MULTI-PROXY RECORDS OF HOLOCENE CLIMATE AND VEGETATION CHANGE FROM ETHIOPIAN CRATER LAKES

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ABSTRACT

The sediments of Ethiopian crater lakes have differentially sensitive palaeoclimate indicators that vary with time. Lake Tilo, in the south-central Rift Valley, shows a 10,000-year diatom and oxygen-isotope sequence that may be interpreted in terms of hydrochemical and hydrological responses to century-scale climate changes. The diatom record of lake salinity became sensitive to climate variability only after a sharp reduction in hydrothermal inflow at 5500 ^{14}C yrs BP. In contrast, the oxygen isotope composition of the lake as recorded by authigenic calcite varied in response to early Holocene climatic change despite the hydrothermal influence and became especially sensitive to climate variability after hydrothermal flow diminished. Pollen data from the same core show savanna vegetation throughout the Holocene, indicating that strong rainfall seasonality has long been characteristic of the region. Deposits of aragonite varves in Lake Hora, a crater lake on the western margin of the Rift Valley, may reveal climate variability at annual to decadal timescales. Because the aragonite is precipitated during dry-season mixing, aragonite δ^{18}O values for individual white laminae reflect the composition of the entire lake integrated over its water-residence time of about ten years. Nevertheless, the high-resolution varve chronology presents an opportunity for calibrating the isotopic record against instrumental climate data, provided that the climatic controls on the isotopic composition of these groundwater-fed lakes are fully understood.

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INTRODUCTION

Crater lakes are attractive sites for palaeoclimatic research because of their small surface catchments, simple basin morphology and rapid sediment accumulation. They have a relatively uniform size and shape, in contrast to the varied morphology of other lake types, which makes it easier to compare sedimentary records between sites and minimises differences in lake sensitivity to climate change. They are sometimes thought of as giant rain gauges, filling up in periods of high rainfall and evaporating to shallow, saline conditions during drought intervals (e.g. Williams *et al.* 1998, 162). However, many crater lakes have significant groundwater inflows and outflows, and all are affected by volcanic and hydrothermal activity at some time in their history.

In this paper, I summarise the results of multi-proxy palaeoenvironmental investigations of two crater lakes in Ethiopia, Lake Tilo and Lake Hora (Telford and Lamb 1999; Lamb *et al.* 2000; in press). Lake Tilo, in the south-central Rift Valley, has small hot springs at its margins. The sedimentary record from this lake shows that hydrothermal flow from the springs has had a variable influence on lake salinity and hydrology, making it more difficult to reconstruct past climate from the palaeolimnological data. Lake Hora, at higher elevation on the western margin of the Rift Valley, has no significant hydrothermal influence at present. Laminations in the surface sediments of Lake Hora provide an opportunity to obtain a high-resolution record of climate variability calibrated against instrumental climate data for the last 100 years.

Previous palaeoclimatic research in Ethiopia has been based on shorelines and sediments of the larger Rift Valley lakes, which are fed by rivers flowing from the adjacent uplands. Street (1979) and Gillespie *et al.* (1983) traced Holocene shorelines of the Ziway–Shalla lakes, showing that they formed a single lake during early Holocene highstands and overflowed northwards into the Awash River, terminating in the closed lakes of the Afar triangle in the northeast of the country. The Ziway–Shalla and the Afar lakes (Gasse and Street 1978) show evidence for dramatic depth changes, notably at about 7500 ^{14}C yrs BP (8200 cal yrs BP), when an abrupt and short-lived 120m drop in water level occurred, and at 4500 ^{14}C yrs BP, when the lakes fell permanently to near their modern levels. Similar evidence for an arid interval during the generally moist early Holocene is now well documented from many sites in northern Africa and western Asia (Gasse and van Campo 1994; Lamb *et al.* 1995). Most current hypotheses about the cause of this event involve a temporary halt in the northward transfer of heat by the Atlantic circulation, reducing the ocean–continent temperature and pressure gradients and dampening the intensity of the African monsoon (Street-Perrott and Perrott 1990). Tests of these hypotheses require precise information about the timing of the arid event, which is more readily obtainable from continuous core records than from shoreline data. We chose to examine sediment cores from crater lakes rather than from the larger structural Rift Valley lakes, where patterns of sediment deposition are likely to be complex and the problems of core recovery more acute. The modern climate of Ethiopia is strongly seasonal, with heavy rainfall of Atlantic origin during May to September preceded by a shorter episode of lighter spring rains. The dry season is from October to January. Seasonal temperature variation is negligible in comparison to diurnal temperature variation, which is especially marked at higher altitudes during the dry season.

LAKE TILO

Lake Tilo lies within a maar formed by explosive release of volcanically heated water below the Rift Valley floor (Lorenz 1986). It is one of three adjacent craters lying at an elevation of 1545m near the western edge of the Rift Valley in south central Ethiopia (Fig. 1, Pl. I). The area around the site is now occupied by farming communities that grow maize and tef (*Eragrostis tef*, an indigenous cereal) and tend cattle. This cultivated land replaced semi-natural savanna vegetation very recently, within the memory of the oldest inhabitants. Afro-montane forest is present on the adjacent uplands, including *Podocarpus falcatus*, the principal pollen-producing tree species. Lacustrine marls with abundant freshwater molluscs and ostracods are evident on the crater walls, 40–60m above the present lake surface. The lake has a maximum depth of 10m and is saline and dark brown in colour; the hot springs are relatively dilute. Estimates of the hydrological and salinity budgets for the lake (Telford and Lamb 1999) suggest that the springs account for only twelve per cent of water inflows to the lake (Fig. 2a), but sixty-seven per cent of the solute inflows, the remaining thirty-three percent of the solute inflows being derived from the surface catchment via overland flow. If the lake were to fill the crater, as it apparently did in the early Holocene, the catchment area would be reduced to near zero, so that almost all solutes entering the lake would be from the hot springs. The mineral sediments, including carbonates and diatom silica, are thus principally derived from solutes in the hot springs and their accumulation rates may be interpreted as a record of hydrothermal inflow.

