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Speleogenesis of the Mount Elgon elephant caves, Kenya

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ABSTRACT

The eastern flanks of Mount Elgon, an early Miocene stratovolcano, host caves (~150 m long, ~60 m wide, ~10 m high) of debatable origin. Many animals, primarily elephants, "mine" the pyroclastic bedrock for sodium-rich salts. Speleogenesis has been argued to be primarily zoogeomorphic, or primarily dissolutional with only minor zoogeomorphic modification. This report provides the first detailed mapping and geomorphological study of the caves. Speleogenesis is polygenetic and strongly related to lithology. Geological units are, from the top down, ~2 m of dense pyroclastic agglomerate cap rock over which water falls, ~10 m of more permeable agglomerate, up to ~0.2 m of discontinuous impermeable lava, ~2 m of very soft and permeable agglomerate, and >2 m of impermeable swelling-clay tuff. Caves develop behind waterfalls under surface stream valleys by sapping of the incompetent agglomerate above the clay, and failure of the clay (aquiclude and base level for speleogenesis), followed by collapse of harder agglomerate layers above. The dominant passage shape is breakdown dome, with abundant fresh collapse. Geophagy by elephants and other species, and human mining significantly modify and enlarge the caves and remove collapse debris. These activities, focused on accessible and salt-rich units, create quasi-horizontal undercuts (up to ~4 m tall and deep), the loci of which move upward as collapse raises the floor. Significant erosion also occurs by incongruent dissolution, corrosion, pressure release, efflorescence flaking, and biogeochemical activity from huge bat colonies. No evidence was found of channeled flow, or of phreatic or vadose activity. These caves are probably no older than Holocene.

Keywords: speleogenesis, geophagy, bioerosion, volcanospeleology, Kenya, elephant.

INTRODUCTION

The eastern flanks of Mount Elgon, an ~4000 km^2, 4321-m-high stratovolcano of early Miocene age (25–10 Ma) on the border of Kenya and Uganda (Fig. 1), are penetrated, at altitudes of 2400–2500 m, by several voluminous caves up to ~250 m long, ~80 m wide, and ~10 m high. These caves, in pyroclastic agglomerate host rock (which forms the greatest portion of the mountain: Davies, 1952), are known to be regularly visited by a variety of animals, including elephants, that "mine" the rock for its sodium-rich salts. The "elephant caves" of Mount Elgon have been internationally recognized since they were first described by Joseph Thompson in the late nineteenth century (Thompson, 1885); they were well known to local people for centuries before that; and they have been a source of some controversy to scientists ever since. Thompson was unable to decide if the caves were of natural

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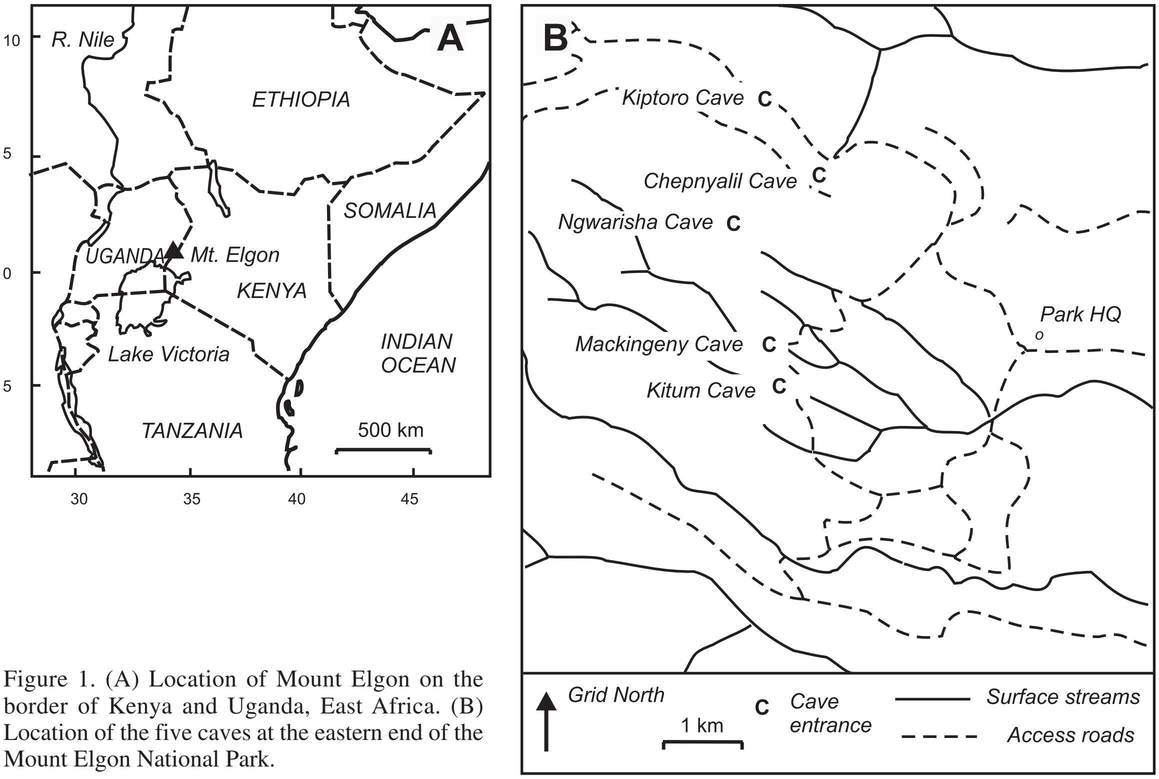

Figure 1. (A) Location of Mount Elgon on the border of Kenya and Uganda, East Africa. (B) Location of the five caves at the eastern end of the Mount Elgon National Park.

or human origin. Hobley (1918) developed a theory of natural origin involving a postulated ancient lake, but Oswald (1918) quickly dismissed Hobley's theory, preferring instead an origin by percolation dissolution. Oswald's theory was taken up by Ollier and Harrop (1958), who provided additional observations supportive of a percolation-dissolution origin, and in 1961 a phreatic half tube was reported by Wright (1961). Nevertheless, the matter has never been settled. Sutcliffe (1973) described the evidence for mining by the El Kony people in some of the caves, but, noting that at least one cave channels an active stream, presumed that the caves were naturally formed prior to use by animals, and only modified by both human and animal mining activity. Beginning in the early 1980s, Redmond (Redmond, 1982; Redmond and Shoshani, 1987) pioneered a program of study focusing on the use of the Mount Elgon caves by elephants, concluding that at least Kitum cave was largely formed by elephants excavating the walls for their salt content (Redmond, 1992). A geochemical study provided additional useful data (Bowell et al., 1996), but left the issue of the quantitative contribution of geophagous elephants unresolved. Thus, the caves' genesis has been argued as being either primarily zoogeomorphic or primarily dissolutional with only secondary modification by elephants.

