



Middle Pleistocene to recent diatoms and stratigraphy of the Magadi Basin, south Kenya Rift

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Abstract Two cores were recovered from the Lake Magadi and Nasikie Engida Basins in the south Kenya Rift. Core MAG14-2A (194 m) contains a middle Pleistocene to Holocene record, whereas core NAS15/19 (4.36 m) covers only the late Holocene. Surficial sediments from springs and shallow-water sites were sampled in both basins. MAG14-2A rests on trachyte dated at 1.08 Ma. Diatoms are rare in the oldest sediments, but well preserved after about 545 ka, documenting a trend from less to more saline water.

Core MAG14-2A contains fifteen facies, five of which are diatomaceous. In contrast, NAS15/19 is dominated by two facies, each containing well-preserved diatoms. Both sequences are distinct from others of similar age in the Kenya Rift in lacking pedogenic horizons, reflecting the location of Lake Magadi and Nasikie Engida in a tectonic sump where aquatic environments were maintained by geothermal and meteoric springs. Canonical Correspondence Analysis distinguishes three assemblages in the modern surface

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muds of Lake Magadi and Nasikie Engida, but with no pre-Holocene counterparts. Eleven diatom zones are recognised in MAG14-2A: Zones D2 to D10 contain rare to common diatoms dominated by *Aulacoseira granulata* and its varieties, *Aulacoseira agassizii*, *Thalassiosira faurii*, *Thalassiosira rudolfi* and *Cyclotella meneghiniana*. Individual samples commonly include a mixture of benthic and planktonic taxa and saline and freshwater species. These assemblages indicate waters that ranged between pH 7.4 and 11.5 with conductivities of ~ 300 to $> 25,000 \mu\text{S cm}^{-1}$. Correlations with the neighbouring Olorgesailie and Koora Basins indicate four major environmental phases that affected the south Kenya Rift during the last million years with fresh to moderately saline water, or land surfaces, developing during Phase I (1000 to 750 ka). These environments gave way to generally wetter conditions and freshwater lakes in all basins during Phase II (~ 750 to 500 ka). Phase III (~ 500 to 325 ka) was characterised by drier conditions with paleoenvironments becoming more variable and dry during Phase IV (325 ka to present).

Keywords Geochemistry · Diatoms · Sedimentology · Mineralogy · Paleolakes · Magadi

Introduction

Quaternary paleoenvironmental research in the Kenya Rift has been based primarily on the analysis of spatially separated outcrops representing periods of 10–100 kyr, or short Holocene cores that mostly span < 10 kyr. For example, deposits in the Suguta Valley (inset, Fig. 1a), contain discontinuous outcrops that extend back > 1 Ma, yet only the late Pleistocene to Holocene sequences have been described (Junginger et al. 2014). In contrast, Lakes Turkana, Baringo, Bogoria, Nakuru, Elmenteita and Naivasha have been cored, yielding detailed late Pleistocene and Holocene records (Richardson and Richardson 1972;

Richardson and Dussinger 1986; Tiercelin et al. 1987; Halfman et al. 1992; Kiage and Liu 2009).

In the south Kenya Rift (Fig. 1a), environmental reconstructions have been based on outcrops in the Olorgesailie (1.2–0.5 Ma: Owen et al. 2008; Potts et al. 2018) and Oltululei (< 0.32 Ma: Behrensmeier et al. 2018) formations. Recently, high-resolution data have been obtained from long (up to 194 m) Lake Magadi cores (1 Ma until present) (Owen et al. 2018a, b, 2019) and the Koora Basin (1000–97 ka) (Muiruri 2017; Deino et al. 2019). The Magadi core (MAG14-2A, Fig. 1b) was recovered as part of the *Hominin Sites and Paleolakes Drilling Project* (HSPDP), which aims to develop local and regional paleoenvironmental histories as a background to hominin evolution in East Africa. Owen et al. (2018a, b) synthesised geochemical, sedimentological, diatom and pollen data from MAG14-2A. Detailed follow-up studies on core and outcrop geochemistry showed increased aridity and climate variability in the region since the onset of the northern hemisphere glaciation (Owen et al. 2019).

This study focuses on diatoms in Pleistocene to modern sediments of the Magadi Basin, including: (1) a half-million-year diatom record from Lake Magadi, (2) late Holocene core deposits from neighbouring Nasikie Engida, and (3) modern diatoms from surficial sediments at Lake Magadi and Nasikie Engida. The aim of this work is to: (1) reconstruct hydrological variability and environmental change based on diatom assemblages, including an assessment of modern and late Holocene floras as analogues for Pleistocene communities; (2) examine factors that drove changes; and (3) explore regional and global environmental trends, influences, and correlations in the context of the Quaternary history of the Magadi Basin.

Study area

Lake Magadi (20×4 km; ~ 605 m above sea level) lies in the 70-km-wide south Kenya Rift (Fig. 1a) and forms a tectonic sump towards which surface and groundwater flow. The ephemeral lake seasonally forms a saline pan of trona ($\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$) with marginal spring-fed lagoons (Fig. 1b). Dilute ephemeral streams feed lagoons maintained during dry periods by hot- and ambient-temperature springs, which produce waters in which $\text{HCO}_3 \gg \text{Ca} + \text{Mg}$ (Table 1). After evaporation this leads to development

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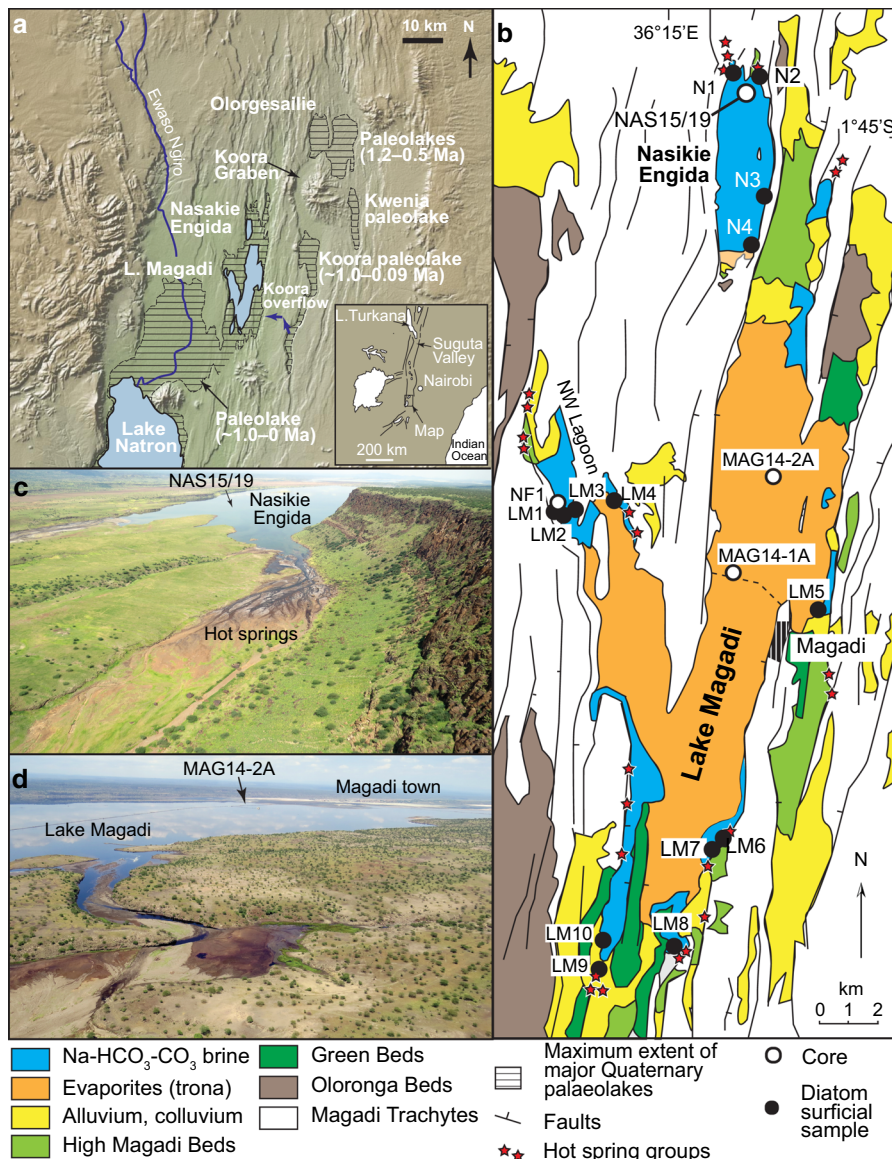


Fig. 1 Topographic and geological setting. **a** Location of later Quaternary paleolakes showing maximum lake extent attained (hatched lines) during at least parts of the periods indicated. Basemap from GeoMapApp (<http://www.geomapp.org>). **b** Core locations and geological map. Core MAG14-1A lies

close to a structural high with depth to trachyte of ~ 133 m and MAG14-2A lies within a sub-basin with a depth to trachyte of ~ 194 m. **c** Nasikie Engida from the north with NAS15/19 location. Note hot springs at NE corner of the lake. **d** Lake Magadi from the northwest showing MAG14-2A location

of Ca- and Mg-free Na–CO₃–SO₄–Cl brines, with SO₄ reduction controlling the formation of Na–CO₃–Cl fluids (Eugster 1980, 1986).

