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Contents

Preface

The articles of this volume of *Documenta naturae* are an outcome of research activities undertaken at the Department of geology, Makerere University, Kampala, Uganda. All the contributions compiled here, convey first of all the common spirit of work ambitions in a country where research was quite difficult to carry out for a long period. Furthermore, the publication of these articles was stimulated by innovative advances during recent times:
The Geological Society of Uganda (GSU), already launched in 1970 but dormant more or less up to 1991, has been revitalized during a revival meeting on 16^{th} October, 1991, when 25 members enthusiastically participated. In § 51 of its constitution it is written that "the Society shall at an appropriate time promulgate a publication...". Thus, this volume is also understood as a contribution of the GSU to the progress of geology of Uganda.
On 26^{th} June, 1992, the new Japanese-donated Faculty of Science building (see frontcover) was officially opened by the Vice President of Uganda, Dr Samson Kisekka, and the Japanese ambassador to Uganda, Mrs. Sato.
Its ground floor, where the Department of Geology is now housed, contains two laboratories, rooms for rock polishing, mineral dressing, a dark room, a library, a map library, offices for staff and store rooms. But not only these new premises were handed over to the Department of Geology, also a lot of other equipment was received including several polarization microscopes, a mortar grinder, a plane grinder, stereoscopes and field equipment. In addition, to facilitate fieldwork, the department was given two new four-wheel-drive-vehicles. Thus undoubltly this generous project will have a strong impact on earth sciences in Uganda. Research and research-orientated teaching and learning with the aim to apply geological knowledge and techniques in the development of natural resources and in the managment of environmental demands has tremendously advanced. To contribute to these achievments with results of recent research activities is the aim of this volume.

The authors are most grateful to the co-editor of this volume, Dr R. Kohring (Berlin), for his technical assistence, and to Dr H.J. Gregor, the publisher of *Documenta naturae*.

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Meteorite Fall at Mbale, Eastern Uganda, 14th August 1992, a preliminary report

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and

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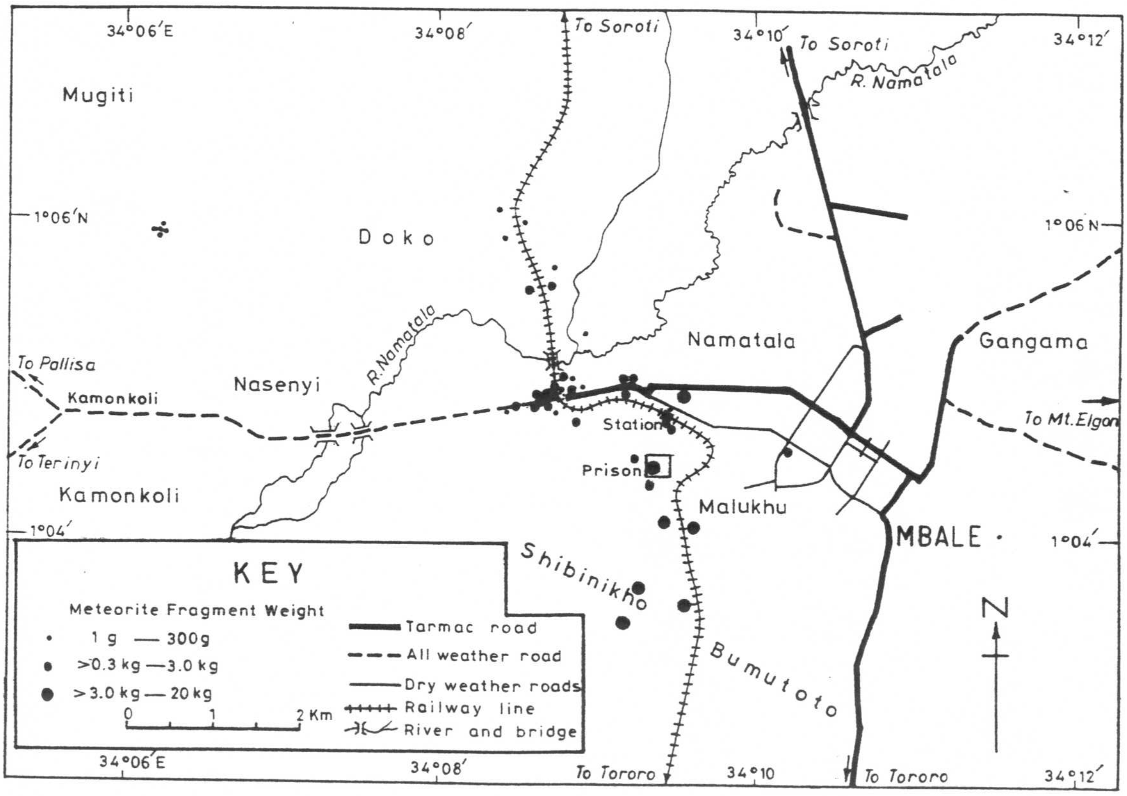
Abstract: On August 14th, 1992, at approximately 15.40 hours East African time, a meteorite fell at Mbale town, E Uganda. About 45 impact localities were traced during a subsequent survey carried out one week later, but their majority was already without fragments. The collected particles range from 3 g to 20 kg, with the trend of smaller fragments NWW and larger S of Mbale. Their strewn field indicated a NWW to SEE movement of the meteorite. On the basis of morphology, mineralogy, density and the presence of chondrules, the Mbale meteorite can be placed in group L of WASSON's classification system, tentatively belonging to the L6 chondrite group, the most common type of meteorite.

1. Introduction

On August 14th, 1992, at approximately 15.40 hours East African time, the residents of Mbale town and its outskirts were thrown into panic when they heard several loud explosions in the sky. These explosions preceded the fall of meteoritic material around the town. As much of the material fell on the township (where due to international scientific agreement for the naming of a meteorite also the next postoffice is based) it seems appropriate to call this the Mbale meteorite. This work reports on preliminary fieldwork and research carried out in the first few weeks following the fall.

It has been estimated that some 500 tons of rock debris enter the earth's atmosphere each day (SHORT 1975), but of this perhaps only 150 meteorites larger than 10 cm reach continental land masses each year. Of these perhaps only 5-10 are recovered annually.



Text-Fig. 1: Map of Mbale and surrounding areas, showing the strewn field. The meteorite was moving from the NWW to the SEE where the largest fragments fell.

The proportion recovered in Africa is less than elsewhere comprising only approximately 5% of the total of recovered meteorites. SASSOON (1967) put the number at 104 African meteorites comprising of 65 stones, 3 stoney-irons and 35 irons. Considering that many of these are finds (not seen to fall) rather than falls, this shows the fall of the Mbale meteorite is extremely significant.

There are two well documented meteorites from Uganda (ROBERTS 1947). The first fell at Maziba, near Kabale, SW Uganda in September 1942. It has been analysed and classified as a group L chondritre. The second fell on Soroti, E Uganda (approximately 100 km NE of Mbale) in September 1945. This fall was observed and well documented. The Soroti meteorite is an iron rich type but anomalous so falls in no category (WASSON 1974). The lack of other meteorite data for Uganda emphasizes the great value of the Mbale meteorite to indigenous research.

2.Location

Mbale town is located in the E of Uganda between latitudes 01°04'00" and 01°06'30" N and longitudes 34°09'45" and 34°12'30" E, about 250 km E of Kampala. It stands on the W flank of Mount Elgon at an elevation of 1100-1250 m. Much of the area around the town is under agriculture but other areas to the SW are swampy and the slopes of Mt. Elgon are wooded making the recovery of meteorite fragments difficult.

3. The Fall of the Mbale Meteorite

A survey of the area a few days after the meteorite fell included locating meteorite fragments, inspecting crater sites and interviewing local people to obtain eye witness accounts. The general concensus of opinion was that there were three loud explosions in the sky, followed by several smaller ones. The explosions were followed by a whistling sound which gave way to a cracking noise just prior to stones falling in various parts of the town. The loud explosions were presumably supersonic shock-wave bangs caused by the compression of air around the meteorite. Other explosions and cracking noises are caused by the meteorite breaking up in mid-air. The break up is caused by air pressure stress forces and by the differential heating between the outer layers and the interior. The outer layers are extremely hot due to frictional heating which in the case of the Mbale meteorite forms a black glassy ablation crust. The interiors remain at the very cold temperatures the meteorite experienced in outer space. A policeman who touched a sample soon after impact described the rock as feeling cold.

In addition to the noises, eye-witnesses saw a trail of smoke. most of them said that it moved approximately from N to S. One recalled the trail being in the opposite direction. The discrepancy may be in part due to fragments moving out in all directions after explosions as the meteorite breaks up in mid-air. In fact the people of Doko claimed one explosion occurred directly overhead and observed smaller trails scattering in all directions from the main N-S trail.

No eye witnesses claimed to have seen a fireball (meteor) which usually accompanies such a fall, however this is often easier to observe further away from the impact. But it was not yet possible to gather reports from further N (e. g. Soroti, Gulu) where a fireball may have been observed.

4. Strewn Field of the Mbale Meteorite

Text-Fig. 1 shows the distribution of fragments of the meteorite that were collected or reported. Unfortunately some people thought the stones had economic value or were useful in the treatment of AIDS, and hence removed them. Thus many of the larger fragments were subsequently artificially broken up for distribution and transportation. For these fragments estimates for their weight were made combining eye witness reports and measurements of the craters produced. In all about 45 impact localities were found, the majority without fragments. Fortunately nobody was injured, although one small boy claimed to have been hit by a tiny fragment. Not much damage to property occurred but one fragment broke through the factory roof at the African Textile Mill in the industrial estate, forming a small hole in the cement floor and another broke through the roof of the Mbale Railway Station respectively (Pl. 1, Fig. 1).

The smallest particles (1 - 300 g) were collected between Kamonkoli and Mugiti to the ENE of Mbale. Intermediate size fragments (0.1 - 3.5 kg) were collected from Doko, Namatala, the industrial area, near the railway station and the N part of the prison. The heaviest (3 - 20 kg) of the falls were found to the S of the town from the prison through Malukhu to Shibinikho village. Other areas to the N (Nakaloke, Kolonyi and Namunsi) and to the E (Gangama) were visited but reported no falls. Most craters range from a few cm to about 1 m in diameter and from 3-50 cm in depth (Pl. 1, Fig. 2; Pl. 2, Fig. 1).

The strewn field covers an area from Mugiti to Shibinikho-Bumutoto villages of total area of about 20 km^2. During a meteorite fall the small stones fall first followed by the heavier ones. This means the trajectory of the meteorite was from the NWW to the SEE. Obviously some areas of the stream field were inaccessible or covered by dense vegetation. However, about 100 kg of material was recovered. We estimate that accounts possibly for around 20 % of the material that fell around Mbale.

But the original size of the meteorite was much larger and a lot burnt up as it entered the atmosphere at around 80 km. It would have travelled at about 15 - 20 km/sec. Over Doko the altitude was 5 - 10 km, by then the velocity and mass would be much less just prior to the explosion that caused disintegration.

5.Morphology of the Meteorite

5.1.Macroscopic Aspects

Many of the fragments have angular glassy black interiors (Pl. 1, Fig. 3, 4 and 6; Pl. 2, Fig. 2, 4 and 7). The black crust is thin (1-2 mm thick), has ridges and furrows, and this represents the melting or ablation crust (Pl. 1, Fig. 5; Pl. 2, Fig. 3, 5 and 8). Inside the samples are fresh with a pale grey-green colour. The rock is fine grained (grain size < 0.5 mm), however silvery metallic grains can easily be seen. These metallic grains turn red-brown on exposure to moisture indicating the presence of iron. The presence of iron was further indicated by using a magnet which could attract cm size chips. Application of HCl caused the liberation of H_2S. This is probably due to the presence of troilite (FeS). As troilite is non-magnetic and bronze in colour, it seems likely that iron also exists in another phase, most likely a Fe-Ni alloy. Black glassy veins about 1 mm thick, similar to the ablation crust dissect some samples. Such veins are common in meteorites (KRINOV 1960). The density of the Mbale meteorite was found to be 3.53 g/cm^3. KRINOV (1960) found most chondrites having an average density of 3.54 g/cm^3 and in a table compiled by WASSON (1974) the density of the Mbale meteorite would lie in group L or E.

5.2.Thin Section Study

In thin section the main mineral is olivine, probably forsterite (colourless, 2V, around 90° (+ve)). Some of the larger olivine grains (around 0.25 mm) are subhedral, but all grains are cracked and fragmented. Much of the groundmass is olivine. There are also a few chondrules (around 1 mm diameter). They are composed principally of either radiating grated prismatic crystals of orthopyroxene. The orthopyroxene is colourless and lacks pleochroism, but the 2V around 70° (-ve) indicates bronzite or possibly hypersthene. A few isolated phenocrysts of orthopyroxene occur outside the chondrules. The remaining 15-20 % of the rock is made up from opaques assumed to be Fe-Ni alloy and troilite. The opaque phase sometimes has olivine inclusions and shows iron staining in surrounding grains.

5.3.Classification

On the basis of the morphology, mineralogy, density and the presence of chondrules, the Mbale meteorite should be placed in group L using WASSON's (1974) classification system. The petrological type corresponds best to type 6 (namely, presence of orthopyroxene, absence of igneous glass, poorly defined chondrule, crystalline matrix). Despite the fact that not all the criteria relevant to classification have been determined so far, we would tentatively classify the Mbale meteorite as a group L6 chondrite. This is the most common type of meteorite.

6. Acknowledgements

We would like to thank Mr. J. BETLEM of Mt. Elgon Conservation Project who acted quickly to acquire samples and provided logistical support. We are also grateful to the local authorities (District Administration, Police, Army, Railways, Prisons and others) who allowed us to collect samples in the district. We should not forget the many residents of Mbale town and district who aided our investigations. Finally, thanks to the staff of Makerere University Geology Department, who aided us with advice, logistics, thin section preparation and map preparation.

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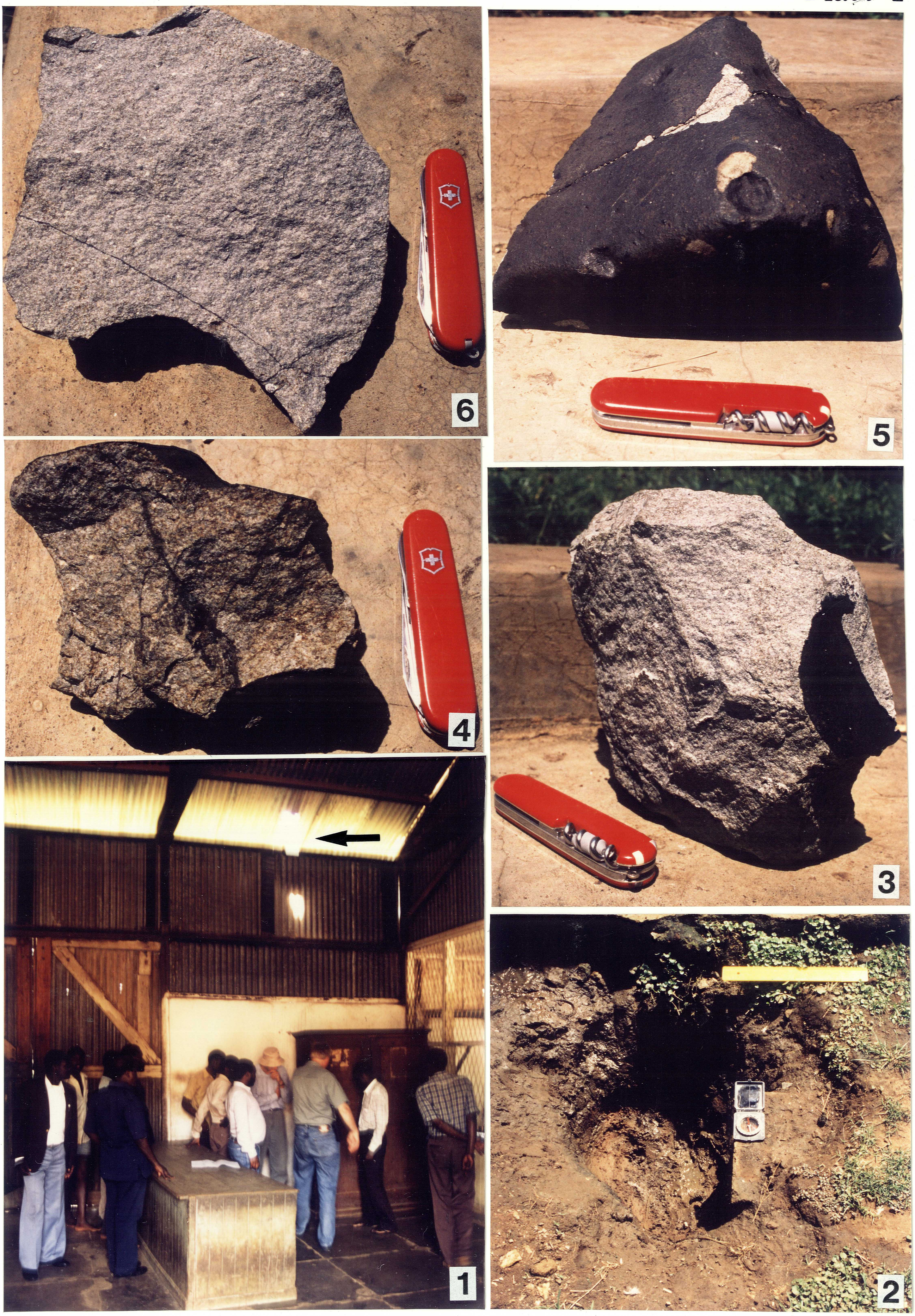
Plate 1

Fig. 1: Mbale Railway Station inside with the hole in its roof (black arrow) caused by the meteorite.
Fig. 2: Impact crater ca 1 week after the fall of the meteorite, near the prison, in a soft and clayey subsurface.
Fig. 3: Fresh larger and broken sample.
Fig. 4: Fresh larger and broken sample. Note the black glassy veins.
Fig. 5: Fresh sample with the typical black crust.
Fig. 6: Fresh larger and broken sample.

Plate 2

Fig. 1: Empty impact crater caused by the meteorite in a tarmac road of Mbale.
Fig. 2: Fresh larger and broken sample. Note some bigger metallic grains.
Fig. 3: Fresh sample with the typical black crust.
Fig. 4: Fresh larger and broken sample. Note some bigger metallic grains.
Fig. 5: Fresh sample withthe typical black crust.
Fig. 6: Fresh larger and broken sample.
Fig. 7: Fresh larger and broken sample.
Fig. 8: Fresh sample with the typical black crust.

Plate 1

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Variations in Petrography of Rubanda, Chitwe and Masha-Kibaran Granites and its Genetic Significance

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Abstract: Petrographic characteristics of W-bearing, Sn-bearing and barren syn- and post-tectonic granites are subtly different. The minerals present are common for the three types of granites but their modal abundance is variable. The granites consist essentially of quartz, microcline, orthoclase, albitic plagioclase, biotite and minor muscovite. Accessories include tourmaline, zircon, apatite, and allanite. The secondary minerals are epidote, sericite, chlorite and clay minerals. The rocks have a porphyritic texture and are commonly foliated at the periphery of the plutons. Phenocrysts are mainly K-feldspars. Myrmekitic and perthitic intergrowths are common in the granites.

The modal composition of the three types of granite differs. The youngest (W-bearing) granites are mostly alkaline and syenogranite, some tending to quartz granites; Sn-bearing granites vary between compositions of monzogranite, syenogranite and quartz granite. The oldest barren granites are mostly granodioritic.

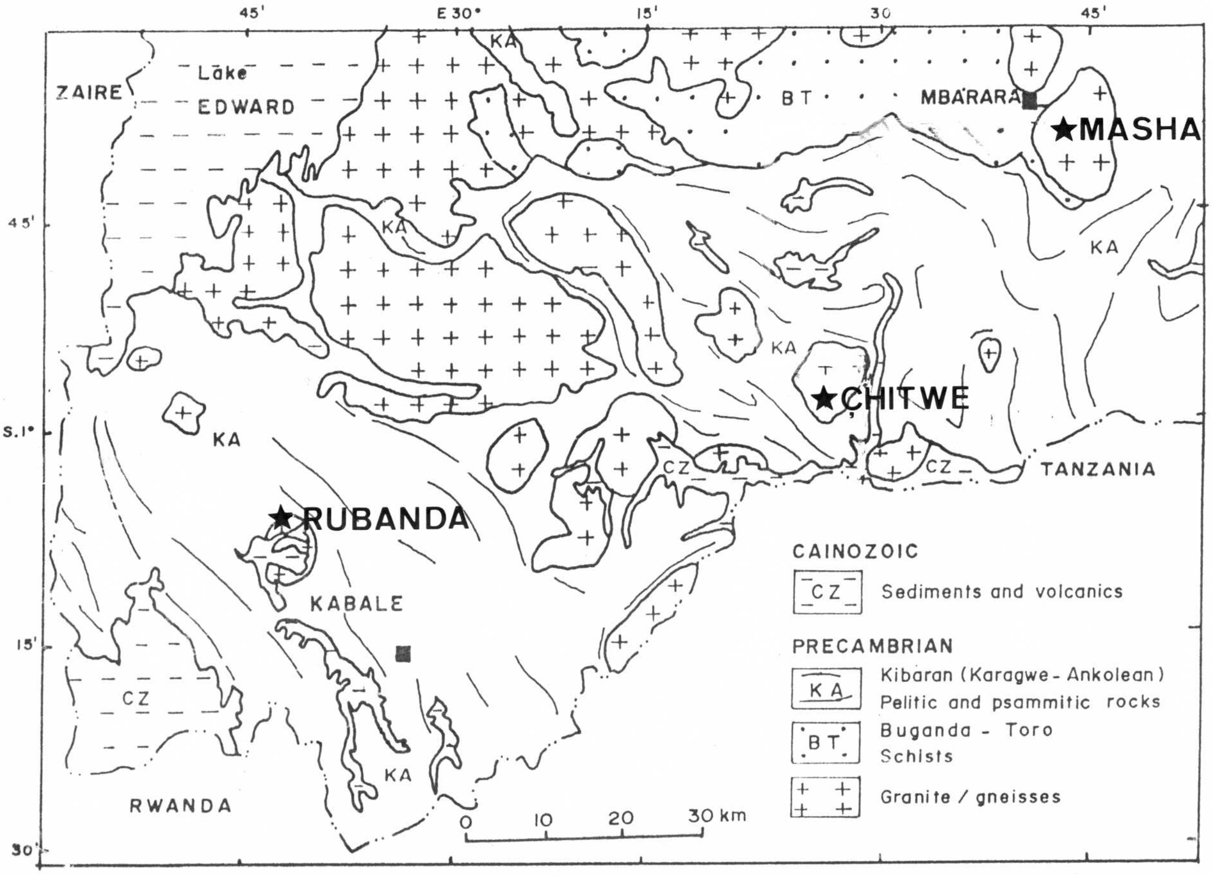
The difference in age, stages of alteration, modal composition and type of associated mineralization may indicate different sources of their parent magmas.

1. Introduction

The Karagwe-Ankolean system in Uganda represents the northernmost extension of the Kibaran orogenic belt. It consists of weakly metamorphosed argillaceous and arenaceous rocks intruded by different phases of granitic plutons.

The three granite plutons representing W-bearing (Rubanda Granite), Sn-bearing (Chitwe Granite) and the barren (Masha Granite) (Text-Fig. 1) have been studied to investigate their mineralogical and petrographical characteristics. These granite plutons vary in age, morphology and petrography.

The barren Masha granite is the oldest (1825 my), Chitwe Sn-bearing granite is middle Proterozoic (1188 my) and Rubanda W-bearing granite is late Proterozoic.



Text-Fig. 1: Generalised geological map of SW Uganda showing the localities of the three granites of Rubanda, Chitwe and Masha (slightly modified after published geological maps).

(950 my, measurements of younger ages indicate probably juvenation and not emplacement) (for more detailed chrono-stratigraphic discussions see CAHEN & SNELLING 1984).

Masha Granite shows a planer arena ("arena" is a term used for a topographic feature in SW Uganda where according to KING & De SWARDT (1967) erosion as expression of dome-like structures has exposed the underlying basement floor) with very short, gently sloping hills and scarce granite exposures compared to Chitwe and Rubanda which have steeper hills on which extensive granitic exposures occur. Masha and Rubanda granites also consist of extensively weathered outcrops compared to the more fresh exposures of Chitwe. This is most probably related to the high amount of silica (quartz) in Chitwe granite compared to the other two. In Masha, possibly the age also accounts for the advanced weathering while in Rubanda weathering may have been accelerated by its occurrence at higher structural level than the others.

Recently some addititional papers concerning the geochemistry, mineralogy and petrography of granitic rocks of the Kibaran (Karagwe-Ankolean) Belt were published (GUENTHER et al. 1989, IKINGURA et al. 1990 and OCEN 1989), but their conclusions could not be considered and integrated into this study.

2.Petrography

2.1.Rubanda Granite

The essential minerals in thin sections of Rubanda granite include quartz, K-feldspar (microcline and orthoclase), plagioclase, biotite and muscovite. Accessories are tourmaline, zircon and apatite. Epidote, allanite, sericite and chlorite are the secondary minerals.

Quartz is the most abundant mineral (>35%) and and occurs in two sizes. The coarse quartz is undulose and shows cracks which are filled with secondary micas. The mostly anhedral grains interlock forming serrated consertal grain boundaries of coarse quartz. Some of it is enclosed in other minerals, e. g. muscovite and K-feldspars.

K-feldspar is next abundant (25-55%) and consists of microcline and orthoclase. These minerals are relatively less altered than the plagioclase but appear cloudy. They form phenocrysts which poikilitically enclose quartz, biotite and plagioclase. Plagioclase feldspar is less abundant (1-10%), highly weathered and and it is mostly an albite with high anorthite content (An_{10}).

Biotite (0-9%), shows moderate pleochroism (green-yellowish green) with pervasive pleochroic halos which are developed around the enclosed zircons. Some biotite is found in cracks in close contact with the rarer muscovite, which is mostly secondary, finer and characteristically sandwiched between other minerals.

Accessory tourmaline is dispersed in the granite concentrated in clusters together with quartz. The tourmaline is of the schorlite type and is slightly pleochroic (bluish green-yellowish brown). Zircon occurs mostly enclosed in biotite, being mainly responsible for the pervasive pleochroic halos. Allanite has a very high relief and is developed close to some biotite. Opaques are mostly alteration products of biotite.

The textures include the common myrmekite, microperthite and overall porphyritic texture with quartz and K-feldspar phenocrysts in a groundmass of plagioclase, biotite and other fine-grained minerals.

2.2.Chitwe Granite

This is a well exposed arena granite with its numerous hills covered with granite outcrops which range from massive to small. Sharp edged blocks occur frequently.

Hand specimens of this granite are fresh, grey and hard, save for the greisenised contact outcrops which are soft and friable.

Thin sections consist of quartz, microcline, orthoclase, plagioclase, muscovite and biotite as the essential minerals.

Quartz (40%) ranges in size from fine to coarse with normal extinction, and consertal arrangement between the mostly anhedral grains.

K-feldspar ranges between 6-60% with microcline and orthoclase equigranular grains forming phenocysts of the porphyritic granite texture. These phenocysts poikilitically enclose quartz and plagioclase. Perthitic intergrowth is very common. The K-feldspar in Chitwe granite is also less altered than the plagioclase. Plagioclase is less abundant (3-26%) and is often altered to sericite, epidote and clay minerals. At the contact between K-feldspar and plagioclase an extensive development of myrmekite is notable.

Biotite (0-17%) is the sole mafic mineral in this granite and is evenly distributed, imposing a spotted appearance in hand specimens. It is slightly pleochroic, from green to light green with plenty of pleochroic haloes around radioactive mineral inclusions. Some of the biotite encloses quartz, feldspars, and other minerals. Muscovite is represented in minor amounts (0-0.5%) except in greisenised zones where it gets up to 2.5%.

Accessory minerals include apatite, zircon and cassiterite. Zircon is mostly enclosed in biotite. The cassiterite is zoned and is surrounded by zircon within an enclosure of radially crushed quartz, implying its forceful later growth within the granitic matrix.

2.3.Masha Granite

This is an older granite pluton with perfect arena morphology and it is a barren. There is a general lack of outcrops in this granite. Most exposures are flatlying although some isolated outstanding exposures may be observed in the centre of the arena. Mylonitised and weathered exposures are more extensive along the arena margin.

This granite body is highly weathered especially at the contact where only relic carse feldspar phenocrysts are observed in the mostly mylonitised, chloritised and kaolinised rocks.

Hand specimens are mostly grey and sometimes buff. Greenish biotite is spotted evenly in a felsic matrix composed of bluish, stubby, heavily cracked quartz. Also coarse twinned white to pinkish K-feldspars and fine-grained plagioclases occur.

