some gastropods and mussels, and occasional oysters. A similar assemblage of mollusks was found dispersed through higher levels of the core. This core can also be interpreted to record lake mud sedimentation above a shallow, weathered basement. The abundance of shells in the interval immediately above the basement interface suggests a condensed lag representing a significant period of time. The lack of shell fossils in adjacent auger hole COO-A1 may be due to dissolution associated with penetration by plant roots and associated freshwater influx.

Cores COO-V2A, -V3A, -V4, -V6 and -V7 show lithologically similar, although thicker, sections dominated by medium blue-grey clays with dispersed mollusk shells similar to the previously described cores. In all cores a sandy mud unit containing abundant mussels and gastropods was noted in the uppermost ~50 cm of section (penetrated depth). Other concentrations of shells or, in the case of COO-V2A complete large oyster shells, were noted at greater depths particularly at 130–160 cm below sediment surface. The uniform lithology throughout these cores indicates consistent patterns of sediment accumulation over much of the Holocene history of the lake, with little if any significant change over time. Sediments are inferred to have been deposited from suspension, in a setting similar to the present lake. Drilling experience at site COO-V3, where the pipe became lodged in the basement at ~5.5 m, suggests that this lithology occurs almost down to the basement interface in the centre of the lake basin. The sedimentary successions penetrated in the remaining cores indicate a section perhaps equivalent in age to the condensed section of COO-V1 but considerably expanded due the increased accommodation space available in the lake depocenter.

Site COO-V5A, from near the northern (outlet) end of the lake, is worthy of special mention because it is the only site to have encountered a sandy lithology. A composite, coarsening-upward sand body was noted in the uppermost 106 cm in COO-V5A. The sand body contains a shell accumulation in the uppermost 30 cm, as in other holes, and other shell material lower down. The sand body is penetrated extensively by mangrove roots. Below 106 cm, the lithology fines downward into medium blue-grey clays similar to those encountered in other cores. The abundance of sand in core COO-V5A cannot be satisfactorily explained by its proximity to the axial drainage channel, because other cores drilled close to channels did not encounter such sands (e.g. COO-V7, drilled close to the mouth of the inlet channel at the southern end of the lake). Rather, it is suggested that the sand, which seems to be abundant at and near the surface at the northern end of the lake, may have been transported landward from the coastal zone, perhaps forming a flood–tidal delta complex. It is not clear whether or not this system is still active, but it may also explain the presence of elevated, sediment-cored islands at the northern end of the lake.

### *Geochemistry*

#### TOC, TN, AND TP CONTENTS

The TOC, TN, and TP in Coombabah Lake sediments were measured to determine the concentration and source of nutrients and organic matter in the sediments. The TOC and TN contents range from 0.4 to 2.0 wt% and 230 and 1420

