



Diatomaceous sediments and environmental change in the Pleistocene Olorgesailie Formation, southern Kenya Rift Valley

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ABSTRACT

The Olorgesailie Formation is comprised of lacustrine, volcanoclastic and alluvial sediments that formed in the southern Kenya Rift between about 1.2 million and 490,000 years ago. Diatoms are common in much of the sequence and preserve a record of environmental change within the basin. A high-resolution diatom stratigraphy has been developed for these deposits. The data document the presence of freshwater and saline lakes as well as wetlands. Transfer functions indicate that these water bodies ranged in conductivity between about 200–20,000 $\mu\text{S cm}^{-1}$, with pH varying between about 7.5 and 10.3. Pedogenesis affected multiple horizons within the succession, reflecting periods of emergence that encompass much of the time represented by the Olorgesailie Formation. A variety of other sedimentological indicators (carbonates, rhizoliths, mudcracks, erosional channels) also record periods when the sampled portions of the basin were dominated by terrestrial conditions. Stone tools are common at several levels, indicating the use of the area by hominins. Lakes and wetlands were potentially usable as sources of potable water by hominins for part of the basin history, but at other times were undrinkable. Other water sources (springs, rivers) would have been necessary during these periods. Paleoenvironments in the basin were complex and changed frequently with time. Such shifts in resources and habitat distribution during Olorgesailie Formation time seem likely to have influenced the behavior and evolution of local plant and animal populations, including *Homo*.

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1. Introduction

Over the last few decades there have been many attempts to develop continuous high-resolution (decadal to annual) records of paleoenvironmental change in eastern Africa. These studies have largely been based on data from cores recovered from late Pleistocene to Holocene sediments in modern lakes (Richardson and Richardson, 1972; Barker, 1992; Johnson, 1996; Stager et al., 1997; Telford et al., 1999; Chalié and Gasse, 2002; Johnson et al., 2002; Legesse et al., 2002; Russell et al., 2003; Cohen et al., 2007), and to a lesser extent within wetland areas (Ashley et al., 2004; Driese et al., 2004; Owen et al., 2004). Miocene to Pleistocene stratigraphic records have also been developed from lacustrine rocks exposed in outcrops as a result of faulting and/or erosion, although the latter studies tend to reconstruct environmental conditions at discrete intervals rather than attempt to develop detailed stratigraphies through temporally long sequences

(Gasse, 1974; Owen, 1981; Owen and Renaut, 1986; Renaut et al., 2000; Trauth et al., 2003).

Paleolimnological studies have been used to generate paleogeographic information and records of past climatic conditions and variability. The information has been of use to archeologists interested in the environmental settings that supported early human populations, and to paleoanthropologists and geologists who have focused on the linkages between climate change and human evolution (Potts, 1996, 1998, 2004, 2007; Feibel, 1997; Potts, 1998; Bobe and Behrensmeyer, 2004; Behrensmeyer, 2006; Trauth et al., 2007). In some cases, researchers have used the contemporaneous development of large lakes in different drainage basins to suggest Pleistocene wet periods and have related these to hominin evolutionary hypotheses (Trauth et al., 2005). In this context, questions about the stability of the inferred paleolakes are important and detailed temporal reconstructions are necessary to evaluate the potential evolutionary impact.

An important issue in these studies concerns the way in which early hominins responded to their surroundings. This has formed a central theme in recent investigations of the Olorgesailie Basin of the southern Kenya Rift Valley (Potts, 1994; Potts et al., 1999; Sikes et al., 1999; Potts, 2001), where researchers have examined the spatial distribution of hominin artifacts in paleolandscape settings over distances of a few

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hundred meters to several kilometers. A second theme of this research has been to assess how hominin behaviors and animal lineages were able to persist or change in relation to environmental variability over time, as reflected in the sediments of the Olorgesailie Basin (Potts, 1996, 2001; Behrensmeier et al., 2002; Brooks et al., 2007).

The deposits at Olorgesailie formed in a variety of environments that included terrestrial settings associated with soil formation, fluvial situations, swamps, lake-marginal wetlands, and lakes of varying size, water depth, and chemistry. Many of the stone tools are associated with paleosols and shallow river channels located in the eastern outcrops of the Legemunge Plain, within or close to the Site Museum (Fig. 1; Isaac, 1977; Potts et al., 1999). Questions have been raised as to whether the hominins lived in lowland settings close to lake margins or in upland regions, visiting lakeshore areas for food and other resources (Potts et al., 2004). Recent research efforts have been directed towards the determination of vegetation types (Sikes et al., 1999) and paleolandscape reconstructions in which the hominins lived (Potts, 1994; Potts et al., 1999). For example, there appears to be a relationship between the concentration of stone artifacts and shallow paleochannels close to lava ridges, which may have represented boundaries between lowland and upland zones traversed by the hominin toolmakers (Potts et al., 1999). The quality and location of water resources also likely had an influence on hominin activities, and consequently an understanding of past aquatic environments is an important aspect of archeological research in the area. For example, lake water might not have been drinkable during times of relative aridity and high salinity. Under such circumstances springs and swamps would have been preferred sites for potable water.

This research presents a new diatom stratigraphy for the eastern Legemunge Plain (Fig. 1), an area that includes the Site Museum (referred to as Locality C) and other main locations (Locality A) where Acheulean stone tools have been recovered. The major aims of this study are: 1) to develop a high-resolution diatom stratigraphy for the

Olorgesailie Formation; 2) to integrate the diatom data with sedimentological evidence and to incorporate data on pedogenically modified deposits in order to integrate both submergent and emergent parts of the basin's environmental history; and 3) to examine how fluctuations in lake level and chemistry might have affected ancient hominins. The sediments studied comprise Members 1 to 12 of the Olorgesailie Formation, deposits that were laid down between about 1.2 million and 0.60 million years ago (Deino and Potts, 1990, 1992; Behrensmeier et al., 2002).

2. Geological background and archeological setting

The Olorgesailie deposits were first described by Gregory (1921). Subsequently, Louis and Mary Leakey (Leakey, 1952) discovered abundant Acheulean handaxes, which stimulated further archeological and geological studies (Isaac, 1968, 1977, 1978; Potts, 1989, 1994; Potts et al., 1999, 2004). Shackleton (1955, 1978) undertook detailed geological mapping, with some of his results being included in a Kenya Geological Survey report (Baker, 1958). Later, Baker and Mitchell (1976) referred to the deposits as the “Legemunge Beds”, with Isaac (1978) raising their status to that of a formation. Marsden (1979) described the general setting and history of the Olorgesailie Formation. Owen (1981) and Owen and Renaut (1981, 2000) have presented accounts of the sedimentology, diatom stratigraphy, and diatom spatial distributions and demonstrated that the Olorgesailie sediments were laid down in water bodies that ranged from fresh to saline-alkaline. Koch (1987) examined aspects of vertebrate taphonomy and paleoecology. Since 1985, collaboration between the Smithsonian Institution and National Museums of Kenya has led to new paleoanthropological, geological, and paleoenvironmental research in the Olorgesailie region, which has been directed by Potts (e.g., Potts, 1994; Deino and Potts, 1990; Potts et al., 1999; Sikes et al., 1999; Potts, 2001; Behrensmeier et al., 2002).

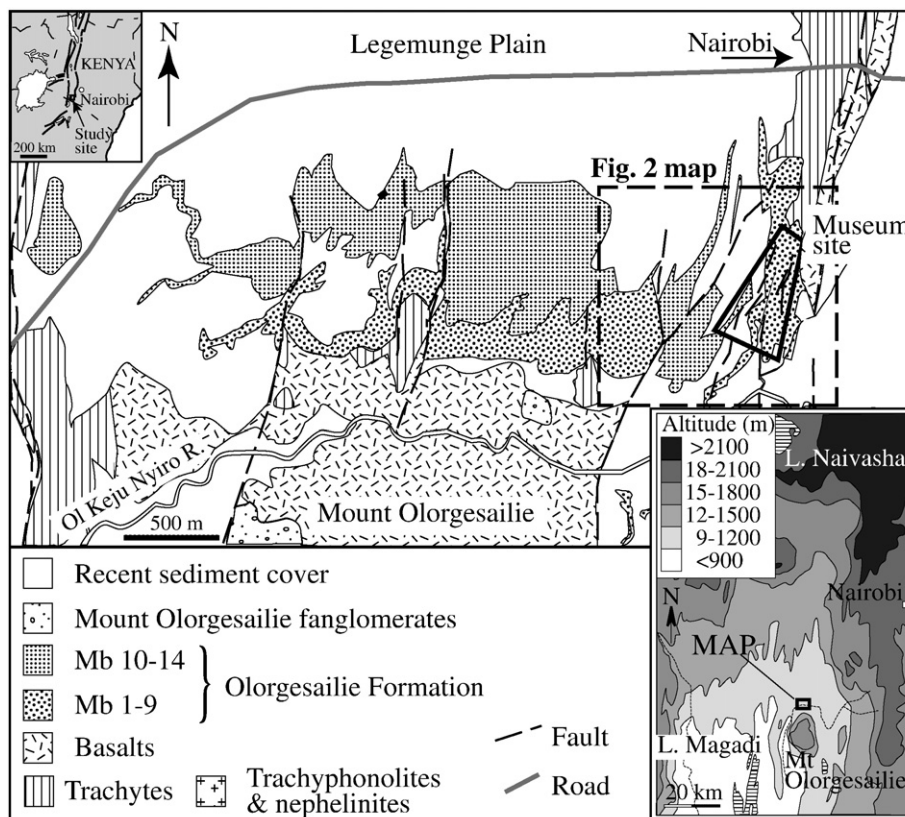


Fig. 1. General location of the Olorgesailie Formation and outcrop distribution.

Evernden and Curtis (1965) and Miller (1967) reported middle Pleistocene ages for the Ologresailie Formation. Subsequently, Isaac (1977) suggested that K–Ar dates of 0.42 and 0.48 Ma were compatible with the faunal and archeological evidence. However, Bye (1984) and Bye et al. (1987) later reported older ages ranging between 0.93–0.6 Ma. Deino and Potts (1990, 1992) expanded on this work to set up a detailed geochronological framework for the Ologresailie Formation, based on single-crystal ⁴⁰Ar/³⁹Ar techniques. Their continuing research indicates an age of about 1.2 Ma for the lowermost diatomaceous deposits in Member 1 and 992 ka for the middle of Member 1 (M1), with the uppermost M14 dated at 493 ka.

The Ologresailie Basin (36°26'E, 1°34'S) lies within the southern part of the Kenya Rift between the modern Lakes Naivasha and Magadi. The Ologresailie Formation has a composite thickness of about 80 m, covers an area of about 150 km² (Fig. 1; Behrensmeier et al., 2002), and includes a wide range of lacustrine, wetland/swamp, fluvial, and colluvial sedimentary rocks. The deposits are nearly horizontal and were laid down in north–south trending grabens that were faulted and eroded into the underlying trachytic and basaltic lavas. Faulting occurred during and after deposition with displacements reaching up to about 50 m (Shackleton, 1955). Subsequent to the initial faulting and erosion of the basin floor and the deposition of the Ologresailie Formation, the basin has been subjected to at least three major periods of valley incision and infilling that took place between about 500 ka and the end of the Pleistocene (Behrensmeier et al., 2002), with younger deposits (the Olkesiteti and Oltepesi Fms.) accumulating in a variety of colluvial, alluvial, spring, and lacustrine settings (Behrensmeier et al., 2007; Brooks et al., 2007; formal description of these younger formations is in progress). Today, the Ologresailie Formation is largely hidden below the Legemunge and Oltepesi plains, but excellent exposures are present along an east–west trending scarp on the southern margins of the

Legemunge Plain (Fig. 1). Additional outcrops occur along riverbanks on the Oltepesi Plain, and along the northern slopes of Mount Ologresailie, an eroded Pliocene central volcano, which served as a southern barrier to drainage during some periods of deposition.

The paleolakes at Ologresailie represent only one of many areas of aquatic deposition that occurred along the length of the Kenya Rift Valley during the Pleistocene. Fresh to alkaline water bodies of varying extent occupied the northern rift in the area of modern Lake Turkana (Cerling et al., 1988). Other paleolakes that may have existed at about the same time include a large alkaline water body within the Baringo District (Renaut et al., 2000), lakes in the Nakuru–Naivasha area, and a large lake in the Magadi region that gave rise to the cherts of the Oloronga Beds (Behr, 2002).

3. Methods

Samples for diatom analyses were obtained from 11 trenched sections (C91/04R, C97/16, C91/07, C04/B1, C00/2a, C7/14, A307, A97/02, A93/04 and A91/01) in Localities A and C of the Ologresailie Basin (Potts et al., 1999). These sections record sedimentation through Members 1 to 12 of the Ologresailie Formation. The sediments shown on the various logs are based on original field descriptions, which tend to overestimate actual diatom content (see Discussion). Diatom abundance and fragmentation data were estimated visually from smear slides. Lithological unit numbers, shown in the diatom stratigraphies, were derived from field logs, except for Sections C7/14, C00/02a, C97/16, and C91/07, for which no unit numbers were originally assigned. For the purposes of this paper, RBO has assigned numbers to the lithological units in these sections.

The samples were generally collected at 10–15 cm intervals, offering a much higher level of stratigraphic resolution than in prior investigations

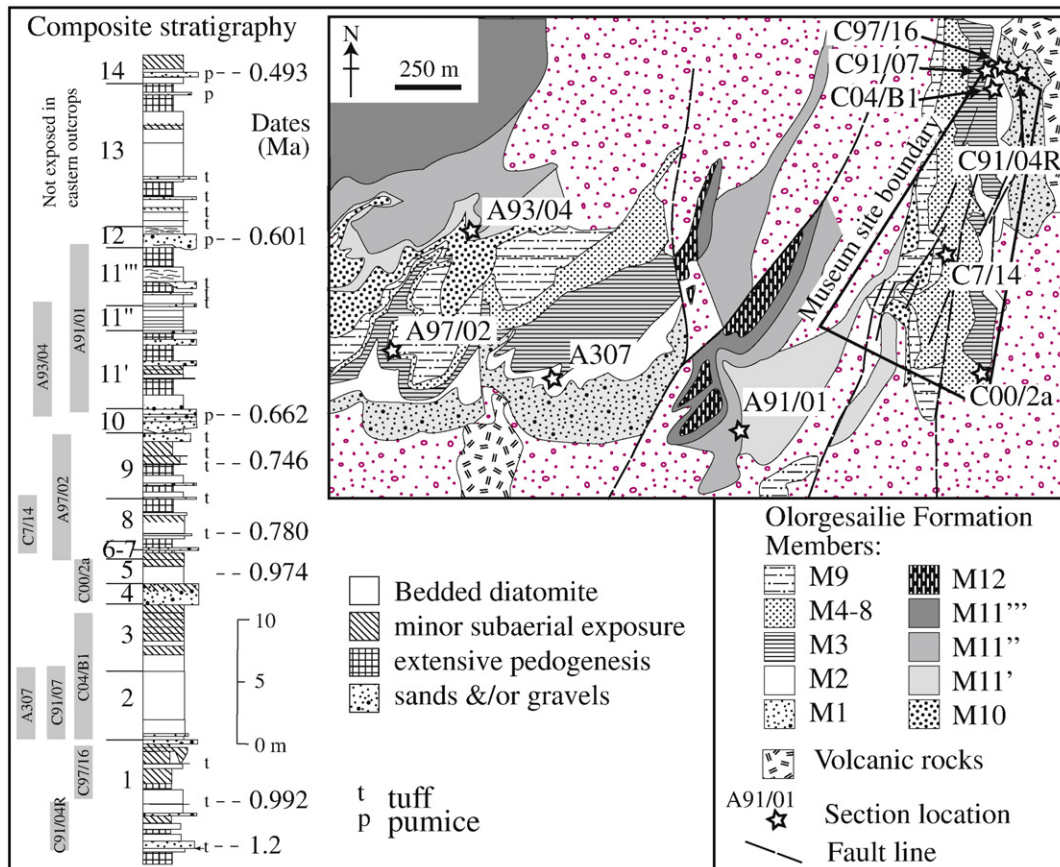


Fig. 2. Geological map of Members 1–12 of the Ologresailie Formation in Localities A and C. A composite section for the Ologresailie Formation is shown to the left, together with chronological dates (after Behrensmeier et al., 2002; A. Deino, pers. communication 2007). Note the stratigraphic location of sections examined in this study (gray bars to left of column).

of East African paleolake sedimentary outcrops. At one section, C04/B1, samples were taken at 50 cm intervals in M2 and at 10 cm intervals in M3, which was the principal target of sampling for this section. Carbonates were removed by adding HCl to about 1 cm³ of sediment, which was then rinsed with distilled water. This assisted in the disaggregation of samples, which were then mounted on smear slides using naphrax.

