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## Formation of cave salts and utilization by elephants in the Mount Elgon region, Kenya

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**Abstract:** Herbivores such as the African elephant receive most of their nutrient uptake through digested vegetation or water. When these nutrient sources do not fulfil dietary requirements, eating and digestion of soil and rock can be a common phenomenon. In the Mount Elgon National Park on the Kenya-Uganda border, elephants have taken this activity one step further. Deposits of calcium-sodium-rich alkaline rocks show evidence of quarrying by elephants on the surface, but most of the activity takes place underground in caves. The Na-Ca-Mg-rich rocks are leached by groundwater which reacts with animal excreta in the humid environment of the cave floor to form a series of secondary carbonate, sulphate, halide, nitrate and phosphate minerals by evaporation. Additionally some salts are precipitated on the cave walls by direct evaporation of the cave waters. Inside the caves, elephants tusk and ingest the salt-enriched rock fragments. In an area like Mount Elgon, where supergene processes leach chemical elements essential for dietary requirements from the surface ecosystem, the secondary salts in the caves are potentially an important mineral supplement for wildlife nutrition. Although elephants are the principal exploiters, other wildlife species and humans (for livestock) also utilize the cave salts and surface diggings.

Wildlife species, such as the African elephant (*Loxodonta africana* (Blumenbach 1797)), spend most of their time foraging for food and vital nutrients (Wyatt & Eltringham 1974) with most of their nutritional requirements satisfied through vegetation and water. Little is known, however, of the effects of nutritional imbalances on wildlife or of their ability to respond to such deficiencies (Bell 1982; Maskall & Thornton 1989, 1991; McNaughton 1990; Ben-Sharhar & Coe 1992; Bowell & Ansah 1993, 1994). In a series of studies on the nutritional needs of the African elephant, Weir (1969, 1972, 1973) identified the importance of water soluble sodium in its daily diet and the importance of salt licks. All animals require a balanced intake of mineral salts and if there is a deficit they can go to great lengths to correct it (Denton 1972; Weeks & Kirkpatrick 1976; Dethier 1977). The dietary requirement for Ca, I, Mg, K and Na may be met by forage, water soluble forms or by soil ingestion (FAO 1961; Dougall & Sheldrick 1964; McCullagh 1969a,b; Weir 1972, 1973). The use of mineral salts tends to be seasonal with the most frequent utilization during the dry season when water and forage, the principal sources of macronutrients for elephants, are in short supply (Weir & Davidson 1965). The utilization of mineral salts by wildlife has been documented for other herbivores in Africa

(French 1945; Weir 1969; Henshaw & Ayeni 1971; Ansah 1990; McNaughton 1990; Schulkin 1991) and elsewhere (Cowan *et al.* 1949; Dalke *et al.* 1965). As African wildlife is increasingly confined to well fenced reserves, both to protect the animals from poaching and to protect farms and crops, the utilization of salt-licks is more apparent. Consequently animals can no longer range over a wide area and become increasingly reliant on their immediate environment to satisfy their nutritional requirements (Maskall & Thornton 1989, 1991; Bowell & Ansah 1993, 1994).

In the Mount Elgon National Park on the Kenya-Uganda border (Fig. 1) elephants have taken this activity a stage further, exploiting mineral salts deposited in the caves (Redmond 1982, 1991, 1992; Redmond & Shoshani 1987). To reach and exploit this nutrient source, elephants have worn a narrow path to several caves, the largest of which is the Kitum cave. From a 40 m wide, letterbox-shaped entrance in a cliff at the head of a small valley, Kitum cave extends more or less horizontally into the mountain for 160 m (Ollier & Harrop 1958; Sutcliffe 1973; Redmond 1982). Inside the cave widens to more than 100 m, a cul-de-sac with interior walls scalloped by years of mining activity (Fig. 2). As well as tuskling directly from the cave walls, elephants have been seen tuskling

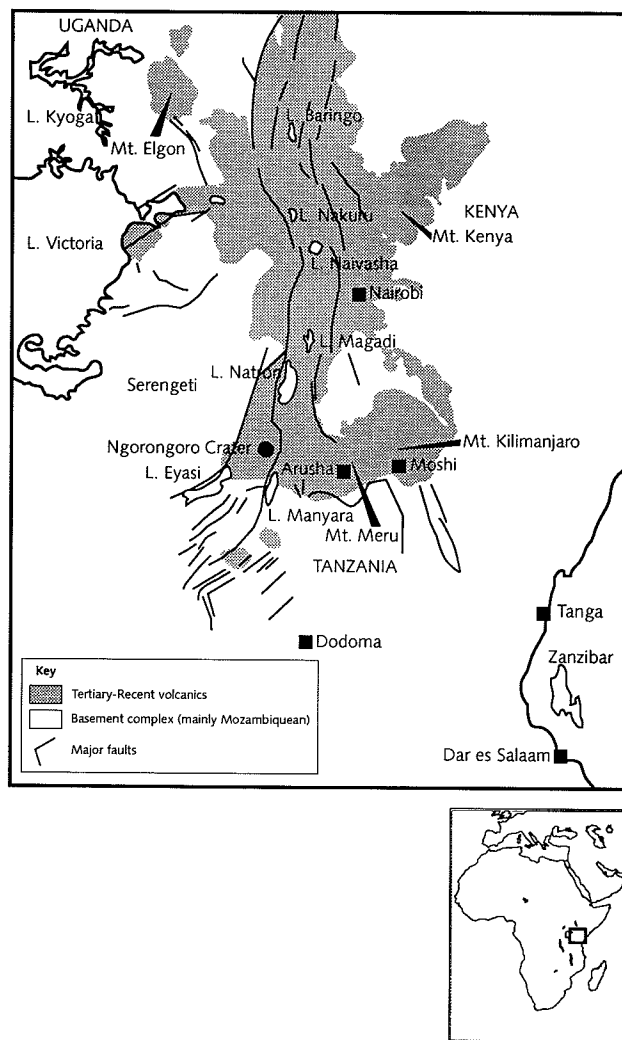


Fig. 1. Simplified topographic and geology map of Kenya and North West Tanzania showing location of the study area

at huge sections of fallen roof and picking up smaller, broken rock fragments from the floor to eat. They have also been observed pulling large fragments of rock from the cave roof, which then lie on the cave floor. Salt crusts form on the fallen rock fragments. Rock types quarried by the elephants are characterized in appearance by the presence of calcite-zeolite veins and vugs. Where no zeolites are present there is little or no evidence of elephant exploitation above or below ground. These rock types are softer than the other lithologies and so are relatively easy to mine.

The temperature of the cave interior remains a

constant  $13.5^{\circ}\text{C}$ , so extended visits by the elephants during the night could be to keep warm, given that at this altitude (2 600 m) night temperatures can fall to  $8^{\circ}\text{C}$ . The caves represent a warm safe haven for the elephants with available water as well as salts. Also, the other main cave occupants are bats (chiefly fruit bats, *Rousettus* spp.) which are most active at night so the elephants tend to have the caves to themselves. Other cave visitors such as local tribesmen, bushbuck (*Tragelaphus scriptus* (Pallas)), baboons (*Papio cynocephalus* (Linnaeus 1758)) and leopard (*Panthera pardus* (Linnaeus 1758)) only make use of the caves during the

day. The knowledge of the caves and their mineral content is passed down from elephant to elephant through the generations, from mother to calf. The extensive poaching of the 1980s reduced elephant numbers from a 1970 estimate of 1200 to as few as 100 today (Redmond & Shoshani 1987; Redmond 1992). Poachers sometimes ambushed elephants in the cave mouth, which led to a reduced use of the cave salts and greater use of the surface soil licks. Intriguingly this period coincided with poorer tusk development in many elephants possibly due to a deficiency in mineral salts in their diet (P. Malisa, pers. comm.). Greater control on poaching in the area has led elephants to return once again to the caves. Use of the cave salts imprints its characteristic mark on salt-digging elephants who show worn down tusks (Fig. 3). Although elephants are the principal exploiters of the salts, other wildlife species, particularly bushbuck, are reported to visit the caves and, in addition, make use of the elephants diggings on the surface (for both salt and water). Local people also use the salts as dietary supplements for livestock.

