Use of the geochemical and biological sedimentary record in establishing palaeo-environments and climate change in the Lake Ngami basin, NW Botswana

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Abstract

Sediment samples from a continuous 4.6 m profile in the dry bed of Lake Ngami in NW Botswana were analysed for geochemistry and dated using both ^{14}C and TL methods. Certain units in the profile were found to be diatom rich and these, with the geochemical results, were used as indicators of high and low lake levels within the basin. The Lake Ngami sediments contain a high proportion of SiO_2 (51–92.5 wt%, avg. 72.4 wt%) and variable levels of Al_2O_3 (2.04–17.2 wt%, avg. 8.88 wt%). Based on elevated Al_2O_3 and organic matter (LOI_{orgC}) results, lacustrine conditions occurred at ca. 42 ka until 40 ka and diatom results suggest that relatively deep but brackish conditions prevailed. At 40 ka, the lacustrine sedimentary record was terminated abruptly, possibly by tectonic activity. At ca. 19 ka, shallow, aerobic, turbulent conditions were prevalent, but lake levels were at this time increasing to deeper water conditions up until ca. 17 ka. This period coincides with the Late Glacial Maximum, a period of increased aridity in the central southern Africa region. Generally, increasing Sr/Ca ratios and decreasing LOI_{orgC} and Al_2O_3, from ca. 16 to 5 ka, suggest decreasing inflow into the basin and declining lake levels. Based on the enrichment of LREE results, slightly alkaline conditions prevailed at ca. 12 ka. Diatom results also support shallow alkaline conditions around this time. These lake conditions were maintained primarily by local rainfall input as the region experienced a warmer, wetter phase between 16 and 11 ka. Lake levels rose rapidly by 4 ka, probably in response to enhanced rainfall in the Angolan catchment. These results indicate that lake levels in the Lake Ngami basin are responding to rainfall changes in the Angolan catchment area and local rainfall. The results confirm that the present-day anti-phase rainfall relationship between southern Africa and regions of equatorial Africa was extant during the late Quaternary over the Angolan highlands and NW Botswana.

1. Introduction

The geochemistry of sediments reflects a combination of provenance, chemical weathering, hydraulic sorting, abrasion, redox condition and diagenesis (Taylor and McLennan, 1985; Condie, 1993). Lake deposits provide a continuous record of environmental changes which record climatic, hydrologic, sedimentological, tectonic, geochemical, biological and biochemical conditions. The focus of this study is the currently dry Lake Ngami, a 3000 km^2 basin at the distal reaches of the Okavango Delta (Shaw et al., 2003). The Okavango Delta in northwest Botswana is an unstable hydrological system and change to this system is assumed to take place along five major pathways. These are characterised in terms of their driving agents as: climatic (with inputs of rainfall and solar energy); geological (neotectonic inputs); hydrological (surface and

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sub-surface water inputs); vegetational-geomorphological (channel blockages, island-floodplain building inputs); zoological (wildlife inputs) and human induced (fire and land-use change inputs) (McCarthy and Ellery, 1993; Gieske, 1996; McCarthy et al., 1998a, b; Government of Botswana, 2002; Ringrose et al., 2003).

Nicholson and Entekhabi (1986) report an inverse correlation between annual rainfall over southern Africa and parts of equatorial Africa for the period of meteorological record. Tyson et al. (2002a) compare data from lake sediments in Lake Naivasha in Kenya and a stalagmite record from Cold Air Cave in Makapansgat valley in South Africa over the past 1100 years. They report that during drier, cool periods in Lake Naivasha, conditions were warmer and wetter at Makapansgat. Conversely, cool dry conditions at Makapansgat correspond to periods of high lake levels at Naivasha.

Given the contrasting controls of weather in the equatorial region and subtropical Africa, inverse links between climates of the Angolan Highland catchment and the Lake Ngami basin may be expected. With future climate change scenarios (in particular, rainfall), there is often a discrepancy between the models and how well the models represent the present day climate. However, the model of change in wet season (December–February) precipitation from 1960–1990 to 2070–2100 (HadCM2 IS92a) developed by the Hadley Centre (http://www.metoffice.com/research/hadleycentre/models) shows an anti-phase effect in precipitation where a net decrease in precipitation for this period is shown for central southern Africa and an increase for tropical Africa, including the Angolan highlands.

The goals of this paper are: (1) to describe and interpret the Quaternary sediments deposited in the Lake Ngami basin, (2) to document climate-related changes in the sediment and (3) to indicate tectonically induced shifts in sedimentation patterns.

2. Local setting and climate

The Okavango River, which drains from the Angolan highlands, enters the Makgadikgadi–Okavango–Zambezi (MOZ) rift depression (Ringrose et al., 2005), through a narrow NW-SE-trending swamp called the Panhandle before extending into a large inland alluvial fan (McCarthy et al., 2000). Lake Ngami (Fig. 1) is a depression at the distal end of the Okavango Delta, laterally linked by a network of low gradient channels to the Makgadikgadi and Mababe depressions.

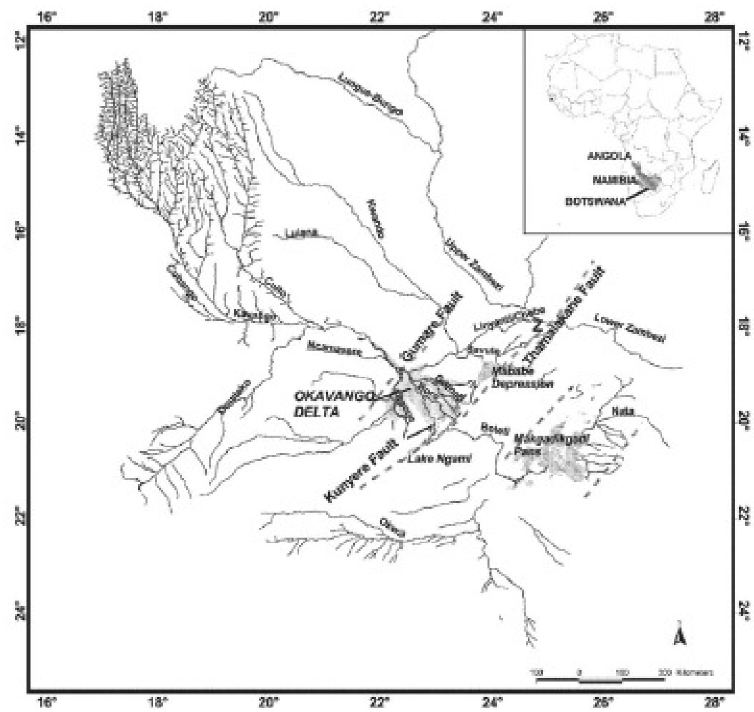

Fig. 1. Okavango Delta in NW Botswana showing Lake Ngami to the southwest.

