Indirect Detection of Subsurface Outflow from a Rift Valley Lake

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Abstract

Naivasha, highest of the Kenya (Gregory) Rift Valley lakes, has no surface outlet. However, unlike other Rift lakes it has not become saline despite high potential evaporation rates, which indicates that there must be some subsurface drainage. The fate of this outflow has been the subject of speculation for many years, especially during the general decline in lake water level during the 1980's. Particularly to the south of the lake, there are few opportunities to obtain information from direct groundwater sampling. However, the stable isotopic composition of fumarole steam from late Quaternary volcanic centres in the area has been used to infer groundwater composition. Using a simple mixing model between Rift-flank groundwater and highly-evaporated lakewater, this has enabled subsurface water flow to be contoured by its lakewater content. By this method, outflow can still be detected some 30 km to the south of the lake. Stable isotope data also confirm that much of the steam used by the local Olkaria geothermal power station is derived from lakewater, though simple balance considerations show that steam use cannot alone be responsible for the fall in lake level observed during the 1980's.

INTRODUCTION

The falling surface level of Lake Naivasha during the 1980's has prompted research into the hydrogeology of the lake and its environs (Ase et al., 1986; Anon., 1988). In this respect calculations of the lake's water balance are important. At Naivasha rainfall averages 608 mm yr^{-1} (Anon., 1966), but low relative humidity and an average daily maximum temperature of 25°C combine to cause annual potential evaporation of 1500-1900 mm yr^{-1} (Ase et al., 1986), far in excess of rainfall. The lake appears to be fed chiefly by the perennial Malewa and Gilgil rivers, which collect runoff from the Nyandarua (Aberdare) Mountains and their foothills to the northeast of the lake, and which discharge into a papyrus swamp forming part of the lake. Three studies based on river gauging and evaporation-rate measurement have given comparable results for subsurface outflow of 43 x 10^6 m 3 yr^{-1} (Sikes, 1935), 34 x 10^6 m^3 yr^{-1} (McCann, 1972) and 46–56 x 10^6 m^3 yr^{-1} (Ase et al., 1986). These are likely to be underestimates, as not all inflows could be gauged, but suggest that substantial outflow is occurring.

Lake Naivasha lies at some 2 000 m.a.s.1, on the culmination of the Kenya Rift Valley, which arches from north to south (Fig. 1). Because of this, groundwater flow away from the lake is potentially possible in both these directions. It is tentatively concluded from well-water level data that between 50 and 90% of lake outflow is directed towards the south, but data are sparse and cease within a few km of the lake (Allen et al., 1989). Although the presence of lakewater can be detected in the chemistry of these well waters, no further direct measurements of water level or chemistry are possible until some 100 km to the south, around Lake Magadi.

However, the high evaporation from Lake Naivasha has raised amounts of the heavy isotopes ^{2}H and ^{18}O in the lakewater to concentrations considerably above those of river and groundwater from direct meteoric sources. The strong signal provided by this isotopic enrichment has enabled the progress of subsurface outflow to be followed, particularly to the south, by means of fumarolic steam discharges from the various late Quaternary volcanic centres of the region (Fig. 1).

SAMPLING AND ANALYSIS

To establish the stable-isotope characteristics of Rift Valley water movement, samples were collected from four sources: (1) rainfall, from 21 meteorological stations from 2°S to 2½°N; (2) cool groundwaters (< 50°C) from springs and boreholes; (3) deep, high-temperature fluids from geothermal wells; and (4) steam from fumarolic discharges.

Samples of high-temperature fluids were obtained from the East Olkaria geothermal field by collection of liquid and vapour phases through the wellhead separators. Fumarole steam condensates were collected by means of an inverted funnel inserted into the fumarole and sealed from the atmosphere by the clayey material resulting from rock alteration. Steam from the funnel stem was drawn through tubing into a stainless-steel cooling coil immersed in water, where it condensed to be collected at the other end in a glass bulb.

All samples were stored in 28 ml McCartney bottles prior to analysis, which was performed at British Geological Survey (B.G.S.) Wallingford on a VG-602E mass spectrometer following preparation by standard methods: 180/160 by equilibration of CO_2 with a 5 ml water sample, $^{2}H/^{1}H$ by reduction of 10 μl of water sample with zinc shot at 450°C using the batch method of Coleman et al. (1982).

Fuller details of sampling sites, together with tables of analytical data, are provided by Allen et al. (1989).