Nasikie Engida (7 × 2 km), northwest of Lake Magadi (Fig. 1a–c), is a 1.6-m-deep perennial lake with a surface that fluctuates ~ 3–5 m above contemporary Lake Magadi. It is maintained by perennial, hot (> 75 °C), saline-alkaline springs (Table 1) and

minor meteoric seepages. The northern waters of Nasikie Engida have a Na–HCO₃–CO₃–Cl composition that becomes more saline southward, reflecting evaporative concentration (Renaut et al. 2021). The water contains negligible Ca and Mg, moderate concentrations of K, SO₄ and F and high SiO₂, similar to Lake Magadi waters. A solid nahcolite (NaHCO₃)

Table 1 Selected water analyses for the South Kenya Rift Sources: 1: Jones et al. (1977); 2: Original (this study)

Sample	Location	Date	Source Field	pH °C	T mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	HCO ₃ mg/l	CO ₃ mg/l	Cl mg/l	SO ₄ mg/l	F mg/l	SiO ₂ mg/l	NO ₃	
<i>Dilute rivers</i>																	
M5/73a	Oloibortoto	5–1973	1	7.2	19	5	2	6.5	3.6	46		4	4	0	19		
M5/73b	Uaso Nyiro (Steel Bridge)	5–1973	1	7.42	23	39	15	12	2.7	148		8	9	2	29		
<i>Hot springs</i>																	
LM9	E Lagoon spring	8–2007	2	9.89	33.7	7100	148	0.5	< 0.1	3270	4510	3480	65	57	70	0.66	
LM7	SE L. Magadi spring	8–2007	2	9.52	39.1	12,400	150	0.5	< 0.1	9030	7200	4580	220	102	79	8.4	
LM5	SE L. Magadi spring	8–2007	2	9.59	38.8	9500	182	0.5	< 0.1	7170	5230	5120	160	89	80	19	
LM6	SW L. Magadi spring	8–2007	2	9.75	33.4	25,700	388	1.6	< 0.1	10,200	17,800	15,800	470	245	103	1	
LM1	NW Lagoon hot spring	8–2007	2	8.77	42.2	9400	212	0.6	< 0.1	13,500	1720	5080	240	93	92	5.8	
N2	NW Nasikie Engida	8–2007	2	9.01	82	11,200	260	0.6	< 0.5	13,300	3970	4900	210	165	90	< 0.04	
N6	NE Nasikie Engida	8–2007		8.72	76.1	11,500	290	0.5	< 0.5	15,700	2230	5580	230	165	95	< 0.04	
<i>Lake waters</i>																	
LM2	NW Lagoon, L. Magadi	8–2008	2	9.61	23.2	33,100	630	4	< 1	20,000	20,300	17,400	550	320	306	55	
LM3	Central L. Magadi	8–2008	2	10.5	33.4	168,000	2980	< 1	< 1	< 1	120,000	122,000	1900	2100	1660	30	
LM4	Central L. Magadi	8–2008	2	10.81	34.8	157,000	4300	< 1	< 1	244	99,500	144,000	2100	1840	1470	4	
LM10	E Lagoon	8–2008	2	9.96	28.2	10,000	275	2	< 0.1	4200	6820	5360	120	100	81	7	
LM8	Bird Rock Lagoon	8–2008	2	9.62	33.1	15,100	315	1	< 0.1	9590	8840	8210	250	104	100	4	
N1	NW Nasikie Engida	8–2007	2	9.21	48.4	12,400	250	0.9	< 0.5	13,600	4990	5980	200	180	132	15	
N5	N shore Nasikie Engida	8–2007	2	9.49	33.8	16,900	350	0.5	< 0.5	15,300	8290	8600	240	250	125	20	
N4	N shore Nasikie Engida	8–2007	2	9.34	32.8	14,400	330	1.4	< 0.5	14,200	6170	7120	260	210	120	28	
N8	E shore Nasikie Engida	8–2007	2	9.45	35.4	64,700	1490	2	< 1	36,100	58,400	11,000	780	1100	440	26	
N9	S shore Nasikie Engida	8–2007	2	9.45	34.5	77,500	1830	2	< 1	26,100	61,000	34,300	870	1290	482	3	

crust underlies 85% of the lake floor and trona accumulates along the southern shores in dry years.

These modern lakes are successors to a series of paleolakes (Fig. 1a) that have occupied the area since eruption of flood lavas (Magadi Trachyte Formation) about one million years ago (Baker 1958). The resulting subdued topography was then fragmented by NNE-SSW faults (Owen et al. 2019). In outcrop, the oldest sediments (Oloronga Beds) include fluvial silt and sand, lacustrine zeolitic silt, tufa and chert (Behr 2002), dated between 0.8 and > 0.3 Ma (Röhricht 1999; Behr and Röhricht 2000) and capped by a thick calcrete (Eugster 1980; Felske 2016). The Oloronga paleolake probably connected with the Natron Basin to the south (Fig. 1a) and extended at least 5 km north of Nasikie Engida, forming a large fresh to moderately saline lake (Williamson et al. 1993).

The overlying Green Beds include massive to laminated zeolitic silt and silty clay and chert (Baker 1958; Behr and Röhricht 2000; Behr 2002). They are U/Th dated at 98.5 ± 20 and 40.0 ± 6.5 ka (Goetz and Hillaire Marcel 1992) and 191.8–163 ka (Owen et al. 2019). The deposits are confined to the axial rift, implying a smaller saline, alkaline lake than during Oloronga times (Surdam and Eugster 1976; Behr 2002).

Late Pleistocene to Holocene lacustrine tuff, tuffaceous silt, magadiite and Magadi-type chert comprise the High Magadi Beds (Baker 1958; Surdam and Eugster 1976), which accumulated in an expanded lake during the African Humid Period (~ 15–5 ka) (Baker 1958; Behr 2002). Laminated sediments in Core NF1 (Figs. 1b, 2a) from the Northwest Lagoon of Magadi contain diatoms dated at 17.71–10.80 ka, which implies that freshwater flowed into a saline lake (Barker et al. 1990). Damnati et al. (2007) also provided pollen, organic carbon, carbonate and paleomagnetic data for NF1. Trona, > 40 m thick, constitutes the middle to late Holocene Evaporite Series (Baker 1958; Owen et al. 2018a, b), the surface of which is exposed during dry periods.

Materials and methods

Cohen et al. (2016) provides drilling details for the 194-m-long HSPDP-MAG14-2A core from Lake Magadi (Figs. 1, 2), recovered in June 2014 by the

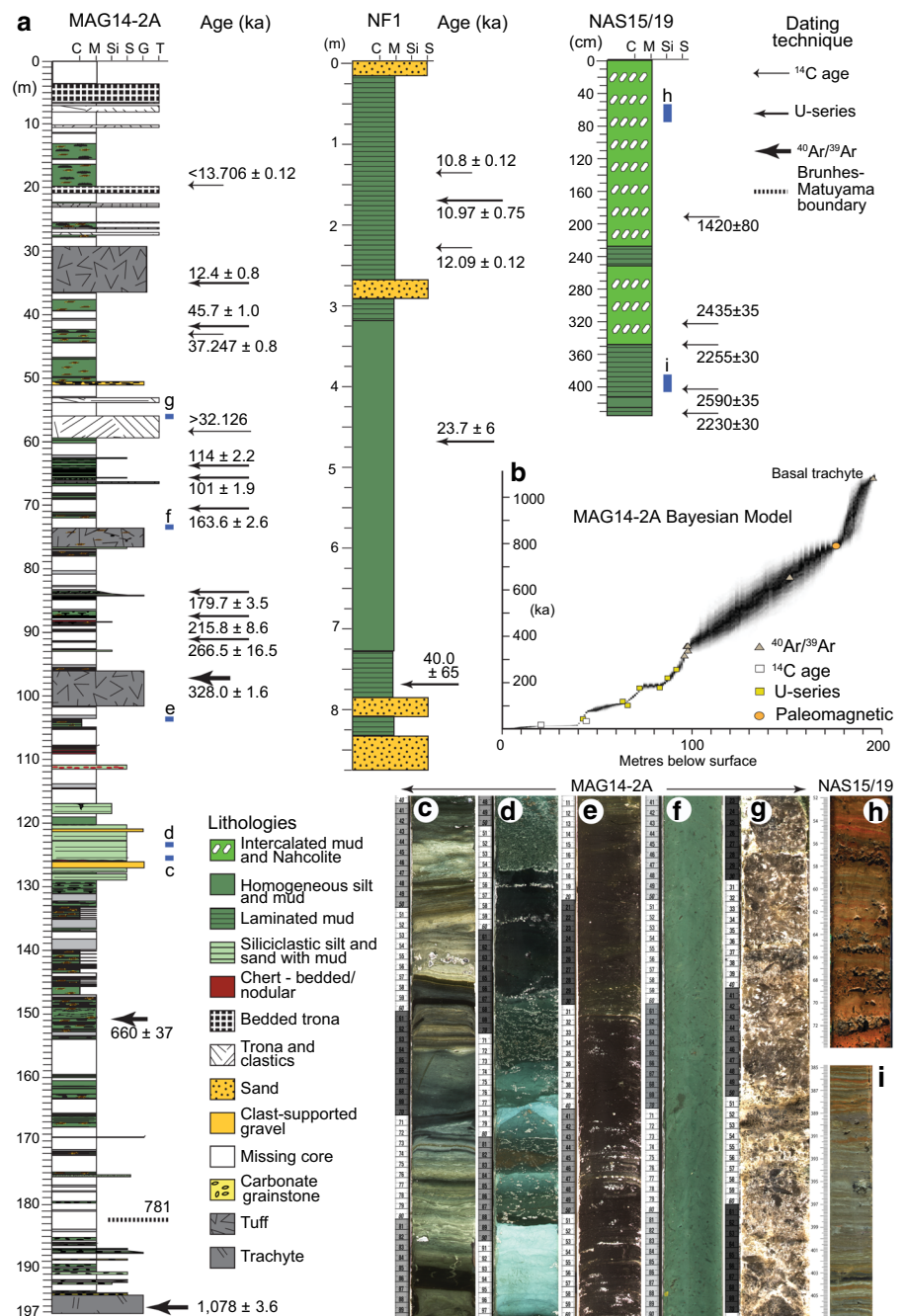
HSPDP. Core dating (Fig. 2a) is based on $^{40}\text{Ar}/^{39}\text{Ar}$, radiocarbon, U-series and paleomagnetic techniques. Details are described by Owen et al. (2018a, 2019). Bayesian chronological modelling used Bacon v2.2 software (Fig. 2b; Owen et al. 2018a, b). A short piston core (NAS15-1P) was obtained from Nasikie Engida in August 2015 but contained a ~ 1-m gap (De Cort et al. 2019). Integration of this core with piston-core sections taken in August 2019 resulted in continuous 4.36-m sediment sequence NAS15/19 (Figs. 1b–c, 2a). The Bayesian chronology is based on five charcoal radiocarbon dates with details described by De Cort et al. (2019).