Flooding in the Okavango Delta is influenced by local rainfall and inflow from the catchment in the Angolan highlands. Under the current climatic conditions, rainfall over the Okavango Delta is influenced by the anti-cyclonic conditions that dominate the interior of southern Africa and rainfall patterns are subject to an 18-year oscillation. The Angolan catchment climate is currently more strongly influenced by the Inter-Tropical Convergence Zone (ITCZ) and the Congo Air Boundary (CAB). The Okavango River derives its water from two major tributaries, the Cubango in the west and the Cuito in the east. The Cubango River responds to variability in the Atlantic equatorial westerlies and the Cuito River responds to tropical lows in the Indian Ocean easterlies. Rainfall over the Cubango catchment shows a quasi-18-year rainfall oscillation which is out of phase with that of central southern Africa (McCarthy et al., 2000).

Fluvio-lacustrine deposition in northern Botswana has predominantly occurred within a large structural depression formed by a southwesterly propagating extension of the East African rift system. This depression was drained and filled periodically by southeasterly flowing rivers during the Tertiary and Pleistocene as the area was faulted and half grabens developed (Cooke, 1980; Mallick et al., 1981; Modisi et al., 2000). The MOZ depression is controlled by a series of NE-SW normal faults related to incipient rifting which reactivated Proterozoic and Karoo structures (Baillieul, 1979; Smith, 1984; Modisi et al., 2000). Tectonic activity along the same trend resulted in the uplift along the Zimbabwe–Kalahari axis possibly during the late Pliocene–early Pleistocene (Partridge and Maud, 2000; Moore and Larkin, 2001) causing the impoundment of proto Okavango, Kwando and upper Zambezi drainage and the development of the Makgadikgadi, Ngami and Mababe sub-basins (Cooke, 1980; Ringrose et al., 2005).

3. Previous work on climate change and lake levels

3.1. Regional palaeo-environmental studies

Climate forcing due to changes in the eccentricity of the earth's orbit (Milankovitch cycles) and to the precession of the equinoxes have both been evident in southern Africa during the late Quaternary (Tyson and Preston-Whyte, 2000; Tyson et al., 2002b). Based on oxygen isotope temperatures from deep sea sediment cores, cycles with periods of about 100,000 years, 43,000 years, 24,000 years and 19,000 years have been identified (Imbrie et al., 1984; Petit, 1999). During perihelion conditions, wetter summers prevail as the meridional temperature gradient between the equator and the South Pole strengthens as does the ITCZ (Tyson and Preston-Whyte, 2000). The 23,000-year cycles have been detected in the granulometric analysis of the sediments in a 90 m core taken from the Tswaing impact crater lake (formerly the Pretoria Saltpan) in the northern South Africa. The proxy rainfall series indicate five major rainfall intervals occurring between 100 and 200 ka with less well developed peaks occurring over the past 100 ka (Partridge et al., 1997).

Tyson and Preston-Whyte (2000) cite evidence for a warm period in southern Africa during the Last Interglacial at 125 ka and a short period of cooling during the Pleniglacial at about 75 ka. The Inter-Pleniglacial from 65 to 25 ka was a long period of cooler conditions that changed just before the start of the Last Glacial Maximum (LGM) at ca. 21 ka. A minimum of less than 40% of present mean annual rainfall was experienced over the Kalahari during this time (Partridge et al., 1997). Between 16 and 11 ka a rapid increase of temperature occurred in southern Africa. Across much of the sub-continent the temperature rise seems to have been accompanied by increased moisture supply, as in the Kalahari (Shaw and Cooke, 1986).

During the Holocene Altithermal between 7 and 4.5 ka, the currently semi-arid western interior of southern Africa, which includes the Lake Ngami basin, received between 10% and 20% more precipitation than the current mean annual precipitation for the region (Partridge et al., 1997). A regional high-resolution record from the middle Holocene (6.6 ka) to the present is the stable isotope record for the Cold Air Cave in the Makapangsgat Valley in northern South Africa (Repinski et al., 1999). A number of events are apparent in the $\delta^{18}O$ record. The first is the end of the warm Holocene altithermal until just after 6 ka BP. Warmer conditions occurred again at around 4 and 2.2 ka. Five centuries of cooling associated with the Little Ice Age from A.D. 1300 to 1800 were also recorded.

3.2. Palaeo-environmental studies conducted in the MOZ basin

Sedimentological and geochemical evidence suggests that the Okavango Delta has expanded and contracted over the past 400,000 years and the region may have been subject to extensive flooding prior to 110, 80–90 and 41–43 ka (Ringrose et al., 2005). Past levels of palaeo-Lake Tsodilo, in northwestern Botswana are a reflection of direct local precipitation as channels do not drain into the basin (Thomas et al., 2002). Mollusc remains found in palaeo-Lake Tsodilo suggest that permanent deep water occurred from 40 to 32 ka and diatom evidence suggests that from 36 to 32 ka the lake became more eutrophic and seasonal. In addition, dune construction around Tsodilo, probably associated with drier and windier climatic conditions, occurred at 36–28 ka. Lacustrine conditions occurred in palaeo-Lake Tsodilo from 27 to 22 and 19 to 12 ka (Thomas et al., 2002). It is possible that the period between 22 and 19 ka may indicate a drying period in the region which coincides with the LGM in southern Africa (Partridge et al., 1999; Thomas and Shaw, 2002; Thomas et al., 2002).

Diatomite beds in Lake Ngami were first reported in the Southern Okavango Integrated Water Development Phase 1 final report (SMEC, 1987) covering an area of approximately 30 km^2 over the eastern portion of the basin. A study of lake Ngami shorelines, diatoms and Holocene sediments conducted by Shaw et al. (2003) suggested an extensive and slightly alkaline lake at 11 ka. They suggest that lake levels rose between 4 and 3 ka and conclude that this increase in lake levels must represent increase flow from the Okavango Delta and a more humid climate at least in the region of the rivers headstreams in Angola. In addition, Shaw et al. (2003) investigate diatoms at six sites in Lake Ngami. They report that the diatom taxa in the lake contrast with the *Eunotia* dominated acid pH taxa of the present day Okavango system reported in Ellery (1987). Robbins et al. (1998), based on archaeological investigations near Toteng, further suggested that a deep lake existed around 4 ka after which lake levels fell slightly between 3.8 and 2.4 ka (Fig. 2).

Shaw (1985) reported that, based on documentary records, Lake Ngami was still a substantial lake in the 1850s but was becoming seasonal and by 1880 became a closed lake when inflow from the Thaoge channel ended. Inflow through the Kunyere was also significant, based on the presence of extensive diatom beds near Toteng (SMEC, 1987). Having been dry since 1989, Lake Ngami received water through the Kunyere in 2004. Prior to this, satellite imagery shows that 1984 and 1989 were the last two years with substantial water in the lake. These two years and 2004 correspond to the highest Okavango Delta inflow at Mohembo between 1981 and 2004 (P. Wolski, pers. comm.), suggesting that the lake is an integral part of the Okavango system.