RESULTS AND DISCUSSION

Data from samples collected at the meteorological stations are plotted in Fig. 2, and define a Kenya Rift Valley meteoric line with the relationship:

$$\delta^{2}H = 5.56\ \delta^{18}O + 2.04\ (r^{2} = 0.88) \qquad (1)$$

Lines were fitted separately to data for the smaller and larger rainfall events to check for bias such as that caused by the amount effect or evaporation from collection containers, but none of significance was found. A regression carried out on 80 Rift Valley groundwaters (Fig. 3) from Magadi in the south to Silali in the north resulted in a line described by

$$\delta^{2}H = 5.49\ \delta^{18}O + 0.08\ (r^{2} = 0.81) \qquad (2)$$

which is close to the rainfall line. While this may be partly coincidental, as the regression is biased by isotopically heavier groundwaters from the lower and hotter Magadi area to the south, the rainfall regression seems likely to be representative since a similar one was observed for 35 samples of rainfall from the Chyulu Hills in southeast Kenya:

$$\delta^{2}H = 5.68\ \delta^{18}O + 6.04\ (r^{2} = 0.89)$$

(B.G.S., unpubl. data). However, there is limited evidence from the composition of the River Malewa (Fig. 3) which drains the 3900 m Nyandarua Mountains that a slope nearer 8 may obtain at higher altitudes. The reason may be that the Nyanduruas are high enough to interact with airflow above the sub-tropical inversion (Vincent et al., 1979). The difference is of some significance, since much of Lake Naivasha's inflow is delivered by the River Malewa. Attempts to estimate lake outflow using isotopic balance techniques are highly dependent on the input value used (Panichi and Tongiorgi, 1974; Allen et al., 1989).

Rainfall on the Rift flanks in the Naivasha area results in groundwater with typical values of –25‰ δ^2H, –4.8‰ δ^{18}O (Allen et al., 1989). These figures are at the depleted end of the range of values shown in Fig. 3 because the Naivasha area is situated on the highest point of the Rift. Analysis of water level data (Allen et al., 1989) shows that flows must be directed towards Lake Naivasha from the east and west Rift flanks, and therefore groundwater with these average values is likely to mix eventually in most proportions with evaporated outflow water from Lake Naivasha, which possesses values of the order of +36‰ δ^2H, +6.6‰ δ^{18}O. A δ^2H vs. δ^{18}O crossplot (Fig. 4) shows such a mixing line between 100% lakewater and 100% Rift-flank water with a positive horizontal displacement of 1‰ δ^{18}O to allow for a small amount of isotopic exchange between water and rock. This figure is based on the average of analyses of deep geothermal fluid from six wells in the East Olkaria geothermal field (Fig. 1). In addition the crossplot shows the Rift Valley meteoric line as a reference.

Isotopic compositions of fumarole steam condensates are also shown in Fig. 4. It is assumed that the steam sampled in many of the fumaroles is the product of single-stage separation from a high-temperature geothermal fluid; such a process is known to occur in other geothermal areas (Giggenbach and Stewart, 1982). Lines have therefore been superimposed on the inset to Fig. 4 to show the theoretical consequences of single-stage steam separation between 100°C (local surface boiling point is actually around 93°C) and 260°C (a typical local geothermal reservoir temperature (Armannsson, 1987; Bodvarsson et al., 1987)) from various mixtures of lakewater and Rift-flank water. It is apparent that more than half of the data points fall on or near the theoretical lines; these points together with well-water data have been used to construct a contour map of lakewater influence (Fig. 5), insofar as this is possible in what must be a complex three-dimensional groundwater system. Data points more negative than the theoretical lines are presumed to represent a zero lakewater contribution, the more remote examples being probably the results of steam condensation below surface, a process considered by Darling and Armannsson (1989).

The contour map (Fig. 5) demonstrates a tendency for the proportion of lakewater to diminish with increasing distance from Lake Naivasha, as would be expected. However some volcanic centres (Eburru, Longonot and Mount Margaret) show little or no evidence of lakewater, indicating that subsurface outflow is restricted to certain zones. At Suswa only the fumaroles at or near the centre of the volcanic complex appear to contain a substantial proportion of lakewater. This suggests that beneath Suswa, outflow is at a depth such that only the hotter parts of geothermal convective cells can bring it to the surface (though depth and extent of rock fracturing must also be a key factor). Very little is known about the hydrogeological conditions between the Olkaria-Longonot area and Suswa. Two boreholes drilled about 10km south of the Olkaria-Longonot area struck steam at around 200m, and a borehole drilled 20km further south proved to be dry to 250m. It is apparent therefore that groundwater in the Suswa area is unlikely to be present in the upper 200m.