**Table 2.** Geochemical data for Coombabah Lake sediment samples.

| Depth [a] (cm) | TOC (wt%) | TN (ppm) | TP (ppm) | C:N | C:P | $SiO_2$ (wt%) | $Al_2O_3$ (wt%) | $Fe_2O_3$ (wt%) |
|---|---|---|---|---|---|---|---|---|
| **COO–V1** | | | | | | | | |
| 1.0 | – | 801 | 524 | – | – | 67.2 | 7.4 | 3.6 |
| 13.0 | – | 541 | 304 | – | – | 65.1 | 6.5 | 3.7 |
| **COO–V2A** | | | | | | | | |
| 1.0 | – | 780 | 477 | – | – | 63.0 | 10.2 | 4.1 |
| 51.1 | – | 1009 | 661 | – | – | 49.0 | 15.5 | 7.5 |
| 101.5 | – | 1012 | 665 | – | – | 49.9 | 14.8 | 7.3 |
| 151.5 | – | 1004 | 702 | – | – | 47.3 | 14.7 | 7.1 |
| 201.0 | – | 1054 | 732 | – | – | 48.3 | 15.6 | 7.6 |
| 251.0 | – | 1007 | 737 | – | – | 48.5 | 15.4 | 7.3 |
| 291.0 | – | 1080 | 684 | – | – | 49.5 | 15.0 | 7.1 |
| **COO–V3A** | | | | | | | | |
| 3.8 | – | 693 | 476 | – | – | 66.4 | 9.5 | 4.1 |
| 16.5 | – | 596 | 343 | – | – | 71.5 | 8.1 | 3.8 |
| 34.5 | – | 495 | 377 | – | – | 71.7 | 7.2 | 3.4 |
| 69.0 | – | 957 | 713 | – | – | 49.0 | 15.6 | 7.7 |
| 108.5 | – | 1032 | 688 | – | – | 48.7 | 15.5 | 7.6 |
| 145.0 | – | 947 | 717 | – | – | 48.7 | 14.8 | 7.4 |
| 161.0 | – | 1001 | 679 | – | – | 49.4 | 14.8 | 7.3 |
| 187.5 | – | 968 | 696 | – | – | 50.8 | 14.8 | 7.4 |
| 211.5 | – | 1069 | 756 | – | – | 50.1 | 15.8 | 7.7 |
| 240.5 | – | 1084 | 702 | – | – | 50.1 | 16.0 | 7.7 |
| 288.0 | – | 1160 | 710 | – | – | 49.9 | 15.6 | 7.5 |
| **COO–V4** | | | | | | | | |
| 2.0 | 0.5 | 510 | 263 | 10.0 | 19.4 | 80.5 | 7.3 | 3.2 |
| 5.0 | 0.6 | 600 | 295 | 9.7 | 19.6 | – | – | – |
| 10.0 | 0.7 | 640 | 291 | 11.2 | 24.6 | – | – | – |
| 15.0 | 0.8 | 730 | 547 | 10.9 | 14.5 | 66.4 | 6.5 | 3.9 |
| 20.0 | 1.0 | 830 | 337 | 12.5 | 30.8 | – | – | – |
| 30.0 | 0.9 | 640 | 319 | 14.0 | 28.0 | 60.6 | 7.0 | 4.7 |
| 40.0 | 1.1 | 690 | 445 | 15.8 | 24.5 | 58.7 | 8.3 | 6.5 |
| 50.0 | 1.0 | 660 | 419 | 14.7 | 23.1 | – | – | – |
| 60.0 | 0.7 | 610 | 443 | 11.8 | 16.3 | – | – | – |
| 80.0 | 1.6 | 1130 | 655 | 13.8 | 23.8 | – | – | – |
| 100.0 | 1.8 | 1280 | 727 | 13.8 | 24.3 | – | – | – |
| **COO–V5A** | | | | | | | | |
| 2.0 | 0.4 | 360 | 330 | 10.1 | 11.0 | 78.6 | 4.3 | 1.6 |
| 5.0 | 0.6 | 480 | 446 | 13.4 | 14.4 | 74.1 | 4.1 | 1.6 |
| 10.0 | 0.9 | 550 | 405 | 15.5 | 21.0 | – | – | – |
| 15.0 | 0.7 | 500 | 257 | 13.4 | 26.1 | 73.7 | 5.6 | 2.6 |
| 20.0 | 0.7 | 510 | 225 | 13.5 | 30.5 | – | – | – |
| 30.0 | 0.4 | 330 | 171 | 11.1 | 21.4 | – | – | – |
| 40.0 | 0.3 | 230 | 108 | 12.8 | 27.3 | 80.1 | 3.1 | 1.3 |
| 50.0 | 0.4 | 280 | 165 | 14.1 | 23.9 | – | – | – |
| 60.0 | 0.4 | 320 | 186 | 13.4 | 23.1 | – | – | – |
| 80.0 | 0.5 | 320 | 210 | 15.5 | 23.6 | – | – | – |
| 100.0 | 1.1 | 700 | 522 | 15.7 | 21.1 | 53.8 | 12.1 | 8.5 |
| **COO–V6** | | | | | | | | |
| 5.0 | 1.1 | 810 | 382 | 13.1 | 27.7 | – | – | – |
| 10.0 | 1.3 | 850 | 457 | 15.2 | 28.3 | – | – | – |
| 15.0 | 1.4 | 890 | 415 | 16.2 | 34.8 | – | – | – |
| 20.0 | 2.0 | 1420 | 575 | 14.3 | 35.3 | – | – | – |
| 30.0 | 1.9 | 1270 | 519 | 14.8 | 36.2 | 55.5 | 15.2 | 8.7 |
| 40.0 | 1.6 | 910 | 543 | 17.5 | 29.4 | – | – | – |
| 50.0 | 1.6 | 1150 | 722 | 14.0 | 22.3 | – | – | – |
| 60.0 | 1.6 | 1150 | 720 | 14.3 | 22.8 | 49.7 | 14.9 | 10.8 |
| 80.0 | 1.6 | 1140 | 715 | 14.0 | 22.3 | – | – | – |
| 100.0 | 1.7 | 1170 | 730 | 14.8 | 23.7 | – | – | – |