4. Sampling and analytical procedures

Fieldwork took place between 2003 and 2004. A topographic profile across the lake bed was conducted using a Trimble 4700 Differential GPS to determine the elevation of the pit (Ng-02) and related lake basin and shoreline features. GPS points were corrected to benchmark BPS274 with an elevation of 926.550 masl. Sediments from a 4.6 m pit (Ng-02) dug into the lake bed (Fig. 2) were collected at 10 cm intervals to give 46 samples. Dried subsamples were used for the analysis of major, trace and rare earth elements (REE), loss on ignition (LOI) and S.

Major, trace and REE analyses were performed at Chemex Laboratories in Canada. Major elements were determined using ICP-AES. Trace and REE were analysed using ICP-MS (detection limits generally between 0.1 and 0.5 ppm) with the exception of Cr, Ni and Pb that were determined by flame AAS (detection limits 1 ppm). Total S was measured at the HOORC Environmental Laboratory on 300 mg samples by combustion and infrared absorption spectrometry using a Leco S-144DR sulphur analyser. The organic and carbonate contents were estimated from weight LOI at 550 °C (LOI_{orgC}) and 950 °C (LOI_{inorgC}), respectively. For all geochemical data, the significance of correlation was tested using the two-sided test at a 95% confidence limit (Rollinson, 1993).

Three samples were dated at the University of Botswana using thermo-luminescence (TL) techniques (Aitken, 1985) after protecting the samples from exposure to sunlight. It was assumed that the samples had undergone total bleaching in a shallow water environment before deposition. TL was used because it provided reliable dates in the past (Blumel et al., 1998; Ringrose et al., 2003)

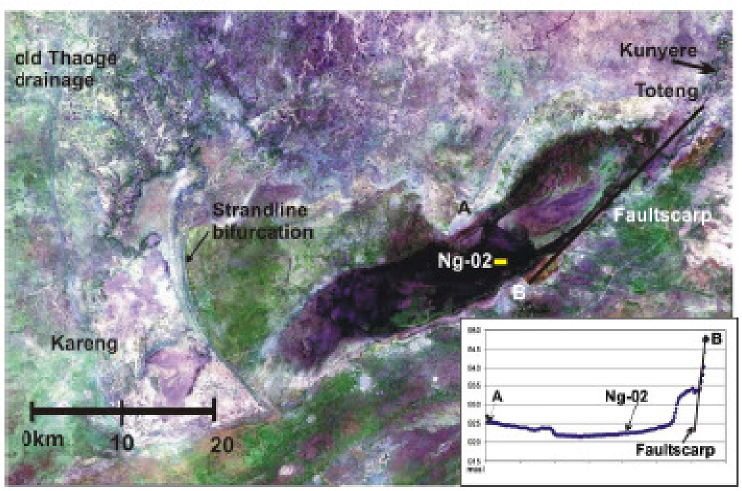

Fig. 2. Satellite image of the Lake Ngami basin depicting the location of sampling site Ng-02, shoreline features and the faultscarp bounding the lake to the south.

and literature sources suggest a degree of comparability between TL and OSL (optically stimulated luminescence) (e.g. Botter-Jensen and Duller, 1992; Radtke et al., 1999; Huaya et al., 2004). Alpha counting was carried out on a portion of the whole sample using an Elsec 7286 (low-level alpha counter) to determine abundances of uranium and thorium (ppm) and a Corning 410 Flame Photometer to determine potassium weight percentage (Table 1). Carbonates and iron staining was removed using hydrochloric acid and organic matter using hydrogen peroxide. TL values were determined using a Riso D12 reader. The environmental dose rate was determined by a low-level alpha counter (Elsec 7286) using a 42 mm ZnS screen (Zoller and Pernicka, 1989). The values shown assume secular equilibrium for both U and Th chains (Carl, 1987). Uncertainty levels (Table 2) represent one standard deviation. The cosmic dose was calculated taking into consideration depth of burial, overburden density and porosity, sample co-ordinates and altitude.

AMS ^{14}C dating was conducted at Poznan Laboratory in Poland. The samples were mechanically cleaned under binocular microscope to remove root fragments. The datable pieces of sample were collected, rinsed with 4% HCl (room temperature), 0.5 M NaOH (60 °C) and again 4% HCl (room temperature) to remove all traces of carbonates in the samples. The combustion to CO_2 was performed in a closed quartz tube together with CuO and Ag wool to 900 °C. The sample CO_2 was then reduced with H_2 over approximately 2 mg of Fe powder as a catalyst, and the resulting carbon/iron mixture is pressed into a pellet in the target holder (Czernik and Goslar, 2001). The ^{14}C concentration of the samples was measured with a National Electrostatics Corporation "Compact Carbon AMS" spectrometer by comparing the simultaneously collected ^{14}C, ^{13}C and ^{12}C beams of each sample with those of oxalic acid standard, CO_2 and coal background material (Goslar et al., 2004). Conventional ^{14}C ages were calculated with a $\delta^{13}C$ correction for isotopic fractionation (Stuiver and Polach, 1977) based on the $^{13}C/^{12}C$ ratio measured by the AMS-system simultaneously with the $^{14}C/^{12}C$ ratio. As this $\delta^{13}C$ includes the effects of fractionation during graphitisation in the AMS-system, it cannot be compared with $\delta^{13}C$ values obtained per mass spectrometer on CO_2. For the determination of the measurement uncertainty (standard deviation), both the counting statistics of the ^{14}C measurement and the variability of the interval results that, together, make up one measurement were observed. The larger of the two was adopted as the measurement uncertainty. To this the uncertainty connected with the subtraction of the

Table 1
Data inputs for TL

Sample	Ng-02 T220	Ng-02 T380	Ng-02 T440
Equivalent dose (Gyr)	32.59 ± 0.48	33.57 ± 1.64	73.89 ± 2.29
Diameter of grains (μm)	107 ± 17	107 ± 17	107 ± 17
Density of quartz grains (gcm^{-3})	2.65	2.65	2.65
Sediment U (ppm)	3.68 ± 0.25	0.73 ± 0.06	2.83 ± 0.19
Sediment Th (ppm)	9.62 ± 0.0.82	1.18 ± 0.0..18	5.90 ± 0.62
K (wt%)	1.22 ± .03	0.64 ± .03	0.86 ± 0.03
Water content (wt%)	12 ± 8	12 ± 8	15 ± 5
Cosmic dose rate (uGya^{-1})	170.00 ± 17.00	150.00 ± 15.00	140 ± 14
Dose rate (uGya^{-1})	2.672 ± 277	943 ± 91	1824 ± 132
Age (years BP)	12,197 ± 1277	35,602 ± 3851	40,499 ± 3187
Additive dose (Gyr)			
+ b1	19.9	26.53	66.33
+ b2	39.8	66.33	132.67
+ b3	82.92	116.08	232.17
+ b4	149.25	199	331.67
+ b5		331.67	497.5

Table 2
Results from C14 and TL dating

Sample	Description	Depth (cm)	Age estimate	Method
Ng-02 T90	Organic FeO-rich fired clay	90	3.675 ± 0.030 ka BP	C14
Ng-02 T220	Diatom-rich organic silt	220	12.197 ± 1.277 ka	TL
Ng-02 T220	Diatom-rich organic silt	220	14.740 ± 0.080 ka BP	C14
Ng-02 T320	Organic-rich lake sediment	320	17.890 ± 0.080 ka BP	C14
Ng-02 T380	Fine pale yellow sand with minor diatoms	380	35.602 ± 3.851 ka	TL
Ng-02 T440	Diatom-rich lake sediments	440	40.499 ± 3.187 ka	TL

background was added. The quoted 1-sigma error is thus the best estimate for the full measurement and not just based on counting statistics.