Diatom samples were collected from MAG14-2A every ~ 32 cm, and where facies changed, yielding 354 samples, of which 113 contained diatoms. Diatoms from NAS15/19 were sampled at ~ 10–20 cm intervals yielding 34 diatomaceous samples. Surficial sediments were collected from the edges of lakes, brine pools and spring outflows ($n = 14$) (Fig. 1b). Diatom preparations used 35% H_2O_2 and 10% HCl to remove organic matter and carbonates, respectively. Diatom residue was dried onto cover slips and mounted using Naphrax, and 400 frustules were counted per slide. Diatom abundances were determined by adding microspheres to the sample prior to cleaning. Identifications follow Gasse (1980, 1986), updated using AlgaeBase (Guiry and Guiry 2020).

Diatom data were analysed statistically using XLSTAT. Taxa that formed $\geq 3\%$ in at least two samples were included in analyses. Indirect ordination using Detrended Correspondence Analysis (DCA) suggested a unimodal response model was appropriate. Correspondence Analysis (CA) was used to explore taxa relationships and the results were compared with known ecological preferences (Gasse 1986). Fossil diatoms were investigated using Agglomerative Hierarchical Clustering (AHC) and Pearson dissimilarity with aggregation by unweighted pair-group averaging. The number of taxa was reduced by including only diatoms that formed $\geq 5\%$ of the assemblage in at least three samples. Modern floras from springs, lagoons and shorelines were examined in relation to water chemistry (SiO_2 , HCO_3^- , CO_3^{2-} , F, pH) and temperature using Canonical Correspondence Analysis (CCA) in CANOCO 4.51.

Conductivity and pH transfer functions were generated using ERNIE (v.1.2) software and the

Fig. 2 Chronology, core logs and facies types in the Magadi-Nasikie Engida Basin. Note variable depth scales. Core locations in Fig. 1. “c–g” = diatomaceous facies from MAG14-2A (note marked intervals located with the same letter code adjacent to core log); “h–i” = facies in NAS15/19 (note corresponding letter codes next to NAS15/19 log). **a** Core logs. NF1 after Damnati et al. (2007). NAS15/19 collected and described by De Cort et al. (2019). C = clay, M = mud, Si = silt, S = sand, G = gravel, T = trona. **b** Bayesian chronology after Owen et al. (2018a, b). **c** Laminated, calcitic or zeolitic, siliciclastic silt and clay. **d** Bedded zeolitic or clayey silt. **e** Massive to weakly laminated black mud with organics. **f** Homogeneous green zeolitic mud. **g** Bedded and massive trona. **h** Alternating nahcolite (NaHCO₃) and feldspathic erionitic silty mud. **i** Laminated feldspathic and erionitic silty mud



“Combined Salinity Dataset” in the European Diatom Database (EDDI), with taxa matched to the EDDI classification scheme (Battarbee et al. 2000). Transfer functions were based on Locally Weighted-Weighted Averaging. Preference statistics indicate respective *r*² and RMSEP values of 0.67289 and 0.38397 for pH and

0.73686 and 0.39768 for conductivity. Habitat classifications follow Gasse et al. (1983) and Gasse (1986).

Filtered (45- μ m mesh size) waters were analysed within 3 months of collection by atomic absorption spectrometry (major ions), ion chromatography (SO₄), titration (CO₃, HCO₃) and Orion™ ion specific electrodes (Cl, F).

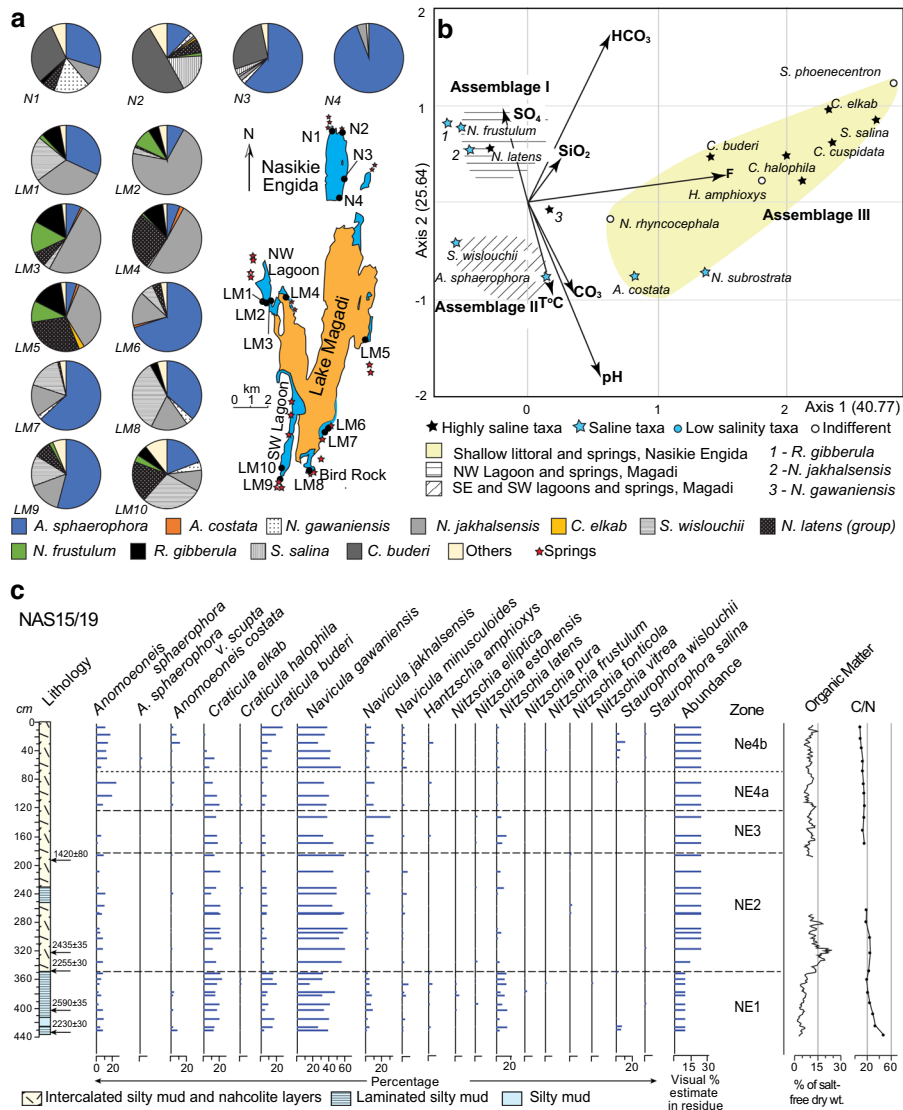


Fig. 3 Modern and late Holocene diatoms. **a** Diatom floras from surficial samples. Locations shown on map. **b** Canonical correspondence analysis of diatoms in surficial muds in the Magadi and Nasikie Engida basins. Axis 1 separates Magadi diatoms from Nasikie Engida diatoms. Axis 2 mainly reflects pH

Results

Modern and late Holocene diatoms in Lake Magadi and Nasikie Engida

Barker (1992) reported diatoms from springs and saline lagoons at Lake Magadi. This study resampled sediments close to the NW lagoon, SW lagoon and Bird Rock sites of that study, with additional surficial

and CO₃ versus HCO₃. **c** Diatom stratigraphy of Core NAS15/19. Organic matter (OM; using three point moving average) and C_{org}/N_{org} data after De Cort et al. (2019). Dates and associated errors are in ¹⁴C years BP

spring and near-shore sediments from locations east of Magadi and at Nasikie Engida (Fig. 3a). Water chemistry and temperature are given in Table 1 with CCA results for modern diatoms in Fig. 3b.