CORE STRATIGRAPHY, CHRONOLOGY AND SEDIMENT ACCUMULATION RATES

We obtained 23m-long duplicate cores using a Livingstone piston sampler from a raft at the lake centre at a depth of 10m. Coarse tephra layers caused difficulty during the coring operation and may have prevented recovery of deeper sediments. The cores may be divided into three lithological units, numbered from the base upwards. Unit TL-1 (2330–800cm) is a calcite-rich diatomite, unit TL-2 (800–345cm) is similar but with a higher organic content and unit TL-3 (345–0cm) is composed of millimetre-scale laminations of variable thickness and colour, with a high organic content and high but variable magnetic susceptibility values. The cores cover almost the entire Holocene, according to a chronology based on 11 AMS radiocarbon dates for grass charcoal fragments (Table 1) and adjusted for rapid deposition of tephra layers. Some of the charcoal retains epidermal characters such as micro-hairs, indicating that they entered the lake via airfall following savanna fires and are not redeposited from older sediments. Above 800cm, dated to 5500 ^{14}C yrs BP, there is a sharp fall in the sediment accumulation rate (Fig. 3). This occurred 1000 years before the nearby Ziway–Shalla lake levels fell in response to a permanently drier climate, so the two events are probably unrelated. A possible explanation for the sudden decline in sedimentation rate could be that a minor tectonic event diverted hydrothermal pathways away from the crater, reducing the flow of the hot springs and diminishing the rate of solute incorporation into the mineral sediments.

DIATOM AND OXYGEN ISOTOPE STRATIGRAPHY

Diatom analysis of the cores shows that unit TL-1 is dominated by *Aulocoseira granulata*, indicating a deep, eutrophic and well-mixed freshwater lake (Fig. 4). Above 800cm (5500 ^{14}C yrs BP), *Aulocoseira* is replaced by *Cyclotella stelligera*, also a freshwater species, but one that has lower nutrient requirements. This change therefore supports the interpretation of a reduction in hydrothermal solute flux to the lake at 5500 ^{14}C yrs BP. *Cyclotella* in turn gives way to a series of halophilous taxa, indicating progressive salinization of the lake in the drier climate since 4500 ^{14}C yrs BP. The absence of a depth or salinity response to the arid interval at about 7500 ^{14}C yrs BP (Gasse and Street 1978; Gillespie *et al.* 1983) is probably because strong hydrothermal inflows kept the lake full to overflowing despite reduced rainfall (Fig. 2b).

Plate I—Lake Tilo. The trees include *Acacia* (with beehive), *Combretum*, and *Cordia*.

Plate II—Lake Hora, Debre Zeit.

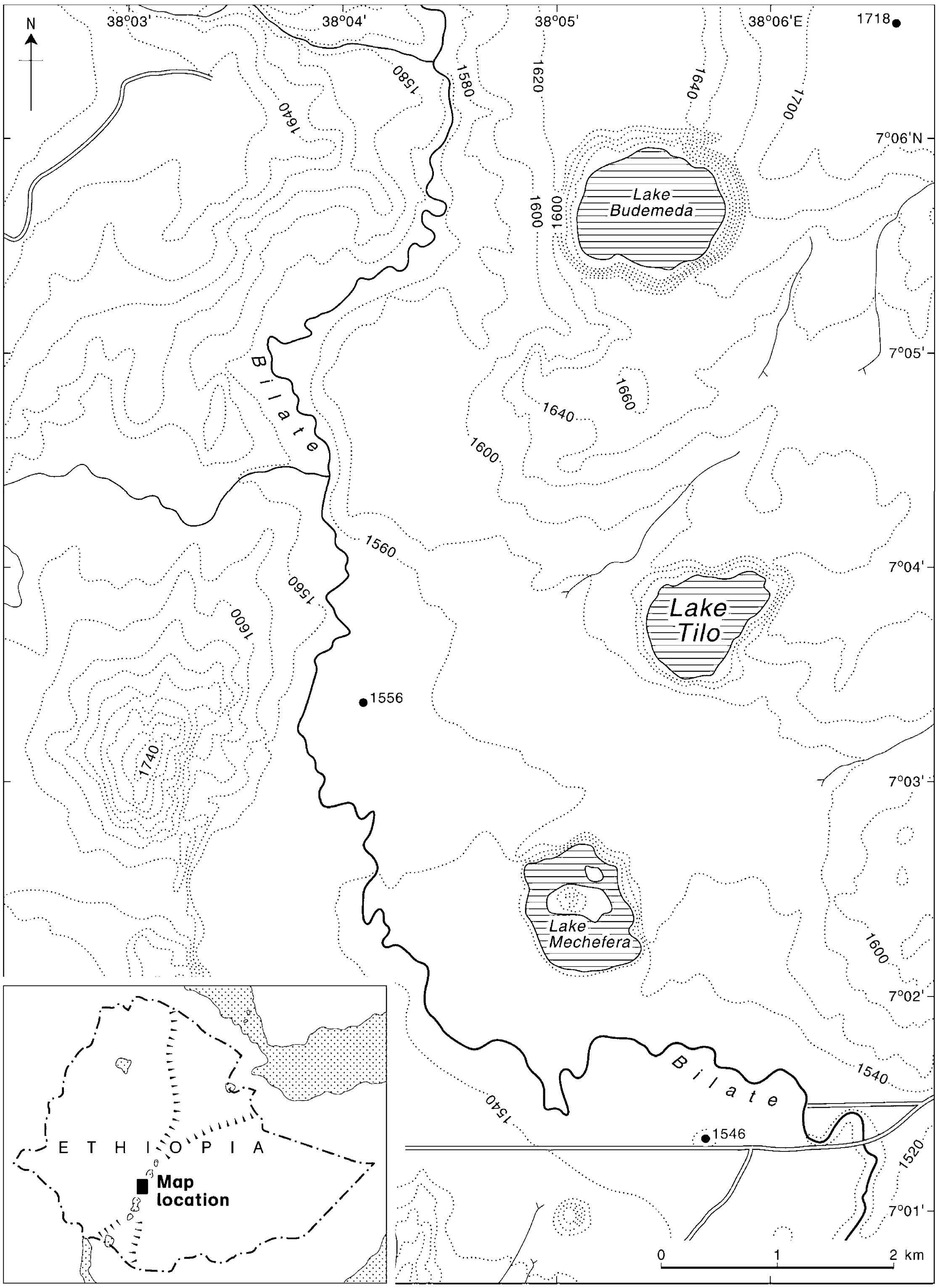

Fig. 1—Map of Lake Tilo and adjacent crater lakes in the Rift Valley of Ethiopia.