Research Methods

In order to try to unravel this mystery, from 28 May to 4 June 2003, toward the end of the wet season, we studied the five best known and accessible caves in Mount Elgon National Park, Kenya (Figs. A1–A4; on loose inserts accompanying this volume and in the GSA Data Repository[1]): Kitum Cave, Mackingeny Cave, Ngwarisha Cave, Chepnyalil Cave, and Kiptoro Cave. All five caves were surveyed (using global positioning system [GPS], Sunto compass/clinometer, and laser range finder; to BCRA grade 5, loop closure 1.2%), which included many detailed cross sections and extensive observations on the geomorphology. In order to get a rough idea of microclimate, and as the basis for future research plans, we measured temperature (precise to ±0.5 °C) and humidity (precise only to ±5%) for a few days each in four parts of Kitum Cave with two Hobo data loggers. Rudimentary tests of water uptake by rock specimens were done to provide a rough measure of primary permeability. Thin sections were made of field specimens for microscopic examination.

No geophagous activity was directly observed during this research; no elephants visited the caves, because they had not yet returned from their customary wet-season sojourn in Uganda (Thaddeus Obari, Mount Elgon Caves National Park, 2003, personal commun.). Much of the information about animal behavior was supplied by the published literature and by discussion with Ian Redmond and members of the Kenya Wildlife Service and the Mount Elgon Caves National Park.

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[1] Figures A1–A4 are available as GSA Data Repository item 2006125, online at www.geosociety.org/pubs/ft2006.htm; on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA. Also at: http://dx.doi.org/10.1130/2006.2404(06).FA1A; http://dx.doi.org/10.1130/2006.2404(06).FA1B; http://dx.doi.org/10.1130/2006.2404(06).FA2; http://dx.doi.org/10.1130/2006.2404(06).FA3; http://dx.doi.org/10.1130/2006.2404(06).FA4.

It was noted that many caves seem to have multiple names, and that names given in previous literature may not correspond with caves of the same name today. Location coordinates are not supplied in the literature, and the only survey published is a rudimentary one of Kitum Cave (Sutcliffe, 1973, in which the cave is misnamed; Redmond and Shoshani, 1987).

GEOMORPHOLOGY AND PROCESSES OBSERVED

Geological Setting

The host rock is a pyroclastic, sodium-rich agglomerate, with <1% of lava (Davies, 1952), and fine-grained tuffs. In the vicinity of the caves, four units are apparent, including, from the top down, the grey agglomerate (the topmost, densest layer, which acts as a cap rock), the brown lava, the yellow-grey agglomerate, and the green clay (Fig. 2). The grey agglomerate is the thickest, at 10 to15 m. However, none of the layers is consistently flat, or consistently thick; stratigraphy and level of cementation vary laterally and vertically. All drape over, or infill, pre-existing relief. Even the clay, although the most level feature, varies slightly in elevation over a few hundred meters. The lava is not always apparent between the upper and lower agglomerate. In no part of the caves is the base of the clay unit exposed. The geology of the region is discussed in detail in Davies (1952), Walker (1969), and Bowell et al. (1996). Brief notes on the relevant units are given in the following.

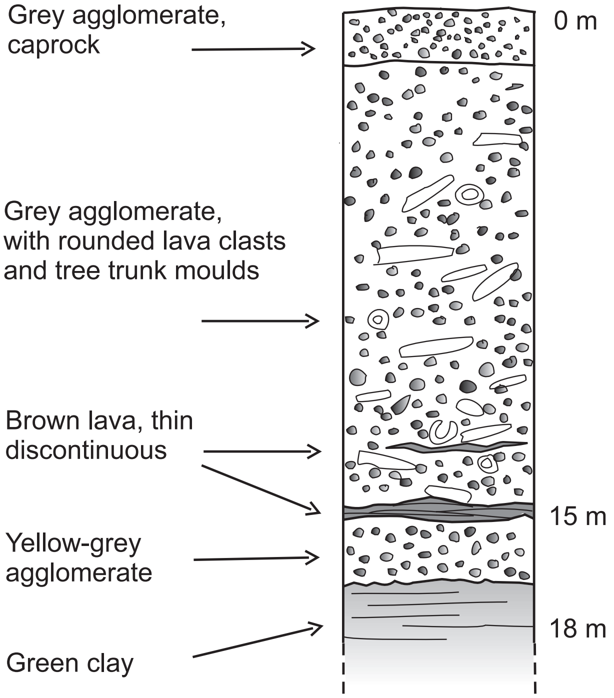

Figure 2. Generalized geological cross section in the vicinity of the caves. Thickness, although variable for each unit, is given from the top of the cap rock.

The Grey Agglomerate

The grey agglomerate (Fig. 3A) is the major rock unit, exposed in most of the chamber walls and roofs. It is pyroclastic, blue to grey in color, with dark-colored clasts of varying sizes, but which are usually <50 cm in diameter, subrounded, of alkalic lava or hypabyssal basalt, and have groundmass of light-grey ash (Davies, 1952; Hazlett, 2005, personal commun.; and field observations). Davies noted that the lavas are mainly composed of nepheline $(Na,K)AlSiO_4$, pyroxene $(Mg,Fe)SiO_3$, and magnetite Fe_3O_4. The fine-grained groundmass between blocks is ashy, with crystals of nepheline and pyroxene, vesicular in zones; the vesicles are irregular, subrounded, and lined with acicular zeolites. The bedding surfaces are often somewhat undulating; the beds are typically 1–1.5 m thick, often lenticular, and 20–30 m wide. In several places, slickensiding between units is apparent, giving flat to gently curved smoothed and polished separation surfaces, now apparent as a particularly flat, smooth part of the cave roof.

One of the most interesting features of the agglomerate is the very many fossil remnants it contains. These include trees trunks (up to 1 m in diameter, typically in random orientations), trunks with intact root systems, twig piles, and occasional mammal bones. The wood is often replaced by zeolites or calcite (Sutcliffe, 1973), but the wood form is retained (at least macroscopically). Many tree-trunk molds have developed where decayed trees left voids (Fig. 3F); the molds are often lined with sharp needles of zeolite crystals, sometimes acquiring stalactitic forms (Fig. 3E).

In general, this unit is well lithified and mechanically strong, with few vertical joints. It shows a gradation from top to bottom, from strongly to less lithified, from less to more groundmass, and from fewer to more vesicles. The uppermost couple of meters, the cap rock (over which the waterfalls fall), is particularly well lithified. The paucity of roof drips in the caves and of visible roof cracks suggests that the cap rock and upper layers of the grey agglomerate have low primary and fracture permeability. The lower layers of grey agglomerate, less well-lithified and with more ashy groundmass, have higher primary permeability and more secondary salts.

The Brown Lava

This very distinctive, 0–30-cm-thick, dark-colored, brown-black lava flow (Fig. 3B) contains numerous spherical, silica-filled amygdules (up to 2 mm in diameter) and is up to 20% vesicular (Hazlett, 2005, personal commun.). It forms smooth blocks with conchoidal fracture, and is composed of nepheline and pyroxene, but mainly pyroxene (Davies, 1952). This layer is often discontinuous, or complex, made up of several separate layers separated by a few centimeters of white ash, draped over the undulations of the underlying rock; it is thicker where it filled shallow swales. It has very low primary permeability and thus acts as a local leaky aquiclude and is the source of most of the cave roof drips.