Axis 1 of the CCA separates Lake Magadi diatoms, with negative values, from Nasikie Engida taxa. Axis 2 appears to reflect contrasts in pH and carbonate versus bicarbonate. Three major assemblages are recognised. Assemblage 1 occurs in springs and

shallow lagoons in NW Lake Magadi and is dominated by *Rhopalodia gibberula* (Ehrenberg) O. Müller, *Navicula jakhalsensis* Van Landingham (as illustrated by Barker 1990) and *Nitzschia latens* Hustedt. Assemblage 2 is present in springs and shallow lagoons from southern Lake Magadi where *Staurophora wislouchii* (Poretzky and Anisimova) D.G. Mann and *Anomooneis sphaerophora* Pfitzer dominate. A third assemblage from shallow lake margins along Nasikie Engida is variously dominated by *Craticula halophila* (Grunow) D.G. Mann, *Craticula buderi* (Hustedt) Lange-Bertalot and *Craticula elkab* (O. Müller ex O. Müller) Lange-Bertalot, Kusber and Cocquyt, with several other species also present. *Navicula gawaniensis* Gasse was more broadly represented in a variety of spring, lagoon and shallow saline, alkaline waters.

Many modern taxa are present in the late Holocene core NAS15/19 with Assemblage III from modern Nasikie Engida most closely resembling the core floras. NAS15/19 consists of alternating nahcolite and silty mud overlying laminated silty mud devoid of macroscopic salt crystals (Fig. 2a, h–i) and dating back to ~ 2800 yr BP. Four diatom zones were distinguished based on frustule abundance and floral composition (Fig. 3c). *Navicula gawaniensis*, which indicates strongly alkaline shallow water (Gasse 1986), is common throughout the core but varies in relative dominance. Diatom-based transfer functions imply high values for conductivity (60,000–145,000 $\mu\text{S cm}^{-1}$) and pH (9.15–10.38) throughout NAS15/19. This compares with measured conductivity values of 207,000 $\mu\text{S cm}^{-1}$ and pH of 9.6–10 for surface waters at the core site in 2015 and 2019 (De Cort et al. 2019 and unpublished), and pH values of 9.2–9.9 along the littoral environment in 2006.

Zone NE1 (436–344 cm) is dated at ~ 2800–2300 yr BP and coincides with finely laminated silt (Fig. 2i). Apart from *N. gawaniensis* (16–60% of NE1 assemblages) and *C. elkab* (12–21%), the zone contains relatively high percentages of the saline taxa *N. latens* and *Craticula buderi*, which are common in modern shoreline samples from Nasikie Engida. Frustules are well-preserved due to high silica contents, but form a low percentage of sediment residues. The planktonic or periphytic *N. latens* group is commonly associated with alkaline lakes and hot springs (Gasse 1986). The planktonic assemblage is consistent with a slightly deeper lake than today, but

the abundant benthic taxa argue against a major lake-level change.

The transition from zone NE1 to zones NE2–4 is characterized by an increase in frustule abundance and coincides with the appearance of nahcolite (Fig. 2h). This sodium-carbonate mineral indicates elevated CO_2 in the sediments and water column (Owen et al. 2018a, b, 2019; De Cort et al. 2019). Organic matter throughout zones NE2–4 ($11.8 \pm 3.8\%$ of dry sediment excluding salt) is also higher than in NE1 ($6 \pm 1.8\%$).

Zone NE2 (344–180 cm) is dated at ~ 2230–1200 yr BP and is distinguished by the highest abundances of *N. gawaniensis* in NAS15/19 (45–64%), as well as a decrease in *N. latens* and *C. buderi* relative to NE1. *Craticula elkab* continues at similar percentages to NE1. All other taxa are present at low percentages. *Craticula elkab* is common in the periphyton and plankton of shallow lakes (Gasse 1986) and has conductivity and pH optima of ~ 14,000 $\mu\text{S cm}^{-1}$ and 9.36 (Gasse et al. 1995).

NE3 (180–120 cm; ~ 1200–800 yrs. BP) comprises three samples, in which *Navicula gawaniensis* declines (38–45.5%) and *N. latens* and *Navicula jakhalsensis* increase. *Navicula jakhalsensis* is common today in Assemblage 1 from springs around Lake Magadi and was cited by Gasse (1986) as aerophilous and common on alkaline hot spring mud. It may, therefore, be washed in from hot springs to the north of sample N1 (Fig. 1b). Zone NE3 resembles NE1, but with more diatom frustules and fewer *C. buderi*.

Zone NE4 (120–0 cm; ~ 800 yr BP to present) is distinguished by increased *Anomooneis sphaerophora* Pfitzer, *A. sphaerophora* var. *sculpta* (Ehrenberg) O. Müller, and *A. costata* (Kützing) Hustedt. *Navicula gawaniensis* remains dominant (33.5–55%). The zone can be subdivided into NE4a and NE4b, with NE4b showing a decline of *C. elkab* to the lowest levels in NAS15/19 and *C. buderi* increasing to levels comparable to NE1. *Staurophora wislouchii* reappears in NE4b after having been absent from most of the core except for the lowermost two samples. *Anomooneis sphaerophora* and varieties are usually found in strongly saline, alkaline lakes, often among benthic floras, although it may also enter the plankton (Gasse 1986). Gasse et al. (1995) indicate a conductivity optimum of 18,000–19,000 $\mu\text{S cm}^{-1}$ and a pH preference of 9.52.

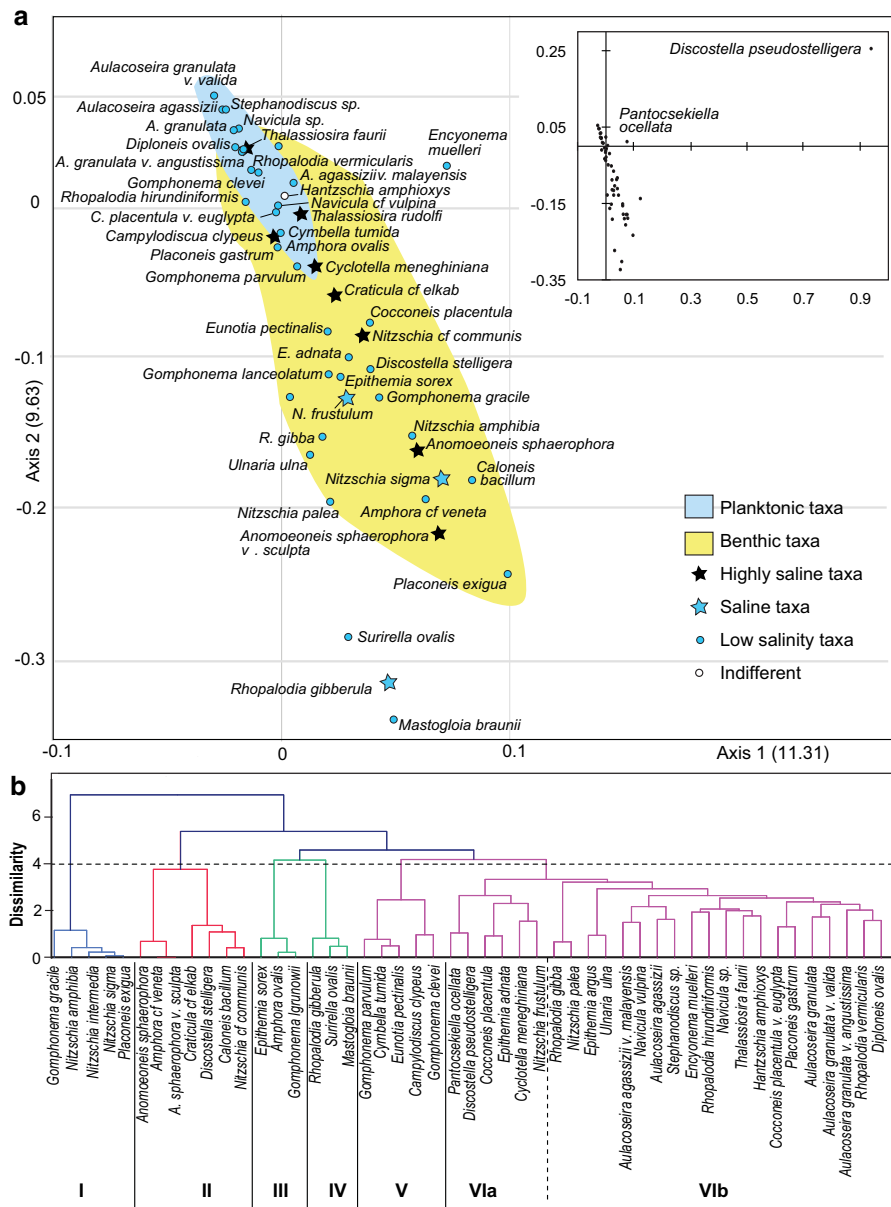


Fig. 4 Floral composition in MAG14-2A. **a** Correspondence analysis showing overlapping distributions of fresh versus saline species and benthic versus planktonic taxa. **b** Agglomerative