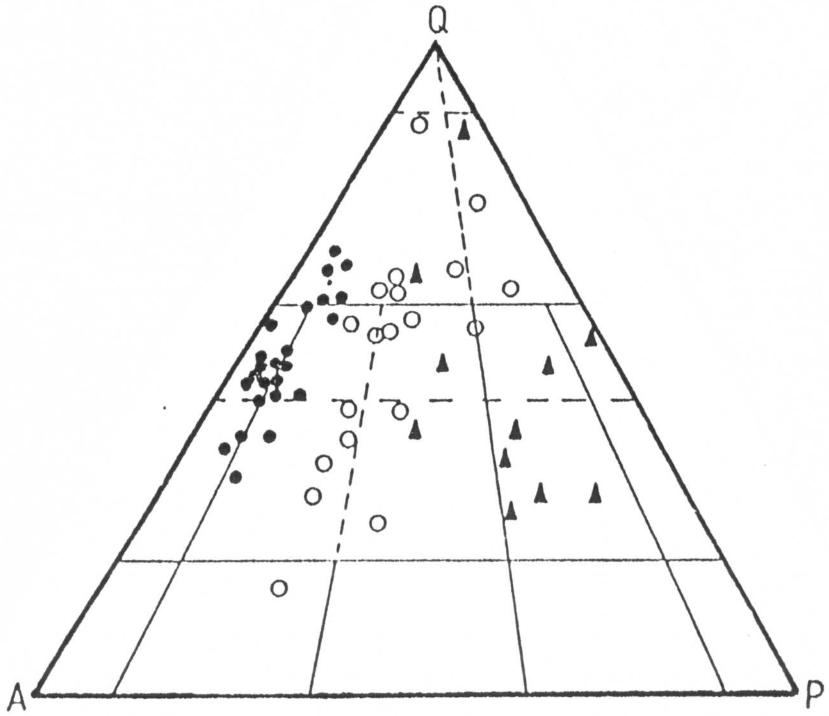
Thin sections indicate the presence of quartz, microcline, orthoclase, plagioclase, and biotite as the essential minerals. Also a minor content of muscovite is available.

The modal quartz composition ranges from 22% to 76%, averaging 45%. Mostly anhedral, the quartz is often fractured and occurs in two sizes, one coarse and the other fine. The coarse type exhibits consertal interlocked edges. Undulosity of the coarse quartz and the crushed beadlike enclosed fine quartz represent effects of mylonitization.

Microcline and orthoclase range from 2-22%. Both are coarse-grained and form phenocrysts which poikilitically enclose other minerals, e. g. quartz, plagioclase and mica. The K-feldspars are relatively less altered compared to plagioclase. Plagioclase makes 10-42% of the granite and its anorthite content is in the range of An_{0-20}%. Plagioclase may also poikilitically enclose other minerals, particularly quartz.

Biotite containing zircon and allanite inclusions is the predominant mafic mineral (2-25%). It is pleochroic, from light to dark green and contains relatively few pleocroic inclusions. Some primary muscovite (0.3-10%) is found in close contact with biotite but the bulk of the muscovite is secondary.

Although generally most of the granite shows granitic texture, foliated gneissose texture indicated by biotite and elongated quartz dominates at the periphery where these arena granites have been mylonitised.



Text-Fig. 2: Combined modal mineralogy of Rubanda (o), Chitwe (•) and Masha (▲) granites plotted on AQP diagram with boundary lines of the IUGS granitoid classification scheme.

A few perthitic or myrmekitic intergrowths are observed in Masha samples. Secondary muscovite and cordierite are formed by retrogressive metamorphism of the mylonitised granites.

3. Modal Variation of the Granites

On the QAPF plutonic rocks classification adopted by IUGS (STRECKEISEN 1967), the three granite plutons show varying modal composition (Text-Fig. 2).

Most of the W-bearing (Rubanda) granite samples plot within the alkali feldspar granite and syenogranite fields and a few in the quartz-granite field. Chitwe Sb-bearing granite is more variable and less alkaline; less than half of the samples plot in the syenogranite field, some in the monzogranite and quartz granite fields and a few in the quartz granodioritic field. Rubanda W-bearing granites are predominantly alkaline, Chitwe Sb-bearing granite is mostly syenogranite or monzogranite (granite per se) and Masha barren granite is granodioritic. These granites could possibly have originated from different original primary magmas.

4. Discussions and Conclusions

The granites of SW Uganda especially the three arena granites of Chitwe, Rubanda, and Masha are characterised by biotite as the major mafic mineral and the predominant mica. The colour of this biotite varies, being predominantly green or brown, depending on the oxidation state of the present iron. Green biotite has mainly Fe^{++} while the brown variety has Fe^{+++}. Although biotite is much greater in amount than muscovite, at least a little muscovite is also found in each granite.

The amount of quartz is rather too high in some samples, especially those of Chitwe granite. In weathered granites, the high quartz would probably be due to the resistance of quartz to weathering; while other minerals are completely weathered out, quartz remains unchanged and so it is relatively increased in amount. Moreover quartz is also part of the products of chemical alteration especially sericitization. It is also possible that some of the granites crystallized from silica-rich residual magma during late stages of emplacement. This may explain the presence of high amounts of quartz in Chitwe granite which is the least weathered of the three. The other possibilty is that some of these granites might have incorporated highly siliceous material from the country rocks by stoping. This has been for instance recorded from the so-called G_3 pegmatitic granites (terminology after POHL 1989) at Dwata which contain large xenoliths of schists of country rock origin.

The micrographic intergrowth, myrmekitic, poikilitic and perthitic textures indicate a readjustment during the slow cooling of the granite (SPENCER 1938). Perthite is simply an exsolution texture whereby predominantly potassic alkali feldspar form albite islands in the dominant microcline upon cooling from high to low temperature. SPENCER (1938) explains the formation of myrmekite also as being due to exsolution and rearrangement of albite and hypothetical calcic feldspar $(CaAlSi_2O_7)_2$ found held in solution in K-feldspars.

Although poikilitic textures are common in basement granitic rocks in Rakai (PHILIPS 1959, SINABANTU 1979), which have evidence of granitization by K-feldspathization in-situ, it is not the sole indication of the present type of granitization. In addition, the basement rocks have foliation and their poikilitic textures are pervasive. In the present three granites, foliation and limited poikilitic textures are caused by crystallization of the K-feldspar, later than the enclosed already formed minerals. Here the plagioclase composition is low in calcium rarely reaching An_{20}.

Alteration of these granites seems to be related to three factors: age, prevailing hydrothermal stage and the style of their emplacement. Hydrothermal alteration (sericitization in feldspars) seems to be widespread in Rubanda granite while it is only mild in Chitwe granite. Both these granites are mineralized, i. e. Rubanda for tungsten (W) and Chitwe for tin (Sb). Possibly, the high level of the Rubanda granite makes it more susceptible to alteration than Chitwe which is of low level. The alteration of Masha granite seems to be more related to age and style of emplacement. This granite dates much older than the Kibaran orogeny (CAHEN & SNELLING 1984). The reworking of the granites mylonitizes its margins relative to its core, thus promoting chemical alteration at the margins.

The three types of granite show differences in modal composition, W-bearing Rubanda granite being predominantly alkaline, Sb-bearing Chitwe granite being mostly syenogranite and monzogranite (granite per se) and the barren Masha granite is granodioritic. This difference in their mineral composition and their age and grade of alteration indicate that the original magmas for these granites were certainly different.

5. Acknowledgements

The original draft of this paper (completed already in 1989) could not more be improved by the late Dr. S. S. SINABANTU. - Dr. J. R. IKINGURA of the Department of Geology, University of Dar es Salaam, C. HAMPTON, and Prof. Dr. T. SCHLÜTER, Department of Geology, Makerere University, revised the manuscript and gave several new suggestions. It was also felt as an obligation to publish the last scientific will of Stephen SINABANTU.

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Unusual Source of Carbonate for Speleothem Formation at Nyakasura, W Uganda

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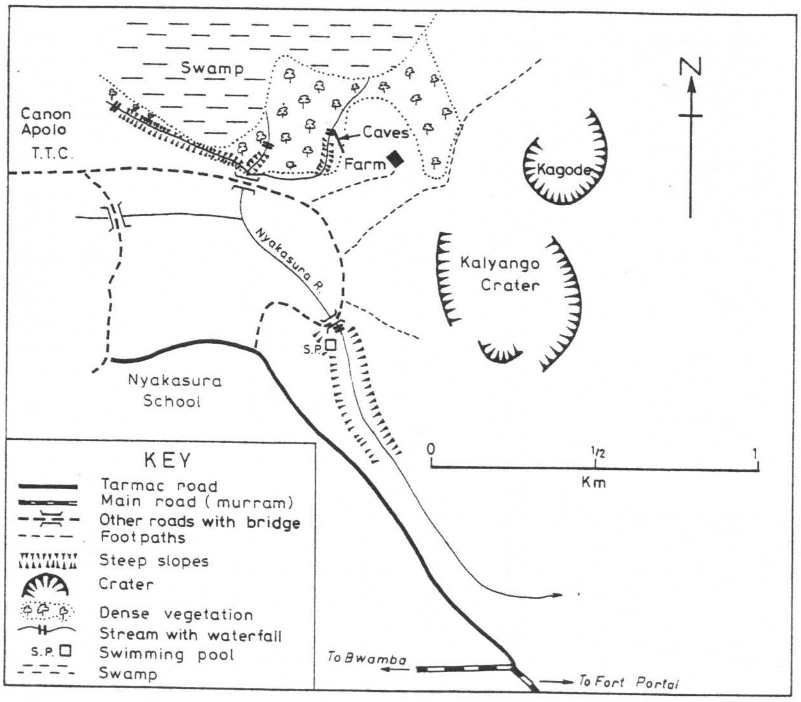
Abstract: The speleothems formed at caves near Nyakasura, Fort Portal are unusual in that the carbonate used for their formation originated from an igneous lava. Estimates of growth rates suggest that the larger speleothems took between 2.000 to 20.000 years to form. The combination of carbonatite lava overlying soft clay, in close proximity to a stream produce conditions for speleothem formation at Nyakasura, that may be rarely occur at other carbonatite localities.

1.Introduction

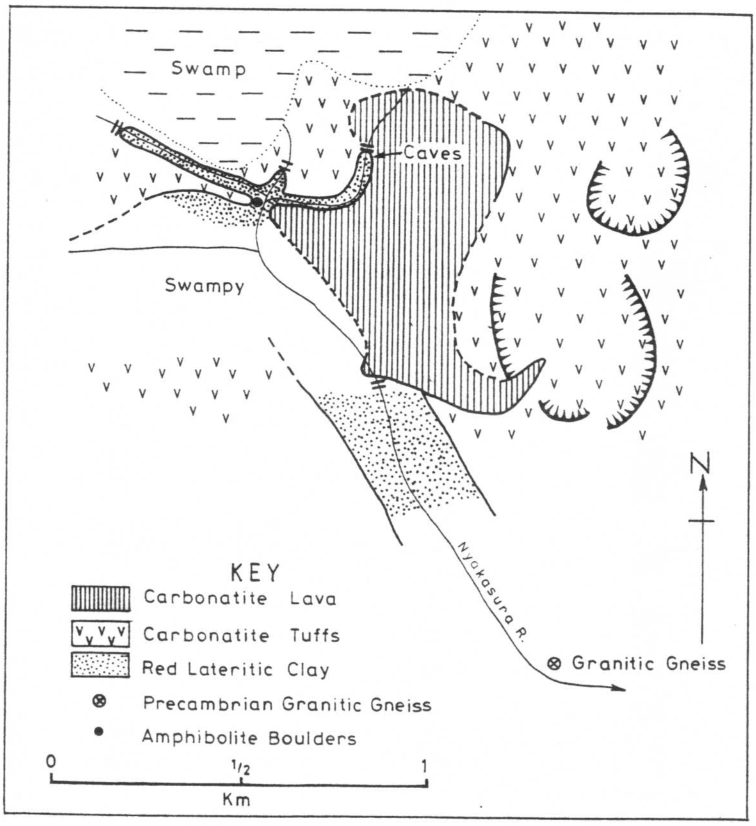
Speleothem is a general term describing all crystalline deposits found in caves, including the well known stalactite and stalagmite forms. Stalactites usually occur in limestone caves or on wetted overhangs on open cliff faces. The vast majority of speleothems occur in limestone caves produced by solution weathering attacking joints and bedding planes. Africa has many well known examples of caves formed in this way that contain stalactites and stalagmites, such as Cango caves, South Africa, Maputo cave, Mocambique, Amboni caves, E Tanzania, and at Mt. Hoyo, NE Zaire (BUCKLE 1978). The caves that occur near Nyakasura School, Fort Portal, W Uganda, are small in comparison to other caves and their speleothem formation is less impressive. What is unusual about these caves is that they occur in a region of volcanic rocks rather than in the usual limestone or marble environments.

2.Location

The caves are locally known as the "Amabere ga Nyinamwiru": literally translated as "the breasts of the mother of Mwiru". According to tradition a legendary king of the Bacwezi, called Ndahura, lived in these caves, and was fed as a child from the "breasts" (stalactites) that cripped a milky liquid. The caves are situated about 500 m off the road that runs between Nyakasura school and Canon Apolo T. T. C., about 10 km W of Fort Portal town (Text-Fig. 1).



Text-Fig. 1: Map showing location of the caves near Fort Portal.



Text-Fig. 2: Geological map of the area around the caves and Kalyanga crater.

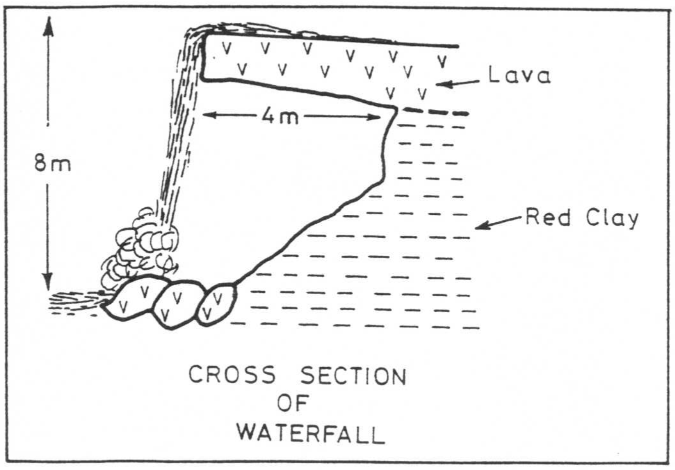
The caves lie on land belonging to a local farmer, Mr. Rubombora, who has cleared the vegetation covering the caves, fenced it off and now charges a small admission fee, in order to try and preserve these interesting phenomena.

3.Local Geology

The area W of Fort Portal is dominated by a line of Quaternary age volcanic craters which form the basis of the Fort Portal volcanic field. This area was first described by COMBE (1939), then mapped in more detail by NIXON & HORNUNG (1973). Detailed analyses of the rocks have been made by von KNORRING & du BOIS (1961), NIXON & HORNUNG (1973) and BARKER & NIXON (1989). These studies have shown that the craters and surrounding areas are covered mainly by volcanic carbonatite tuffs, which have a primary $CaCO_3$ content that makes up nearly half the composition of the rock. The tuffs themselves are often friable, flaggy and porous and would seem unsuitable for cave formation. On the W flank of Kalyango crater, there is a lava flow, an unusual feature for this field (Text-Fig. 2). The lava is a massive grey rock, vesiculated throughout and probably formed by agglutination of spatter from lava fountains (BARKER & NIXON 1989), and so does not extend far beyond the crater. The lava does not have a well developed joint pattern but cracks do pervade the rock.

The caves themselves lie at the W edge of the lava flow. WAYLAND (1933) briefly visited the caves while investigating some fossils found nearby and assumed the caves were formed from limestone. In the vicinity of the caves the lava covers a horizon of red lateritic clay, at least 7 m thick (the base is not visible here). The clay seems to be a weathering product of underlying Precambrian gneisses that can be seen outcropping about 1 km down stream. Near the point where the three streams coming out of the swamp they converge before flowing under the road, there is an amphibolite. It occurs as several large boulders on both sides of the stream suggesting it may be in situ. It is possible that it represents a former basic dyke running E-W that has resisted erosion. It might underlie the long narrow E-W ridge (on which Canon Apolo College stands), running between the swamp behind the college and the school. The lava flow seems to have reached this ridge and blocked or modified the existing S flowing stream creating a swamp in the valleys upstream.

The combination of a hard consolidated layer of lava over soft red clay produces the classic conditions for caprock waterfall formation (Text-Fig. 3). In fact there are 3 waterfalls in this area with around 6-8 m drops on 3 streams coming from the swamp. In addition there is waterfall with a smaller drop downstream near the Nyakasura school swimming pool (the location where WAYLAND (1933) found fossils and artifacts). On the downstream side of all the waterfalls are deep gorges cut into the red clay. The tuff being softer does not produce overhangs, caves or speleothems. The whole of this area round the waterfalls is covered with dense vegeatation making observation difficult.



Text-Fig. 3: Diagram showing the relationship between the rocks at the N cave. At the other waterfall the caprock is volcanic tuff and the depth of the overhang is much less.

4. Caves

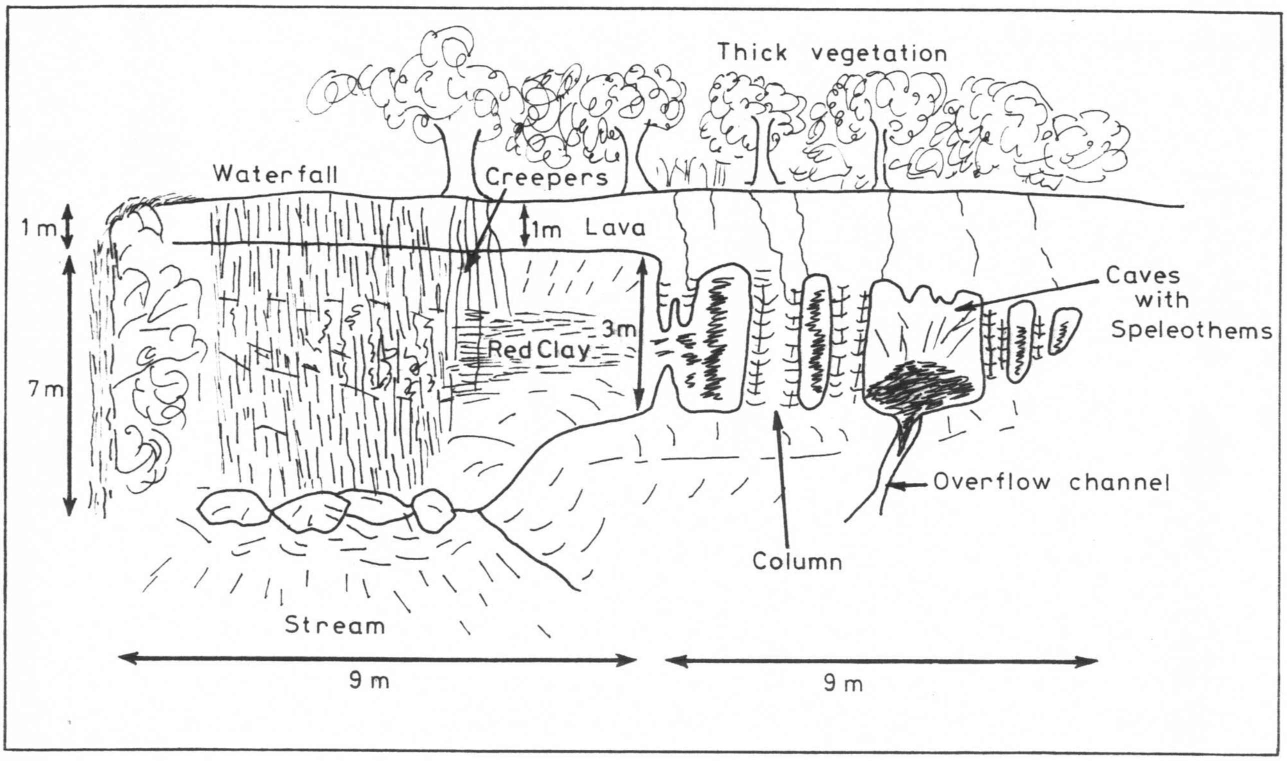
The caves follow the W edge of the lava and extend for 80-100 m on a trend N 15^0 W. There are 3 major caves that are exposed. Each one is 10-20 m long, around 7 m high and about 4-6 m deep at their maximum point. There are other smaller caves inbetween the main ones. The most N cave lies under the present course of a stream and so is the site of a waterfall. In this cave (Text-Fig. 4) the main speleothem formation has taken place at the E end of the cave away from the waterfall. At this end, water can be seen dripping from cracks, stalactites, and during heavy rain from over the edge of the lava. The other caves are much drier and the speleothems are a little smaller. It seems likely that speleothem formation is not aided by large quantities of water and certainly directly behind the waterfall there is a constant fine spray that could redissolve the carbonate and erode the speleothems. It is not clear weather the other caves were formed by the present stream having shifted its course westwards with time, or whether the stream undercut the clay from below the lava.

4.1. Speleothems

Stalactites of varying size occur, from a few mm up to more than 1 m in length. On the floor of the cave there are many fragments of soda straw stalactites. There are a few in situ and this could be due to their destruction by visitors to the caves. Such destruction has occurred from WAYLAND's time to the present day. Stalagmites are also common, but less numerous than the stalactites. In addition columns have formed, especially at the mouth of the cave. The largest one observed was 3 m high and has a girth of 3.7 m. The surface of many of these columns is covered with vines, creepers and ariel roots, many of which are being coated by travertine. Other speleothem forms observed were small drapes and curtains around 30 cm long and around 2 cm deep. On the cave floor flowstone is forming often containing petrified leaves and roots. The flowstone is sometimes coloured green or yellow by impurities, perhaps due to algae. Rimstone forms around small pools a few cm across, that occur at the base of some stalagmites.

4.2. Rate of Growth

The Fort Portal volcanoes have not been radiometrically dated so their age is unknown.



Text-Fig. 4: A field sketch of the most N cave of the "Amabere ga Nyinamwiru, Nyakasura".

Early studies on volcanic areas in the Western Rift of Uganda (WAYLAND 1932) suggested that the volcanoes may have been erupted within tribal memory, perhaps less than 10.000 years ago. More recent studies on the relationship between the Kasio beds and the Katwe-Kikorongo volcanics (SENUT et al. 1990), suggest a lower Pleistocene age for the volcanics. If the Fort Portal volcanics eruptedat at a similar time it would make them considerably older than 10.000 years.

In one cave a rapid drip rate was measured at 2 drops per second. Rates of growth have been measured at other caves around the world and a rate of 0.25 mm/year seems to be average (FORD 1968). The rates, however, can be highly variable reaching up to 3 mm/year and in some cases stalactites can stop growing or even start to redissolve. It is, however, generally agreed that speleothems grow more rapidly in tropical areas.

Fragments of 2 types of speleothem were recovered from the floor of the cave. One was a soft stalactite composed of calc tufa, which is known to occur where evaporation is important at the mouth of a cave. Measurements on this showed layers 1 mm thick, often composed partly of voids into which small crystals of calcite grow. The other was flowstone and soda straw stalactites made of travertine, which forms dense concentric layers. These white and buff layers are around 0.1 mm thick and might represent either the cycle of a year, or perhaps at least a wet season (white) followed by a dry season (thin buff layer). In this area there are usually 2 wet seasons per year.

Using a growth rate of 0.1 mm/year, it would take 15.000 years for a column 3 m to form, assuming it was growing equally at both ends, and it might take another 5.000 years to thicken 1 m diameter. However, columns this size only occur at the mouth of the cave where they are artificially thickened by incorporating creepers and ariel roots and would be expected to be formed of calc tufa. If this is the case the faster rate of 1 mm/year would mean a large column would take as little as 2.000 years to form. Probably the correct answer lies between the two. Another factor to consider is damage by visitors to the cave, however, it is assumed the large forms have mostly escaped untouched.

5. Discussion

Caves containing speleothems are not common. Limestone is their most common source rock. The caves at Nyakasura are not especially spectacular, but they are unusual in that the source of the carbonate is an igneous rock rather than a sedimentary or metasedimentary rock. Carbonatites are the only igneous rocks with sufficient carbonate to be source rocks for speleothems. Although speleothems should occur at other carbonatite localities (the author has seen a photograph of a small stalactite at Oldoinyo Lengai, N Tanzania, taken by the mountaineer Mr. Paul Clarke), they do not seem to be common occurrences.

There could be several reasons for this:

1. Speleothems and the chemistry of igneous rocks represent different fields of interest so each may not merit comment by workers researching in each field.
2. Carbonatites are a relatively uncommon form of igneous rock, although Africa is better endowed than other continents. Where they do occur the volume of erupted material is small. HUGHES (1982) estimates around 500 km^2 from 320 or so recorded carbonatites. Of this material much is erupted as tuffs, small dykes or volcanic plugs (TUTTLE & GITTINS 1966). Lava flows, which should provide the best environment for speleothem formation, are rare.
3. A number of carbonatites in Africa occur in arid regions, where water essential for dissolving the carbonate is not abundant. When it does rain the water comes rapidly producing erosive rather than depositional effects. Even where rain is abundant the carbonate may be located in upland areas or the centre of volcanoes where streams are intermittent.
4. Unlike limestone the lava does not have a well developed joint pattern to act as pathways for underground water. Even where suitable cracks occur, the lava is unlikely to be thick enough to allow for the formation of caves in which speleothems could form. In order for caves to form, special conditions are needed such as those at Nyakasura where a stream, a hard carbonatite lava, and an underlying rock occur in close proximity. This is unlikely, especially as many carbonatites occur outcropping next to other resistant volcanic rocks such as nephelinites or ijolites.

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Influence of Geologic Structure and Lithology on the Drainage System of Bunyoro, Western Uganda

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Abstract: Qualitative and limited quantitave drainage analysis of Bunyoro (Masindi and Hoima Districts) was carried out. The objective was to establish the degree of geological control on the drainage patterns and drainage densities of the area. Data were collected from a drainage map of a scale 1:250,000, compiled from topographic map sheets of a scale 1:50.000.

The geology of the area has appreciably affected the drainage system although the regional slope is still the major controlling factor in flow directions of the main channels. NE trending geologic structures parallel to the present rift have affected the drainage more than structures in other directions.

1. Introduction

Qualitative and quantitative drainage pattern analysis of a region may reveal the degree to which the drainage system has adjusted itself to the underlying rock structure. In numerous examples drainage pattern analysis has proved a valuable tool in geologic studies. In W Uganda where thick soils and vegetation conceal outcrops the tool of drainage analysis in geologic investigation is very relevant.

In the present paper more emphasis is put on qualitative analysis although limited quantitative analysis is employed as well. According to PITTY (1982), the complexity and irregularity of forms and processes, together with complicated changes in time promote an essentially qualitative approach as the only realistic way of approaching many geomorphologic problems. He, however, notes that, sufficient regularity has been recognised in some forms and several processes to encourage more exact (quantitative) approaches. According to ZERNITZ (1932), drainage patterns form one of the most immediate approaches to the understanding of geologic structure. In a region where neotectonic movements have been common, the nature and the degree of drainage lines captured by younger structures is investigated.

1.1.Location and Brief Description of the Area

The study area is shown in Text-Fig. 1. The intake areas (Lake Albert, River Kafu and Victoria Nile) join to form a near elliptical belt with longest axis oriented NE. Rivers Kafu and Nkusi have a stair case like channel and at least the NNE, NE to ENE trending segments are thought to be partially influenced by faults and ridges (BIRYABAREMA 1988). Channels of River Kafu and River Nkusi were originally a single channel of a westward flowing river before it was reversed by upwarding of the rift shoulders (Text-Fig. 2). Lake Albert is a structural lake occupying an inner graben within the rift floor. Its waters are receded from the most recent rift scarp. The Victoria Nile channel, considering its large angle deflections, should be partially controlled by basement structures and indeed the Nile channel after Lake Albert and in S Sudan is controlled by the rift structures and the Aswa shear zone respectively. The intake areas are at least partially structurally controlled. The detailed nature of this control can be a subject of another research. The catchment areas have certainly been affected by these Tertiary / Quaternary diastrophic movements that have affected this region.

1.2.Geologic Setting of the Area

The geologic setting is shown on the geologic map of the area (Text-Fig. 3). This indicates a big part of the area covered by the Precambrian "gneiss complex" with a late Precambrian sedimentary basin (Bunyoro Series) in the centre and Miocene and younger rift sediments laterally.

In detailed mapping (1:50.000) in N central part of the study area, van STRAATEN (1976) identified 4 metamorphic rock units in the so-called "gneiss complex", namely a granulite facies, a granite, dorelite dykes and a metasedimentary series - in that order of younging. Isoclinal folds with NE trend were found to be associated with the granulite facies. Numerous NE and WNE striking mylonite zones cut both the granulite facies and granite. Dorelite dykes run parallel to rift faults and mylonite zones.