Oxygen isotope values for authigenic calcite can be interpreted as a record of evaporative concentration of the lake water. In this semi-arid environment, the effects of water source and temperature are relatively insignificant (Talbot 1990). The isotope stratigraphy shows generally stable values throughout unit TL-1, increasing values after 5500 ^{14}C yrs BP and an unusually wide range

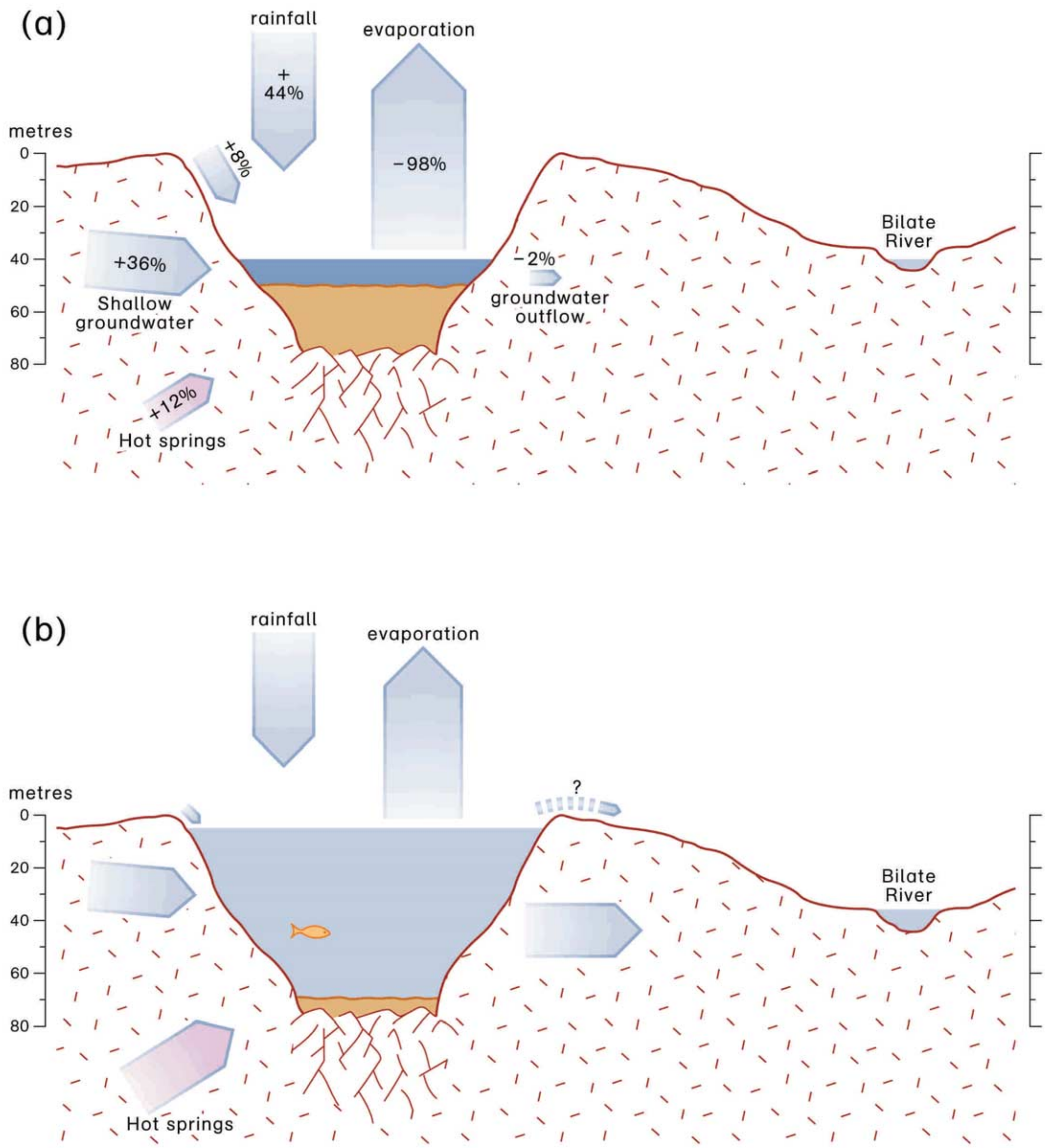

Fig. 2—Schematic summary of the hydrology of Lake Tilo, comparing (a) modern and (b) reconstructed early Holocene conditions.

Table 1—AMS radiocarbon-dated charcoal samples from the Lake Tilo core.