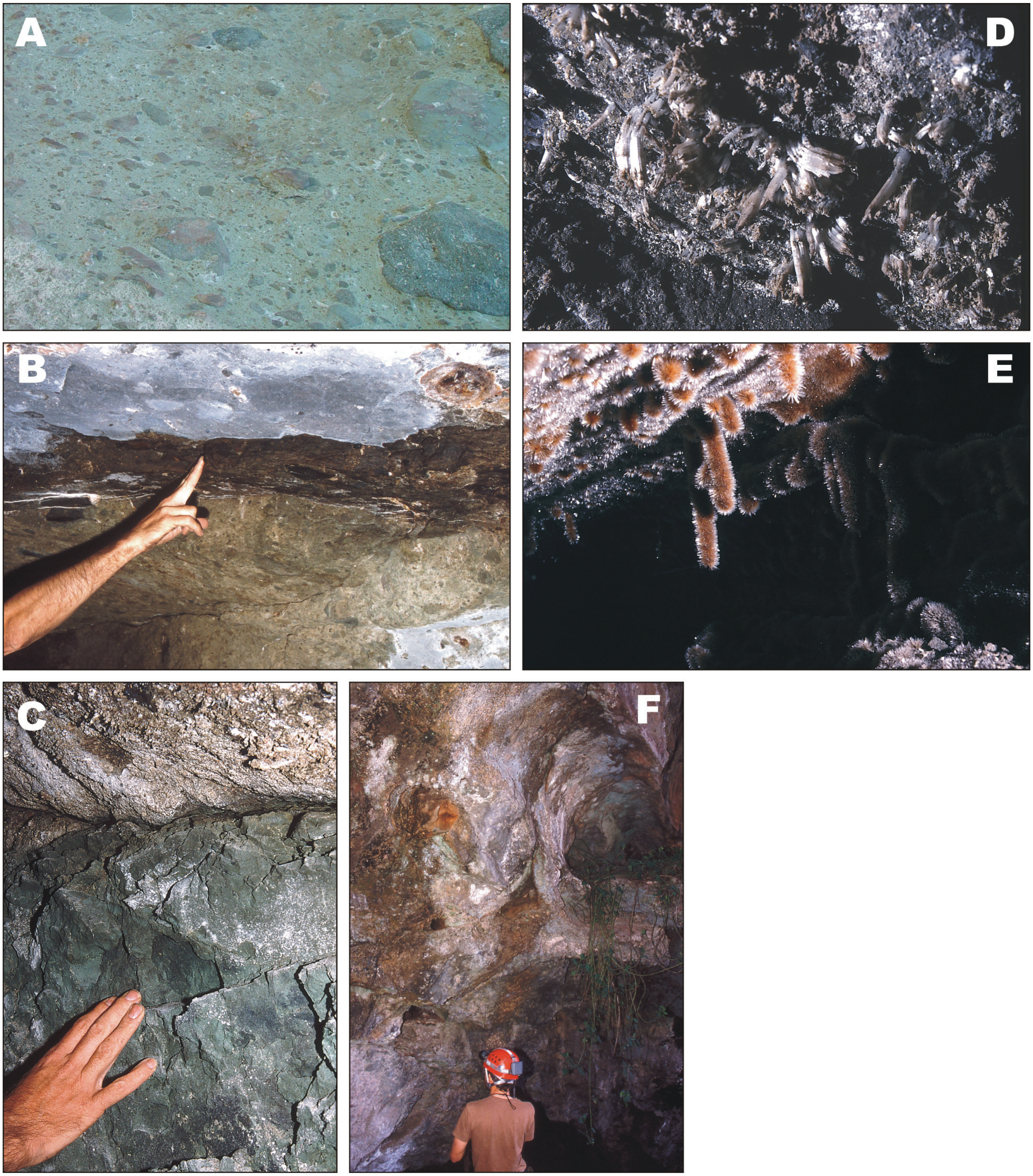

Figure 3. (A) Grey agglomerate with subrounded lava clasts, up to ~50 cm in diameter. (B) The contact of the upper grey agglomerate with the thin brown lava layer above the yellow-grey agglomerate. (C) The contact of the yellow-grey agglomerate above the green clay unit. (D) Mirabilite crystals growing on the yellow-grey agglomerate. (E) Zeolite crystals lining large tree-trunk void in grey agglomerate, stalactitic forms are ~10 cm long. (F) Tree-trunk void in the roof to right of the caver's head resembles phreatic tube and ends ~2 m into rock face.

The Yellow-Grey Agglomerate

The yellow-grey agglomerate (Fig. 3B) is also a tuff breccia but is noticeably less well indurated and more permeable compared to the upper grey agglomerate; it is sometimes quite friable and ashy or clayey. The bed thickness is variable at ~2–4 m. It also contains many clasts of variable sizes, of subrounded, glassy basaltic lava. It is much more porous than the grey agglomerate; it also more readily produces secondary salts.

The Green Clay

The green clay unit (Fig. 3C), of smectite swelling clay, is an altered (weathered) tuff that formed by settling of a pyroclastic density flow incorporating a few pieces of country rock. It shows very fine texture, well-developed bedding, and is not indurated. The bed is at least 2 m thick (but the lower contact was never observed), with an often slightly undulating upper surface. The clay is wet (clay surfaces in the cave usually weep), but may dry and crack on exposure to cave air. This layer acts as an aquiclude, more effective than the lava flow, because it is more laterally continuous. This clay is the local base level for the caves; no passage cuts below this unit.

Secondary Minerals

Much of the agglomerate and lava has been replaced by zeolite (most commonly natrolite, a hydrated sodium aluminum silicate $Na_2Al_2Si_3O_{10}$-$2H_2O$) and calcite ($CaCO_3$). Davies (1952) estimated that 30%–40% of the volcanic pile may be zeolite or calcite. Most of the zeolite is microcrystalline, but in voids, it can form acicular crystals a centimeter or so in length.

Evaporation from damp surfaces, especially toward the backs of caves, causes rapidly growing efflorescences of secondary salts. Most publications focus on the sodium sulfate salt, mirabilite (Fig. 3D). Ollier and Harrop (1958, p. 159) reported thick encrustations of sodium sulfate crystals "curling like a pig's tusk." Hill and Forti (1997, p.198) suggested that the caves of Mount Elgon offer the "best display of mirabilite flowers anywhere." Bowell et al. (1996) identified ten salts in the wall salt crust, the most common of which were (in no particular order) calcite ($CaCO_3$), halite (NaCl), anhydrite ($CaSO_4$), polyhalite ($K_2MgCa_2(SO_4)\cdot 2H_2O$), natron ($Na_2CO_3$), and mirabilite ($Na_2SO_4\cdot 10H_2O$).

The Caves

We surveyed five caves (Figs. A1–A4 [see footnote one]), three of which are relatively large: Kitum Cave (main chamber and antechamber; 165 m in length), Mackingeny Cave (250 m), and Ngwarisha Cave (150 m). Chepnyalil is a small, wide cave (26 m deep, 54 m wide). Kiptoro (10 m deep) is essentially an extended rock shelter. Elevations of cave entrances were estimated with GPS; four of the caves are at roughly the same elevation, 2400 m, and Ngwarisha Cave is ~100 m higher.

The typical cave entrance is marked by a small waterfall spilling over the entrance cliff. The water does not run into the caves, rather it seeps downslope into collapse blocks and vegetation. No streamway emerges from any of the entrances.