**Table 2 (Continued).** Geochemical data for Coombabah Lake sediment samples.

| Depth [a] (cm) | TOC (wt%) | TN (ppm) | TP (ppm) | C:N | C:P | $SiO_2$ (wt%) | $Al_2O_3$ (wt%) | $Fe_2O_3$ (wt%) |
|---|---|---|---|---|---|---|---|---|
| **COO–V7** | | | | | | | | |
| 2.0 | 1.1 | 900 | 447 | 12.6 | 25.3 | 67.7 | 11.7 | 6.2 |
| 5.0 | 1.4 | 890 | 460 | 15.5 | 30.1 | – | – | – |
| 10.0 | 1.4 | 890 | 402 | 15.9 | 35.1 | – | – | – |
| 15.0 | 1.4 | 950 | 425 | 15.2 | 33.9 | 67.9 | 9.7 | 6.8 |
| 20.0 | 1.1 | 810 | 368 | 13.4 | 29.5 | 63.0 | 9.0 | 5.8 |
| 30.0 | 1.6 | 1330 | 684 | 12.2 | 23.7 | 49.9 | 16.6 | 11.0 |
| 40.0 | 1.6 | 1310 | 689 | 12.1 | 22.9 | – | – | – |
| 50.0 | 1.6 | 1400 | 738 | 11.5 | 21.7 | – | – | – |
| 60.0 | 1.7 | 1270 | 660 | 13.5 | 26.0 | – | – | – |
| 80.0 | 1.8 | 1390 | 657 | 12.8 | 27.1 | – | – | – |
| 100.0 | 2.0 | 1220 | 710 | 16.6 | 28.5 | – | – | – |

TOC, total organic carbon; TN, total nitrogen; TP, total phosphorus.
[a] Recovered depth.

ppm, respectively, and correspond to average concentrations (0.3–2.3 wt% for TOC and 230–1600 ppm for TN) in Australian estuarine sediments (Heap *et al.* 2001). By contrast, the TP contents in Coombabah Lake sediments are unusually high, averaging 508 ± 186 ppm, with the highest values found in sediments that lie below the uppermost shell concentration at approximately 50 cm depth. These TP values, when compared to the Australian average of 120–450 ppm (Heap *et al*. 2001), indicate the presence of a large pool of potentially available phosphorus in the sediment column.

Bulk concentrations of TOC, TN, and TP in estuarine sediments are controlled to a large degree by factors such as grainsize, plant uptake, and anoxia (Alongi *et al*. 1992), with the highest concentrations expected in mud-dominated sediments (Eyre & McConchie 1993) in which anoxic conditions have developed. Anoxic conditions at depth in Coombabah Lake sediments are inferred by the $H_2S$ smell noted during core recovery, the presence of Fe monosulphides (visible in some cores immediately after splitting), and scattered pyrite. There is considerable spatial variation in the concentrations of TOC, TN and TP (Table 2), with the highest concentrations occurring in cores COO-V7 and -V6, located in the southern half of the lake near the Coombabah Creek inlet. Average concentrations in sediments from these cores are 1.5 wt% TOC, 1089 ppm TN and 565 ppm TP. By contrast, cores recovered from the northern half of the lake are characterized by lower overall TOC, TN, and TP contents, with the lowest average concentrations occurring in core COO-V5A (0.6 wt% TOC, 416 ppm TN and 275 ppm TP). These differences correspond to variations in sediment source and grainsize, with lower concentrations (northern part of lake) associated with sand-dominated sediments derived from the coastal zone. At site COO-V5A, where the upper ~50 cm is penetrated by mangrove roots, lower TOC, TN, and TP concentrations in this interval may also reflect plant uptake.

#### MAJOR ELEMENT CONCENTRATIONS

Surface sediments show the highest average concentration of $SiO_2$ (66 wt%) and lowest average concentrations of $Al_2O_3$ (9 wt%) and $Fe_2O_3$ (3.7 wt%) (Table 2). With the exception of site COO-V5A, which penetrated a sandy lithology in the upper ~100 cm, $SiO_2$ concentrations decrease below the uppermost shelly horizon that occurs at 50 cm depth. $Al_2O_3$ and $Fe_2O_3$ vary antithetically with $SiO_2$ (Figure 3). In core COO-V3A, for example, the average $SiO_2$ concentration decreases from 69.7 wt% in the upper 50 cm to 49.7 wt% in the lower parts of the core (Figure 4). Over the same interval, average $Al_2O_3$ contents increase from 8.3 to 15.4 wt% and $Fe_2O_3$ increases from an average of 3.8 to 7.5 wt%. These downcore variations correspond at each site to the lithological changes noted above: whereas the decrease in Si content at ~50 cm depth coincides with the decrease in quartz sand and silt, the downcore increases in Al and Fe concentrations correspond to observed increases in clay. Given the dominance of silica in detrital sand and silt particles and Al in clay minerals, these relationships suggest that $SiO_2$ and $Al_2O_3$ contents serve as a proxy for stratigraphic variations in grainsize (e.g. relative abundance of quartz sand, silt and clay).

## Discussion

### *Stratigraphy*

Despite an initial impression of a monotonous mud succession in Coombabah Lake, elements of a stratigraphy can be established, and are here illustrated by two cross-sections drawn east–west and south–north across the lake (Figure 2). The east–west section shows the lateral transition from a condensed section at the western shore of the lake into and beyond the centre of the basin, while the south–north section suggests a relatively consistent basement elevation along the basin axis. The overall succession thickens abruptly eastward into the lake basin from the western margin, indicating a relatively steep-sided but flat-bottomed paleovalley.

