Historical and contemporary perspectives on the sediments of Lake Rotorua

David Hamilton[1], Lisa Pearson[2], Chris Hendy[2], David Burger[1,3], Mark McCarthy[4], Terry Healey[5]

[1]Department of Biological Sciences, University of Waikato, Hamilton [2]Department of Chemistry, University of Waikato, Hamilton [3]Currently at Delft Hydraulics, The Netherlands [4]Marine Sciences, The University of Texas at Austin, United States [5]Department of Earth and Ocean Sciences, University of Waikato, Hamilton

Lake formation

Lake Rotorua is probably the oldest continuously inundated lake in New Zealand, occupying a caldera formed by or closely associated with the eruption of the Mamaku ignimbrite and the collapse of the Rotorua caldera (Healy, 1975; Lowe and Green, 1991). The lake has undergone drastic changes in size and depth as a result of tectonics, volcanic activity and erosion. Since the Rotoehu eruption, (~60 kyr), the lake level has fluctuated between 120 m above present (280 m asl) and 10 m below present level. The modern lake covers an area of 79 km^2 and has a mean depth of 10 m. Despite its long history of sedimentation, Lake Rotorua has an irregular bathymetry with features including faulted blocks, slumps, hydrothermal explosion craters, springs and large methane discharge pock marks.

Sediment and tephra deposition

The floor of Lake Rotorua comprises two quite different sediment types (Fig. 1). In waters shallower than about 10m the sediment is coarse, consisting of sand and pumiceous gravel reworked from the Kaharoa (AD 1314 ± 12) and earlier tephras. In these shallower waters, wind-driven turbulence prevents low-density fine sediments from accumulating (Gibbs, 2004). In deeper waters the sediment consists predominantly of fine diatomaceous ooze interspersed with tephra from the Okataina, Taupo and more distant volcanic centres. There is little evidence of physical reworking of this sediment. The presence of the tephras provides chrono-stratigraphic markers enabling sedimentation rates to be determined. The Tarawera eruption of 10 June 1886 deposited a 1-3 cm thick bed of dense grey mud (Rotomahana mud) (Pullar and Kennedy, 1981) across the lake which now occurs to depths as great as 1.2 m below the sediment surface. Our estimates are comparable to those of Fish (1979) who estimated sediment deposition rates around 1 cm yr^{-1} since the Tarawera eruption. The Kaharoa tephra (Pullar and Kennedy, 1981; Hogg et al., 2003) is evident as a layer of 8-10 cm of hard white pumice layer approximately 3m below the sediment surface (Fig. 2b). Between the tephra is a diatomaceous ooze that is dominated by frustules of *Aulacoseira granulata* (Foged (1979). Sediment density is relatively constant at around 0.07 g cm^{-3} in an upper layer of 10-15 cm of loose, flocculent sediment, but increases rapidly thereafter with compaction of the diatomaceous ooze.

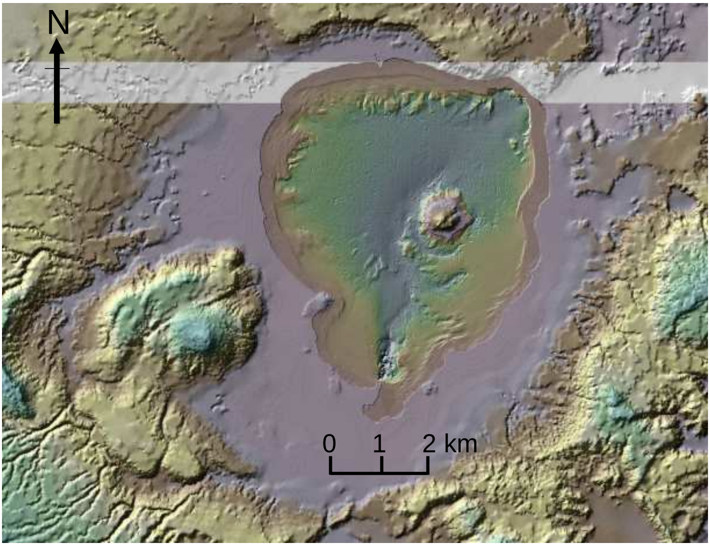

Fig. 1. Bathymetry of Lake Rotorua, including elevation of the surrounding landscape. Note the historical lake bed (shaded mauve), the current lake extent (delineated by the brown-shaded region of coarse sediments within the historical lake bed) and the transition to fine sediments of the inner lake basin (blue regions in the interior). Mokoia Island is readily distinguished near the centre of the present lake basin.

