The Morphology and Genesis of Cold-Phase Diamicts in High Altitude Lake Sediments of Mount Kenya, Kenya

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ABSTRACT.
Lake sediment cores spanning the last interglacial-glacial-present interglacial cycle have been recovered from Sacred Lake and Lake Nkunga on the northeastern flank of Mount Kenya, Kenya. Within these cores are diamicts which occur at the last interglacial-glacial transition (*ca.*110,000 yr BP) and between 58,000 and 48,000 yr BP. The occurrence of the diamicts (formed by active freeze-thaw processes in the lake catchments) is associated with periglacial and concurrent relatively humid conditions at the altitudes of the lakes. In addition, their temporal occurrence is correlated with abrupt low temperature extremes and/or rapid transition rates to lower temperature regimes at high latitude regions. Close modern corollaries of such sediments have been documented at higher altitude on Mount Kenya, but there is no known documentation of such sediments in the late Quaternary records of the tropical high mountains.

Keywords: Lake sediments, Diamicts, Morphology, Genesis, Mount Kenya

INTRODUCTION

In this paper, the morphology, genesis and palaeoclimatic significance of diamicts occurring in late Quaternary lake sediments of Mount Kenya are discussed. Each of the two sediment cores here presented temporally span almost the whole of the late Quaternary period. The diamicts are recorded at the last interglacial-glacial transition and from 58,000 to 48,000 yr BP. There is no known previous documentation of such sediments within the late Quaternary sediment records heretofore recovered from lakes and swamps of the tropical high mountains.

Mt. Kenya is an extinct, heavily denuded volcano that lies on the equator at about 37°E. It lies within the East African climatic zone, and exhibits vegetation zonation of a similar type to that of the other highland regions of East Africa. Sacred Lake, a closed crater lake occupying a basaltic explosion crater *ca.*1km across, is located at 0°03'N, 37°32'E, at an altitude of 2,350m a.s.l. in the humid montane rain forest of Mt. Kenya, where the mean annual rainfall is *ca.*1,780mm (Fig.1). Lake Nkunga, a closed crater lake as well, is located at 0°07'N, 37°36'E , at an altitude of 1820m a.s.l. in the dry montane forest of Mt. Kenya, where mean annual rainfall is *ca.*1,020mm (Fig. 1).