Hierarchical Clustering for common diatoms. Seven major groups can be distinguished

Pleistocene diatoms in MAG14-2A

Modern Magadi Basin floras and the late Holocene diatoms in Nasikie Engida have no fossil counterparts in MAG14-2A, although modern Assemblages I and II (Fig. 3b) resemble late Pleistocene floras in Core NF1 (Fig. 2) from the NW Lagoon (Barker et al. 1990). Relationships between fossil taxa in MAG14-2A were

explored using CA (Fig. 4a). The low variation (20.94%) for axes 1 and 2 suggests that a complex set of factors account for the floras. Most planktonic taxa plot with positive values on both axes, with benthic species associated with negative values. Shallow-water diatoms *Hantzschia amphioxys* (Ehrenberg) Grunow and *Gomphonema clevei* Fricke plot with planktonic species. Highly saline

Thalassiosira faurii (Gasse) Hasle, *T. rudolfi* (Bachmann) Hasle and freshwater (*Aulacoseira* spp.) planktonic and benthic taxa also overlap in Fig. 4a. The analysis implies considerable mixing of floras that formerly lived in contrasting ecological settings, either temporally or spatially (Owen 2002).

AHC analysis also suggests mixing (Fig. 4b). Seven clusters, at a dissimilarity of 4, can be observed among 49 common taxa. Group I (*Nitzschia sigma* (Kützing) Smith, *Nitzschia intermedia* Hantzsch, *Nitzschia amphibia* Grunow, *Gomphonema gracile* Ehrenberg, and *Placoneis exigua* (W. Gregory) Mereschkovsky) exhibits the highest degree of separation. These diatoms are present in a variety of modern saline, alkaline habitats (Gasse et al. 1995; Zalát and Vildary 2007). *Nitzschia amphibia* is reported from fresh littoral habitats and springs. *Gomphonema gracile* is oligohalobous, benthic and epiphytic, and indicates freshwater swampy habitats.

Groups II–V include benthic taxa with variable salinity tolerances that again suggest mixing (Fig. 4b). Group II includes *A. sphaerophora* and varieties, *Halamphora veneta* (Kützing) Levkov, *C. elkab*, *Discostella stelligera* (Cleve and Grunow) Houk and Klee, *Nitzschia communis* Rabenhorst and *Caloneis bacillum* (Grunow) Cleve. *Anomoeoneis sphaerophora*, *N. communis* and *C. elkab* are salt tolerant, but found in a wide range of saline, alkaline waters (Zalát et al. 2007). In contrast, *C. bacillum* has been recorded from fresh littoral habitats, springs and flowing waters. *Discostella stelligera* is present in planktonic and littoral settings in small dilute to mesohaline lakes (Gasse 1986). Group III consists of benthic and epiphytic, fresh to mildly saline *Epithemia sorex* Kützing, *Amphora ovalis* (Kützing) Kützing and *Gomphonema grunowii* R.M. Patrick and Reimer. It is closely related to Group IV, which includes littoral benthic and fresh to mesohalobous assemblages dominated by *R. gibberula*, *Surirella ovalis* Brébisson and *Mastogloia braunii* Grunow (Gasse et al. 1995). Group V is dominated by freshwater epiphytic *Gomphonema parvulum* (Kützing) Kützing, *G. clevei*, *Cymbella tumida* (Brébisson) Van Heurck and *Eunotia pectinalis* (Kützing) Rabenhorst. *Campylodiscus clypeus* (Ehrenberg) Ehrenberg ex Kützing is present, but is generally reported from shallow mesohaline inland African lakes (Gasse 1986, 1987).

Group VI includes taxa associated with shallow to deep and saline to fresh lakes (Fig. 4b). At a

dissimilarity of 3.4, two subgroups can be recognised. Group VIa includes benthic and epiphytic species (*Cocconeis placentula* Ehrenberg, *Epithemia adnata* (Kützing) Brébisson) and facultative planktonic taxa (*Cyclotella meneghiniana* Kützing, *Discostella pseudostelligera* (Hustedt) Houk and Klee) and moderately fresh to saline species (*Nitzschia frustulum* (Kützing) Grunow) (Hecky and Kilham 1973; Richardson et al. 1977). *Cyclotella meneghiniana* thrives where salinity varies frequently (Stone et al. 2011). In contrast, *Pantocsekiella ocellata* (Pantocsek) K.T. Kiss and Ács is indicative of deeper, slightly alkaline, oligosaprobic waters (Zalát et al. 2007).

Group VIb includes planktonic, freshwater *Aulacoseira granulata* (Ehrenberg) Simonsen and *Aulacoseira agassizi* (Ostenfeld) Simonsen and rare *Stephanodiscus* sp. as well as taxa with varied ecological preferences. *Aulacoseira granulata* is common in deeper, silica-rich ($> 10 \text{ mg l}^{-1}$) lakes with conductivities of 47–1300 $\mu\text{S cm}^{-1}$ and pH of 6.5–9 (Gasse 1986), but is replaced by *Aulacoseira granulata* var. *angustissima* (O. Müller) Simonsen and *Aulacoseira granulata* var. *valida* (Hustedt) Simonsen as conductivity and pH increase (Kilham 1971; Gasse et al. 1983). Group VIb also includes freshwater benthic and epiphytic diatoms (*Navicula vulpina* (Kützing), *Encyonema muelleri* (Hustedt) D.G. Mann, *Rhopalodia vermicularis* O. Müller, *Ulnaria ulna* (Nitzsch) Compère) and aerophilous and shallow-water taxa such as *Diploneis ovalis* (Hilse) Cleve, *H. amphioxys*, *Cocconeis placentula* var. *euglypta* (Ehrenberg) Grunow, and *Placoneis gastrum* (Ehrenberg) Mereschkowsky (Owen et al. 2004). Group VIb includes *T. faurii*, which has been reported from many saline settings (Gasse 1986). Chalié et al. (2002) suggested that it has a wide salinity tolerance, but Gasse et al. (1995) inferred an optimum of $\sim 9000 \mu\text{S cm}^{-1}$. A link to higher salinities is supported by its abundance in the alkaline Guidimouni Swamp in Niger (Gasse et al. 1995) and its occurrence with other high-salinity indicators (Telford 2014).

Contrasting autecologies for the various groups suggest floral mixing (Owen 2002). This could have been caused by: (1) lakes that seasonally, or over longer time scales, alternated between fresh and saline conditions and/or deep versus shallow phases, followed by mixing in sediments, or (2) introduction of littoral and freshwater species to deeper saline and fresh water bodies, or (3) development of a dilute

mixolimnion over a saline monimolimnion in a periodically stratified lake, perhaps enhanced by inflow of sublacustrine saline springs (Haberyan and Hecky 1987).

Discussion

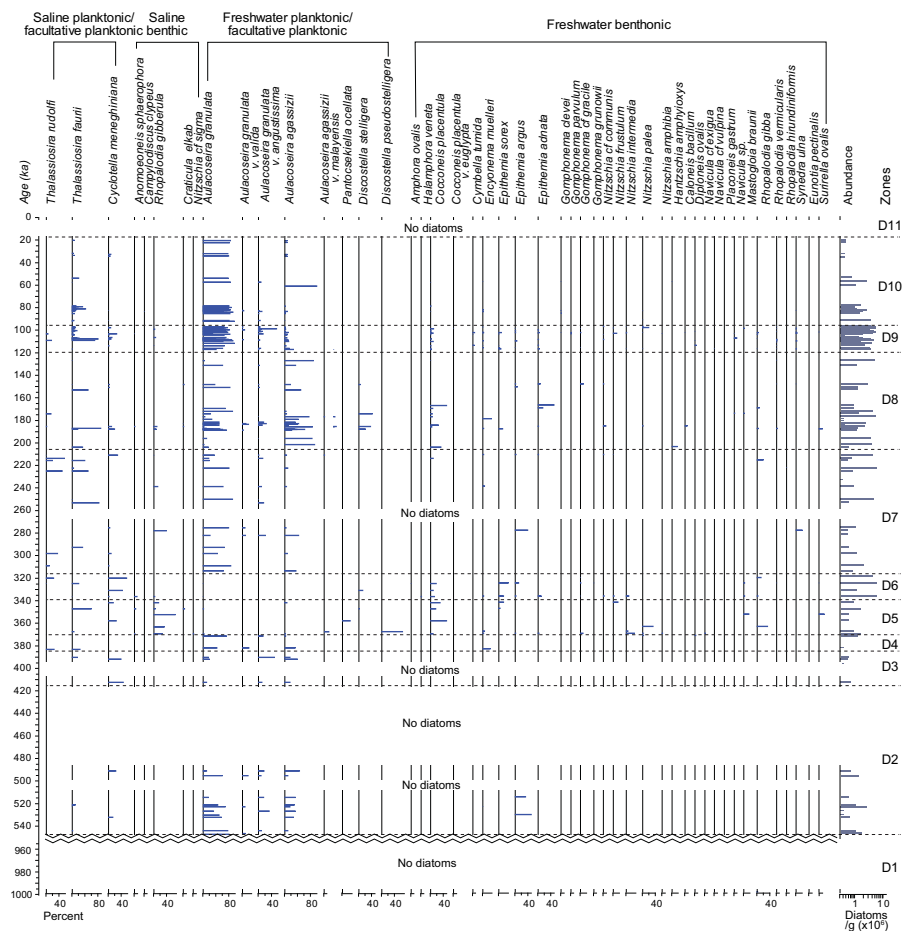
Environmental interpretation of MAG14-2A and NAS15/19

