Ice core studies from Mt Kenya, Africa, and their relationship to other tropical ice core studies

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ABSTRACT   Mt Kenya, located at the Earth's equator, is one of the few tropical mountain areas in the world where glaciers exist today. Two ice cores to a depth of 13.4 and 11.4 m were retrieved from the col (4870 m) between the Lewis and Gregory glaciers. Microparticle, oxygen isotope and total β radioactivity analyses were conducted. The results of these measurements, as well as those from other tropical glaciers, indicate the lack of a clear relationship between $\delta^{18}O$ values and surface mean air temperature in tropical regions. In the few tropical areas where samples have been retrieved high particle concentrations tend to be correlative with high radioactivity. A comparison of the microparticles, oxygen isotopes and total β radioactivity for these limited areas is presented and their potential as palaeoclimatic indicators for low latitude glaciers is assessed.

INTRODUCTION

The tropics act as the firebox of the global energy system, yet tropical meteorological records are scarce and limited to recent decades. Therefore, the possible application of ice core techniques developed in polar regions to tropical glaciers merits particular attention. Moreover understanding the mechanisms producing these variations in microparticles, stable isotopes and total β radioactivity should facilitate better interpretation of these variations in polar regions.

Mt Kenya is one of three mountain regions in East Africa where glaciers exist today. The largest glaciers extend west and south of the highest crest. At present there are 12 small glaciers on Mt Kenya with a total area of 1.2 km². The largest of these, the Lewis Glacier (0.3 km²) has decreased steadily since the late 1800s (Hastenrath, 1975).

In February and March 1978, samples for detailed microparticle, oxygen isotope and total β radioactivity measurements were collected from two snow pits and associated cores drilled on the col (4870 m) between the Lewis and Gregory Glaciers. The location chosen for drilling was a small dome in the snowfield feeding the Gregory Glacier to the northeast and the Lewis Glacier to the southwest (Figs 1 and 2). Each core was split in half. One half was analysed for oxygen isotopes and total β radioactivity at the Geophysical Isotope Laboratory in Denmark. The other half of the core was analysed for microparticles at The Ohio State University under class 100 clean room conditions

Fig. 1   Photo of snow pit sites excavated on col between the Lewis Glacier (*right*) and the Gregory Glacier (*left*) as viewed from Pt Thomson.
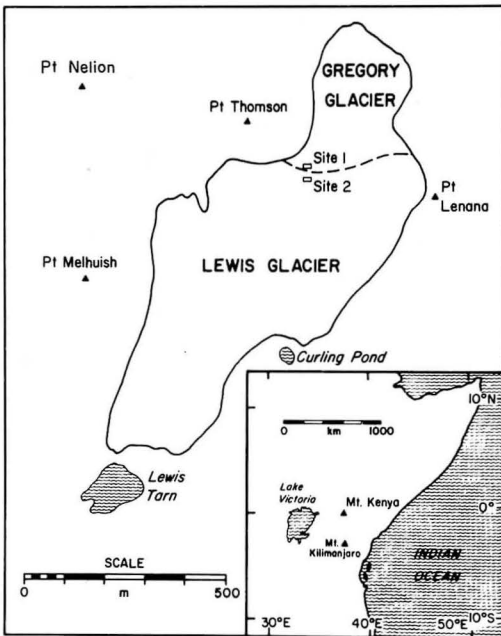

Fig. 2   Map of Lewis and Gregory Glaciers. Snow pit and SIPRE core sample sites are indicated.

(Thompson, 1977).   The 519 samples analysed were cut, melted and placed in clean containers while in the field.

A 2.5 m snow pit was excavated at Site 1 (Figs 1 and 2) and a SIPRE drill provided a core to a depth of 13.4 m.   The drilling was unusual.   At a depth of 8.3 m the drill fell 30 cm through a void before striking ice once more.   At a depth of 9.4 m the drill

fell again, this time through a 3.5 m void in the ice before striking ice again at a depth of 12.9 m. A second drill site was chosen 40 m south of Site 1 and a second continuous ice core was drilled to depth of 11.4 m. The density profile (Fig. 3) established from the two sites varies from 390 kg m^{-3} at the surface to 900 kg m^{-3} at 11 m. As Fig. 3 illustrates densifi-cation proceeds very rapidly. This is due largely to the amount of percolation. Surface air temperature profiles from both sites exhibit temperatures of -3°C, while firn temperatures reach 0°C at 0.5 m indicating that the ice is temperate.