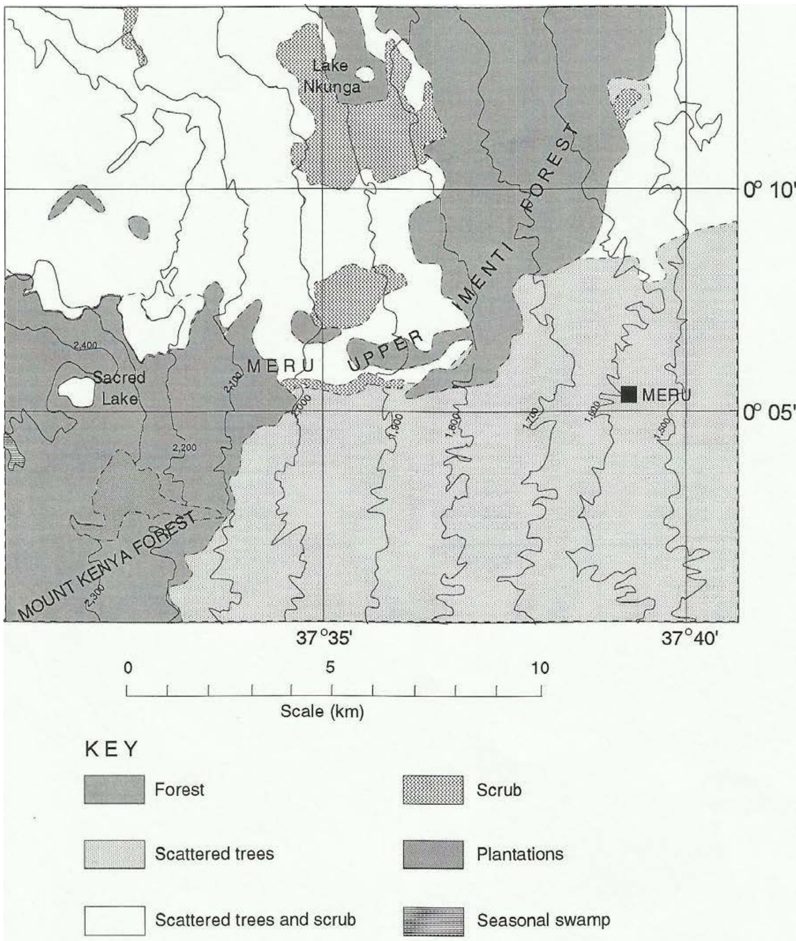


Figure 1. Location of Sacred Lake and Lake Nkunga on the northeastern flank of Mount Kenya, Kenya.

MATERIALS AND METHODS

The lake sediment cores were retrieved using a raft-mounted Livingstone corer. The Sacred Lake core (core SL1, 1634cm) was retrieved from a water depth of 2.5m, and the Lake Nkunga core (core NK1, 2120cm) at a water depth of 1.8m. Sacred Lake had a maximum depth of 5m at the time of coring, whilst Lake Nkunga had a maximum depth of 1.9m. The cores were described in the field, then wrapped in cling film, aluminium foil and sheet plastic, placed in hard plastic tubes, then shipped to the U.K. where they were put in cold storage (4°C) at the School of Geography, Oxford University. In the laboratory, the cores were sectioned longitudinally and described in detail prior to subsampling. The Munsell Colour Chart was used to classify the sediment colours. The diamict samples for thin-sectioning were initially vacuum-impregnated with resin prior to slicing, then ground to standard optical thickness using 600F carborundum powder with water as a lubricant. The slices were then resin-bonded to glass microscope slides and examined using a Zeiss petrological microscope. Conventional radiocarbon dating of the cores was carried out by D. Harkness at the NERC Radiocarbon Laboratory, Glasgow, Scotland. Accelerator Mass Spectrometry (AMS) radiocarbon dating was done at the Radiocarbon Accelerator Unit, Oxford. Experimental U/Th dating was done by M. Ivanovich at the Analytical Sciences Centre, UK Atomic Energy Authority, Harwell, Oxon. The Sacred Lake core chronology was established by a combination of a third order polynomial curve incorporating both the radiocarbon and experimental U/Th dates (1634 to 600cm) and an interpolated curve (600 to 0cm) [1]. Due to problematic dates, the chronology of the Lake Nkunga core NK1 was established by correlation with the Sacred Lake core SL1 using various sedimentological variables (Fig. 2) [1].