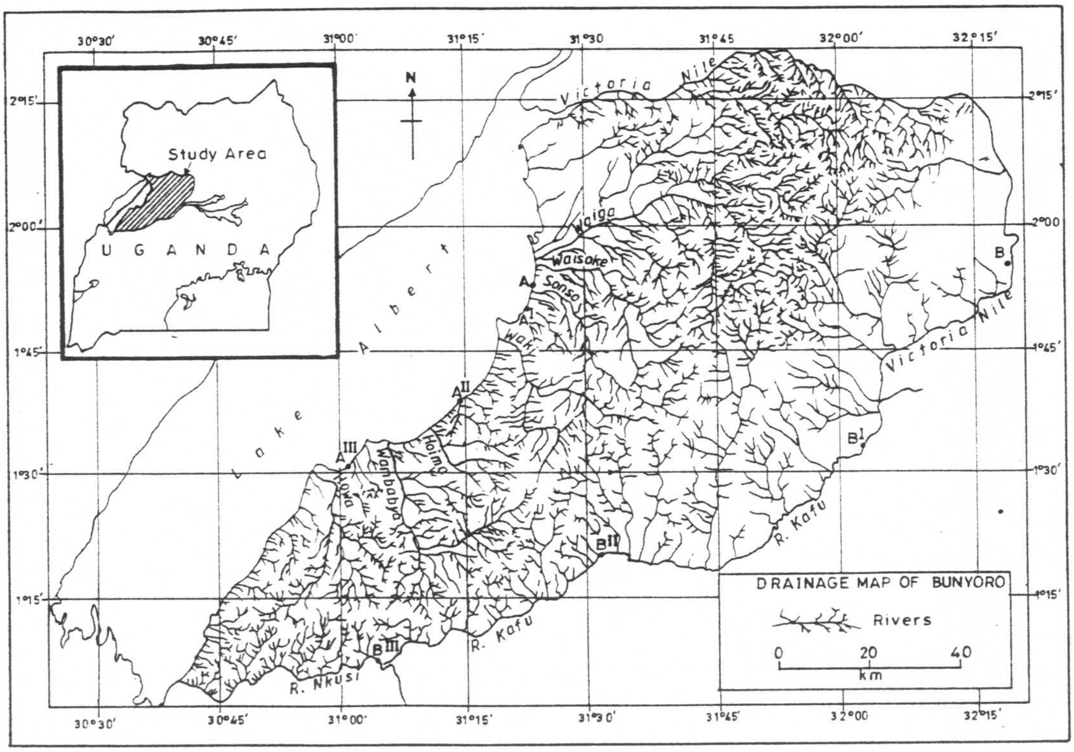
Bunyoro Series basin is known to be partly structurally controlled. DAVIES (1939) working in the S of the study area mapped N to NE local faults. The two mapped sedimentary units in the basin are: the Lower Tillite Group and the Upper Argillaceous Group striking NE.

Major rift faults have NNE to NE trends. The majority of major landsat lineaments and ridge belts in the study area trend NNE (BIRYABAREMA 1988). Topographic profiles across indicated directions on Text-Fig. 1 are shown in Text-Fig. 4.

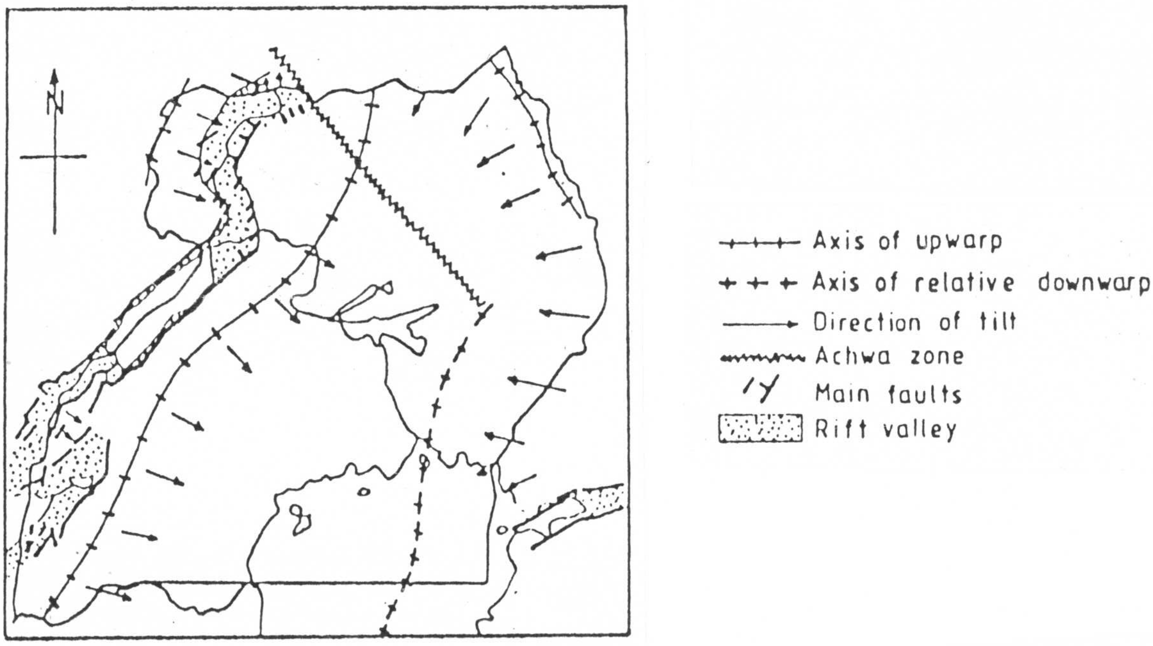
2.Drainage Patterns

2.1.Drainage Map Complication

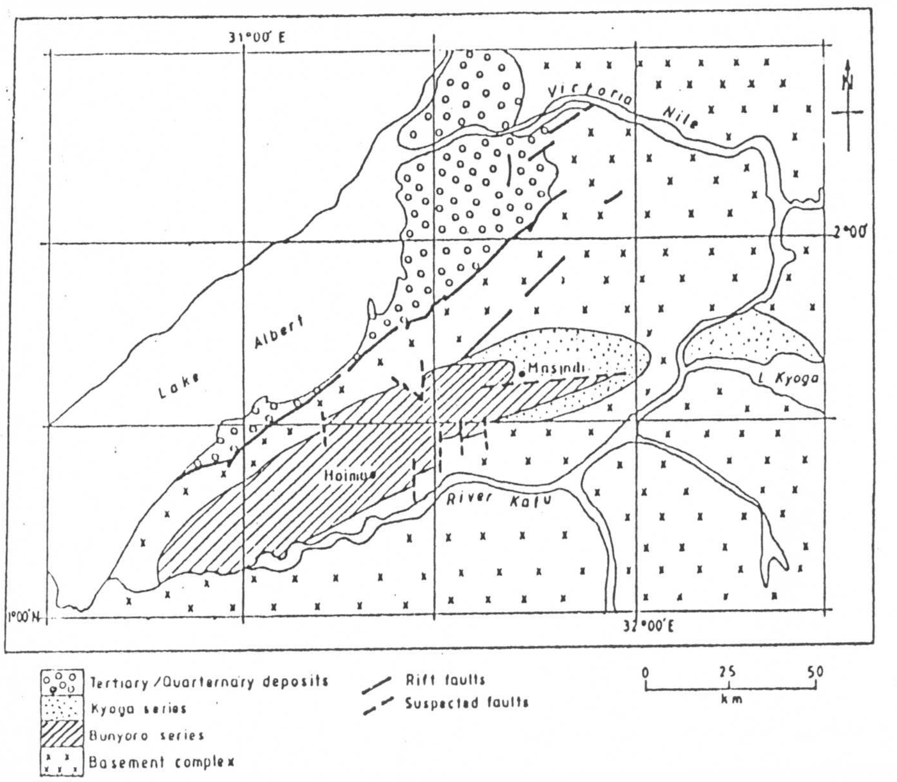
A drainage map of the area (Scale 1:250.000) was the source of the data used in the present research. This map was compiled from published topographic maps (scale 1:50.000). Blue drainage channels were traced and reduced to the former scale by a mechanical pantograph. The drainage map of the area shown in this paper (Text-Fig. 1) was photographically reduced from the 1:250.000 scale map.



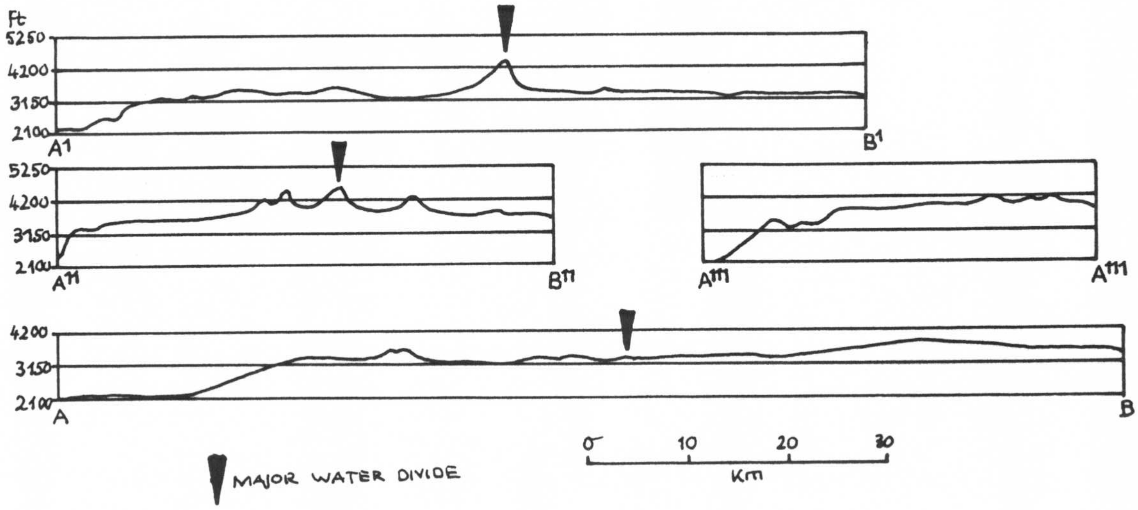
Text-Fig. 1: Drainage map of Bunyoro prepared from topographic sheets (scale 1:50.000).



Text-Fig. 2: Sketch map of Uganda showing the axes of upwarps and downwarps (after unpubl. Rep., Lands and Surveys, Uganda, 1969).



Text-Fig. 3: The geology of the area of study (after Geol. Surv. Uganda, 1960).



Text-Fig. 4: Topographic profiles across the area studied.

Stream ordering after STRAHLER (1957) was carried out on the 1:250.000 scale map and the law of stream numbers was tested on the whole area.

2.2.Qualitative Drainage Characteristics

In the E part of the study area (Bunyoro) the drainage density is low to very low. Major stream channels display a sub-parallel pattern although rectangular turns are evident. The low drainage density is due to accumulation of both alluvial sands and may be sands resulting from weathering of acidic basement rocks. The area is mainly covered by sandy loams.

In the N part, the drainage density is high to very high. The drainage pattern is dendritic with anomalous stream channel alignments and deflections. The area is covered by "gneiss complex rocks". The NE trend of alignments and deflections is parallel to the known rock structure: strike, intrusions, folds and faults, in areas where detailed mapping has taken place. According to the geologic map of the area (Text-Fig. 2) this portion is covered by "gneiss complex" like the E part discussed earlier. The drainage densities vary rather extremely. Despite the fact that differences in relief, degree of weathering, cover type and alluvium overburden could lead to differences in drainage patterns on similar lithologies, the case in point may as well demonstrate the degree of heterogeneity of the so-called "undifferentiated basememt" or "gneiss complex" rocks. Detailed field mapping would be necessary to understand the overriding factors in the drainage pattern control. The high uniform drainage density in the N part emplies a rock unit of approximate uniform composition and with low resistance to stream erosion and low permeability.

In the central belt, the drainage density is medium to high. The relatively low drainage density in some areas is partly due to forest development. The drainage pattern is rather complex: sub-dendritic, sub-rectangular and trellis with very conspicuous NE deflections of the trunk channels. This has affected the major drainage channels: Rivers Wambabya, Waki, and Waisoke (Text-Fig. 1). The lithology is mainly made up of argillites of the Bunyoro series with its cover type and associated adjustments related to rifting.

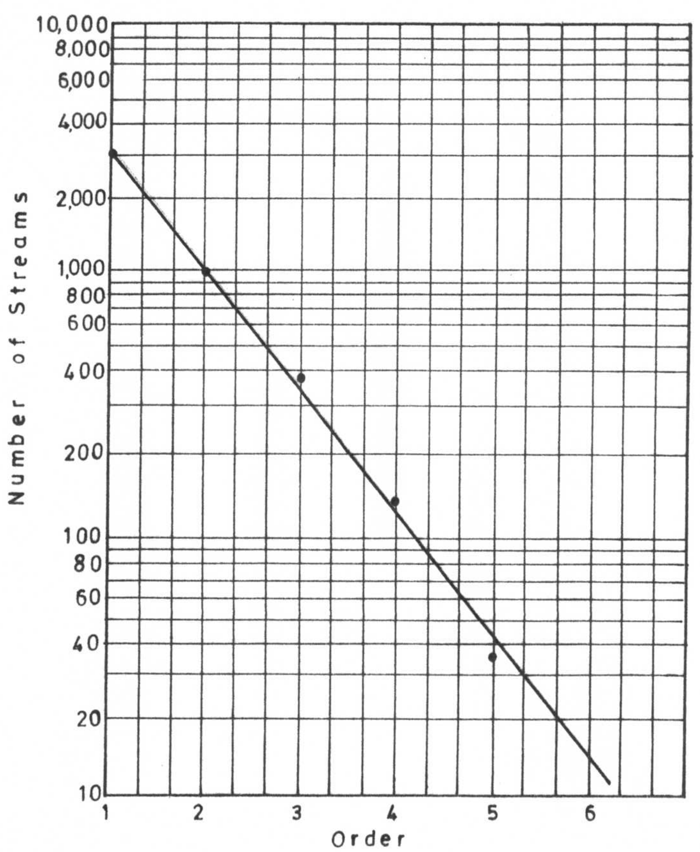
In the extreme SW of the study area the drainage density is medium. The drainage pattern is sub-parallel to sub-trellis, considering the main tributaries of River Nkusi. NE structural control of the major tributaries and a appreciable number of smaller tributaries is evident. Adjacent to Lake Albert areas of low drainage densities are covered by the rift sediments. Numerous first order streams are associated with the most recent rift scarp. A much older topographic feature to the E of the scarp associated with lower order streams with a relatively higher degree of branching than those associated with the rift scarp may be related to the rift but much older than the more spectacular scarp.

2.3.Law of Stream Numbers Tested on Bunyoro Drainage

The law of stream numbers was tested on the whole area (Text-Fig. 5). This law states that the sum of stream segments in an order form an inverse relationship with the order number in a drainage basin. According to HORTON (1945) departure from this law, if other conditions are normal, may generally be ascribed to geologic controls.

Order	Sum of Stream Segments	Bifurcation Ratio	Average Bifurcation Ratio
1	3214	3.25	
2	989	2.62	
3	377	2.88	3.52
4	131	3.54	
5	37	5.29	
6	7		

Table 1: Order, corresponding sum of stream segments ratios for the whole of Bunyoro.



Text-Fig. 5: Graph of numbers versus stream orders for the whole area studied.

The area cannot be taken to be a single drainage basin, but interestingly enough, all the intake areas join up. The morphometric results of the whole area are a combination of several drainage basins and sub-basins. This means that local modifications of smaller basins are overriden by the regional controls.

According to SPARKS (1981) and CLOWS & COMFORT (1983), the bifurcation ratios of basins which are not greatly distorted by geologic factors usually vary between 3.00 and 5.00. The calculated values of the area (Tab. 1) do not deviate greatly from the above figures. However, deviation that occurs may not be insignificant. Geologic controls where possible have been discussed earlier. It suffices to mention that geologic controls are rather not overriding.

3.Conclusion

Influence of geology on the drainage patterns and drainage densities is apparent in Bunyoro. Detailed field work would, however, have to be carried out to determine the factors responsible for the extreme diversity in the relative drainage densities on the "gneiss complex" rocks.

The regional slope is still the main factor controlling the stream directions but capture of some stream courses by structures reveals a lot about the structural grain of the region. The prevalent NE deflections and alignments of tributaries and trunk channels is parallel to dominant Precambrian and Cenozoic rock structures. This is very apparent in the W portion of Bunyoro bordering the present Western Rift Valley. High order lineaments have been mapped in this part of Bunyoro. Their major trend direction is NNE to NE which subtly might be expressing themselves topographically. The degree of deflections and the size of alignments generally decrease towards Lake Albert. This may represent a younging direction in the reactivation of the features on the rift shoulders by movements related to rifting. The alignment of rift faults with further inland geologic structures of varying ages may further indicate that present rifting in Bunyoro might have developed by reactivation along already existing basement structures.

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Statistical Evaluation of Geologic Control of the Shape, Size and Orientation of some Isolated Hills in Southern and Western Uganda

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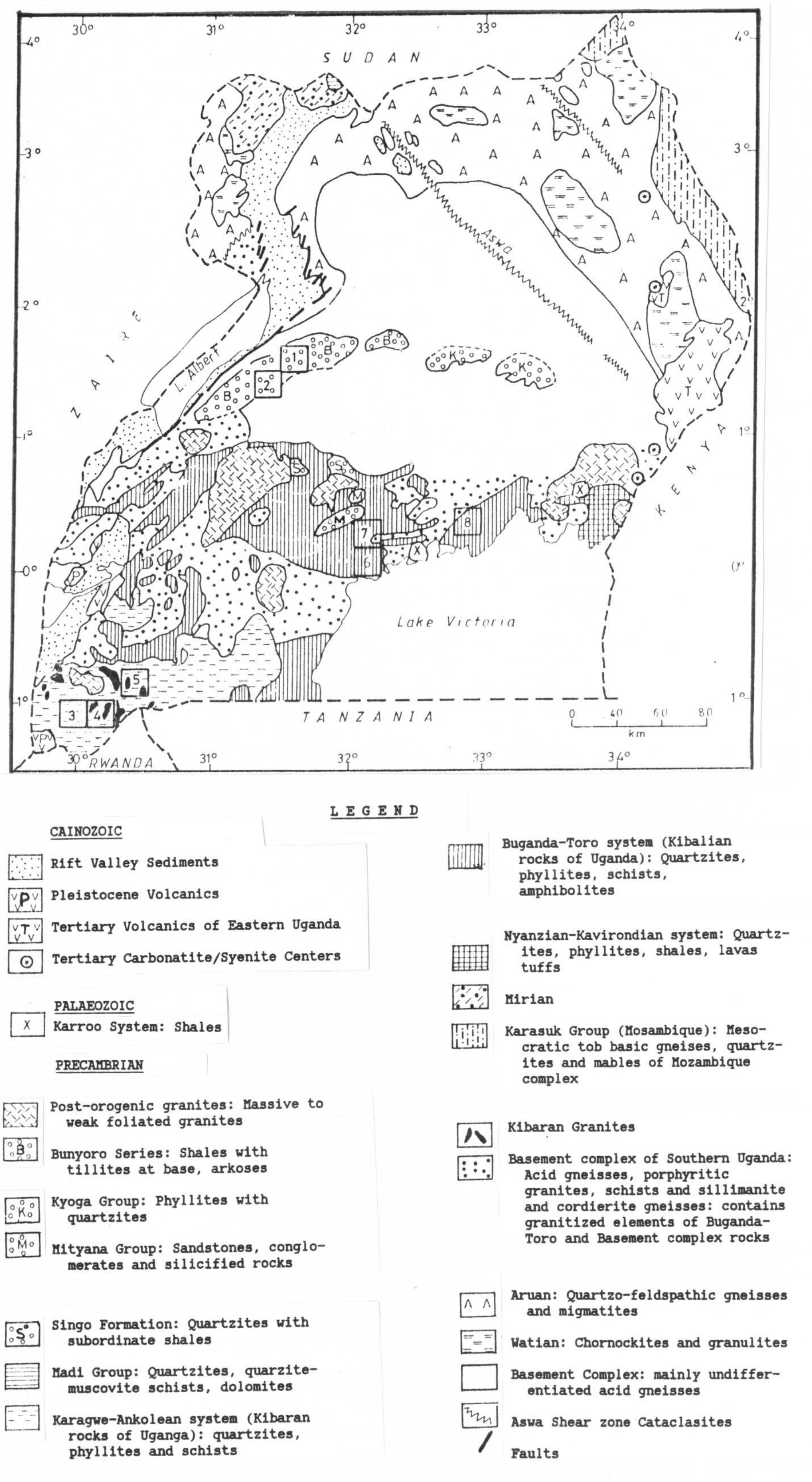
Abstract: Statistical methods of the student's t-test and azimuth analysis were employed in studying the influence of geology on the evolution of landforms in W and S Uganda. In the student's t-test comparisons of average hill shape and average hill size were carried out between areas covered by various rock types to find out whether both or one of the parameters may be directly dependent on the geologic factor. It was found out that the shape of hills in this region is highly influenced by the geology while size is largely affected by the denudation history of the areas.
The azimuth analysis of hills showed striking parallelism between orientation of hills and structural orientations especially where the denudational history is not very advanced.

1. Introduction

The complex interplay between exogenetic and endogenetic processes through time determines the morphology, size and stability of landforms. However, PITTY (1982) states that "between the crust of the earth and the force of erosion, there is unequal interplay that has brought landforms of extreme varities".

In the present study, statistical methods are used in the preliminary consideration of the importance of lithologic and structural (geologic) parameters in the evolution of the present landforms of W and S Uganda. These landforms are largely formed of unmetamorphosed and metamorphosed series of argillaceous and arenaceous rocks overlying the gneiss complex rocks and in some areas associated with syntectonic and post-tectonic granites.



Text-Fig. 1: Positions of topographic map-sheets superimposed on the geologic map of Uganda, used in the hill analysis: 1. Masinid, 2. Hoima, 3. Rubanda, 4. Mpalo, 5. Ntungamo, 6. Mitala-Maria, 7. Mityana and 8. Lugazi (Geologic map slightly modofied after geological survey, Uganda, 1973.)

Areas 1 and 2 (Text-Fig. 1) have been influenced to a reasonable extent by the tectonics of rifting.

Broadly, the landforms are denudational. Inverted relief in some areas of SW Uganda and regular isolated hills of S and central Uganda are part of the evidence that denudational processes have been operating for a long period. The length of time and the intensity are variable as evidenced by the planation surfaces (laterite surfaces) of different ages and variable forms of the hills considered. However, geologic control of the subsequent denudational processes and hence present landforms in some areas appears to be obvious and therefore merits study and documentation. The shape, size and orientation of the hills to a large extent cannot be accounted for by various operations of the denudational processes alone. The geologic factor is apparent even in those that are more mature.

The ultimate objective of this study is to find out whether geologic information can be obtained from the study of landforms in some areas of Uganda. This is relevant because of the paucity of outcrops due to inherent concealment by soil and vegetation.

2. Statistical Analysis

As stated by KING (1967), the statistical method in geomorphology is rarely the main feature of study but is one of the means by which the final goal of a complete understanding of the processes in the production of landforms under consideration can be approached. It should be clear that the relationship determined statistically does not solve the problem until the factors on which it depends are elucidated.

Usage of some terms: Some terms need clarification because of their possible different usage.

Hill Shape: TINKLER (1971) described it as the ratio between lengths of 2 principal axes measured at right angles, which he termed ellipticity index (EI). In PROCTOR & EL-ETR (1968), the shape of the pegmatite bodies was defined as the ratio between the length and the width. In this paper, it is defined as the ratio between the length of the long axis (L_{max}) and the width (Wav.) measured perpendicular to each other:

$$\frac{(L_{max})}{Wav.}$$

Hill Size: This is defined as the product of the long axis (L_{max}) and the width (Wav.):

$$(L_{max} \times Wav.)$$

The Null-Hypothesis: In the present paper, it is expressed in the following way: there is no significant difference between the mean hill-shape or mean hill-size of 2 areas being compared. Geomorphological significance of the hypothesis has to be sought. The comparison is by the student's t-test:

$$\frac{t = x_1 - x_2}{s^2 \sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}$$

Structural Control: It is taken to mean not only the landforms in their primary relationship with geologic structure but also the subsequent denudational forms where the factor of geology is still significant.

Map Sheet: This is based on the standard (1:50.000) $0^{\circ}15'$ x $0^{\circ}15'$ sheets of the Uganda Survey and Mapping Department. They are referred to by their local names and they form the basic sampling unit. Their location and underlying geology are shown in Text-Fig. 1.

3.Brief Description of the Lithology and Structure of the Rock Systems Referred to in the Text.

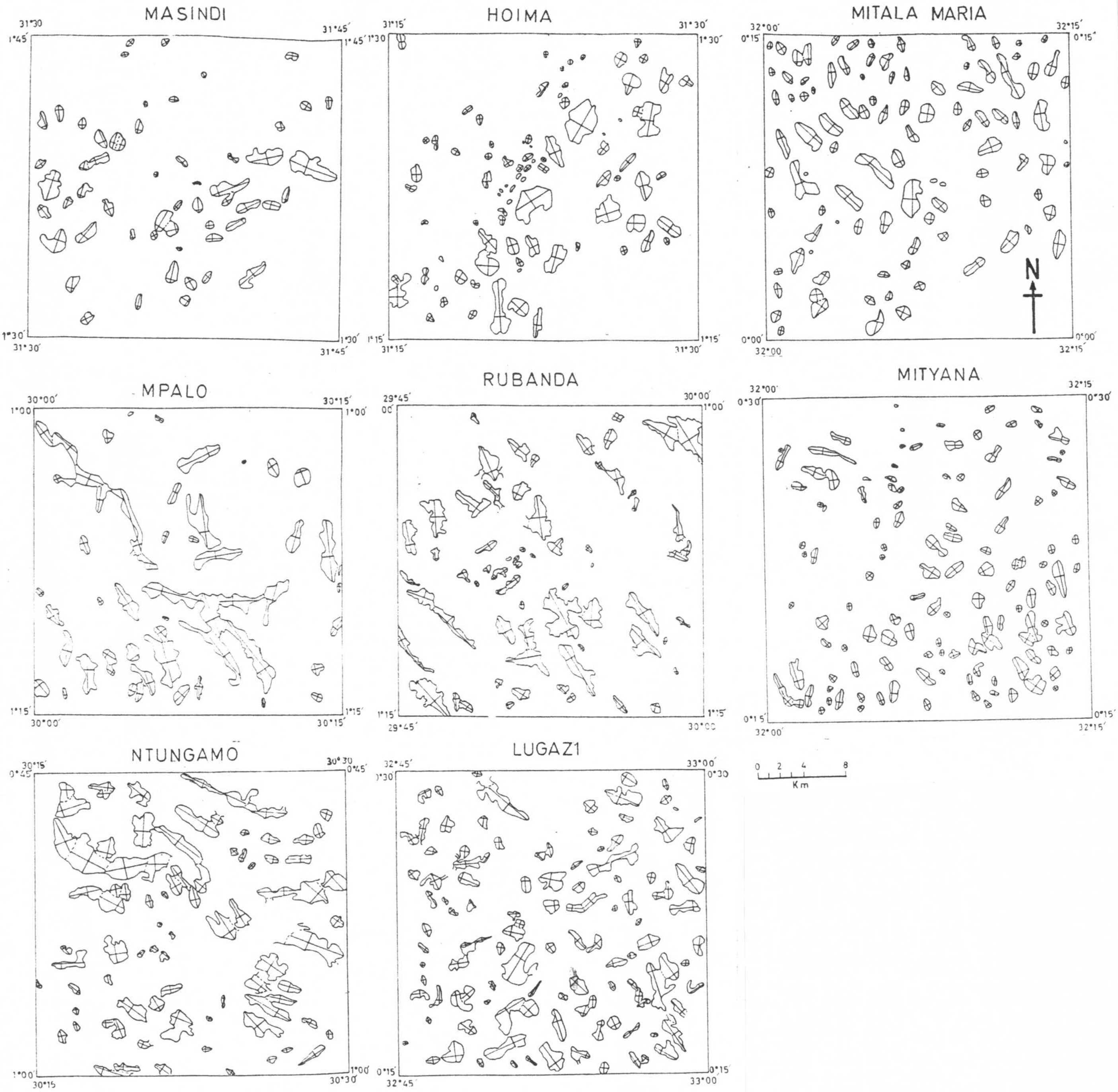
Kragwe-Ankolean (K-A): This system of rocks is part of a larger system, the Kibaran Orogeny rocks (Kibaran Supergroup) with an approximate age of 1.300 - 1.400 my. It is predominantly argillaceous with relatively minor arenaceous formations present in the whole section though strongly developed in few areas. The system is characterised by low grade metamorphism with the degree of metamorphism increasing with depth. The main rock types are mudstones, shales, slates, phyllites, schists (at the base and locally associated with intrusive granites), quartzites and conglomerates.