The purpose of this contribution is to describe the geochemistry of the cave salts and surface salt-licks, to present possible models for their formation and to discuss the possible benefit of utilizing the caves' salts as a source of nutrients by the elephants and other herbivores.

## Methodology

### Field sampling and analysis

Samples of rocks, soils and waters were collected from the Mount Elgon National Park and from a government borehole 5 km to the east of the park. Soil and salt lick samples in the park were collected by use of a soil auger with at least 1 kg of material collected at each site. Water samples were collected from salt licks and areas away from salt licks by means of a soil auger and extraction using the procedure of Patterson *et al.* (1978). Groundwater was sampled by means of a hand pump and deep drilling by the Kenya Water for Health Organization, just outside the Mount Elgon National Park. Three 1 l water samples were collected at each site: unfiltered; unfiltered and acidified with 10% (v/v)  $\text{HNO}_3$  acid; filtered through a  $0.45 \mu\text{m}$  Durapore membrane filter and acidified with 10% (v/v)  $\text{HNO}_3$  acid. Measurements of Eh, pH, electrical conductivity (E.C.), temperature and dissolved oxygen were made at each sample site using Oakton field instruments.

Faecal coliforms were enumerated in the field

using a DelAgua water testing kit (DelAgua Ltd., University of Surrey, Guildford, UK). Immediately upon collection, water samples (100 ml, 50 ml or 10 ml) were passed through a  $0.45 \mu\text{m}$  sterile filter membrane. Each membrane was placed onto a pad containing Membrane Lauryl Sulphate Broth and incubated for 14–18 hours at  $44^\circ\text{C}$ . Colony forming units of faecal coliform bacteria were then counted.

### Mineralogy and lithochemistry

Mineral identification was carried out by optical and electron microscopy (Hitachi 2500S) and confirmed by X-ray diffraction (XRD, Phillips 1820 with Co-filtered  $\text{Cu-K}\alpha$  radiation) using the programme PCIDENTIFY and single grain determinations. Fourier transform infra-red spectroscopy (Perkin Elmer 1720) was also carried out on some of the cave salts. Chemical analysis of the rocks and soils was carried out by inductively coupled plasma atomic emission spectrometry (ICPAES, Fisons ARL3410 Mini-torch). Trace elements were extracted from 5 g of material by digestion with 15 ml of nitric acid (70%), 15 ml of hydrofluoric acid (40% v/v) and 15 ml of perchloric acid (70%). Precision of the technique was checked against known standards and found to be 2%.

### Hydrogeochemistry

Waters were analyzed by ion-chromatography (Dionex-300) using for anion analysis, an AS4A-AMMS column with  $\text{Na}_2\text{CO}_3$  (1.8 mM) eluent at a flow rate of 2.5 ml/min and for group I/II cation analyses, a CS 12 column with methane sulphonic acid eluent (20 mM) at a flow rate of 2 ml/min and detection by a pulsed electrochemical detector in conductivity mode. Transition metal analysis was accomplished with a Dionex CS 5 column with pyridine-di-carboxylic acid eluent and 4 (2-pyridylazo) resorcinol post column derivitization and measurement by a variable wavelength detector in the range 520–530 nm. All water samples were also analyzed by ICPAES.

## Results

### Mineralogy and geochemistry of the Kitum cave volcanics

The Kitum caves occur within the Elgon volcanics which are largely alkaline-mafic lavas and tuffs of foidite, phonolite, tephriphonolite and phonotephrite compositions (Davies 1952;



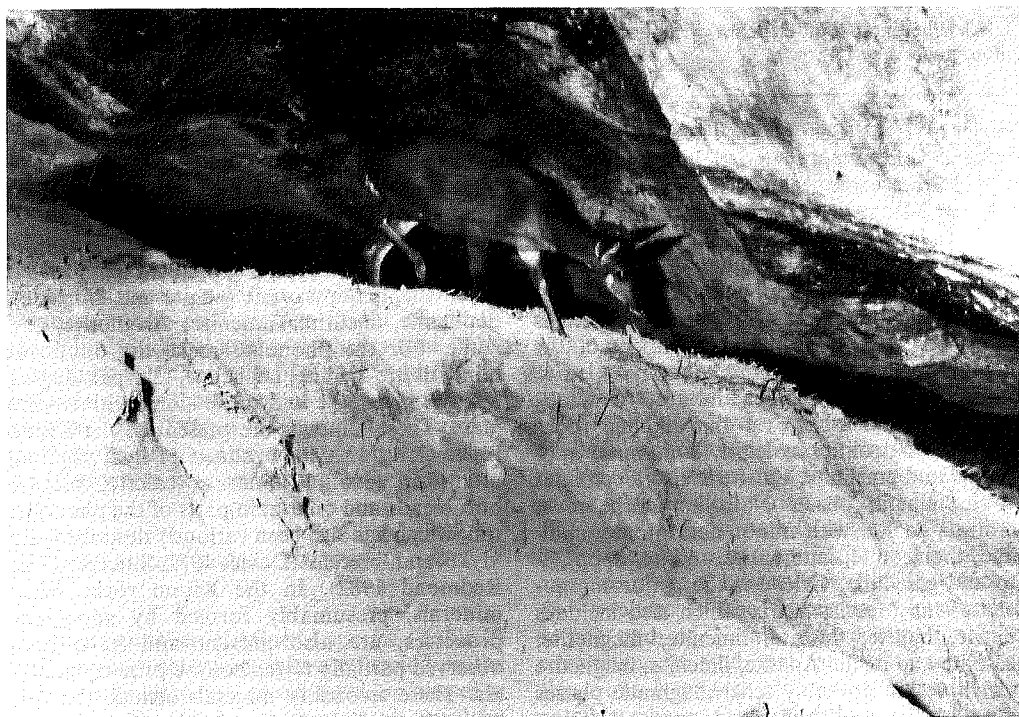
(a)



(b)



(c)



(d)

Fig. 2. Photographs of elephant and bushbuck utilization of cave salts in the Kitum cave. Photographed by IR.