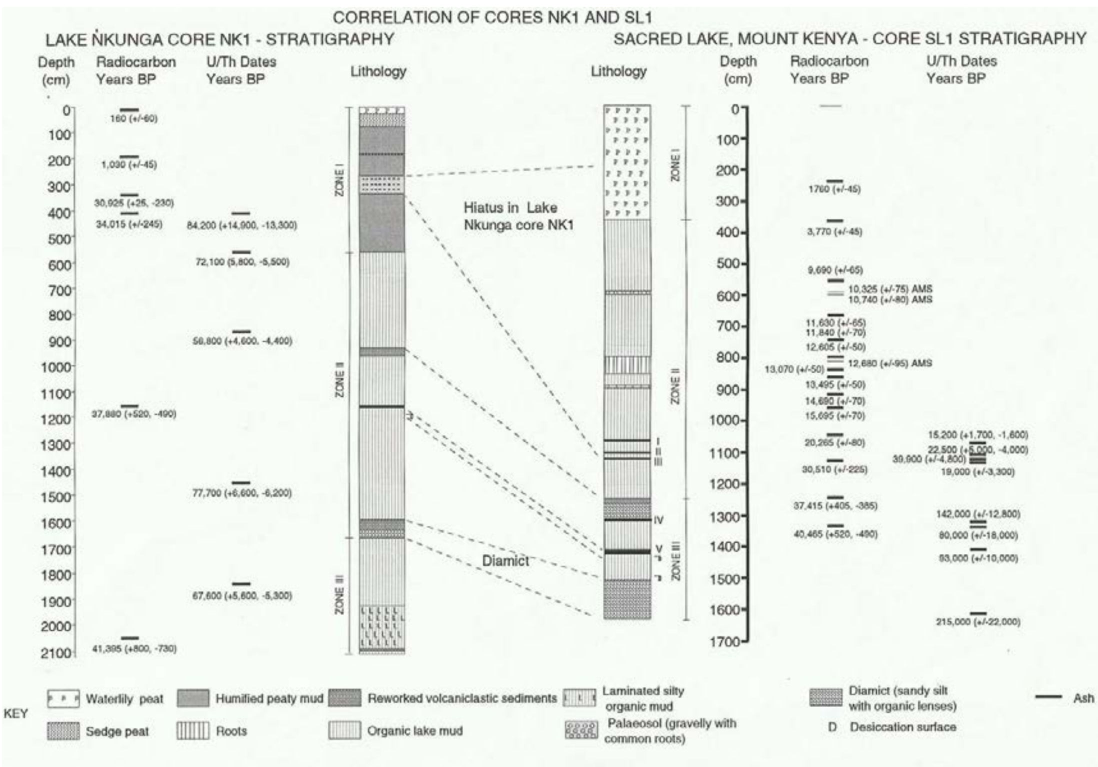


Figure 2. Stratigraphy, chronology and correlation of Sacred Lake core SL1 and Lake Nkunga core NK1.

RESULTS AND DISCUSSION

Sacred Lake Core SL1. The principal sedimentary units are: waterlily peat, organic lake mud, sandy silt with organic lenses, root mats, volcanic ashes and diamicts. Of these sedimentary units, the organic lake mud is by far the most dominant (Fig. 2). The sediments are carbonate-free, and are diatomaceous except between 806 and 221cm, where diatoms are rare or absent. Zone III (1634 to 1248cm) is characterized by diamicts and/or reworked volcaniclastic sediments at the bottom and top of the section - these sandwich an organic lake mud bed which contains a root mat and two tephra horizons (Fig. 2). Zone II (1248 to 371cm) consists of an extensive organic lake mud bed with relatively thin root mats and three tephra horizons (Fig. 2). Zone I (371 to 0cm) is dominated by a waterlily peat with varying proportions of plant macrofossils (Fig. 2).

Lake Nkunga Core NK1. The principal stratigraphic units in lake Nkunga are: waterlily peat, sedge peat, humified peaty mud, graded and laminated sandy to organic silt, organic lake mud, organic silt, and a gravelly palaeosol (Fig. 2). Plant macrofossils also occur within the diatom-rich sediment sequence, mainly in the upper sections. In Zone III (2020 to 1653cm), silty organic sediments, which are strongly laminated in the basal section of the core, are dominant. Zone II (1653 to 562cm) is dominated by a colour-banded organic lake mud bed (Fig. 2). Other units include: a diamict similar to those in the Sacred Lake core at the base of the zone (1653 to 1630cm), and an organic silt belt between 972 and 938cm. Zone I (562 to 0cm) is characterized by humified peaty mud containing abundant macrofossils (Fig. 2).

Diamict Macromorphology: Sacred Lake Core SL1. The basal diamicts (1634 to 1512cm) are heterogeneous sediments with no obvious textural attributes. The diamicts have a silty organic mud matrix (Munsell colour 10 YR 3/1) which contains clasts of sand-sized and gravel-sized (5 to 10mm) weathered pumice fragments as well as clasts of dark organic mud (10 YR 2/1) which span a wide range of sizes (1-2mm to 10-20mm). The clasts tend to be horizontally aligned, but sorting and bedding are lacking. Three subunits, recognized on the basis of changes in colour and textural attributes, occur in the sections: 1634 to 1544cm; 1540 to 1519cm; and 1519 to 1512cm. From 1319 to 1269cm occurs the second diamict bed which has a sharp lower boundary with the underlying ash IV (Fig. 2). Two subunits are recognized: 1319 to 1298cm and 1293 to 1269cm. The diamict at 1319 to 1298cm exhibits lenticular bedding: the lenses consist of dark organic matter (10 YR 3/1) embedded within a lighter-coloured matrix consisting of a mixture of organic and inorganic matter. Its upper boundary is sharp and curved with tiny flame structures. The diamict between 1293 and 1269cm (10 YR 4/2) is similar to that between 1319 and 1298cm. Separating these two diamicts is a smooth dark organic lake mud unit (1298 to 1293cm; 10 YR 2/1) with abrupt boundaries on either side (Fig. 2).