ESEM analysis was undertaken at the University of Botswana using a Philips XL30 environmental scanning electron microscope to obtain micro-textural information and to make critical taxonomic identifications on some of the main diatom species found in the sediments. An in-depth quantitative investigation of diatom changes in the lake is currently being prepared, but here we report briefly on summary, qualitative diatom composition of several samples spanning the length of the stratigraphic sequence. This information is useful because species composition can further highlight relative changes in lake chemistry associated with prevailing climatic conditions (Mackay et al., 2003) and diatoms have shown to be particularly useful proxies in African lakes (Gasse et al., 1997; Stager et al., 1997). Sediment samples were prepared according to standard laboratory procedures (Battarbee et al., 2001) and examined at high magnification (×1000) using oil-immersion light microscopy with phase contrast. Taxa were identified using a range of diatom flora, especially those of African lakes (e.g. Gasse, 1986) and oligotrophic, temperate lakes (e.g. Krammer and Lange-Bertalot, 1986–1991).

5. Topographic and stratigraphic results

Ng-02 lies at an elevation of 922 m, close to the lake sump at 921 m. The lake bed rises gradually to 925 m in a southerly direction (B) with a terrace at 934 m and up to 948 m along the fault scarp (Fig. 2). The lowest unit of Ng-02, UP460 (Fig. 3), comprises an unconsolidated silty sand with minor calcrete. Freshwater diatoms are present in this unit as evidenced by the presence of valves of genus *Aulacoseira ambigua* (Fig. 4a) and fragments of a periphyton taxon belonging to the genus *Surirella engleri* (Fig. 4b). The unit directly above (UP440) consists of a compact fine grain pale yellow sand with minor diatom fragments and calcrete nodules (Fig. 4c and d). Early stages of amorphous silica forming on the quartz grains is also evident in Fig. 4d. The sand unit changes abruptly into a white diatomite (UP350) with a thickness of about 20 cm (Fig. 4e). Diatoms in this bed include fragmented pieces of genus *Nitzschia* (e.g. *N. amphibia*) before changing abruptly into an organic rich silty sand of 30 cm thickness (UP330). This grades gradually into a gray laminar (cm scale) diatomaceous silt with FeO staining (UP300) and then a diatom rich silt of 80 cm thickness (UP240). Silt with minor calcrete nodules (UP160) is overlain by a dark gray laminar diatomite (UP120) of 20 cm thickness. Large intact valves of *Surirella engleri* from UP120 were found in the sample collected at 110 cm depth. Valves from *Aulacoseira ambigua* and broken fragments of genus *Surirella* were found at 100 cm depth (Fig. 4f–h). UP120 is overlain by organic rich clay with laminar (cm scale) and columnar structure (UP100) with evidence of burnt peat. The top 10 cm of the profile is an organic rich silt. More detailed diatom descriptions are given below.

6. Geochemical characteristics of the Ng-02 samples

The Lake Ngami sediments contain a high proportion of SiO_2 (51–92.5 wt%, avg. 72.4 wt%) and variable levels of Al_2O_3 (2.04–17.2 wt%, avg. 8.88 wt%) (Table 3). Al_2O_3 and SiO_2 are significantly negatively correlated ($r = -0.94$). TiO_2 varies between 0.23 and 0.77 wt% with an average value of 0.51 wt%. TiO_2 and SiO_2 are significantly negatively correlated ($r = -0.94$). TiO_2 and Al_2O_3 are positively correlated ($r = 0.91$) being both associated with the flux of fine sediment into the basin.

6.1. Redox condtions

Al_2O_3 and LOI_{orgC} are significantly positively correlated ($r = 0.75$) and are both elevated in the UP460, UP330 and UP100 units (Fig. 5a). LOI_{orgC} and Fe_2O_3 are also significantly positively correlated ($r = 0.79$). Elevated LOI_{orgC} is an indication of anaerobic conditions in the basin. Organic matter accumulates in wetland environments that are saturated with water thereby inhibiting decomposition (Collins and Kuehl, 2001). Elevated Al_2O_3 suggests clay minerals were either washed into the basin or weathered in situ, both indicating wet conditions. P_2O_5 values are generally low (<0.01 wt%) with the exception of the UP100 upper unit suggesting higher nutrient levels in the water towards the final stages of the lake (Fig. 5b).

The UP100 unit shows high levels of S (Fig. 5b). LOI_{orgC} and S are significantly positively correlated ($r = 0.87$). Values of Fe_2O_3/Al_2O_3 and S are both elevated in the upper UP100 unit indicating that free dissolved sulphide was present in the bottom water or subsurface anoxic conditions (Fig. 5c). The marked increase in LOI_{orgC}, S and Fe_2O_3/Al_2O_3 in the UP100 unit is significant, suggesting a change from suboxic to anoxic. This occurs again in the UP330 unit, and to a lesser extent in the UP460 unit.

The degree of pyritisation in the sedimentary record could also indicate anoxic conditions. The extent of correlation between the transition metals V, Cr, Ni, Co, and Pb to S was calculated resulting in $r = 0.40$, 0.26, 0.47, 0.68, and 0.57, respectively. V, Ni, Co and Pb are significantly correlated suggesting that these elements' concentrations are related to sulphide accumulation in the Lake Ngami sediments. These transition metals exhibit similar patterns when plotted versus depth of samples (Fig. 5d). These in turn correlate closely to the patterns generated for LOI_{orgC} and Al_2O_3. Mo can also exhibit a large uptake on pyritisation (Huerta-Diaz and Morse, 1992) and this appears to occur in the UP100 unit suggesting anoxic conditions (Fig. 5e).