Lake Magadi, to the south, forms a natural sump for drainage in the southern Kenya Rift. It is presumed that much of the outflow from Lake Naivasha terminates there. There is however little prospect of detecting it at this distance (100 km) because of excessive dilution by Rift-flank waters.

North of Lake Naivasha the groundwater table lies at a much shallower depth, which should facilitate detection of outflow. The scarcity of wells makes this speculative, but the few in the Elmenteita area (Fig. 5) suggest that the lakewater is generally more diluted than below parts of Suswa, which is slightly further away from Naivasha. This would indicate a smaller amount of flow to the north of the lake.

Since 1981, the Olkaria geothermal power station has used steam produced from a fluid which appears from present isotopic evidence to be 60-70% lakewater (Fig. 4), thus confirming a persistent local speculation as expressed in Smith (1988). To what extent this means an additional discharge from the lake rather than merely a diversion of outflow is difficult to tell from existing data, but based on recent production history (Bodvarsson et al., 1987) it represents at worst an anthropogenic increase in outflow of some 2×10^6 m^3 yr^{-1}. This would be a small fraction of the estimated total discharge, and Olkaria power station therefore cannot be implicated in the decline of lake level. Apart from climatic considerations, irrigation for the prolific agricultural activity in the area is a more plausible cause of water loss from the lake.

CONCLUSIONS

The interpretation of stable-isotope measurements presented here supports the tentative hydrogeological model, based on sparse well data, of considerable southerly outflow from Lake Naivasha supplemented by lesser northerly outflow. The stable isotope data further suggest that the northerly outflow is confined to the area between Eburru and Gilgil and the southerly outflow between Olkaria and Longonot (Fig. 1), with a considerable depth to water table beneath Suswa. Though much of the steam at Olkaria must ultimately be derived from lakewater, there is no evidence that extraction has had any effect on lake level.

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FIGURE CAPTIONS

Fig. 1. Physical features of the Lake Naivasha section of the Kenya Rift Valley, showing the relative position of the lake and the various volcanic complexes on which fumaroles are situated. The culmination of the Rift floor occurs in the Naivasha area.

Fig. 2. Stable isotope crossplot of rainwater sampled at Rift Valley meteorological stations from 2°S to 2½°N.

Fig. 3. Stable isotope crossplot of unmodified Rift Valley groundwater collected from wells and springs. The regression shows a close similarity to that of rainfall in Fig. 2. The River Malewa contains depleted water from the Nyandarua Mountains which lies on the world meteoric line.

Fig. 4. Stable isotope crossplot of condensed steam from fumaroles of the Naivasha region shown in relation to the Kenya Rift meteoric line. Fumarole numbers refer to geographical location as shown in Fig. 5. Also shown are the values of average Rift margin rainfall, Olkaria deep thermal fluid, and Naivasha lakewater. Inset: the central portion of the plot with lines superimposed showing the theoretical composition of steam derived over a range of temperatures from groundwater containing various percentages of rainfall.

Fig. 5. Contour map of percentage of lakewater in the groundwater system of the Naivasha region, based on the isotopic content of fumarole steam and water from wells and springs.