A minimum of 400 diatoms were counted along transects on each smear slide, except where diatoms were rare, in which case all diatoms were counted. Diatoms were included in counts when more than half of an individual specimen was present. This may have resulted in some underestimation of the more fragile taxa. Apices were counted for fragmentary long thin taxa, mainly *Synedra* and *Nitzschia* spp. Corrosion of diatoms was minimal in most horizons and is not believed to have led to any significant errors due to loss of weakly silicified species. Taxa were identified to species level using light microscopy with phase contrast at 1000×, with reference mainly to the taxonomic works of Gasse (1980, 1986), Hustedt (1927–1930), Krammer and Lange-

Bertalot (1986–1991), and Patrick and Reimer (1975). Some diatom identifications were confirmed using a Leo 1530 Field Emission Scanning Electron Microscope.

Taxa forming >5% of the flora in at least one sample were used in statistical studies and for stratigraphic diagrams. Correspondence analyses used CANOCO 4.51. Diatom stratigraphies for each section were drawn using the plotting program “C2”. Environmental reconstructions are based on training sets and transfer functions provided by the European Diatom Database (EDDI, <http://craticula.ncl.ac.uk/Eddi/jsp/index.jsp>). Diatom taxa reported in this work match the classification and merging system used in the EDDI database. Reconstructions for conductivity and pH have made use of the EDDI “Combined Salinity Dataset”, and “Locally-weighted Weighted Averaging” (LWVA). This generates a local training set for each fossil sample based on the 50 closest analogues defined by the minimum squared chi-squared distance. Water depths have been assessed qualitatively using known habitat preferences of diatom taxa (Owen, 1981; Gasse, 1986; Gasse et al., 1983).

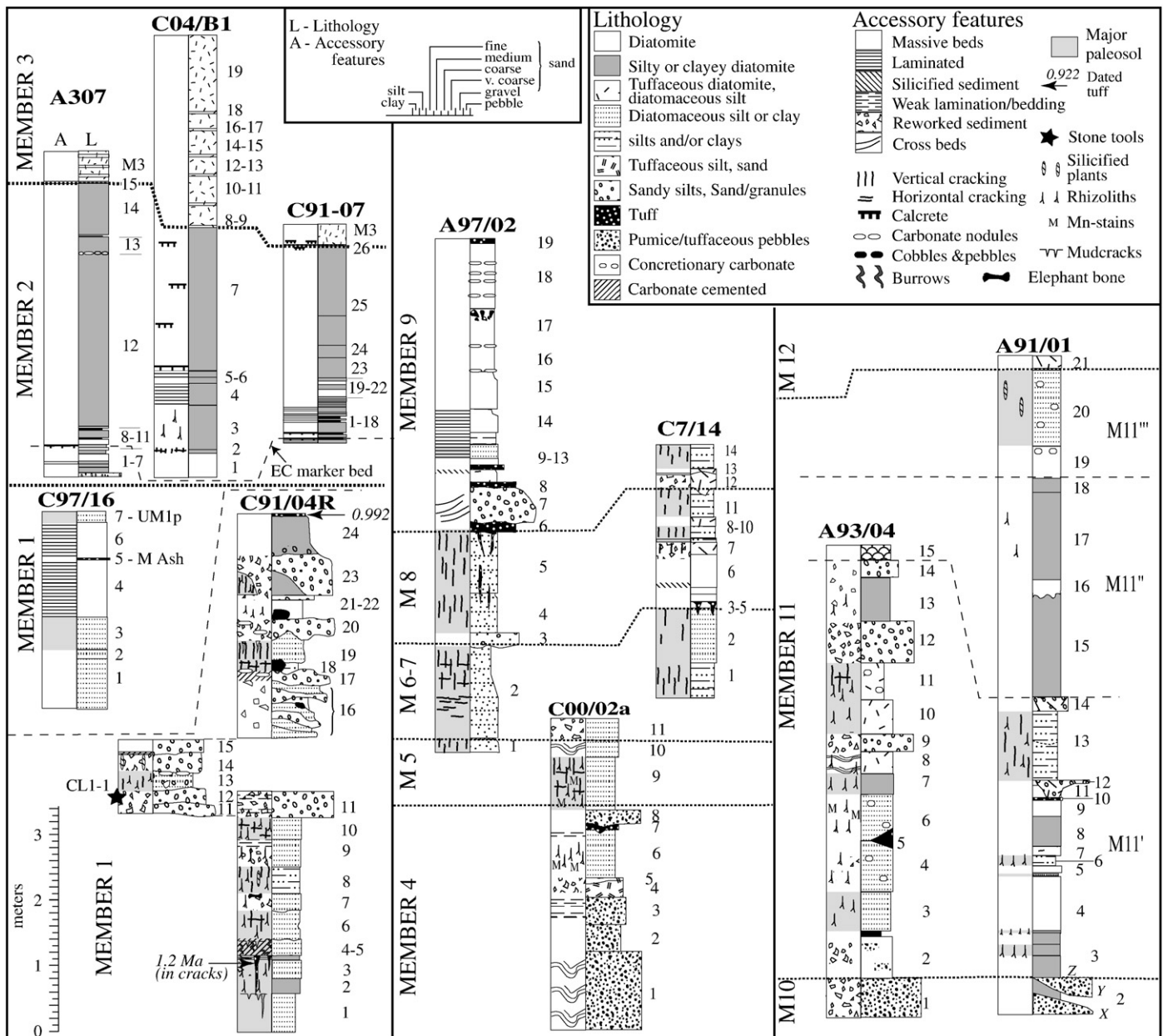


Fig. 3. Lithostratigraphy of Members 1–12 of the Ologresailie Formation. The lithologies shown in the sections are based on field descriptions only. Sections are labeled with a capital letter to indicate the locality, two digits to indicate the year, and a slash followed by the section number.

4. Results

4.1. Sedimentology

The Olorgesailie Formation is comprised of mixtures of primary and reworked volcanic ash and pumice, biogenic materials (mainly diatoms), clastic minerals, and lithic fragments. The lithostratigraphy of Members 1–12, exposed in the eastern outcrops (Localities “A” and “C”; Fig. 2) of the Olorgesailie Formation, is shown in Fig. 3. In this part of the basin, these members have an aggregate thickness is 57.6 m and date between about 992–601 ka, according to the chronological framework established by Deino and Potts (1990, 1992), with recent analyses that indicate an age of about 1.2 Ma for the base of the sequence (A. Deino, Pers. Comm. 2007) (Fig. 2).

The sediments are subhorizontal (Fig. 4a, b) and show lateral variability in thickness, partly due to syndepositional faulting (Isaac, 1977, 1978; Shackleton, 1978). Nevertheless, many of the Members can be traced laterally over considerable distances. This continuity, and an

absence of major erosion surfaces, indicates net subsidence during deposition of the Olorgesailie Formation (Behrensmeier et al., 2002). The ten sections shown in Fig. 3 are based on field descriptions of the sediments, carried out by AKB and PD over the last fifteen years.

The logs distinguish between differing diatom contributions to the sediments, and recognize diatomites, silty or clayey diatomites, diatomaceous sediments, and deposits lacking diatoms. This distinction is very difficult to achieve with accuracy from field examinations (Owen, 2002). Consequently, some caution needs to be applied to the terms used with regard to the diatom component. Nevertheless, broad patterns are clear with diatom-rich units being present mainly in M2, and in parts of M1, M3, M8, M9, and M11. Diatomaceous deposits, and occasional diatomites, are also present in M5–M8 and M12, but in these units diatoms are generally less common and more fragmentary. Members 4 and 10 are largely comprised of fluvial pumiceous sands and gravels in the sampled sections (Fig. 4h).

The Olorgesailie Formation includes undisturbed, bioturbated, and reworked diatomaceous and non-diatomaceous sediments

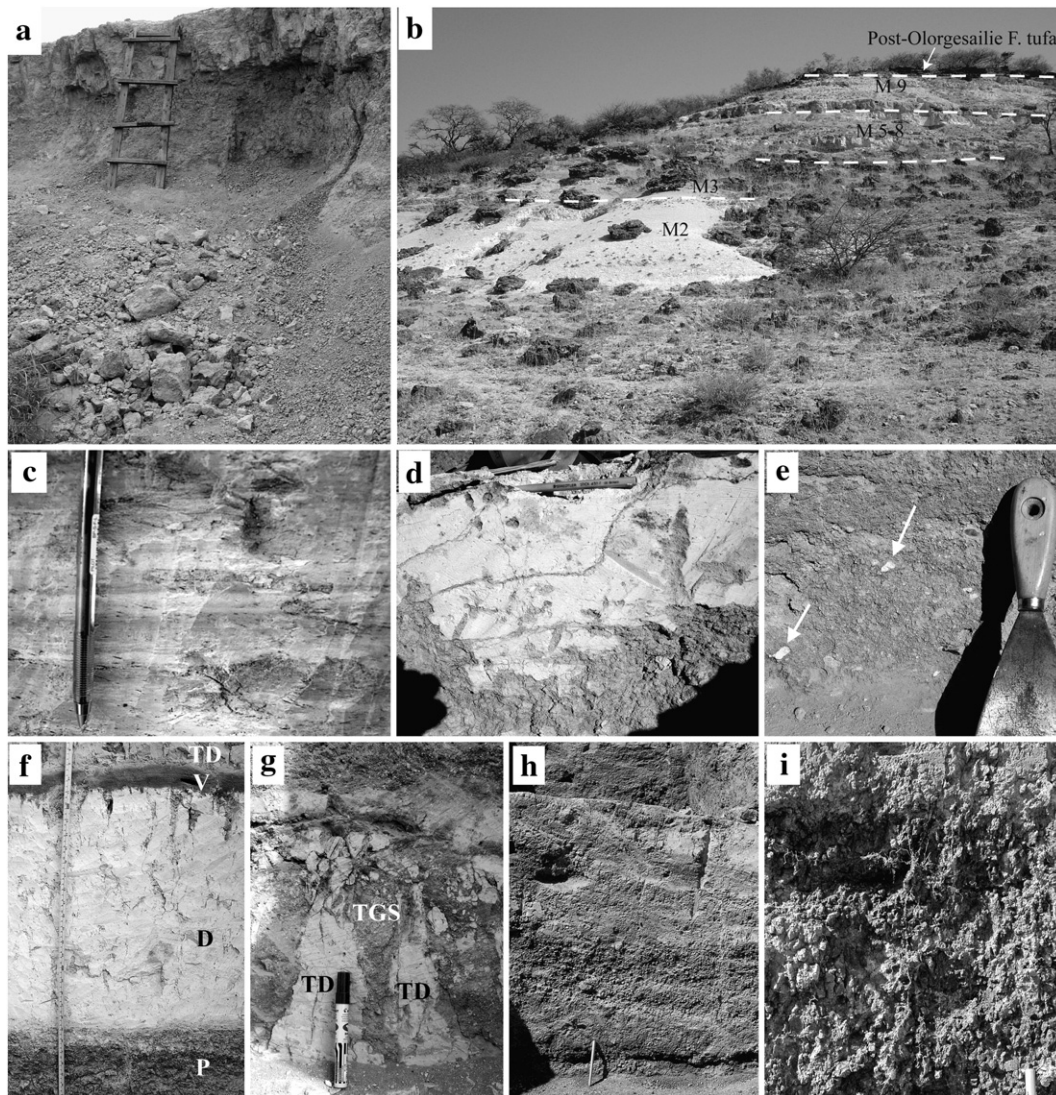


Fig. 4. Field photographs of the Olorgesailie Formation sediments. a: Lower M1 (Section C91–04). b: Western outcrops (Locality D) of M2–9 show the near-horizontal nature of the sediments. The light-colored M2 consists mainly of siliciclastic diatomites and massive diatomites. Sediments higher up the sequence contain generally fewer diatoms. The tufa at the top of the succession post-dates the Olorgesailie Formation. c: Laminated siliciclastic diatomites in M1 (Section C97/16). d: Burrow traces in massive diatomite in M7 (Locality B). e: Reworked diatomite clasts in a poorly sorted sandy gravel in M8 (Locality B). f: Sediments at the M7/M8 boundary (Locality D). Note the basal, pedogenic (yellow-green) silty clay (P), which lies in M7. This is overlain by M8, with a massive diatomite (D) giving way to a volcanic sand (V) and tuffaceous diatomite. g: Continuation upwards of the sediments shown in photograph f. The tuffaceous diatomite (TD) is cut by several wide cracks infilled with a tuffaceous gravely sand (TGS). h: M10 (Locality B) pumice showing cross beds and variable grain sizes from sand to gravel. i: Buff diatomitic clay (M11, Locality B) showing vertical cracking and blocky structure indicative of pedogenesis.

(Fig. 4). Finely laminated and bedded deposits occur in several parts of the sequence and indicate a lack of bioturbation and reworking (Fig. 4c). Bioturbated sediments generally lack lamination, and, in some cases, burrow traces may be preserved (Fig. 4d). Some lithologies include clearly reworked angular diatomaceous clasts derived from previously consolidated diatomites (Fig. 4e). Locally, diatomaceous clasts are found within a diatomaceous matrix. Several diatomaceous lithologies are comprised of mostly fragmentary diatoms and imply reworking and transport of unconsolidated diatom frustules. The reworked nature of these deposits is not always recognizable in the field.

Table 1 summarizes the range of lithofacies that occur within the Ologesailie Formation and is modified from the work of Behrensmeier et al. (2002). The latter study recognized ten facies, whereas we now distinguish eleven. The terminology has also been altered to reflect the classification of diatomaceous sediments suggested by Owen (2002). Consequently, diatomites are defined as those sediments that contain >90% diatoms. Other diatomaceous sediments are defined as follows: siliciclastic or tuffaceous diatomite (>70–90% diatoms), subdiatomite (>50–70%), diatomitic sediments (>10–50%), and diatom-poor deposits (\leq 10%). These terms refer to the total diatom content (fragmented and intact), and further qualifications are needed to reflect the state of preservation.