The shell-rich interval in the uppermost 50 cm of section occurs virtually throughout the lake, and is the most consistently recognizable feature in the cores, including the sand-rich COO-V5A at the northern end of the lake. Further laterally persistent shell concentrations occur 70–100 cm below the sediment surface and 200–250 cm below the sediment surface. Other horizons occur but are not as readily correlated. The distribution and continuity of the shelly horizons suggest that several hiatuses in sediment accumulation or periods of winnowing occurred during the depositional history of the lake, allowing invertebrate shells to become concentrated into persistent layers. The concentration 200–250 cm below the sediment surface (which locally splits into two discrete layers) is notable for containing complete, large flat oyster shells, suggesting development of conditions conducive to oyster growth at some time in the past. This layer in core COO-V7 is tinged brown at the top, indicating a degree of oxidation similar to that at the present sediment surface. Consideration of both the distribution and composition of the shelly intervals suggests that the shell-rich layer that overlies basement in COO-V1 is a condensed section, which may represent much of the time recorded in the deeper cores to the east.

*Age constraints*

The rate of sediment accumulation in Coombabah Lake is estimated on the basis of the activity of unsupported $^{210}Pb$ in a series of samples from core COO-V3A, located in the lake's center. The activity of excess $^{210}Pb$ in core COO-V3A is extremely low throughout the interval examined. The sample with the highest activity, 0.87 disintegrations per min per g of sample (dpm/g), encompasses the uppermost 2.5 cm of the core. The activity of this sample is much lower than the range typical for lacustrine surface sediments (5–10 dpm/g). As such, the results are consistent with two interpretations: (i) the sediment in the uppermost 2.5 cm of core COO-V3A represents material that is relatively old with respect to the resolution of the $^{210}Pb$ dating technique (>~150 years); or (ii) younger sediments have been removed or reworked, revealing 'older' material at the sediment–water interface. Both interpretations imply a low rate of sediment accumulation in Coombabah Lake. The low activities of excess $^{210}Pb$ in core COO-V3A make it difficult to constrain a reliable sedimentation rate that is valid for the entire time represented by the core. However, if only samples in which activities of excess $^{210}Pb$ are detectable (near the top of the core) are considered and compaction related to the coring process is taken into account, calculations indicate that the minimum sedimentation rate in Coombabah Lake is on the order of 0.10–0.45 cm/year. Significant compaction requires that this rate must be considered a minimum estimate. The range is consistent with average sedimentation rates (0.11–0.43 cm/year) compiled for Australian estuaries by Heap *et al*. (2001).

Assuming little change in average rates of sediment accumulation throughout the history of Coombabah Lake, it is possible to estimate the age of the base of the sedimentary section, located a maximum of 5.5–6 m below the sediment–water interface. Using an average sedimentation rate of 0.1 cm/year suggests that Coombabah Lake began forming at least 5500–6000 years ago, when the sea-level along the Queensland coast is postulated to have been 1.0–1.5 m higher than present (Flood 1983, 1984; Larcombe *et al*. 1995).

*Depositional history*

With the exception of the northern end of the lake (where the uppermost 1 m of section is sand-dominated), the succession cored at sites V1–V7 indicates a quiet, shallow, brackish-water body fed by fine-grained sediment dropped from suspension, throughout the Holocene history of Coombabah Lake. During this time (5500–6000 years), periods when mud accumulation was relatively rapid were punctuated by intervals when invertebrate shells became concentrated by winnowing. The persistence of shell concentrations in the subsurface suggests that these intervals affected much of the lake basin, and the greater number of such concentrations in the eastern part of the lake (Figure 2) suggests that it was most