Pock marks and methane eruptions

Early attempts to use seismic techniques to survey the stratigraphy of the lake sediments (Davey, 1992) were unsuccessful due to the absorption of acoustic signals by gas within the sediments. This gas was interpreted to be of geothermal origin. A recent seismic survey (Pearson, 2007) also showed no structural features of the lake sediments except where there are small, circular, flat-bottomed depressions, detectable in Fig. 1 as minute depressions in the diatomaceous ooze of the deeper bed of the lake. The depressions are typically steep-sided and up to 5 m deeper than the surrounding lake bed, and around 50 m in diameter. Similar circular depressions are common in shallow marine and lacustrine sediments and have been termed pockmarks, with their formation interpreted as a result of gas discharge (Rodgers et al., 2006). Evidence of ebullition of gas can commonly be observed at the surface of Lake Rotorua on calm days (Fig. 2), particularly over pockmarks, and also in sediment cores raised to the lake surface (Pearson, 2007). Gas captured from beneath the water surface was a mixture of

Fig2. Gas erupting on the surface following sediment disturbance by gravity corer.

97% methane and 3% carbon dioxide. The isotopic signature of this gas ($\delta^{13}C_{(carbon\ dioxide)}$ of +10.5‰ and $\delta^{13}C_{(methane)}$ of -64.3‰) provides strong evidence that it is formed as a result of anaerobic fermentation of organic matter.

Within the depressions acoustic sounding shows the presence of tephra layers separated by diatomaceous ooze (Fig. 3). Coring within pockmark areas shows a limited amount of reworking based on the presence of small amounts of coarser tephra components within the upper sediment layer. There also appears to be hierarchy of depressions, with the deepest transmitting acoustic signals and shallower depressions absorbing them. We interpret this to be a result of episodic methane release resulting in sediment with a transparent sonic signal interspersed with periods of methane regeneration when the sediment recovers its lost volume and loses its sonic transparency.

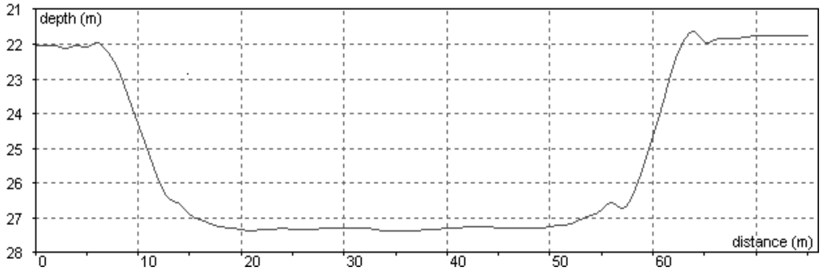

Fig 3. Example of a pockmark of c. 50m diameter in the sediments of Lake Rotorua at a location of 38° 05´ 37.41´´S and 176° 16´ 12.99´´E denoted by bathymetry of the track across the depression derived from the multibeam sounding. Depth is below the water surface.

Chemical features of the sediments

Despite the lack of mechanical reworking within the diatomaceous ooze, there is considerable chemical activity resulting in translocation of significant quantities of iron, manganese, sulfur, carbon, phosphorus and nitrogen. The loose surficial sediments appear to become anoxic within the first few millimetres below the surface, with iron- and manganese-bound trace elements consequently being released and free to migrate along concentration gradients (Motion, 2007). Constant remobilisation of adsorbed trace element species, e.g. phosphate, maintains maximum concentrations not only in surficial sediments, but also near the centre of the lake (Fig. 4). For example, phosphate concentrations may be more than three orders of magnitude higher in overlying waters than in sediment pore-waters of the inner lake.