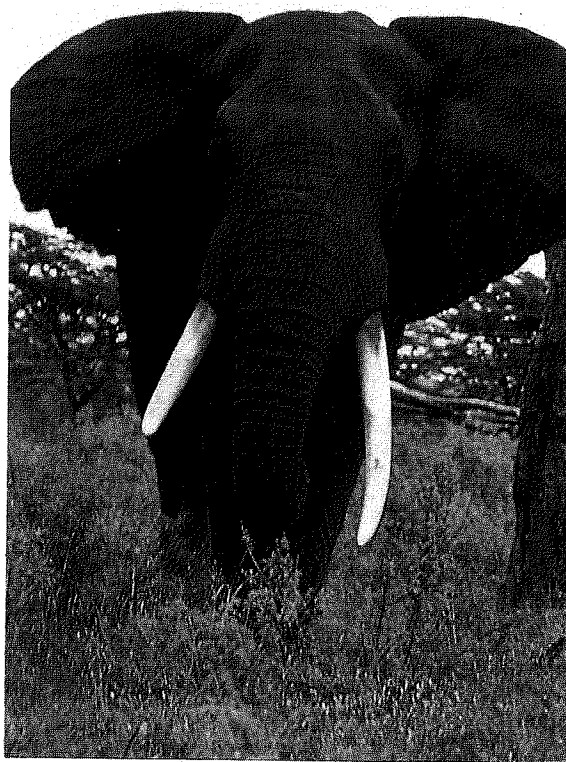


Fig. 3. Photograph of elephant with one worn tusk, probably due to extensive rock and soil digging (photographed by IR).

Searle 1952; Le Bas 1977). These Miocene to Pliocene volcanics are underlain by metamorphosed Proterozoic granitoids and amphibolites.

In the Kitum Cave, the main rock type is a melilitite lava overlain by melilite melanephelinite lavas and a phonolitic nephelinite tuff (Table 1). The phonolite has the appearance of a friable clay-calcareous agglomerate which is highly porous. Following emplacement of the volcanic sequence, hydrothermal activity led to the precipitation of zeolites and other minerals. The zeolite assemblage in the alkaline rocks comprises natrolite, analcime, laumontite, apophyllite and gmelinite. Calcite is also a common vesicle mineral phase. Natrolite is the most common zeolite with minor harmotome, analcime, thomsonite, laumontite, stilbite, apophyllite and gmelinite. Calcite is the major component of the breccia matrix which also includes apatite, biotite, fluorite, ilmenite, magnetite, pectolite and rutile. Apatite, ilmenite, magnetite and rutile are probably relict magmatic phases while biotite and hornblende are alteration products of magmatic ferromagnesian silicates. The general order of infill in the veins are: Na-

zeolite and biotite then Na,Ca-zeolites, then calcite and fluorite. All the rocks in Kitum cave have been subjected to a lesser or greater degree to interaction with groundwater.

The dominant mineralogy of the nephelinite rocks of Mount Elgon is given by Davies (1952) as olivine, clinopyroxene (augite and diopside), nepheline, melilite, ilmenite, magnetite and rutile. For the phonolite rocks the dominant minerals are melilite, nepheline, feldspar, augite, apatite, magnetite and rutile along with silicate glass. These minerals are present in the Kitum rocks along with the products of hydrothermal alteration (zeolite minerals, calcite, biotite, hornblende and quartz) in parts of the phonolite tuff, which has also been variously described as a 'dyke' and 'breccia' (Davies 1952; Sutcliffe 1973; Redmond 1982). In the Kitum rocks other minerals, presumably formed by supergene processes, are also present and have been observed partially to replace the primary minerals. These secondary minerals include the clay minerals kaolinite and smectite (others have also been reported by Davies (1952)), quartz, goethite, allophane, leucoxene, gypsum and

Table 1. Geochemistry of silicate rocks from the Kitum cave, Mount Elgon

Component	Phonolitic nephelinite	Melilite melanephelinite	Melilitite
wt% oxide			
SiO <sub>2</sub>	43.0	40.3	37.5
TiO <sub>2</sub>	2.33	2.59	2.51
Al <sub>2</sub> O <sub>3</sub>	12.7	10.2	9.23
Fe <sub>2</sub> O <sub>3</sub>	13.1	14.7	13.1
MnO	0.23	0.28	0.67
MgO	5.02	6.72	10.8
CaO	11.4	14.6	19.0
Na <sub>2</sub> O	5.52	3.67	2.16
K <sub>2</sub> O	2.52	2.18	1.62
P <sub>2</sub> O <sub>5</sub>	0.41	0.58	0.51
LOI	3.77	4.23	2.92
ppm element			
S	509	219	244
Sc	29	26	21
V	259	198	232
Cr	61	189	219
Co	80	62	79
Ni	29	79	111
Cu	13	36	44
Zn	60	113	88
Ga	12	16	16
Rb	49	33	38
Sr	650	556	529
Y	33	29	21
Zr	214	226	136
Ba	1120	971	965
Pb	1.4	3.2	2.0
La	89	98	82
Ce	153	165	118

extensive rock and soil digging

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possibly secondary calcite. The major element changes which result from the supergene alteration are loss of Ca and Mg and consequent relative enrichment of Si, Al and Fe.

On the assumption that the elements leached from the rocks are then precipitated from solution at the rock surface in the chamber, the encrustations that the elephants find palatable must be rich in salts of Ca, Na and Mg. In order to study the nature of the salts, samples were collected from a fallen roof block on the floor of the cave and precipitates on the wall of the cave where tusking was regularly observed.

#### Mineralogy and geochemistry of the cave salts

A greater number of mineral species (Table 2) and a greater volume of salts are formed on the fallen rocks than are precipitated on the cave wall. Only those salts which were observed by more than one technique are shown; several other phases were also observed by bulk X-ray

diffraction but await confirmation.

Anhydrite, calcite, epsomite, hexahydrate, mirabilite, natron, polyhalite, sylvite and syn-genite are present on the cave walls. Although no reliable bulk sample could be collected which was not contaminated by wallrock phases the major element chemistry, based on the mineralogy, is essentially Ca-Mg-K-Na-Cl-S. These salts are precipitated on the surface of the wallrock minerals.

The salt crust developed on the rock debris on the floor of the cave differs in being considerably thicker (30 cm as opposed to < 1 cm on the wall) and is mineralogically more complex. The major differences are: gypsum is present in the cave floor assemblage but anhydrite is absent; the presence of Fe-Al secondary salts (halotrichite and a phase of the tschermigite-lonecreekite series) and of N-salts (stercorite, mohrlite, nitromagnesite and tschermigite-lonecreekite); also trona is present along with natron. Other possible phases include nitrates, phosphates, other sulphates and a calcium iodide (seen in an infra-red pattern). NH<sub>4</sub> was observed in the

Table 2. Mineralogy of salt crusts

Mineral	Wall salt crust	Floor-rock boulder salt crust
Calcite ( $\text{CaCO}_3$ )*	xx	xx
Halite ( $\text{NaCl}$ )	xx	xx
Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ )		xx
Anhydrite ( $\text{CaSO}_4$ )	xx	
Arcanite ( $\text{K}_2\text{SO}_4$ )		xx
Polyhalite ( $\text{K}_2\text{MgCa}_2(\text{SO}_4)_2 \cdot 2\text{H}_2\text{O}$ )	xx	xx
Epsomite ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ )	x	xx
Natron ( $\text{Na}_2\text{CO}_3$ )	xx	xx
Aphthitalite ( $\text{K}, \text{Na})_3\text{Na}(\text{SO}_4)_2$		xx
Sal-ammoniac ( $\text{NH}_4\text{Cl}$ )		xx
Magnesite ( $\text{MgCO}_3$ )		x
Mirabilite ( $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ )	xx	xx
Hexahydrite ( $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$ )	x	xx
Halotrichite ( $\text{Fe}^{2+}\text{Al}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$ )		x
Sylvite ( $\text{KCl}$ )	x	x
Mohrlite ( $(\text{NH}_4)_2\text{SO}_4 \cdot 3\text{H}_2\text{O}$ )		x
Stercorite ( $\text{NaNH}_4\text{HPO}_4 \cdot 4\text{H}_2\text{O}$ )		x
Blodite ( $\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 4\text{H}_2\text{O}$ )		x
Syngenite ( $\text{K}_2\text{Ca}(\text{SO}_4)_2 \cdot \text{H}_2\text{O}$ )	x	x
Nitromagnesite ( $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ )		x
Trona ( $\text{Na}_3(\text{CO}_3)(\text{HCO}_3) \cdot 2\text{H}_2\text{O}$ )		x
Tschermigite-Lonecreekite ( $(\text{NH}_4)(\text{Fe}^{3+}, \text{Al})(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ )		x