Quartzites generally form the most prominant ridges, nevertheless, large numbers of hills are of argillaceous formations. In the extreme SW Uganda the system is associated with simple, rather regular SE folds. Elsewhere folding is dominated by the SE trend, the trend being locally modified by transverse or cross-fold SW trends. The structure is in places complicated by granitic intrusions. Faults where they occur are post-folding and progressively replace limbs of sharp folds.

Buganda-Toro (B-T): This system is part of a larger system, the Kibalian Orogeny Supergroup with an approximate age of 1.800 - 2.000 my. It is overlain unconformably by the Karagwe-Ankolean. It is also largely argillaceous with relatively minor arenaceous formations which are not as strongly developed as in the Karagwe-Ankolean. The system compared to the latter is relatively more strongly metamorphosed and structurally more complex. The main rocks are mudstones, slates, phyllites, schists, amphibolites and quartzites. The system is associated with steep or vertical planes. Over most of the area occupied by the Buganda-Toro, there is evidence of at least 2 directions of folding, the most dominant trend being SW, swinging to EW at some places. A transverse direction of folding, varying in trend from SE to NS is also evident. This is often subordinate to the former trend but in the W parts of the system the SE folding becomes dominant. The 2-fold directions are found superimposed upon each and are thought to be contemporaneous. SSE recumbent minor folds with primary axial plane cleavage are present.

Bunyoro-Series (B-S): This is divided into the Lower Conglomerate Group, consisting of lenses of hard dark blue tillites set in softer white, buff, blue or pink mudstones and arkose grits and the Upper Argillaceous Group consisting of argillites and shales of different colours. The group occasionally contains feldspathic material. The age of the series is thought to be Upper Precambrian.

Faulting is common. The orientation is NNE. EW faults have also been recorded. The persistent strike direction of the Bunyoro Series is NE and the basin is known to be partially fault controlled.



Text-Fig. 2: Isolated hills and highlands of Masindi, Hoima, Rubanda, Mpalo, Ntungamo, Mitala-Maria, Mityana and Lugazi. Topographic map sheets showing longest axes and axes of approximate average width.

Map Sheet (Area)	Number of Hills	Mean Size	Standard Deviation	Mean Shape	Standard Deviation
Masindi	64	1.0048	1.2701	2.1482	0.9440
Hoima	113	0.7414	1.0039	2.2579	0.8693
Rubanda	69	1.8136	2.0516	2.9586	1.5360
Mpalo	55	1.8253	1.7226	3.9168	5.4343
Ntungamo	84	2.003	2.3151	2.6470	1.1089
Mitala-Maria	107	1.0956	0.8885	2.4529	1.4373
Mityana	124	0.7621	0.6949	2.5205	1.3592
Lugazi	123	1.1373	1.0740	2.5256	1.2275

Table 1: Number of hills, mean values of size and shape and standard deviation of size and shape of hills of the areas studied.

Areas compared	Calculated values of t		Degrees of freedom	Tabled values of t	
	Size	Shape		95 %	99 %
Hoima/Masindi	1.50329	0.76427	175	1.645	2.326
Hoima/Mityana	0.13171	2.53386	235	1.645	2.326
Hoima/Mpalo	4.13813	2.39813	166	1.645	2.326
Hoima/Mitala-Maria	2.38664	1.88987	218	1.645	2.326
Hoima/Ntungamo	4.49469	3.41591	195	1.645	2.326
Hoima/Lugazi	2.55487	2.74241	234	1.645	2.326
Hoima/Rubanda	3.89698	4.00825	180	1.645	2.326
Masindi/Mityana	1.73191	1.54641	186	1.645	2.326
Masindi/Mpalo	3.10759	2.94430	117	1.658	2.358
Masindi/Mitala-Maria	0.59656	1.06952	169	1.645	2.326
Masindi/Ntungamo	3.52942	9.30233	146	1.645	2.326
Masindi/Lugazi	0.83562	1.65441	185	1.645	2.326
Masindi/Rubanda	2.91919	3.19428	131	1.645	2.326
Mityana/Mpalo	4.42034	1.87973	177	1.645	2.326
Mityana/Mitala-Maria	3.14071	0.36535	229	1.645	2.326
Mityana/Ntungamo	4.75880	0.73652	206	1.645	2.326
Mityana/Lugazi	3.25666	0.03112	245	1.645	2.326
Mityana/Rubanda	4.12744	1.97756	191	1.645	2.326
Mitala-Maria/Mpalo	2.94655	1.96286	160	1.645	2.326
Mitala-Maria/Lugazi	0.32243	0.40923	228	1.645	2.326
Mitala-Maria/Ntungamo	3.39114	1.05776	189	1.645	2.326
Mitala-Maria/Rubanda	2.74579	2.18644	174	1.645	2.326
Lugazi/Rubanda	2.54916	2.00933	190	1.645	2.326
Mpalo/Ntungamo	0.51012	1.70973	137	1.645	2.326
Mpalo/Lugazi	2.73380	1.87733	176	1.645	2.326
Mpalo/Rubanda	0.03455	1.26792	122	1.645	2.326
Ntungamo/Lugazi	3.19020	0.74065	205	1.645	2.326
Ntungamo/Rubanda	0.52867	1.40995	151	1.645	2.326

Table 2: A test-comparison of shapes and sizes of different areas, degrees of freedom (total number of hills in areas being compared) and tabled values of t corresponding to the degrees of freedom at 95% and 99% confidence levels.

4. Nature of Study

The present study was carried out in 2 stages:

1. Comparison of mean shape and mean size of different areas (sheets) using the student's t-test.
2. Azimuth analysis of hills and comparing prominent orientations with the orientations of known geologic structures.

4.1. Mean Shape and Mean Size Comparison

The lowest closed to almost closed contours of hills were traced and axes inserted (Text-Fig. 2) and their lengths measured. Shapes and sizes were computed and mean shape and mean size of hills of the study areas and corresponding standard deviations were also computed (Tab. 1). Inter-sheet comparisons were carried out using the student's t-test at 95% and 99% confidence levels (Tab. 2). Significant similarities and differences are shown in Tab. 3.

The areas of study were chosen from areas of different rock systems (Text-Fig. 1), each system with characteristic structural grain. Lithologies may be similar in some instances but varying in age and degree of metamorphism. Some structural orientations also overlap.

The basement complex terrain represents largely a featureless broad surface except where it has been affected by rifting and intruded by Precambrian porphyritic granites. Hills and highlands are largely characteristic of the cover formations whose lithology and associated structure in combination with denudational processes are thought to have led to the development of landforms of different varieties.

4.2. Observations

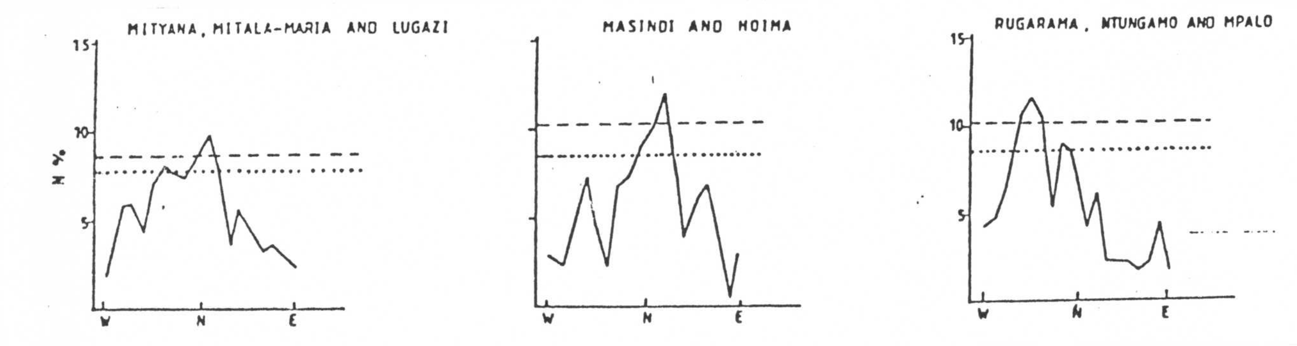
1. The mean shape of hills from areas covered by the same cover rocks are significantly similar in all comparisons made. However, the relationship between shape of hills of Mpalo and Ntungamo is weaker. This could be due to complications brought by porphyritic granite intrusions in Ntungamo and also due to ruggedness of the hills/highlands associated with Karagwe-Ankolean (Kibaran) cover rocks.

2. The mean sizes of hills from areas underlain by the same bedrock are significantly similar but with some discrepancies as can be seen between hills from areas covered by Buganda-Toro (Kibalian) cover rocks.

3. The mean shape of hills from areas covered by the Karagwe-Ankolean have significant similarity with hills from areas covered by the Buganda-Toro at 99% confidence level but at 95% confidence level only 3 out of 9 comparisons are significantly similar. This similarity is therefore not as strong as one indicated between areas underlain by the same cover rocks. The similarity in shape at 99% confidence level is not accompanied by similarity in size.

4. The 2 variables (shape and size) are not always controlled by the same factors. Significant differences in shape are now always accompanied by significant differences in size.

Azimuth Analysis: Significant differences or similarities in shape of hills expressed using the student's t-test above is followed by an attempt to establish some causative factors. In the present study, the orientation of hills is compared with the orientation of known structures associated with the bedrock. Structural and topographic orientations are compared.



Text-Fig. 3: Orientations of the longest axes of hills from the areas studied grouped according to their main cover rocks. POISSON's levels of significance at 95% and 99% are inserted.

Areas compared	Bed rock	Significance			
		95%		99%	
		Size	Shape	Size	Shape
Hoima/Masindi	B-S/B-S	+	+	+	+
Mityana/Mitala-Maria	B-T/B-T	–	+	–	+
Mityana/Lugazi	B-T/B-T	–	+	–	+
Mitala-Maria/Lugazi	B-T/B-T	+	+	+	+
Mpalo/Ntungamo	K-A/K-A	+	–	+	+
Mpalo/Rubanda	K-A/K-A	+	+	+	+
Ntungamo/Rubanda	K-A/K-A	+	+	+	+
Hoima/Mityana	B-S/B-T	+	–	+	–
Hoima/Mitala-Maria	B-S/B-T	–	–	–	+
Hoima/Lugazi	B-S/B-T	–	–	–	–
Masindi/Mityana	B-S/B-T	–	+	+	+
Masindi/Mitala-Maria	B-S/B-T	+	+	+	+
Masindi/Lugazi	B-S/B-T	+	–	+	+
Hoima/Mpalo	B-S/K-A	–	–	–	–
Hoima/Ntungamo	B-S/K-A	–	–	–	–
Hoima/Rubanda	B-S/K-A	–	–	–	–
Masindi/Mpalo	B-S/K-A	–	–	–	–
Masindi/Ntungamo	B-S/K-A	–	–	–	+
Masindi/Rubanda	B-S/K-A	–	–	–	–
Mityana/Mpalo	B-T/K-A	–	–	–	+
Mityana/Ntungamo	B-T/K-A	–	+	–	+
Mityana/Rubanda	B-T/K-A	–	–	–	+
Mitala-Maria/Mpalo	B-T/K-A	–	–	–	+
Mitala-Maria/Ntungamo	B-T/K-A	–	+	–	+
Mitala-Maria/Rubanda	B-T/K-A	–	–	–	+
Lugazi/Mpalo	B-T/K-A	–	–	–	+
Lugazi/Ntungamo	B-T/K-A	–	+	–	+
Lugazi/Rubanda	B-T/K-A	–	–	–	+

Table 3: Correlation between bedrock and results of the t-test of hill shapes and sizes. Designations: B-S: Bunyoro-Series. K-A: Karagwe-Ankolean. B-T: Buganda-Toro. The (+) sign stands for significant similarity and the (-) sign stands for significant difference.

The orientation of the longest axes of the hills were determined and map sheets (study areas) underlain by the same cover rocks were grouped together and graphs of percentage number (N%) versus orientation were constructed and the 95% and 99% significant level inserted (Text-Fig. 3). The major orientations determined were then compared with structural trends reported by earlier workers (Tab. 4).

5. Discussion

1 Shape is controlled by structure during landforms evolution in this area while size, though partly influenced by geology is mainly time dependent in the geomorphic history. Similarity in shape of hills of areas underlain by different cover rocks may be due to some identical structures and structural orientations. Since the orientation of the long axis of a hill is essentially the orientation of its shape parameter, then it follows from the azimuth analysis that the shape of a large number of hills is controlled by structure.

2. Structural trends have been found to be closely related to relief trends in some areas. The likely nature of the relationship is:

a) Most hills associated with the Bunyoro Series are structurally controlled. DAVIES (1939) associated most hills he mapped in this area with faults. Most of them are likely to be fault blocks, their movements having been influenced by the multiple displacements along the rift related faults. In the field (by the junior author) some hills in the area were found to be protected by relatively competent sandstone layers overlying relatively weak mudstones and tillites.

b) Most of the studied hills associated with the Karagwe-Ankolean are parallel to the main trend of folding in NW orientation. Locally, however, where cross folds develop (NE trending) hills trend in that direction. The strike of these ridges is parallel to the strike of the quartzites that cap them in many areas but even where the protective competent quartzite layer has been completely eroded, or is non-existent the general trend of hills is in the direction of the axis of folding. Reversed relief is a common phenomenon but this has not fundamentally affected the parallelism of structure and the strike of ridges.

c) Most hills from Buganda-Toro trend N to NW. This coincides with the trend of transverse folding (subordinate). Relatively few hills trend ENE (the main fold trend).

3. Structural control in the orientation of hills of the Karagwe-Ankolean and the Bunyoro Series is very evident. However, the structural control of the orientation of the hills of Buganda-Toro, though somewhat evident, is complicated. Although WAYLAND's (1920) statement that 'the hills of Buganda are not anywhere controlled by internal structure' is questionable. The modification of structural control by denudational processes is very advanced.

4. Geologic control in the evolution of the landforms in the studied areas is still evident but the extent to which it is influential varies from area to area due to varying denudational histories and neotectonic diastrophism that has affected the older lithologies and structures.

Despite the inferences of parallelism of structure and geomorphic features in some areas, direct geologic data may not be read from geomorphic features.

Group of areas	Characteristic peaks	Structural trends
Hoima and Masindi	N25W-N30E (with a sharp peak at N15E), NS5E,NS5W.	N-S, NNE, NE, E-W, NW
Rubanda, Mpalo and Ntungamo	N70W-N25W (with nose at N45W),N20W-N (with a sharp nose at N15W), N15E,N75E	NW,NNW, N-S, NE, E-W.
Mitala-Maria Mityana and Lugazi	N55W-N20E (with sharp noses at N05E and N35W), N70W-N80W, N35E, N65E (very minor)	ENE, E-W,NW-N

Table 4. Comparison between peaks of the grouped areas and structural trends reported by earlier workers. (Note: The main hill orientation and structrural trends are underlined in this table. The structural orientation are after KING & de SWART (1967) and DAVIES (1939).

Complications are the rule rather than the exception. This calls for careful examination of the complimentary role of geomorphology and geology in this part of the country. Certainly geomorphic features are the surface phenomenon that could be employed in additional understanding of the structural grain, especially in the W parts, in a country where outcrops are rare and this study is a step in that direction.

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Geomorphology and Sedimentology of Lake Manyara Environs, Tanzania, East Africa

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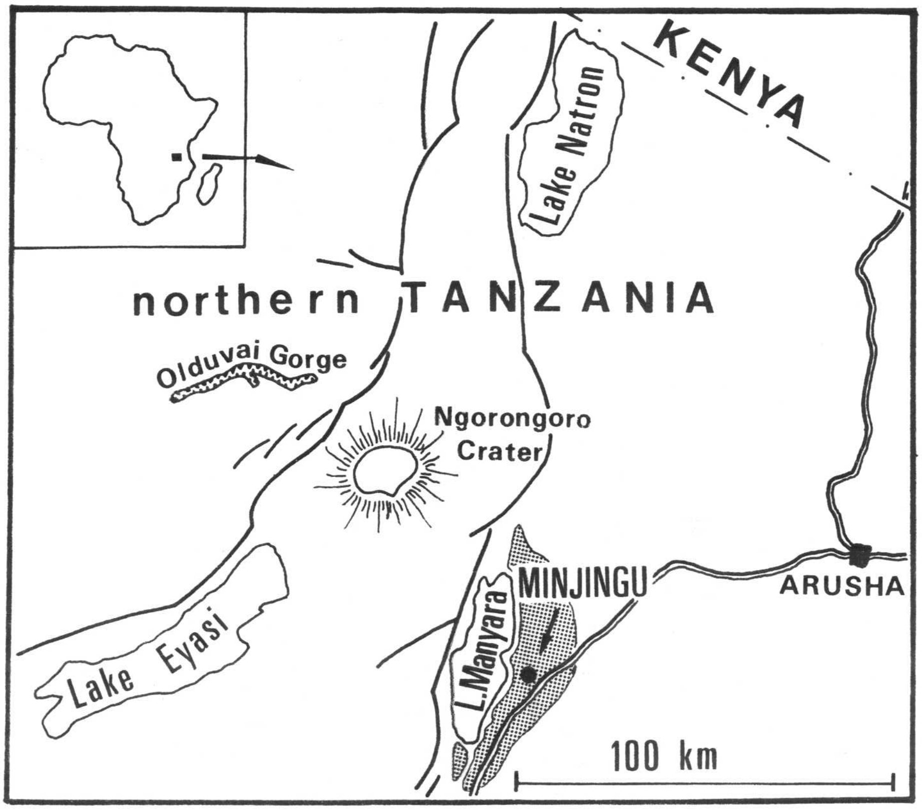
Abstract: An area of about 2000 km^2 around Lake Manyara and Lake Burungi, in NW Tanzania, was geomorphologically mapped using aerial photographs on a scale of 1:42.250. Field traverses were made to check the interpretation and collect samples of rocks and sediments, with special emphasis on the phosphorites of Minjingu, ca. 5 km E of Lake Manyara.

Lake Manyara is situated along the S part of the Eastern or Gregory Rift in the depression of its W shoulder. The area consists of late Proterozoic metasediments, Neogene volcanics, and Plio-Pleistocene and Holocene lake beds. There are plateaus, rolling plains, and features like alluvial fans, scree, migrating deltas, besides various others usually found in a fluvial and lacustrine terrain. A few faults and fractures within the lake beds have been recorded from lineaments on the aerial photographs as well as during the subsequent field traverses. Also evidence for neotectonics is cited as reflected in the morphological changes of features associated with stream terraces and lacustrine ridges.

Macroscopic and microscopic studies of rock samples from the lake beds indicate the following rock types: 1. coarse fragmented carbonate rocks, 2. stromatolitic and oncolitic rocks, 3. oolitic rocks and 4. dolomitic rocks. Some of them are closely interbedded with volcanic debris. It is inferred that the lakes should have occupied a much wider area and periodically shrunk to give rise to sub-parallel ridges close to the present shorelines; a majority of the sediments is of chemical origin. The phosphorites of Minjingu represent a guano deposit with bone bed features.



Text-Fig. 1: Sketch map of northern Tanzania. The extension of the Plio-Pleistocene Lake Manyara Beds is stippled. Major faults of the Eastern- or Gregory Rift Valley are given in black lines.

1. Introduction

Lake Manyara, situated along the S end of the Gregory Rift in NW-Tanzania (Text-Fig. 1), covers an area of approximately 480 km^2 at an altitude of 960 m above MSL, extending NNE-SSW. Its water depth is only a few meters. Observations on its present ecosystems have been done for example recently by KINOTI et al. (1961). 12 km SE of Lake Manyara lies Lake Burungi which covers 40 km^2, but has recently almost dried out. Both lakes are of the saline-alkaline type.

The area around Lake Manyara was geologically mapped during the early sixties. Quarter Degree Sheets 69 and 53 (Mbulu and Ngorongoro) were published in 1963 - 1965 by ORRIDGE, and in 1962 - 1963 by PICKERING respectively on a scale of 1:125.000. Detailed studies of the late Proterozoic rock units as well as of the Neogene volcanics are presented elsewhere (e. g. WILKINSON et al. 1986). At least 3 old lake shoreline features have been traced in the SE part of the area under study, near the inselberg of Minjingu, wherefrom phosphorites are presently exploited. A few shorelines are indicated around Lake Burungi and also NE of Lake Manyara. None are shown in the W part.

The aim of this study was to prepare a geomorphic map of the area around Lake Manyara and Lake Burungi, to analyse the Plio-Pleistocene and Holocene sediments therein, and to interprete their paleoenvironments. The geomorphic map presented here (Text-Fig. 2) was prepared from an interpretation of aerial photographs on a scale of 1:42.250 of flights in 1958, and considering the available topographic and geologic maps of this area. The scale given here is only approximate as the details were visually transferred with limited horizontal control. Though many more examples of the listed features are met within this area, only a few are included because of the limitations of the scale. A few traverses were made to check the results inferred from the aerial photographic interpretation, and some samples of sediments from the lake beds were collected for a detailed study. Various aspects of the sedimentology of the phosphorites, their fossil faunal composition and their palaeoenvironment have already been published (SCHLÜTER 1986a, 1986b, 1987, 1991, SCHLÜTER, KOHRING & MEHL 1992, SCHLÜTER & KOHRING 1992).

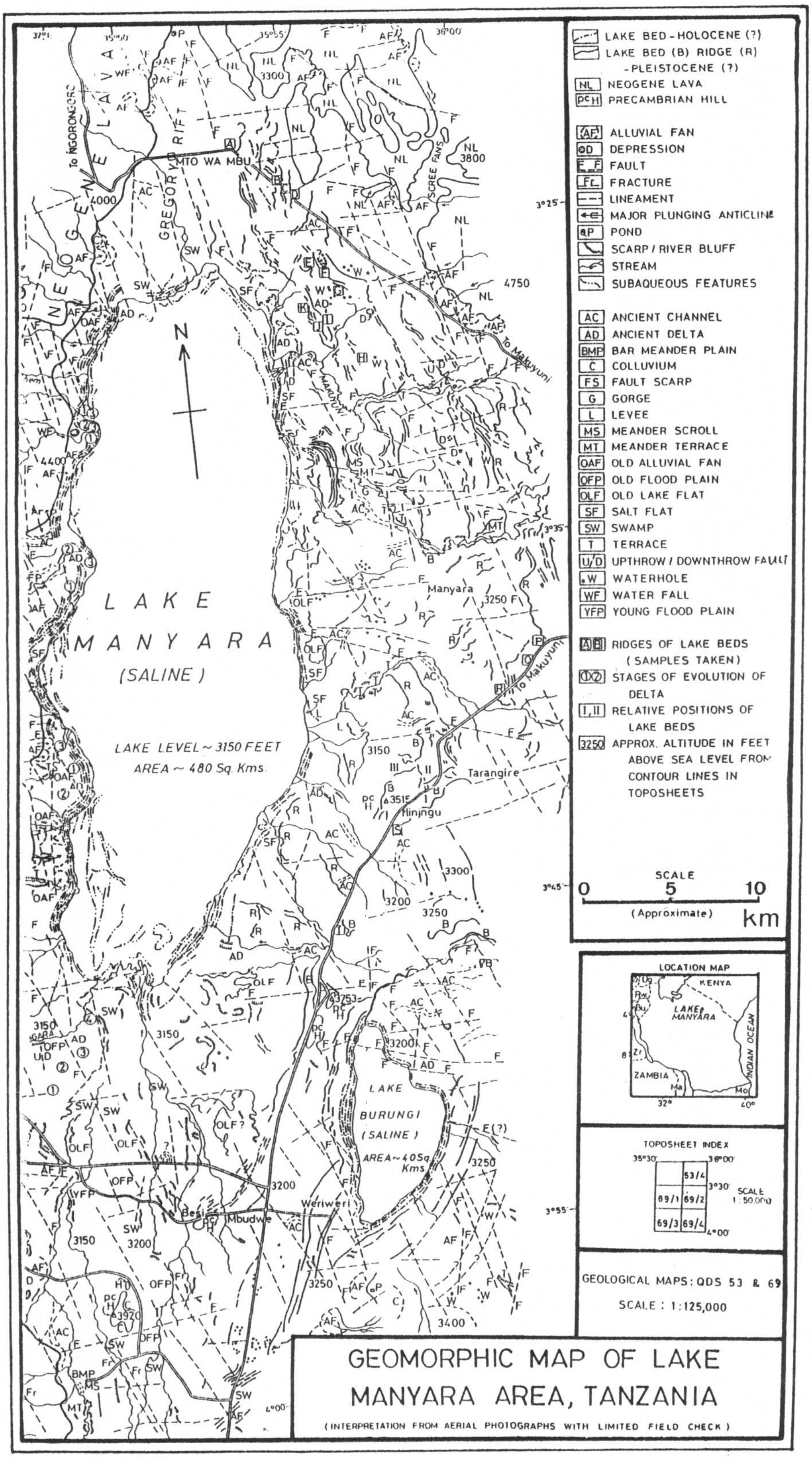
2. Lithology and Stratigraphy

The late Proterozoic rocks of Usagaran age are metasediments (hornblende-garnet gneiss, biotite gneiss, quartzo-feldspathic gneiss, quartzites etc.) with intrusions of pegmatite and quartz reefs, and occur in force a little beyond all along the W margin of Lake Manyara. These form high mountains ranging in altitude from 2250 m in the SW to 1140 m in the NW. The Neogene volcanic extrusives are essentially basaltic, though andesite, nephelinite, phonolite, trachyte, ignimbrite etc., are also reported.

The lake beds are made up of grey silty ash clays and marls with horizons of chert nodules (for their origin see EUGSTER 1967, ICOLE et al. 1984) and calcareous algal concretions (compare also CASANOVA 1986a, 1986b, 1988, CASANOVA et al. 1988, TAIEB 1986, TAIEB et al. 1987). Interbedded with them are current bedded sandstones, pebbly limestones, conglomerates and occasional tuffs. In the lower part of the sections, oolites, pisolites and massive algal limestones are well developed (see chapter 6). KENT (1942) was probably among the first to report on a detailed section of these lacustrine deposits near Makuyuni (approximately 20 km E of the present area of study) and suggested a middle-Pleistocene age for them. The sediments exposed in the plains NE of Lake Manyara were assigned to Plio-Pleistocene by JAMES (1956: 89). The age of the phosphorites of Minjingu has been controversial, although an upper Pliocene age of their deposition is most likely (SCHLÜTER 1991). In Text-Fig. 3 the available stratigraphic data are compared and summarized.

3. Structure

Lake Manyara is bound in the W by the long Manyara fault escarpment which indicates the southernmost end of the Gregory Rift Valley in East Africa. However, it is not a single long fault, but is made up of many arcuate faults extending in directions NW-SE to NE-SW. Some of these are displaced by cross faults extending WNW-ESE. It appears as though the lake is in a tilted block. The published geological maps of this area (QDS 53 and 69) show the major faults to the W of the lake in the late Proterozoic rocks and in the piedmont zone.



Text-Fig. 2: Geomorphic map of Lake Manyara area, based on aerial photographs, available topographic and geologic maps and limited field observations.

Only a few faults are recognizable N of the lake within the Neogene volcanics. None are shown within the Plio-Pleistocene and Holocene sediments, though a suggestion is made in the accompanying text that some of the sediments must have been affected by post-Pleistocene faulting. According to JAMES (1956: 91) while there is block-faulting and tilting in the Gregory Rift Valley, there is no trough faulting (graben type). According to SHACKLETON (1955) main faulting in the Gregory Rift Valley might have occurred after the completion of the end-Tertiary surface and before the Pleistocene deposits began to accumulate (for further discussions see also GROVE 1986). An isolated deposition of gravelly sands on the top of the Gregory Rift scarp over the W hills close to Chem Chem river is interpreted as a remnant of superficial sand which was deposited before the rifting took place.