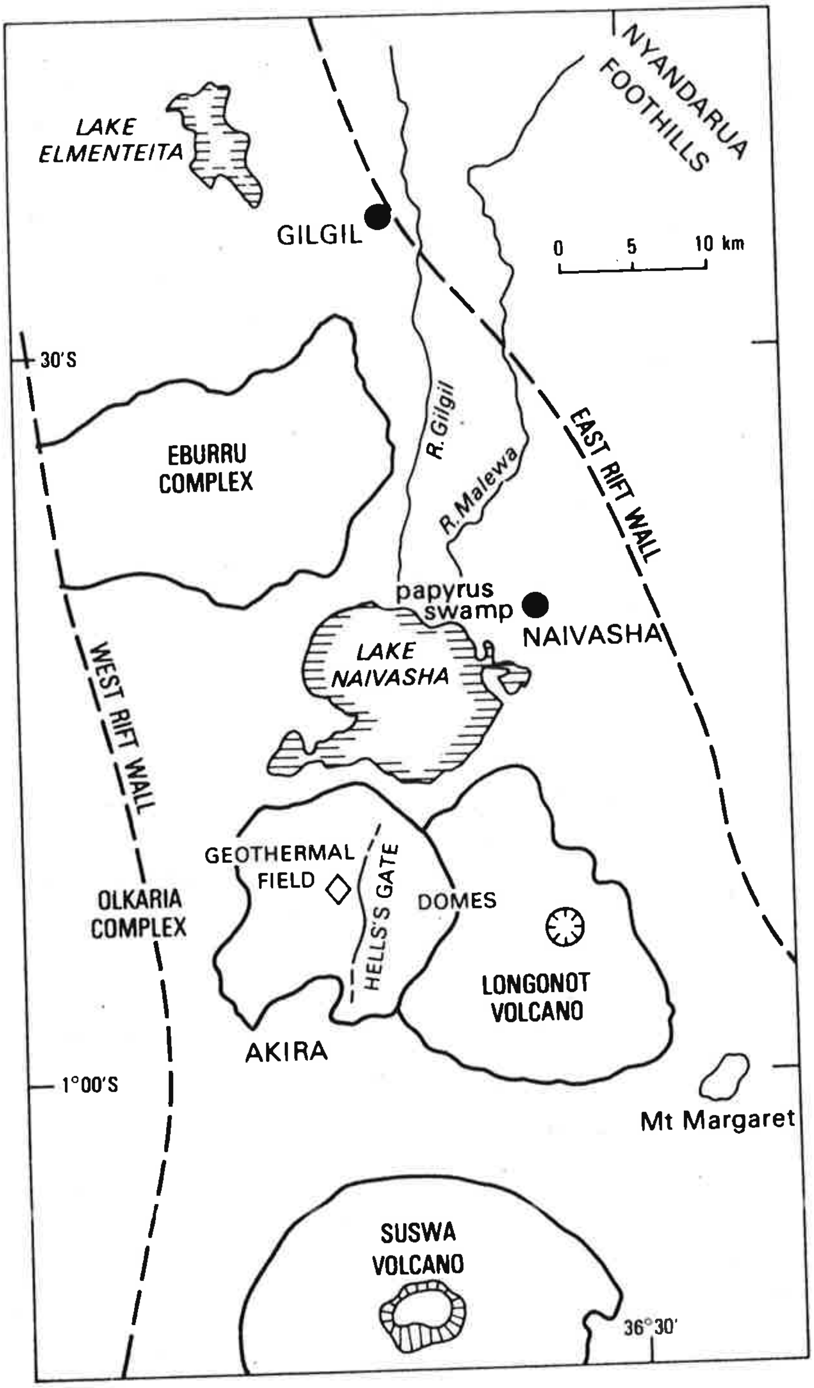

LAKE ELMENTEITA
GILGIL
NYANDARUA FOOTHILLS
0 5 10 km
30'S
EBURRU COMPLEX
R.Gilgil
R.Malewa
EAST RIFT WALL
papyrus swamp
NAIVASHA
LAKE NAIVASHA
WEST RIFT WALL
GEOTHERMAL FIELD
HELL'S'S GATE
DOMES
OLKARIA COMPLEX
LONGONOT VOLCANO
AKIRA
1°00'S
Mt Margaret
SUSWA VOLCANO
36°30'