\* Calcite may be a residual hydrothermal phase or precipitated by evaporation/supergene mineral-water reaction. xx, common mineral; x, uncommon/trace mineral.

infra-red spectra of some natrolite grains but further quantitative work has so far failed to confirm this. The salt crust can be divided into a 'mixed layer or zone' in which the secondary salts (listed in Table 2) are intermixed with primary minerals and supergene products (such as the zeolites and smectite; Fig. 4 a, b) and an 'outer crust of hydromorphic salts' with very little (< 20%) wallrock material.

Using this division, a number of chemical changes can be observed in the composition of the overall salt crust.  $\text{Cl}^-$ ,  $\text{I}^-$ ,  $\text{SO}_4^{2-}$  and P, increase in concentration going from unreacted rock to the outer crust of salts (Fig. 5). An increase in Na, K, Ca and Mg is also apparent going from rock to salt crust with a large increase in the mixed layer and, as predicted from the mineralogy, further increases in the salt layer. Conversely, the concentrations of  $\text{SiO}_2$ , Al, Fe, all decrease substantially as do the trace elements Cr, V, Zr, Cu and Co (Fig. 5).

#### Mineralogy and geochemistry of surface salt licks

During the late Pliocene to Recent, active chemical weathering in a tropical regime has

taken place in the area, leading to extensive leaching of alkalis and other mobile elements from the rocks and formation of thick residual lateritic and volcanic soils (up to 4 m thick). The surface soils consist largely of kaolinite, smectite, mica, goethite, quartz, magnetite, leucoxene and chlorite. The soil geochemistry is essentially  $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-Fe}_2\text{O}_3$  with minor CaO and  $\text{TiO}_2$  (Table 3). At a few surface locations, such as at Saito dam, a surface salt pan is formed with halite, gypsum and natron present as a surface crust. These crusts are comparable in bulk geochemistry with the floor-rock salt crusts in the Kitum cave. The higher P concentration (Table 3) of the salt-licks compared to the cave floor-rock salt crust is probably a reflection of the higher volume of apatite in surface soils compared to the precursor rock and possibly a greater volume of animal excreta as the diversity and biomass of species visiting the surface salt-licks are that much greater than in the Kitum cave. The surface salt-lick sites also have higher concentrations of  $\text{SiO}_2$ ,  $\text{TiO}_2$ , V, W, Ni and Zr (Table 3) reflecting the presence of soil minerals in the salt pans. It should be noted that the sites of the salt pans are often in more open terrain so utilization of the salts by animals may also be influenced by the location, with a lower chance of ambush in these more open sites.

Table 3. Geochemistry of surface salt-licks, soils and Kitum cave salt crust, Mount Elgon National Park

Element	Salt-lick 1		Saito Dam		Soil† near Kitum		Cave Salt‡
	surface	120 cm	surface	100 cm	surface	100 cm	
wt%							
SiO <sub>2</sub>	10.6	48.9	22.4	40.8	50.9	49.7	16.9
TiO <sub>2</sub>	0.64	2.52	0.96	2.73	1.77	1.80	0.38
Al <sub>2</sub> O <sub>3</sub>	10.6	18.3	11.8	21.8	21.3	19.8	6.23
Fe <sub>2</sub> O <sub>3</sub>	5.46	7.92	4.98	8.33	14.5	14.0	4.78
MnO	0.11	0.21	0.13	0.20	0.12	0.19	0.30
MgO	10.3	2.34	6.43	2.23	0.29	0.89	10.2
CaO	11.3	4.54	10.6	5.42	2.71	5.22	7.10
Na <sub>2</sub> O	14.9	6.76	12.1	7.94	2.31	3.22	18.3
K <sub>2</sub> O	10.6	2.11	9.89	2.14	0.86	0.99	8.23
P <sub>2</sub> O <sub>5</sub>	4.98	2.34	8.16	2.77	0.31	0.29	1.78
LOI*	20.6	4.03	12.6	5.65	4.98	3.90	25.8
ppm							
SO <sub>4</sub> <sup>2-</sup>	779	428	622	312	408	327	10000
V	258	264	270	279	261	282	78
Cr	67	80	29	52	139	149	60
W	29	33	34	51	25	33	19
Co	49	50	60	72	71	85	48
Ni	105	118	83	91	96	131	65
Cu	44	67	62	72	18	31	59
Zn	35	44	49	64	79	105	37
Rb	48	56	39	49	26	41	39
Sr	960	670	689	669	312	397	689
Zr	124	124	120	123	112	120	98
Ba	989	959	668	690	528	608	722

\* LOI, Loss on ignition (measure of volatile content). † Soils collected 150 m west of Kitum cave. ‡ Cave salt from surface of fallen rock in Kitum cave.

