Climate-driven variations in geothermal activity in the northern Kenya rift valley

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HIGH-TEMPERATURE continental geothermal systems are primarily associated with volcanic activity at plate margins[1]. It has long been known that the activity of these geothermal systems is intermittent, and this is generally attributed to the effect of magmatic intrusions or fault motions. Recently, however, it has also been recognized[2–4] that surface-water hydrology and climate variations can influence the evolution of individual silicic caldera-hosted geothermal systems, although it is difficult to judge the general importance of such effects in controlling the long-term behaviour of continental geothermal systems. Here we report uranium-series ages for the hydrothermal deposits of past geothermal activity from several Quaternary volcanic centres in the northern Kenya rift valley. We find that the ages correspond well to periods of high lake level within the rift, suggesting that the elevated water table and increased availability of meteoric water associated with more humid climates can promote greater transfer of heat and mass from deep, long-lived heat sources to the surface.

In the northern Kenya rift valley, geothermal activity is associated with a series of Quaternary volcanoes (Fig. 1). Hot, hydrothermally altered ground and relatively weak fumaroles, but no active hot springs, are found on these volcanoes. On the intervening rift floor are hot springs representing deeply circulated groundwaters not involved significantly with the high enthalpy systems of the volcanoes[5]. The lack of hot springs and the weak nature of fumaroles on the volcanoes reflect deep water tables, a consequence of the semi-arid to arid climate of the region.

Former geothermal discharge areas have recently been recognized on the flanks and summits of several of these volcanoes. These are manifested by hot-spring sinters, silica veins and associated hydrothermal alteration. This former hot-spring activity at high elevations on the volcanoes could indicate that the region was more geothermally active in the past; the activity may have declined as a result of waning heat sources. However, gas geothermometry on fumaroles indicates high temperatures (~300 °C) at depth in some of the geothermal systems[5–7]. Emuruangogolak and the Barrier volcanoes have erupted within the past 100 years, suggesting that magmatic heat sources are still available to drive the geothermal systems. An alternative explanation for the presence of geothermal silica deposits high on the volcanoes is that deposition occurred when water tables were considerably higher during humid climates. High water tables would have been conducive to hot springs at elevated locations, without requiring changes in the intensity of heat sources. To understand better the geothermal history of the region, we collected samples of geothermal silica (Fig. 1) for age determination by uranium-series (U-series) methods (Table 1).

A striking result of these age determinations is the correlation between the times of hot-spring activity at elevated locations on volcanoes and high lake levels within the rift during the past 200 kyr (200,000 years). Evidence for high lake levels in the past consists of old shorelines associated with skeletal remains of aquatic organisms and littoral stromatolites, and subaqueous volcanic products (such as pillow-lava/hyaloclastite sequences intercalated with diatomites) on the flanks of several of the volcanoes. Figure 2 shows a compilation of age determinations indicating times of high lake levels for the Kenya rift valley in comparison with results from the present study.

Three lakes within the study area fluctuated in size and depth during the late Quaternary. These are Lake Baringo in the south, Lake Turkana in the north, and the former Lake Suguta which occupied the inner trough of the rift between Emuruangogolak and the Barrier volcanoes at various times[8]. At one stage (~12–7 kyr ago) Lake Suguta covered an area of ~2,000 km^2 and reached depths of more than 300 m, but it has since desiccated in response to an increasingly arid climate[8].

Sinter deposits associated with active fumaroles around the western rim of the caldera of the Barrier volcano have U-series ages ranging from 6.9 ± 0.3 kyr to 9.3 ± 0.5 kyr. These ages correlate with the period when Lakes Turkana and Suguta reached maximum levels on the flanks of the Barrier volcano. Lake Turkana fluctuated around a maximum level between 9.5 kyr and 7.5 kyr ago[9], and the highest shoreline on Lake Suguta has a radiocarbon age of 9.7 ± 0.2 kyr[8]. Silica veins near active fumaroles along the Nakoporon fault zone on the western flanks of Korosi volcano have U-series ages of 11.9 ± 0.6 kyr and 12.7 ± 0.6 kyr. Lake Baringo, adjacent to Korosi, reached its highest recorded stand at 985 m elevation between about 12 kyr and 11 kyr[10], when the nearby silica veins (1,000 m elevation) were deposited at Nakoporon. These deposits on the Barrier and Korosi volcanoes were contemporaneous with very high lake levels that occurred throughout the Kenya rift between about 12 kyr and 7 kyr ago[8–12], and correspond to a humid climate associated with the latest glacial-to-interglacial transition of stages 2 to 1 in the marine ^{18}O record.