Diffusion transports ions both upwards into relatively dilute overlying lake waters, with important consequences to the overlying water quality (Burger et al., 2007), and downwards into deeper sediments. As sulfate is reduced to sulphide, insoluble sulfide minerals, especially iron, form precipitates some of which include framboidal pyrite. As there is insufficient sulfate reduced to accommodate all of the ferrous iron produced, other ferrous minerals (siderite and vivianite) also precipitate. The mass of diagenetic minerals estimated to be present in the lake sediments (Pearson, 2007) appears to account for the gross difference in mass between mineral loads in inflows and outflows. Recycling of the mineral may be highly dynamic and repeated several times before burial within the lake sediments or loss to the Ohau Channel outflow.

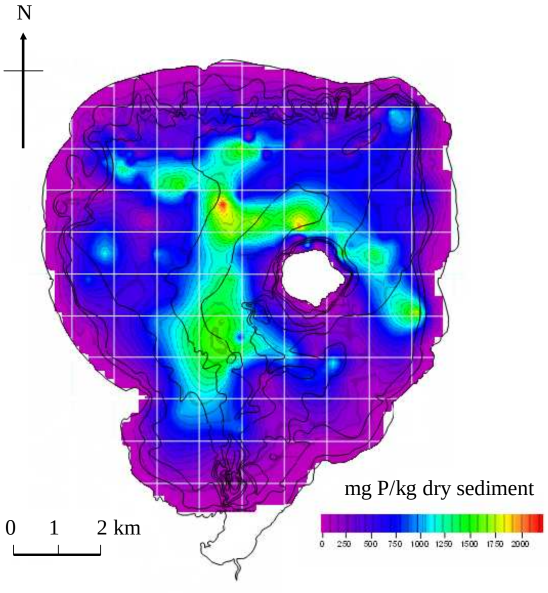

Fig 4. Phosphorus concentrations represented by coloured contours for the upper 10 cm of dry sediment from Lake Rotorua. Concentric dark lines represent depths at 3m intervals.

Eutrophication

Loads to Lake Rotorua of minerals, notably phosphorus and nitrogen, have increased markedly over recent decades in association with replacement of indigenous vegetation by pasture and exotic forestry (currently 52 and 14 % of the catchment land cover, respectively). In addition, Lake Rotorua received discharge of treated sewage from Rotorua city (population 60,000) between 1973 and 1991 (Hoare, 1980; Rutherford et al., 1996) but loads from this source have been reduced markedly following land-based effluent 'polishing' in the Whakawerawera forest. Tributaries to Lake Rotorua arise mostly from very large groundwater aquifers that have long residence times; recent isotopic dating of lake inflows indicates time lags of c. 15 to 140 years for water from the catchment to be expressed in tributary inflows (Morgenstern et al., 2006). Consequently there is a lag in the time that it takes for tributary inflow composition to equilibrate to the prevailing land use. For example, current nitrogen loads are estimated to have increased approximately 7-fold from those of the 1950s and may not plateau until around 2200 when they will be nearly 10-fold higher than 1950 levels. None of the projections of future nitrogen loads takes account of intensification of pastoral land, for which nitrogen fertiliser use is estimated to have increased by around 160 % in six years to 2002 (Parliamentary Commissioner for the Environment, 2003; Hamilton 2005). This increase in nitrogen loading to Lake Rotorua has overwhelmed the benefits of reducing nitrogen loads through removing wastewater inputs to the lake in 1991.

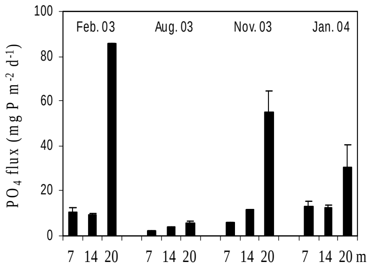

Fig 5. Mean phosphate fluxes from 4-day in situ benthic chamber incubations for four periods in 2003-4 at three stations of depths denoted on the horizontal axis.
Error bars are standard deviations.