4. Geomorphology

On the basis of easily recognisable variations of morphology, the area around Lake Manyara can be divided into the following geomorphic provinces (Text-Fig. 4, adapted and modified from the geological maps of this area - QDS 53 and 69, and Fig. 5, showing a block diagramme of the area):

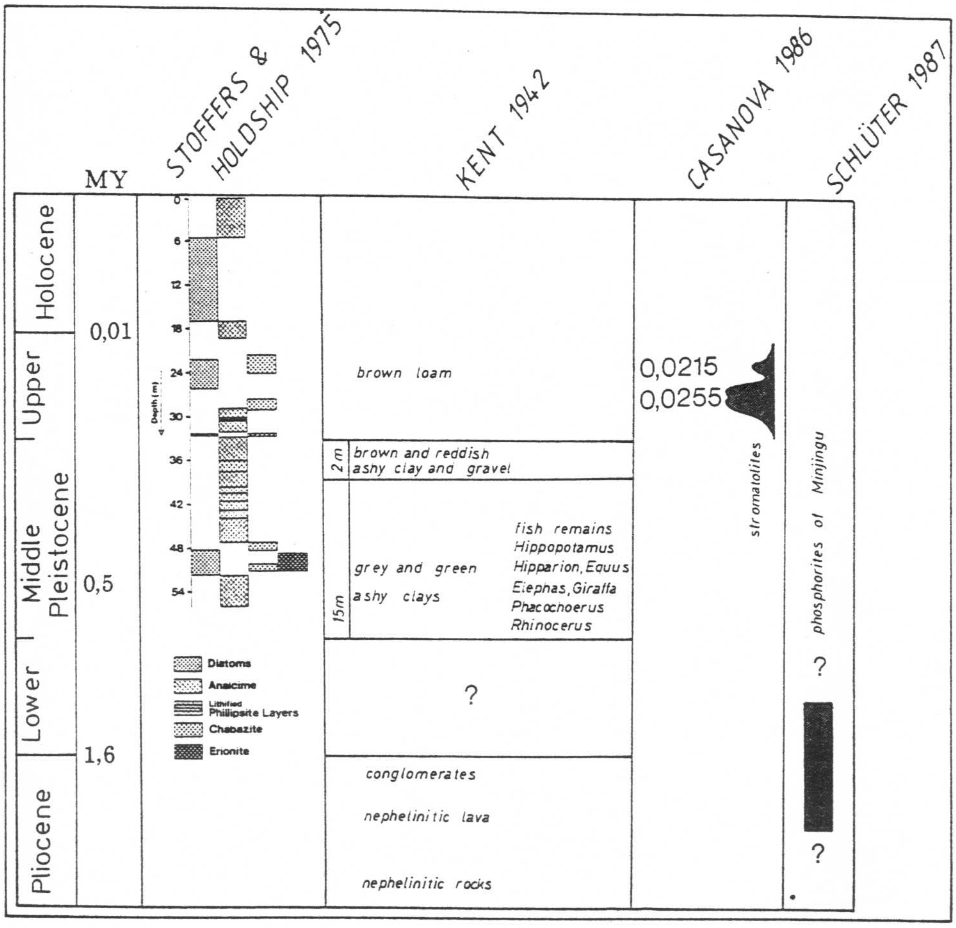
1. Plateau and hills of gneisses (late Proterozoic - Usagaran)
2. Plateau and hills of lavas (Neogene)
3. Rolling Plains of Lake Beds (Plio/Pleistocene)
4. Piedmont terrain (Holocene)
5. Plains (Holocene)

4.1. Landforms

Lake Manyara is bound by a long continuous range of hills in the W mainly made up of late Proterozoic formations. There appears to be an erosion surface here gently sloping towards NNE from 2250 m in the SW to about 1525 m in the NW. Whereas there are detached flat surfaces often obscuring the structure, indicating them as remnants of erosion surfaces, where they are dissected by numerous streams, the folded nature of the strata is quite obvious to the extent, that antiforms and synforms can clearly be recognised in the aerial photographs of this area. However, the ridges are made up of rather resistant strata.

In the NW, Neogene lavas unconformably overlie the late Proterozoic gneisses. These also form high mountains with long escarpments in the NW rising up to approximately 1220 m from a ground level of 976 m (= 2196 m MSL), N of Mto wa Mbu, a small village along the road from Ngorongoro to Arusha in the N part of the area. On a regional scale there is no conspicuous discordance in the landscape as one passes from the gneisses in the SW to the lavas in the NW along the W boundary. However, where dissected by streams, a few buttes and mesas could be observed - features resulting from denudation of areas with a horizontal capping of resistant lava flow. The same Neogene lavas in the NE are, however, dissected into rugged hills. This may partly be due to the very nature of the origin of these lava flows here, having emanated from individual ancient volcanoes (Central type).

The lake beds of Plio-Pleistocene, about a couple of km away from the E shoreline of the lake occur either as low flat-topped hills or as long ridges.



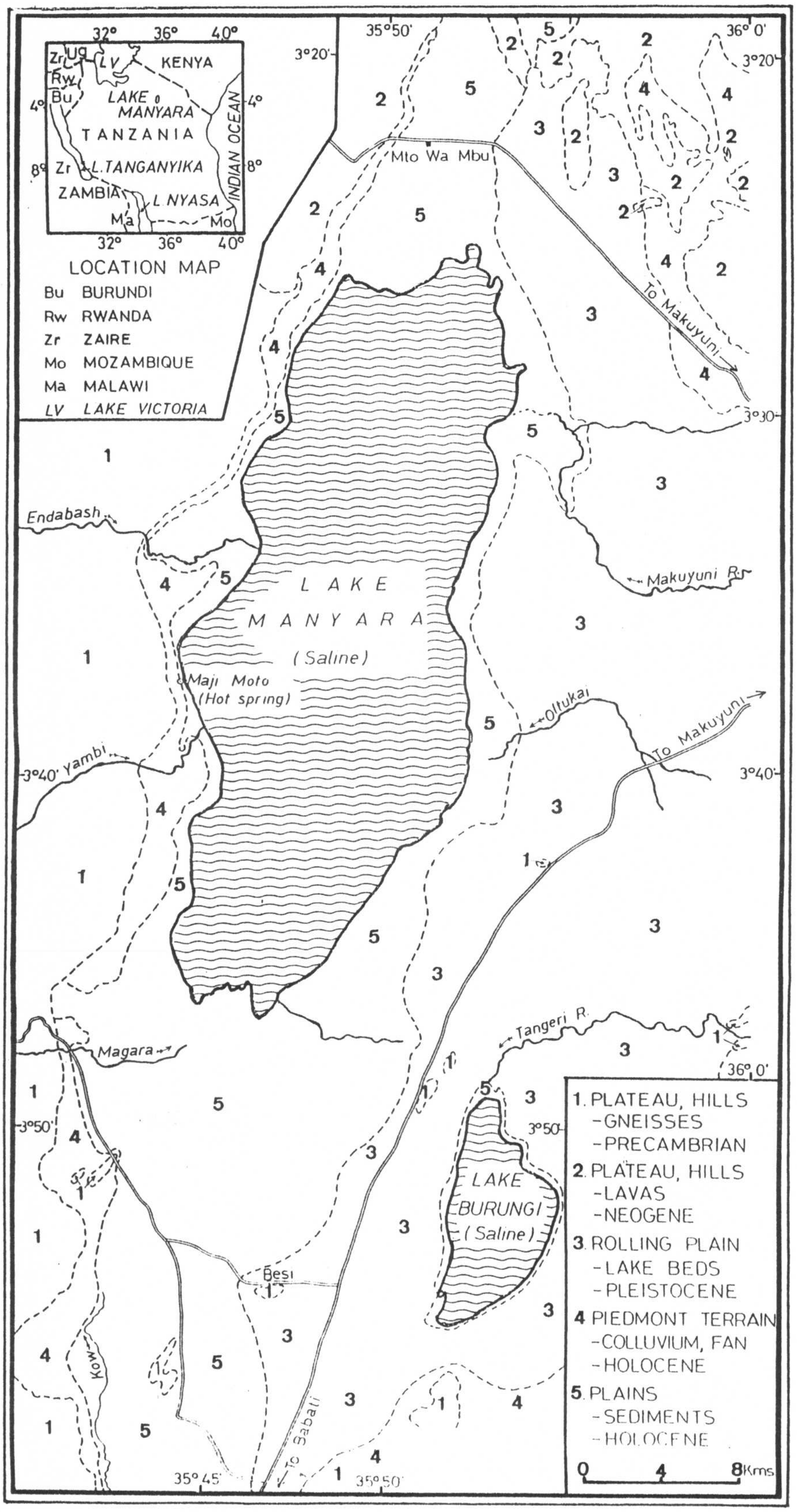
Text-Fig. 3: Stratigraphic correlation of Lake Manyara area, after different sources.

Majority of the ridges (only some of them may actually indicate old shorelines) are detached. The ridges range in relative height between 3 - 7 m above the adjoining ground level. The width of the outcrop of the ridges varies from 3 - 30 m. On the other hand, the unconsolidated Holocene lake sediments close to the present shoreline do not exhibit a conspicuous relief. Generally, these are best recognised and traced from aerial photographs.

From the extent of the lake beds, it is obvious that Lake Manyara must have occupied at least 3 to 4 times the present area of extension before it shrank to its present position. The disposition of the old shorelines suggests that the lake must have shrunk gradually, though it can not be denied that occasionally there might have been a few transgressions as well (intermittent increase in lake water level). This is evident from the fact that even today Lake Manyara shows a few submerged shorelines (subaqueous ridges) (Text-Fig. 2). These are preserved because of being made up of relatively resistant beds. As one traverses across the older lake sediments from E to W, the old shorelines can be detected as a series of resistant ridges at successively lower altitudes till one comes to the present lake bed (Text-Fig. 2).

It is equally possible that a few of the ridges may turn out to be only volcanic debris deposited along the edge of the old lake, beyond the reach of the present lake waters. Nature and disposition of the ridges is related to the sediments in the lake beds or along the shoreline which depends upon factors like:

1) proximity to the active volcanoes,



Text-Fig. 4: Geomorphic provinces of Lake Manyara area, adapted and slightly modified from the geological maps of this area (QDS 53 and 69).

2) pluvial or non-pluvial periods leading to a lot of erosion and transportation of volcanic debris into the lake or in the lake bottom beyond the shoreline,
3) it being an area practically not receiving any sediment from the land beyond, but is place where only chemical sedimentation takes place and
4) erosive action of consequent streams on the gentle slopes of the uplifted lake beds.

The apparent absence of the prominent old lake ridges on the W flank of the present lake may be either due to erosion, or submergence under recent deposits. The demarcation of lake beds as those belonging to Plio-Pleistocene and Holocene in Text-Fig. 2 is purely tentative, based on their location with respect to the present shoreline and the degree of compaction and nature of sediments.

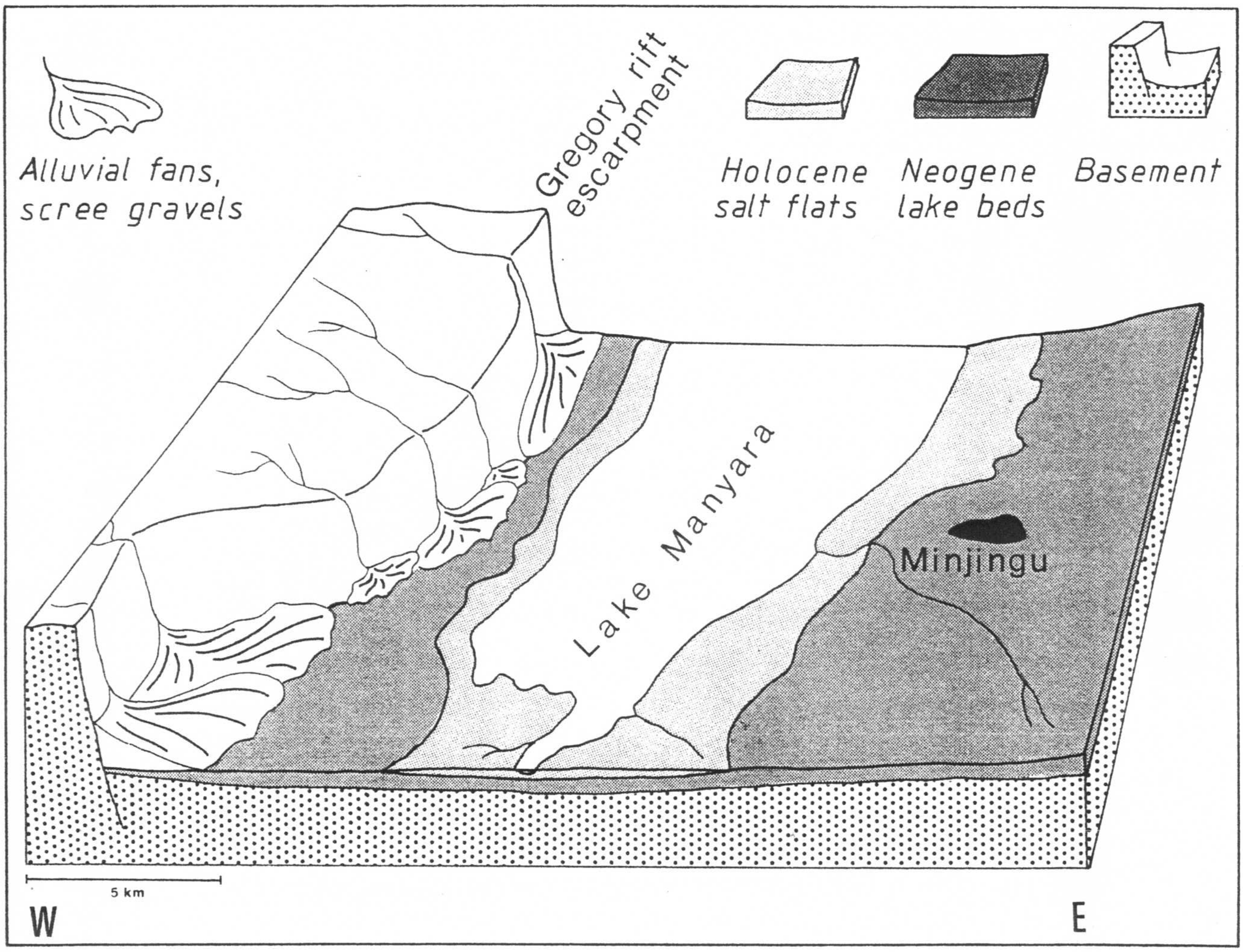
Numerous other minor geomorphic features were recognised in the aerial photographs and some of them are indicated in Text-Fig. 2. It is possible that whereas some of the subaqueous ridges may have formed beneath water, some, however, may be those formed along the shore, but later submerged due to a rise in the lake level during an intermittent pluvial period.

4.2.Recent Surficial Deposits

Where streams debouch into the lake from the W highlands, deltas in the form of fans are invariably formed. Even in these, the successive lowering of the lake level can be recognized besides lateral migration of the delta lobes. This is particularly seen well in the case of rivers Magara, Yambi, Endabash, Bagoya and Ndala, as one proceeds from the S to the N along the W margin of the lake (Pl. 3, Fig. 1-3). As a contrast only very incipient deltaic deposits are seen along the E margin of the lake. This is mainly due to lack of enough material to be carried into the lake, low gradient and intermittent and ephemeral nature of streams flowing in these parts. Closer to the hills, scree, colluvium and alluvial fan deposits can be seen. These are mainly close to the piedmont zones in the W range and around the volcanic hills in the NE. The relative ages of adjoining and overlapping alluvial fans can be reasonably inferred from their mutual field relations. Close to the shore of the lake, saline efflorescence (salt flats) is seen in some places. Near the hills SE of Lake Burungi are brown silty soils with concretionary layers.

4.3.Drainage

The rivers from the W highlands flow through narrow gorges, more often controlled by fractures and faults and in cascades and rapids down to the lake. There are a few waterfalls too along the E margin of the W ranges. The area is in a semiarid climate and a majority of the rivers in the E plains are dry most of the year. A few terraces have been recognised on one or both sides of the streams. It is rather difficult to say if all of them owe their existence to the same cause, though it can not be denied that a certain amount of rejuvenation of younger streams across this plain has given rise to entrenched meandering, and in a few cases where faulting has tilted sections of this plain, drainage has become tortuous and anastomosing, particularly along Makuyuni and Tangeri rivers on the E plains adjoining Lake Manyara (Text-Fig. 2, 4 and 5). Straight alignments of sections of streams and shores of lake indicate the structural control on these features either due to faulting or due to fractures. Misfit streams in certain sections indicate possibly piracy.



Text-Fig. 5: Block diagramme of Lake Manyara area.

It is quite possible there might have been a few planation piracies as well in the E lacustrine plain.

Some of the ancient channels may be only dry channels of the streams close to the flowing ones, but some are distinctly at a higher elevation than the river bed. Associated with these are sometimes found meander terraces and scrolls. These indicate that either the present stream has cut through its own river bed due to a fall in the local base level (Lake Manyara in this case) or due to some hydrodynamic condition or rejuvenation. Particularly in the case of Makuyuni in the E and Magara in the SW, faulting and uplift are the most likely causes. Both in the case of floodplains and lake flats, the differences in elevation of adjoining ones indicate their relative ages, the upper usually being older than the lower.

Swamps are present particularly along the N and S shore of the recent lake into which some of the minor streams flowing down the gently sloping plains around the lake disappear. Disappearance of the streams even before they reach the lake shore may be due to their getting into a depression or a sinkhole.

A few ancient deltas (AD in Text-Fig. 2) are recognised about 2 to 3 km inland from the present shoreline. Besides indicating that some of the small streams branch further into a few small distributaries and formed these deltas in those places, it also indicates that the shoreline was close to these delta fronts earlier, before receding to the present position.

5. Neotectonics

That the lake beds have been possibly disturbed by post-Pleistocene faulting has already been mentioned by ORRIDGE (1963-1965), though were exactly he had observed it, was not recorded (QDS 69). The published maps also do not show any faults or fractures within the lake sediments. Maji Moto hot springs (Text-Fig. 4) close to the W shores of the lake is an indication of recent tectonic activity. On the N side of the river section of Bagoyo, flowing into the lake from the W, the present slope of the ground (top surface) can be seen inclined towards the lake in the E, but the lake beds beneath the fluvial sediments are however, inclined towards the land to the W (Text-Fig. 5). This might be due to postdepositional tilting of the lacustrine beds towards the W, prior to fluvial deposition. The fault scarps in the W range invariably show facets, suggesting their recent origin. A few faults have been recognised in the following places:

1. Close to the N shore of Lake Manyara.
2. Along the N E-W tributary of Makuyuni river.
3. Across Makuyuni river.
4. N of Tarangire, across the road.
5. N and NE of Lake Burungi.
6. Across the river Chem Chem.
7. Along the SW shore of Lake Manyara, N of Magar river.

Fractures with a size from a few km to 10 km extend NNW-SSE on both sides of the lake, and a few extend ENE-WSW in the E part. These have been recognised in the field, particularly within the late Proterozoic and the volcanic rocks. Also numerous lineaments have been identified in the airphotographs but it should be admitted that most of them could not be confirmed in the field.

6. Sedimentology of the Lacustrine Beds

The studies made and the inferences drawn here on the nature of lake sediments are based on fresh surface samples picked up during the ground follow-up of the study of aerial photographs. Absence of borehole information and sections cutting through the entire pile of lake strata does not permit presentation of the results in greater precision. Some of the places were not accessible and that left gaps in the information and perhaps even in the inferences. The interpretations made here are on the premise that the composition of the lake waters was not the same throughout the long history of the lake. It is known that it was not as alkaline or saline in the past as it is today (YURETICH & CERLING 1983, SCHLÜTER 1991), though many ions would have withdrawn from the lake waters as distinct mineral phases to be deposited as sediments.

The present lake, like many others throughout the world, is only a small remnant of an originally larger one. The ridges formed were a result of sedimentation in the lake environment and of tectonics. In conformity with the shrinking of the lake, the order of the ridge formation must be from the outermost towards the innermost one but could as well be partly the other way in some cases or even erratic depending upon the lake level at a certain point of its history. Similarly, formation of major ridges indicates major changes and longer durations of the presence of lake stands in the neighbourhood of the sites of ridge building. The ridges on the E side of the lake are formed by carbonate rocks and especially stromatolitic ones (Pl. 6, Fig. 3). The coarse fragmented carbonate material associated with them indicates a stage of non-deposition when original rock material was broken down and reworked before consolidation. Poor cementation of some coarse fragmented carbonate rocks indicates complete witdrawal of the lake from the depositional area, or it otherwise suggests occasional quick runoff starving the rocks of any kind of calcitic cement.

The rocks laid down in the lake basin include carbonate rocks, tuffs and reworked volcanic detritus, ashy clays and marls with horizons of chert nodules and calcareous algal concretions. A special case are the phosphorites of Minjingu (see chapter 7).Majority of the rock materials on the ridges are carbonate rocks which could be broadly grouped into the following types:

1. Coarse fragmented carbonate rocks
2. Stromatolitic carbonate rocks
3. Oolitic carbonate rocks
4. Dolomitic rocks.

6.1.Coarse Fragmented Carbonate Rocks

These rocks are very widespread and are found close to the base of the ridges. They also form cores of the oncolites or are found associated with the stromatolites. The abundance of coarse fragmented carbonate rocks especially highly heterogenous ones, may be attributed to repeated reworking of the rock material caused by pulsating lake levels and strong surface runoffs.

In most of their properties, these rocks show large variations. They have a wide range in the size of the fabric elements (clasts and pebbles) from 2.00 mm to over 50.00 mm. Their shape varies from angular to well rounded. The petrographic composition is also highly heterogenous and the clasts and pebbles are made up of oomicrite, oosparite, pisoliths, marl, stromatolitic rocks, intramicrite, biomicrite, pelmicrite, intrasparite, pelsparite, dismicrite, clusters of dolomite crystals etc., besides occasional inclusions of chert, volcanic rock fragments and heavy minerals. Some of these fabric elements show thin rims of micrite, fibrous or sparry calcite and stromatolitic laminae. They are well to poorly sorted. Cementing materials are micritic, spar and carbonate debris.

The fabric elements are greenish grey, light purplish grey and light brownish grey. Cement is generally light brownish cream to light grey. The degree of induration of these rocks also varies. Some rocks are completely indurated, others are cemented by loose joining of clasts while big voids remain unfilled. Some of these rocksalso show mud cracks indicating subaerial desiccation followed by submergence resulting in crack-filling by mud or silt. The rocks are sometimes so completely mixed up or heterogenous that it becomes impossible to define the sequence of events of their formation.

6.2.Stromatolitic and Oncolitic Rocks

Widespread distribution of stromatolites occurs for several km on the ridges to the E of the lake (DIXIT 1983). They are a dominant rock group and are prominently encountered on the ridge tops. Important stromatolite forms are close laterally linked hemispheroids (LLH-C) (Pl. 6, Fig. 1-3) and discrete hemispheroids with variable basal radii (SH-V) sensu LOGAN et al. (1964), and cryptalgalamites sensu AITKEN (1967).

The unattached oncolite forms of this area are very compressed spheroid bodies with almost flat bases and convex tops. They are characterised by their exceptionally large size (usually up to 75 cm in diameter). Their cores are also large and composed of oolitic, pisolithic or coarse fragmented carbonate rocks. The oncolites are genetically connected and commonly associated with the attached larger stromatolitic forms; and their laminae are similar and, in general, have a notable "ridged" (Pl. 6, Fig. 2-4) ornamentation (DIXIT 1984). Desiccation cracks are often seen when the layers of these algal structures are broken.

The laminae of these structures are made up of radially fibrous calcite. In some cases, nearly opaque laminae of extremely fine grained material intervene between these fibrous calcite laminae. These laminae could either be an original micritic dust or be due to micritization caused by endolithic algae (LINK & OSBORNE 1978). In most cases, the calcite of the laminae shows all attributes of a precipitated mineral rather than that of the trapped and bound one by the algal mats (DIXIT 1984). They could have formed by the inorganic precipitation of calcium carbonate caused by mixing up of calcium rich water coming into the saline-alkaline lake waters (SURDAM & STANLEY 1979) or by biological precipitation caused by photosynthetic activity of algae. Association of calcareous tufa layers and desiccation cracks indicate emergence of submerged areas close to the lake margins. The formation of the tufa layers could be ascribed to the activity of non-filamentous algae in the marginal part of the lake (BUCHBINDER et al. 1974).

The important factors in the formation of large-scale stromatolites are an appropriate growth of blue-green algal microbiota, optimum physical conditions and a favourable chemical environment to provide precipitated mineral matter. This is generally possible from the sublittoral zone with perhaps maximum growth in the littoral part. If some stromatolites were also formed in a fluvial environment in this area, they did not present any peculiar features typical of that environment confirming observations of ABEL et al. (1982).

The oncolites are believed to be formed in the sublittoral to marginal zone of the lake, punctuated by the intermittent periods of subaerial exposures, as indicatedby the presence of desiccation cracks and layers of calcareous tufa (DIXIT 1984).

6.3.Oolitic Rocks

Ooids are the most ubiquitous and dominant of all the allochemical elements including pisoliths, intraclasts and peloids in the lacustrine deposits of this area. Oolitic rocks are basically of two types, viz. oomicrites and oosparites (FOLK 1959), the former being much far dominant. Ooids in these rocks differ in size and often outgrow to form pisoliths. In outline, they are commonly circular or oblong. The ooids in the rocks of this area are basically of 3 types:

1. Normal ones with a core and cortex (consisting of one or more rings) (most common)
2. The ones without a cortex (occasional)
3. Spherulites with crystals radiating from the centre (rare)

In most cases they have a light brown colour. In respect of core and cortex all ranges of size exist from extremely small core and thick cortex to a large core and very thin cortex. Some ooids show corrosion of their cortex indicating the breaking down of the fringes during their transport before they find themselves embedded in micrite or spar.

The nuclei of ooids are formed by single euhedral crystals of dolomite or their clusters, micritic material, sparry calcite, fossils or rock debris. The relation between dolomite crystals and ooids indicates that dolomite crystals were formed sporadically and in an early stage before the formation of ooids and oolitic rocks. However, there are instances (e. g. material from the ridges B and D) across the road from Makuyuni to Mto wa Mbu, where both the dolomite crystals and ooids are in abundance but this relationship does not hold good. Cemented micritic material often shows bird's eye structures indicating activity of boring organisms.

Apparently the lake waters in marginal regions were often subject to pulsating movements favouring formation of ooids which were subsequently incorporated with the microcrystalline calcite in sublittoral or deeper areas to form oomicrites or were cemented together by sparry calcite in the supralittoral areas to form oosparites when the receding lake waters abandoned them there. Subsequent to their formation, the oolithic rocks were subject to subaerial erosion, fragmentation and transportation before they were incorporated in the coarse fragmented carbonate rocks or were associated with oncolites and stromatolites.

6.4. Dolomitic Rocks

Although the mineral dolomite is very common in the calcareous rocks of this area, occurrences of dolostones are rather occasional. The later occur in hard compact layers of light greenish-grey colour and up to several tens of cm in thickness of ridge H and in the lowermost beds closest to the present lake stand. These beds are overlain by stromatolitic rocks. These dolostones consist practically entirely of dolomite rhombs with insignificant amount of micritic matrix.

Most of the soluble substances present in the lake waters must have been derived from the volcanic rocks, fluvial and pre-existing lacustrine and metamorphic rocks in that order. In the case of Lake Turkana (YURETICH & CERLING 1983) and many other East African lakes (CERLING 1979), high magnesium carbonates have not been observed. These authors, therefore, suggest that most of the Mg_{2+} in these lakes has been removed to form sepiolite, kerolite or smectite. In the case of the Lake Manyara, it does not appear to be entirely so and an appreciable amount of magnesium might have gone in the formation of dolomite at least sometimes in the history of the lake. Part of magnesium may have been used up in the formation of smectite especially associated with the volcanic activity, this being a dominant clay mineral in most of the East African Rift lakes where pH and total salinities are comparatively high (BAUMANN et al. 1975, YURETICH 1979).

In the case of Lake Manyara, the ooids are commonly seen to have dolomite rhombs as their cores. This seems to be possible only under the conditions when these dolomite crystals were physically detached from the location of their formation and brought into pulsating lake waters which would not have been far removed from supralittoral and marginal areas of the lake.

Dolomite has been seen to be associated with super-saline brines in some lake deposits and it is generally accompanied by evaporite minerals (BERNER 1979). Absence of evaporites in association with the Lake Manyara dolomites could be explained by their redissolution during rains or by rise in lake levels drowning the evaporitic flats while dolomite is not dissolved. Similar evidence has been cited by BERNER (1979). PETERSON et al. (1963) have found from the growth of dolomite crystals in the Deep Spring Lake that there exists a linear relation between C^{14} age and size. Since the size of most of the dolomite crystals associated with limestones in the Lake Manyara area is generally microscopic (usually far less than 1 mm), the conditions for dolomite formation did not prolong much, except in the case of thin bedded deposits of greenish-grey dolomites.