Sample depth (cm from sediment surface)	*Laboratory number*	*$\delta^{13}C$ PDB (‰)*	*Age (^{14}C yr B.P. $\pm 1\sigma$)*	*Age (cal. yr B.P.)*	*Age range (cal. yr B.P. $\pm 1\sigma$)*
174–186	Beta-106145	−15.9	1390 ± 50	1290	1330–1270
341–353	Beta-106146	−15.9	2400 ± 50	2430	2490–2340
592–597	Beta-106147	−19.1	4140 ± 60	4670	4810–4560
802–806	Beta-90886	−18.1	5520 ± 80	6320	6410–6210
1287–1292	Beta-106148	−17.3	6880 ± 50	7660	7710–7620
1762–1766	Beta-90887	−21.1	7930 ± 90	8740	8950–8580
2314–2319	Beta-106149	−15.6	8840 ± 50	9850	9920–9680

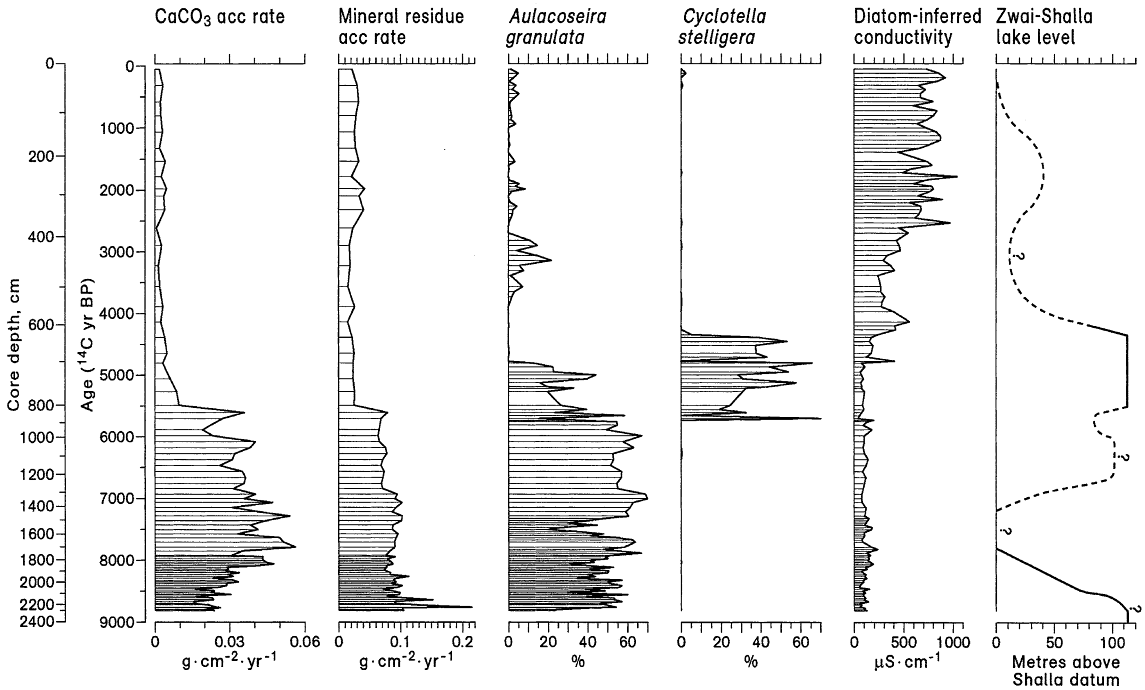

Fig. 3—Mineral accumulation rates and lakewater conductivity from the Lake Tilo core and comparison with the Ziway–Shalla lake-level curve (Gillespie *et al*. 1983). Conductivity is inferred from the diatom stratigraphy, using the transfer function of Gasse *et al*. (1995).

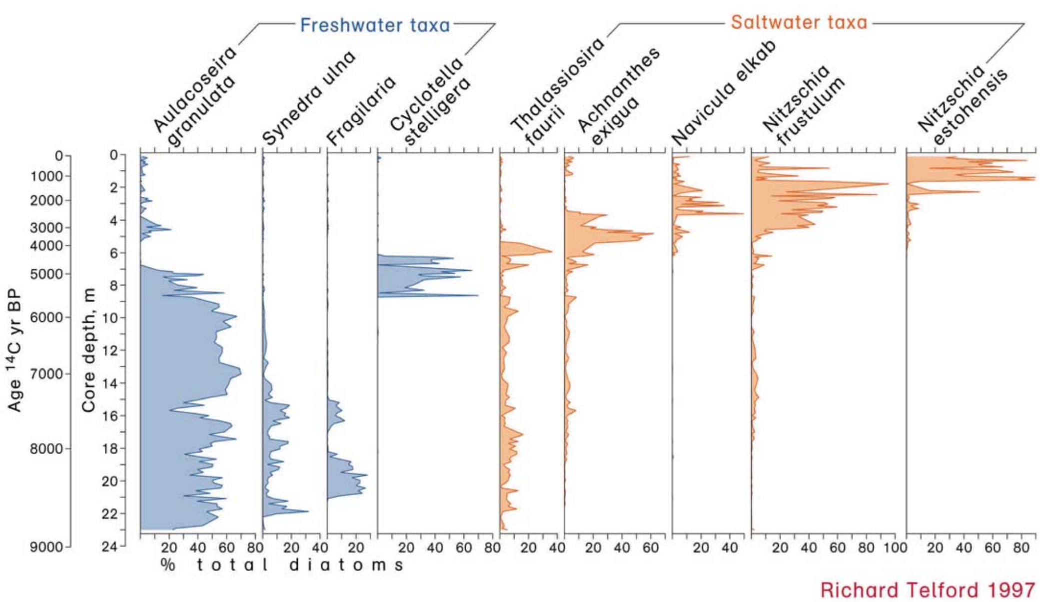

Fig. 4—Summary diatom stratigraphy of the Lake Tilo core (Telford and Lamb 1999).

of values in unit TL-3 (Fig. 5). In contrast to the diatom record, $\delta^{18}O$ values show a peak at about 7800 ^{14}C yrs BP at about the time of the abrupt fall in the level of the adjacent Ziway–Shalla lakes (Gillespie *et al*. 1983), followed by increasing values that may indicate a trend of increasing aridity. Following the switch from hydrothermal to surface water dominance in the lake's hydrologic budget at 5500 ^{14}C yrs BP, more variable $\delta^{18}O$ values record greater climate sensitivity of the shallower lake. Highly variable $\delta^{18}O$ values in unit TL-3 may represent occasional dilution of the surface waters by intense monsoon rains followed by mixing with the dense, saline and