The entrance regions and part of the main chambers are open to light, and reduced humidity. The more distal parts of the caves are fully dark and climatically isolated from diurnal oscillations of temperature and humidity. The larger caves have very large populations of the megachiropteran bat *Rousettus aegypticus*, and the roosting areas (at the apices of the collapse domes) have elevated temperatures and humidity. Elephant trails are well marked in some parts of the caves. These are lined with a soft layer of degrading dung. Where the route is restricted between large collapse boulders, e.g., at the entrance to Kitum Cave, the pathway is entrenched by some decimeters.

The cave interiors are essentially somewhat elongate to quasi-circular, cul-de-sac chambers (Figs. A1–A4) filled with collapse slabs. In many cases, the collapse is very recent, the slabs on the floor being only slightly fractured and all the fracture surfaces still fresh and unweathered. The most recent collapse in the Kitum Cave main chamber is known to have occurred in 1982, when a large section fell, killing at least one elephant (Redmond and Shoshani, 1987). Exploration of the less accessible parts of the caves, beyond the collapse blocks and under the deep undercuts of the extremities, revealed that the base of most of the cave walls (at least those not obscured by collapse) is in the green clay unit. No part of any cave extends below the clay unit. The long sections are essentially horizontal just above the level of the top of the green clay, with one major collapse dome and debris pile toward the back of the each cave. The basal cave walls are more-or-less dentate, made up of a series of alcoves and cusps, most of which are undercut to some extent.

Channeled Water Flow and Dissolution

The caves are almost invariably associated with surface water streams; they were initiated behind waterfalls under small surface stream valleys. However, no evidence of channeled water flow was found inside the caves, even after heavy rain. Ollier and Harrop (1958) reported one "water-worn channel," but they reported no active water flow. The only clear-water pool, perched on the clay aquiclude at the back of Kitum Cave, shows no active flow, although it may drain slowly to groundwater. Channeled water flow above an aquiclude should produce piping, but a search in the extremities of the cave for evidence of piping above the clay layer proved unsuccessful.

The caves are surprisingly dry inside, even during the wet season. The grey agglomerate cap rock does not appear to allow any drip water through. Percolation of groundwater (focused underneath the shallow surface stream valleys) occurs in the lower layers of the grey agglomerate and, especially, in the yellow-grey agglomerate. Seepage from the cave wall is apparent only in the lowermost meter or so of the yellow-grey agglomerate (from the aquifer perched above the green clay) and from the green clay. Roof drips are limited to cracks in the lava (from small perched water bodies), and close to entrances where the cap rock is beginning to crack. In the dry season, most of the undercuts marking chamber edges remain muddy; in the rainy season many parts are inundated with standing water. All caves have isolated patches of muddy floor where the roof drips. The only other damp spots were some guano piles under the bat roosts (some of these unpleasantly, fetidly damp!).

Since both vadose and phreatic passages have been reported (Ollier and Harrop, 1958; Wright, 1961), a careful search was made for such features. However, no evidence was observed of simple karst dissolution (i.e., congruent dissolution), either active or relict, in the passage form, or in the details of rock surface morphology. We consider that the round tree-trunk molds in the grey agglomerate may have been mistakenly identified as phreatic tubes. These molds, on close examination, prove to be often lined with zeolite crystals, and to be limited in length (Fig. 3E–3F), some ending in a mass of root remains. The elephant-worn pathways superficially resemble, and may have been interpreted as, vadose channels. A similarly unsuccessful search was made for evidence of karst resurgences in the surface valleys below the caves.

No passages showed evidence of phreatic or vadose action, and no rock surfaces showed evidence of scalloping or erosional marks from fluid flow. The sediments making up the cave floor today are clay, guano, dung, and lots of collapse blocks. These do not show any evidence of current activity (although it is acknowledged that sediments that may have been deposited early in speleogenesis and since buried by collapse are not now accessible). Our conclusion for these five caves of Mount Elgon is that there is no morphological evidence for karst dissolution or for any kind of channeled flow.

Geophagy

Animals are presumed to engage in geophagous ("eating dirt") activity to supplement low sodium levels in food and water supplies (e.g., Holdø et al., 2002). Krishnamani and Mahaney (2000) suggested that it may also supplement iron at high altitudes. Geophagy is obviously a common activity in the Mount Elgon caves. In addition to the elephants, a variety of animals uses the cave, including buffalo, bushbuck, rock hyrax, leopard, hyena, and primates (Redmond and Shoshani, 1987; Redmond, 1982, 1992; Bowell et al., 1996). The evidence of elephant tusking of the walls, both recent and old, is clear. The question is of the significance of geophagy to speleogenesis.

Evidence for three main types of geophagous activity was documented in the details of the cave walls: (1) by elephants, (2) by bushbucks (and possibly other small animals), and (3) by humans (indirectly geophagous; humans mine the salts for their cattle). The softest lithologies (mainly the yellow-grey agglomerate) are clearly favored by all species, presumably because they are easiest to excavate. However, if the harder material is supplied by natural collapse (see following), then it is eaten. Bowell et al. (1996) suggested that the collapse material is rendered more attractive by chemical alteration. Other animals, such as buffalo, are geophagous, but they do not directly excavate the cave walls; rather, they eat the rock that has already been dislodged by elephants.

A process that removes mineral material from the caves, related to animal activity, but not directly geophagous, is the carrying out of mud on the feet and bodies of the animals. Tree trunks in the vicinity of cave entrances are smeared with mud from passing animals.

Elephants

Tusking, carried out in an upward motion, produces scars typically ~2–4 cm wide and 10–30 cm long, of elongate form, and relatively flat cross section (Fig. 4A). They are curved, often forming a criss-cross pattern. Where the tuskings are old, they show a furry lining of fibrous mirabilite crystals. Mirabilite forms new crystals rapidly (Sutcliffe, 1973), so these "old" tuskings may not be very old in absolute terms.

Tusking causes impacts at two levels. On the larger scale, tusking impacts location and form of alcoves at floor level or at the access point; at the smaller scale, it impacts the form of the rock surface. Tusked notches are up to ~4 m high and generally ~3 m deep; the floors are not particularly flat (Fig. 4D, 4F). Several examples exist where access to tusking sites has been blocked by large-scale collapse; new collapse blocks provide access to higher parts of walls; thus the locus of tusking moves in tandem with collapse, and the simple floor-level notch becomes a more complex series of notches. Tusking is also apparent on the larger and more stable collapse blocks. Some of the tusked areas, especially those in association with human mining, have a complex three-dimensional alveolar pattern that superficially resembles phreatic spongework. Tusked walls and ceilings develop a medium-scale roughness. Lava clasts surrounded by tusk marks emerge as the groundmass is removed around them; they eventually fall out, producing piles of roughly rounded debris on the floors that are quite distinct from angular collapse blocks.

The locus of tusking is clearly related to lithology. Elephants show a distinct preference for the soft yellow-grey agglomerate (Fig. 4F). Areas with few, separated, large clasts, and thus lots of easily mined groundmass, are well tusked. Areas with many small clasts are not as popular. In places, the division between tusked and nontusked is very clearly demarcated. The elephants may not tusk the upper unit much; however, Redmond and Shoshani (1987) observed that they happily eat the fallen material.