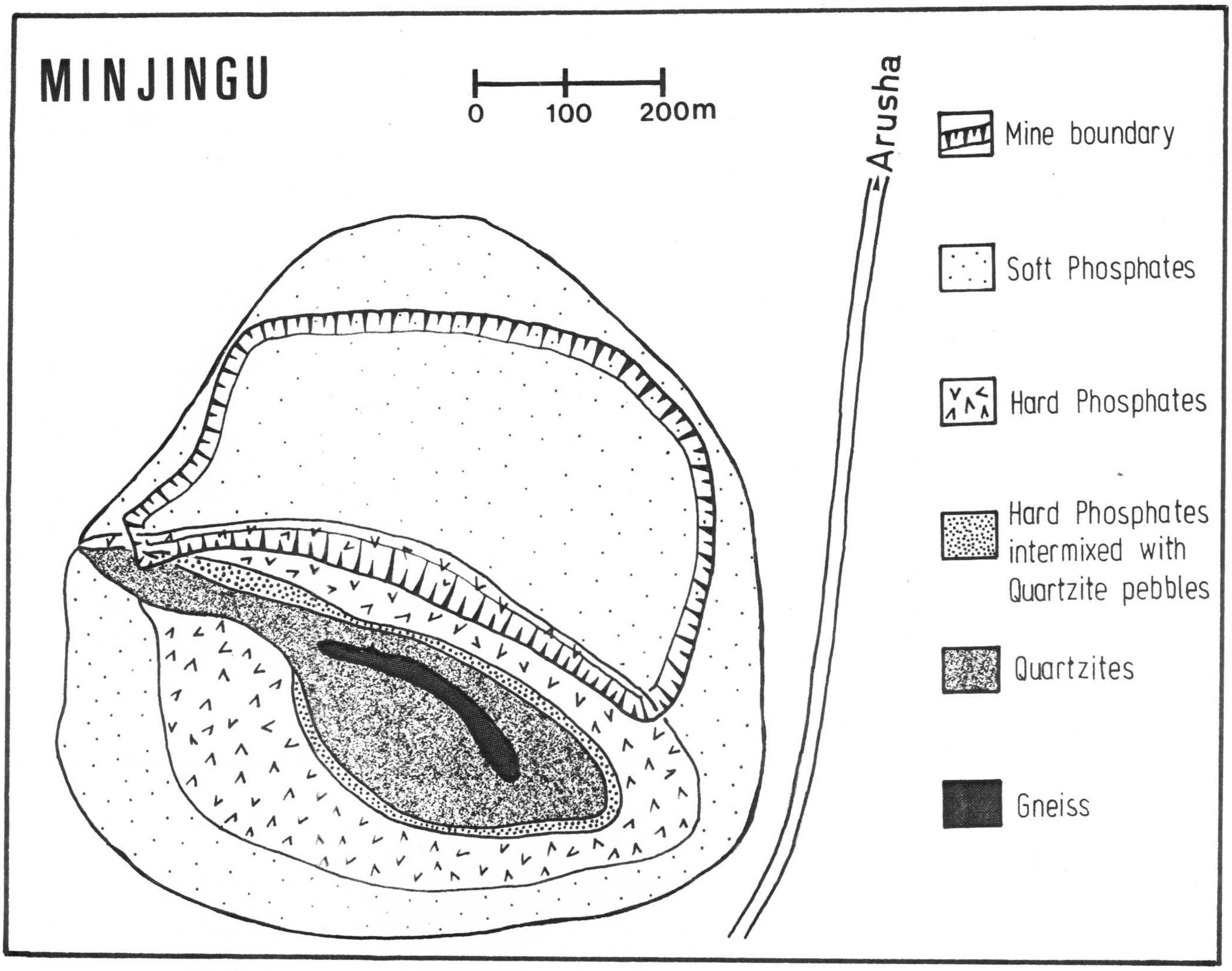
In some Australian lakes, the dolomite formation is accompanied by elevated pH (VON DER BORCH 1965). In the Great Salt Lake deposits, the dolomite formation was hastened by elevated temperatures and favoured by high alkalinity (BISSEL & CHILINGER 1962). MÜLLER et al. (1972) favour dolomitisation of calcareous sediments in the Lake Tuz Golu area within a very short time after deposition during a subaquatic phase by an extremely high Mg/Ca ratio in the lake water. This kind of high ratio was definitely not widespread in the case of Lake Manyara waters. Locally, thin dolomite beds may have formed under such conditions.

From the above interpretation, it seems reasonable to believe that dolomite was formed in this area in the marginal to sublittoral part of the lake with a high alkalinity and salinity, and in a rather arid sort of climate. The conditions of dolomite formation at any time did not prolong much as is indicated by the microscopic size of the crystals and their dissemination as cores of ooids. However, in case of thinly bedded greenish-grey dolomite favourable conditions must have prevailed at least locally for appreciable time.

7. The Phosphorites of Minjingu

7.1. Lithology, Sedimentology and Fossils

The Minjingu phosphate deposits were discovered in the late 1950‘ in the course of airborne geophysical surveying for minerals (ORRIDGE 1963-1965). They consist mainly of a sequence of phosphorites alternating with clayey layers (Pl. 7, Fig. 1 and 2). Their stratigraphic age is stll debated, originally middle Pleistocene was assigned by SCHLÜTER (1986a), but due to geomorphic indications, CASANOVA (1986a) reported early Pleistocene or even Pliocene, an opinion, that was followed subsequently by SCHLÜTER (1991).



Text-Fig. 6: Geological sketch map of the formations surrounding the Minjingu-Kopje. Age of the quartzites and the gneiss: Upper Proterozoic (Usagaran).

These sediments surround unconformably the lower part of the so-called Minjingu-Kopje. The Kopje itself is formed by massive quartzites of Usagaran age (Upper Proterozoic) and in its centre by a small band of gneiss. 2 different phosphorite layers exist, made of soft phosphates (Pl. 7, Fig. 3) and of hard phosphates, whose mineralogy has been discussed by SINGH (1980) and MAKWEBA (1989). The commercially mined phosphorites (Pl. 7, Fig. 4 and 5) extend to a maximum thickness up to 20 m, surrounding the flankes of the hill in an oval shape and outcropping especially along its N slopes. Laterally their thickness decreases and the phosphatic layers are gradually substituted by more clayey layers. The often observable slumping structures in the soft phosphates (Pl. 5, Fig. 6) are due to regional inclination of the hill's slopes, from which these not yet consolidated sediments glided into deeper zones. However, these forces were not sufficient to demolish much of the abundant bone material washed away from the former island or cliff. Biostratonomically these isolated bones - predominantly belonging to an extinct cormorant, *Phalacrocorax kuehneanus* SCHLÜTER, 1991 (Pl. 3, Fig. 5), and fishes of the cichlid genus *Sarotherodon* or *Tilapia* (Pl. 3, Fig. 6-9 and Pl. 5, Fig. 1-6c) - never indicate a specific flow regime, hence leading to the conclusion that these bones were never destroyed by potential scavengers nor transported far away.

From their microfacial analysis the phosphorites of Minjingu are built up by mostly clastic particles. A distinction of skeletal material (predominant), phosphatic lithoclasts, detrital quartz grains and calcareous biogenic debris seems to be practicable. These components are bound by different cements or matrix types, e. g. calcareous, dolomitic, siliceous and clayey materials. Most likely Guano played also an important role during the deposition. Only very few microfossils have yet been discovered in the phosphorites, and these could not be sufficiently assigned to living taxa (Pl. 4, Fig. 1 and 2).

7.2.Palaeoenvironment

The abiotic environmental factor of alkalinity in the paleolake can be determined by consideration of the metabolic requirements of fossil fish recorded in the phosphorites of Minjingu. Already CERLING (1979) used the well known autecology of certain organism groups for the estimation of the paleoalkalinity in Lake Turkana, N Kenya. Most lakes of the Eastern or Gregory Rift are today sodium carbonate to sodium bicarbonate in composition (BEADLE 1981), and their alkalinity is ranging from 2.2 HCO_{3-} + CO_{3--} milliequivalents per liter (meq/l) in Lake Naivasha to 3170 meq/l in Lake Magadi (SCHLÜTER 1987). Fishes for example are strongly affected by the composition of water. Lakes with an alkalinity of 40 meq/l or more tend to harbour only specialized cichlid fishes, e. g. *Tilapia* or *Sarotherodon* sp. (see also TREWAWAS 1937), with the trend to dwarfism. Also the occurrence of fossilized fish hyperostoses (so-called "Tilly-bones") (SCHLÜTER, KOHRING & MEHL 1992) (Pl. 3, Fig. 7-9 and Pl. 5, Fig. 1-3) indicates a high paleosalinity, because the growth of hyperostotic bones in recent fishes is entirely limited to families living in a salt water environment.

A similar trend can be drawn by the occurrence of 2 species of gastropods in the upper parts of the profile. One species has been determined as *Bellamya unicolor*, which is palaeogeographically associated with nilotic drainages, and was apparently extant in Lake Manyara until quite recently (KAT 1986, pers. comm.). The other species is the today in the region still very common *Melanoides tuberculata* (Pl. 4, Fig. 3-5).

7.3.Bentonitic clays

Yellowish green to light olive green bentonitic clays can be seen underlying and intercalating the Minjingu phosphates (prominent is the so-called Samaki-bed with its compressed fish skeletons of Pl. 5, Fig. 7 and 8), and also in the Makuyuni River section. These locations appear to be almost on the fringe (?) of the original lake and indicate a major volcanic activity during the initial period of the lake's history. It has been suggested that the volcanic ash with moderate amount of magnesia on falling into saline, alkaline lake waters would produce smectite, the clay mineral which almost entirely makes for bentonitic clays (GRIM 1968, BLATT et al. 1972). In this process the excess silica might have precipitated as chert, the formation of which perhaps was helped by several factors including photosynthesis causing high pH and then subsequent lowering of pH because of organic decomposition or dilution of water due to rains (PETERSON & VON DER BORCH 1965, EUGSTER 1967). It is not known as to how many such bentonitic beds are there in the area. Normally each of these layers would indicate the intensity and duration of volcanic activity.

Thus volcanic debris, especially ash in shallow alkaline and saline lacustrine environment of Lake Manyara might have produced smectite giving rise to bentonitic clays in the area.

Calcite is the most profound mineral in the sediments of this lake. Although calcite found in the stromatolitic and oncolitic limestones could be attributed to the organic activity of the algae, the abundant microcrystalline calcite should have come from inorganic precipitation (YURETICH & CERLING 1983, DIXIT 1984).

In this lake the majority of the sediments is of chemical origin. Terrigenous sediments are of small quantities and are thought to have been deposited in fluvial settings or in marginal lake environments close to the termination of the river, the only exception being the bentonitic clays which are considered to be associated with the volcanic activity and were formed in a proper lake environment.

8. Acknowledgements

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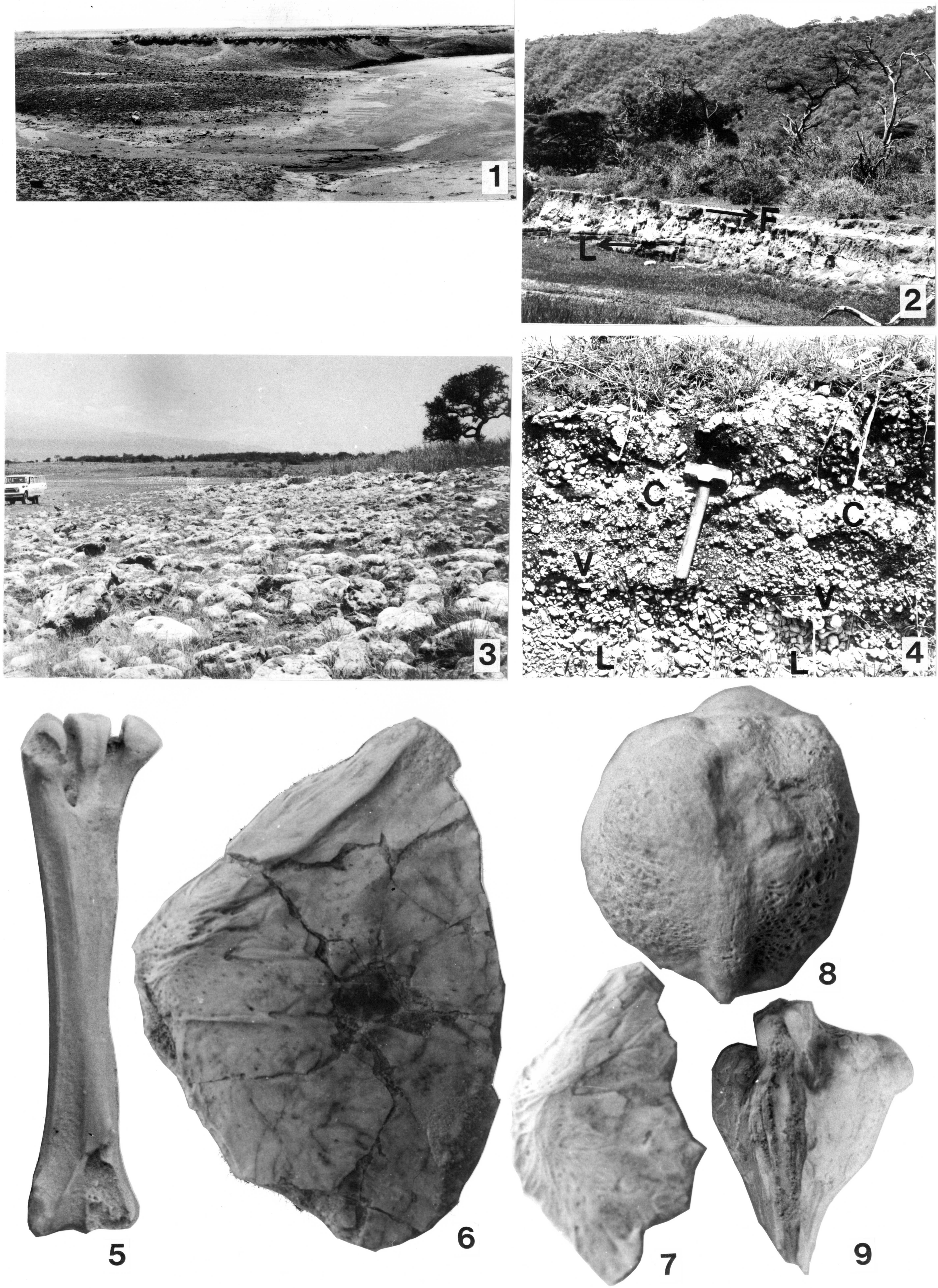
Plate 3: Outcrops and fossils of Lake Manyara area.
Fig. 1: Plio-Pleistocene lake beds dissected by the meandering Makuyuni River.
Fig. 2: Fluvial sediments (F) dipping to E - underlying are lacustrine marly-clayey layers (L), near Bagoyo.
Fig. 3: Stromatolitic rocks over ridge A (see Text-Fig. 2 in text), 4 km ESE Mto wa Mbu.
Fig. 4: Rudaceous rocks in a limestone (R), volcanic fragments (V) and chert (C), near Mto wa Mbu.
Fig. 5: Isolated bone (Tarsometatarsus) of the fossil cormorant *Phalacrocorax kuehneanus* from the phosphorites of Minjingu.
Fig. 6 and 7: Operculae of fossil cichlid fishes (*Tilapia* or *Sarotherodon*) from the phosphorites of Minjingu.
Fig. 8 and 9: So-called "Tilly Bones" (hyperostotic altered fish bones) from the phosphorites of Minjingu.

Plate 4: Fossils from Minjingu
Fig. 1 and 2: Spherical microfossils of unknown affinities.
Fig. 3: The gastropod *Bellamya unicolor*.
Fig. 4 and 5: The gastropod *Melanoides tuberculata*.

Plate 5: Fossil fishes from Minjingu
Fig. 1-3: So-called "Tilly Bones", hyperostotic altered fish bones.
Fig. 4: Operculum of a presumable cichlid fish (*Sarotherodon* or *Tilapia*).
Fig. 5: Isolated vertebra of a presumable cichlid fish (*Sarotherodon* or *Tilapia*).
Fig. 6a-c: Different views of an isolated spine of a presumable cichlid fish (*Sarotherodon* or *Tilapia*).

Plate 6: Stromatolitic rocks and slumpimg structures of the Lake Manyara area.
Fig. 1-3: Ridged stromatolites exposed as a reef near Mto wa Mbu.
Fig. 4: Ridged stromatolitic rock from Minjingu.
Fig. 5: Stromatolitic rocks from the upper part of the profile of Minjingu with assemblages of gastropods.
Fig. 6: Slumping structures in the soft phosphates of Minjingu.

Plate 7: The phosphorites of Minjingu.
Fig. 1 and 2: Alternating soft phosphates and dark-green clayey layers.
Fig. 3: Soft phosphates with an accumulation of bird bones (*Phalacrocorax kuehneanus*).
Fig. 4 and 5: Mining operations at Minjingu.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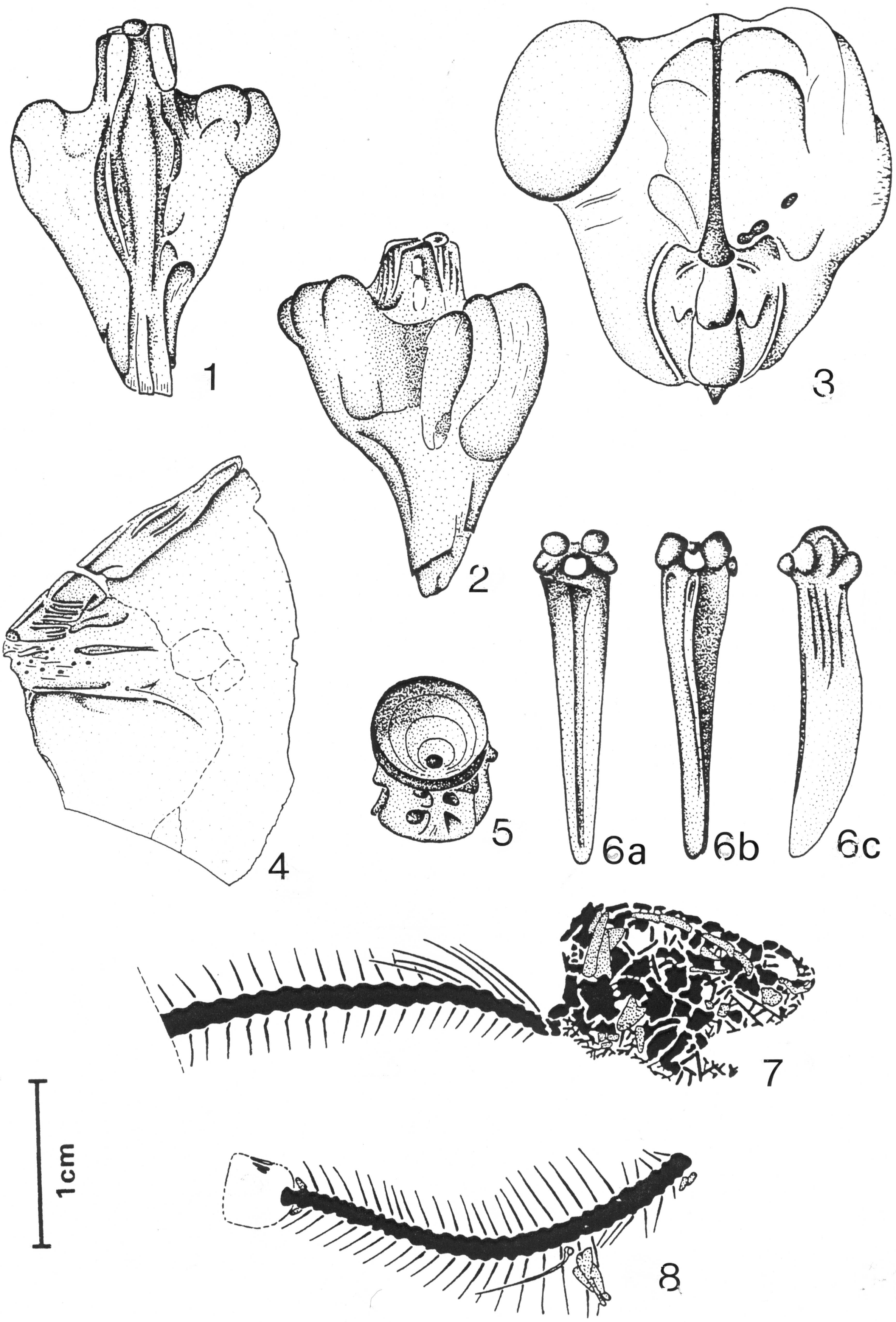
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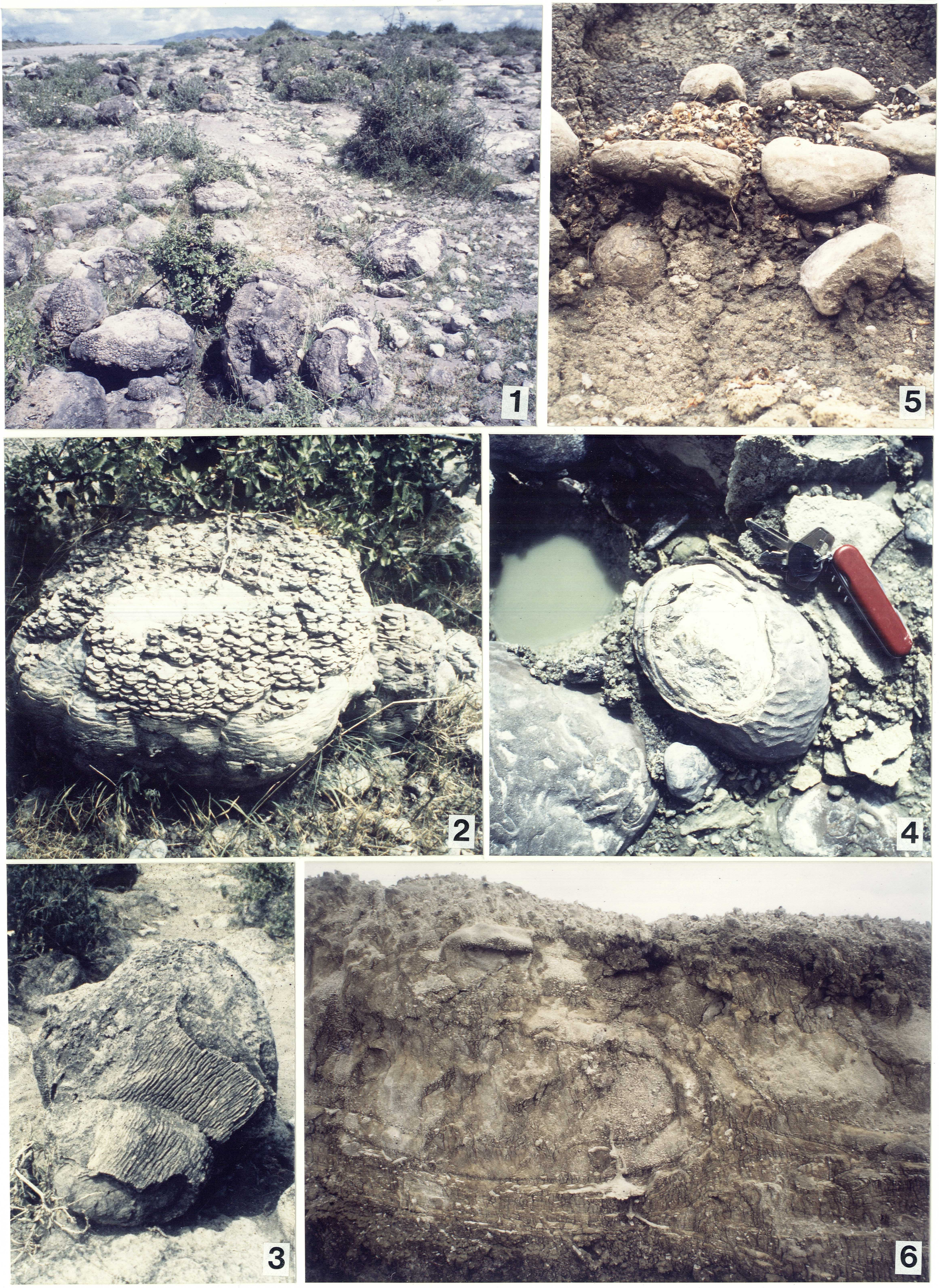
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The East African Copal - an almost Forgotten Fossiliferous Resin

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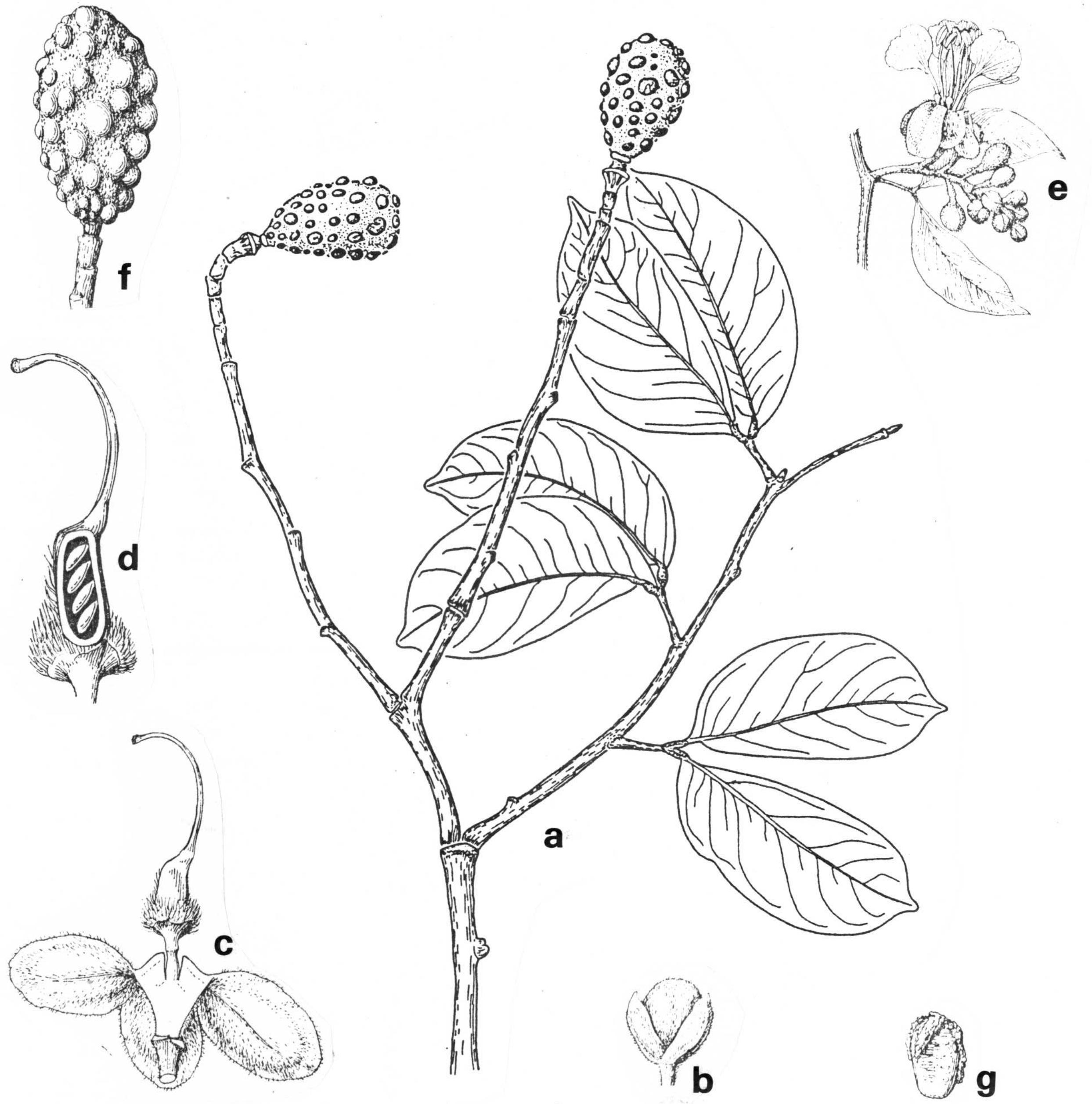
Abstract: An extensive exudation of resin from trees of the Leguminosea-species *Hymenaea verrucosa* is responsible for the formation of fossil and recent copal in E Africa. A model of its depositional environment is presented: The resin is found in the soils around the particular tree (primary deposition), in the sandy-clayey soils of an estuarine environment (secondary deposition) or along the coastal shorelines (tertiary deposition). The stratigraphic age of fossil copal in E Africa is still uncertain, presumably ranging down to the Pliocene. In its abiotic properties the copal shows many similarities with other known fossil resins and ambers. The organic inclusions are normally in an excellent mode of preservation. Several species of Arachnida, Insecta and Retilia have been described, predominantly already in the beginning of the 20^{th} century. They indicate a highly diversified paleobiocenosis, most likely not much different from the conditions of today.

1.Introduction

Fossil resins embedded in any type of sediments (e. g. clays, siltstones, sands etc.) are normally called amber, or according to their stratigraphically younger age copal. From E African coastal deposits copal has been reported since at least the year 1859, when ROSCHER in KERSTEN (1869) published one of the earliest detailed topographical maps of this region, in which he marked near an area where the town of Dar es Salaam is situated today, the so-called "Kopalgruben" (probably best translated as small scale mining pits of copal).

Before World War I the export of this then mostly Zanzibar or Gum copal named resin from Dar es Salaam to Imperial Germany played an economically important role (233.000 kg for example in the year 1898), because it was used for the incorporation in high grade varnishes. But due to the increase of artificial resins in manufacturing the knowledge of the deposits of the E African copal was later almost lost, and it is today generally not possible to get copal for instance on market places of Zanzibar or along the coast.