REEs are used as chemical indicators of geologic processes, including assessment of crustal sources, the redox state of water and depositional environment. The

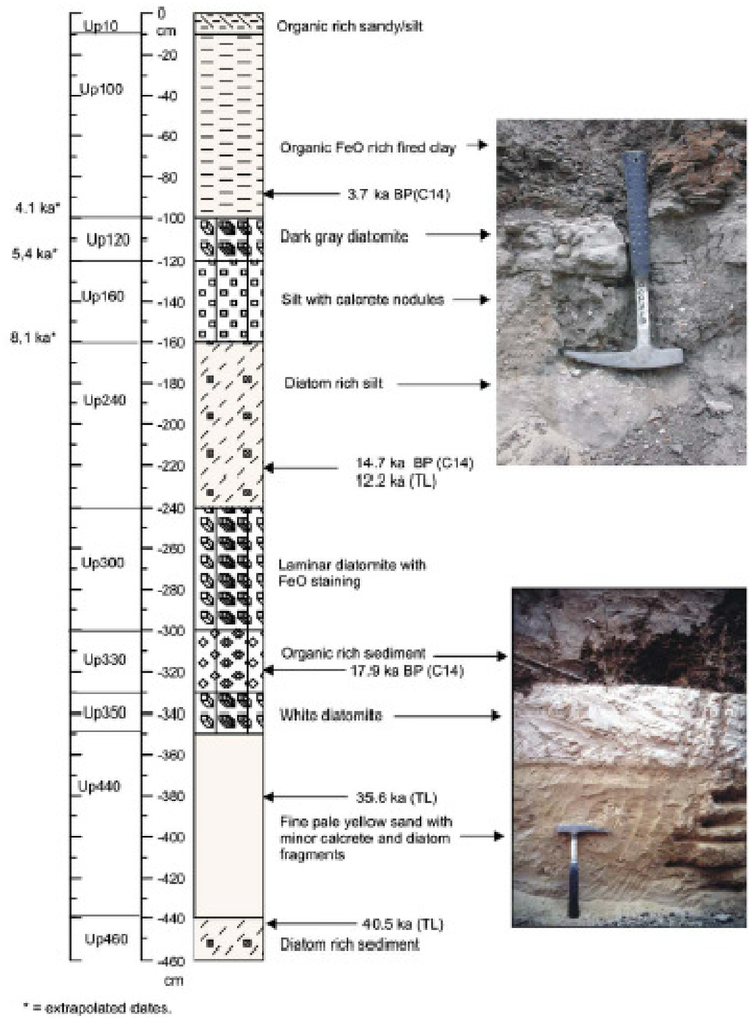

Fig. 3. Stratigraphic log of Ng-02 depicting the units within the sampling pit.

REEs are insoluble and are present in low concentrations in terrestrial waters; thus, the REEs present in terrigenous sediment are chiefly transported as particulate matter and reflect mainly the chemistry of their source. Studies have indicated that high pH water show enrichments in heavy REEs (HREE) and the degree of enrichment appears to increase with increasing alkalinity (Moller and Bau, 1993; Johannesson et al., 1994). For the high pH alkaline waters, speciation modelling (Johannesson et al., 1994) indicates that REE dicarbonate complexes are the only important form of dissolved REE. The HREE are more strongly complexed in alkaline solution leading to enrichment of the HREE over light REEs (LREE) in the water. This implies that certain sediments should be the site of preferential accumulation of LREE.

La_N/Yb_N ratios vary slightly between the different units with values ranging between 0.53 and 1.16 with an average value of 0.93. Values are lower (0.53–0.84, avg. 0.68) for the UP440 unit indicating a moderate depletion of LREE. Samples Ng-02 T190 and Ng-02 T200 taken from the UP240 unit show slight enrichment in LREE, indicating possible alkaline conditions.

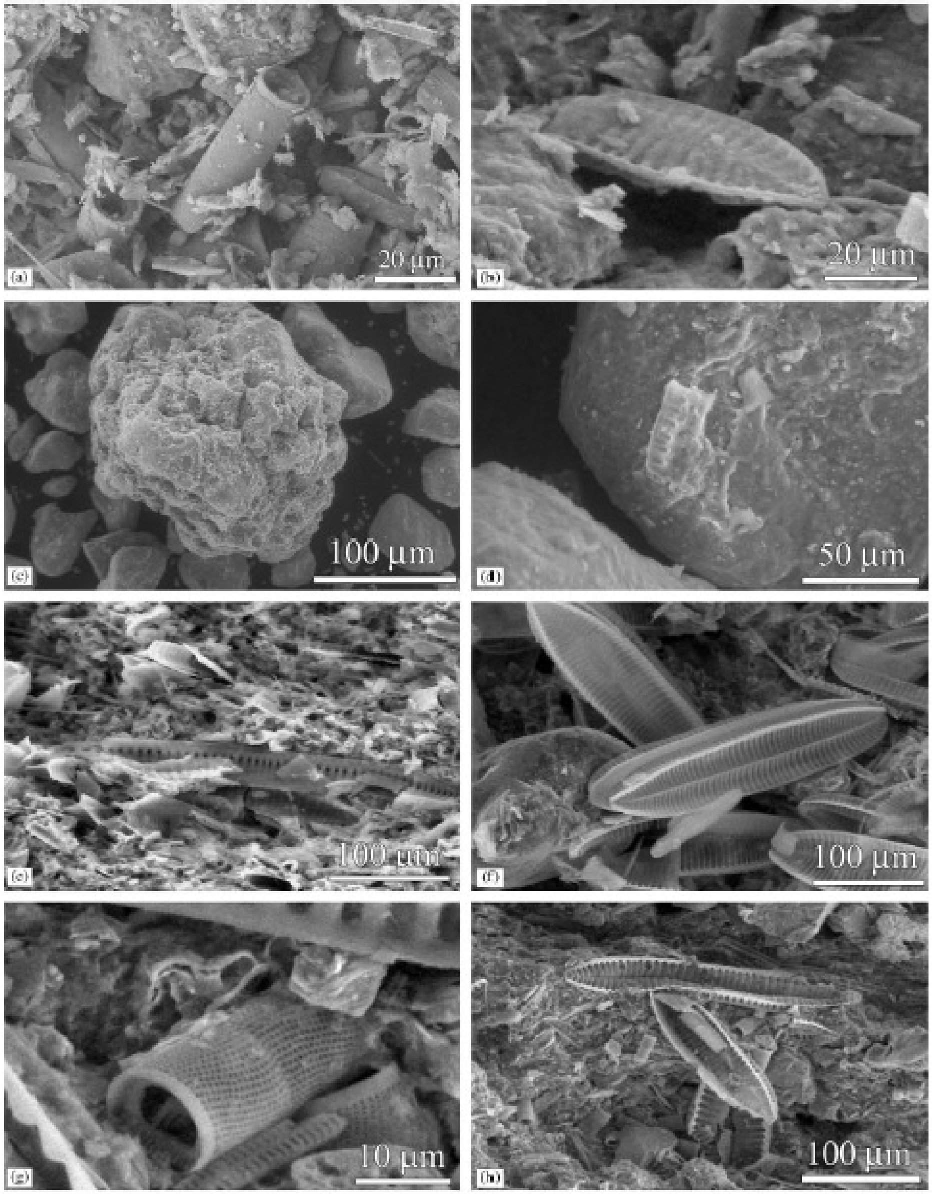

Fig. 4. ESEM images of selected samples: (a) centric valves of genus *Aulacoseira*; (b) broken *Surirella* fragments from UP460 unit; (c) calcrete nodule and quartz grains in UP440 unit; (d) fragment of diatom on quartz grain from UP440 unit; (e) broken diatom of genus *Nitzschia* from UP350 unit; (f) large intact *Surirella* from UP120 sampled from a depth of 110 cm; (g) genus *Aulacoseira* from UP120 sampled from 100 cm depth; (h) broken fragments of genus *Surirella* taken from UP120 unit at 100 cm depth.