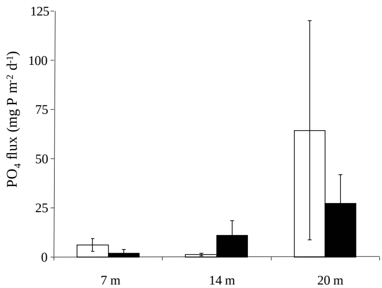

Fig 6. Mean phosphate fluxes from continuous flow laboratory core incubations of sediments taken Feb 2006. Incubations were carried out with overlying water that had either not been altered (unshaded) or had been enriched to 1 mg L^{-1} nitrate concentration (shaded).
Error bars are one standard error.

The impact of additional nutrient loading from tributary inflows to the lake has reinforced the significance of the lake sediments to the eutrophication process (White et al., 1978; Burger et al., 2007). Additions of organic matter directly from historical wastewater inputs and indirectly from decay of nutrient-stimulated algal biomass have created a high sediment oxygen demand that is reflected in periodic deoxygenation of bottom waters when the lake water column stratifies for more than a few days during periods of warm calm weather (Burger et al., 2005). This process enhances the translocation of minerals, and is accompanied by notable releases of phosphorus and nitrogen, to such an extent that these internal fluxes strongly dominate the gross nutrient loads to the lake system. Both *in situ* measurements of these fluxes (Fig. 5), using benthic chambers to isolate the parts of the sediment, and laboratory incubations (Fig. 6) confirm the exceptionally high releases of nutrients that occur from the lake bed. Interestingly, in the latter case artificially increasing nitrate concentrations in the overlying water appeared to suppress nutrient releases from the sediments (Fig. 6), most likely associated with the oxidation of the bottom sediments arising from the oxidised cation nitrate. This finding provides insight into the array of interacting processes that govern nutrient releases and the eutrophication process in Lake Rotorua, and the significance of integrating a variety of time scales in understanding sediment dynamics in relation to the sedimentation and release of organic matter and nutrients. It is increasingly apparent that mitigation of eutrophication in Lake Rotorua in the short to medium term is likely to involve reducing internal nutrient loads as well as external loads, based on nutrient budgets for the lake (Fig. 7), though there are preliminary indications that phosphorus content of surficial sediments may have decreased by as much as 40 % since 1995 (D. Trolle, pers. com.). Assessments of the feasibility of dredging lake sediments and adding materials to aid retentiveness of nutrients in the sediments, as well as several other engineering actions, have already been undertaken (www.envbop.govt.nz/Water/Lakes/Technical-Reports.asp). Implementation of these actions will require approval of the lake bed owners, the Te Arawa iwi, as well as further detailed scientific, economic and cultural assessments to assist the relevant lake management authorities (e.g., Environment Bay of Plenty, Rotorua District Council and Te Arawa Lakes Trust) in the decision making process.

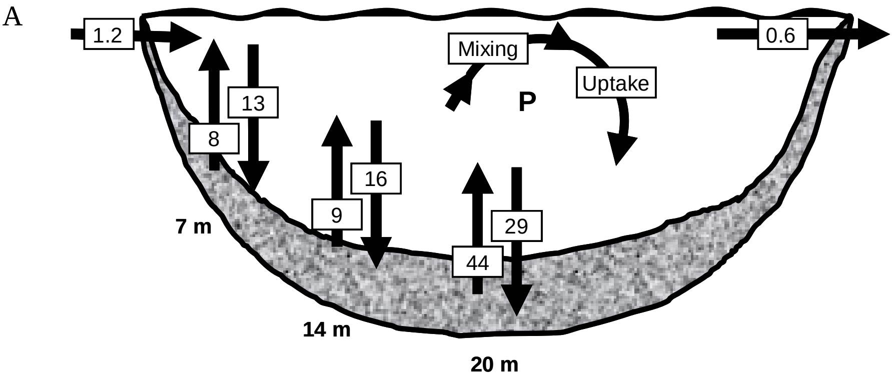

Figure 7. Total phosphorus fluxes for Lake Rotorua for inflows, outflows and based on mean fluxes from replicate benthic chamber incubations at 7 m, 14 m and 20 m. Units are expressed as daily areal loads (mg P m^{-2} d^{-1}).

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