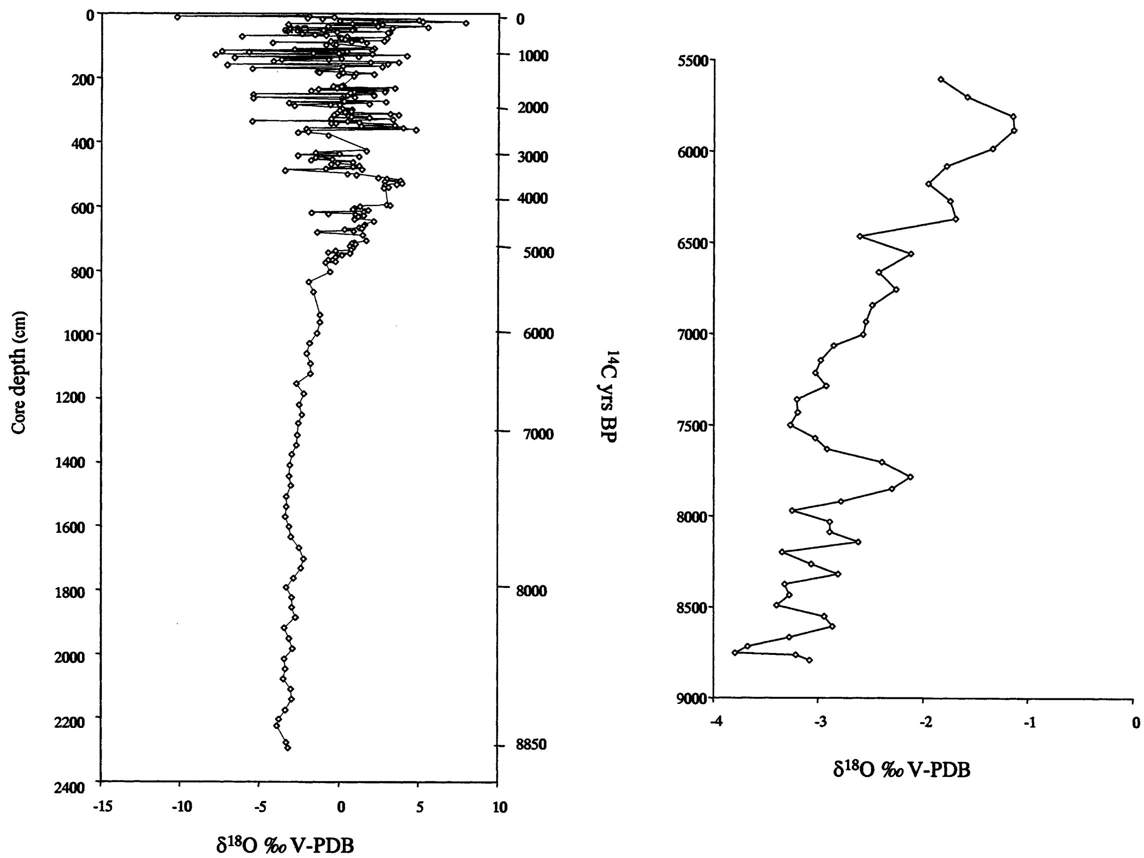

Fig. 5—Oxygen isotope stratigraphy of the Lake Tilo core. The completed record against depth scale is on the left, and data for the early mid-Holocene, with an expanded $\delta^{18}O$ scale on the *x*-axis, is on the right (after Lamb *et al.* 2000).

isotopically enriched hypolimnion (Lamb *et al.* 2000).

POLLEN STRATIGRAPHY

The abundance of Poaceae pollen throughout the Lake Tilo cores (Fig. 6) is evidence that savanna has been the dominant vegetation of the Rift Valley throughout the Holocene, despite the lake-level and palaeolimnological evidence for strong variations in the moisture regime. Savanna (the term encompasses a range of community types from grassland to woody scrub) is characteristic of a climate with marked rainfall seasonality, so the pollen record suggests that the Holocene climate of the area has always been characterised by contrasting wet and dry seasons. The presence of pollen of woody taxa, albeit at very low abundances due to their notoriously low pollen production and dispersal (Vincens *et al.* 2000), shows that the savanna included a higher proportion of trees and shrubs until about 7000 ^{14}C yrs BP. Moisture indicators, especially ferns and Urticaceae, were also present, supporting the palaeolimnological evidence for a wet early to mid-Holocene climate and suggesting that summer rainfall was higher than at present. The pollen record shows no vegetation response to the early Holocene arid interval that has been inferred from a fall in the level of the nearby Ziway–Shalla lakes (Gillespie *et al.* 1983). Nevertheless, higher relative abundance of *Hyparrhenia* epiderms and decreased abundance of other Panicoideae (Lamb *et al.*, in prep.) may be a reflection of arid conditions at this time. Decreasing *Myrica*, *Dodonaea*, Urticaceae and fern spores after about 7000 ^{14}C yrs BP suggest diminishing moisture availability, an interpretation that broadly fits the oxygen isotope record.

At 5500 ^{14}C yrs BP, when the palaeolimnological data show a reduction in hydrothermal inflow to the lake, ferns became rare, grasses increased and the diversity of woody species declined further. The change in lake hydrology was apparently unrelated to climate but probably resulted in a lowering of the lake level. Thus, the pollen stratigraphic change may be due to increased representation of local vegetation growing on the newly exposed crater margins. The apparent reduction in moisture indicated by a decline in ferns and woody taxa may have been a result of lower soil moisture associated with the fall in lake