Sinter deposits associated with active fumaroles on the caldera rim of Emuruangogolak volcano have a U-series isochron age

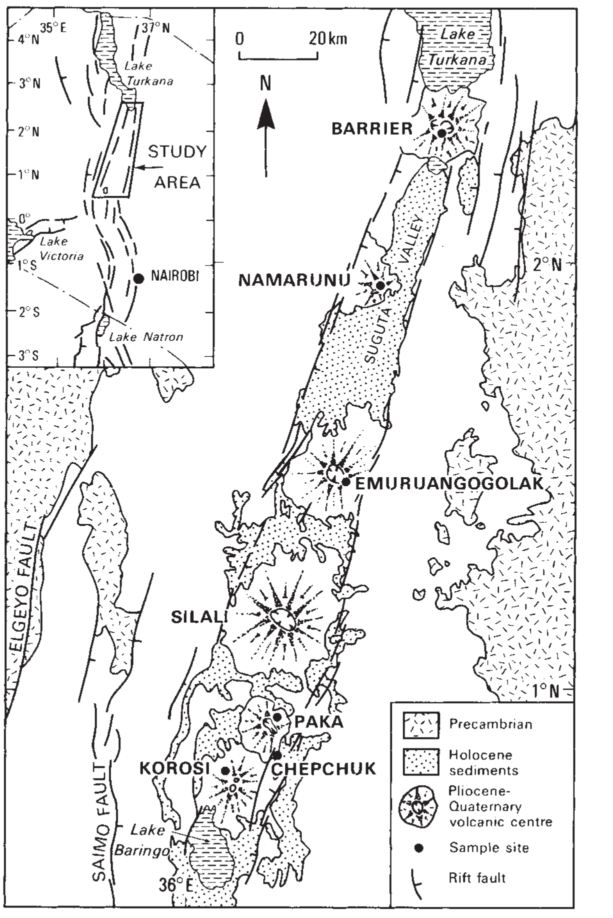

FIG. 1 Map showing location of sampled localities within the inner trough of the northern Kenya rift valley.

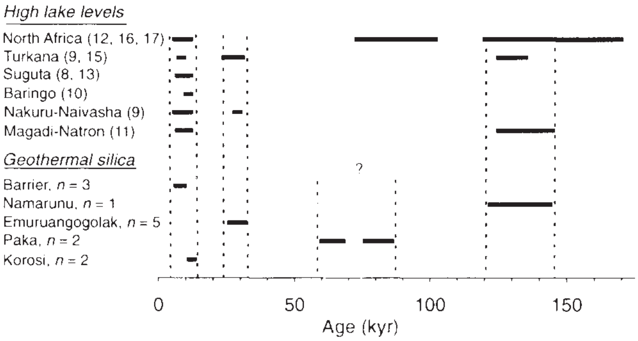

FIG. 2 Diagram showing U-series ages of geothermal silica deposits (this work) compared to periods of high lake levels in the Kenya rift valley and northern Africa during the past 200 kyr. Numbers in parentheses indicate references cited in text and n is the number of data points portrayed. Vertical dashed lines enclose periods of contemporaneous high lake levels and elevated geothermal activity on rift volcanoes.

of 29 ± 3 kyr. This falls within the period from about 35 kyr to 25 kyr when lakes in East Africa were again high[9,13,14].

Extensive silica deposits occur on the upper flanks and summit area of Namarunu. A massive vein from the upper eastern flank has a U-series age of 133 ± 11 kyr, contemporaneous with a period of high lake levels. A U-series age of 121 ± 20 kyr obtained from littoral stromatolites on a shoreline in the Namarunu area indicates that Lake Suguta reached high levels at this time[13]. High shorelines also occur in the southern part of the rift around the Magadi–Natron basin, where littoral stromatolites have U-series ages of 135 ± 10 kyr[11]. There is also corroborative evidence for high stands in Lake Turkana around 130 kyr[15]. Hillaire-Marcel *et al.*[11] suggested that the high lake levels at 135 ± 10 kyr represent a humid climate during the glacial–interglacial transition of stages 6-5 in the marine ^{18}O record. Most of the Namarunu samples analysed are much older, but their high $(^{234}U/^{238}U)$ values indicate ages <2 Myr.

Silica veins associated with active fumaroles on the Lower Pleistocene volcanic centre of Chepchuk have poorly resolved U-series ages of 350 ± 60 kyr and 430 ± 120 kyr. These may correspond to a period of high lake levels found elsewhere in the rift. Stromatolites related to former high lake stands in the Lake Magadi-Natron basin have uncorrected U-series ages of about 300 kyr, although a corrected age of 250 ± 40 kyr may be obtained by assuming that ^{234}U had been preferentially leached[11]. This could represent a humid climate during the glacial-interglacial transition between stages 8 and 7 of the marine ^{18}O record[11].

Minor silica veinlets within faulted trachyte flows on the lower flanks of Paka volcano have U-series ages of 64 ± 4 kyr and 81 ± 5 kyr. These do not correlate with any known period of high lake levels in East Africa, although in northern Africa there is evidence for lake transgressions at around 90 kyr[16,17]. This may be evidence for a previously unrecognized phase of humid climate in Kenya.