Paleosols (Fig. 4i) and pedogenically modified diatomaceous and non-diatomaceous sediments are a common feature of the Ologesailie Formation (Fig. 3). In this study, paleosols were recognized in the field based on the presence of distinct beds or zones (usually 20–100 cm in thickness) with massive (unstratified) sediment, prismatic cracking, slickensides, smaller scale ped and cutan development, and/or concentrations of biogenic structures such as root and burrow traces. Within M1, M7, and M11, a few of these paleosols (and associated erosional hiatuses) represent substantial time intervals. Additionally, all members, except M2–M3, show less developed pedogenic alteration at multiple levels that probably represent shorter periods of time (e.g., 10^1 – 10^2 years). The well-developed paleosols differ in thickness, color, texture, and lateral

continuity in the different members. They contain variable clay content and have blocky ped structures and slickensides. Carbonate nodules and root traces also occur. The upper M1 paleosol (UM1p), for example, is composite, with distinct textural layers and relatively low clay content (Potts et al., 1999). The upper M7 paleosol (UM7p) is dominantly a waxy green claystone (locally up to 1 m thick); this soil and its capping unconformity likely represent the longest time interval of apparent landscape stability (or at least non-deposition) in the Ologesailie Formation, estimated at ~190 kyr (Potts et al., 1999). Members 11 and 13 have several intervals of pedogenically modified brown silt that represent a third type of paleosol. These paleosols generally lack well-preserved diatoms and possess a variety of pedogenic features (cracking, root traces, clay illuviation), which in some cases (e.g. UM1p) penetrate down into underlying diatomites. Of these major paleosols, only UM1p contains abundant artifacts and vertebrate remains (Potts et al., 1999), although the others have occasional occurrences of these materials. A different type of paleosol is developed on the pumiceous gravels of M4. In this case, the exposed surface of the original deposit was penetrated by roots, burrows, and termiteries; the resulting trace fossils indicate extensive modification by bioturbation. M10 also has evidence of pedogenesis in its upper 50 cm, although this is not as extensive as in M4.

Far more common, in terms of stratigraphic frequency, are minor paleosols developed on diatomaceous and other sediments. These can be recognized by disrupted bedding, a massive appearance, brecciated sediment clasts, root traces, mudcracks, admixtures of siliciclastic sediment, and the occurrence of fossils and artifacts. The minor paleosols can be laterally continuous over 100's to even 1000's of meters, but more commonly are restricted in extent. These paleosols represent wetlands and drier substrates, i.e., relatively short periods of partial to complete emergence of the depositional plain above the local water table, allowing plants to colonize the surfaces, desiccation cracks to form, and animals to bioturbate the sedimentary layers. The stratigraphic patterns of emergence and submergence represented by these paleosols are important as potential records of climatic cycles (Behrensmeier et al., 2002).

Table 1
Sedimentary facies in the Ologesailie Formation. The terminology for the diatomaceous sediments follows that suggested by Owen (2002). Facies modified after Behrensmeier et al. (2002)

Lithofacies	Lithology	Color	Lithology, structure, and diatom content	Assoc. features	Environment
1	Massive diatomite (MD), siliciclastic and tuffaceous diatomite (SD and TD)	White	Homogeneous, >90% diatoms for MD, >70–90% for SD and TD; benthic taxa common. Mostly in beds <10 cm thick, sometimes bioturbated.	Sponge spicules, phytoliths, ostracods	Shallow to moderately deep lake
2	Laminated diatomite	White to yellow	Fine laminations, sometimes contorted, >90% diatoms, mostly planktonic	Sponge spicules, phytoliths	Deep lake
3	Silty and tuffaceous subdiatomites	White, light green, yellow	Massive or contorted bedding, relict lamination. Diatoms generally 50–70%.	Bone artefacts, gastropods, ostracods	Wetlands
4	Reworked diatomites, subdiatomites, and diatomitic deposits	Dirty white, buff-green, greenish brown.	Massive or irregular bedding. Diatom content reflects emergence of a variety of facies. Diatoms often broken, intraclasts may be present	Rhizoliths, some bones, artifacts	Lake margin or emergent lakebed
5	Clayey diatomites, subdiatomites and diatomitic sediments	Green, yellow-green	Massive, brecciated diatomaceous sediments. Diatom fragmentation common, intraclasts may be present	Rhizoliths, some bones, artifacts	Pedogenically modified, lakebeds
6	Clay or silty clay	Dark green, greenish brown	Ped structures, clay skins, CaCO ₃ nodules, diatoms absent	Rhizoliths, some bones, artifacts	Paleosol
7	Silt, sandy silt	Light brown, buff to greenish brown	Massive or irregular bedding, CaCO ₃ nodules	Rhizoliths, rare silica rhizoliths, artifacts, bones	Fluvial overbank, paleosol, eolian (?), hot springs (forming silica rhizoliths?)
8	Sand, gravel	Light brown, greenish brown	Poor sorting, cross stratification, intraclasts	Artifacts, bones locally abundant, reworked plants	Fluvial channels, sheetwash, proximal splays
9	Silt-grade ash	Dark to light gray	Well-sorted, laminated, laterally extensive	Burrows and rhizoliths, rare silica stems	Air fall tuffs
10	Silty to sandy tuffs	Dark to light gray and gray-brown	Moderate to poor sorting, laminated to massive, laterally variable.	Burrows and rhizoliths, plant impressions, rare bones and artifacts	Fluvial and eolian reworked volcanic debris
11	Sand to gravel-grade volcaniclastics	Dark gray, brown	Poorly sorted, bedded to massive, cross stratification, contorted bedding	Burrows and rhizoliths, occasional bones and artifacts, occasional plant casts	Fluvial channels and low angle alluvial fans

4.2. Common diatom taxa and habitats

A total of 186 diatom species and varieties were identified in 419 sediment samples. A correspondence analysis (CA) for common diatoms (>5% of the sediment in at least one sample) in the Ologresailie Formation is shown in Fig. 5. Gasse et al. (1995) noted that diatoms respond principally to conductivity (or total salinity) and to ionic ratios: $\text{Na}^+-(\text{Ca}^{2+}+\text{Mg}^{2+})$ and $(\text{HCO}_3^-+\text{CO}_3^{2-})-(\text{SO}_4^{2-}+\text{Cl}^-)$. Rift lakes in Kenya are mainly dominated by carbonate–bicarbonate water (Renaut et al., 1987), and this is also likely to be the case during deposition in the Ologresailie paleolakes and wetlands, which were fed by streams draining similar volcanic rocks as those present today. Furthermore, the dominant taxa present in the Ologresailie Formation have been reported as indicative of $\text{HCO}_3^-+\text{CO}_3^{2-}$ settings (Gasse et al., 1997). Carbonate–bicarbonate ionic composition is therefore unlikely to be a cause of variation in the diatoms. Based on the literature on diatom ecology (e.g. Hecky and Kilham, 1973; Haworth, 1977; Gasse et al., 1983, 1995; Evans, 1997), we suggest that Axis 1 broadly approximates conductivity tolerances, with possible contributions from pH and cation ratios, and that Axis 2 largely reflects water depth.

Aulacoseira spp. are among the most common taxa within the Ologresailie Formation and occur within quadrants interpreted as indicating fresher water conditions. These data reflect habitat trends noted elsewhere for *Aulacoseira* spp. For example, *A. agassizii*, *A. ambigua* and *A. distans* (common in M5 and M8) all lie within Quadrant II, and are generally found in shallow, or swampy, dilute water bodies (Richardson and Richardson, 1968; Stager, 1984; Gasse, 1986). *A. agassizii* is favored

by a low mineral content, with conductivities of $<200 \mu\text{S cm}^{-1}$ and a medium pH (7–8) (Gasse, 1986). *A. distans* var. *africana* tends to be common where the pH is slightly below neutral. Although relatively uncommon, *A. italica* var. *bacilligera* also occurs in Quadrant II and has also been reported from plankton samples in dilute waters (e.g. Lake Tana; Gasse, 1986). One or more of the taxa *A. granulata*, *A. granulata* var. *valida*, *A. granulata* var. *angustissima* and its form *curvata*, are present throughout the Ologresailie Formation, with the former two being especially abundant in M2 and M9. These species are planktonic and occur in Quadrant I of the CA.

Gasse (1986) reported that *A. granulata* and its varieties are well developed in freshwater lakes (conductivities=47–1300 $\mu\text{S cm}^{-1}$; pH=6.5–9; alkalinity=0.4–9 meq l^{-1} ; silica $>10 \text{ mg l}^{-1}$), and that *A. granulata* tends to be replaced by *A. granulata* var. *angustissima*, and then by *A. granulata* var. *valida*, as conductivity, pH, and alkalinity increase, which is reflected in the trends shown in relation to Axis 1 of the CA. Gasse also noted that *A. granulata* var. *valida* is only found in sodium-rich lakes. Kilham and Kilham (1971) pointed out that *A. granulata* is favored by high silica, and Kilham et al. (1986) suggested that different *Aulacoseira* spp. are favored under different combinations of phosphorus and light. They noted that *A. distans*, outcompeted *A. ambigua* and, in turn, *A. agassizii* and *A. granulata* as phosphorus decreased and light levels increased. The resulting successions of species would probably reflect variations in turbidity and depth of mixing within the water bodies they inhabited.

Stephanodiscus astraea and *S. astraea* var. *minutula* (= *S. minutulus*) occur mainly in the upper part of M2 and in M3. These diatoms have

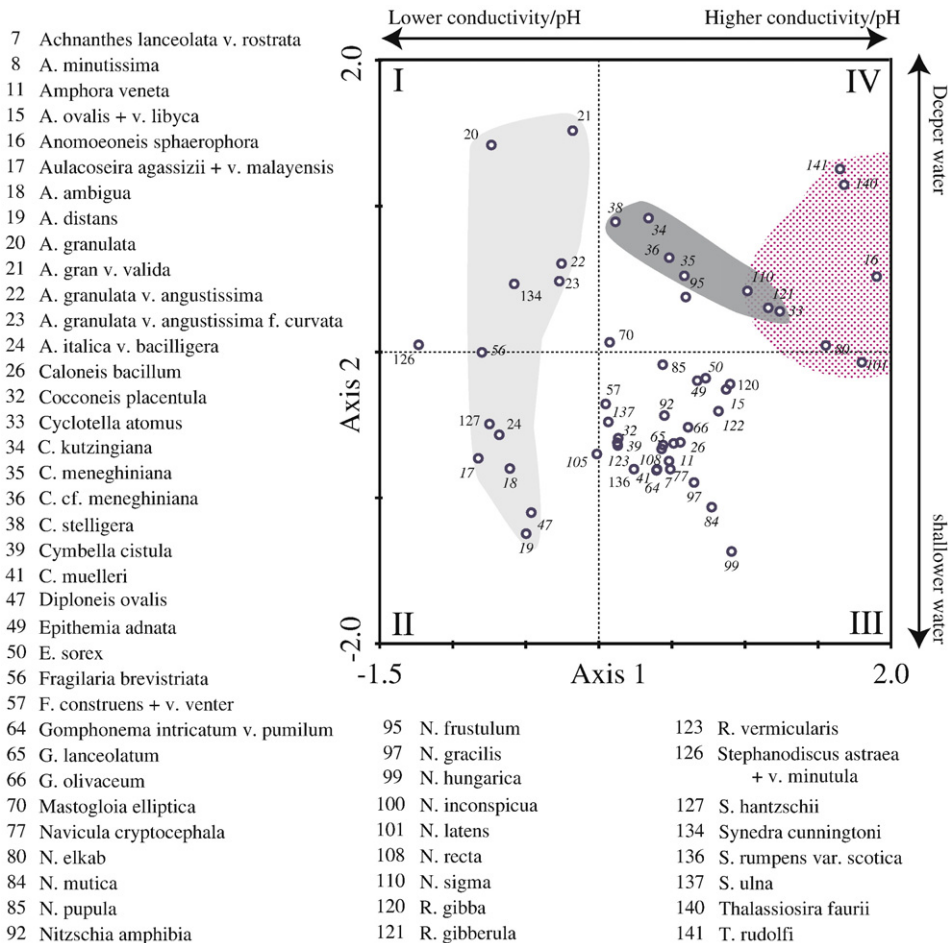


Fig. 5. Correspondence analysis of major diatoms in the Ologresailie Formation. Axis 1 appears to reflect control by either conductivity or pH. Axis 2 probably reflects water depth. Light grey field encompasses the range of *Aulacoseira* spp. Dark grey shows the range of *Cyclotella* spp. Stippled field includes diatoms typical of high conductivities in modern lakes. See text for details.

similar ecologies and have been grouped together in the diatom counts, following the EDDI merging system. They plot on the CA between Quadrants I and II, and have very low values along Axis 1. These taxa are reported mainly from dilute waters usually with low silica concentrations, and occur in the plankton and bottom mud of many rift lakes (Gasse, 1986; Kilham et al., 1986).

Several *Cyclotella* spp. are also common, particularly in parts of M1, M9 and M11. All of these diatoms lie within Quadrant IV of the CA, which suggests deeper and more saline water. *C. kuetzingiana* and *C. stelligera* plot close together and are reported as occurring in both planktonic and littoral habitats in small dilute to mesohaline lakes of a carbonate–bicarbonate type. *C. kuetzingiana* and *C. stelligera* are indicative of pH 9.2–10.3 and 6.8–8.0, respectively (Gasse, 1986, 1987). *C. meneghiniana* (= *Stephanocyclus meneghiniana*) lies further to the right on the CA and is a facultative planktonic taxon favored by moderately alkaline (4–50 meq l⁻¹) conditions (Hecky and Kilham, 1973; Richardson et al., 1978). *Cyclotella* cf. *meneghiniana* resembles small specimens of *C. meneghiniana* (6–10 µm), possessing similar striae densities (8–10/10 µm), a central area with a tangential fold and 1–2 fultoportulae, and marginal fultoportulae with three satellite pores. However, the marginal fultoportulae generally only occur on every second rib and external spines are absent as noted for aberrant forms of *C. meneghiniana* by Schoeman and Archibald (1976), although this might also reflect corrosion which is common on these diatoms. *Cyclotella* cf. *meneghiniana* plots close to *C. meneghiniana* on the CA and has been merged with it in constructing conductivity and pH stratigraphies. Among the *Cyclotella* spp., *C. atomus* (merged with *Cyclotella* cf. *caspia* in the EDDI diatom database) is located furthest to the right on the CA, suggesting a possible relationship with the higher salinity diatoms that occur within the Olorgesailie Formation. This species has also been reported from modern coastal and estuarine situations in waters of varied chemistry (Trigueros and Orive, 2000; Tibby and Reid, 2004). Belcher and Swale (1978) note that it lives mainly in freshwater, although it has halophilic tendencies.

Diatoms suggestive of higher salinities plot on the right of the CA and occur mainly in parts of M1, basal M2, and M11. These species occur with salt-tolerant benthic forms such as *Anomoeoneis sphaerophora*, *Rhopalodia gibberula*, and *Nitzschia sigma* (Gasse et al., 1995; Legesse et al., 2002). The benthic diatom *Navicula elkab* (= *Craticula elkab*) and facultative planktonic taxon *Nitzschia latens* are associated with strongly alkaline water (Gasse, 1986; Legesse et al., 2002), but are not abundant in the Olorgesailie sediments. *Thalassiosira faurii* tolerates highly saline conditions and is often found together with *T. rudolfi*, although the latter diatom is usually present in slightly less concentrated lakes (Hecky and Kilham, 1973; Haberyan, 1987; Barker et al., 1990). Both are planktonic.

Quadrant III of the CA contains several taxa that are found in shallower waters and which mostly occur as accessory species. Diatoms that attain dominance (>20% in at least one sample), within M1, M5, M9, M11, and M12, include: *Cocconeis placentula*, *Cymbella muelleri* (= *Encyonema muelleri*), *Epithemia adnata*, and *E. sorex*. All occur in epiphytic habitats (Gasse, 1986, 1987). Abundant *C. placentula* are generally found in waters with conductivities <400 µS cm⁻¹, and this taxon prefers a pH above 8. *C. muelleri* can enter the plankton in deeper water and has a wide tolerance range for pH and salinity, but is mainly present in lakes with moderately concentrated waters. *E. adnata* prefers slightly to moderately alkaline water, but can survive higher mineral content in sodium bicarbonate lakes (Gasse, 1986). *E. sorex* is favored by higher salinities than *E. adnata*, but has a wide tolerance range for water chemistry.