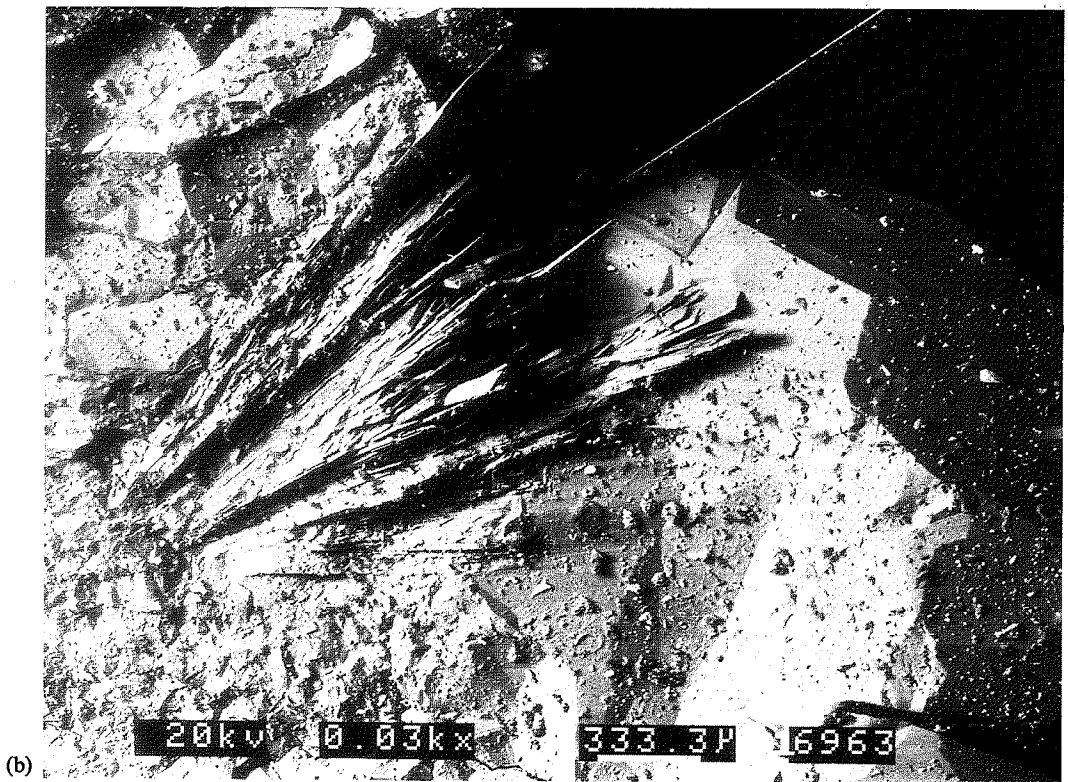
### Hydrogeochemistry

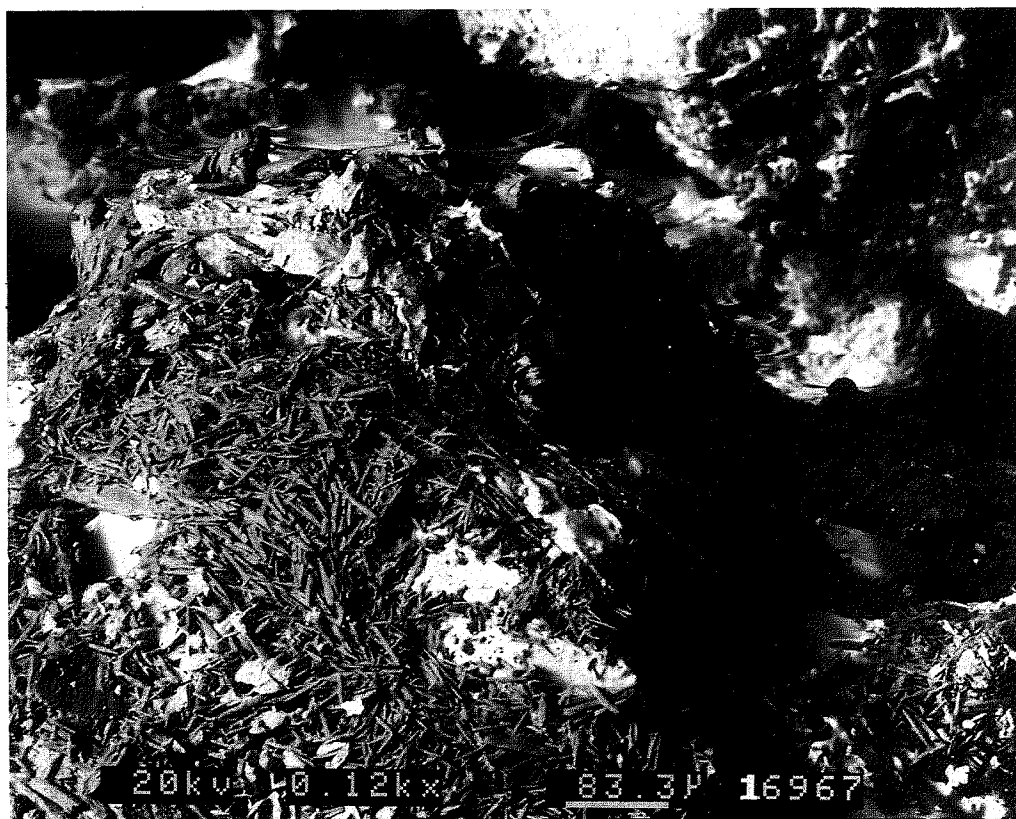
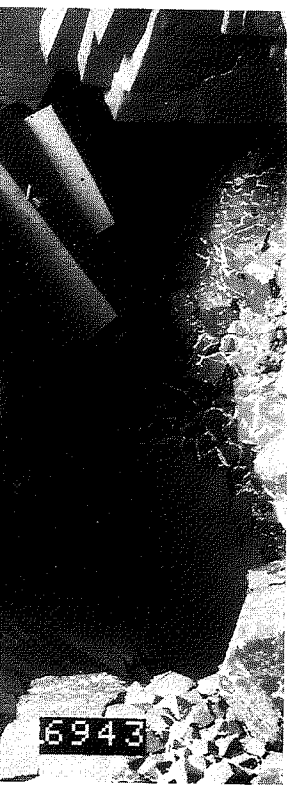
The surface and groundwater of the Mount Elgon area are essentially alkaline Na-Ca-HCO<sub>3</sub> waters with minor Mg, K, SO<sub>4</sub><sup>2-</sup>, Cl<sup>-</sup> and variable F<sup>-</sup> content. In comparison with waters at major salt occurrences elsewhere in East Africa (such as Lake Magadi; Eugster 1970; Jones *et al.* 1977) all the waters, except the Saito dam, are dilute.

The soil porewaters from the National Park tend to be more acidic and less saline than other waters, except at the salt-lick sites (Figs 6, 7). However, the soil porewaters extracted from the borehole at Saboti village 5 km to the east of Mount Elgon are much more saline and more acidic than those in the park and also have much higher total Al and Fe concentrations (Table 4). The salt-lick soil porewaters from Saito dam are more saline and alkaline than any other waters analyzed from the park and will be greatly influenced by the saline chemistry of Saito dam (total dissolved solid, (TDS) content of 3690 mg l<sup>-1</sup>, Table 4).

Non-saline soil porewaters have a lower Na content than groundwater but similar ranges of Ca, K, Mg, Al and Fe concentrations and only slightly lower SiO<sub>2</sub> content (Table 4). This would suggest that the groundwaters are largely meteoric with little or no geothermal contribution as has been proposed in earlier studies (Davies 1952). The highest Al and Fe concentrations are associated with low pH and high salinity in porewaters extracted from soils of the Saboti borehole. These are total metal concentrations and will include particulate material as well. Both Al and Fe were below the 0.1 mg l<sup>-1</sup> detection limit in filtered porewater and groundwater extracts. In the salt-lick porewater, Fe and Al concentrations are in the range 3–5 mg l<sup>-1</sup>, which is higher than non-saline acidic soils from elsewhere in the National Park (Table 4). The high mobility of Fe and Al may be influenced by the high salinity of the waters.

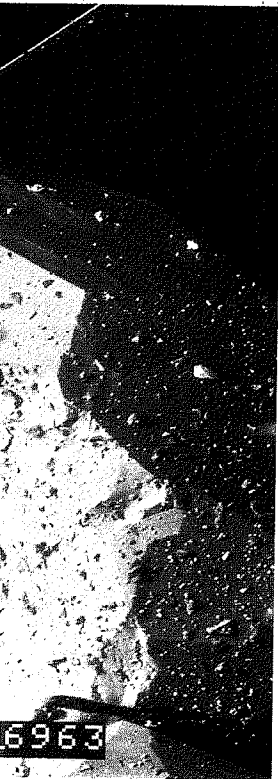
Nitrate and phosphate levels are highest in surface soils and decrease with depth; for example in the park soil porewaters concentrations in the top 20 cm are 1.4 mg l<sup>-1</sup> for nitrate





(c)

Fig. 4. Electron micrographs of salt crusts from Kitum caves: (a) analcime, natrolite and mesolite in vug; (b) smectite, gypsum and polyhalite on natrolite and calcite; (c) salt crust surface.



and  $0.12 \text{ mg l}^{-1}$  for phosphate. At a depth of 40–60 cm these have dropped to  $0.34 \text{ mg l}^{-1}$  nitrate and  $0.06 \text{ mg l}^{-1}$  phosphate (Table 4). Despite the high soil P level at the salt-licks (8.16 wt%  $\text{P}_2\text{O}_5$ , Table 3), the porewater concentration is low ( $0.29 \text{ mg l}^{-1} \text{ PO}_4^{3-}$ ) suggesting that much of the P is in a non-labile form, such as apatite. By comparison the cave waters show a much higher level of phosphate in solution ( $0.37$  and  $0.99 \text{ mg l}^{-1}$ , Table 4) despite a lower content of P in the cave salts (1.78 wt%  $\text{P}_2\text{O}_5$ , Table 3). This P is largely held in guano and precipitated phosphate evaporites and as such is more readily leached.