It is hard to quantitatively estimate the importance of tusking. The ceilings of most chambers are too high for elephant access; thus tusking has to be restricted to the cave edges and to blocks in the floor. Geophagous consumption of small floor blocks obviously leaves no evidence, except in the dearth of floor blocks; thus, it is inherently more difficult to find evidence of

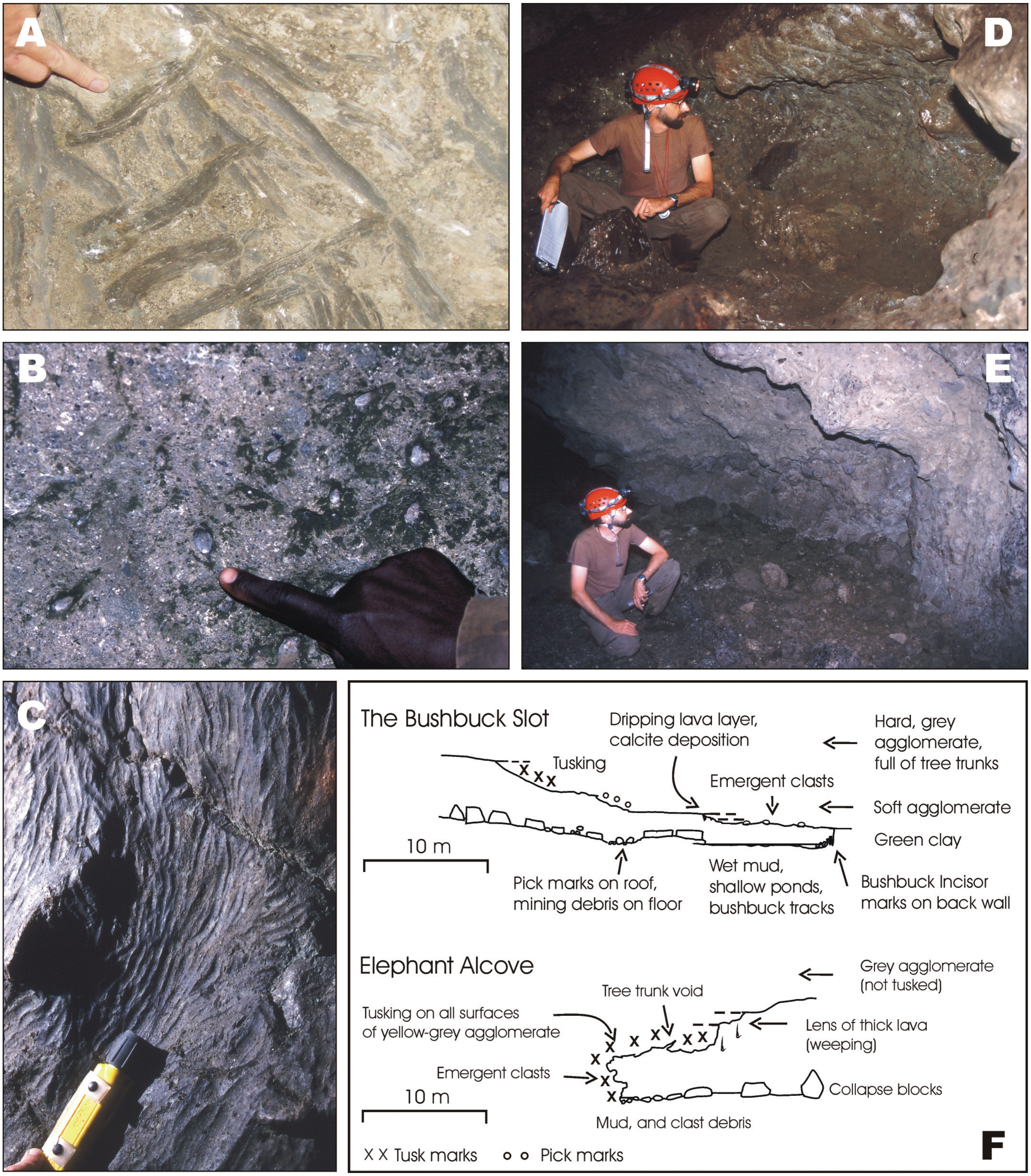

Figure 4. (A) Elephant tusking in Kitum Cave, yellow-grey agglomerate. (B) Pick marks in Mackingeny Cave, yellow-grey agglomerate. (C) Teeth marks from bushbuck incisors in Ngwarisha Cave, green clay. (D) Alcove in Kitum Cave full of tusked surfaces and emergent clasts, yellow-grey agglomerate. (E) Alcove from human mining, full of pick marks, characteristic rounded mining debris on floor, yellow-grey agglomerate. (F) Cross section of the "bushbuck slot" in Ngwarisha Cave and "elephant alcove" in Kitum Cave.

geophagy on collapse blocks. Except for Chepnyalil (the shallow rock shelter), all the caves show evidence of tusking, although in some places the walls and ceilings are so weathered and flaked (see following) that details of previous processes are obscured, so that old tusking would not be now visible. Roughly half of the cross sections show evidence of tusking, and about one sixth of the cave edges show tusking. However, about one third of the basal walls cannot be seen because of collapse. Thus, the absence of tusk marks in the survey is not necessarily an indication of the absence of tusk marks on the basal walls. In some cases, it seems evident that tusking alone is creating the passage; e.g., section D of Kitum Cave (Fig. 5C) shows a passage completely excavated by tusking behind the main cave wall, which is also completely tusked up to a level of ~3 m. Almost all of the right-hand wall in this section of the cave shows tusking, but most of the basal wall to the left, around the 1982 collapse, cannot now be seen.

From field observations of the volumes of material ingested by individual elephants, Redmond and Shoshani (1987) made a very rough estimate of the volume of rock that may be removed by elephants. One elephant was observed removing an estimated 10 L volume of rock in one hour. This level of activity may be extreme, so a very conservative estimate of the level of removal by all the elephants in Kitum Cave per night was 1–2 L or ~0.75 m^3/yr (Redmond and Shoshani, 1987). From our new survey, the volume of Kitum Cave is 70,800 m^3. Using the most conservative estimate of elephant ingestion and current elephant population levels of ~150 individuals (P. Omondi, 2003, personal commun.), the necessary mass removal could have been accomplished in ~90,000 yr (if elephant geophagy were the only process in operation). Using the historical population (pre–twentieth century poaching) of ~1200 forest elephants (Redmond and Shoshani, 1987), mass removal could have been achieved within the Holocene, particularly since it was achieved by more than this single process (see following).