Table 3
Geochemical results for selected samples

Sample Depth (cm)	Ng-02 T20 20	Ng-02 T80 80	Ng-02 T100 100	Ng-02 T110 110	Ng-02 T120 120	Ng-02 T190 190	Ng-02 T270 270	Ng-02 T320 320	Ng-02 T330 330	Ng-02 T380 380	Ng-02 T440 440	Ng-02 T460 460
SiO_2 (%)	56.6	51	60.8	78.1	91.6	75.1	69.1	60.6	75.2	90.9	76.7	73
Al_2O_3	14.35	16.3	9.08	4.46	2.04	8.56	11.6	14.85	7.02	2.36	6.36	7.64
Fe_2O_3	5.51	6.16	4.6	2.09	1.1	3.48	4.66	6.44	3.3	0.99	3.07	4.12
CaO	0.44	0.16	0.28	0.41	0.11	0.29	0.56	0.85	1.92	0.39	2.66	1.42
MgO	0.83	0.99	0.92	0.41	0.14	0.67	0.89	1.03	0.76	0.17	0.67	1.02
TiO_2	0.74	0.71	0.65	0.62	0.25	0.44	0.56	0.6	0.54	0.25	0.38	0.53
P_2O_5	0.05	0.07	0.07	0.02	<0.01	<0.01	0.01	0.01	0.01	<0.01	<0.01	0.03
LOI (orgC)	16.3	15.2	16.7	9.29	2.32	7.29	8.65	10.8	3.43	0.97	6.05	11.9
LOI (inorgC)	1.16	2.39	2.25	1.04	0.15	0.71	1.31	1.25	2.70	0.59	2.15	2.27
S	0.088	0.108	0.132	0.066	0.013	0.015	0.01	0.015	0.012	<0.005	0.012	0.01
Co (ppm)	19.7	20.7	15	7.6	3.2	14.2	10.8	13	7.2	2.4	8.7	11.7
Pb	20	15	12	9	5	14	15	19	12	<5	10	12
Cr	190	130	130	210	250	100	100	100	130	80	170	120
Ni	35	37	29	17	12	27	26	41	22	8	21	25
V	148	164	111	46	14	108	126	149	74	23	70	103
Sr	67	53.6	77	110	46.5	49.9	53.6	73.6	83.8	42.4	103	101.5
Th	12	11	7	3	1	6	9	11	6	2	5	6
Mo	3	2	3	4	3	<2	<2	<2	2	<2	2	2
Y	27.7	20.6	15	9.3	4.6	19.3	17	16.3	12.6	3.7	8.7	11.2
La	36.1	29.9	20.7	12.4	5.9	26.7	25.6	25.6	16.7	3.9	13.8	14.6
Ce	69.4	56.1	41.1	26.7	11.6	49.1	50.2	51.3	34	6.5	26.9	27.3
Nd	31.9	25.7	19.7	12.5	5.5	22.8	23.7	25.1	16.7	3.2	12.6	14.6
Sm	6	4.9	3.8	2.4	1	4.6	4.5	5	3.3	0.6	2.5	2.9
Gd	5.5	4.6	3.5	2.1	1	4.1	4.1	4.2	3	0.6	2.2	2.6
Yb	2.6	2.1	1.6	1.1	0.5	1.7	1.8	1.8	1.5	0.5	1	1.3

consistent with substitution of Th, Y and MREE in the lattice of Ca-phosphate.

6.2. Salinity and alkalinity levels

In a closed lake, as the volume of the lake changes as a result of variations in the hydrological regime of the catchment, so the chemistry of the water evolves. As the water level drops during periods of decreased precipitation/evaporation (P/E) ratio, the dissolved ions are concentrated until a point is reached where the least soluble minerals start to precipitate. Calcium carbonate ($CaCO_3$) is precipitated early in this process and is virtually insoluble except at low salinities (Eugster and Hardie, 1978). The trace element chemistry of Mg and Sr is an indicator of palaeo-salinity as during evaporative concentration of lake water in closed basins, precipitation of $CaCO_3$ often gives rise to an increase in the Mg/Ca and Sr/Ca meq ratio of the water and consequently a positive correlation with salinity (Eugster and Kelts, 1983).

CaO values in the Lake Ngami sediments are generally low (0.1–3.84 wt%, avg. 0.62 wt%) with higher values associated with the UP460 unit. MgO values range between 0.14 and 1.09 wt% with an average value of 0.68 wt%. Sr levels in the Lake Ngami sediments range between 41.1 and 132 ppm (avg. 64.4 ppm). The significant positive correlation between MgO and LOI_{inorgC} ($r = 0.72$) and Sr and LOI_{inorgC} ($r = 0.57$) is an indication that Mg and Sr in the sediments are partially controlled by chemical sedimentation of carbonates. However, unlike Sr and CaO, MgO values are also correlated with Al_2O_3 and TiO_2 ($r = 0.77$ and $r = 0.90$, respectively), which demonstrates that MgO concentrations are also controlled by the input of clay minerals into the basin. Consequently, only Sr and CaO are used for palaeo-salinity reconstruction of the Ng-02 sediments.

There appears to be an overall increase in the Sr/Ca ratio between 320 and 120 cm suggesting a period of increased salinity. This corresponds to a period of decreasing LOI_{orgC} implying aerobic conditions and lower Al_2O_3, therefore less clastic input which again suggests a lowering of lake levels. At a depth of 120 cm (UP120), the 20 cm bed of diatomite indicates that diatoms were the dominant component in the lake, with very little clastic input.

7. Diatom composition of Ng-02 samples

The lower section of the core (sample Ng-02 T440) taken from unit UP460 (ca. 40.5 ka) contains abundant diatom remains. The assemblage is dominated by *Aulacoseira ambigua*, *Denticula kuetzingii* and *Fragilaria construens*, while other common taxa include *Fragilaria brevistriata*, *Nitzschia amphibia*, *Synedra ulna*, *Rhopolodia gibba* and *Cyclotella pseudostelligera*. This assemblage suggests that well-mixed conditions prevailed as *Aulacoseira ambigua* is an obligate planktonic diatom that grows in open freshwaters (Gasse and Van Campo, 2001). *D. kuetzingii* may also be found growing in open water, although it can be classified as epiphytic too, i.e. it grows attached to aquatic macrophytes growing in the littoral regions of the lake. However, it is usually classified as growing in waters with high electrolytic composition, suggesting that the lake at this time was relatively deep (compared with other sections of the core) but brackish. The presence of *R. gibba* confirms this interpretation.