The Kitum cave waters are similar to groundwater collected from the Saboti borehole with similar pH and bicarbonate ranges but higher chloride contents (Figs 6, 7). The cave waters also contain higher levels of nitrate, phosphate, sulphate, iodide, Na, K, Ca and Mg, with a similar concentration range for TDS, Al, Fe and

$\text{SiO}_2$  but much lower fluoride (Table 4).

Waters were tested for the presence of faecal coliform bacteria, which are indicators of faecal contamination. The presence of high numbers of faecal coliforms ( $> 250$  per 100 ml) in the stream and soil porewater samples is not surprising given that a variety of animals regularly utilize these resources. However, their presence in deep groundwater, albeit at low concentrations, was not expected. These findings suggest that nutrient levels in the groundwater will influence, and to some extent be influenced by, the biota (protists and bacteria) present in the subsurface. However, the very high faecal coliform count of 65 per 100 ml at 45 m depth in the borehole also coincides with increased concentration of chloride, iodide, nitrate, K, Al and Fe (Table 4). These results should be treated with caution as they may be due to contamination of the sample by faecal matter or soil porewaters during collection, rather than to high microbial activity

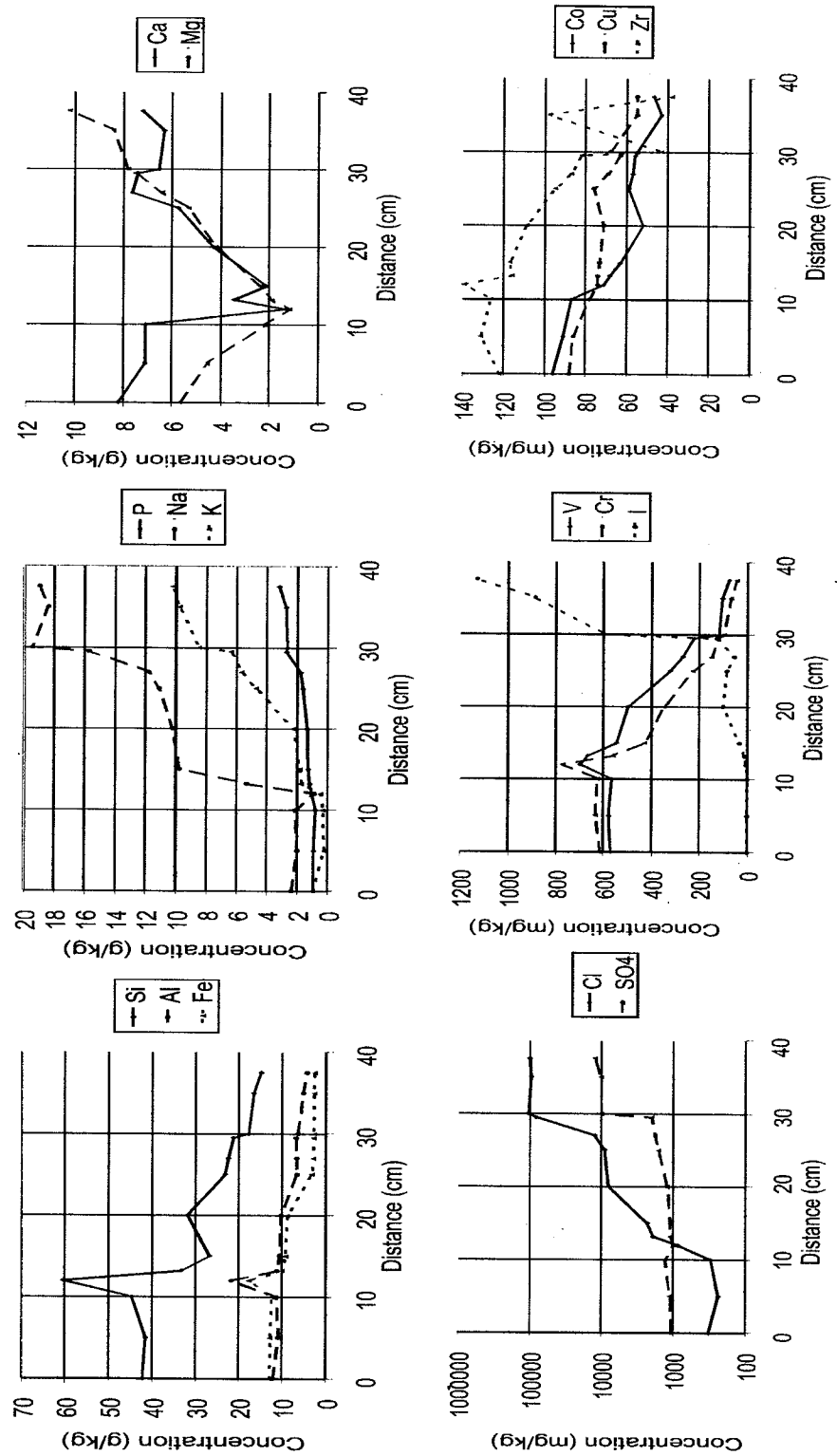


Fig. 5. Geochemical trends of major and minor elements through a salt crust layer: 0-12 cm: unaltered rock; 12-27 cm mixed layer; 27-38 cm outer salt crust.

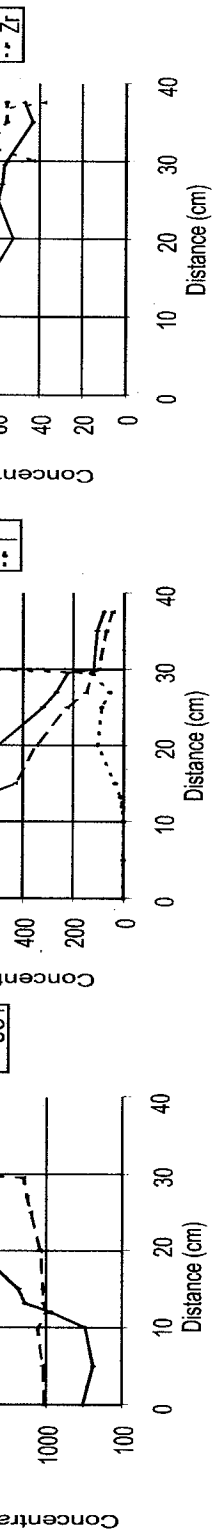


Fig. 5. Geochemical trends of major and minor elements through a salt crust layer: 0–12 cm: unaltered rock; 12–27 cm mixed layer; 27–38 cm outer salt crust.