MAG14-2A sediments rest on fissure-erupted flood lava (~ 1.08 Ma; Owen et al. 2018a, b) of the 120-m-thick Magadi Trachyte Formation (Baker 1958). These flood lavas infilled pre-existing grabens to produce a subdued land surface prior to the formation of Lake Magadi. There is no significant paleosol development on the trachyte, implying rapid lake transgression soon after eruptions ceased.

The spatial distribution of the overlying Oloronga Beds indicates that the early paleolake extended across modern Lake Magadi and a large area to the west and south (Owen et al. 2019 and unpublished results), and several kilometres north of Nasikie Engida. Although Zone D1 (194–132 m; ~ 1056–545 ka) is characterised by a lack of diatoms, a second core (MAG14-1A; Fig. 1b) contains benthic and epiphytic taxa (*E. adnata*, *E. argus*, *R. gibberula*, *E. muelleri*) in a basal limestone that indicate fresh, shallow water with abundant macrophytes. Chert, at ~ 190 m depth, suggests an early enhanced supply of silica to the basin. A few overlying cherts in D1 include benthic *A. sphaerophora*, which indicates moderate to high salinity (Gasse 1986) and possibly proximity to springs, given its common presence in modern Magadi springs.

The absence of diatoms in most of D1 (Fig. 5) indicates either post-mortem dissolution or their

Fig. 5 Diatom stratigraphy of MAG14-2A. Zones reflect diatom abundance, saline versus freshwater taxa, contrasts between *A. granulata* and *A. agassizii* dominance and the presence of benthic species. Note that many horizons contain mixed floras with saline and freshwater taxa



absence in the palaeolake. Diatom opaline silica dissolves when pH rises above ~ 9.5 (Barker et al. 1990). Zone D1, however, is also characterised by sediments with high Ca/Na ratios and calcite and Mg-calcite (Owen et al. 2019), which implies lower salinities than during zones D5–11, in which zeolites and/or trona are abundant. Diatoms can be absent from lake sediments for reasons other than dissolution. For example, they are scarce in Lake Turkana sediments (inset, Fig. 1a) because of high turbidity, which restricts light penetration, and rapid sedimentation that dilutes frustules. Lake Turkana is moderately saline ($\sim 1000\text{--}4000\text{ mg l}^{-1}$) and alkaline (pH 9.2–9.5) (Ferguson and Harbott 1982) and its sediments contain calcite and Mg-calcite, reflecting ostracods and chemically precipitated micrite, especially in the southern lake basin (Halfman et al. 1992). Competition could also be important because *Microcystis*, *Botryococcus* and *Planktonema* are dominant in its northern waters. In contrast, diatoms are more common in the less turbid and more saline southern Lake Turkana (Ferguson and Harbott 1982).

Diatom diversity and abundance are low in D2–D4 (132.0–100.5 m; $\sim 545\text{--}370$ ka) with parts of these zones lacking diatoms (Fig. 5). Ca/Na ratios remain high (declining in D4) with calcite and Mg-calcite present, suggesting fresh to mildly saline water (Owen et al. 2018a, 2019). These zones correlate with the upper Oloronga Beds (Owen et al. 2019), indicating that the paleolake covered an area similar to that during D1 deposition (Fig. 6di). The diatom flora is dominated by planktonic freshwater *A. granulata* (0–73%), *A. granulata* var. *valida* (0–22%), *A. granulata* var. *angustissima* (0–33%) and *A. agassizi* (0–47%). More saline (facultative) planktonic taxa such as *C. meneghiniana* and rare *T. faurii* form a small component ($< 10\%$, rarely up to 47%) or are absent (Fig. 5). Except for three horizons with *E. argus* or *E. muelleri*, benthic species are rare (up to 1.6%) or absent. Mean transfer functions for all diatoms suggest pH of $\sim 7.4\text{--}8.5$ and conductivities of $\sim 300\text{--}3000\text{ }\mu\text{S cm}^{-1}$ (Fig. 6a).

In zones D5–D6 (100.5–97.0 m; $\sim 370\text{--}315$ ka) diatoms are more diverse than those of D2–D4 with frustules ranging from rare to common (Fig. 5). Zeolites are varied and abundant, Ca/Na ratios decline, and calcite and Mg-calcite are absent (Owen et al. 2018a, 2019), indicating a more saline lake, suggesting generally drier conditions. *Aulacoseira* are absent

in most horizons. Planktonic and facultative planktonic saline taxa (*T. faurii*, *T. rudolfi*, *C. meneghiniana*, together 0–81%) occur mixed with benthic saline species such as *R. gibberula* (D5) and benthic freshwater taxa that include *E. sorex* (D6) and *C. placentula* (D5–D6). The increase in saline species supports geochemical and mineralogical inferences for a trend towards more saline, alkaline water, but the presence of freshwater taxa implies inputs of fresher water and subsequent mixing.

Mixed diatom assemblages were reported by Barker et al. (1990) and Gasse et al. (1997) in a late Pleistocene to Holocene core from Magadi's NW Lagoon. They separated freshwater benthic species (pH 7.5–8) and saline lacustrine taxa (pH > 10), suggesting that 'fluvial' freshwater diatoms had been introduced to a shallow saline lake. The D5–D6 freshwater diatoms might also have been introduced from nearby swamps or shallow lakes via rivers, perhaps involving periodic floods. Zones D5–D6 overlap with terminal Oloronga Beds deposition, which was followed by an arid phase when calcrete accumulated (Owen et al. 2019). This would have brought ephemeral rivers closer to the MAG14-2A site, potentially delivering freshwater benthic taxa (Fig. 6dii). Excluding 'fluvially derived' diatoms (21–76% in zones D5–D6), the saline species imply a pH of 9.5–10.2 and conductivity of $> 12,000\text{ }\mu\text{S cm}^{-1}$, values compatible with the geochemical data, and which suggest the potential for post-mortem dissolution (Barker 1992; Ryves et al. 2009).

Despite the saline, alkaline conditions, diatoms show minimal corrosion or fragmentation. Hecky and Kilham (1973) observed well-preserved diatoms in sediments of 11 alkaline and 10 meromictic modern carbonate lakes in East Africa, despite pH above 10. Ryves et al. (2006) reported improved diatom preservation in anoxic marine and saline lake basins and noted that organic coatings on diatom valves may reduce dissolution under hypoxic or anaerobic conditions. They also suggested increased silica in pore waters might slow dissolution. Both conditions were present at Magadi when frustules were buried. Anoxic bottom water is indicated by well-preserved organic matter and the presence of pyrite (Owen et al. 2019). Silica-rich spring fluids and seasonal runoff enter the modern hyperalkaline lake, with silica reaching 1660 mg l^{-1} (Table 1). Chert and/or magadiite are common through the core, suggesting that silica