4.3. The sediment and diatom stratigraphy

Given the level of detail in this study and the potential for spatial variability across the basin, the data presented should be considered representative only of the study areas in Localities A and C (Fig. 2). The

diatom and sediment stratigraphies are shown together in Figs. 6–9. Several lithological units are recognized and numbered in each section. The terms used for the sediments follow the original field descriptions rather than the amended terms for diatomaceous sediments noted earlier. Data for diatom fragmentation and abundance are derived from visual estimates of smear slides. The diatom content is very variable, ranging from scarce or absent to nearly 100% of the sediments. Diatoms are especially common in M2, and in parts of M9 and M11.

Diatoms, excluding fragments, are absent or rare in several parts of M1, M5–8, M9, and M11, and are largely absent in the volcanoclastic gravels of Members 4 and 10. The diatom floras are best preserved in M2 and parts of M9. Silt-grade diatom fragments resulting from physical breakage tend to form a common background component in much of the Olorgesailie Formation deposits. Diatom dissolution appears to be minimal in most horizons. However, partial dissolution is more prevalent where *Thalassiosira* spp. form part of the flora.

4.3.1. Member 1

Sections C91/04R and C97/16 represent M1 (Figs. 2, 3, and 6), which varies greatly in thickness because of the undulating topography of the underlying lava. Contact with this trachyte is not visible at the base of the section designated C91/04R, but lower M1 laps onto a trachyte paleoridge about 10 m east of this section. A small stratigraphic gap also occurs between C91/04R and the base of C97/16, which lies directly on trachyte. The top of M1 is a paleosol (designated UM1p) that can be traced over an east–west distance of at least 4 km (Potts et al., 1999).

Diatom data for M1 are presented in Fig. 6. Lithological Unit 1, at the base of Section C91/04R, is a silty clay with crack fills and a crumbly ped structure. Scarce *A. granulata* occur at the base and increase in abundance towards the top, where *A. agassizi* is also abundant. These taxa continue to dominate in an overlying pedogenically modified silty diatomite, and into Unit 3 where *E. sorex* is also common in a diatomaceous silt with cracks infilled by an ash dated at 1.2 Ma (Deino and Potts, 1990, 1992, and unpublished). Field logs indicate that Units 4–10 are comprised of silty diatomites and diatomaceous sandy silts with a variety of burrow structures, rhizoliths, reworked clasts, and pedogenic stains. Despite the field descriptions, diatoms only form 0–20% of the sediment (see later discussion) and are often fragmentary. *Epithemia* and *Thalassiosira* dominate, with variable *A. granulata*, *Nitzschia* (mainly *N. sigma*), and *Cyclotella* spp.

Diatom abundances increase (ca. 25–60%) in Units 11–15, where *Cyclotella* cf. *meneghiniana* dominate and *Thalassiosira faurii* forms a small (5–10%) but consistent part of the flora. The sediments range from sandy silts to gravelly silty sands with reworked clasts and pebbles. Stone tools occur in Unit 12 at excavation CL1/1 (Fig. 6). Silica plant stems are present in Unit 14. Scarce *Cyclotella*, *Thalassiosira*, *Nitzschia* and *Anomoeoneis sphaerophora* (often broken) occur in Units 16 and 17, which were logged as sands and diatomaceous silts. The deposits forming Units 18–24 are comprised of a variety of silty clays (with a prismatic pedogenic texture), diatomaceous silts, diatomites and gravelly sands that, in some horizons, contain reworked clasts, plant fragments, hardened carbonate-rich horizons and large scoria boulders that probably represent downslope movement of lava blocks from the nearby, elevated “NE Lava Outcrop” into the lake margin sediments (Potts, et al., 1999). Diatoms vary in abundance and resemble the floras in Units 16–17. A volcanic ash (992 ka; Deino and Potts, 1990), lacking diatoms, lies at the top of C91/04R.

Section C97/16 represents the upper part of M1. Units 1 and 2 are comprised of massive diatomaceous silts (Figs. 3 and 6). The floras are similar to those in Units 18–24 of C91/04R, but with an increase in *Epithemia* spp. and a decrease in *Cyclotella* cf. *meneghiniana*. Diatoms are scarce in Unit 3, which was logged as diatomaceous silt with weak pedogenesis. Fragmentation is common, and the flora becomes increasingly dominated by *Thalassiosira*, which continues to dominate in Unit 4 up to about 220 cm. Diatoms are abundant in the upper part

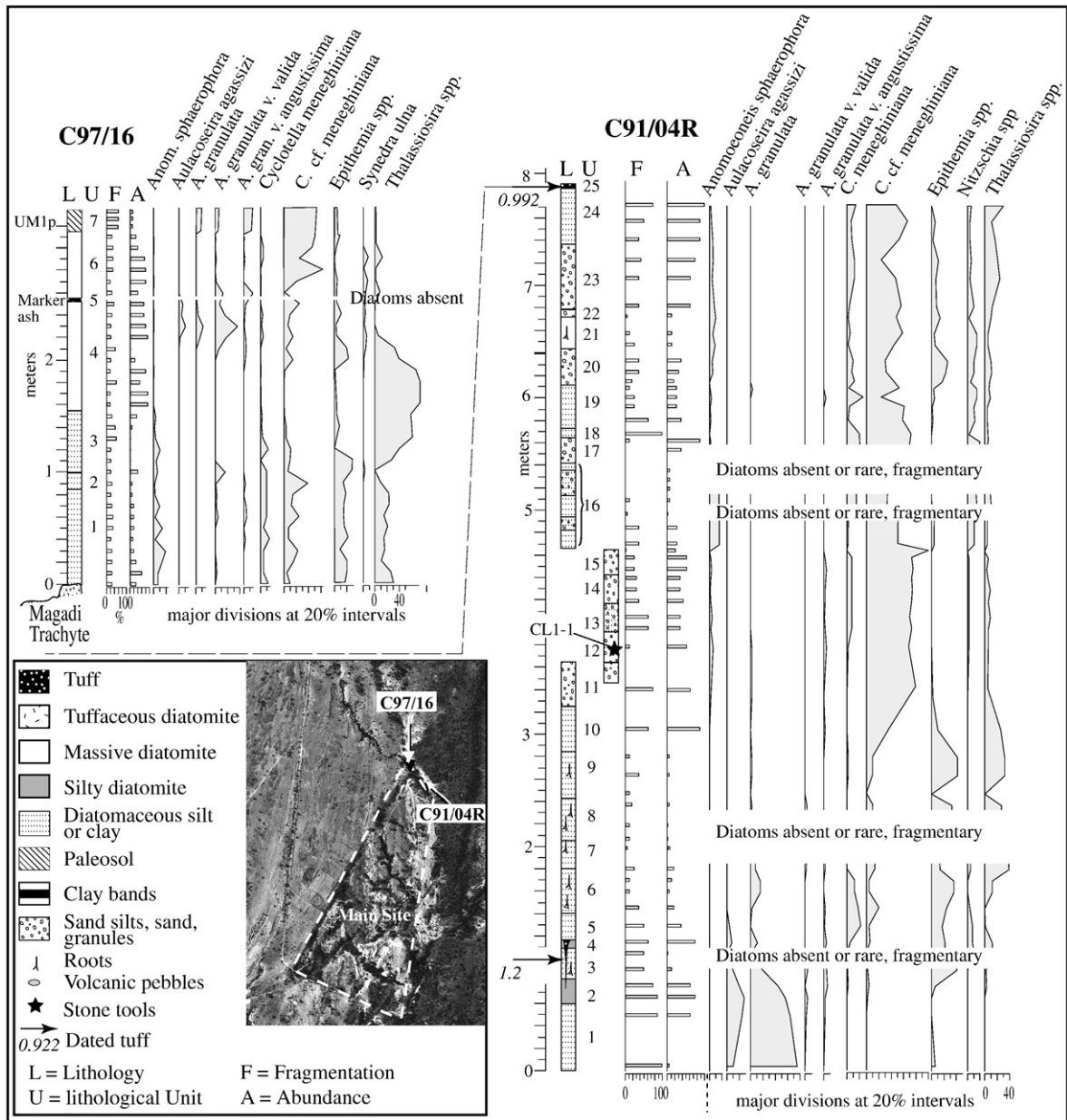


Fig. 6. Diatom stratigraphy of Member 1. Taxa included account for ≥5% in at least one sample.

of Unit 4, which contains several *Aulacoseira*, *Cyclotella*, and epiphytic diatoms (Fig. 6). Unit 5 is a volcanic ash that lacks diatoms and has been used as a marker bed (the “Marker Ash”; Potts et al., 1999). Unit 6 is dominated by *Cyclotella* spp. Unit 7 is part of the UM1p paleosol, which yielded fragmented *Cyclotella* and *Aulacoseira* spp.

4.3.2. Members 2 and 3

M2 and M3 are represented by Sections A307, C91/07, and C04/B1 (Fig. 3). The M2 diatom stratigraphies of Sections A307 and C91/07 correlate well with one another (Fig. 7), but the relationships with C04/B1 are less clear, possibly because M2 samples were collected at less frequent intervals (ca. 50 cm). A distinct marker horizon (the Evaporite/Carbonate, or EC, marker) occurs towards the base of A307 and C91/07, and probably lies just below the exposed sequence at C04/B1. The EC marker is comprised of a 2–15 cm thick layer of calcium carbonate that infills desiccation cracks, and which includes cubic crystal molds that suggest replacement of NaCl in an evaporite crust (Potts et al., 1999).

The basal 80 cm of M2 in Section A307 consists of eleven thin sedimentary units (1–16 cm thick) comprised of tuffaceous sands, silty diatomites, diatomites, and clays. Eighteen similar units occur in the lower 80 cm of C91/07. The diatom floras from these basal deposits show varied dominance by several *Aulacoseira* spp. *Cyclotella meneghiniana* and *Thalassiosira* spp. occur in a number of horizons and are especially common in the EC marker sediments (Sections A307 and C91/07; Fig. 7). In A307, highly fragmented diatoms (mainly *Aulacoseira*) occur at the base of this marker.

Unit 12 (A307) is comparatively thick (2.6 m), and is dominated by *A. granulata* var. *valida*, giving way to *A. granulata* from 210 cm upwards. This pattern is repeated in C91/07, but the change is not clear in the less intensively sampled M2 in C04/B1. *Stephanodiscus* spp. are mostly absent in the lower parts of all three sections, but are then present continuously through to the middle of M3. Their first appearance in A307 and C91/07, apart from a few isolated levels with low percentages of *S. astraea* var. *minutula*, may represent a basin-wide change of potential value for correlation (Fig. 7).

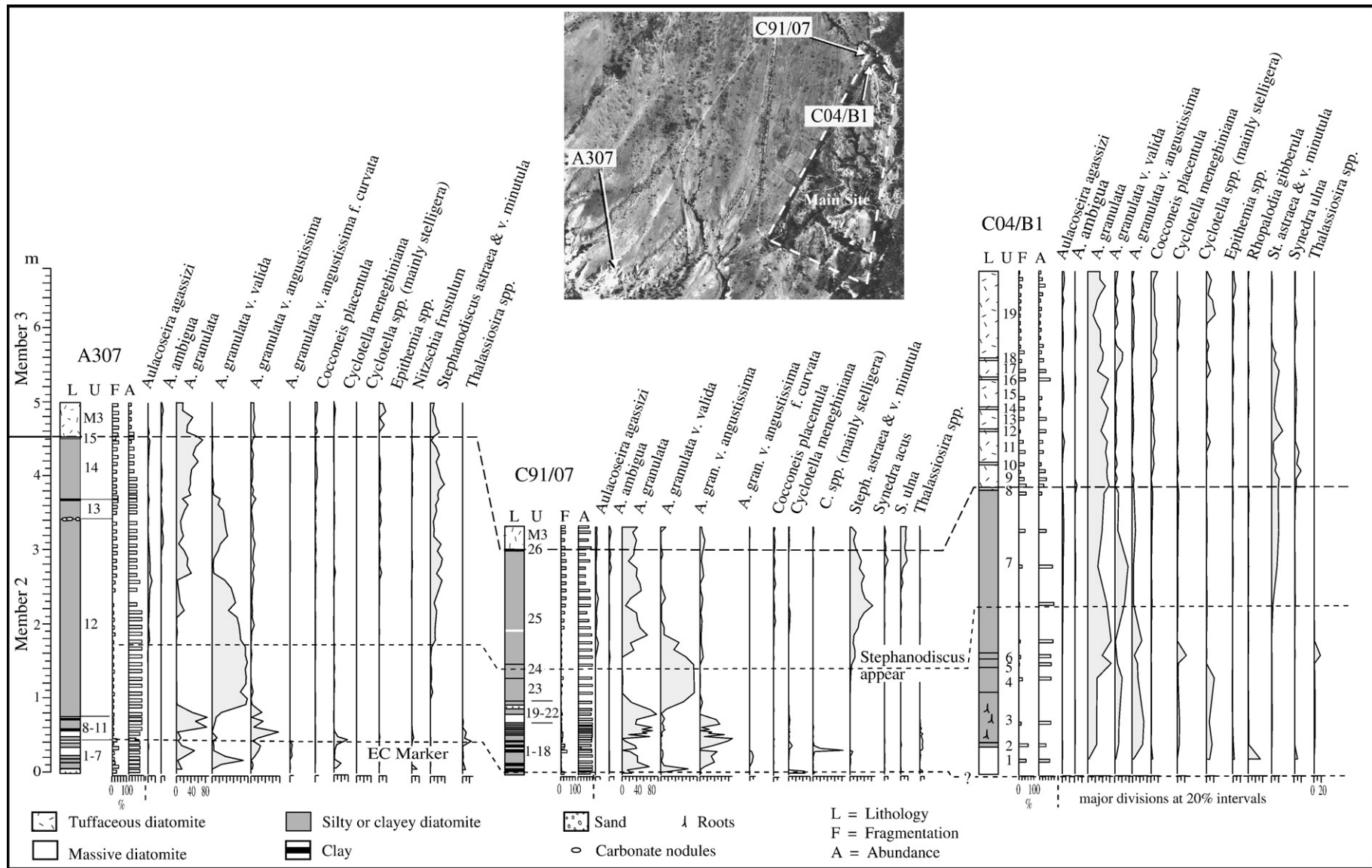


Fig. 7. Diatom stratigraphy of Members 2–3. Taxa included account for ≥5% in at least one sample.