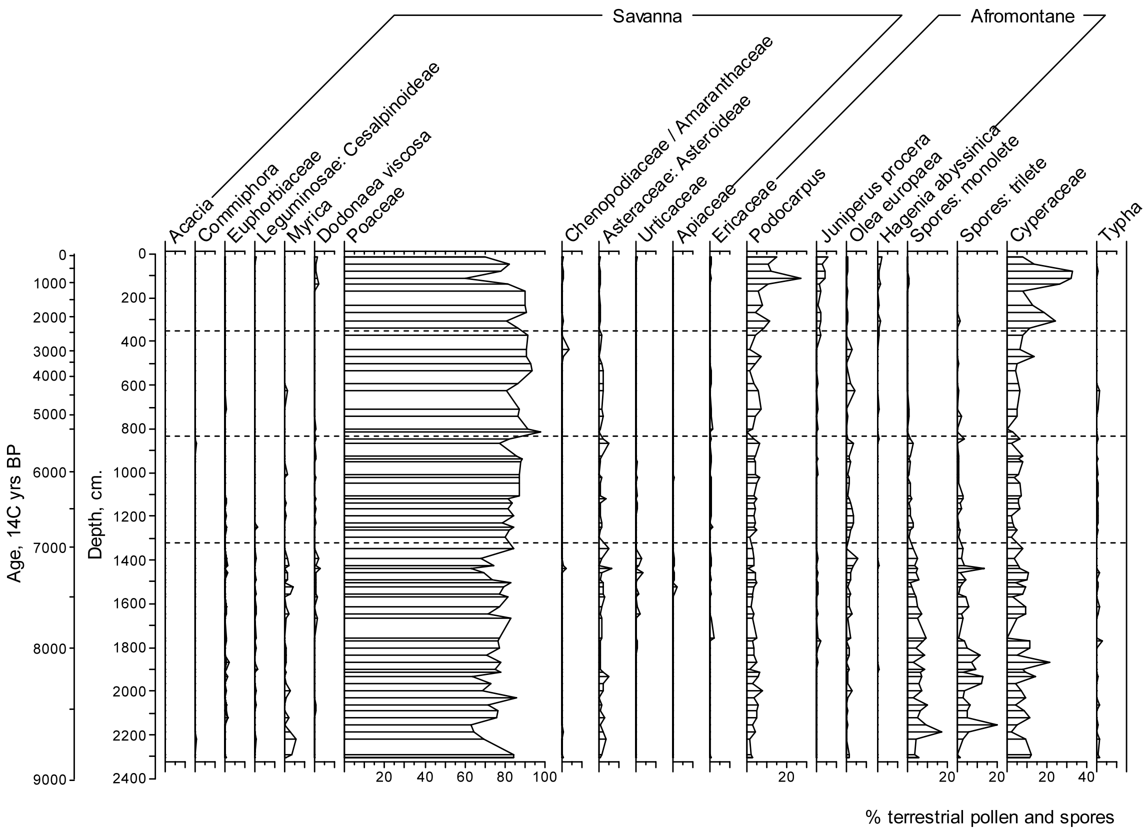

Fig. 6—Summary pollen stratigraphy of the Lake Tilo core, zoned according to the results of CONISS (Grimm 1987).

level. At *c.* 4500 ^{14}C yrs BP, Lake Tilo began to desiccate in the drier climatic regime, and its level probably fell further. However, the pollen record shows no marked vegetation response to this lasting climate change, just as it shows no response to the earlier, short-lived arid event. Only *Typha* disappears from the record, perhaps in response to a reduction in the littoral zone or increasing lake salinity. Among the grasses, *Hyparrhenia* abundance increased while other Panicoideae declined (unpublished grass epidermal data). A decrease in charcoal accumulation rates may indicate that grass biomass available for burning declined with the change to drier conditions.

The most distinct pollen-stratigraphic evidence for vegetation change from the Tilo record is dated to 2400 ^{14}C yrs BP. *Podocarpus*, *Juniperus* and *Hagenia* increased on the uplands on either side of the Rift Valley. A similar *Podocarpus* rise recorded at many sites in East Africa has been interpreted as a response to drier climate. Locally, sedges increased substantially, suggesting a further fall in lake level to expose marginal springs. Chloridoideae, *Themeda* and *Heteropogon* became more abundant (unpublished grass epidermal data); this may reflect the climate change or, because these grasses are more resistant to grazing and trampling than *Hyparrhenia*, may indicate human settlement and pastoralism in the area.

LAKE HORA

Lake Hora, one of five crater lakes at Debre Zeit at 1850–2000m altitude, is 45km southeast of Addis Ababa (Fig. 7, Pl. II). The lakes were first described geologically by Mohr (1961), who estimated their age as early Holocene. Their bathymetry and limnology were investigated in detail by Wood *et al.* (1976; 1984). Lake Hora, a double crater, has a maximum depth of 38m and is relatively fresh (conductivity 2235μS cm^{-1}). Its seasonal cycle of stratification and mixing is probably like that of nearby Lake Babogaya (Pawlo), which it most resembles hydrochemically. The lake stratifies during the February–October wet season, and mixes as a result of heat loss to clear night skies during the dry season. Groundwater flux was estimated by solving the hydrological and solute budgets for the lake simultaneously (Lamb *et al.* in press). Groundwater inflow represents about forty per cent of the total water inflow to Lake Hora, but only about three per cent of its water loss, the remainder being lost by evaporation. The lake water residence time is estimated to be about ten years. Isotopic analyses of water samples taken at approximately monthly intervals suggest that wet-season rainfall can cause significant dilution of the epilimnion. The immediate surrounds of the lake are semi-urban in character, with many planted