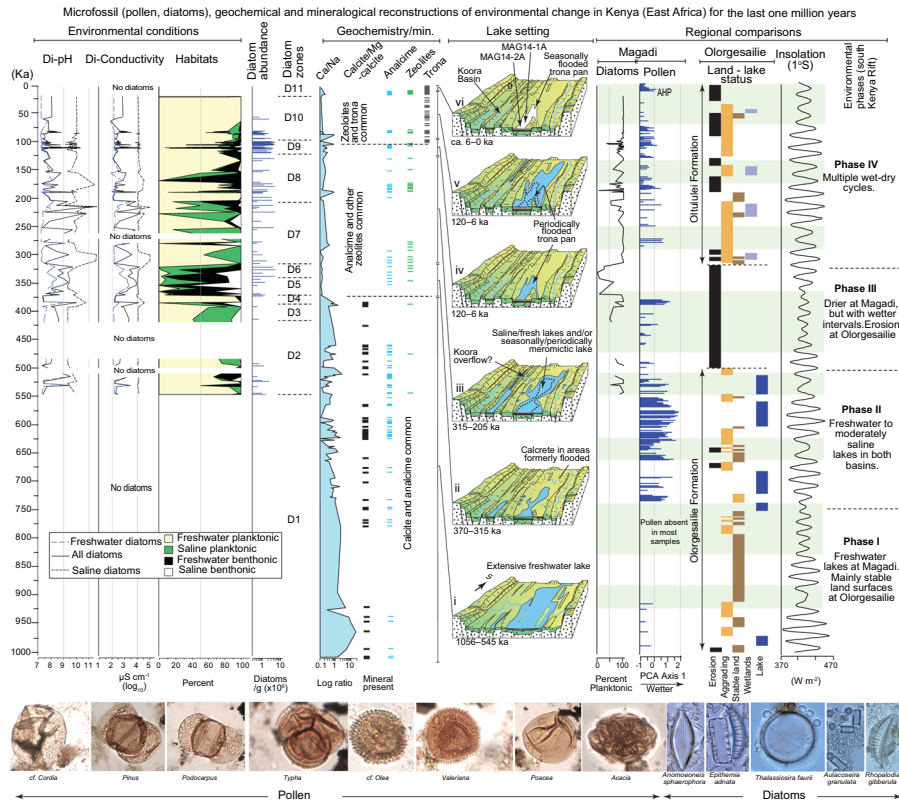


Fig. 6 Environmental data and regional correlations for Core MAG14-2A. Olorgesailie land-lake status from Potts et al. (2018). Magadi pollen data from Owen et al. (2018a, b). Note diatom sampling intervals shown by abundance data. **a** Summary lake pH, conductivity and habitat based on Magadi diatoms. Note pH and conductivity plotted for fresh, saline and all diatoms separately. **b** Summary Magadi diatom zonation and abundance. See Fig. 5 for details. **c** Summary Magadi geochemical and mineralogical data. After Owen et al. (2019). **d** Block diagrams showing Magadi- and Koora-Basin paleogeography for different time intervals after Owen et al. (2019).

concentrations were high in the past and that elevated pore water silica could explain the well-preserved diatoms.

Diatoms are absent to common in D7 (97.0–87.0 m; ~ 315–205 ka) with floras dominated by mixed freshwater *Aulacoseira* spp. (0–94%) and saline *T. faurii*, *T. rudolfi* and *C. meneghiniana* (0–100% combined: Fig. 5). Ca/Na ratios are low with a variety of zeolites indicating saline conditions (Fig. 6c). Transfer functions for saline taxa suggest pH and conductivities of 9.5–11.5 and 10,000 to > 25,000 $\mu\text{S cm}^{-1}$, respectively. Benthic diatoms are rare or absent. The dominance of planktonic species suggests deeper water than during D5–D6 times (Fig. 6diii).

The diagrams show an initially broad fresh paleolake that becomes fragmented by grid faulting, with the Magadi paleolake restricted to a narrow axial zone and becoming more saline. **e** Regional correlations for the Magadi and Olorgesailie Basins. Magadi (percent planktonic) diatoms show deeper lakes to the right and shallower water to the left. Magadi PCA pollen data—positive values reflect wetter conditions. Note overlap between low insolation variability (shaded) and decreased moisture in the south Kenya Rift, with Phase II wetter conditions giving way to considerable variability and generally drier conditions

The mixed assemblages could represent alternating fresh and saline lakes followed by mixing in the sediments (Gasse et al. 1997), which represent up to ~ 100 years for the 1-cm sample sizes. Alternatively, freshwater diatoms could have grown in low-salinity water above a saline bottom layer (Haberyan and Hecky 1987). This might reflect seasonal or longer cycles of flooding with diatoms blooming for as long as nutrients were available and prior to evaporative concentration. Seasonal flooding is an annual feature of the modern lake, but today the lake evaporates to form a salt pan.

It is unlikely that the D7 paleolake ever dried out completely given the abundance of well-preserved

planktonic taxa that suggest blooms in a paleolake with little sediment influx, and minimal pedogenesis and erosion that would indicate exposure. The deposits also preserve fine laminae and organics. Potential water sources could have included rift axial rivers from the north, or an overflow from the neighbouring Koorra Graben to the southeast (Figs. 1a, 6diii) (Baker 1958; Marsden 1979).

Zone D8 (87.0–66.5 m; ~ 205–120 ka) includes rare to common diatoms with increased diversity. *Aulacoseira agassizi* (0–93%) and *A. granulata* (0–91%) vary in abundance, dominating in most samples. Saline planktonic species vary considerably (0–88%) with benthic saline and freshwater taxa also recorded (0–31%; 100% in one sample). Transfer functions for saline taxa indicate pH and conductivities similar to those for D7. Both of the dominant freshwater *Aulacoseira* are cited as euplanktonic (Gasse 1986), but with *A. agassizi* more common in shallower, less turbid water than *A. granulata* (Gasse 1986). Kilham et al. (1986) suggested that *A. agassizi* outcompetes *A. granulata* with increased light levels and reduced phosphorus. Increased benthic taxa likely reflect flood events that could have introduced shallow water taxa to the deeper lake. *Discostella pseudostelligera*, for example, in parts of D8, may reflect transport, given this taxon is cited from rivers and shallow aquatic environments (Gasse 1986).

Zones D9–D10 (66.5–18 m; 120–16 ka) are similar to D8, but with fewer *A. agassizi* (0–14%, 1 sample with 100%). *Aulacoseira granulata* is consistently and abundantly present (12–97%, 1 sample with 0%). Geochemically, zones D9–D10 are characterised by low Ca/Na, zeolites and trona, indicating very saline water. Saline *Thalassiosira* and *Cyclotella* spp. are common intermittently through both zones (0–89%) and dominant in parts of D9. The mixed planktonic flora again suggests periodic flooding and the development of freshwater lakes that became saline with evaporation, or development of a freshwater mixolimnion caused by periodic/seasonal flooding (Fig. 6iv–v). Transfer functions indicate saline water (~ 10,000–20,000 $\mu\text{S cm}^{-1}$) with pH ~ 9.2–10.5. Benthic species are common in D9 (2–64%) where they include freshwater taxa, suggesting flood inputs to a saline water body.

Zone D11 (16–0 ka) lacks diatom frustules. Diatoms are also absent in late Pleistocene to early Holocene outcrops (Owen et al. 2019). Core NF1,

however, contains a varied series of saline diatom assemblages that developed between 12.8 and 10 ka (Roberts et al. 1993). The assemblages contain many more *Nitzschia* than in MAG14-2A, especially during the Younger Dryas, and indicate spatial variability across the basin. This could, for example, reflect an association with N-fixing cyanobacteria against the escarpment at NF1. Owen and Crossley (1992) also reported increased *Nitzschia* close to subaqueous fault scarps and areas with fluvial inputs in recent deposits from Lake Malawi, both of which settings would have been present at the NF1 site. Paleoshorelines around Lake Magadi indicate that water depths reached at least 12 m at NF1 during parts of the African Humid Period (AHP; ~ 15–5 ka) (Baker 1958). Subsequently, extensive bedded and massive trona accumulated from ~ 6 ka at MAG14-2A, reflecting late Holocene desiccation (Fig. 6dvi).

Late Holocene diatoms are absent in MAG14/2A, but are present in NAS15/19 at Nasikie Engida where they indicate a shallow and permanent, highly saline, alkaline lake. This apparent stability likely reflects the maintenance of lacustrine conditions through the last ~ 2800 years by spring inflow despite the semi-arid setting. Spring inflow has also masked the strong seasonal changes characteristic of the nearby Magadi Basin where that lake seasonally floods and dries to a trona pan.

Environmental change in the south Kenya Rift

Environmental reconstructions in the south Kenya Rift have been based on outcrops of the Munya wa Gicheru Beds (~ 1.9–1.6 Ma) and the Ologesailie (~ 1.2–0.5 Ma) and Oltululei (0.32–0.036 ka) formations (Owen et al. 2014; Behrensmeier et al. 2018; Potts et al. 2018). The Lake Natron Basin to the south includes lacustrine sediments in the Peninj Group (< 1.7–1.15 Ma) (Issac 1965; Icole et al. 1987; Luque et al. 2009) and the late Pleistocene to Holocene High Natron Beds (Baker 1963; Hillaire-Marcel et al. 1986). Those records, however, are problematic because of time gaps related to pedogenesis, non-deposition, erosion, and difficulties associated with comparing samples from outcrops in different locations. The record has been significantly improved through core data (Owen et al. 2018a, b; 2019), which offer an opportunity to explore links between regional and global environmental change.

The nearby Olorgesailie and Koora Basins are linked to each other by the Koora Graben (Fig. 1a), which is dry today, but during the early Holocene overflowed via an outlet at about 730 m, some 46 m above the adjacent valley floor (Fig. 1a; Marsden 1979). In contrast, Lake Magadi (605 m) is located in a separate basin connected only during overflow from Koora (Fig. 1a). The Olorgesailie Basin documents major environmental changes that overlap with those at Magadi and which can be related to global climate events and local tectonics (Owen et al. 2019). Four broad phases can be distinguished in the south Kenya Rift. Diatoms were absent in the Magadi paleolake during Phase I (~ 1000–750 ka; Fig. 6e), except for epiphytic taxa during an early stage when limestone was forming. Mineral data (Fig. 6c) indicate fresh to mildly saline water with an absence of pollen (Fig. 6e) because of oxic conditions (Owen et al. 2018a, b; 2019). Diatom data from the Koora Basin (Muiruri 2017) show a dominance by freshwater planktonic *Aulacoseira* spp., indicating a fresh lake that must have overflowed at least periodically to maintain low salinities (Muiruri 2017). Overflow could reflect tectonism, since early stage faulting would likely have been associated with a lower relief than the modern topography (Owen et al. 2019). At Olorgesailie, an initially deep lake gave way to stable land surfaces and extensive pedogenesis (Fig. 6e; Potts et al. 2018).