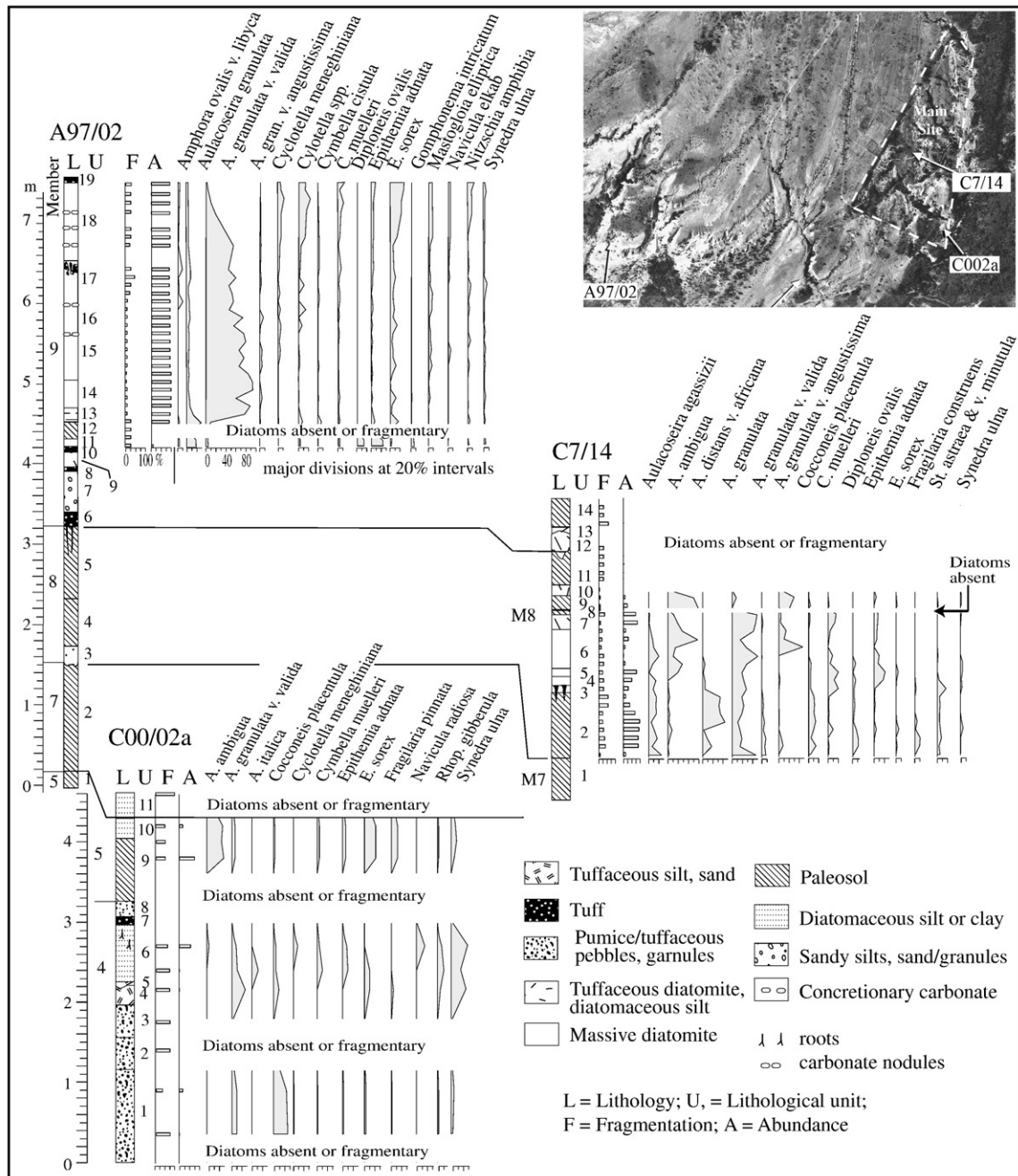


Fig. 8. Diatom stratigraphy of M4–9. Taxa included account for $\geq 5\%$ in at least one sample. Note the upper 50 cm of A97/02 has been added to the original section logged by P. Ditchfield.

Small percentages of epiphytic and benthic species occur throughout the sections (Fig. 7). These diatoms are present in low percentages in the layered basal deposits, decrease where *A. granulata* var. *valida* is most common, and then gradually increase again toward the top of M2. M3 is more tuffaceous than the deposits below (C04/B1; Figs. 3 and 7), and contains a flora dominated by *A. granulata*.

4.3.3. Members 4–9

Sections C00/02a, C7/14 and A97/02 are representative of Members 4–9 (Figs. 3 and 8). Diatom abundance and fragmentation differ considerably as do the lithologies, which include a variety of diatomaceous sediments, as well as pumice and tuff. Paleosols and pedogenic imprints occur at several levels. Dates of 974,000, 780,000, and 746,000 years have been reported from M5, M8 and M9, respectively (Fig. 2; Behrensmeyer et al., 2002; Deino and Potts, 1990).

M4 (Section C00/02a, Figs. 3 and 8) is comprised of tuffaceous silts, sands and gravels, plus pumice (Units 1–8). Rhizoliths are common in Unit 6. The diatom flora in M4 is sparse or absent (Fig. 8), except for a single horizon in Unit 6, where identifiable diatoms form up to 40% of the deposit. The flora, where present, is dominated by benthic taxa, with most diatoms being broken. M5 occurs in the upper part of Section C00/02a (Units 9 and 10) and is comprised of a pedogenically altered deposit, described as “diatomaceous silt” on field logs. However, diatoms are either absent or present only as fragments in the basal part of M5 (Fig. 8). Diatoms are common at about 380 cm, but scarce in the remainder of Units 9 and 10, where *A. ambigua* dominates. Unit 11 was formerly designated as part of Member 6 until this was merged with Member 7 (Potts et al., 1999). Diatoms are absent apart from a few fragments.

Member 7 is present in Sections A97/02 and C7/14 (Fig. 8). In the latter section, it consists of a green clay-rich paleosol (UM7p; not sampled),

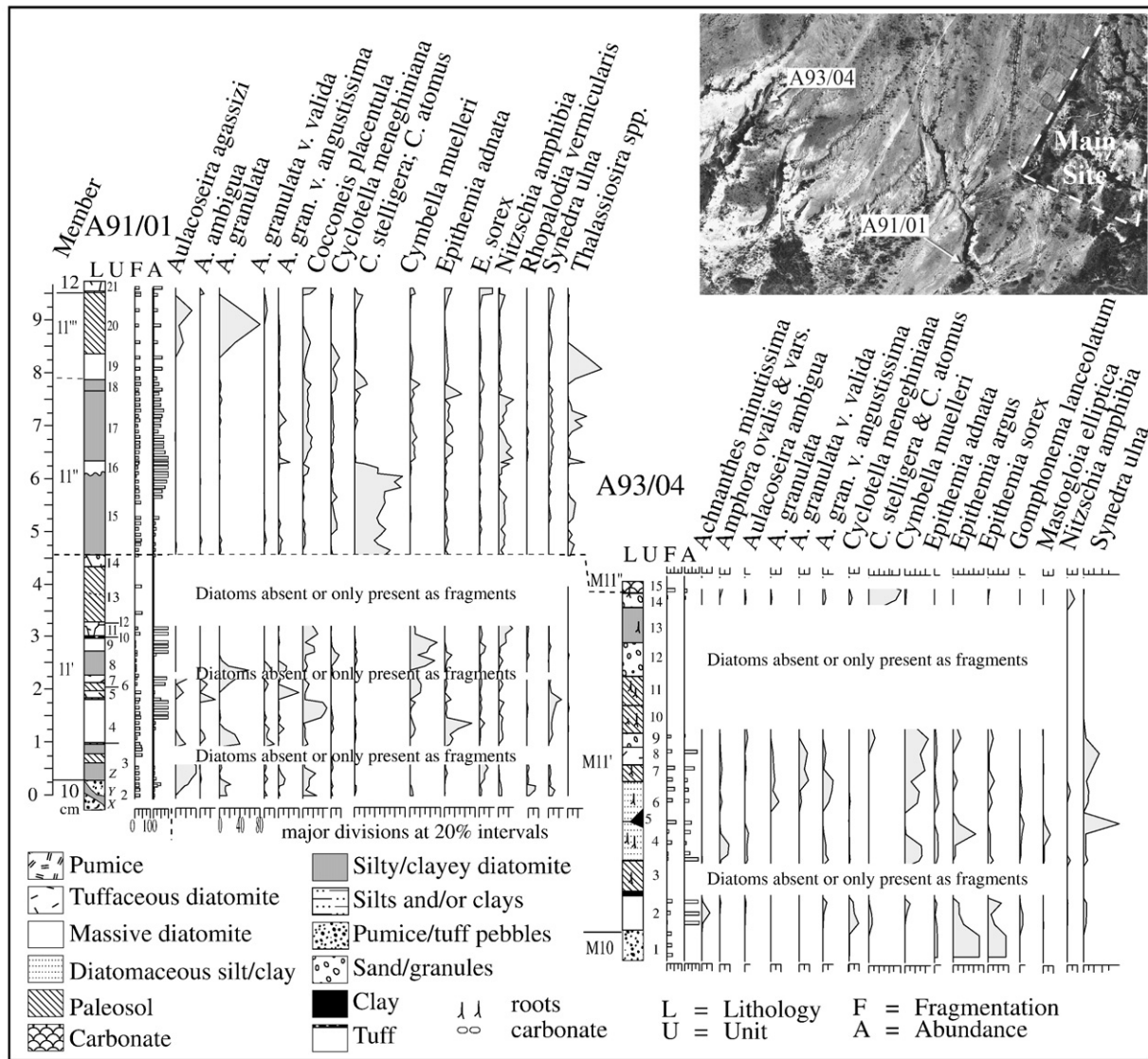


Fig. 9. Diatom stratigraphy of M10–12. Taxa included account for $\geq 5\%$ in at least one sample.

which is overlain by a buff paleosol (M8; Unit 2) with subaerial ash infilling fissures at the top. Diatoms are abundant in Unit 2 and are dominated by *A. agassizii* and *A. distans* var. *africana*, which are common for the first time, together with benthic taxa. Field logs indicate that Units 3–11 (within M8) are composed of tuffaceous diatomites, diatomites, and paleosols. However, diatoms are infrequent in Units 3–5, although abundances increase upwards. *A. distans* var. *africana* is replaced mainly by *C. muelleri* and *E. sorex*. Diatoms are scarce in Unit 6, which is dominated by *A. ambigua* and *A. agassizii*, and contains fewer epiphytic taxa than the deposits below. Diatom abundances increase in Unit 7, which is dominated by *A. granulata* and *C. muelleri*. In contrast, diatoms are scarce or absent in Units 8 and 9 (middle M8).

Units 6–19 of Section A97/02 comprise M9, which begins with a volcanic ash that fills cracks into the top of M8. These cracks are overlain by ~ 1 m of volcanic ashes and fluvial reworked sediments that were not sampled for diatoms. *Aulacoseira* spp. and benthic taxa occur in low numbers in Unit 11, and diatoms are absent, or rare and fragmentary, in Unit 12. Both of these thin units bear evidence of pedogenic alteration. Diatoms are abundant in Unit 13, a laminated diatomite that commences with common *Amphora ovalis* var. *libyca*. Assemblages higher in the sequence are dominated by *A. granulata* var. *valida*, which reaches peak abundance in Unit 14, and is then gradually replaced by benthic species.

A widespread, 5–10 cm thick airfall tuff occurs within the diatomites of M9 (Unit 17 in Section A97/02).

4.3.4. Members 10–12

Two sections representing M10–12 were sampled for diatoms (Fig. 9). Section A91/01 includes the upper part of M10, M11, and the basal deposits of M12. Section A93/04 contains sediments that belong to upper M10, M11' and basal M11'' (Fig. 3). Diatoms are rare and often fragmentary in Member 10, with benthic taxa dominating.

In both sections, Member 11' is characterized by highly variable diatom abundances, with several horizons lacking diatoms entirely or containing only occasional fragments. This is especially true of deposits that have been pedogenically altered. For example, 3 pedogenic zones (Beds 3, 7 and 10–11) occur in A93/04. Two lack a good diatom record and one (Bed 7) retains a diatom stratigraphy, suggesting that its soil was less well developed than the other two zones. Benthic species are dominant through most of this sequence. Planktonic taxa (mainly *Aulacoseira* spp.) are common in the lower 230 cm of A91/01, but are less common in A93/04. Diatom floras vary considerably in M11' in both sections (Fig. 9).

M11'' is more completely represented in A91/01 than in A93/04. Units 15 and 16 in A91/01, and Units 14 (top M11') and 15 in A93/04, are

both dominated by *Cyclotella* spp. Benthic diatoms are present, but scarce. Units 17–19 (A91/01), are characterized by an increase in benthic taxa. The frequencies for *Thalassiosira* spp. are variable through this part of the sequence, becoming especially common in Unit 19. *Aulacoseira* spp. dominate in Unit 20 (A91/01) – a pedogenically modified unit – where *Thalassiosira* spp. are rare and benthic diatoms are less common than in the lower units.

Unit 21 constitutes the basal part of M12 and consists of mixed diatomite and tuff on lithological logs. The diatoms in these sediments

are abundant, well-preserved, and dominated by benthic and epiphytic diatoms.

5. Discussion

5.1. Environmental interpretation

Fig. 10 shows a summary environmental stratigraphy for the aquatic depositional phases of the Ologresailie Formation; Fig. 11 provides a key

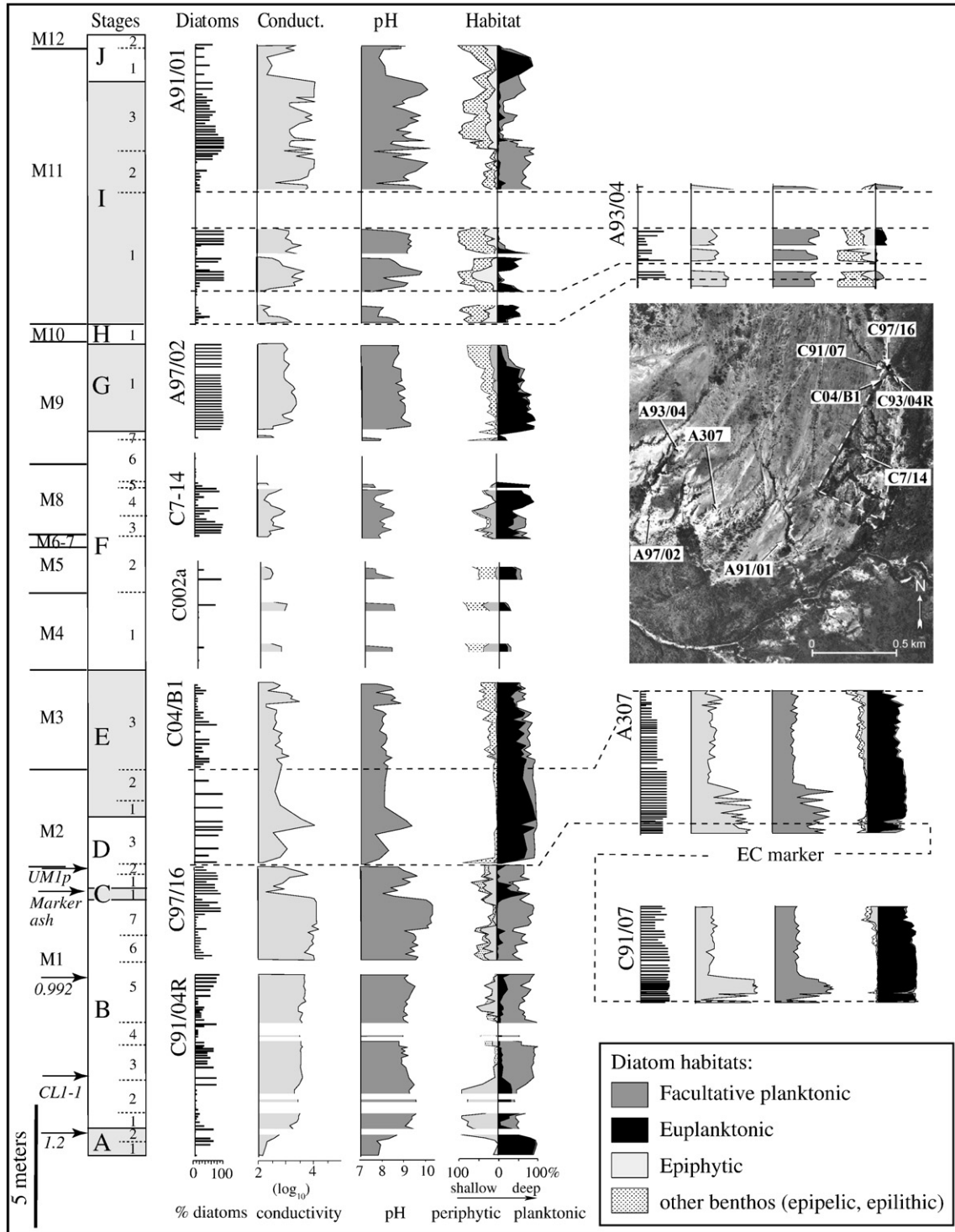


Fig. 10. Environmental stratigraphy. The data are derived from diatom assemblage transfer functions. In some horizons mixed saline and freshwater diatoms occur suggesting these values are averages (see text). Pedogenesis overprints several parts of the sequence and points to times of non-deposition of diatoms. These gaps in the diatom record are shown in Fig. 11, which also provides a key to stratigraphic bed numbers (Figs. 6–9) associated with each diatom stage. Note that gaps in the records of individual sections reflect diatom absence or extensive fragmentation of frustules.