Bushbuck

Geophagy by bushbuck (*Tragelaphus scriptus*) has received very little attention in the literature, possibly because the evidence of their activity is not usually separable from that of elephants. However, our survey showed that they can have a considerable and geomorphologically distinct impact. In Ngwarisha Cave (Fig. 4C, 4F), bushbuck have mined the clay unit rather than, or in addition to, the agglomerate. The deeply incised, very muddy "bushbuck slot" is only ~1.5 m high, too small for elephants. The incisor teeth marks run vertically down the wall, each <1 cm wide and 5–10 cm long. Teeth marks have only been found in the clayey tuff. Bushbuck have been observed beside the agglomerate (photograph by Redmond published in Bowell et al., 1996), but if they do actively mine it, the evidence of small incisor marks would not be retained in this coarser-grained material or would be destroyed by elephant activity. The volume of material removed in this slot can be calculated from its dimensions (~16 m wide, ~10 m deep, ~1.5 m tall); this is ~240 m^3 or ~96,000 kg of material. The area of the bushbuck slot (~160 m^2) comprises roughly 2% of the cave's total area (~8500 m^2).

Humans

There is a long history of human mining for salts to supplement cattle feed. This is recorded on the cave walls by round pick-axe marks. Picking is carried out in a downward motion; the scars are usually ~1–2 cm wide, <10 cm long, and end in a narrowing pointed pit (Fig. 4B). The pattern is of round holes more than elongate scars, often all in the same orientation. On the larger scale, the result of picking is complex rounded alcoves (Fig. 4E); these are ~1.5 m high (but can reach 2.5 m), and are often quite deep into the rock face, e.g., ~6 m. These old mines can be recognized by the flat floors and unique mining debris—a single layer of rounded clasts, cleaned of all groundmass and typically 10–30 cm in diameter. Sometimes the contact of the softer agglomerate with the harder upper unit forms a nearly horizontal roof to the mine (Fig. 5D). As with the elephants, the locus of picking is largely confined to the softer agglomerate; pickings stop at the upper level of the clay unit. Many of the large floor blocks are also well picked.

Ngwarisha Cave has some of the best developed sites of human mining activity; many of the old pickings predate roof collapse. It has the best examples of picked floor boulders; for some, half of the boulder has been removed. For boulders taller than ~2 m, the picking of the lowest level resulted in a round-ended, triangular undercut (Fig. 5A). Another example of this picked notch is well developed both inside and outside Kiptoro Cave (Fig. 5F); very little rock material is left between the inside and outside picking alcoves.

Kiptoro Cave is an example of the general observation that elephants and humans often focus on different parts of the cave: Tusking is apparent in the darker and muddier parts of the cave, while human activity is more commonly apparent in the drier and brighter zones.

Humans also occupied some caves for shelter. Chepnyalil Cave was occupied until ~90 yr ago (local knowledge, from park rangers). The walls and ceiling show lots of soot. The alcove with the wall and fence appears to have a more artificial shape than the rest of the cave; it is only ~1.5 m tall, and shows evidence of picking. It is surmised that this whole alcove was created by humans.

Again, it is very difficult to estimate the total impact of human mining activity. Ngwarisha Cave shows evidence of picking on about one quarter of the walls, but about one third of the basal wall is obscured by collapse. Kitum Cave shows picking on about one sixth of the wall, but about one third is obscured by collapse. Mining by humans has decreased noticeably since World War II, although some activity remained at least until 1973 (Sutcliffe 1973), so this type of geophagous activity has largely stopped now.

Collapse

Collapse is obvious, recent and ongoing. The large caves have abundant fresh surfaces on ceilings, and large blocks on the floor, some of which have scarcely broken in their fall and

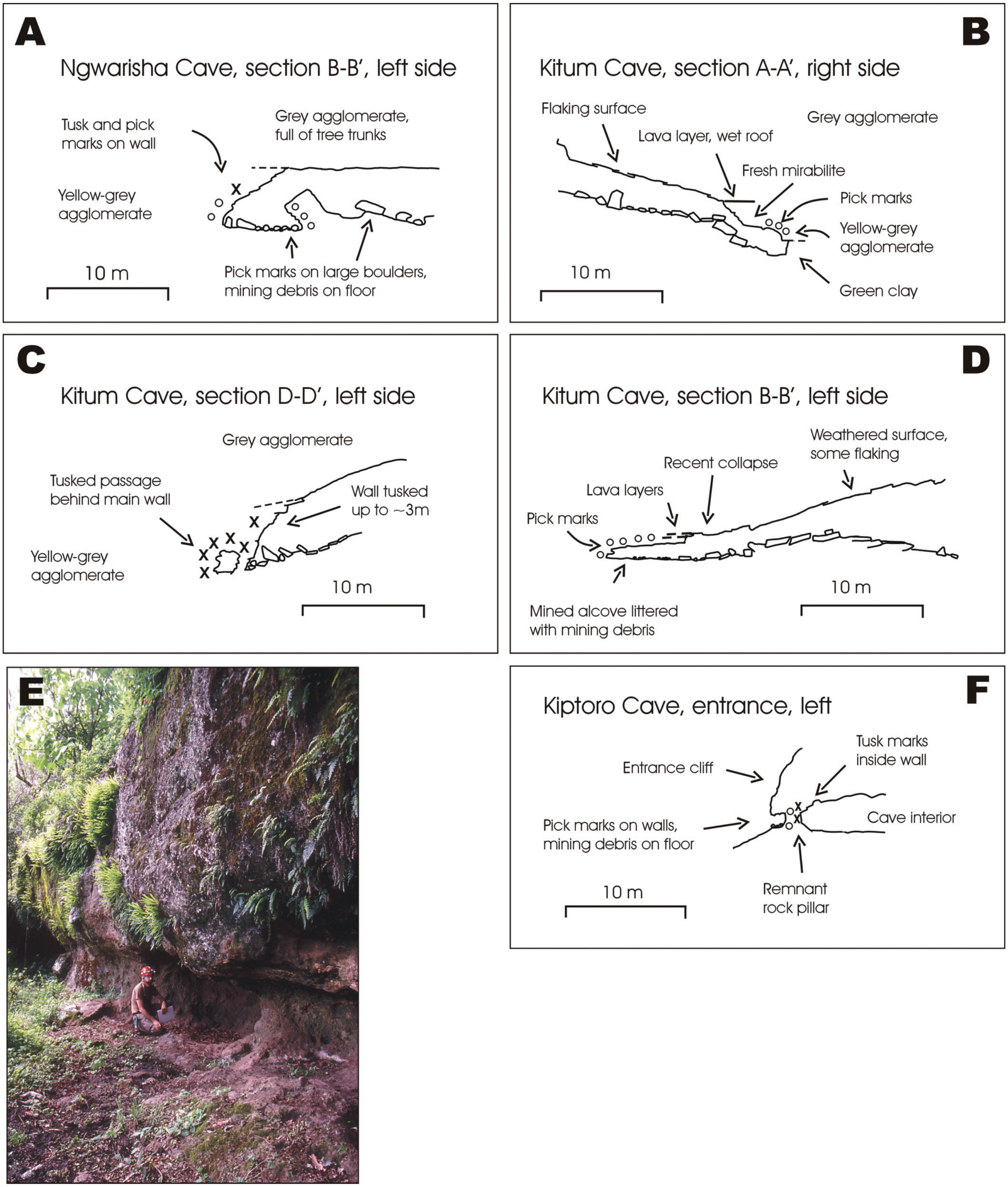

Figure 5. (A) Ngwarisha Cave: floor boulders and wall are mined by humans, creating "mushroom rock" effect. (B) Kitum Cave: example of a cave extension along green clay, augmented by human mining of yellow-grey agglomerate. (C) Kitum Cave: extensive tusking is noted in yellow-grey agglomerate at back of cave, the wall of the main chamber is tusked up to contact with hard grey agglomerate, and the chamber behind the main wall was created by tusking. (D) Kitum Cave: the alcove was created by human mining in yellow-grey agglomerate, the ceiling is made up of the lava layer, and the grey agglomerate has not been picked. (E) Kiptoro Cave: left side of entrance cliff, a quasi-horizontal notch has been cut by mining into yellow-grey agglomerate. (F) Cross section of Kiptoro Cave from outside cave to interior, showing extent of mining removal of support wall.