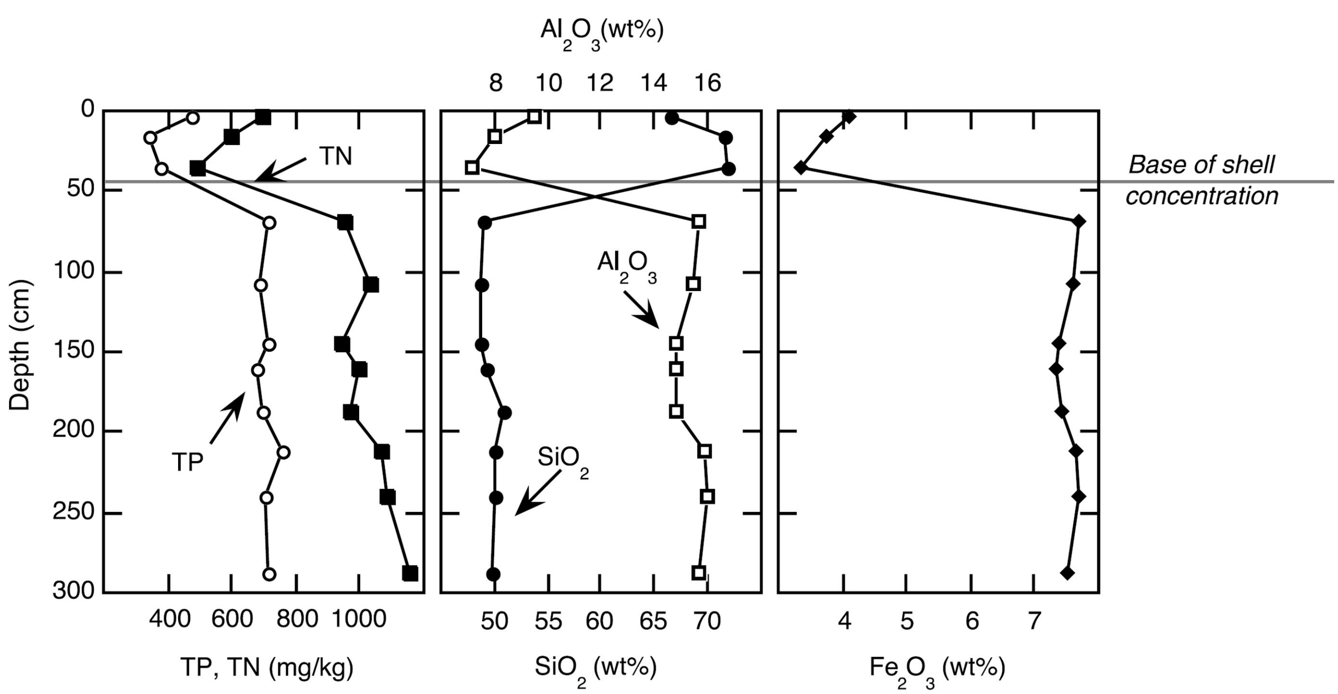



**Figure 4.** Variations in concentrations of total phosphorus (TP) and total nitrogen (TN) (left), $Al_2O_3$ and $SiO_2$ (middle), and $Fe_2O_3$ (right) *vs* depth in core COO-V3A. Vertical scale denotes recovered depth.

frequently affected by such conditions. The higher concentration of shells in the uppermost unit (average 50 cm thick) suggests that sediment accumulation in the lake has been relatively slow in recent times, despite the slightly sandier lithology. Thus, rather than recording a significant increase in sediment input due to anthropogenic factors, this layer records a period of relatively slow sediment accumulation.

The near-surface, shell-rich layer is interpreted to record a change in the sediment budget of the lake due to the filling of accommodation space. Infilling was replaced by reworking, partial bypass of sediment (as indicated by the network of anastomosing channels) and concentration of heavier shell debris by winnowing. Assuming constant sedimentation rates, the transition to the present depositional regime is postulated to have occurred approximately 500 years ago, well before significant European settlement and subsequent land clearing (Capelin *et al*. 1998). As such, there is no sedimentological evidence of a significant increase in sediment input to Coombabah Lake in the most recent past (last 50 years). The only significant sand accumulation is at the northern end of the lake, around and beneath the islands and probably focused at the outlet. Data suggest that this sand has accumulated by backfilling of the northern lake via sand supply from the coast, transported inboard by flood–tidal currents.

*Geochemistry*

Organic matter in pure marine sediments is generally assumed to consist of diatomaceous phytoplankton, which has an average C:N:P ratio of 106:16:1, known as the Redfield ratio (Redfield *et al*. 1963; Froelich *et al*. 1979). But because of the shallow depositional setting and brackish nature of coastal systems, the organic matter metabolized in estuarine sediments tends to consist of variable mixtures of material derived from marine phytoplankton, aquatic plants, and terrestrial vegetation. The breakdown of organic matter contributed from different sources, combined with the effects of plant uptake and diagenesis, leads to the development of C:N:P ratios that differ from the Redfield ratio. Coombabah Lake sediments have C:N and C:P ratios ranging from 9.7 to 17.5 and 11.0 to 36.2, respectively (Figure 5). The C:N ratios are consistent with the average range (10.1–24.3) for Australian estuarine sediments (Heap *et al*. 2001) and reflect a large contribution of organic matter from aquatic plants such as seagrass and macroalgae (Atkinson & Smith 1983). The C:P ratios, in contrast, are anomalously low compared with the Australian average range of 46.2–201.3 (Heap *et al*. 2001). Extremely low C:P ratios are also found in mud-dominated regions of nearby Moreton Bay (Figure 1) (Dennison & Abal 1999) and suggest that high P contents are typical for the region.