Sample Ng-02 T410 from unit UP440 contains very few diatoms, but for those that are present, *Denticula kuetzingii* is the most common. This perhaps suggests a shallow water environment with abundant macrophytes in littoral regions.

Sample Ng-02 T320 occurs in the unit UP330 (ca. 18 ka). In this section, there were rather fewer diatoms present than in Units UP460-440, and many valves were broken, making positive identifications of some of the smaller benthic taxa more difficult. Nevertheless, the assemblage was dominated by *F. construens*, while *D. kuetzingii*, *F. brevistriata* and *N. amphibia* were all common. *Aulacoseira ambigua* was present too, although this species can grow in shallower waters, but still as a planktonic diatom (Gasse, 1986; Kilham, 1990). It is likely therefore that the lake was deep enough to support populations of *Aulacoseira ambigua*, although the distribution of this species is likely to have been restricted.

Samples Ng-02 240 and 180 between units UP300-240 (ca. 15–10 ka) contains the largest number of different taxa (i.e. these units are characterised by a large alpha diversity) and diatom valves were relatively well preserved. The assemblage was dominated by the brackish species *D. kuetzingii* and *N. amphibia*, while other common taxa included the shallow water, epiphytic species *F. construens*, *F. pinnata*, *Achnanthes minutissima* and *Cymbella gracilis* and the alkalophilous species *Cyclotella meneghiniana*. The lake is likely to have been shallow at this time, and fairly alkaline with a basic pH, and with significant macrophyte growth in the extended littoral regions of the lake. Interestingly though, taxa such as *Aulacoseira ambigua* was also found, suggesting that either pockets of deeper water remained, or lake levels were perhaps undergoing considerable fluctuations, from marshy to deeper water environments. The presence of *Cyclotella stelligera* also suggests fluctuating water levels, as this species can grow both in pelagic and littoral regions of a lake.

Samples Ng-02 110 and 100 in unit UP120 (ca. 5–4 ka) are characterised mainly by shallow water taxa including the periphytic *Achnanthes minutissima*, *Cymbela silesiaca* (which grows mainly in shallow water, circumneutral waters, attached to plants), *D. kuetzingii*, *N. amphibia*, *R. gibba* (another epiphyte which grows in waters with moderate to fairly high conductivity) and the very large *Surirella engleri* (valves were over 200 μm long). The ecology of this latter taxon is not well known, although Gasse (1986) has found it both in the plankton and living on the bottom sediments of freshwater lakes often in slightly alkaline waters.

The final two samples in this qualitative assessment were Ng-02 T80 and T40, from unit UP100 (ca. 3–2 ka). In both these samples, very few diatoms were present, with considerable numbers of broken valves, making positive identifications of small benthic taxa difficult. Sample Ng02-T80 contained very few taxa (e.g. *N. amphibia* and low numbers of *F. construens* and an unidentified *Eunotia* spp.). Palaeo-environmental reconstructions are therefore difficult, except to say perhaps that very shallow water conditions prevailed. Sample Ng-02 T40 was dominated by *F. pinnata* and *N. amphibia*, but also abundant were the taxa *Aulacoseira ambigua* and *Cyclotella stelligera*, suggesting lake water conditions perhaps becoming deeper, with increased mixing of the water column.

8. Palaeo-environmental interpretation

Based on slightly elevated but declining Al_2O_3 and LOI_{orgC} results, lacustrine conditions occurred in Lake Ngami at ca. 42 ka until ca. 40 ka. Diatom results indicate that relatively deep but brackish conditions prevailed. The higher CaO values of the UP460 unit might suggest more saline conditions; however, Sr/Ca ratios are relatively low in this unit. Work conducted on stalagmites in the Gcwhiaba Caves, approximately 70 km from Lake Ngami, reported enhanced local rainfall between 45 and 37 ka (Cooke, 1984). Lake Tsodilo had lacustrine conditions between 40 and 32 ka. This suggests that enhanced local rainfall in addition to inflow through the Okavango River system contributed to lacustrine conditions in the lake Ngami basin.

The lacustrine conditions in the basin appear to have been terminated rapidly at ca. 40 ka. Within the margins of error, the sample dated at 40 ka (UP460) and the sand unit (UP440) sample dated at 36 ka are identical, suggesting that these events could be co-incidental events. This would suggest that the lower sand unit was deposited rapidly implying fluvial sedimentation. Shaw et al. (2003) also report compact yellow sand at the bottom of one of their profiles in the lake bed on the northern edge of the lake. We believe that the sand unit occurs as a result of shallow flow-through conditions in the basin, and this is supported by grain size data. Samples from this unit show a distinct 3Φ peak. report an increase in the 3Φ peak in fluvial environments as opposed to the 2Φ "dune" peak. The onset of this sedimentary environment may have resulted from tectonic tilting of the basin. Strandline bifurcation (Fig. 2) is evidence that tilting has occurred in the basin. Gumbricht et al. (2001) describe tilting of palaeo-shorelines in the Mababe Depression and relate this to neo-tectonic activity in the Okavango Delta.

The sharp transition between the sandy UP440 unit and the overlying diatom unit (UP350) and the large gap between the dates of UP440 and UP330 suggests a depositional hiatus and possible erosion. This could reflect a possible seismic and/or fluvial event in the basin, or just non-deposition due to dessication of the lake.

At ca. 19 ka, shallow, aerobic, turbulent lake conditions were prevalent, but lake levels were at this time increasing to deeper water conditions until ca. 17 ka. This period coincides with the Late Glacial Maximum (LGM), a period of increased aridity and cooler conditions in the region (Partridge et al., 1999). The fact that the Lake Ngami basin appears to have been filling during this time of regional aridity appears to result from increased flow from the Okavango River and a more humid climate in the region of the rivers headwaters in Angola, suggesting an anti-phase climate between the two regions.

Increasing Sr/Ca ratio and decreasing LOI_{orgC} and Al_2O_3, from ca. 16 ka, suggest decreased inflow into the basin and a lowering of lake levels. Lacustrine conditions were probably maintained primarily by local rainfall input as the region experienced a warmer, wetter phase between 16 and 11 ka (Shaw and Cooke, 1986). Based on the enrichment of LREE in the UP240 unit, slightly alkaline conditions may have prevailed at ca. 12 ka and again in the UP120 unit (ca. 5 ka). Diatom results from Ng-02 T240 and T180 also support shallow alkaline conditions at this time. Shaw et al. (2003) suggested an extensive and slightly alkaline lake at 11 ka.