Text-Fig. 1: Morphology of the Recent *Hymenaea verrucosum* OLIVER 1871 (compiled after different sources) - a: part of branchlet showing the wart like excrescences, b: flower-bud showing overlapping bracteoles, c: section through hypanthium showing ovary and three of four sepals, d: ovary showing ovules, e: branchlet with inflorescence, f: resin-filled wart like excrescence, g: seed (scale of specimens varies), a drawn after a preparation slide stored in the Herbarium of the Department of Botany, University of Dar es Salaam.

2. *Hymenaea verrucosa* OLIVER 1871 - the Supplying Plant

The E African copal is derived almost entirely from a species of the angiospermid family Leguminosae (Subfamily: Caesalpinaceae), the tree *Hymenaea* (genus name is often synonymously mentioned as *Trachylobium*) *verrucosa* OLIVER 1871, and the copal may be collected from wounds of the living tree, from the soil in a semifossilised form having dropped from trees still existent, or fossilised from areas where the former trees do no longer exist. The last instance constituted economically the best quality of copal, that from the living trees the poorest.

2.1. Morphological Features and Phytogeographic Distribution of *Hymenaea verrucosa*

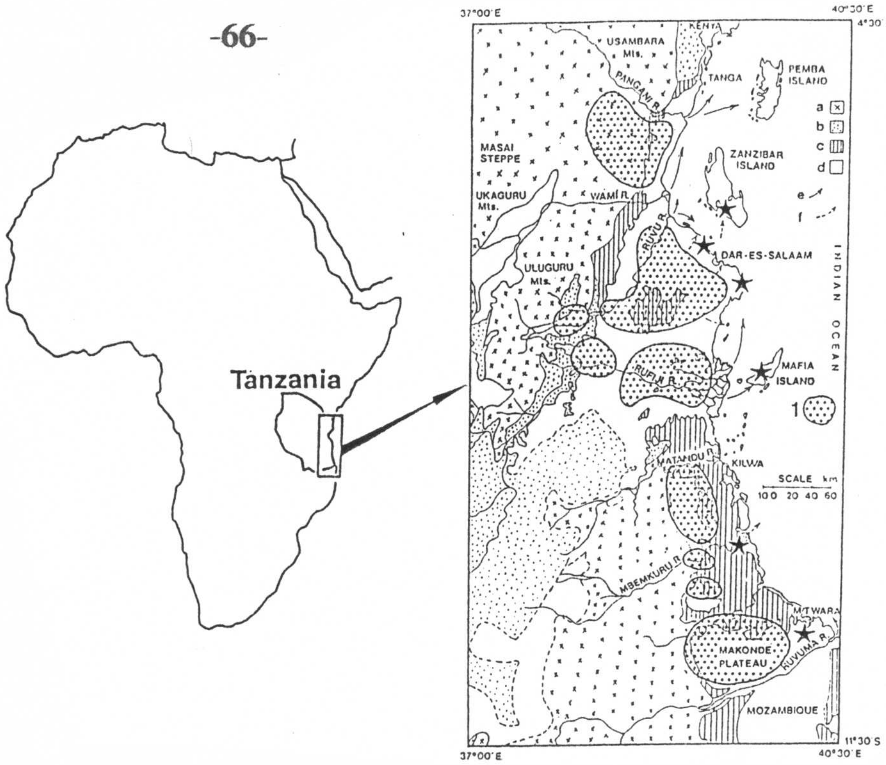
Hymenaea verrucosa is a timber tree with a height of up to 35 m which developes a clear cylindrical trunk up to 15 m in length. Its bark is smooth, light grey, much fissured or often with short longitudinal shallow cracks. The leaves consist of one pair of leaflets. These are obliquely long or elliptical, up to 10 cm long, coraceous, glabrous, glossy above, shortly and bluntly acuminate, with a rounded base and a ca. 2 cm long petiole. The flowers are generally white with pink axillary panicles. The fruit is stout, up to 5 cm long and 3 cm broad, indeshiscent and covered with resin-filled wart like excrescences (Text-Fig. 1, Pl. 8, Fig. 1-3). The timber is hard and durable, dark brown in colour. It is used for making doors and frames. Some more morphological details are given by BRENAN (1967).

Hymenaea verrucosa is known in its recent phytogeographic distribution pattern from Tanzania, Kenya, Somalia, Madagascar and even the Seychelles and Mauritius (BRENAN 1967), thus from all of these countries semifossil or fossil copal is already known or can potentially be expected. In E Africa the tree normally does not occur directly along the coast line as shown in Text-Fig. 2 from the slightly modified sketch of STUHLMANN (1909).

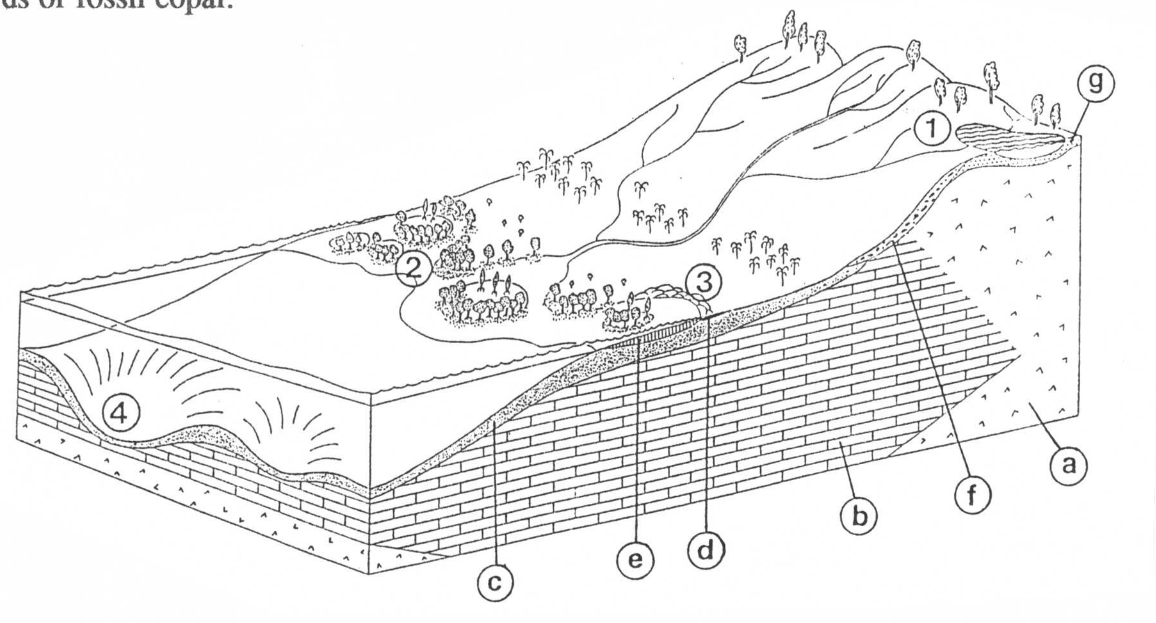
2.2. Fossilisation Potential, Biostratonomy, and Abiotic Properties

In the 19th century the E African copal was traditionally dug from arm deep holes especially in a sandy environment, which often produced at least 5 kg of the resin. Most of the copal came from a belt removed 20-30 km from the coast line; a good example was the Makonde plateau (STUHLMANN 1909). The semifossilised resin occurs frequently in flat disc-like pieces. Normally it is covered by a crust resulting from the reaction of the associated soil to the weathering surface of the resin. After removal of the crust in caustic soda the copal is very well characterised by its roughened so-called "goose-skin" surface. From the primary deposit carried away pieces which are sometimes found along the coastal shoreline (similarly as in the Baltic amber) lack the weathering crust, but they often show the goose-skin (Pl. 8, Fig. 4).

The copal's colour varies from vitreous, a very pale yellow to reddish. These differences are probably due to the particular grade of oxidation. Pieces stored since a long time under the influence of sunlight and atmosphere - e. g. in the National Museum of Zanzibar (Pl. 8, Fig. 5)- are very dark red and brown, brittle, often opaque and deteriorate on physical contact.



Text-Fig. 2: Geological sketch map of coastal Tanzania (modified from KENT et al. 1971 and CILEK 1976) showing the distribution of the Recent *Hymenaea verrucosa* and records of fossil copal (slightly modified after STUHLMANN 1909 and SCHLUETER & von GNIELINSKI 1987). - a: crystalline rocks of Precambrian, b: Karoo, c: Jurassic, Cretaceous and Paleogene, d: marine and non-marine Neogene, Quaternary, e: direct sediment transport by main perennial streams from potential primary sources, f: sediment by smaller and intermitted streams from transitional sources, 1: distribution of the living Hymenaea verrucosa, asterisks: records of fossil copal.



Text-Fig. 3: Depositional model of the E African copal as presented on a geological block diagram (modified from SCHLÜTER 1989). - a: crystalline rocks of Precambrian, b: Limestone derived from former coral platform, c: sandy formations, d: concentrations of heavy minerals, e: mangrove swamps, f: slope debris, g: plateau soils, 1: primary deposition of copal around the particular tree, 2: secondary deposition of copal in the sandy clayey soils of the estuary, 3: tertiary deposition of copal along the coastal shorelines, 4: deposition of copal in submarine depressions.

	ZANZIBAR		DARESSALAM	
	STOCKLEY	KENT et al.	STOCKLEY	KAAYA etc.
Recent Holocene	Alluvium Raised beach sands and sandstones	Alluvium Beach sandstones	Alluvium Raised beach sands and sandstones	Beach sands lagoonal sediments
Pleisto- cene	Reef limestone	Reefal limestone	Costal limestone	River valleys submerged channels different terraces — Reef limestone shallow water limest. calcareous sandstone
	Mazingi-beds		Mikindani beds	
Pliocene	Loams, sands rolled fragments of ingeous and other rocks Sandstone with *Chlamys werthi*	Limestone and soft sandstone	Sands and sandy clay with rolled fragments of Eozoic and Jurassic rocks	Erosional surface
Miocene		Fossiliferous limestone Marly sand Clayey sands with subordinate limestone		Claybound sands — Deltaic estuary — Kaolinitic and dolo- mitic sandstone and shales

Text-Fig. 4: Stratigraphy of Zanzibar and the region of Dar es Salaam in Neogene. Due to informations of different authors (STOCKLEY 1928, KENT et al. 1971 and KAAYA 1984).

According to STUHLMANN (1909) the fresh resin's density is slightly lower than that of water, the fossilised resin's density slightly higher, thus enabling for both types a transport in suspension even in low energetic water movements.

3. Geological Setting

3.1. Depositional Environment

From the S American inhabitated *Hymenaea coubaril*, which produces resin in large quantities, the depositional environment of copal is well known: *Hymenaea coubaril* grows commonly along rivers that enter the ocean in mangrove-fringed estuaries. The dropping resin accumulates already in the soil around the tree, but also resin production in the roots might be the reason for increasing concentration (SCHLEE 1984a & b). Much of this copal later becoming fossilised is either deposited in the sandy-clayey soils of such an estuarine environment with abundant mangrove vegetation, or it is washed away under the quickly changing conditions of an estuary and might be deposited later on a secondary ground along the coastal shoreline (LANGENHEIM 1969).

A quite similar mode as presented for *Hymenaea coubaril* should also be assumed for the depositional environment of the E African copal, which at least derived from a taxonomically very closely related plant.

Text-Fig. 3 shows an idealised sketch of the fringe at Kunduchi mangrove basin (15 km N of Dar es Salaam), where recently some lumps of copal have been found. In this basin a small tidal creek flows into the ocean. The basin is below the mean high water level and therefore subject to regular tidal submergence. The soils in the basin are of coarse, sandy texture except for a small area along the W and S fringe where a fine, silty clay predominates McCUSKER (1975). The banks of the creek accomodate a mixed mangrove forest, in the upper parts reduced to bushland height. McCUSKER (1975) presented the following ecological succession: *Rhizophora mucronata* and *Ceriops tagal* are the most abundant species. *Sonneratia alba* is very frequent in the lower parts but drops out rapidly above, while *Bruguiera gymnorrhiza* and *Xylocarpus granatum* extend also into the upper parts. In the uppermost zones the vegetation consists of pure or mixed stands of *Ceriops tagal* and *Rhizophora mucronata*. On the outward fringe the trees of *Avicennia marina* become progressively sparser.

3.2.Stratigraphy and Age Dating

The occurrence of fossil copal in E Africa is restricted to areas with stratigraphically young sediments (Neogene). STOCKLEY (1928) reported fossil copal from the Mikindani Beds (Text-Fig. 4) of the Tanzanian mainland, which he assigned to be of Upper Pliocene. For Zanzibar he gave many localities, which are almost always situated in the so-called Mazingi Beds (Text-Fig. 4), according to this author belonging to the Upper Pliocene. These are stratigraphic assignments of copal associated with sediments older than Pleistocene. STOCKLEY's statements are by any means surprising because all the palaeontological authors always believed the copal inclusions to be not older than Pleistocene, or even to belong to the Holocene. But stratigraphic columns of the region (e. g. KAAYA 1984, KENT et al. 1971) indicate potential deposits down to the Lower Miocene.

However, it should be pointed out that the stratigraphic history of the Neogene deposits of the region is still tentative due to the lack of precise age determination by useful index- or guidefossils or by radiometric dating. Generally it can be concluded that the fossil copal could in fact be older than formerly assumed. Also for the copal (or so-called Kauri-gum) in the SW Pazific region exist continuous stratigraphic age ranges over the last 40 million years (THOMAS 1968, BROWN 1990).

4.Organic Inclusions

The organic inclusions of copal have been distinguished from amber fossils at least since the articles of BLOCH and DALMAN were published already in 1776 and 1825 respectively. These two authors name as original sources of their examined copal inclusions several different but unspecified localities in S America, E India and Guinea. Some new species of Insecta and Arachnida were described and figured by both of them, but it is not clear if these specimens do all belong to the same type of copal.

Systematic descriptions of copal inclusions were generally rarely presented compared with those of the Baltic or - more presently - the Domincan amber, most probably due to the stratigraphically by far older ranges of these two sorts of fossilised resins. But the preservation of copal fossils seems to be often almost better than that of ambers. In Cretaceous fossiliferous resins translucent or almost opaque and frequently cracked or brittle material predominates (SCHLÜTER 1978). The famous Baltic amber Arthropoda often show a unilateral clouding, probably induced by post-mortem exudation processes of the enclosed animals (SCHLÜTER & KÜHNE 1975).

Similarly as amber also copal deteriorates on contact with sunlight and air. One of the factors leading to the destruction of the material is its drying out as a result of the evaporation of volatile substances, resulting in strains between the exposed surface layer and the temporarily protected interior (LARSSON 1978). Hence either a permanent storage of the resin specimens concealed under water with a small amount of antiseptics is imperative for their long stability, or the following technique for the preparation and observation of the organic inclusions should be persued: Inspection under water or under another organic liquid (e. g. paraffine) with a binocular microscope; wet grinding; embedding in an artificial polyester resin or in Canada balsam; grinding and polishing of the inclusion bearing copal fragment in its polyester or Canada balsam mantle to obtain an oriented surface; polishing; repetition of these processes until optimal visibility has been achieved. This and similar procedures have been applied with excellent success on organic inclusions of different amber types during the last years (SCHLEE & GLÖCKNER 1978, SCHLÜTER 1978).

5. The Former Biocenosis

Generally the E African copal is very rich in inclusions, which in most cases do not occur singly, i. e. once the search has yielded at least one arthropod, the same copal piece is likely to provide further specimens along the same or earlier resin flows. Occasionally the inclusions retain their colour, for example in this mode the eyes of Diptera are sometimes preserved. The animal remains normally range only from 1 to 3 mm, evidently a reflection of taphonomic processes. This small size arises for a number of reasons, e. g. larger specimens still had the power to climb out of the sticky resin and to free themselves, or the position of resin exudation, intimately associated with bark, means it is more accessible to small organisms etc. (HENWOOD 1992).

Compared to other fossiliferous resins the amount of described species from the E African copal is relatively low. However, their systematic affiliations already show similar tendencies as the records of inclusions from Baltic amber or from the Dominican Republic indicate: Diptera, Hymenoptera, Coleoptera and Isoptera are predominating, but these groups also represent at least 3/4 of the today living species of insects. Quite interesting is the comparatively high amount of Isoptera (termites). A similar frequency has also been reported from the amber of the Dominican Republic.

Generally it can be assumed that the fauna of the E African copal does not show significant differences from the fauna living today in this region, i. e. all the trapped specimens represent Recent species. But most likely many of the resin-preserved species have not yet been discovered by using "normal" catching methods.

6. Comparisionary Notes on Copal and Other Fossil Resins

Presently approximately 300 different fossil resins are mentioned in the literature, stratigraphically ranging down to the Carboniferous (SCHÜTER 1978). But only around 10% of these - mostly belonging to the Tertiary - have yielded organic inclusions. Since antiquity the supremacy of the Baltic amber is evident - several thousands of its inclusions have been described and they illustrate a very exact image of parts of the terrestrial paleobiocenosis in Eocene and Oligocene of the Baltic area. But obviously the effect of selection can never provide absolute measures of faunal diversity. The rare discovery of a certain organism in a fossil resin does not reflect its rare occurrence in the former forest.

Unexpected records in the E African copal were for instance two reptiles. A lizard was originally assigned to be preserved in

Baltic amber, but LOVERIDGE (1942) clearly identified this lizard as belonging to the Recent species *Holaspis guentheri*, which today ranges across tropical Africa from the Usambara Mountains to Sierra Leone. Also the presence of a gecko embedded in Zanzibar copal was discussed by this author, leading to the conclusion that the gecko should be identified as the scarcely distinguishable *Lygodactylus grotei*, which is a common species of the adjacent coast and the neighbouring islands.

Comparing the localities and source plants of copals in a worldwide scale, it is recognisable that the formation of copal is mainly integrated into areas with a tropical (or at least subtropical) climate (Text-Fig. 5). The Leguminosae-genera *Hymenaea* and *Copaifera* contribute mostly to the production of copal in S and Middle America (*Hymenaea coubaril*), in E Africa and Madagascar (*Hymenaea verrucosa*) and in W Africa (*Copaifera* sp.), while in the SW Pazific region the Araucariaceae-genus *Agathis* is the main supplier (BROWN 1991, THOMAS 1968).

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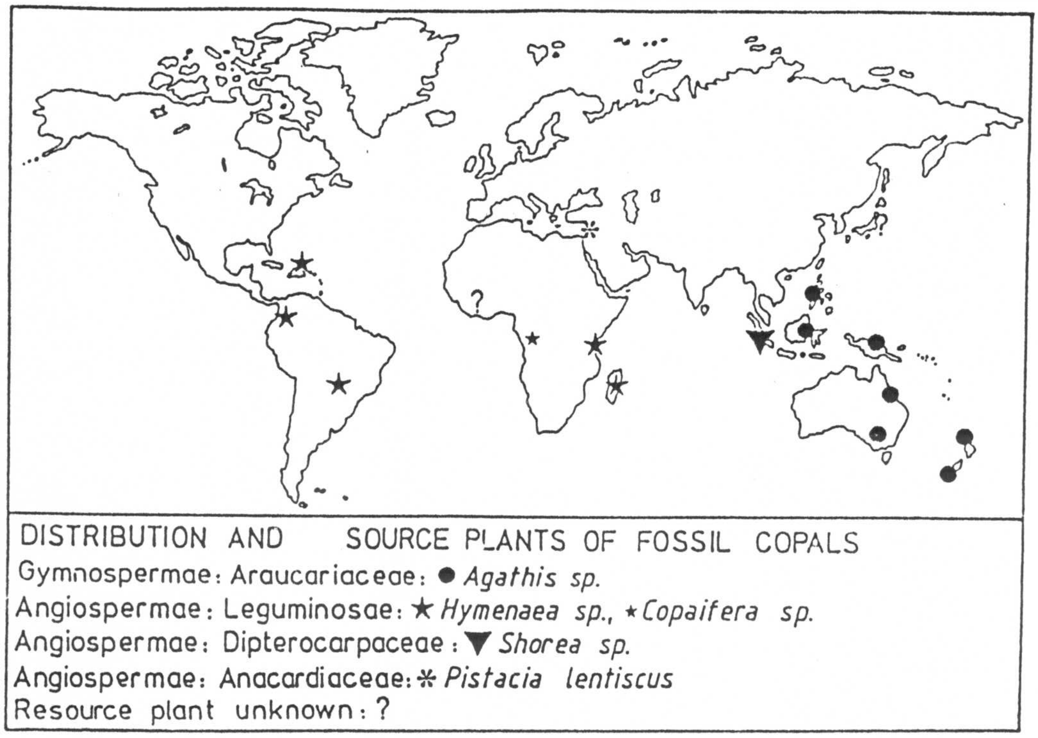

Text-Fig. 5: Distribution and source plants of different types of copal.

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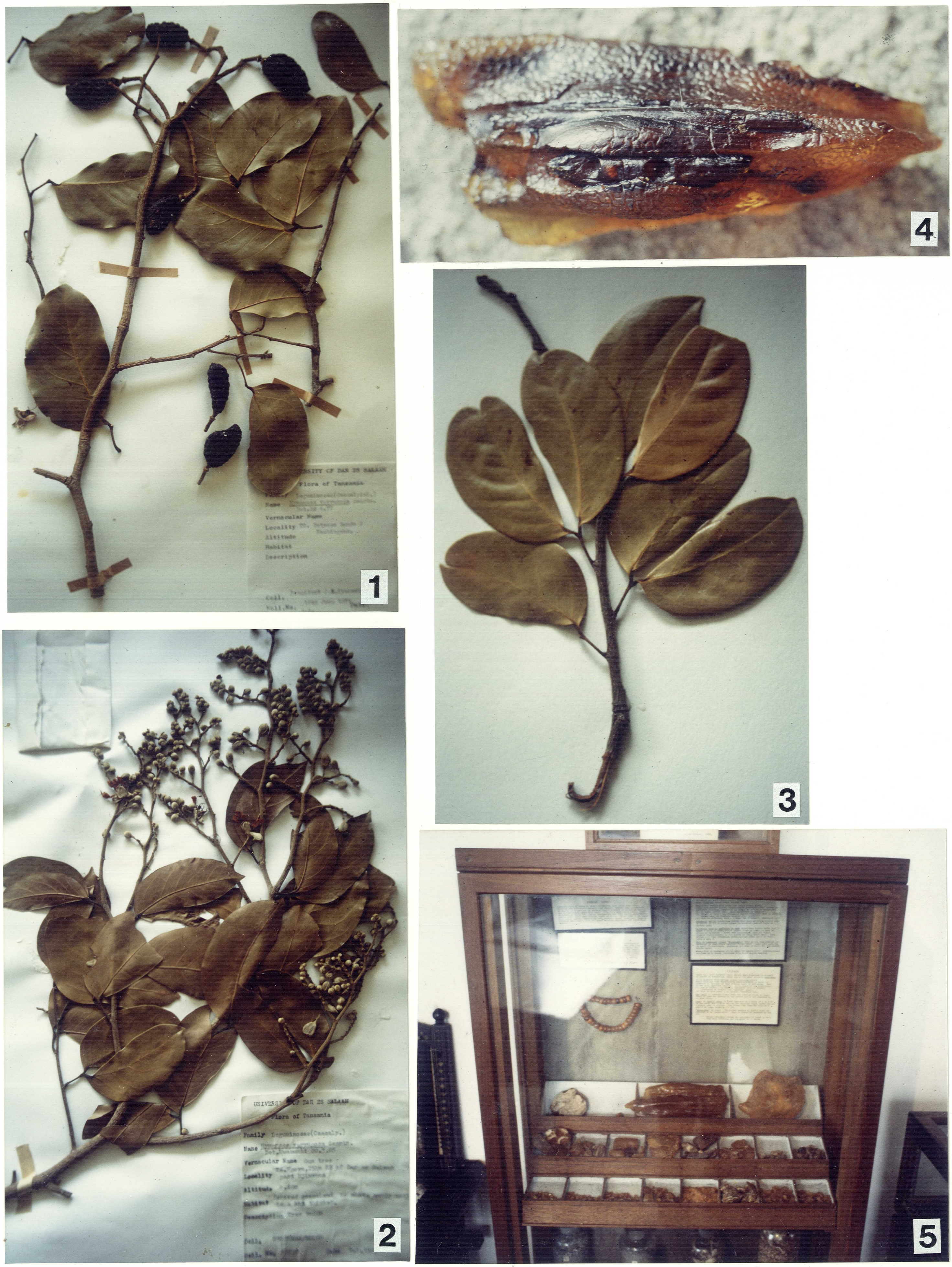
Plate 8: *Hymenaea verrucosa* and its copal.

Fig. 1-3: branchlets with leaves and wart-like excrescences

Fig. 4: copal specimen collected from Kunduchi mangrove basin showing the so-called goose-skin

Fig. 5: Shelf in the National Museum of Zanzibar exhibiting copal pieces.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Geological Development and Economic Significance of Lacustrine Phosphate Deposits in Northern Tanzania*

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* Paper presented at the conference of GEOSOM (Geology of Somalia and surrounding regions, December 1987). The paper was accepted for publication in the Proceedings of GEOSOM, but the manuscript was apparently lost during the civil war since 1989. The original draft manuscript was subsequently updated.

Abstract: Phosphate bearing Pliocene or Pleistocene sediments at Minjingu, N Tanzania, host one of the few commercially exploitable reserves of this essential fertilizer material in E Africa. However, contrary to the formations of large deposits in Morocco, Algeria, Tunisia, Egypt and the Western Sahara, the geological origin of theses resources in N Tanzania is completely different and locally restricted. The phosphorites of Minjingu are mainly formed by bone fragments of birds (*Phalacrocorax kuehneanus*) and fishes (cf. *Tilapia* sp.), indicating a former lacustrine environment with an increased paleoalkalinity up to 40 meq/l HCO_3^- + CO_3^{--}. The reserves of these phosphorites, commercially exploited since 1983, are limited for approximately 20 years (production target: 100.000 t/y). However, they are one of the overall objectives to advance the agricultural production in Tanzania by building up its own fertilizer industry. A few other, mainly in the SW Mbeya region located phosphate deposits (both carbonatites and phosphorites) are presently evaluated in the context of the Tanzania/Canada agrogeology project, and it is suggested that in future these resources will also contribute as locally available soil additives.

1. Introduction

The Minjingu phosphate deposits near Lake Manyara in N Tanzania (a in Text-Fig. 1) were discovered in the late 1950's in the course of airborne geophysical surveying for minerals (ORRIDGE 1963-1965). Subsequently several geological, mining dressing and economic studies in the field and in laboratories by different international organisations have been carried out during the period from 1957 to 1970. From all of these observations it followed that the phosphate ore reserves of Minjingu are sufficient to supply TFC (Tanzania Fertilizer Corporation) with raw material at less than half of the world market price and much less in foreign exchange.

After another revision of the reserves in 1975 and a borehole drilling campaign carried out by STAMICO (State Mining Corporation of Tanzania) in 1976, negotiations of the Tanzanian government with various potential contractors led to the selection of KONE-corporation of Finland to be responsible for the project engineering and the construction of industrial work. Plant erection and mine development were completed in August, 1982, and the commercial production of phosphates started in January, 1983.

2. Geological Setting

The Minjingu phosphate deposits consist mainly of a sequence of phosphatic beds alternating with clayey layers. Their stratigraphic age is still uncertain, a younger Pleistocene was assigned (SCHLÜTER 1986b), but also Pliocene or early Pleistocene has been reported (CASANOVA 1986).

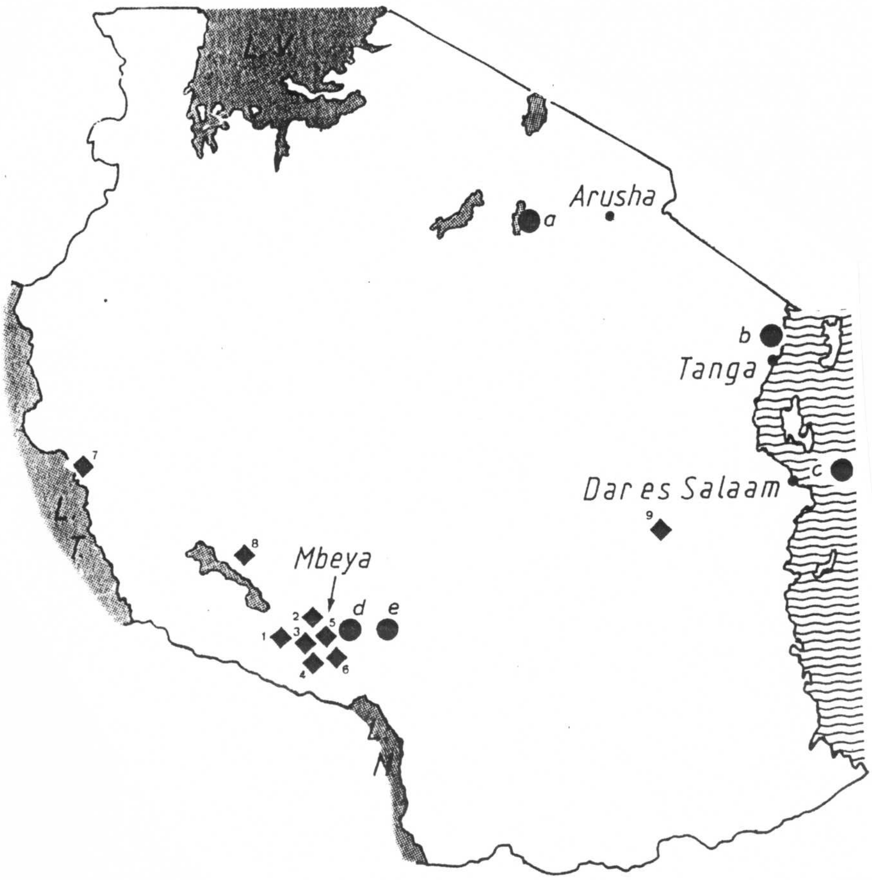
These lacustrine sediments surround unconformably the lower part of the so-called Minjingu-Kopje (Text-Fig. 2) of late Proterozoic age (Usagara-Formation). The Kopje itself is formed by massive quartzites and in its centre by a banded gneiss. The phosphate formation comprises two ore types which differ both in structure and consistency.