Positive PCA values for Magadi pollen reflect increased *Podocarpus* and Cyperaceae, indicating a wetter catchment during Phase II (~ 750–500 ka) (Fig. 6e) (Owen et al. 2018a, 2019), which correlates well with diatom data for lakes at Olorgesailie (Owen et al. 2008). In the Koora Basin, Phase II diatoms were dominated by freshwater planktonic taxa, indicating deep fresh water (Muiruri 2017). Diatoms were absent in the contemporary Magadi paleolake, where mineral data (Fig. 6c) suggest fresh to mildly saline conditions, which would suggest a possible, but uncertain, link to Lake Natron to the south.

Phase III (500–325 ka) is associated with increased lake salinities at Magadi and at Koora (Muiruri 2017), which could be explained by tectonic and/or climatic controls. Diatoms in Magadi are absent from ~ 480 to 420 ka and rare during the rest of this phase, with geochemical and mineralogical data indicating increased salinity after 375 ka (Fig. 6c). Magadi outcrop distributions indicate the paleolake shrank towards the rift axis (Owen et al. 2019) with the

paleolake unlikely to be connected to Lake Natron. Koora diatoms document a shift towards shallow, closed-basin, saline conditions (Muiruri 2017), which might reflect either a climate control or loss of overflow caused by a fault-driven rise in outlet height. This period of increased salinities overlaps with Marine Isotope Stage 11, a particularly dry period in the global climate record, supporting climate as a major driver. Parts of Phase III also correlate with erosion (500–320 ka) at Olorgesailie, which has previously been related to both fault-induced base level changes (Behrensmeier et al. 2002) and increased aridity (Owen et al. 2018a, 2019).

Phase IV (~ 325–0 ka) diatoms in the Magadi and Koora Basins differ. At Magadi, freshwater and saline planktonic taxa dominate with fluvial freshwater taxa introduced episodically, especially during interglacial times (Owen et al. 2018a, 2019). Magadi pollen suggest generally dry catchment conditions (Owen et al. 2018a, b, 2019). In the contemporary Koora Basin, floras alternated between times when fresh or saline planktonic diatoms and saline benthic species dominated (Muiruri 2017). Phase IV, at Koora, was also characterised by episodes of pedogenesis and erosion. At Olorgesailie, deep lakes were absent, with the area characterised by springs, ponds, stable land surfaces and fluvial environments (Fig. 6e) (Behrensmeier et al. 2002, 2018; Lee et al. 2013; Potts et al. 2018). Regionally the area appears to have been drier through Phase IV, but with wetter intervals. The Magadi record, however, shows no indication of desiccation at the MAG14-2A core site, perhaps because of meteoric and/or hydrothermal spring inputs, as happens today at Nasikie Engida. Hillaire-Marcel and Casanova (1987) and Casanova (1987) used high-level stromatolites in both the Magadi and Natron Basins to suggest three expanded late Quaternary lake phases (~ 240 ka, ~ 135 ka, ~ 12–10 ka) when the Magadi and Natron paleolakes may have been connected, although Owen et al. (2019) raised questions about the dating of the first of these phases, which they considered to be much older.

The similar timing in major environmental changes across different basins suggests that regional and global climate were important drivers. For example, Fig. 6e shows insolation values for the south Kenya Rift with drier episodes, as reflected in diatom and pollen data, tending to develop during periods of low-amplitude insolation variability. This may reflect

observations by Trauth et al. (2009) who noted that eccentricity minima lead to the lowest-amplitude insolation peaks and weaker monsoons at precessional timescales.

Climatic versus tectonic controls on diatom floras and preservation

The evolution of the south Kenya Rift paleolakes reflects how the impacts of global climate can be modified by local tectonics. Changes in lake status would have altered diatom floras. For example, the presence of mixed fresh and saline taxa suggests either seasonally variable salinities or the episodic introduction of fresh water over permanent saline lakes, which would also imply a strong barrier to water column mixing. Pollen and sedimentological data indicate that conditions became drier after about 575 ka, but with all basins documenting wetter intervals as well (Owen et al. 2018a, b; 2019). At Magadi, diatom data show both fresh and saline waters during Phases III and IV, suggesting inputs of freshwater by rivers and/or springs into a semi-arid basin. This may have taken place episodically, following rains over adjacent higher ground, or possibly on a seasonal basis, as takes place today when rivers flood and form a shallow lake over the dry trona flats that develop during the rest of the year.

These broad climate-driven trends were modified by tectonism. Subsidence of the axial graben and uplift of rift shoulders would have gradually resulted in a rainshadow, which today enhances drier conditions over the rift. A shallow, laterally extensive, freshwater Palaeolake Magadi first developed on a low-relief surface. Accommodation space, however, increased as faulting created and then deepened grabens. Such fault movements would have altered lake outlet heights, sometimes allowing overflow of higher-elevation basins supplying water to Magadi, with consequent dilution and the development of freshwater diatom floras. In contrast, increased graben subsidence or uplift of horsts would have led to loss of overflow from neighbouring grabens such as Koora to the west (Fig. 1a), resulting in increased salinities and saline taxa. During climatically wetter episodes lake levels would have risen in the grabens, favouring planktonic assemblages, with dry conditions and evaporative water loss leading to the development of benthic floras.

Today, faults in the south Kenya Rift allow magmatic CO₂ to rise to the surface (Lee et al. 2016), which influences sedimentation and affects lake alkalinity, pH and aqueous silica concentrations, major controls on diatom floras. This is the case today at Nasikie Engida where abundant CO₂ rises along faults catalysing trona and nahcolite precipitation (De Cort et al. 2019). The abundant trona from about 100 ka in the Magadi Basin may therefore reflect the initiation or enhancement of ascending CO₂ and, in turn, modifications of lake alkalinity and pH.

The relative continuity of sedimentation in the paleolake depocenter at Magadi contrasts with conditions in the Koora and Ologesailie Basins where erosion surfaces and paleosols are common (Owen et al. 2008; Muiruri 2017). Lake Magadi lies within a regional sump with faults bringing meteoric and hydrothermal waters to the surface at springs. In addition to maintaining lakes over long periods and through climatically dry intervals, hydrothermal water also increased silica supply, after ~ 500 ka at Ologesailie (Owen et al. 2014) and soon after initiation of Lake Magadi ~ 1000 ka (Owen et al. 2019). This had important implications for diatom preservation. Diatoms commonly dissolve in saline lakes after death (Hecky and Kilham 1973; Barker 1992), but they are well preserved at Magadi (MAG14-2A) and Nasikie Engida (NAS15/19) where high silica concentrations in spring waters (up to > 100 mg l⁻¹ SiO₂; Table 1) are increased to very high levels after evaporation and/or evapotranspiration in lake (up to > 1600 mg/l SiO₂; see Table 1) and ground waters (Jones et al. 1967).

Conclusions

The Magadi Basin preserves aquatic sediments that document environmental change through the last million years. Prior to ~ 500 ka, the basin contained a fresh to moderately saline lake. Subsequently, this became increasingly saline and, at times, possibly meromictic, culminating in the seasonally flooded trona pan of today. The modern diatom floras in Magadi hot springs and shallow pools and late Holocene lacustrine sediments from Nasikie Engida formed under high salinity and alkalinity. They bear little to no resemblance to past episodes in the history of Lake Magadi, testifying to the intense

environmental transformation that occurred through the Pleistocene. This study also shows that diatoms can be useful paleoenvironmental indicators even in high-pH environments, where poor preservation is normally expected.

Four climate phases can be recognised. Phase I (1000–750 ka) was characterised by well-oxygenated, fresh to moderately saline lakes at Magadi and Koora, with land surfaces prevailing at Olorgesailie. Phase II (750–500 ka) was wet, with all basins harbouring freshwater lakes. Phase III (500–325 ka) was drier, with moderately saline to very saline lakes at Magadi and Koora. Faulting contributed to erosion at Olorgesailie and drainage modifications at Magadi where the paleolake was confined to a narrow axial position. The Koora lake desiccated during parts of this period, but water was present at Magadi throughout, probably because of spring contributions. Phase IV (350–0 ka) was variable in all basins with Magadi recording fluctuating inputs of fluvial diatoms that suggest periodic flooding.

These major changes were driven by decreased moisture after ~ 575 ka and especially after the Mid-Brunhes Event around 430 ka. In part this reflects broader global climate patterns, but also the influence of tectonics on accommodation space, catchment drainage, springs and rising magmatic CO₂ along faults.

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