Fig 1

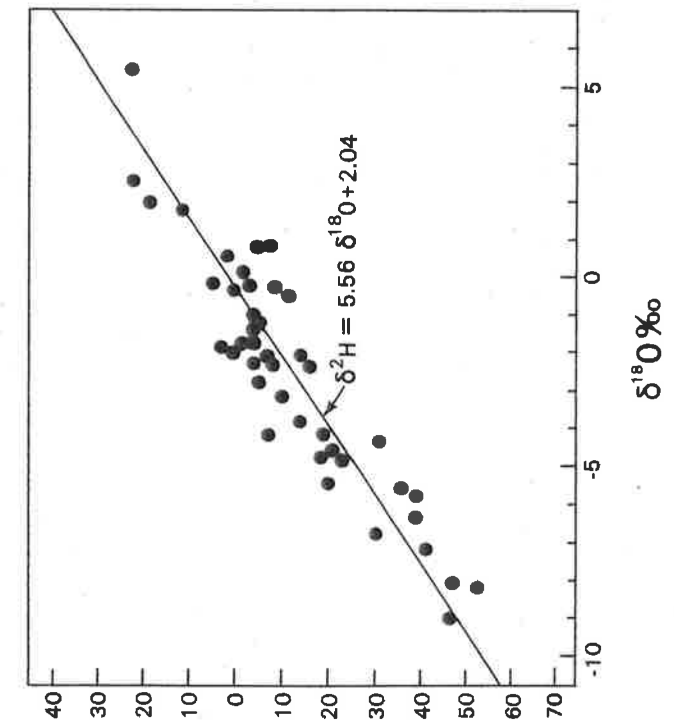


Fig. 2