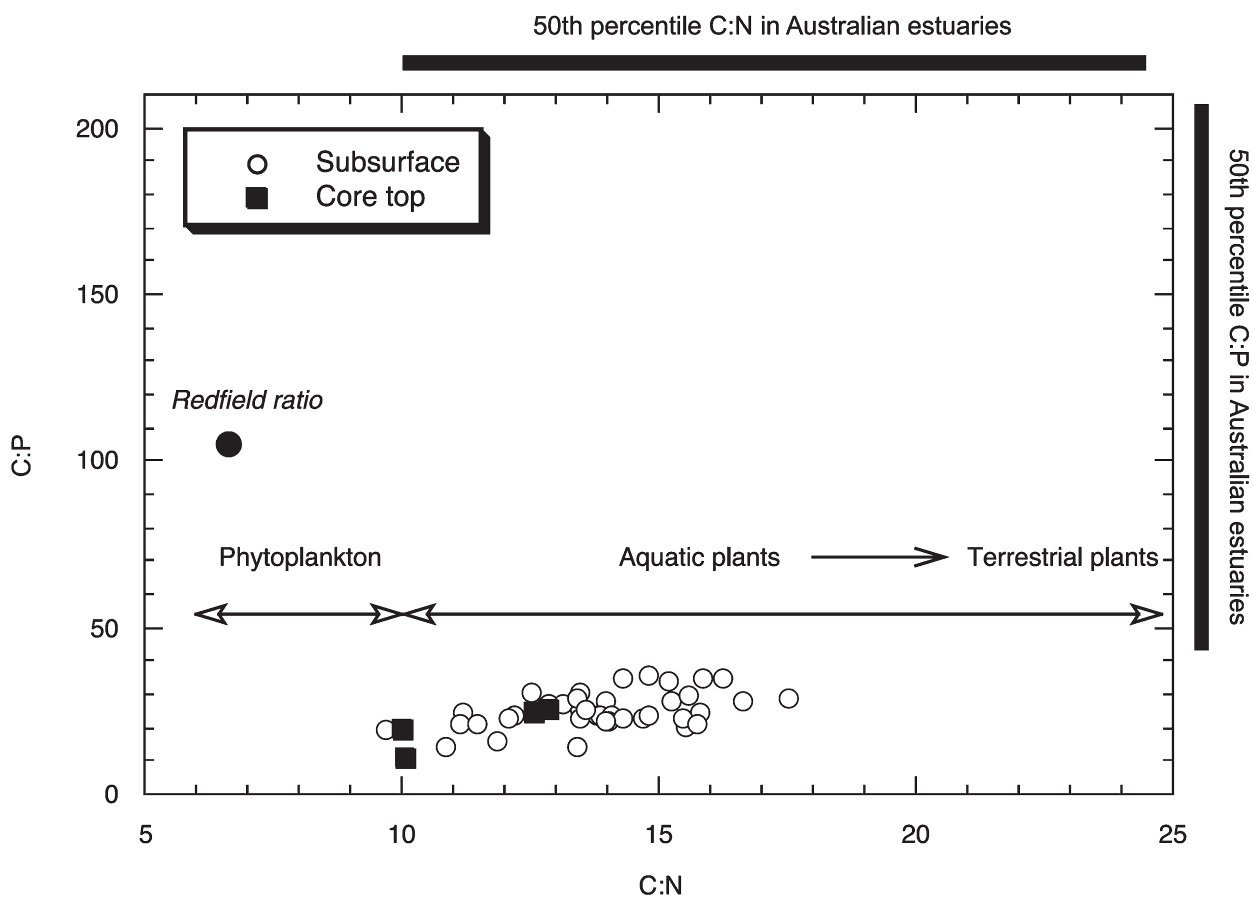



**Figure 5** C:P ratios *vs* C:N ratios in Coombabah Lake sediment samples. Filled squares are core top samples; open circles are subsurface samples. Also shown are the median (50th percentile) ranges for C:P and C:N ratios (filled bars) in Australian estuarine sediments (Heap *et al*. 2001) and the ranges of C:N ratios typical of organic matter derived from marine phytoplankton, aquatic plants, and terrestrial plants (Atkinson & Smith 1983).

