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6000 years of environmental changes recorded in Blue Lake, South Australia, based on ostracod ecology and valve chemistry

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ABSTRACT

A 4 m long core taken from the freshwater Blue Lake crater near the township of Mount Gambier in southeastern South Australia provided a high-resolution palaeoclimatic record for the last six millennia. Accelerator Mass Spectrometry (AMS) radiocarbon (^{14}C) dates were obtained from organic plant fibres and biogenic carbonates from the laminated sequence of the core and from a modern water sample. Large discrepancies between the radiocarbon ages determined from plant fibres and biogenic carbonates indicate the presence of a time-variable lacustrine reservoir, which is consistent with what is known of the lake's hydrology.

Ostracod assemblages, associated with stable isotope ($\delta^{13}C$, $\delta^{18}O$) analyses and, in combination with Mg/Ca, Sr/Ca and Na/Ca analyses done on ostracod valves, infer salinity, temperature and water level changes in Blue Lake over the last 6 millenia. The influence of local aquifers through time has also been determined from the Na/Ca of ostracod valves. Approximately 900 year cycles are evident in the $\delta^{13}C$ record from 5.4 ka to 1.8 ka.

The history of Blue Lake records an initial period of high hydrological variability around 6 ka, becoming increasingly deeper as groundwater flowed into the basin. By 4 ka, the lake had reached steady state with the lake level fluctuating by as much as 9 m, although significant geochemical variations represent temperature fluctuations until European settlement near the lake in 1839.

1. Introduction

Hydrologically closed volcanic crater lakes from southeastern Australia act as giant rain gauges with lake levels responding to variations in the regional climate (Currey, 1970; Bowler, 1981; De Deckker, 1982a; Jones et al., 1998; 2001). Changes in climate affect crater-lake water levels through variations of E/P (evaporation/precipitation). Increasing (decreasing) E/P results in shallowing (deepening) of the lakes' water level (Bowler, 1981; Jones et al., 1998, 2001). The absence of river inflow or outflow, a well defined rim and the steep-sided nature of these craters mean the non-water surface area of the catchment is relatively small compared to the water surface area (De Deckker, 1982a; Jones et al., 1998, 2001). As such, surface flow into these lakes is negligible and the predominant water source is from precipitation. When water levels are below the crater rim, water loss is mostly through evaporation. Some leakage may also occur through the porous lithologies (e.g. scoria) of the craters. Thus, variation in lake level also engenders either concentration or dilution of dissolved ions in the water and, thus, changes salinity (Currey, 1970; De Deckker and Forester, 1988).

Unlike many of the volcanic crater lakes in southeastern Australia, Blue Lake intersects the regional groundwater table and, at present, the lake level is predominantly controlled by groundwater flow, E/P and pumping for human consumption (Holmes and Waterhouse, 1983; Ramamurthy et al., 1985; B.L.M.C., 2001). Groundwater inflowing into Blue Lake is chemically distinct from rainwater having chemically reacted with the surrounding basalt and limestone (Blackburn and McLeod, 1983; Love et al., 1993, 1994). The significant groundwater influence in Blue Lake complicates interpretations of lake level variation through E/P variations, and to solve this effect, evidence is examined from several proxy records preserved in the lake's sediment.

This paper describes the high-resolution palaeoenvironmental and palaeoclimatic changes recorded in the Holocene sediments and associated fossil microbiota and hydrochemistry of Blue Lake. In conjunction with a companion paper focussing on the crater Lakes Keilambete and Gnotuk located in western Victoria, some 200 km east of Blue Lake (Wilkins et al., in preparation), this paper seeks to provide geochronologically-constrained, high-resolution lacustrine Holocene paleoenvironmental and paleoclimatic histories from southeastern Australia.

2. Regional setting

2.1. Site description

Blue Lake (37° 50.713′S, 140° 46.486′E) is the largest and deepest of four lakes (Valley, Leg of Mutton and Brownes Lakes) in the maar

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complex near the township of Mount Gambier in South Australia (Fig. 1). The water from Blue Lake has been used as Mount Gambier's water supply since 1883 and is pumped from the northern crater rim just below the water's edge.

Tamuly (1970) described Blue Lake's surface area, volume and mean and maximum depths as 0.6 km^2, 36.8 million m^3, 61 m and 77 m, respectively. The catchment area of Blue Lake is a mere 10% greater than the lake's surface area. The very steep crater walls and small surface area to volume ratio of the lake indicate that the primary mechanisms for water to enter the lake system are via precipitation and groundwater flow (Fig. 1) (see Herczeg et al., 2003).

Tamuly (1970) showed that Blue Lake is oligotrophic and monomictic, becoming thermally stratified in October (austral spring). Peak stratification occurs in January to February (summer) with surface waters recording temperatures greater than 22 °C, while bottom waters remain relatively constant at about 13 °C all year round (Tamuly, 1970; Vanderzalm et al., 2009). Complete thermal mixing occurs during the winter months from June to September (Telfer, 2000; Vanderzalm et al., 2009). This time coincides with the colour change from grey to blue by the precipitation of tiny calcite crystals in the water column and concentrating humic substances during the degassing of CO_2 during stratification (Telfer, 2000). Turner et al. (1984) found that Blue Lake is always supersaturated with respect to calcium carbonate.

2.2. Modern climatology

The local climate is characterised by cool, wet winters and hot, dry summers. The lowest mean minimum/maximum temperatures at Mount Gambier occur in July (5.3 °C/13.8 °C) and the highest in February (11.9 °C/24.8 °C). Regional precipitation decreases northeast of the southern coast (Blackburn and McLeod, 1983); however, Blue Lake is within 25 km of the coast. Mean minimum precipitation (29 mm) occurs in February, and mean maximum precipitation (107.1 mm) occurs in July (Fig. 2) (Data courtesy of the Bureau of Meteorology, http://www.bom.gov.au/climate/averages/tables, 2008).