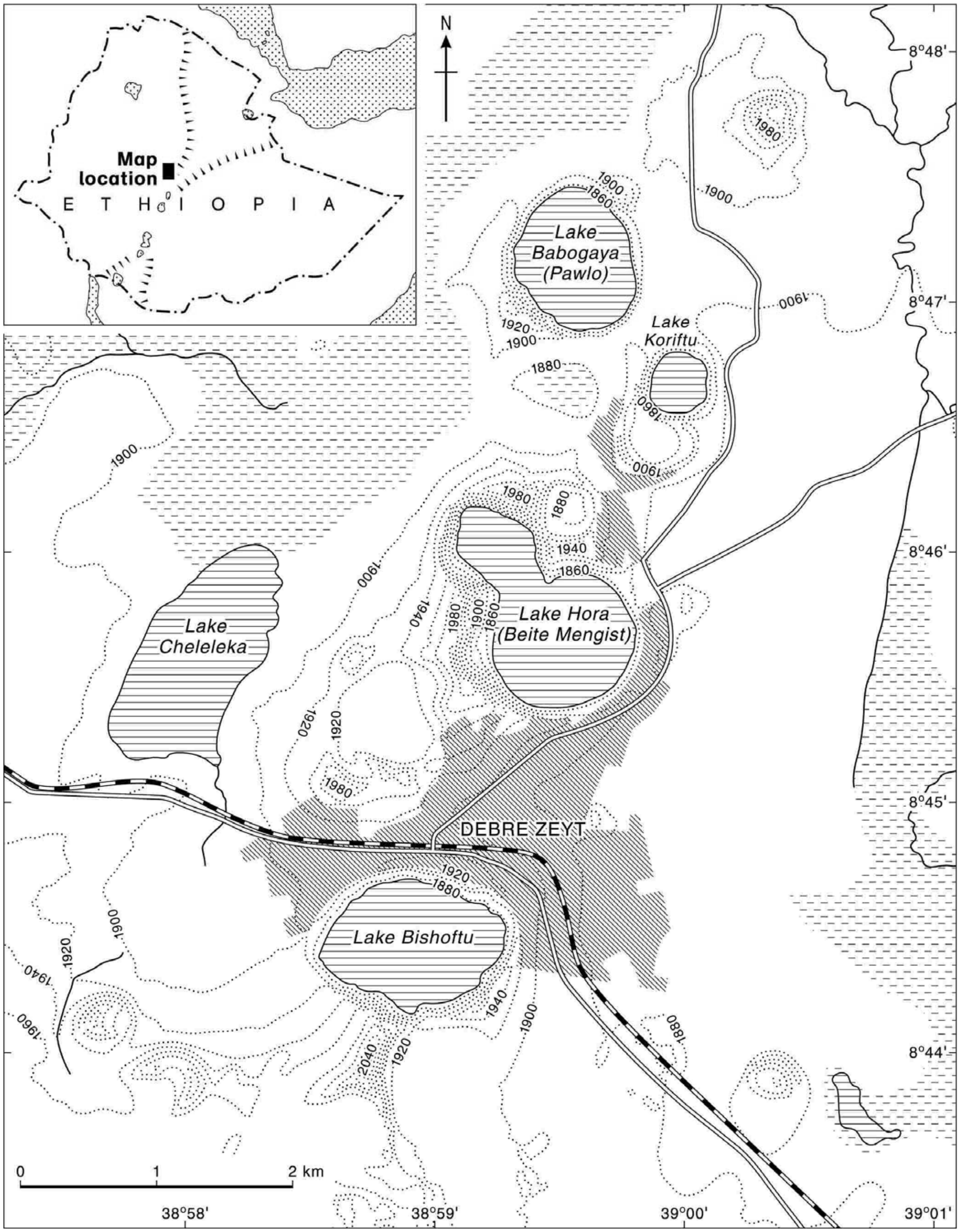

Fig. 7—Map of Debre Zeit, to show the location of Lake Hora.

and invasive exotics (e.g. *Eucalyptus*, *Casuarina*, *Schinus and Opuntia*). Cereal cultivation has entirely replaced the natural vegetation of the surrounding landscape, apart from high-altitude *Juniperus* forest on nearby mountains and *Dodonea* scrub with scattered *Hagenia* trees on their slopes.

Short surface cores of sediment from Lake Hora reveal alternating white carbonate and dark organic laminations very similar to the millimetre-scale calcite varves that are well known from temperate lakes (e.g. Lotter 1989). Scanning electron microscopy shows that the white laminae are composed of rice-grain-shaped crystals of aragonite rather than calcite. Both calcite and aragonite are precipitated from lake surface waters as a result of algal photosynthesis, but aragonite is characteristically formed in lakes with Mg:Ca ratios greater than 3 (Kelts and Hsu 1978). The laminations cannot be assumed to be varves because the seasonal pattern of variation in lake temperature and productivity is very different in this tropical environment. To determine their origin, we counted the laminae in freeze-dried sections of the surface cores, including the modern sediment surface, and compared the lamina counts to a ^{210}Pb chronology from the same sediments. A few pairs of closely set laminations were assigned to the same year because they may represent occasional breakdown of summer lake stratification, like that recorded in July–August 1966 (Wood *et al.* 1984). The sediment accumulation rate estimated from the lamina counts, assuming annual deposition, is 2.9 mm yr^{-1}, identical to that derived from the ^{210}Pb chronology (Lamb *et al.* in press); this indicates that the laminae are almost certainly deposited annually and may be interpreted as biochemical varves. The seasonal timing of lamina deposition is relevant to palaeoclimatic interpretation of their oxygen isotope composition (Fig. 8). If the white layers are formed when the lake is stratified, they represent surface water conditions for the wet season and could provide an annually resolved record of rainfall variation. If they are deposited during the dry season when the lake waters are mixed, aragonite δ^{18}O values for individual laminae reflect the composition of the entire lake integrated over its water-residence time of about ten years. Sediment trap studies may clarify the issue. However, $\delta^{18}O_{lakewater}$ values calculated for the dark-layer carbonates are consistently lower than those for the white layers and are especially low for the wet years 1964–7 (Fig. 8), suggesting that the dark layers are formed in the wet season when the surface waters are diluted by rainfall. Thus, the oxygen isotope values for individual white layers may represent a decadally smoothed record of the balance between precipitation to the lake and its supply aquifer and evaporation from the lake surface. To further explore the potential for a high-resolution palaeoclimatic record from isotopic analyses of the sedimentary carbonates, Lamb *et al.* (in press) applied an isotopic mass balance model of the lake. The results show that oxygen isotope composition of the lake varies by about 1‰, which is comparable to the range of δ^{18}O values determined from the laminae. Modelled lake level using the lamina-determined isotope values as input is a reasonable match to observed levels, confirming that climate variability can be interpreted from the isotopic record.