Only one episode of previous geothermal activity since 200 kyr has been dated at each volcano, whereas there are clearly at least three distinct periods of high lake levels. This is not a result of sampling bias on our part, as all known sites of geothermal silica deposits were sampled. Several geological factors may explain this apparent discrepancy. First, evidence of additional periods of hot spring activity on each volcano may have been obscured by a cover of younger volcanic products. For example, the flanks of Emuruangogolak and the Barrier are virtually covered by lavas post-dating the 120-140-kyr high lake stand, and both volcanoes have extensive cover of subaerial basalts and trachytes that even post-date the 10-kyr high lake stand. Second, the region is tectonically active, and substantial faulting and erosion have occurred throughout the Pleistocene. Taking these factors into account, we believe that the correlation of periods of humid climate with the ages of preserved geothermal silica deposits in the northern Kenya rift valley is significant. □

TABLE 1 U-series data and calculated ages for geothermal silica samples

Sample	U ($\mu g\ kg^{-1}$)	$(^{234}U/^{238}U)$	$(^{230}Th/^{232}Th)$	$(^{230}Th/^{234}U)$	Age, kyr
BAR-1-A	1,260 (60)	1.07 (0.02)	40 (5)	0.061 (0.004)	6.9 (0.4)
BAR-1-C	1,060 (40)	1.06 (0.02)	46 (5)	0.082 (0.005)	9.3 (0.5)
BAR-1-F	1,710 (20)	1.07 (0.01)	50 (10)	0.068 (0.003)	7.6 (0.3)
NAM-2-A	350 (10)	1.06 (0.02)	220 (20)	0.71 (0.03)	133 (11)
NAM-2-B	310 (10)	1.40 (0.03)	⩾17,000	1.14 (0.06)	⩾380
NAM-2-C	271 (8)	1.63 (0.03)	1,280 (350)	1.20 (0.06)	⩾440
NAM-2-D	419 (6)	1.36 (0.02)	⩾14,000	1.14 (0.03)	⩾670
EMU-3-A	280 (10)	1.01 (0.04)	4.4 (0.3)	0.28 (0.02)	
EMU-3-C	530 (10)	1.00 (0.01)	7.1 (0.4)	0.27 (0.01)	5-point
EMU-3-D	265 (4)	1.04 (0.02)	1.71 (0.06)	0.43 (0.02)	isochron
EMU-3-E	179 (3)	1.04 (0.03)	3.8 (0.2)	0.40 (0.02)	29 (3)
EMU-3-F	442 (5)	1.04 (0.01)	5.9 (0.5)	0.29 (0.01)	
PAK-1-A	570 (10)	1.01 (0.02)	370 (90)	0.52 (0.02)	81 (5)
PAK-1-B	410 (10)	1.01 (0.03)	430 (150)	0.45 (0.02)	64 (4)
CHEP-2-A	370 (10)	1.29 (0.04)	27 (2)	1.02 (0.03)	350 (60)
CHEP-2-B	249 (9)	1.10 (0.05)	13 (1)	1.02 (0.03)	430 (120)
KOR-1-A	1,110 (30)	1.00 (0.02)	22 (2)	0.104 (0.005)	11.9 (0.6)
KOR-1-B	1,220 (30)	0.99 (0.02)	16 (2)	0.110 (0.005)	12.7 (0.6)

Errors ($\pm 1\sigma$, given in parentheses) based on statistics of α-counting method[18]. Decay constants used for age calculations: ^{230}Th, $9.195 \times 10^{-6}\ yr^{-1}$; ^{234}U, $2.835 \times 10^{-6}\ yr^{-1}$; ^{238}U, $1.551 \times 10^{-10}\ yr^{-1}$. Abbreviations used for sample locations as follows. BAR, Barrier (Kakorinya) volcano. Sinter float and veins on upper southwest wall and rim of caldera, associated with faults and fractures cutting a small trachyte dome. Pervasive alteration, brecciation and fumarolic activity (elevation 910 m). NAM, Namarunu volcano. Silica veins from summit area east of main fault scarp, above area of hydrothermal alteration (elevation 720 m). EMU, Emuruangogolak volcano. Area of sinter float and layered veins on rim and southwest-facing slope of caldera wall, associated with clay alteration and fumarolic activity (elevation 1,140 m). PAK, Paka volcano. Silica float blocks from low, north–south ridge on N flank, associated with fault cutting trachyte lavas (elevation 1,200 m). CHEP, Chepchuk volcano. North–south ridge, east of Nagoreti fault, on northwest corner of former caldera structure, southwest of fumarolic activity. Massive chalcedonic veins and float blocks (elevation 1,100 m). KOR, Korosi volcano. Silica vein cutting Nakoporon fault scarp, northwest flank of volcano, associated with fumarolic activity (elevation 1,000 m).

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