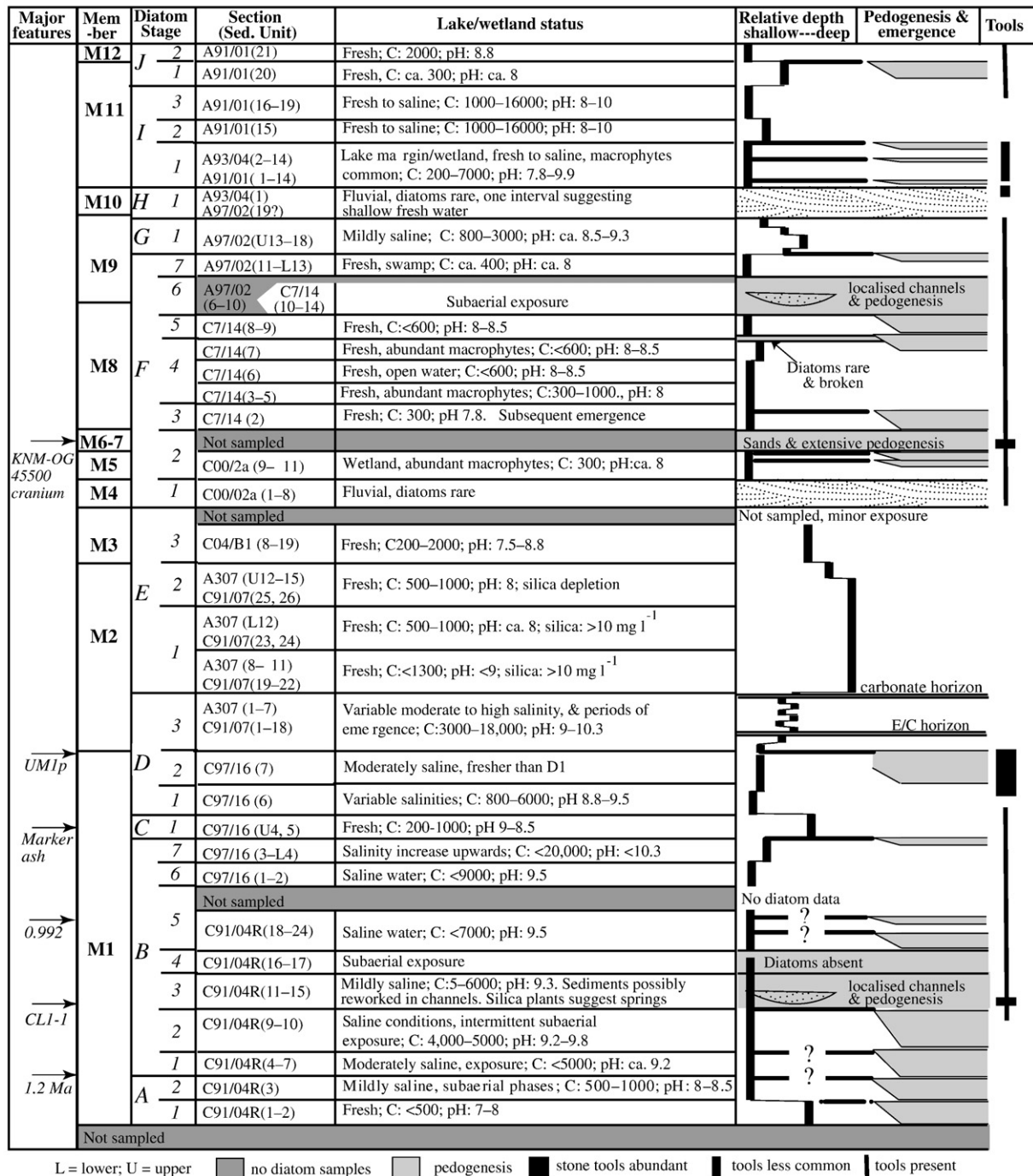


Fig. 11. Integrated environmental stratigraphy. The diagram shows diatom stages and a summary of lake status based on diatom data, together with paleosol-inferred environmental conditions through Members 1–12. The data are arranged by sedimentary units, and are not set to either a chronological or thickness scale; thus the more complex records per unit thickness gain more vertical space (e.g. M1). Actual thicknesses for the various members are shown in Figs. 10 and 12. Note that diatom-based environmental inferences (lake/wetland status and relative depth) do not provide information for the intervening times during which pedogenesis, erosion, or non-deposition took place. Conductivity estimates (C) are given in $\mu\text{S cm}^{-1}$. Pedogenesis and emergence inferences are based on sedimentological parameters (clay development, staining, cracking) that suggest soil formation, and are shown gray to the right. In some cases, diatom absences and fragmentation are also used to infer subaerial exposure. Fluvial inputs are shown by stippled patterns. A general summary of the distribution of the stone tools is given on the extreme right, with bar width being subjectively proportional to the frequency of tools in the sediments. Important stratigraphic dates, a significant tool horizon and the position of the KNM-OG 45500 *Homo cf. erectus* cranium are shown on the left.

to the section bed numbers shown in Figs. 6–9 that correspond to these stages. The conductivity and pH inferences are based on transfer functions for well-preserved diatoms. Saline and fresh-water species coexist in parts of the sedimentary succession (e.g., parts of M1). Since this is probably due to spatial and/or temporal mixing, reconstructions will tend to underestimate conductivities attained during the most saline periods or perhaps in saline bottom-waters. The percentages of planktonic and benthic taxa are also shown in Fig. 10, as these habitat preferences broadly reflect water depth.

High proportions of benthic species suggest shallow-water conditions, with abundant planktonic taxa tending to indicate deeper settings. The diatom stages shown in Fig. 10 correspond with those given in Fig. 11, which attempts to integrate the diatom-based data with information from paleosols that indicate repeated episodes of exposure of the diatomaceous sediments. Major changes in conductivity have been used to distinguish ten major diatom stages (A–J), most of which have been further subdivided.

The floras of Stage A1 were dominated by *A. granulata* and *A. agassizii*. The latter taxon is reported as occurring in shallow water, with low alkalinities ($<2.2 \text{ meq l}^{-1}$) and a pH of 7–8 (Gasse 1986). Transfer data for the whole assemblage suggest conductivities of $<500 \mu\text{S cm}^{-1}$ and a pH of ca. 7–8. This phase of shallow dilute conditions was interrupted by periods of emergence that resulted in desiccation cracks and pedogenesis. During Stage A2 there was a decline in *Aulacoseira* and increase in *Epithemia*, suggesting generally shallower water than was present during Stage A1. Transfer data indicate low conductivities of ca. $500\text{--}1000 \mu\text{S cm}^{-1}$.

Stage B encompasses a considerable amount of time, from ~ 1.2 to 0.992 Ma . It is characterized by the common occurrence of saline taxa such as *T. faurii*, *T. rudolfi*, *Cyclotella* spp., *N. elkab* and *A. sphaerophora*. The diatom-based reconstructions indicate that conductivities fluctuated between about $2000\text{--}5000 \mu\text{S cm}^{-1}$ (Stage B1) and $20,000 \mu\text{S cm}^{-1}$ (B7). Some spatial and/or temporal mixing may have occurred during Stage B1, given that up to 20% of the flora is composed of the freshwater diatoms *A. granulata* or *A. agassizii*. If so, actual conductivities may have been higher, at least periodically (or seasonally?), than suggested by the transfer functions. Furthermore, the diatoms in Stage B1 are less common than during Stage A and are more fragmentary, reducing the reliability of the data and indicating the possibility of some reworking. The presence of pedogenic staining, vertical cracks, and rhizoliths, suggests periods of emergence that might also explain the increase in diatom fragmentation.

Stage B2 includes several lithological units, all of which contain similar floras dominated by scarce *Thalassiosira*, *Epithemia* and *Cyclotella* spp. Diatom reconstructions suggest slightly higher conductivities of about $4000\text{--}5000 \mu\text{S cm}^{-1}$. These moderately saline water bodies probably dried out multiple times given the repeated occurrence of sediment pedogenesis and reworked clasts.

In Stage B3, there is a decrease in *Thalassiosira* (mainly *T. faurii*) and an increase in *Cyclotella* cf. *meneghiniana*. The *Thalassiosira* are often fragmented, but the many small *Cyclotella* are relatively intact, although often corroded. The transfer data suggest that conductivities of the original water bodies would have been relatively constant at about $5000\text{--}6000 \mu\text{S cm}^{-1}$. However, the sediments are relatively sandy and show evidence of fluvial channel cut and fill. It is therefore possible that these diatoms were reworked and size sorted. The occurrence of silicified plants in this part of the sequence might reflect proximity to a spring with silica-rich waters (Deocampo and Ashley, 1999).

Stage B4 is represented by silty and sandy sediments that often lack diatoms, or which contain mostly fragments. Intact taxa are dominated by *Cyclotella* spp., *A. sphaerophora* and *N. sigma*, suggesting saline waters that were subject to desiccation. The subsequent Stage B5 contains floras that are associated with shallow conditions and with conductivities that reached up to $7000 \mu\text{S cm}^{-1}$. The sediments deposited during this interval also contain abundant rhizoliths and reworked clasts, which probably reflect desiccation and exposure.

There is a sampling gap between Stages B5 and B6, with the latter including a higher percentage of epiphytes, suggesting the presence of aquatic macrophytes. This floristic change occurs between two neighboring sections (C91/04R and C97/16) and likely relates to the irregular paleotopography at the time of deposition rather than a change through time. Diatoms are scarce in the lower part of Stage B7, but increase upwards. The flora is dominated by *Thalassiosira* spp., indicating highly saline conditions. Transfer data denote conductivities of up to $20,000 \mu\text{S cm}^{-1}$ and pH values of up to 10.3. Weak pedogenic imprints on these sediments signify a further period of emergence that might correlate with channeling at neighboring sites in Locality C.

The disappearance of *Thalassiosira* distinguishes Stage C, which is not subdivided. Several *Aulacoseira* and *Cyclotella* spp. are common, with a few epiphytic diatoms also being present. These assemblages indicate much more dilute conditions (conductivity ca. $200\text{--}1000 \mu\text{S cm}^{-1}$; pH

ca. 8–8.5) and probably a transgression that led to moderately deep water. A widespread airfall-volcanic ash (the M1 Marker ash), lacking diatoms, lies on the top of sediments formed during this stage.

Stages D1–3 are characterized by very variable diatom floras with some horizons dominated by taxa generally found in moderately to highly saline waters (*C. meneghiniana*, *Thalassiosira* spp.), alternating with species associated with fresher conditions (*A. granulata*, *A. granulata* var. *valida*, *A. granulata* var. *angustissima*, and *C. stelligera*). These diatoms suggest conductivities that fluctuated between about 800 and $18,000 \mu\text{S cm}^{-1}$, and pH values that ranged from about 8.8 to 10. The alternating nature of this sequence may indicate a water body that periodically expanded and contracted, or which became intermittently chemically stratified. Other sedimentological data document several periods of emergence of varying duration and significance. In particular, there is a well-developed paleosol (UM1p) at the top of M1 (Stage D2), representing a period of clastic input and soil formation superimposed on previously consolidated diatomites. Bioturbated volcaniclastic and diatomaceous silts overlain by laminated diatomites document a lacustrine transgression over this soil. The EC marker horizon in lower M2 represents a brief period of desiccation based on salt crystal casts, desiccation cracks, and carbonate precipitation (Potts et al., 1999); there is support for this event in the diatom habitat signal of lower Stage D3 (a small increase in saline diatoms and a large increase in benthic species, Fig. 12). A second period of lake desiccation indicated by a strong peak in saline diatoms near the top of Stage D3 may coincide with a second carbonate horizon documented elsewhere in middle M2 (Fig. 11).

Stage E has a flora dominated by *A. granulata* var. *valida*, which gives way to *A. granulata*, suggesting a relatively deep lake. Diatom-based reconstructions suggest conductivities of $<1300 \mu\text{S cm}^{-1}$ and pH values of <9 that tended to decrease with time. *S. astraea* and its variety *minutula* characterize Stage E2. These euplanktonic diatoms tend to be associated with lower silica levels than *Aulacoseira* spp. (Gasse, 1986). They may therefore imply the development of a seasonal succession, where *Aulacoseira* blooms depleted the concentration of silica, leading to increased growth of *Stephanodiscus*. This change occurred widely across the paleolake, including areas in the western part of the basin (unpublished data). Benthic diatoms become more common in the upper part of Stage E2 and increase through Stage E3 indicating a gradually shallowing lake.

Stage F represents a time when shallow fresh-water bodies developed, and during which these lakes and/or wetlands became subaerial land surfaces. Initially, there was widespread deposition of fluvial pumiceous sediments (F1). During Stage F2, *A. ambigua* and benthic diatoms developed, probably in shallow, swampy water, with low conductivities (ca. $300 \mu\text{S cm}^{-1}$) and pH (ca. 8). The diatoms are often fragmentary and occur in deposits with angular clasts, vertical cracking and rhizoliths, suggesting that these swamps periodically dried out. An unsampled sequence of paleosols and fluvial channel deposits (M6/7) developed subsequently, indicating a long period of subaerial exposure and pedogenesis. Further studies are needed to determine whether diatom deposition occurred between episodes of pedogenesis in this unsampled sequence. Lithostratigraphic evidence indicates that a wetland did occur a short distance to the south of the sampling site in the Site Museum area. A swampy setting developed again during Stage F3 (basal M8), with *A. agassizii* and *A. distans* var. *africana* dominating the floras, together with benthic taxa. Transfer function data indicate a water body with conductivities of about $300 \mu\text{S cm}^{-1}$ and a pH of about 7.8. This swamp also appears to have dried out, with further pedogenesis taking place.