can be matched to the roof from which they fell. Kiptoro Cave is the only one that does not show major, and recent, collapse. Collapse produces the gross morphology of the cave chambers, the wide dome cross section, the avens (only one, in Mackingeny Cave), and the mounds of collapse blocks lining the floors. The breakdown morphology is mainly of the slab breakdown category (White and White, 2000), but block breakdown is also common. The failure is sometimes along sedimentary structures, such as bedding planes and geological contacts (e.g., of yellow-grey agglomerate and clay, and of grey agglomerate and lava), but many times the fracture is of intact rock masses. Individual beds or lenses may be mechanically strong, with the collapse block retaining its coherence. Where collapse exposes the thin lava flow, then water movement is initiated and adds to the potential for further failure, especially immediately above the lava.

Fracture surfaces are usually planar to gently curved in form, and the clasts are often sheared off and pale grey in color. They then get modified by other processes (documented herein) to become black in color and differentially etched with emergent clasts. Cycles occur of fracture followed by modification of surface by physicobiochemical processes, renewed fracture, etc.

The locus of collapse has shifted to the backs of the caves. The extended long sections of each of the three large caves have the same pattern. The front part is relatively stable and has flat floors with only a little old debris. Toward the back, the cave floors rise over the pile of recent collapse, and the cave ends at roughly the same level as, or slightly lower than, its entrance.

Unless there is a mechanism for continued creation of instability, mass movement is inherently limited, because the fallen material creates a buttress. Collapse creates more volume of debris than the original rock volume. Thus collapse can continue only where the collapse material is constantly removed. This must be true of the caves of Mount Elgon, since the mass of collapse blocks toward the entrances has been largely removed. It is obvious that collapse is an ongoing process; removal of material must also be ongoing. In the absence of any evidence of water flow, and in the presence of clear evidence of geophagy, both on walls and on floor blocks, we conclude that the removal of collapse material is effected by animal activity.

Biogeochemical Processes

Biological activity is focused in two areas. One is the bat roosts at the back of the caves, and other is the photic zone at the front of the caves.

Bat Roosts

The caves house large colonies of bats, primarily the frugivore *Rousettus aegypticus*, with smaller numbers of insectivorous species, especially horseshoe (*Rhinolophus*) bats. Temperature, humidity, and presumably CO_2 levels are elevated in the bat chambers. The roofs show etching and discoloration (Fig. 6D). The roosts and staining typically occur at the apex of the roof dome out of reach of animals. An obvious direct association of bats and ceiling corrosion occurs in the Kitum Cave antechamber, where etching has produced emergent clasts to a depth of ~10 cm, immediately above a small pile of bat guano.

Floors under bat colonies are obscured by deposits of guano from insectivorous bats, or bat "honey" from fruit bats. The bat honey is a sticky mess of poorly digested fruit that coats every surface with acidic organic material (Bowell et al., 1996, observed that bat guano has a pH of 3.8 to 5). In addition, bat urine and water from condensation keep the whole surface damp. Chemical degradation is active beneath this carpet. Bowell (1992) and Bowell et al. (1996) suggested that the zeolites react with bat guano to produce secondary halides, phosphates, and nitrate minerals. The processes are likely to be complex, but it seems clear that the organic activity associated with bats contributes to the corrosion of ceilings and to the removal of collapse blocks from the floor.

Photic Zone

Where rock surfaces get some light, they are coated with a black layer of algae/cyanobacteria, which cause biological weathering. The clasts are more resistant and thus become emergent. Kiptoro Cave is almost all within the photic zone. Some of the walls show evidence of tusking and picking, but most show complex carious weathering etching out clasts and tree fossils (Fig. 6C).

Corrosion, Condensation, Efflorescence, Pressure Release

These processes may be minor compared to collapse and geophagy, but they are ubiquitous. Every surface that has not recently fractured shows some evidence of chemical alteration and/or some type of flaking.

Chemical Alteration or Corrosion

Chemical weathering is dominant in the regions of high humidity, both from percolation waters and from condensation. Unlike the simple dissolution associated with karst caves, this corrosion is likely to result from a mix of incongruent dissolution, replacement, oxidation, etc., processes. Typically, the clasts are not significantly affected, while the groundmass becomes decayed. This can be seen as a weathered aureole around large clasts (Fig. 6C). The groundmass falls away, leaving a surface morphology of emergent clasts. In turn, these may fall out, leaving a circular cavity. In the main chamber of Kitum Cave, much of the back wall of the cave and above the pool shows alteration; the surface of the groundmass is softened to a depth of ~10 cm, but the clasts remain unaffected (Fig. 6B). The emergent clast morphology produced by corrosion is more fretted than the emergent clast morphology from geophagy. Note that the clasts are not always resistant to weathering. In Chepnyalil Cave, some of the clasts have become oxidized, yellow-brown and soft, easily pried with fingernails, while some of the clasts remain grey and hard.

Figure 6. (A) Kitum Cave antechamber, close to entrance: Efflorescence flaking of ceiling and wall surfaces in grey agglomerate is shown. (B) Kitum Cave antechamber, close to back of the cave: Spongey carious weathering of ceiling in yellow-grey agglomerate. The rock is soft to a depth of at least 10 cm. (C) Mackingeny Cave: Weathered aureole around large clast in grey agglomerate (~50 cm wide); eventually the clast will fall leaving circular cavity in roof. (D) Mackingeny Cave: roof discoloration from bat roosting; white blobs are ~20 cm wide.

Condensation

Condensation corrosion is now well documented in many karst caves. It might be expected that condensation would also cause weathering in nonkarst situations. As a preliminary check on the possibility of this process in these caves, we took some simple measurements of microclimate. Over the course of six days, temperature sensors were deployed in different parts of Kitum Cave. The outside diurnal temperature oscillation was from a maximum of around 14.5 °C to a minimum of around 12.5 °C, with an average of 13.6 °C. The temperature at the back of the cave, just above the standing water, remained constantly cool at 12.5 °C (it is reported in Bowell et al., 1996, as a constant 13.5 °C). The right-hand entrance above the mud wallow again oscillated diurnally but was the coldest part of the cave, ranging from 12.5 °C by day to 11.5 °C by night. Condensation is probable on these cold walls, both at the back of the cave and at the right-hand entrance. Although the accuracy of the humidity sensors was low, these two locations indicated 100% humidity.