Fairly shallow lake levels prevailed at UP120 but the lake was filling rapidly by 4 ka. Shaw et al. (2003) proposed that lake levels rose between 4 and 3 ka. Talma and Vogel (1992) report a cooling event in southern Africa at 4.7–4.2 ka (post-Holocene Altithermal) recorded in the Cango Cave isotope record. Based on our results, the basin continued to fill until 3.7 ka BP and from then, it appears to have fluctuated and eventually gone into decline as indicated by decreasing S and LOI_{orgC} values until 2.4 ka. Based on LOI_{orgC} values, the lake levels began to rise again until ca. 0.8 ka, when it fell again. This corresponds well with findings of Robbins et al. (1998) who suggested a deep lake around 4 ka and a slightly lower lake between 3.8 and 2.4 ka.

9. Conclusions

Inorganic and organic carbon content, S, Al_2O_3 and various REE have been used in conjunction with diatoms to distinguish between high and low lake levels in the Lake Ngami basin. Lacustrine conditions in the Lake Ngami basin are suggested 42–40 ka consistent with events in palaeo-Lake Makgadikgadi (Ringrose et al., 2005) and Milankovitch cycles. The sedimentary record at 40 ka appears to have been influenced by tectonic activity, as lacustrine sediments are abruptly replaced with fine grained yellow sands. Deeper lake levels are reported for the period ca. 19–17 ka (LGM) followed by predominantly shallower alkaline conditions between 16 and 5 ka. Lake levels were high at ca. 4 ka and continued to fill until 3.7 ka, declined until 2.4 ka, increased until 0.8 ka and from then, lake levels declined.

During the LGM of southern Africa, a period of cooling and drying in the region, Lake Ngami levels were rising.

Conversely, when the southern African region started to become warmer and wetter following the LGM, Lake Ngami was going through a phase of reduced inflow. The results indicate that the present day dipole effect in precipitation between central southern Africa and regions of equatorial Africa was extant during the late Quaternary over NW Botswana and the Angolan highlands.

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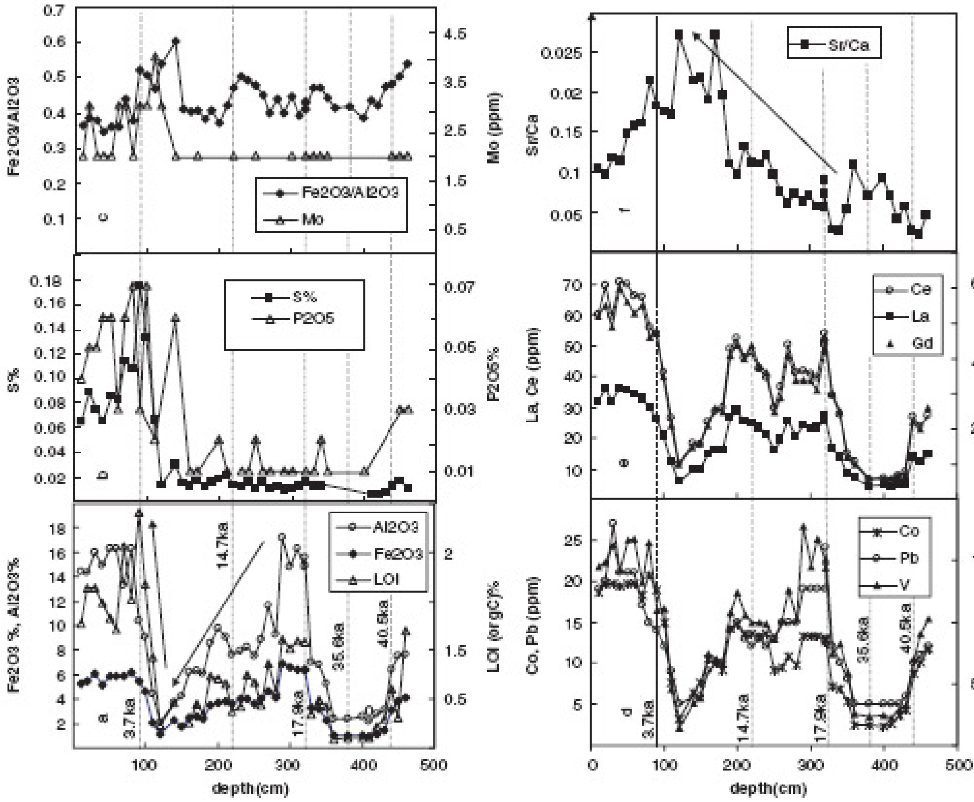

Fig. 5. Selected elements and ratios plotted versus depth for profile Ng-02.

Normalisation of Ce abundances to those of its neighbouring REE, measured in various biogenic and authigenic components, has been used to deduce redox conditions of the water column at the time of REE uptake by these phases. Unlike the other REE, cerium can undergo oxidation from soluble Ce(III) to highly insoluble Ce (IV). Its fixation in particulate matter, including organics, is thought to be responsible for distinctive depletion of Ce in well-oxygenated seawater (Wright et al., 1987; Liu et al., 1988; Bellanca et al., 1997).

Ce/Ce* variations can be explained by simple mixing of various components (essentially biogenic and authigenic) and of detrital materials (dominantly alumino-silicates) with crust-like Ce signatures. A positive correlation ($r = 0.88$) exists between Al_2O_3 and Ce concentrations for the Lake Ngami sediments (Fig. 5e), and a comparison of Ce/Ce* values with concentrations of terrigenous indices SiO_2 and TiO_2 indicate that there are weak significant correlations ($r = -0.37$, $r = 0.34$, respectively) between these factors, suggesting that fine sediment detrital flux does contribute to Ce/Ce* distribution. However, significant correlations exist between Ce/Ce* and S ($r = 0.59$) and Ce/Ce* and LOI_{orgC} ($r = 0.44$), indicating that redox conditions does play a role in the Ce/Ce* distribution in Lake Ngami sediments.

Samples from Ng-02 in general show a slight depletion in Ce/Ce* (0.84–1.02, avg. 0.93), indicating aerobic, alkaline conditions did not predominate in the basin. Only samples from UP120 show a slightly positive Ce/Ce* suggesting that at this stage the water was relatively more oxygenated and alkaline.

Liu et al. (1988) report an enrichment of middle REE (MREE) in fossil apatite. We interpret the lower La_N/Sm_N ratios (0.75–1.08, avg. 0.87) as an expression of MREE enrichments, possibly due to diagenetic phosphates. The weak significant positive correlation between Sm and Nd and P_2O_5 ($r = 0.46$ for both) suggests that phosphate precipitation contributed to MREE distribution. It is also noteworthy that P_2O_5 values are also weakly correlated with Th and Y ($r = 0.38$ and 0.48, respectively) which is