Stages F4 and F5 are both characterized by *A. ambigua* and *A. agassizii*, suggesting the development of fresh, shallow-water conditions. Stage F4 also contains common epiphytic diatoms (*C. muelleri*, *E. adnata*) pointing to the presence of aquatic macrophytes. Epiphytes are largely absent during Stage F5, probably reflecting more open water. Both of these stages were terminated by episodes of emergence

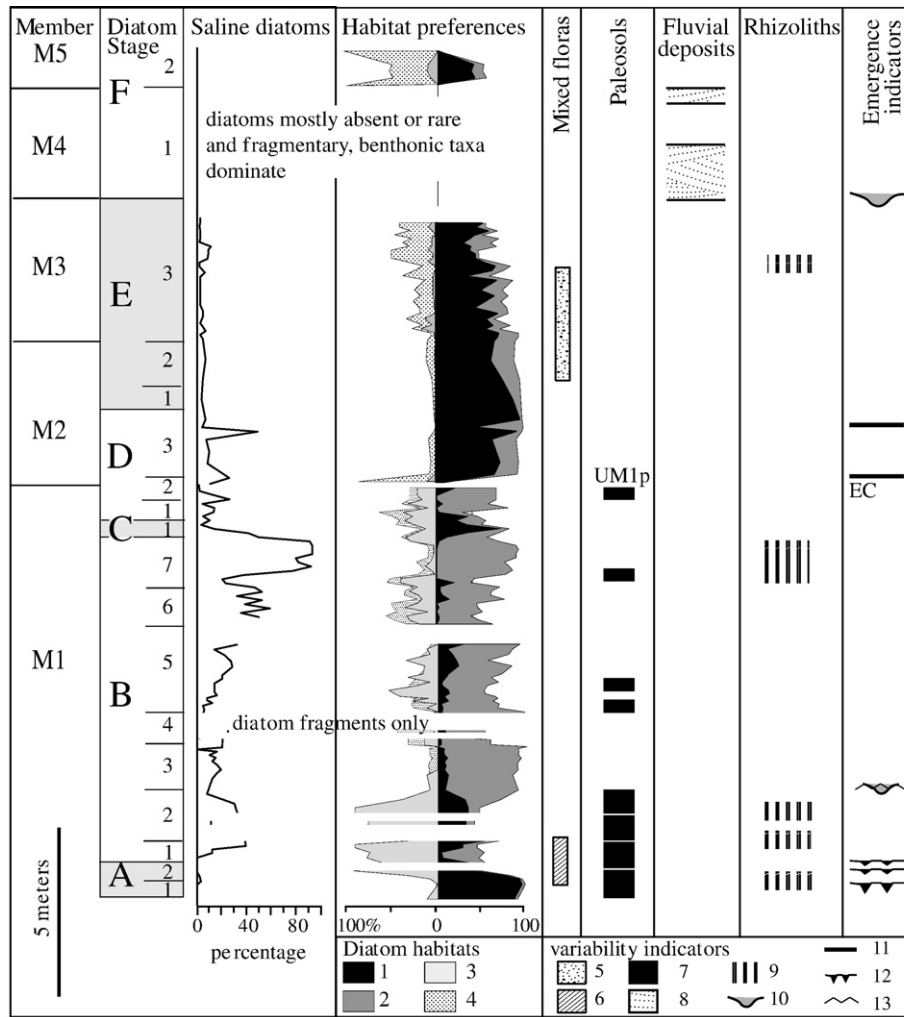


Fig. 12. Environmental variability in Members 1–5. Members, diatom stages, and the percentage of saline diatoms in the sediments are shown on the left. Habitat preferences reflect water depth, with benthic and epiphytic diatoms indicating shallower waters. Note that the longest period of more-or-less deep lacustrine conditions in M2–3 was less than 20 kyr. The five columns on the right show a variety of indicators of seasonality, pedogenesis, or emergence. Diatom habitat key: 1 – euplanktonic; 2 – facultative planktonic; 3 – epiphytic; 4 – other benthonic taxa. Variability indicators: 5 – mixed *Aulacoseira*/*Stephanodiscus* floras; 6 – mixed *Thalassiosira*/*Aulacoseira* floras; 7 – paleosols/pedogenesis; 8 – fluvial deposits; 9 – rhizoliths; 10 – minor channels; 11 – carbonate horizons; 12 – mudcracks; 13 – erosional hiatus.

and soil formation. Sediments at the top of F4 are reddened. Elsewhere in the Ologresailie basin such alteration has been attributed to the effects of fire and combustion metamorphism where intense drying leads to underground combustion of accumulated plant matter and high-temperature sediment baking (Melson and Potts, 2002). The presence of at least three such reddened intervals in M8 appears to indicate strong environmental variability characterized by both arid and moist episodes.

Diatoms are absent or fragmentary in sediments that formed during Stage F6. Unsourced cross-bedded channel gravels (near the base of M9 in Section A97/02, Fig. 3) suggest the development of streams and sediment reworking at this level in Locality A. In Locality C (C7/14 and other unsampled sections), the deposits consist of tuffaceous silts and clay-rich paleosols with no evidence for channeling. Diatoms are rare or fragmentary in Stage F7, which is dominated by benthic taxa (*E. adnata*, *E. sorex*, *C. muelleri*, *R. gibberula* and *Gomphonema intricatum*) and *A. granulata* suggesting shallow fresh, swamps. Moderate pedogenic alteration of the sediments that formed during this stage indicates subaerial exposure and a possible cause for the fragmentation.

The floras in Stage G1 initially were comprised of *Amphora ovalis* var. *libyca* and several other diatoms indicative of shallow conditions. These give way to an assemblage dominated by *A. granulata* var. *valida*, which is gradually replaced upwards by benthic and littoral spe-

cies. The diatom sequence indicates a lake expansion followed by gradual shallowing. Transfer data indicate fresh to slightly saline conditions (Fig. 11). This period of deposition was terminated by an influx of ash (at the top of M9 and into M10) and by pumiceous sands and gravels laid down in a fluvial setting (Stage H1). A diatomaceous interval within M10 (A91/01; Figs. 3 and 9) is dominated by infrequent to moderately common shallow-water diatoms.

Stage I includes highly variable floras and several pedogenic horizons. Stage I1 is characterized by frequent changes in the diatom abundance, the degree of fragmentation, and the dominant species. Benthic taxa are common throughout, with planktonic diatoms (mainly *Aulacoseira* spp.) forming a major component of the floras at several levels. Individual species vary considerably; *A. agassizi*, *A. granulata*, *C. placentula*, *C. muelleri*, *E. argus*, or *S. ulna* comprise >20% of the assemblages at various horizons. A reedy lake margin with fluctuating lake levels could account for the assemblages and their variability. At times a mosaic of fresh to saline wetlands might have formed, with periodic emergence taking place, leading to paleosol development. The transfer data suggest that the aquatic settings varied from fresh to moderately saline, with conductivities of 200–7000 $\mu\text{S cm}^{-1}$ and pH of 7.8–9.9. A major emergent period, implied by the development of a paleosol on sediments that lack diatoms at the top of M11', terminated this phase in the basin evolution.

Aquatic deposition was reestablished during Stage I2. The floras were dominated by *Cyclotella* spp. that often occur in the plankton of fresh to moderately saline, shallow, water bodies. Benthic diatoms (*Epithemia* spp. and *C. placentula*) are also present, but scarce, suggesting that littoral influences and macrophytes were minimal. *Thalassiosira* spp. form a minor component. The assemblages indicate variable water chemistry with conductivities ranging between about 1000–16,000 $\mu\text{S cm}^{-1}$.

Stage I3 is characterized by a major increase in benthic species, suggesting shallow water. *A. granulata* var. *angustissima* appears, and there are increases in *C. muelleri* and both *Epithemia* and *Synedra* taxa. *Thalassiosira* continues to vary through the sequence, and is common at several levels. This appears to indicate a shallow, reedy, lake or wetland, with the water chemistry varying during deposition (conductivity: 1000–16,000 $\mu\text{S cm}^{-1}$; pH: 8.2–10). It may therefore represent the margins of a saline lake or swamp.

Aulacoseira spp., mainly *A. granulata*, dominate Stage J1. *Thalassiosira* spp. are rare and benthic diatoms are less common than in the lower units. The flora indicates fresher (conductivity: ca. 300 $\mu\text{S cm}^{-1}$; pH: 7.8–8.2), deeper waters. Pedogenesis terminated this aquatic phase prior to deposition of the M12 sediments that comprise Stage J2, where the diatoms are dominated by a variety of benthic taxa suggestive of shallow, relatively freshwater.

5.2. Sediment classification and diatom assemblage preservation

Owen (2002) pointed out that some sediments in the East African rift have been erroneously described as diatomaceous even when no diatoms are present and that there is no agreed definition on the meaning of the terms “diatomaceous” or “diatomite”. In order to clarify the actual diatom content in rift sediments, Owen (2002) suggested the use of the terms: diatomite; siliciclastic or tuffaceous diatomite; sub-diatomite; diatomitic; and diatom-poor sediments. These were strictly defined based on diatom content, determined from laboratory analysis. Table 2 shows the percentage of each of these lithologies that contribute to the sediments at the sections examined in this paper. The data show a tendency for field-based studies to overestimate diatom content, a general problem in many investigations of diatomaceous deposits in East Africa. Identification of light-colored, low-density, powdery sediment as “diatomaceous” thus should be provisional until tested with microscopic examination.

The diatoms in the deposits are derived from living floras. However, their accumulation within sediments is also the result of a variety of processes that control deposition and preservation (Owen, 2002). Differential dissolution can, for example, cause significant changes in assemblage compositions (Schrader, 1971; Barker, 1992; Legesse et al., 2002). This may take place within the water column during sinking (especially in very deep lakes), or after burial where alkaline pore waters occur. The Ologresailie floras show minor effects of dissolution, except where there are saline indicator species present. However, this is largely confined to the weakly silicified parts of diatoms. Furthermore, horizons that may have been subject to such effects often also

contain relatively delicate diatoms, suggesting that, in most cases, they are still representative of the original taphocenose.

Bias in diatom reconstructions can also result from fragmentation. In some cases, the broken frustules probably reflect reworked extraneous diatoms that have been introduced into the sediments by water action or in some cases possibly by eolian transport. Several horizons at Ologresailie contain angular clasts of diatomaceous sediments within a diatomaceous matrix. These may have resulted from fluvial or wave erosion of previously lithified diatomaceous deposits exposed in the lake catchment; alternatively these clasts may be the result of bioturbation (e.g., by large vertebrates) or wind-induced re-suspension of consolidated lake floor sediments. Long thin taxa (e.g. some *Synedra* and *Nitzschia* spp.) are more susceptible to breakage. Other relatively robust diatoms (e.g. *A. granulata*) resist fragmentation and consequently can be overestimated during diatom counts. At Ologresailie, this does seem to be a problem for *Synedra*, which are rarely intact. Consequently, caution is required with such data as the fragmentation might imply that they were transported or reworked from other depositional environments.

Diatom fragments, for example, are common together with intact diatoms in much of C91/04R (lower M1), where some horizons also contain partially corroded taxa (e.g. *Cyclotella* in Stage B3; see above). This may be due to transport and mixing with diatoms at the depositional site or bioturbation in soils, which would tend to produce more uniform fragmentation. In spite of this, successive horizons remain floristically distinctive enough to yield clear environmental signals in many of the beds. These signals are derived from precursor lacustrine or wetlands environments which were the original source of the sediments – probably nearby or in situ. Although this complicates interpretations, it provides a good example of why diatomaceous strata cannot always be interpreted as lakes and why sedimentological features need also to be considered.

In a few parts of the Ologresailie Formation, mixing of different environmental signals occurs in the same units, for example when saline indicator species (e.g. *A. phaerophora*) are found together with fresh-water diatoms (*Aulacoseira* spp.). In other horizons, low silica indicators, such as *S. astraea*, occur with taxa favored by higher silica concentrations. Such effects can result from seasonal or longer term environmental changes, followed by mixing in the sediment substrate (Owen, 2002). Density differences between lake water and river inflows may also generate bottom currents or overflows that can combine diatoms with different ecological preferences. In some cases, mixing can take place in stratified lakes, when diatoms living in fresher, less dense, surface layers sink and mingle with floras inhabiting more saline bottom water.

5.3. Time and sedimentary facies in the stratigraphic sequence

The Ologresailie Formation sediments were deposited in a variety of environments (Table 1). These included shallow to deep lacustrine settings, in which laminated and massive diatomites and siliciclastic/tuffaceous diatomites were laid down in generally fresh-water bodies. According to our laboratory reanalysis of diatom content (Table 2), both

Table 2

Lithology frequencies within the Ologresailie Formation, based on sections analyzed in this paper. The table shows data from field-based descriptions and contrasts these with smear-slide analyses. There is no strict equivalence between the two systems, but note the tendency to overestimate diatom content – a problem encountered with many field studies in the East African Rift. Data refer to the percentage of the sediment succession occupied by each lithology and are rounded off

Smear slides (terms after Owen, 2002) Percent of sequence	Diatomite (>90% diatoms)	Siliciclastic and tuffaceous diatomites (>70–90%)	Subdiatomite (>50–70%)	Diatomitic Sediments (>10–50%)	Diatom-poor sediments (<10%)	Non-diatomaceous (0%)
	11	23	6	30	24	6
Field-based terms Percent of sequence	Diatomite	Silty, tuffaceous and clayey diatomites	Diatomaceous silts	Clay and clay-rich paleosols	Tuffs (no diatom content implied)	Sands and granules (no diatom content implied)
	26	30	29	11	1	3

types of diatomite lithologies account for about 34% of the total sampled stratigraphic sequence studied. A variety of sedimentation rates have been suggested for pure diatomites. In southern Lake Malawi, at least 8 m of diatomite was laid down during the last 6000 years (Owen and Crossley, 1992), indicating a minimum accumulation rate of 1.3 m kyr^{-1} . Bonnadonna (1965) suggested a rate of 0.95 m kyr^{-1} for an Italian Pleistocene deposit. Previous studies at Olorgesailie have inferred rates of $0.8\text{--}2.0 \text{ m kyr}^{-1}$ for the various lithologies in the basin (Isaac, 1977; Potts et al., 1999).

Diatomitic sediments and subdiatomites are common, accounting for about 34% of the sequence. These deposits are quite varied in texture and sedimentary structures, and formed in lake margins and littoral settings, or in wetlands, such as spring and/or stream fed marshes and swamps. Many of these water bodies would have been ephemeral, with fluctuating water levels and periodic episodes of total drying out. Given equivalent accommodation space for sediments to accumulate, deposition rates for diatomites mixed with other siliciclastics and tuffs may have been faster than for purer diatomaceous lithologies. Sedimentation rates for deposits with similar diatom contents elsewhere have been estimated at 3.3 m kyr^{-1} for Holocene silts at Lake Turkana (Owen, 1981), 1.9 m kyr^{-1} for diatomaceous silts in Lake Manyara (Holdship, 1976), and $2\text{--}3 \text{ m kyr}^{-1}$ for deposits in Lake Naivasha (Richardson and Richardson, 1972). Sedimentary intervals with mixed diatomaceous and siliciclastic/volcanic components would also reflect more complex processes of deposition, reworking, and erosion, i.e., landscape complexity, compared with the relatively homogeneous intervals of lacustrine diatomite deposition.

Diatom poor and non-diatomaceous sediments account for about 30% of the succession and were formed in shallow wetlands, fluvial, and subaerial settings. Accumulation rates for these deposits are difficult to assess, but probably involve long periods with little active deposition as well as phases of erosion. Much of the half-million year time span represented by the Olorgesailie Formation probably is represented in the intervals of soil formation and also in minor disconformities that formed during phases of subaerial exposure (Potts et al., 1999; Behrensmeier et al., 2002). When soils form on emergent diatomaceous sediments, diatom floral records may be lost through dissolution and/or fragmentation during pedogenesis. In many cases, however, at least a partial record of the precursor environment is preserved. Several of the paleosols in the Olorgesailie Formation appear to have developed on sediments with shallow water, swampy, diatom indicators. In contrast, a long period of landscape stability in upper M7 is marked by a clay-rich paleosol and a subsequent period of low-relief erosion, which together take up the majority of time ($\sim 190 \text{ kyr}$) between 974 ka and the Brunhes/Matuyama magnetostratigraphic boundary (780–790 ka). In some cases paleosols (e.g. UM1p) can be traced laterally for several kilometers and serve as marker horizons (Potts et al., 1999). Paleosols and less obvious pedogenically modified sediments are important as indicators of shallowing or subaerial emergence bounding stratigraphic intervals of deeper, more continuous aquatic deposition. Many of these pedogenically altered horizons provide evidence for the drier portions of climatic cycles of varying duration and intensity, but they are not always easy to detect when only minor pedogenesis has occurred. This recognition problem would be especially difficult when dealing with drill core records, which lack the lateral continuity of outcrops that can help to identify soil horizons in the field.