The results of the microparticle, oxygen isotope and total β radioactivity measurement from Site 1 are illustrated in Fig. 4. Visual examination of the SIPRE core revealed well developed ice lenses as well as visually detectable dirt bands. The core stratigraphy at Site 1 is indicated on the right of Fig. 4. There is an apparant hiatus in this ice core record at 6 m revealed by a 45° tilting in the visual stratigraphy. Consequently, the retrieval of a continuous time series at this location is impossible. Generally, large particle concentrations occur simultaneously with high β radioactivity throughout the core. Near the surface the δ ratios exhibit a range of 5.4°/oo which is smoothed out below 1 m primarily by meltwater percolation. Perhaps the most unusual feature in the δ profile is the large range found in the ice below the first void at 8.3 m. In this section of ice we found the less negative δ values to be associ-ated with high particle concentrations as they were at the surface. No clear explanation for this variation is evident as
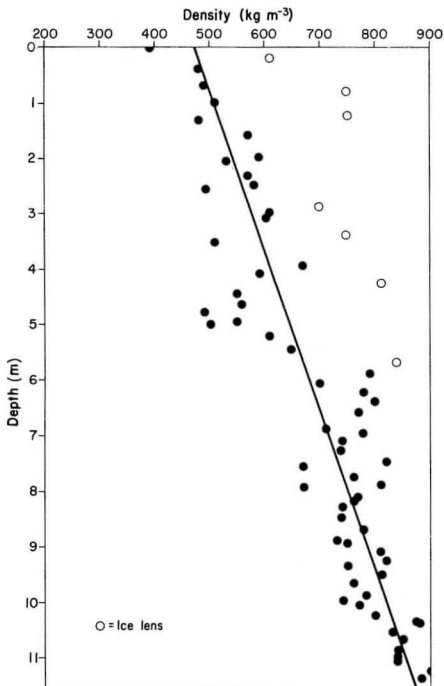

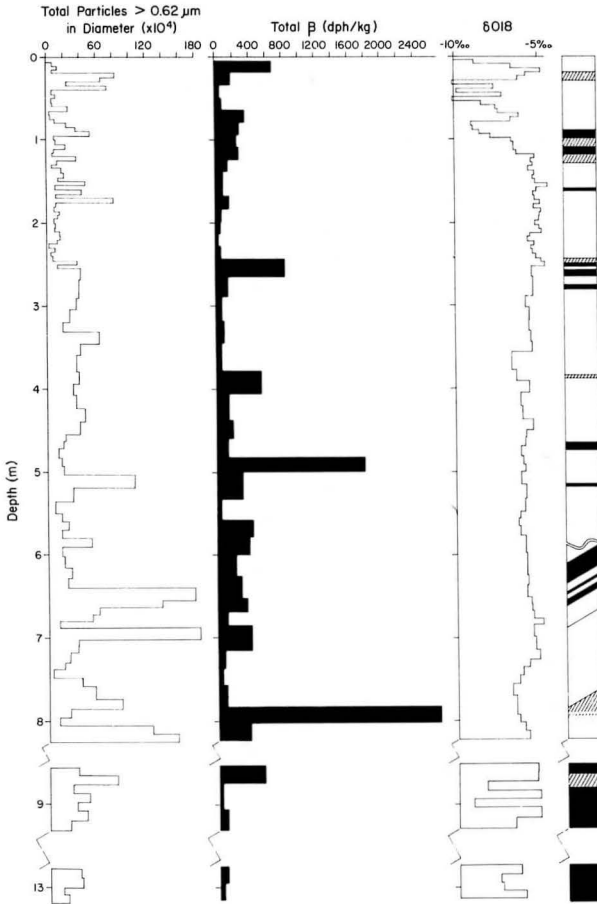**Fig. 3**   Density profile established from the two sample sites.

Fig. 4   Results of sample analyses from Site 1. On the left is the vertical profile of the concentration of microparticles > 0.62 μm in diameter per 500 μl of sample. Centre shaded histogram illustrates the total β radioactivity, and the unshaded histogram on the right illustrates the oxygen isotope ratios. The ice core stratigraphy is illustrated on the far right; solid lines represent ice lenses and hatching represents visually dirtier layers.

there were no open crevasses near the sample site which might allow the present snowfall to become trapped at this depth.