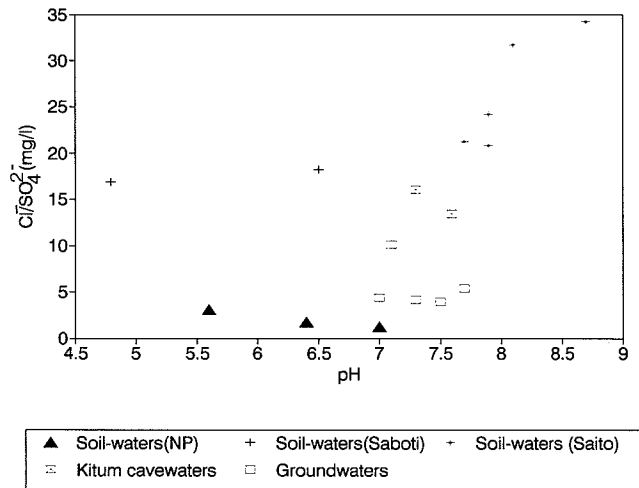


Fig. 6.  $\text{Cl}/\text{SO}_4$  v. pH for all Mount Elgon groundwaters, cave waters and soil porewaters. NP, National Park.

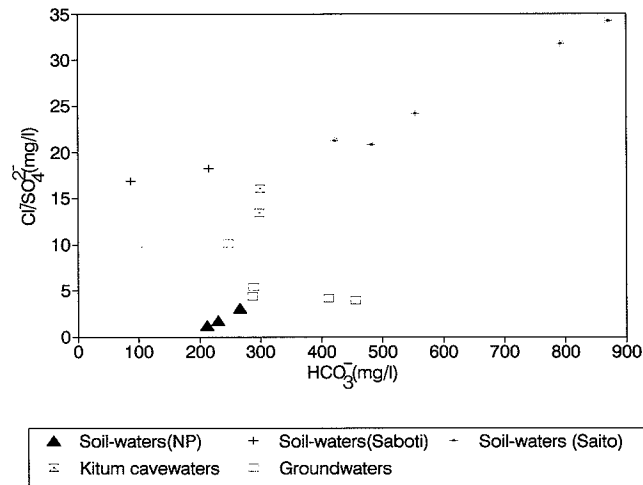


Fig. 7.  $\text{Cl}/\text{SO}_4$  v.  $\text{HCO}_3^-$  for all Mount Elgon groundwaters, cave waters and soil porewaters. NP, National Park.

at this depth in the aquifer. As would be anticipated, the cave waters have a much higher faecal coliform count than the groundwater (Table 4).

### Discussion

The process of salt formation in the caves is likely to be complex and involve evaporation of the cave waters, re-solution of the evaporite salts

and percolation into the wallrock, additional leaching of wallrock minerals, interaction with organic matter and further precipitation of evaporite salts. The formation of the salts is likely to occur through multiple cycles of dissolution–evaporation–reprecipitation and will be an important control on water chemistry. The multiple cycles and percolation of salt-rich cave waters into the rocks is reflected in the complex stratigraphy formed in the cave floor

Table 4. Geochemistry of waters, Mount Elgon area

	pH	TDS	HCO <sub>3</sub> <sup>-</sup>	F <sup>-</sup>	Cl <sup>-</sup>	I <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	NO <sub>3</sub> <sup>-</sup>	PO <sub>4</sub> <sup>3-</sup>	Na	Ca	K	Mg	SiO <sub>2</sub>	Al	Fe	f.c.
Surface waters																	
Maji Chumbi	6.0	280	164	0.8	58	0.84	12.9	0.39	0.12	69	32	9.8	16.9	15	7.9	12.4	>250
Maji Rongai	7.3	494	421	1.3	34	0.45	8.6	0.27	0.09	110	56.5	7.8	12.8	26	1.8	10.8	22
Saito Dam	8.1	3690	5100	10.8	3650	19.9	171	8.9	0.82	3850	79.3	22.5	11.9	49.5	<0.1	<0.1	180
Soil porewaters - National Park, 150 m west of Kitum cave																	
0-20 cm	5.6	255	267	1.9	34	1.05	10.9	1.4	0.12	89	17.9	9.8	8.6	13.4	1.6	1.7	89
20-40 cm	6.4	179	230	2.2	22.9	0.81	12.8	0.56	0.05	106	26.8	5.9	11.3	15.4	0.9	1.2	63
40-60 cm	7.0	165	212	2.9	14.6	0.79	11.5	0.34	0.11	111	29.6	6.2	10.9	16.7	0.9	0.9	25
Soil porewaters - BH 67/3 Saboti village																	
0-20 cm	4.8	270	88	3.1	225	2.7	13.3	7.7	0.06	75	44	43	8.9	10	12.5	29.8	>250
80-100 cm	6.5	189	215	4.2	190	2.3	10.4	1.5	0.05	69	39	13	11.2	12	7.9	18.7	>250
Soil porewaters - salt-lick at Saito Dam																	
0-20 cm	8.7	850	872	2.59	349	16.9	10.2	3.98	0.29	445	85	38	75	20	5.6	3.3	112
20-40 cm	8.1	779	793	2.62	311	11.4	9.8	1.12	0.21	371	76.5	29.2	67.1	18.5	5.2	2.7	98
40-60 cm	7.9	529	554	2.58	288	8.9	11.9	1.59	0.18	272	66.3	24.3	58.4	32.7	4.3	3.4	54
60-80 cm	7.9	452	482	2.63	254	6.3	12.2	1.63	0.14	254	52.3	22.5	64.2	26.2	3.9	3.5	109
80-100 cm	7.7	387	422	2.8	230	4.5	10.8	1.22	0.16	326	69	21	63	27	5.7	4.1	78
Cave waters - Kitum cave																	
site K 2	7.3	298	300	2.5	138	0.97	15.6	3.65	0.37	265	59	11	36	21	3.7	3.1	165
site K 4	7.6	365	299	1.3	291	1.1	21.8	1.22	0.29	358	68.5	18.9	47.6	37.2	3.5	2.9	190
Groundwaters - BH 67/3 Saboti village																	
25 m depth	7.0	363	288	13.98	46	0.14	10.5	0.49	0.05	163	29.2	4.8	14.7	20.9	1.6	1.9	8
45 m depth	7.1	256	247	10.49	87	0.17	8.6	1.54	0.09	150	24.5	7.6	12.5	18	5	3.3	65
55 m depth	7.3	390	412	19.6	28	0.1	6.7	0.34	0.06	199	42.3	3.65	26.1	22	2.3	2.1	0
70 m depth	7.5	422	456	22.9	24.3	0.1	6.1	0.14	0.05	189	39.6	3.2	19.3	25.2	2.3	2.1	0
80 m depth	7.7	224	289	26.8	29	0.1	5.4	0.11	0.07	211	45	2.9	23	21	4.8	2.2	5

All concentrations in mg l<sup>-1</sup> except faecal coliforms (f.c.) which are number in 100 ml water.