Although much P is released to estuarine sediments during the degradation of organic matter (Berner 1974), the largest pool of soluble reactive P is inorganic and delivered from the catchment in particulate form (Boto & Wellington 1988; Froelich 1988). This inorganic P typically occurs either in the form of Ca, Fe, and Al phosphates or adsorbed onto Fe and Al sesquioxides (Alongi *et al*. 1992; Pailles *et al*. 1993), all of which are highly insoluble compounds. The TP in Coombabah Lake sediments shows a positive correlation with $Al_2O_3$ and $Fe_2O_3$ (Figure 3), suggesting that much of the P has indeed entered the lake in the inorganic form(s) indicated above. Assuming that concentrations of $SiO_2$ and $Al_2O_3$ in Coombabah Lake sediments reflect, at least in part, the relative proportions of detrital quartz and clay, respectively, a negative correlation between $SiO_2$ and TP, $Al_2O_3$ and $Fe_2O_3$ (Figure 3) suggests that the larger proportion of P should occur in that part of the sediment column dominated by clayey sediments. This interpretation is supported by the downcore distributions of these geochemical parameters (Figure 4; Table 2) and is consistent with the sedimentological observations discussed above. The TP, $Al_2O_3$ and $Fe_2O_3$ concentrations are lower at core tops and show a pronounced increase to higher values at the base of the uppermost shell horizon (Figure 4), below which sediments are generally sand-free. In core COO-V5A the TP values remain low through sandy sediments of the upper 106 cm and increase to higher values in the mud-dominated sediments that characterize the lower part of the core (Table 2). These downcore patterns indicate that much of the P in the Coombabah Lake sediment is stored in inorganic form >50 cm below the sediment–water interface.

Geochemical patterns suggest that the decrease in the amount of clay in the upper part of the sediment column diminished the ability of Coombabah Lake sediments to preserve organic matter and/or adsorb N and P. In a regional study of Moreton Bay, Dennison and Abal (1999) demonstrated a close association between high nutrient concentrations and mud, and linked the association to increased adsorption on finer sediments (characterized by a large surface to volume ratio) coupled with better preservation of organic matter due to an increased capacity for the development of anoxic conditions. Similar patterns have been noted in other Australian estuary systems (Eyre & McConchie 1993; Pailles *et al*. 1993). A gradual increase in the contribution of sand from the coast in the northern reaches of the lake is evident in the coarsening-upward sequence recovered in core COO-V5A. Lower nutrient levels at this site likely reflect the sand-dominated and oxidizing nature of coastal beach environments, and a low potential for organic matter preservation.

## Conclusions

Sedimentological and geochemical data derived from a series of cores drilled through the Holocene sequence in Coombabah Lake reveal little to suggest that human activities in the surrounding catchment have impacted on conditions in the lake system. Throughout much of its history, sedimentation in Coombabah Lake has been dominated by the settling of fine-grained material transported to the lake from the catchment area that lies to the south. Sedimentological observations indicate a slight change in the sediment budget *ca* 500 years ago, when depositional processes changed from those involved largely with sediment accumulation (filling of the basin) to include reworking of sedimentary material (e.g. the concentration of shell material by winnowing) and the partial bypass of sediment through channels on the eastern side of the lake. Rather than increasing sedimentation rate, this change is interpreted to have initiated a drop in the overall rate of sediment accumulation, such that a delicate balance between sediment input, storage/reworking, and output maintains the current water depth. Facies patterns considered together with $SiO_2$ and $Al_2O_3$ records suggest that the change in prevailing depositional conditions led to a slight increase in the proportion of sand to mud.

Geochemical records show that nutrient storage in the sediment decreased significantly after the transition to the new depositional regime. The overall decrease in the trapping efficiency of Coombabah Lake is interpreted to reflect increased winnowing and flushing of particulate-bound nutrients, an increase in the average size of sediment particles, and a change in the type of sedimentary material entering the system. The coarsening-upward sequence penetrated at site COO-V5A records the gradual development of a flood-tidal delta complex composed of sand transported from the coast and focused near the northern outlet of the lake. Such variations in sediment distribution across the lake are reflected as spatial differences in concentrations of TOC, TN, and TP. Higher organic matter and nutrient levels occur in the southern half of the lake, where the section contains a higher proportion of fine-grained sediment. Lower concentrations characterize areas that receive a higher influx of sand.

## Acknowledgments

This research represents part of a broader environmental impact assessment of Coombabah Lake carried out in 2000 while TDF and CRF were in residence at the Department of Earth Sciences, University of Queensland, Brisbane. The project was sponsored by the Gold Coast City Council and carried out under the tender of the GHD Group, Brisbane. We thank S. Brownlaw, B. Corbett, and M. Petersen for assistance in core collection, and appreciate insightful reviews by D. McConchie and B. Jones, which helped to improve the manuscript.

## References

Alongi D. M., Boto K. G. & Robertson A. I. 1992. Nitrogen and phosphorous cycles. *In*: Robertson A. I. & Alongi D. M. eds. *Tropical Mangrove Ecosystems*, pp. 251–292. American Geophysical Union, Washington, DC.

Atkinson M. J. & Smith S. V. 1983. C: N: P ratios of benthic marine plants. *Limnology and Oceanography* **28**, 568–574.

Australian Bureau of Statistics. 1996. *Census of Population and Housing*. Australian Bureau of Statistics Catalogue no. 2035.0.

Berner R. A. 1974. Kinetic models for the early diagenesis of nitrogen, sulfur, phosphorus, and silicon in anoxic marine sediments. *In*: Goldberg E. ed. *The Sea*, Vol. 5, pp. 427–450. Wiley, New York.