Diamict Macromorphology: Lake Nkunga Core NK1. The Lake Nkunga diamict is occurs at 1653 to 1630cm (Fig. 2). It is composed of a fine silty organic mud (10 YR 2/1) with several clasts of different composition and texture: fine silty mud clasts (2.5 Y 3/3 to 2.5 Y 4/3); fairly compact dark organic clasts (7.5 YR 1.7/1); hard, white pumiceous clasts (10 YR 8/1) of fine to coarse sand size range; and a granule-sized clast at 1648cm. There are common small, fine, fibrous roots. Within the diamict there is a wedge consisting of fine silty mud (2.5 Y 4/3) between 1644 and 1635cm. The wedge has fine interspersed lineations (measuring approximately 1cm in length) which run parallel to the slightly sloping upper boundary, and contains no roots.

Diamict Micromorphology. Microscopic examination reveals that the diamicts are highly organic. The Sacred Lake diamicts consist largely of horizontally-aligned, dark brown organic-rich and light brown organic-poor bands (Fig. 3(i)). There are also organic-rich lenses which are, largely, horizontally-oriented along their long axes, as well as dispersed microcrystalline glass and ferromagnesian minerals within the fine mud matrix (Fig. 3(i)). The light-brown colour of the sediments can be partly attributed to the presence of iron-oxides. The Lake Nkunga diamict, in contrast to the Sacred Lake diamicts, has random orientation of the organic clasts and the short root fibres dispersed within the sediment matrix (Fig. 3(ii)). Within the wedge, however, an indistinct lineation and flattening of the organic clasts is observed (Fig. 3(ii)).

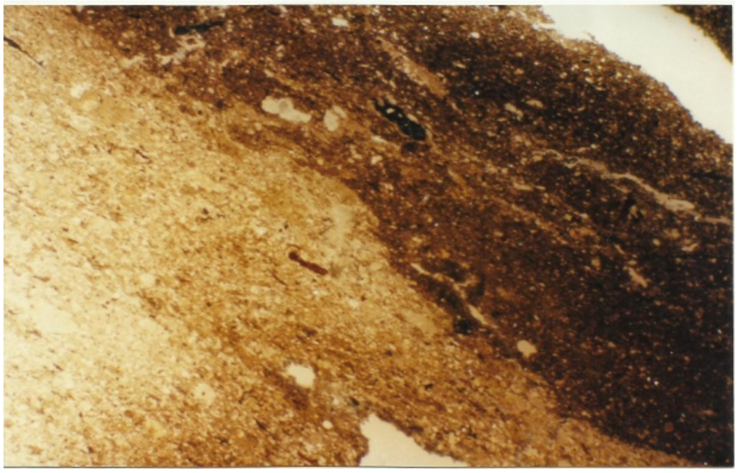
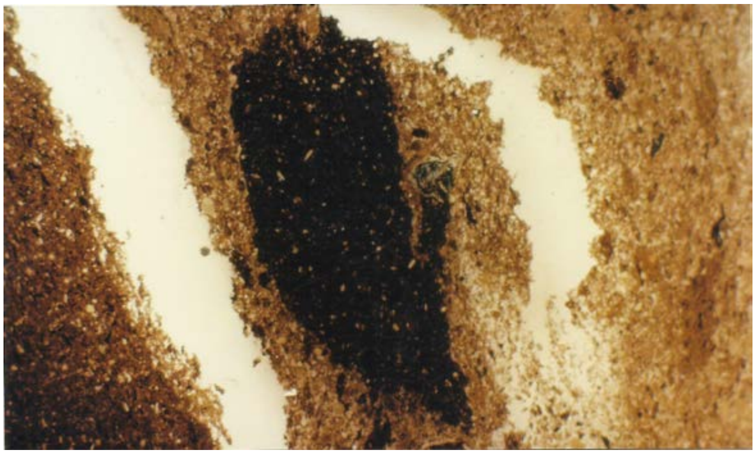