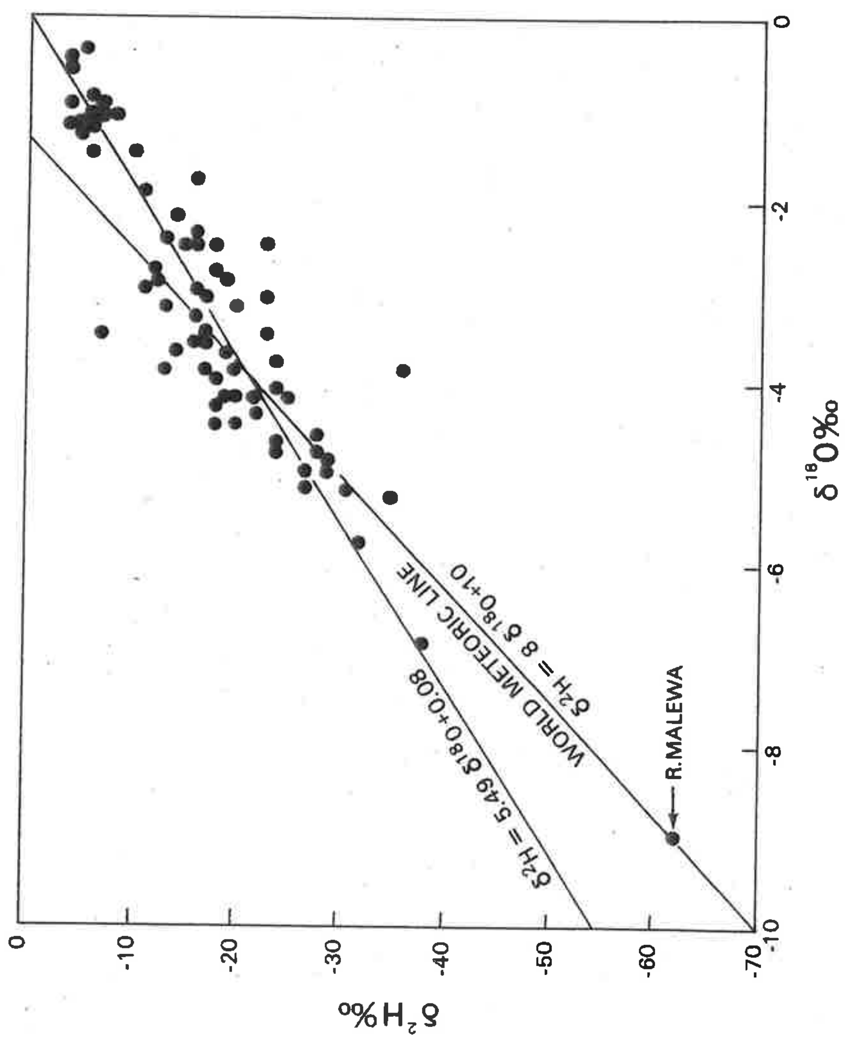
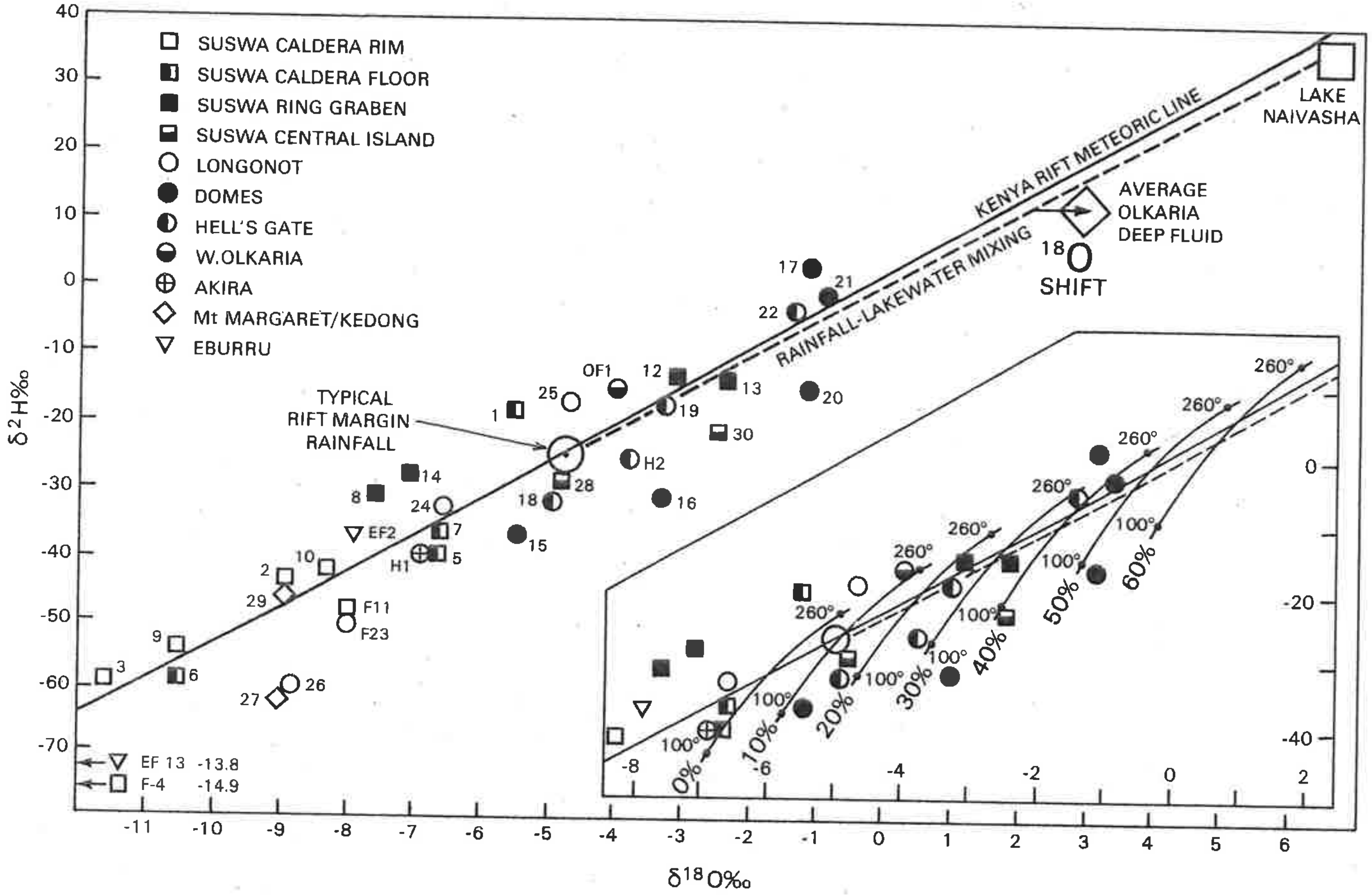