Although major down-cutting episodes of more than $\sim 5 \text{ m}$ are unknown within the Olorgesailie Formation, minor erosional hiatuses do occur and provide additional evidence of changes in aquatic and land habitats and overall base level. Documented hiatuses include minor erosion at the bases of M4 and M10 prior to the deposition of pumiceous sands, localized channeling of M5 prior to deposition of lower M7 (M6/7), local erosion of the clay-rich paleosol capping M7,

and a partially erosional boundary between M8 and M9. There also were several meters of local down-cutting by channels in upper M11' in the western Locality A, associated with faulting along the eastern margin of a small horst known as "Lava Hump."

5.4. Implications for early hominins

A critical paleoanthropological issue, yet one seldom examined, concerns the sources of fresh drinking water to diurnal hominin groups that ranged over many kilometers to obtain food and stone toolmaking material. Our analysis of lake size and chemistry over a period of roughly 400 kyr, when Acheulean handaxe-makers were attracted to the Olorgesailie basin, raises the question of how the availability of fresh lake water might have governed the presence of hominins and their level of activity in the basin.

In the case of cattle and horses, water in the range $8000\text{--}11,000 \mu\text{S cm}^{-1}$ has been considered marginally drinkable with safety (EPA, 1972; Ayers and Westcot, 1976). Tolerance can apparently be higher, especially where Na and Cl are not the dominant ions. Livestock and pastoralists in desert regions routinely drink water with conductivities of $>5000 \mu\text{S/cm}$ and considerably higher depending on the actual ionic composition and habituation (Mike Lane, personal communication; Faillace and Faillace, 1986–87). By contrast, the U.S. Environmental Protection Agency places the upper boundary standard for potable water consumption at about $700 \mu\text{S cm}^{-1}$, with tolerances at approximately 4 \times that level (<http://www.nm.nrcs.usda.gov/technical/tech-notes/Water/water10.doc>). Although such a standard of salinity and total dissolved solids certainly need not have applied to earlier humans, conductivity of $<2800 \mu\text{S cm}^{-1}$ provides a general heuristic for fresh drinking water against which estimates of lake water conductivity for the Olorgesailie sequence can be evaluated.

Hominins were not subject to modern "standards", but at high concentrations physiological problems potentially start to develop. Fluoride, for example, is often high in East African springs, rivers and lakes (Kilham and Hecky, 1973; Owen et al., 2008) and is known to cause biological difficulties. Modern rift lakes are characterized by a variety of fresh to highly saline conditions. Antelopes, crocodiles, and hippopotamus make use of saline-alkaline water in Lake Turkana (ca. $2500\text{--}3300 \mu\text{S cm}^{-1}$), with local people preferring springs and both hand-dug and natural wells for their main water resources (Ministry of Livestock Development, 1991; UNICEF, 2006). In contrast, the waters of Lake Abiyata, Ethiopia (ca. $12,400\text{--}30,000 \mu\text{S cm}^{-1}$; Legesse et al., 2002), are beyond the tolerance limits of large aquatic animals, with crocodiles and hippopotamus preferring rivers and springs in the region. Flamingoes show a greater tolerance, living in both Lake Abiyata and Lake Bogoria (ca. $45,000 \mu\text{S cm}^{-1}$). In these circumstances, spring and river fed wetlands are of greater importance to mammal species and may, therefore, influence the distribution patterns and migration routes of large animals. Gereta and Wolanski (1998) and Gereta et al. (2005), for example, have pointed out the importance of water quality and wetland development for animal movements in the Serengeti and Tarangire National Parks (Tanzania).

Based on the long history of archeological studies at Olorgesailie, several stratigraphic intervals are known to exhibit rich artefact records that are indicative of concentrated activity by Acheulean toolmakers (Fig. 11). Those intervals are lower and upper M1, lower M7, possibly upper M10, and lower M11. Periods of rare and more scattered artefacts suggest that there were other times when hominins only occasionally passed through the basin and/or exploited the food and water resources available there. These intervals include: middle M1, M4, M5, upper M7, M8, M9, upper M11, and M12. By using artefact abundance and spatial concentration as general indicators of the level of hominin activity, we assume that the degree of stone curation (i.e., the probability of artefact discard) was broadly equivalent for a given overall level and duration of activity by the toolmakers within the basin. This seems a safe assumption given that Mt. Olorgesailie and the surrounding volcanic highlands,

which were present at all times, consistently provided suitable rock sources for making stone tools and were located only 0.5 to 5.0 km from the ancient lowland deposits that preserve archeological sites. These local volcanic outcrops comprise >95% of the rocks that make up the artefact assemblages throughout the Olorgesailie Formation.

One complicating factor in using stone artifacts as an indicator of the presence of hominins is that fresh lake water associated with a relatively deep lake sometimes involved a lake so expansive — as is evident in M2 and M3 — that no land-based deposits that might preserve archeological material are available in the exposed sedimentary deposits. Thus the absence of hominin artefacts during the deposition of these two members provides no useful information as to whether hominins were attracted to the relatively freshwater of upper M2 and M3 times, with estimated conductivity generally <2000 $\mu\text{S cm}^{-1}$.

Nonetheless, intervals of low salinity/conductivity (C values) are evident in other members. The following sections outline the fresh-water periods and matches them against the archeological evidence for each member (for $^{40}\text{Ar}/^{39}\text{Ar}$ age control points, see Fig. 2). The deepest, freshest-water lakes of Member 1 are represented by Diatom Zones A1 ($C < 500 \mu\text{S cm}^{-1}$) and C1 ($C = 200\text{--}1000 \mu\text{S cm}^{-1}$). Hominin artefacts occur, but are generally rare, except in a few horizons associated with drying out and/or pedogenesis. For example, numerous stone tools are present near the base of Stage B3 (Fig. 11). They rest on an erosional hiatus and are associated with pedogenically altered sediments that contain saline diatoms, suggesting emergence from a mildly saline, shallow-water body. Similarly, the well-developed paleosol in Upper Member 1 (UM1p) contains a rich archeological record. This interval is associated with a substantial contraction or disappearance of the lake and wetlands, at least from the area represented by the Olorgesailie Formation exposures, and the establishment of plentiful C_4 vegetation and aridity-adapted, open-country fauna within the basin (Potts et al., 1999; Sikes et al., 1999).

Members 2 and 3 were laid down during one of the major intervals of lake deposition in the Olorgesailie region, initially high conductivity ($C = 3000\text{--}18,000 \mu\text{S cm}^{-1}$) gave way to more consistently fresh-water conditions ($C = 200\text{--}2000 \mu\text{S cm}^{-1}$). However, land records are unavailable in the exposures of this stratigraphic interval.

A low to moderate abundance of stone tools is associated with Member 4 sands that filled localized channels after a substantial drop in base level and, presumably, lake size. No data are available relevant to lake conductivity. In the overlying Member 5 there is a low to moderate abundance of stone tools that were associated with a period of a fresh-water wetland ($C = 300 \mu\text{S cm}^{-1}$).

Member 6/7 is unsampled in the sections we have selected so far for diatom analysis. These sections are in areas where stone tools are very abundant and densely concentrated in fluvial sands of lower M7; these represent a landscape of shallow channels that were filled during a period of overall lower base level, and presumably lake levels, compared with M5 times. A partial cranium assigned to *Homo cf. erectus* also occurs at this level (Potts et al., 2004). At the top of M7, low levels of hominin activity are reflected by scarce archeological material in a major paleosol, after which there is an erosional hiatus; both soil and hiatus together represent a duration of >190 kyr (Potts et al., 1999). No data relevant to lake/wetland conductivity are available for either the channel-filling or soil formation intervals of M6/7.

Estimates of conductivity throughout Member 8 are <1000 $\mu\text{S cm}^{-1}$, typically <600 $\mu\text{S cm}^{-1}$, and they reflect swampy to open water conditions. A low background abundance of artefacts occurs throughout this part of the sequence, with only one known minor artefact concentration, which comes from near the base of M8. Diatoms from the middle of M9 indicate an interval of fresh-water wetland ($C \sim 400 \mu\text{S cm}^{-1}$) followed by conductivity estimates of 800–3000 $\mu\text{S cm}^{-1}$. This interval is characterized archeologically by a very low level of evidence for hominin activity and no significant artefact concentrations.

Member 10 was predominantly a fluvial period. Artefact abundance increases and evidence of hominin activity includes at least one substantial stone tool concentration, based on an unexcavated surface artefact accumulation. Hominins were moderately active during deposition of the upper part of M10. Locally, in Section A91/01, there is evidence of an ephemeral, fresh and shallow-water body.

Stone tools are present at low densities in lower Member 11, which was characterized by oscillating aquatic-pedogenic phases (Fig. 12: Diatom Zone I1), with tools becoming strongly concentrated in sandy deposits at the top of this stratigraphic interval. Conductivity of the water bodies represented by Diatom Zone I1 varies widely ($C = 200\text{--}7000 \mu\text{S cm}^{-1}$). In middle M11, conductivity ranges from 1000 to 16,000 $\mu\text{S cm}^{-1}$, and stone artefacts are absent (Diatom Zones I2 and I3). In uppermost M11 (Diatom Zone J1), where the diatoms suggest a moderately deep, fresh-water lake ($C = 300 \mu\text{S cm}^{-1}$), spatially dispersed artefacts have been found in several parts of the basin. The youngest member examined (M12) contains only rare artefacts in a context that suggests a shallow, moderately fresh lake ($C = 2000 \mu\text{S cm}^{-1}$).

The results of this comparison suggest that hominin toolmakers were not especially dependent on lake and wetland waters for obtaining fresh drinking water. Not surprisingly, the most active times of artefact deposition broadly correspond with periods of lake contraction, emergent landscapes, and fluvial deposition. However, a firm correlation between hominin resource utilization and such periods of lake regression is problematic because these are also times when the accumulating sediments would provide the best chance of preserving stone tools in the stratigraphic record. Based on our conductivity estimates, the times of freshest water (lowest conductivity) seem to correspond to periods when hominin activity was sparse — consistent with the toolmakers either passing through the region or having only a modest attraction to the lake margins, and, in some intervals (e.g., M2 and M3), consistent with the lack of subaerial deposits where an archeological record would be preserved. Some support for the interpretation that hominins were not using the resources provided by expanded lakes comes from a prior observation that such resources (e.g., fish) were not a focus of hominin feeding/foraging behavior at Olorgesailie (Potts et al., 1999). Streams feeding into the lakes or wetlands and any other concentration of runoff into ponds at higher elevations may have been more critical sources of drinking water. Such sources of freshwater may have attracted hominins to the basin primarily during wet seasons of the year. During drier periods hominins might also have made use of elephant scrapes or springs.

5.5. Environmental variability and hominin evolution

Several hypotheses have been suggested concerning environmental conditions that may have driven human evolution (Potts, 2007). Some ideas imply that long periods of consistent selection within a particular habitat are required. The savanna hypothesis, for example, suggests that bipedalism developed in response to a sustained expansion of grasslands. More recently, evolution has been linked to repeated episodes of environmental change (Potts, 1998). According to this variability selection hypothesis, temporally variable conditions result in the replacement of habitat specific adaptations by evolutionary trends that increased hominin versatility (e.g., bipedalism, greater intelligence, increasing social complexity) and allowed flexible responses to complex and shifting environments.

The driving force for variability selection is environmental instability. The development of rift environments has involved a complex interplay between tectonism, volcanism and climate (Behrensmeier et al., 2002). Separating their relative influence on sedimentation can be difficult. Trauth et al. (2005), for example, used the simultaneous formation of deep lakes in different drainage basins to suggest that there were three “high moisture phases” at about 2.7–2.5, 1.9–1.7, and between 1.1–0.9 Ma. The evidence for these wet periods is

derived from sediments in the Asal and Abhe basins in Ethiopia, from the Koobi Fora (Lake Turkana) and Kariandusi (Central Kenya Rift) basins, and also from the Ologesailie Formation.

From the perspective of hominin evolution it is important to know whether these were lakes that remained broadly stable for long periods (favoring long-term stability in selection), or were water bodies that expanded and contracted over short time scales, which would imply greater environmental instability and thus conditions potentially favorable to variability selection. Deino et al. (2006), for example, report that diatomites in the Chemeron Formation (west of Lake Baringo) formed during five depositional cycles that occurred between 2.66 and 2.54 m.y. ago (the first “wet” period noted above) at precessional intervals of 23 ka. Trauth et al. (2005) made use of sediments at Ologesailie in recognizing the third of their high moisture phases, noting that the most important lake period was between 0.992 and 0.974 Ma. The majority of M1 through M5 formed during this period. An understanding of the degree of stability of the lake/s during this interval is important for assessing potential selection forces that acted on local hominin populations at that time.

Fig. 12 shows a detailed series of environmental indicators for Members 1–5. The data indicate considerable environmental instability with both wetter and drier periods, contradicting the proposed period of lake stability and wet climatic conditions (Trauth et al., 2005). The proportions of benthic versus planktonic diatoms reflect water depth and are highly variable through the sequence, with deeper water taxa dominating through M2. Saline diatoms suggest fluctuating water conductivities and imply periods of strong evaporation, particularly through M1 and lower M2. Freshwater and saline diatoms occur together in the lower part of M1, which might reflect seasonal changes between wetter and drier periods, or a lake that periodically became stratified with freshwater near-surface diatoms sinking and mixing with diatoms associated with deeper more saline layers. Seasonality may also be indicated by the co-occurrence of diatoms favored by low and high silica concentrations in parts of M2–M3. Paleosols such as UM1p (Fig. 12), and other pedogenically altered horizons, indicate times when the lakes and wetlands retreated or dried out completely. In Locality A, for example, the laterally extensive UM1p soil developed on sediments with swampy diatom floras (units 4LFB and 4MF; see Potts et al., 1999) that gave way to more saline conditions (4LFA) before drying out for a prolonged period. The presence of carbonate rhizoliths indicates either very shallow water or soils fed by calcium-rich groundwater, and further implies episodes of lake retreat. The EC marker bed and other carbonate horizons, the presence of mudcracks and shallow channels also reflect emergent phases. A significant drop in base level is represented by the M4 sands/gravels, although this might be a response to tectonic controls rather than a shift in climate. In sum, these varied lines of evidence indicate considerable environmental complexity through a relatively short period of about 20,000 years (Potts et al., 1999), a time span over which sub-orbital cycles of climate change, rather than tectonics, are likely to have been the major control on lake chemistry and sediment deposition.

Members 1–5 and other parts of the Ologesailie Formation developed in a complex and varied mosaic of habitats that changed through time at frequent intervals. Drier periods alternated with wetter phases. Fresh-water lakes and swamps developed, became more saline, and dried out only to return again. The hominins that inhabited this area of the rift valley during Ologesailie Formation time would have experienced substantial environmental shifts over hundreds to thousands of years, as well as seasonal and decadal fluctuations, rather than environmental stability as implied by interpreting the diatomite record as a sustained “high moisture” phase between 1.1 and 0.9 Ma.

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