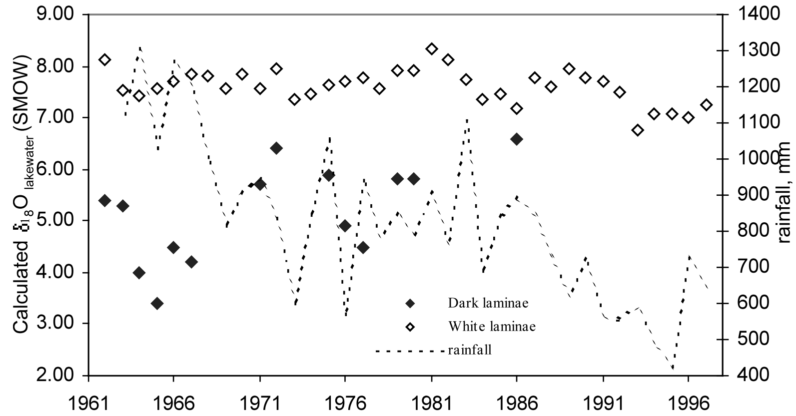

Fig. 8—Calculated $\delta^{18}O_{lakewater}$ from aragonite in dark and light layers of Lake Hora sediments, plotted against year of deposition and compared to mean annual rainfall. Dark-layer $\delta^{18}O_{lakewater}$ values are low for the years 1964–1967, which were years of exceptionally high rainfall. They may represent dilution of the epilimnion by rainfall during wet-season stratification.

DISCUSSION AND CONCLUSIONS

A lake's sensitivity to rainfall variation is dependent on the importance of precipitation and evaporation relative to the other components of its hydrological budget. Closed lakes with small surface catchments, including crater lakes, have simplified water balances because they have no surface outlets and catchment evaporation and runoff are minimal. However, unless contained by impermeable rock basins or perched above the groundwater table, such lakes generally have a proportionately higher groundwater influence than large lakes with extensive surface inflows. They can sometimes be thought of as windows in the water table, in which changes in lake depth and chemistry provide a measure of varying aquifer recharge by rainfall. Even in semi-arid areas, where lakes lose significant amounts of water by evaporation as well as by groundwater outflow, palaeoclimatic interpretation of the sedimentary record requires either the assumption that past groundwater fluxes were the same as those of the present or the use of a sedimentary indicator of groundwater inflow. For example, Ito *et al.* (1999) used calcium accumulation rate as a proxy for past variations in groundwater influx on the basis that all calcium entering the lake is precipitated to the sediments. Geologically young crater lakes in areas of active volcanism, like Lake Tilo, are especially prone to the influence of hydrothermal groundwater. Hydrothermal inflows may have a substantial effect on a lake's solute budget, despite being a relatively minor component of its water balance.

These considerations point to the importance of the 'multi-proxy' or multiple indicator approach to palaeoclimatic reconstruction because each indicator provides information about specific aspects of lake geochemistry and hydrology. In the case of Lake Tilo, mineral sediment accumulation rates provide evidence that hydrothermal inflow was relatively strong during the first 4500 years of the lake's recorded history, but then diminished abruptly, probably because local tectonic movement altered flow pathways. Variations in rainfall that took place before this event are not detectable in the diatom record because hydrothermal flux maintained the depth and conductivity of the lake. In contrast, lake-water oxygen isotope values recorded in the sedimentary carbonates show some variability that may be related either to the water balance of the lake or to the composition of water entering the hydrothermal aquifer, probably at higher altitudes on the Rift Valley margins. Thus lake hydrology recorded by oxygen isotope ratios appears to be more sensitive to climate variability than lake salinity recorded by the diatoms. After the switch to reduced hydrothermal flow, both the salinity and hydrology of the lake became more responsive to climate. The differential sensitivity of diatoms and oxygen isotopes remained; the oxygen isotope composition of surface waters appears to have varied widely in response to short-term variations in rainfall and evaporation, whereas lake salinity remained more constant. It is, however, difficult to judge the proportions of signal and noise in the oxygen isotope record, given that inflows from the hot springs probably continued to vary independently of climate. A comparison of the oxygen isotope and diatom records from Lake Tilo shows differences in timing that cannot readily be explained as differential response to the same climatic variations. As always, palaeoclimatic reconstructions require replicate records from several sites, which justifies further investigation of the lakes at Debre Zeit.

Palaeoclimatic data from the continental tropics, which have an important influence on global climate, can contribute to a better understanding of global and regional climate change. They may also go some way towards a resolution of local problems by providing information on the range and frequency of climatic extremes and their impact on natural resources, especially water availability. The record from Lake Tilo is relevant to understanding the causes of abrupt century-scale changes in the climate of the continental tropics because it facilitates comparison of their timing with marine core records of ocean temperature and circulation (e.g. von Rad *et al*. 1999). However, the Lake Tilo record is compromised in part by non-climatic hydrothermal influences. Similarly, the relatively insensitive pollen record of savanna response to climate makes it difficult to test alternative hypotheses for abrupt climate changes, such as negative feedback of land-surface albedo (Gasse and van Campo 1994), and makes it hard to judge the degree to which local vegetation was affected by past drought. In contrast, Lake Hora has the potential to provide a record of rainfall variability at timescales that have most relevance to local problems in Ethiopia, a country that is especially vulnerable to climatic extremes.

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Although rather distant both geographically and in subject material, the genesis of this paper is ultimately due to Bill Watts and his undergraduate field trip to Ballybetagh, Co Dublin! I can clearly remember breaking open a core at Ballybetagh and seeing perfectly preserved late-glacial willow leaves. That experience and later fieldwork with Bill in Florida sparked my enthusiasm for the subject and eventually led me, via Labrador and Morocco, to research in East Africa. I am immensely grateful to Bill for setting me off on this path. This paper draws heavily on work by my students and collaborators, especially Richard Telford, Angela Lamb, Mohammed Umer and Melanie Leng, to whom I am also indebted.

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