δ²H‰
0
-10
-20
-30
-40
-50
-60
-70
δ¹⁸O‰
-10
-8
-6
-4
-2
0
δ²H = 8 δ¹⁸O+10
WORLD METEORIC LINE
δ²H = 5.49 δ¹⁸O+0.08
R.MALEWA

Fig 3

Fig. 4


SUSWA CALDERA RIM
SUSWA CALDERA FLOOR
SUSWA RING GRABEN
SUSWA CENTRAL ISLAND
LONGONOT
DOMES
HELL'S GATE
W.OLKARIA
AKIRA
Mt MARGARET/KEDONG
EBURRU
KENYA RIFT METEORIC LINE
RAINFALL-LAKEWATER MIXING
LAKE NAIVASHA
AVERAGE OLKARIA DEEP FLUID
18O SHIFT
TYPICAL RIFT MARGIN RAINFALL
EF 13 -13.8
F-4 -14.9
δ2H‰
δ18O‰
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
0%
10%
20%
30%
40%
50%
60%
100°
260°

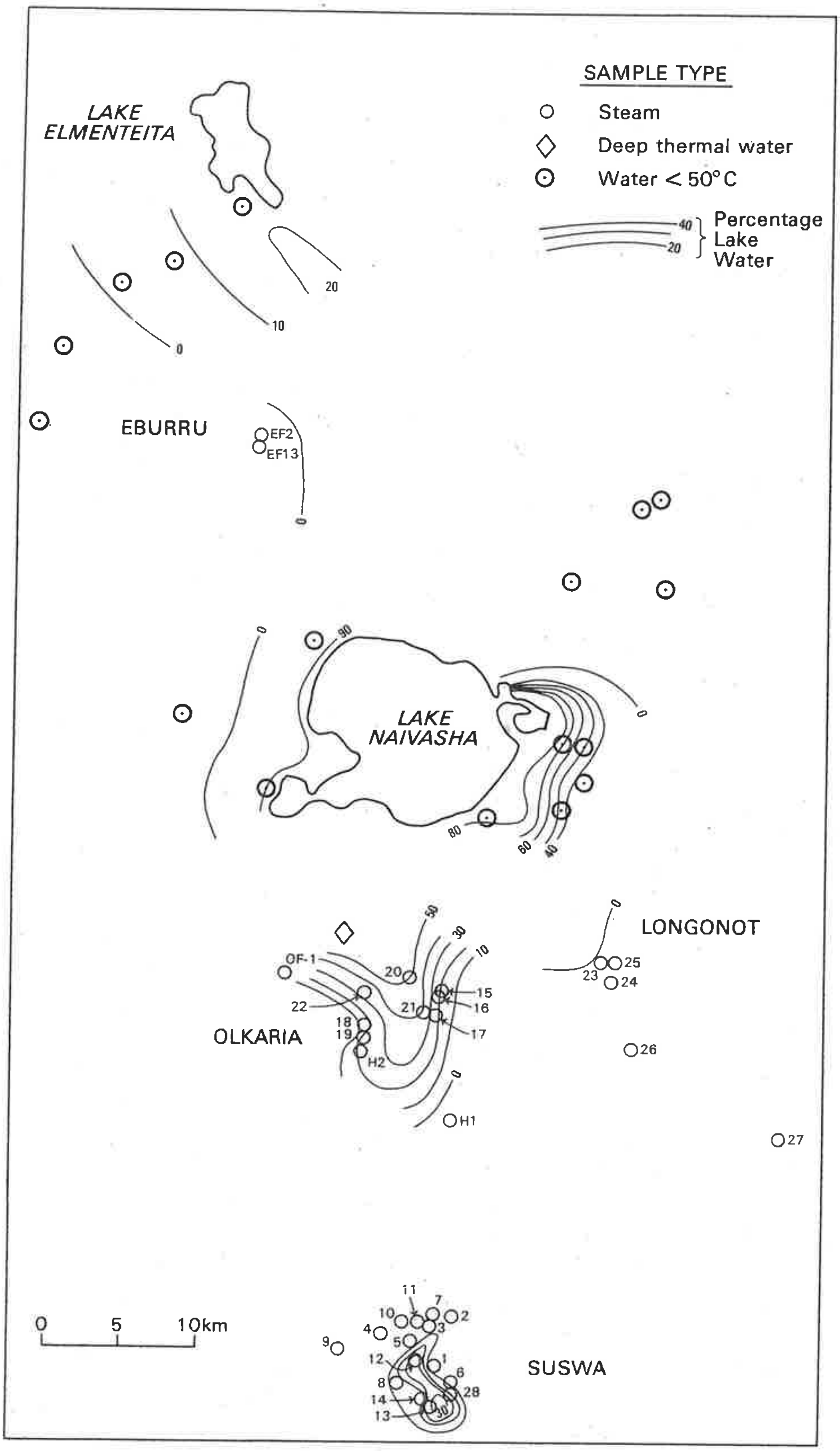

SAMPLE TYPE
Steam
Deep thermal water
Water < 50°C
40
20
Percentage Lake Water
LAKE ELMENTEITA
20
10
0
EBURRU
EF2
EF13
0
90
0
LAKE NAIVASHA
80
60
40
0
50
30
10
OF-1
20
22
21
15
16
17
18
19
H2
0
H1
OLKARIA
LONGONOT
0
25
23
24
26
27
0
5
10km
11
7
10
2
4
3
5
9
12
1
6
8
28
14
13
30
SUSWA

Fig. 5