Site 2 is 40 m from Site 1 (Figs 1 and 2). Some of the samples taken from the 2.1-m pit wall turned bright pink when exposed to the sunlight. The bright pink colour (red snow) is due to a "green algae" *Chlamydomonas nivalis* which contributes to the large microparticle concentrations in the snow pit samples (Fig. 5). Nevertheless, it is difficult to explain the simultaneous 3 to 4 fold increase in radioactivity measurements in the Site 2 pit (Fig. 5) in comparison with those measured 17 m away (Fig. 4) unless the algae in the snow concentrate radioactive material. At Site 2 a SIPRE ice core was retrieved to a depth of 11.4 m. The gap in the record between 2 and 4 m (Fig. 5) is due to a lack of sample bottles. There were no voids or hiatus noted in the core stratigraphy. This ice core became visually cleaner with depth as reflected by the particle profile. The cleaning of snow by percolation in temperate glaciers has been reported by
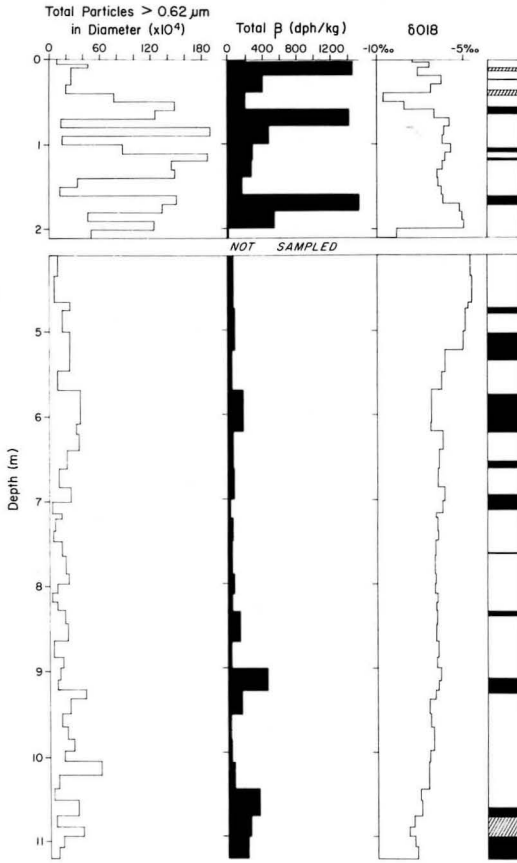
Fig. 5   Results of sample analyses from Site 2. On the left is the profile of the concentration of microparticles > 0.62 µm in diameter per 500 µl of sample. Centre shaded histogram illustrates the total β radioactivity and the unshaded histogram on the right illustrates the oxygen isotope ratios. The ice core stratigraphy is illustrated on the far right: solid lines represent ice lenses and hatching represents visually dirtier layers.

other authors (Glen *et al*., 1977).

There is little relationship between the microparticle, oxygen isotope and β radioactivity measured in core samples from these two sites. The reason for this is related to the large amount of percolation occurring on this tropical glacier. In the core from Site 2 the smoothed $\delta^{18}O$ become more negative with depth which is unusual as δ values become less negative with depth in most temperate glaciers (Sharp *et al*., 1960; Ambach *et al*., 1972; Thompson *et al*., 1979).

One mechanism often producing homogenization and ^{18}O enrichment in temperate glaciers is the refreezing of the meltwater and rain water which percolate into cold, underlying snow or firn (Sharp *et al*., 1960). Snow that accumulates in the cold season generally contains lower δ values. The cold season snow is then overlain by snow or, in some cases, rain with higher δ values which precipitated under warmer conditions. Consequently, refreezing of percolating meltwater and, to a lesser degree, rain water in colder snow is believed to be a primary factor in the

homogenization and relative enrichment of ^{18}O.

The Meren Glacier in New Guinea is one of the few temperate snowfields where $\delta^{18}O$ is depleted with depth. Although Allison (1976) could not fully explain this, he proposes that the difference in the origin of the precipitation in the area is a probable cause. Much of the snowfall is associated with cyclonic activity whereas daily convective clouds bring mainly rain. Assuming the convective air mass is depleted in heavy isotopes, the percolation of the rain water would yield more negative δ values at depth. However, neither the snow nor rain was analysed isotopically, leaving this explanation open to speculation.

There is no evidence that rain ever occurs on the col between the Lewis and Gregory Glaciers under the present climatic conditions (Hastenrath, personal communication 1979). Therefore another explanation is required to account for the depletion of ^{18}O with depth. It appears unlikely that a recent climatic warming could account for the isotopic variations observed ($\Delta\delta = 3.5°/oo$), as temperature data from the Mt Kenya highland area exhibit little variation over the recent past (Hastenrath, personal communication 1979).