Figure 3(i) A - Thin section of the basal diamict in core SL1 showing microbands. The darker bands contain more organic matter than the lighter bands. The organic clasts (dark lenses) are more concentrated in the organic-rich bands (plane-polarised light; magnification - x25)



B - Thin section of the basal diamict in core SL1 showing a large, horizontally-aligned organic clast containing fine-grained detrital inclusions (plane polarised light; magnification - x25).

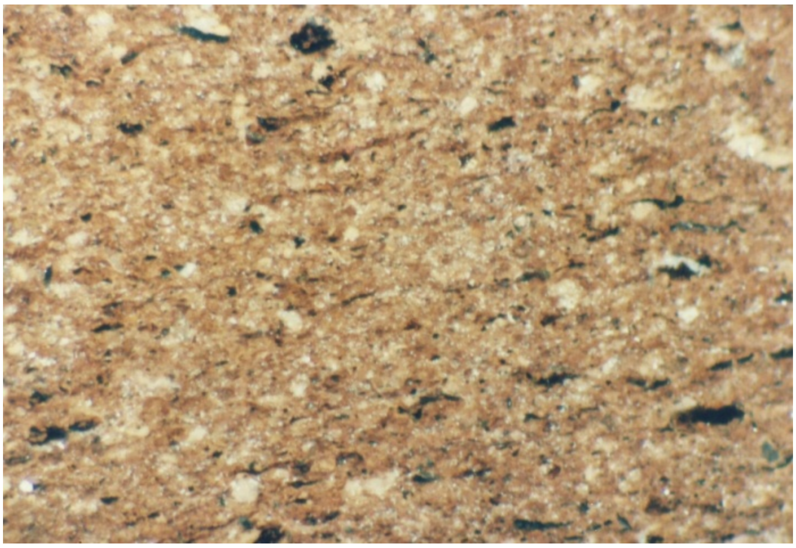
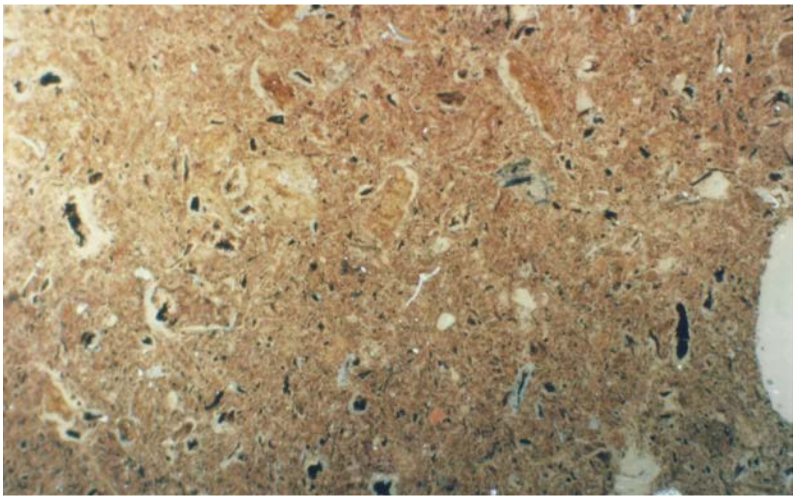


Figure 3(ii) A - Diamict in Lake Nkunga core NK1 containing randomly oriented clasts and short root fibres. B - Wedge within the diamict showing indistinct lineation of the organic clasts.