Boto K. G. & Wellington J. T. 1988. Seasonal variations in concentrations and fluxes of dissolved organic and inorganic materials in a tropical, tidally-dominated, mangrove waterway. *Marine Ecology Progress Series Inter-Research* **50**, 151–160.

Capelin M., Kohn P. & Hoffenberg P. 1998. Land use, land cover, and land degradation in the catchment of Moreton Bay. *In*: Tibbets I. R., Hall N. J. & Dennison W. C. eds. *Moreton Bay and Catchment*, pp. 55–66. School of Marine Science, University of Queensland, Brisbane.

Dennison W. C. & Abal E. G. 1999. *Moreton Bay Study: A Scientific Basis for the Healthy Waterways Campaign*. South East Queensland Regional Water Quality Management Strategy, Brisbane.

Eyre B. & Mcconchie D. 1993. Implications of sedimentological studies for environmental pollution assessment and management: examples from fluvial systems in North Queensland and Western Australia. *Sedimentary Geology* **85**, 235–252.

Flood P. G. 1983. Holocene sea level data from the southern Great Barrier Reef and southeastern Queensland: a review. *In*: Hopley D. ed. *Australian Sea Levels in the Last 15,000 Years: A Review*, pp. 85–92. Department of Geography, James Cook University Monograph Series, Occasional Paper **3**.

Flood P. G. 1984. A review of Holocene sea level data, southeastern Queensland. *In*: Coleman R. J., Covacevich J. & Davie P. eds. *Focus on Stradbroke: New Information on North Stradbroke Island and Surrounding Areas.*, pp. 127–131. Boolarong, Brisbane.

Froelich P. N. 1988. Kinetic control of dissolved phosphate in natural rivers and estuaries: a primer on the phosphate buffer mechanism. *Limnology and Oceanography* **28**, 564–476.

Froelich P. N., Klinkhammer G. P., Bender M. L., Luedtke N., Heath G. R., Cullen D., Dauphin P., Hammond D., Hartman B. & Maynard V. 1979. Early oxidation of organic matter in pelagic sediments of the eastern equatorial Atlantic; suboxic diagenesis. *Geochimica et Cosmochimica Acta* **43**, 1075–1090.

Gallagher G. 2001. Fate of nutrients in Coombabah Lake. BSc (Hons) thesis, University of Queensland, Brisbane (unpubl.).

Heap A., Bryce S., Ryan D., Radke L., Smith C., Smith R., Harris P. & Heggie D. 2001. Australian estuaries and coastal waterways: a geoscience perspective for improved and integrated resource management. *Australian Geological Survey Organisation Record* **2001/07**.

Larcombe P., Carter R. M., Dye J., Gagan M. K. & Johnson D. P. 1995. New evidence for episodic post-glacial sea-level rise, central Great Barrier Reef, Australia. *Marine Geology* **127**, 1–44.

Pailles C., Mcconchie D. M., Arakel A. V. & Saenger P. 1993. The distribution of phosphate in sediments of the Johnstone Rivers catchment–estuary system, North Queensland, Australia. *Sedimentary Geology* **85**, 253–269.

Redfield A. C. B., Ketchum B. H. & Richards F. A. 1963. The influence of organisms on the composition of sea-water. *In*: Hill M. N. ed. *The Sea*, Vol. 2, pp. 26–77. Wiley, New York.

Roy P. S. 1980. Quaternary depositional environments and stratigraphy of the Fullerton Cove Region, central New South Wales. *Geological Survey of New South Wales Records* **19**, 189–219.

Roy P. S. 1984. New South Wales estuaries: their origin and evolution. *In*: Thom B. G. ed. *Coastal Geomorphology in Australia*, pp. 99–121. Academic Press, Sydney.

Roy P. S. 1994. Holocene estuary evolution: stratigraphic studies from southeastern Australia. *In*: Dalrymple R. W., Boyd R. & Zaitlin B. A. eds. *Incised Valley Systems–Origin and Sedimentary Sequences*, pp. 241–263. SEPM Special Publication **51**.

Roy P. S. & Crawford E. A. 1981. Holocene geological evolution of the southern Botany Bay–Kurnell region, central New South Wales coast. *Geological Survey of New South Wales Records* **20**, 159–250.

Skinner J. L., Gillam E. & Rohlin C-J. 1998. The demographic future of the Moreton Region. *In:* Tibbets I. R., Hall N. J. & Dennison W. C. eds. *Moreton Bay and Catchment*, pp. 67–78. School of Marine Science, University of Queensland, Brisbane.

Tibbets I. R., Hall N. J. & Dennison W. C. 1998. *Moreton Bay and Catchment*. School of Marine Science, University of Queensland, Brisbane.