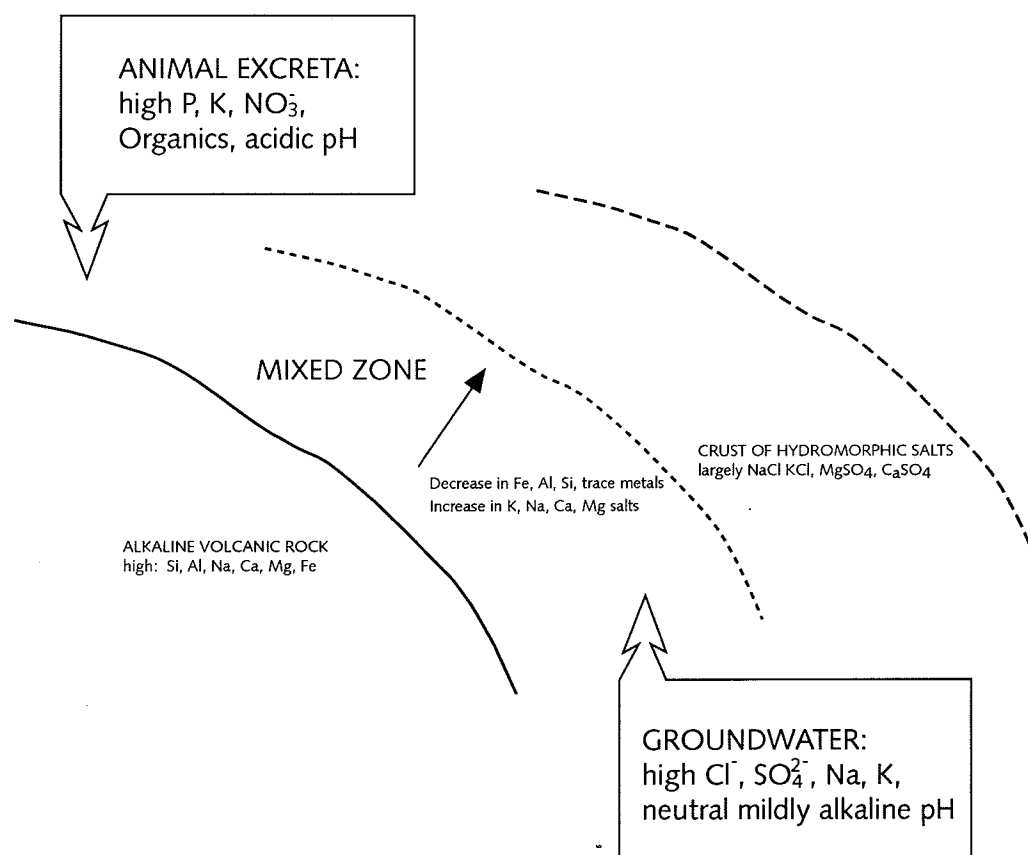


Fig. 8. Schematic diagram of salt crust stratigraphy.

salt crusts (Fig. 8). This stratigraphy of a mixed salt-wallrock minerals zone and an outer hydromorphic salt crust is reflected in the chemical changes observed through the crust with the more soluble salts precipitated in the outer crust (rich in Mg, Ca, K and Na).

Experimental studies of evaporite salt formation have shown that the salts will precipitate out in sequence from the least soluble, such as Ca-carbonates, to the most soluble such as Mg-sulphates, regardless of the total concentration of the brine (Harvie & Weare 1980). The salts developed in the Kitum cave follow this general sequence and show two similar assemblages although these have some major differences as well. The evaporite salts precipitated on rock debris on the floor of the Kitum cave are volumetrically greater and are more varied in mineral species present (21 as opposed to 10 on the cave walls) and chemistry of the salts (the floor salts contain nitrates, phosphates, NH<sub>4</sub><sup>+</sup>, Fe and Al evaporite salts) than those on the cave

walls. But apart from the presence of gypsum in the floor salts and the presence of anhydrite in the wall evaporite assemblage, most of the other major salts are present in both assemblages (calcite, epsomite, halite, hexahydrate, mirabilite, natron and polyhalite) suggesting a common mechanism of formation. However, the chemical differences between the two assemblages suggest that elements from additional sources are available to form evaporite salts on the rock debris on the floor of the cave. These sources have provided nitrate, phosphate, NH<sub>4</sub><sup>+</sup>, Fe, Al and additional sulphate, Na, Mg and K. The additional sulphate, Na, Mg and K may be a product of a greater volume of cave water on the floor of the cave or, alternatively, cave waters may be additionally enriched by mineral-water interaction by percolating through unaltered rocks exposed to supergene leaching by elephant quarrying. Such a process could also enhance Fe and Al, although the concentrations of these elements in the cave waters are no different to

All concentrations in mg l<sup>-1</sup> except faecal coliforms (f.c.) which are number in 100 ml water.

45 m depth	7.1	256	247	10.49	87	0.17	8.6	1.54	0.09	150	24.5	7.6	12.5	18	5	3.3	65
55 m depth	7.3	390	412	19.6	28	0.1	6.7	0.34	0.06	199	42.3	3.65	26.1	22	2.3	2.1	0
70 m depth	7.5	422	456	22.9	24.3	0.1	6.1	0.14	0.05	189	39.6	3.2	19.3	25.2	2.3	2.1	0
80 m depth	7.7	224	289	26.8	29	0.1	5.4	0.11	0.07	211	45	2.9	23	21	4.8	2.2	5

borehole groundwater chemistry (Table 4).

The additional source of phosphate, nitrate and  $\text{NH}_4^+$  is most likely from groundwater interaction with animal excreta particularly from bat guano, which is known to be rich in P and N (Ukumi 1990), and elephant excreta which is volumetrically more important in the Kitum cave. Despite the high nutrient content of bat guano it is only utilized as a nutrient source by a few species such as waterbuck (*Kobus defassa*, Ruppell) (Ukumi, 1990) because of the low pH (3.8–5) and high content of dissolved organic acids. The importance of animal excreta as an additional source of components for the evaporite salt crusts is reflected in observations by Sutcliffe (1973) who found a much lower volume of salts in caves not frequently visited by elephants in the Mount Elgon area. The common presence of zeolites in rocks which are frequently utilized as a nutrient source in the caves is unclear and possibly only a coincidence as the nutrients are more concentrated and soluble in the evaporites. However, the expandable nature of zeolites and their ability to sorb nutrients (Tsitsishvili *et al.* 1992; Bish & Guthrie 1993) could possibly contribute in the formation of the salt crusts or the use of their lithologies as a target of elephant quarrying. However, it must be remembered that those rock units which host zeolites have been hydrothermally altered and are mechanically softer than unaltered equivalent rock types.

The similarities in major nutrients between the salt-licks and cave salts (Table 3) suggest that no additional nutritional benefit is gained from utilization of the cave salts. Nevertheless from the hydrogeochemistry data it is clear that for some elements, such as P, a greater portion is in a labile form in the cave salts than in the soils at the salt-lick. The superiority of the cave salts may have more to do with location than nutritional benefit over surface salt-licks.

### Conclusions

In the Kitum cave, Mount Elgon National Park, a suite of alkaline volcanic rocks is undergoing supergene leaching with the loss of mobile elements such as Na, K, Mg and Ca and consequent relative enrichment of more immobile elements such as Al, Fe and Si. The formation of hydromorphic salt crusts occurs through evaporation of groundwater enriched by mineral–water reactions with wallrock and leaching of organic matter in the caves. Multiple cycles of dissolution–evaporation–reprecipitation lead to a two-zone stratigraphy of salts on the wallrock.

From analysis of surface salt-licks and waters from throughout the national park it is apparent that nutrients are readily available. The surface salt-licks are very similar in composition to the cave salt crusts based on hydrogeochemistry and possibly only inferior in the availability of P. Consequently although the cave salts are a rich source of nutrients in a soluble form, their utilization by elephants is more likely to be influenced by the physical environment of the caves, which provides a warm safe haven with available water where they can quarry the cave wallrock and salt crusts on the cave floor. The salts being more soluble than wallrock minerals would be a more efficient source of nutritional elements. However, any preference for the salt crusts may be related more to the ease of mining the soft salts over the harder wallrock salts.

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