Efflorescence, Salt Weathering

The growth of crystals (mirabilite and other salts) is an effective agent of physical weathering in the Mount Elgon caves. The geomorphic effect is “onion” weathering, i.e., surface flaking, at several scales, from ~1 cm up to ~20 cm (Fig. 6A). As crystal growth fills the interstices, a surface crust develops (usually dark in color from oxidation and/or cyanobacteria) (Bowell et al., 1996). Further crystallization beneath the crust forces it outward, the crust lifts and cracks and finally falls away leaving a white patch. The most descriptive adjectives for the patchy surfaces produced are “leprous” or “scrofulous.” Efflorescence is focused in two main loci: (1) In the yellow-grey agglomerate above the clay unit, especially at backs of caves, mirabilite crystals coat the surfaces not yet grazed by animals, and (2) in the walls and roofs in entrance zones. Diurnal oscillations of cool/humid periods with warm/dry periods trigger cycles of dissolution of salts followed by crystallization.

Pressure Release

Larger-scale flaking that is not associated with white crystals appears to be caused by pressure release. Joints develop parallel to the cave wall, and the resultant slab tilts inward, eventually breaking off to leave a fresh surface. Pressure release seems to operate most clearly on some of the non–bedding plane fresh fracture surfaces, with flakes developing that are ~30–50 cm wide and ~5–10 cm thick.

Clay Failure and Groundwater Sapping

Where the saturated clay is exposed in the cave wall, loss of lateral confining pressure contributes to slow failure. In addition, desiccation/contraction cracking occurs upon exposure to <100% humidity cave atmosphere; the clay disintegrates into fragments, a few centimeters in size up to blocks of ~10 cm. The exposed clay face is nearly always undercut, the roof of the notch delineated by the clay-agglomerate contact, and is floored by mud (Fig. 5B). To maintain this square-ended undercut, the clay must be regularly removed; yet no water flow was observed carrying clay away from the face. Animal activity—the mud is always full of hoof prints—seems to be one way that mud can be removed. However, it is likely that slow groundwater sapping does occur. The clay layer is always the lowest point of any cave and is thus the site of pools in the wet season; the water would gradually eat away at the clay layer.

Impact of Quaternary Climate Change

If it is assumed that the caves predate the Holocene (although this is unlikely with estimated rates of geophagy), then they have experienced several climatic regimes, which would have shifted the balance of processes. Mount Elgon is not glaciated today. Occasional snows still fall on the higher slopes, but accumulations are short-lived. The Last Glacial Maximum was coincidental with colder, drier conditions in the region (Hamilton and Perrott, 1978, 1979; Hamilton, 1987). Mount Elgon glaciers then extended down to below 3400 m (i.e., only ~1000 m above the cave level). Temperature depression was at least 3.5 °C (Hamilton and Perrott, 1979), and temperature ranges were greater. Frost action was probable close to the entrances. It is likely that elephant activity would have moved along with forest limits to lower regions. Deglaciation (ca. 11 ka, Hamilton and Perrott, 1978) may have been the most geomorphologically active period, with the additional melt water raising groundwater and surface water levels.

PROPOSED SPELEOGENESIS

The caves are almost invariably associated with surface water streams; they are initiated behind the waterfalls. They start as simple undercuts, but are obviously enlarged by additional processes. In this, the clay layer is pivotal. Its behavior as an aquiclude forces groundwater movement into the soft yellow-grey agglomerates immediately above the clay, thus focusing groundwater sapping into one narrow zone (a cave might thus be initiated even in the absence of a waterfall). Collapse of the agglomerate layers exposes the attractive sodium-rich salts and stimulates geophagous enlargement of the undercut. The production of secondary minerals is also more effective in the damp layers. The incompetence of the soft yellow-grey agglomerate layer stimulates stoping upwards of the cavity to create a space that can be more easily enlarged by elephants. The clay layer thus governs the level of cave enlargement. Another important process in the lateral extension of the caves is the continuing degradation of the clay layer itself, causing undercutting and collapse of the overlying layers, stimulating further lateral cave extension. It is perhaps fortuitous that the mechanically less tough and hydrologically more permeable yellow-grey agglomerate is immediately above the clay layer (although logical in terms of the volcanic sequence; Ollier and Harrop, 1958). Without this, seepage and efflorescence would be considerably less and the mining by animals of the harder grey agglomerate would have a minor effect.

Caves develop vertically by collapse, creating collapse domes. Collapse produces much of the wall and roof surface morphologies of fresh fracture planes. The locus of collapse moves inward as the cave edges extend along the clay layer. The smaller caves are dominated by complex alveolar animal- and human-mined alcoves with minor roof collapse features. Removal of material is both geophagous and through transport on feet and skin. The ongoing removal of material allows continued collapse.

Complex weathering (a combination of chemical, biological, and physical) modifies all surfaces. Weathering mechanisms include dissolution, pressure release, chemical alteration, biological weathering/erosion from high bat activity, efflorescence, and salt weathering.

The balance of speleogenetic processes shifts as the caves enlarge. Clay layer failure, collapse above the clay layer, and removal of material by animal activity are the dominant early processes. However, as the cave enlarges and the microclimate of the inner reaches becomes more conducive to corrosion, and as the deep environment becomes conducive to bat colonization, geochemical and biogeochemical weathering is added.

In view of the multiplicity of the processes involved, it is impossible to estimate the absolute contribution of each. We conjecture that speleogenesis had been initiated by the late Pleistocene deglaciation, and has been active throughout the Holocene. Working with very rough estimates, if it is presumed that 1200 elephants removed ~6 m^3/yr from Kitum Cave and the cave is 70,800 m^3, the cave would have formed in ~12,000 yr. Additionally, if other animals and perhaps humans provided another 1 m^3/yr of rock removal, then the cave could have formed in 10,000 yr. If the other geomorphological processes discussed here are also considered, estimated at ~0.1 mm of rock surface removal per year (i.e., ~1.4 m^3), then the cave would have formed in ~8500 yr.

CONCLUSIONS

1. The "elephant caves" of Mount Elgon cannot be attributed solely to a single speleogenetic process. The caves result from a fortuitous combination of a suitable geological sequence and a population of salt-hungry elephants.
2. The caves were initiated by undercutting behind waterfalls of small surface streams that flow over a resistant cap rock of dense agglomerate.
3. Cave development is strongly related to lithology and is principally governed by a thin, but laterally extensive, swelling-clay tuff layer at the base. This aquiclude focuses groundwater sapping, lateral extension of the cave walls, and indirectly roof collapse. The clay layer is the base level for cave deepening.
4. Geophagy by animals also plays a pivotal role in that it increases the rate of lateral extension, trigger additional collapse, and remove the products of collapse. Geophagy and human mining govern much of the basal cave wall morphology.
5. Collapse governs the gross cave morphology. The dominant passage shape is breakdown dome, with abundant fresh collapse blocks.
6. A complex suite of chemical and physical weathering processes provides ongoing slow rock removal on all surfaces.
7. Biogeochemical activity starts once the caves are deep enough to house large bat colonies.
8. There is no evidence of water flow within the caves, nor of phreatic or vadose activity.
9. The caves are probably no older than Holocene.

Thus, the main explanation for the initiation of the caves is a simple geomorphological one. However cave enlargement by means of removal of material and continued collapse depends on animal activity. Geophagous elephants and other species, and some human mining for salts, significantly modify and enlarge the caves.

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