In striking contrast to Mt Kenya, the Peruvian Quelccaya Ice Cap (5650 m) exhibits a distinct seasonality in microparticle content, in total β radioactivity and isotope ratios and thus offers the prospect of an excellent mass balance chronology (Thompson et al., 1979; Thompson, 1980). The existence of these distinct seasonal records can be attributed to: (a) the very high elevation and therefore low temperatures which precludes significant melting and percolation and (b) its location in the outer tropics allowing some seasonality in the stratigraphy. The Quelccaya Ice Cap is especially ideal for obtaining a tropical climatic ice core record as it is an extended ice plateau (55 km^2) of gentle topography which minimizes the effects of flow dynamics on stratigraphy. The Quelccaya Ice Cap provides the best potential for acquiring a long tropical ice core climatic record (~1000 years) as it is sufficiently thick (~180 m). The glaciers on Mt Kilimanjaro (5896 m) are the most likely source of climatic ice core records from East Africa. These remnants of a previous ice cap could yield a recent tropical climatic record. However, preliminary field investigations are required to determine the quality of the preserved record.

Table 1 presents a summary of the microparticle and oxygen isotope data from tropical glaciers. The range of $\delta^{18}O$ ratios from the Quelccaya Ice Cap is the largest among the four sites. The $\delta^{18}O$ values from Mt Kenya and Mt Kilimanjaro are similar in magnitude reflecting the geographical proximity and similar climatic environments. There appears to be no clear relationship between the $\delta^{18}O$ ratios and mean surface air temperatures in these tropical regions. The high particle concentrations in the samples from Mt Kenya reflect the proximity of exposed mountain peaks to the core sites. On the other hand, the Quelccaya Ice Cap is the highest point in the area and thus particle concentrations are much lower.

It is concluded that ice core palaeoclimatic indicators can be employed on certain low latitude glaciers. However, the

Table 1   Summary table of oxygen isotope and microparticle data available from tropical glaciers. Data for Lewis Glacier from this paper, data from Quelccaya Ice Cap, Mt Jaya and Mt Kilimanjaro from Thompson *et al.* (1979), Allison (1976) and Gonfiantini (1970) respectively

Quelccaya Ice Cap (summit)	Mt Kenya (Lewis Glacier)	Mt Jaya, New Guinea	Mt Kilimanjaro
13°56'S, 70°50'W	0°9'S, 37°19'E	4°05'S, 137°10'E	3°S, 37°20'E
5650 m	4870 m	4800 m	5895 m
mean near surface $\delta^{18}O$ (−21‰)	mean near surface $\delta^{18}O$ (−7.75‰)	mean near surface $\delta^{18}O$ (−15.3‰)	Mean $\delta^{18}O$*
$\delta^{18}O$ range (22‰) max (−11‰) min (−33‰)	$\delta^{18}O$ range (5.4‰) max (−4.8‰) min (−10.2‰)	$\delta^{18}O$ range (4.3‰) max (−12.7‰) min (−17.0‰)	4600 m = 3.7‰ 4700 m = 4.1‰ 4850 m = 4.2‰ 5100 m = 4.6‰ 5200 m = 4.7‰
most negative $\delta^{18}O$ values occur during warmest season (opposite to polar regions)			5300 m = 5.4‰ 5400 m = 5.9‰ 5700 m = 6.8‰
mean air temperature −3°C	mean air temperature −0.5°C	mean air temperature 0°C	
mean $\delta^{18}O$ (all samples) −19.4‰	mean $\delta^{18}O$ (all samples) −6.04‰	mean $\delta^{18}O$ (all samples) −15.7‰	
mean concentration of particles > 0.62 μm diameter (100 000 per 500 μl)	mean concentration of particles > 0.62 μm diameter (400 000 per 500 μl)	data not available	

*For surface snow samples collected at the above elevations

elucidation of the relationship between current meteorological conditions and such surrogate climatic indicators as micro-particles and oxygen isotopes within precipitation must precede palaeoclimatic interpretations of deep ice core records.   Once this is accomplished, appropriate tropical glaciers such as the Quelccaya Ice Cap will provide important detailed climatic records from the tropics where meteorological information is lacking and where such data should reveal more details about the structure and history of the global climatic system.

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