2.3. Regional geology

Blue Lake occurs in a complex maar crater located in the basaltic and tuffaceous Newer Volcanics in southeastern South Australia that forms part of the western portion of the Otway Basin. The Blue Lake volcanic structure intersects the upper part of the Late Palaeocene to Middle Eocene Dilwyn Formation and the conformably overlying Middle to Late Miocene Gambier Limestone (Fig. 1). The Dilwyn Formation represents a transition from a sandy fluvial environment to a deltaic/interdistributary bay environment, opening to the fossiliferous carbonate open-marine shelf Gambier Limestone (Waterhouse, 1977; Love et al., 1993). Li et al. (2000) identified seven diachronous members of the Gambier Limestone including the fractured dolomitic Camelback Member.

2.4. Geochronology

Numerous studies have been conducted to determine the age of the volcanism of the Blue Lake complex (Gill, 1955; Blackburn, 1966; Kigoshi and Kobayashi, 1966; Blackburn et al., 1982) and the lacustrine sediments within the Blue Lake catchment (Ayliffe, 1983; Leaney et al., 1995). Ages for volcanism in the Blue Lake complex have ranged from 38

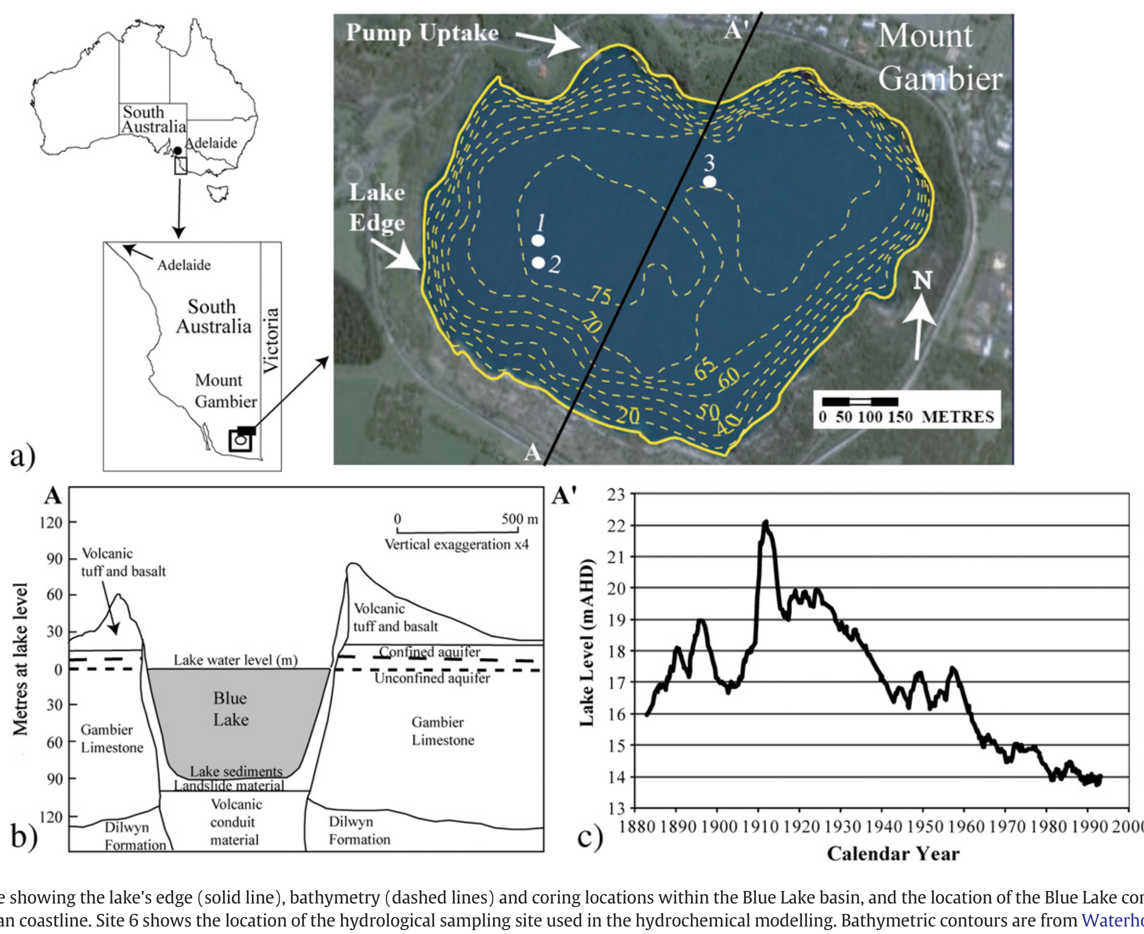

Fig. 1. a) Figure showing the lake's edge (solid line), bathymetry (dashed lines) and coring locations within the Blue Lake basin, and the location of the Blue Lake complex in relation to the Australian coastline. Site 6 shows the location of the hydrological sampling site used in the hydrochemical modelling. Bathymetric contours are from Waterhouse (1977), and satellite image courtesy of GoogleEarth™ version 4.2.0205.5730 (2007), b) line marked A–A′ through a) is the approximate location of the north–south vertical cross section through the Blue Lake volcanic complex showing the main stratigraphical units, and the main aquifers feeding the lake and the current water level. Cross section modified from Leaney et al. (1995) and Sheard (1978), and c) is the historical (1882 to 1993) lake level curve for Blue Lake (from D.W.L.B.C., 2010).