B - Wedge within the diamict showing indistinct lineation of the organic clas

Diamict Genesis and Palaeoclimatic Significance. The diamicts appear to be a mass movement feature of periglacial (cold) climates, forming under sporadic permafrost conditions (*cf.* [2]). It has been noted that several parameters facilitate the mass transport of sediments, and the most important of these parameters are the existence of slopes, water-saturated material, and deposits with a high content of silt or clay: these conditions commonly prevail in glacigenic areas [3], and were satisfied in the Sacred Lake and Lake Nkunga catchments. The diamicts were probably deposited in the lakes in a partially frozen state by temporally broad, episodic mass movement of sediment under periglacial conditions, hence the different subunits. The organic clasts occurring within the sediment matrix were probably formed by cryoturbation, prior to and during the mass movement of the sediment, leading to discrete aggregates of organic matter within the general sediment matrix, and/or by post-depositional, in situ mobilization and flocculation of fine suspended organic matter in relict `ice' cavities (formed within the diamict after deposition and thawing within the lake) as a result of increased salinity and ionic strength of the pore solutions due to the leaching of bases derived from the diamict (*cf.* [4]). The interspersed lineations in the wedge occurring in the Lake Nkunga diamict can be attributed to needle-ice (piprakes) formation.

`Mud channels' or `mud grooves' which tend to be frozen in the mornings, and are, on thawing, transformed to active mud flows during the afternoons, are today found at 4,500 to 4,700m altitude on Mount Kenya [5], where the annual mean minimum temperature is less than 6°C [6]. It was probably by this mechanism on a much larger scale that the diamicts were deposited within the lake. This would suggest that for such phenomena to occur at the Sacred Lake altitude - where the annual mean minimum temperature is 10 to 14°C [6] - annual mean minimum temperatures were depressed by at least about 5°C compared to the present day. However, given the large diurnal temperature variations which are one order of magnitude greater than the mean annual temperature variations in the equatorial tropics [7], mean annual temperature depressions need not have been lower than about 3°C. The important factor would be the condition that the night-time minimum temperatures were below 0°C for a sufficient number of hours to allow freezing of the upper soil layers. Humidity would also have to be relatively high. Although the diamicts themselves are believed to have been rapidly deposited within the lakes, the processes of diamict generation could conceivably have occurred over a much longer period. The diamict deposition phases can therefore be viewed as climatically cold but relatively humid periods, separated by slightly warmer stades when lowest diurnal temperatures were above freezing point at the altitudes of the lakes. These cold episodes could also be viewed as times of climatic instability or fairly rapid transition to lower temperature regimes without substantial concomitant water stress. The occurrence of diamicts in both Sacred Lake and Lake Nkunga at the last interglacial-glacial transition (*ca.*115,000 to 105,000 yr BP) indicate an intense lowering of temperature on the mountain. The diamict dated between 58,000 and 48,000 yr BP in Sacred Lake does not have a corollary in Lake Nkunga, suggesting that the temperature lowering may not have been quite as intense as at the last interglacial-glacial transition, and/or that conditions were comparatively less humid. These diamicts were formed at a time when low temperature extremes or sharp transitions to low temperatures are recorded at high latitudes, for example, in the Vostok ice core, temperatures were at least 6°C lower than present (*cf.* [8]). Glaciers on Mount Kenya may have undergone advances of fairly substantial magnitude. No diamicts were deposited during the last glacial maximum in these lakes, presumably due to: the aridity that prevailed at the time; low catchment productivity and pedogenesis; and, perhaps, a decrease in silt and clay-sized sediment availability.

CONCLUSIONS

The diamicts, as discussed above, have an important palaeoclimatic significance and are linked to global temperature changes. Due to their uniqueness, they can also be used as powerful tools for correlation of sedimentary deposits in the tropical high mountains. The non-documentation of such deposits in high altitude tropical regions can be related to the short temporal span (<40,000 yr) of most of the records so far studied, or to inadvertent omission (e.g. [9]) arising from a lack of detailed stratigraphical analysis of dominantly organic lake sediment sequences.

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