Mineralogically and chemically the lower unit or the so-called soft phosphates consist of calcium phosphate (70 %), carbonates (dolomite and calcite) (10 %), quartz and colloidal silica (5-7 %), feldspar (3-5 %), clay minerals (7 %) and minor amounts of biotite, muscovite, amphiboles, pyroxenes, limonite etc., with a total P_2O_5-content ranging from 24 to 31 %. The upper unit or so-called hard phosphates consist of calcium phosphate (75-80 %), quartz and feldspar (15-25 %) and minor amounts (2 %) of limonite, clay minerals and apatite, with a total P_2O_5-content of approximately 31 % (JONES 1983). However, for technical reasons presently the hard phosphate cannot be used in the processing of fertilizer raw material.

The commercially mined soft phosphates extend to a maximum thickness up to 20 m, surrounding the flankes of the hill in an oval shape and outcropping especially along its N slopes. Laterally their thickness decreases and the phosphatic layers are gradually substituted by more clayey lake beds.

The often observable slumping structures in the soft phosphates are due to the regional inclination of the hill's slopes, from which - below the paleolake level - these not yet consolidated sediments glided into deeper zones. However, these forces were not sufficient to demolish much of the bony material originating from the former island. Biostratonomically the abundant isolated bones of birds (*Phalacrocorax kuehneanus* SCHLÜTER 1991) never indicate a specific flow regime, hence leading to the conclusion that these bones were never destroyed by potential scavengers nor transported far away.

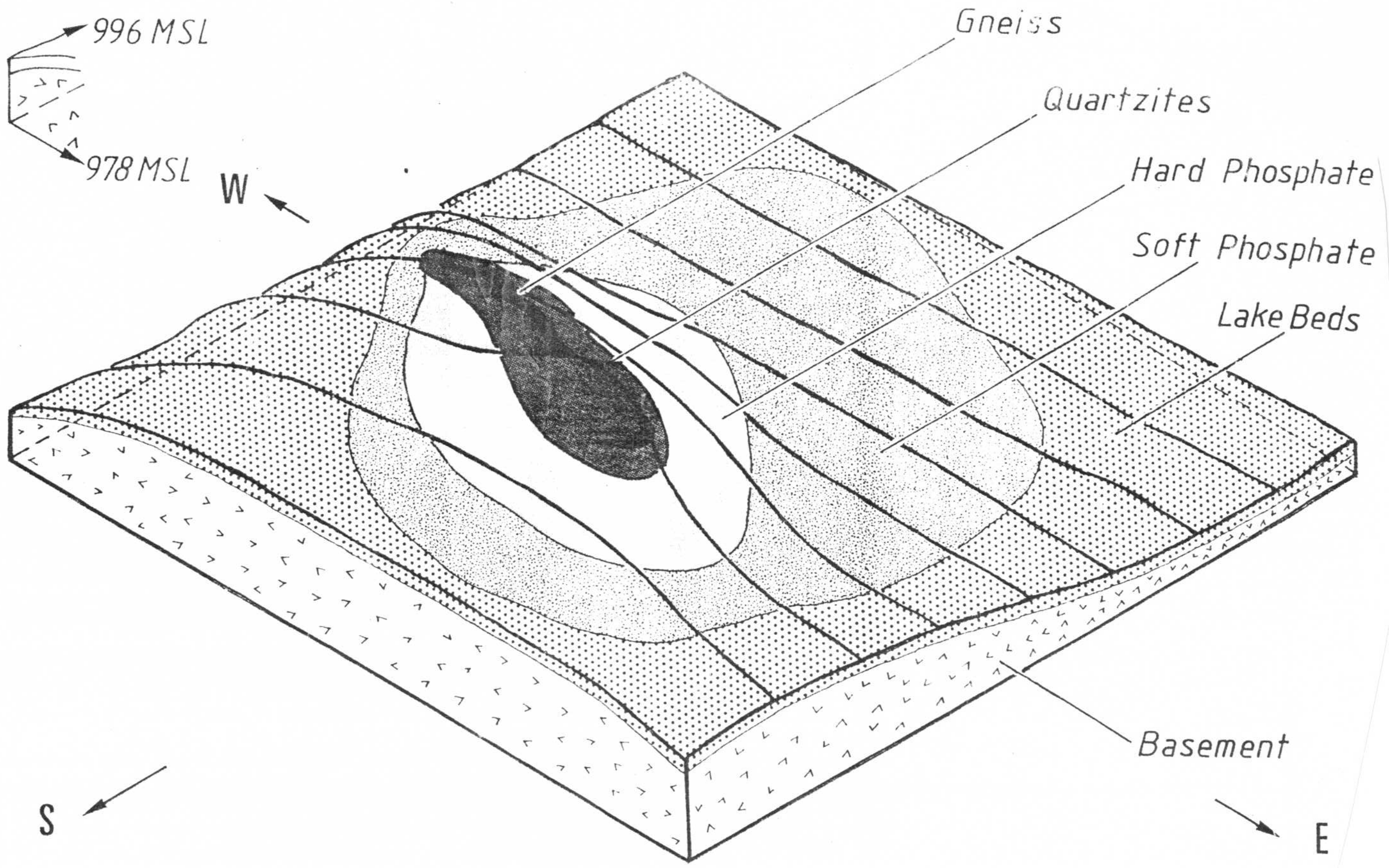
From their microfacial analysis the phosphorites of Minjingu are built up by mostly clastic particles. A distinction of skeletal material (predominant), phosphatic lithoclasts, detrital quartz grains and calcareous biogenic debris seems to be practicable.



Text-Fig. 1: Sketch map of Tanzania, showing the locations of principal phosphate deposits. - Black squares: carbonatites, black circles: phosphorites. Numbers and letters indicate the following localities: 1: Musensi, Mbeya region; 2: Songwe Scarp, Mbeya region; 3: Sukomaweru, Mbeya region; 4: Sageri Hill, Mbeya region; 5: Mbalizi, Mbeya region; 6: Panda Hills, Mbeya region; 7: Sangu Ikola, Rukwa region; 8: Ngualla, Mbeya region; 9: Zizi near Kisaki, Morogoro region; a: Minjingu, Arusha region; b: Amboni caves, Tanga region; c: Latham Island, 60 km E of Dar es Salaam (compiled after different sources).

These components are bound by different cements or matrix types, e. g. calcareous, dolomitic, siliceous and clayey materials.

The abiotic environmental factor of alkalinity in the paleolake can be determined by consideration of the metabolic requirements of fossil fishes evidenced in the phosphorites of Minjingu. Already CERLING (1979) used the well known autecology of certain organism groups for the estimation of the paleoalkalinity in Lake Turkana, N Kenya. Most lakes of the Eastern Rift are today sodium bicarbonate or sodium carbonate in composition, and their alkalinity is ranging from 2.2 $HCO_3^- + CO_3^{--}$ milliequivalents per liter (meq/l) (Lake Naivasha) to 3170 meq/l (Lake Magadi) (SCHLÜTER 1987). Fishes for example are strongly affected by the composition of water. Lakes with an alkalinity of 40 meq/l or more tend to harbor only cichlid fishes (*Tilapia* sp.), with the trend to dwarfism.



Text-Fig. 2: Block diagram of the Minjingu Kopje with the main lithological units. Exploitation of the soft phosphatesis is carried out only along the N and W slopes of the hill.

The very common and comparatively small operculae, vertebrae and fin spines in some of the phosphatic layers belong probably to ancestors of the diminutive species *Tilapia amphimelas*, which today lives in alkaline springs and small lagoons round Lake Manyara. Another indicator of a high paleosalinity is the occurrence of fossilized fish hyperostoses in some of the phosphatic layers (SCHLÜTER et al. 1992), because the growth of hyperostotic bones in Recent fishes is almost entirely bound to species living in a salt water environment.

An interesting analogy could possibly indicate that the formation of the phosphorites at Minjingu resulted in a comparatively short period of time. On the island Chincha along coastal Peru approximately 2 million specimens of the Recent cormorant *Phalacrocorax bougainvillii* produce 50 to 60.000 t of guano per year. Since the size of this peruvian island (0.3 km) is almost equivalent to the area which once has been the resting and breeding place of cormorants on the Minjingu-island in the paleolake Manyara, it can be assumed that a similar quantity of birds was also responsible for a similar guano production rate. The guano was later washed away and precipitated together with the clastic bony material of the birds and their prey, the fishes, shortly behind the shoreline of the island. The total reserves of phosphorites at Minjingu are estimated of around 9 million t (JONES 1983), hence leading to the calculation that the whole ore body in the case of a continuous deposition came into existence only within 2000 years.

3. Economic Significance

Phosphorus is an essential element in agriculture and in cattle feed. Phosphate concentrates are used for the production of chemical fertilizers (77 %), directly applied fertilizers (4 %), cattle feed (7 %) and in metallurgical, detergent, chemical and other industries (KOGBE & AFILAKA 1985). Africa ranges with approximately 70 % of all identified reserves of phosphorites on place one, but in the world production of commercial phosphates Africa accounted for example in 1983 only for about 24 %.

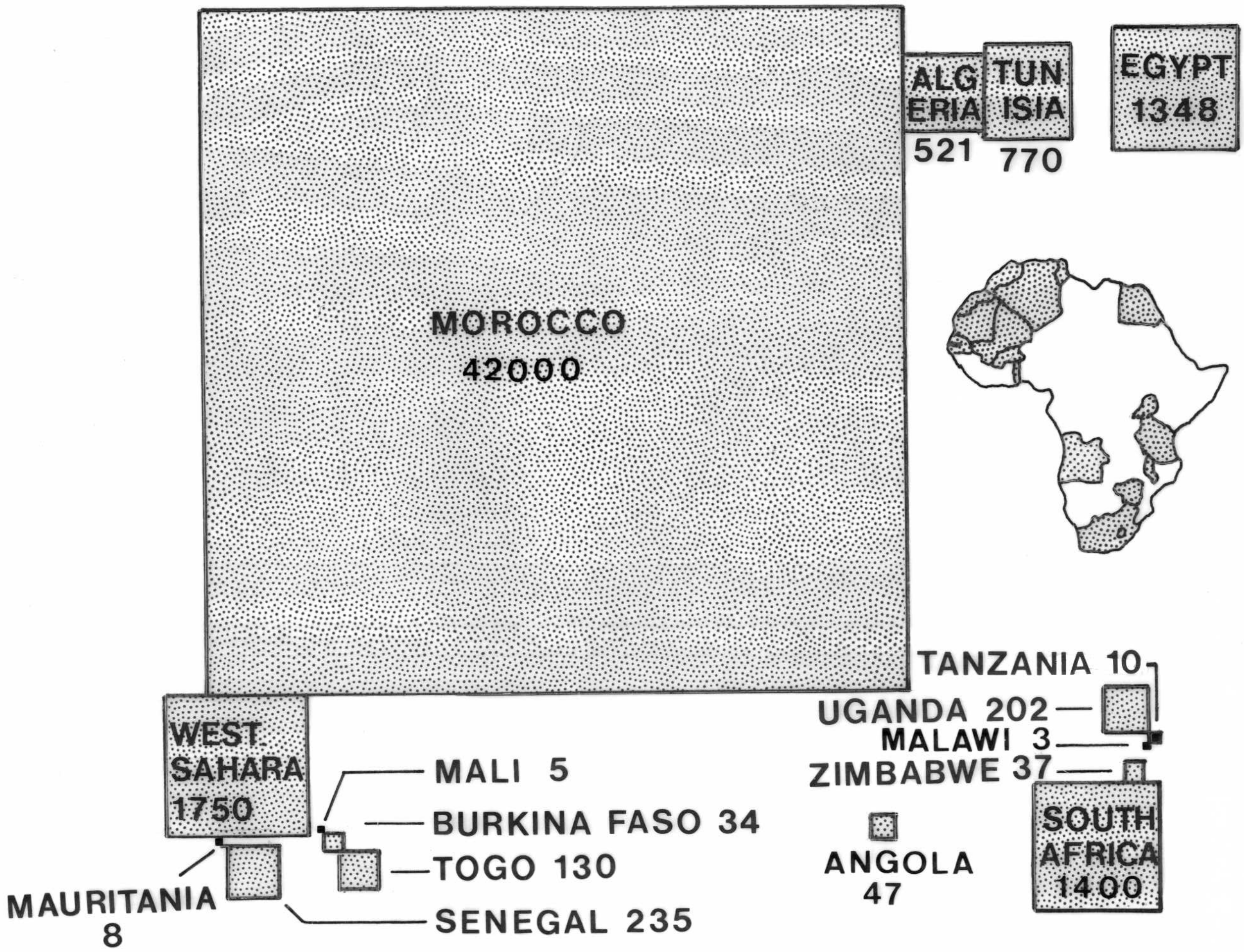
Also the distribution of phosphatic deposits in Africa is uneven, more than 50 % of the world reserves have been discovered in Morocco in marine sediments of Upper Eocene to Cretaceous age. Similar formations occur in the Western Sahara, Algeria, Tunisia, Egypt, Senegal and Togo. In central Africa larger deposits do not exist (KUN 1965), and also E Africa is comparatively poor. The quantitative proportions of the estimated reserves are given in Text-Fig. 3.

However, since in the 1970's internationally the value of phosphate raw material has considerably increased (compared to 1967 - 1969) its selling price has more than doubled) the Tanzanian government started a policy to avoid costs for the importation of raw phosphate material (between 1974 - 1978 up to 80.000 t/y) and also for the high freight rates by establishing its own phosphate industry.

The phosphorites of Minjingu were the first choice because their infrastructure was the best:

1. The P_2O_5-contents of the phosphorites are high (about 25 - 30 % in average) compared with those of the other phosphatic deposits in Tanzania, and they do not need up-grading or blending.
2. Minjingu can be reached by a tarmac road from Arusha.
3. A favourable factor for the processing of the phosphorites at TFC (Tanzania Fertilizer Corporation) is their very low chloride content.
4. The area surrounding the deposit is open and allows waste disposal, loading facilities and laying out of the phosphate dressing without restriction.

Additionally to the exploitation of the Minjingu phosphorites in January, 1985, the Canada/Tanzania project on agrogeology (CHESWORTH et al. 1985) started with the aim to bring together the tradionally separated disciplines of agriculture and geology, and for example to evaluate geological resources as locally available soil additives. Especially in the Mbeya region in S Tanzania (Text-Fig. 1) fertilizer raw materials were reassessed and some new phosphate deposits (both carbonatites and phosphorites) have been discovered, which in future could also contribute to the agricultural production of Tanzania.



Text-Fig. 3: Quantitative proportions of estimated reserves of phosphatic deposits in Africa (in million t), as indicated by proportional squares for each particular country (compiled after different sources).

4. Acknowledgement

I am very thankful to Dr. Peter van STRAATEN, University of Guelph, Canada, as a coworker in Minjingu, and as one of the initiators of the joint Canadian/Tanzanian agrogeology project, for the fruitful discussions with him.

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Some Index and Engineering Properties of a Hydrothermally Altered Granite from St. Austell, Cornwall, SW England

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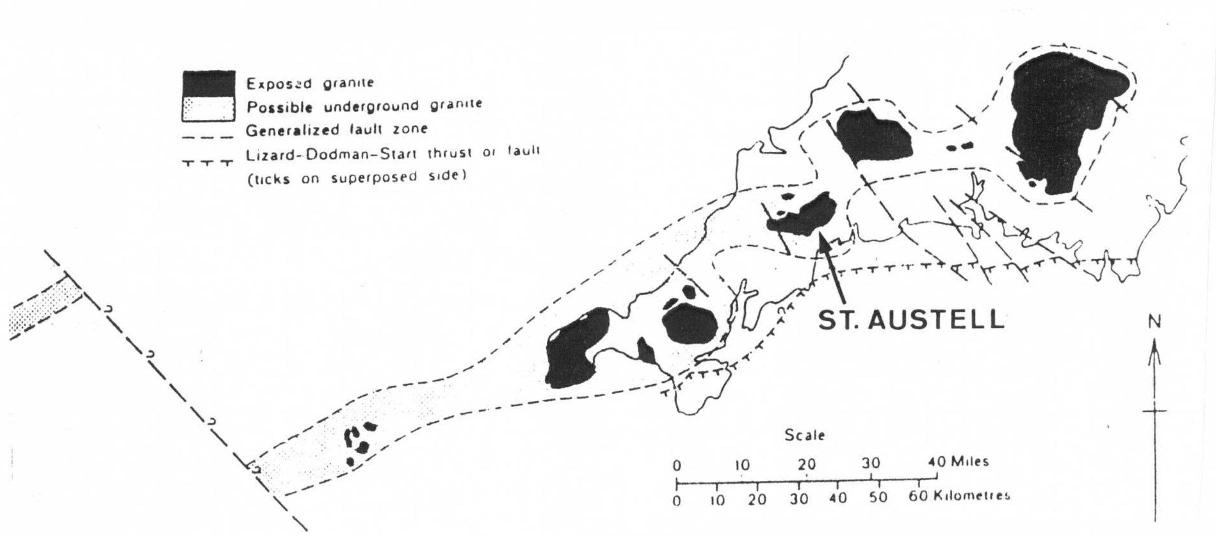
Abstract: The results of field and laboratory studies of a hydrothermally granite from St. Austell, Cornwall, SW England, are presented. The materials are classified into six decomposition grades on the basis of field indices, particulary the N-Schmidt hammer rebound value and the slake test were used. Interrelationships between N-Schmidt hammer rebound value, point load strength and uniaxial compressive strength are evidently linear. This indicates that N-Schmidt hammer rebound value and point load strength can form a reliable basis for a quick assessment of material strength.

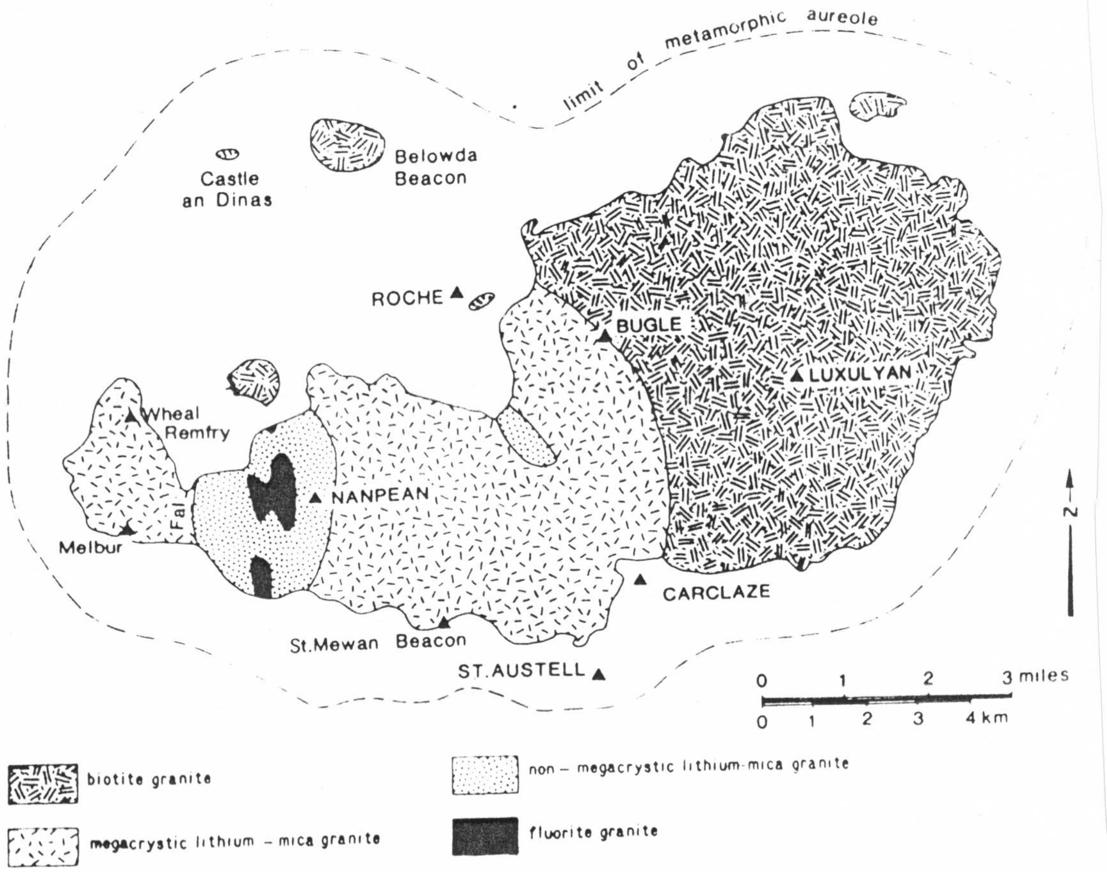
1. Introduction

In SW England, the bulk of granites occuring there (Text-Fig. 1) was strongly affected by post-emplacement alterations involving both hydrothermal activity (COLLINS 1909, EXLEY 1958, BRISTOW 1968) and chemical weathering during the tertiary (LINTON 1955, FOOKES et al. 1971, DEARMAN & BAYNES 1978). The St. Austell granite (Text-Fig. 2) examined for this study has suffered mainly from hydrothermal alteration (COLLINS 1909, EXLEY & STONE 1964, BRISTOW 1968). This study examines the applicability of a field description and classification scheme from weathered materials proposed by HENCHER & MARTIN (1982) to hydrothermally altered granites. Field work which involved description (with emphasis on the material itself) and sampling was carried out in two working china-clay pits, namely Virginia and Treviscoe near St. Stephan. Kaolin (china-clay) has been mined from these pits for a long time.

The rock type in Virginia is grey to greyish pink, a coarse megacryptic biotite granite with crystals of feldspar ranging from 1.5 to 10 cm. In Treviscoe it is a uniform, medium grained non-megacryptic Li-mica granite. It is separated from the biotite granite (Text-Fig. 1) by faulting along the Fal Valley (MANNING & EXLEY 1984).



Text-Fig. 1: Exposed granite in SW England and its possible underground connection (Based mainly on BOTT et al. 1958).



Text-Fig. 2: Distribution of granite varieties in the St. Austell area (after EXLEY & STONE 1982).

A range of laboratory tests was carried out on representative samples. Results were analysed and interrelationships between some of their properties were determined to find out which ones can be used to predict or estimate strength of materials.

2. Quantitative Field Description of Materials

Weathering (and alteration) effects are important for the engineering assessment of rocks. For site, investigation and design assessment, variability in engineering properties is often the key factor: it is therefore essential that the degree of weathering/alteration is described clearly and consistently (KNILL & JONES 1965, MARTIN & HENCHER 1984).
Description methods and classification of weathered rocks have been proposed by many authors e.g. DEARMAN (1974), DEARMAN et al. (1976), HENCHER & MARTIN (1982), MARTIN & HENCHER (1984). Many descriptions and classifications are qualitative, subjective and in many cases do not distinguish between material and mass properties. The scheme proposed by HENCHER & MARTIN (1982) distinguishes grades of material weathering on the basis of simple index tests and was adopted for this study. The tests are summarised in Tab 1. There were used as a basis for the criteria of classifying material in different decomposition grades (Tab. 2).

3. Labotary Tests

A range of laboratory tests was carried out to determine the engineering properties of representative samples of the different grades of material established in the field. Cylindrical and cubic specimens were prepared for those tests which require regularly shaped specimens e.g. uniaxial compressive strength and point load strength. The specimens were saturated by water immersion for 3 days, and were then air dried for 10 days to obtain results for saturation moisture content, dry density and effective porosity. Oven drying was avoided because of its effects on elastic properties of materials (DEERE & MILLER 1966). Quick absorption test indices, slake durability and effective porosity were obtained from lump specimens.

3.1.

A summary of results of laboratory tests for the samples ranging from grade II to IV are given in Tab. 3. Ranges of values for each grade are given in Tab. 4. An average value for each grade is considered unrealistic considering the broadness of the grade classification.

3.2. Discussion of Results

3.2.1. Mineral Specific Gravity

There is an considerable overlap in specific gravity in the different grades. DUNCAN & DUNNE (1967) have noted that specific gravity of the rock is rather insensitive to changes in rock texture and is unsuitable for assessing strength. In this study, mineral specific gravity cannot be used to characterise the engineering grade.

Attribute	Test	Procedure	Classes/Terms
1. Colour	Colour	Hand specimen. Note if material is uniform or mottled. Record colours in order of importance as identified from standard colour charts.	
2. Grain size & texture	Grain size	Handspecimen. Refers to original rock texture. Record texture and grain size of groundmass. In case of colluvium and residual soil this is not applicable.	1. Equigranular (all grains same size). 2. Megacrystic (large crystals significantly larger than groundmass). 3. Inequigranular (grain size vanatsle). a) Coarse (> 2 mm). b) Medium (o.o6-2 mm). c) Fine (< 0.06 mm).
3. Structure	Micro-fracturing	Handspecimen. Record degree of microfracturing.	1. No microfracturing. 2. Minor fracturing (10 mm spacing). 3. Morderate micro-fracturing (5-10 mm spacing) 4. Extensive micro-fracturing (2-5 mm spacing).
4. Cohesion	Slake-ability	Immerse small sample about the size of a fist in water in a container for a few minutes. If it does not disintegrate then it agitated gently a few times	1. Does not slake 2. On agitation breaks down discrete fragments. 3. On agitation breaks down to a slurry 4. Slakes completely
5. Strength	Hand Penetrometer Strength	Using a standard hand penetrometer take an average of 10 values of cohesion avoiding disturbed friable areas.	0-250 kn/qm. If too strong record as > 300 kn /qm. Note: Material tested contained too much quartz and were recorded as > 300
	N-Schmidt Hammer Rebound Value	After seating blows take the average of the highest five of ten blows at the same location. Values between 0-10 are estimated. Only record as zero if there is no rebound.	Rebound value N
6. Decomposition	Feldspar strength	Scratch feldspar with a pen knife. Where are in various stages of decomposition record nature of dominant type.	1. Not scratched 2. Just scratched 3. Easily grooved 4. No feldspars
	Decomposition grade	Record decomposition grade as indicated by criteria in Tab. 2	Six grades (see Tab. 2)

Table 1: Field index tests for description of weathered materials.

Descriptive Term	Grade	Typical Characteristics
Fresh Granite	I	- No visible signs of decomposition - Not easily broken by geological hammer - Makes a ringing sound when struck by a geological hammer
Slightly decomposed	II	- N-SHV > 45 - Several blows of geological hammer to break specimen - Makes ringing sound when struck by a geological hammer - Feldspars cannot be easily scratched by knife
Moderately decomposed	III	- N-SHV = 25-45 - Cannot be broken by hand: can be broken by single firm blow of geological hammer - Feldspars can be scratched with knife - Makes a slight ringing sound when struck by geological hammer
Highly decomposed	IV	- N-SHV = 0-25 - Geological pick cannot be pushed into surface - Does not slake readily in water - Feldspars powdery - Individual grains may be plucked from surface - Makes dull sound when struck with geological hammer - Hand penetrometer shear strength > 250
Completely decomposed	V	- Zero rebound from N-Schmidt hammer - Slakes readily in water - Geological pick readily indents when pushed into surface - Rock wholly decomposed but original rock texture is preserved - Feldspars powdery when present
Residual soil	VI	- Original rock texture completely destroyed - Can be crumbled by hand and finger pressure into constituent grains

Tab. 2: Classification of decomposed granite.

3.2.2. Dry Bulk Density

Dry bulk density is a good index of weathering and strength (IRFAN & DEARMAN 1978). There is a gradual decrease from 2.65 g/cm^3 in slightly altered (decomposed) grade II material to 1.91 g/cm^3 in completely altered (decomposed) grade V material (Tab. 3). The decrease in dry density is particularly significant in the highly and completely decomposed materials.

Saturated bulk densities also show a similar relationship and decrease from 2.61 g/cm^3 in grade II material to 2.34 g/cm^3 in grade IV material (Tab. 3).

3.2.3. Saturation Moisture Content and Quick Absorption Index

Both of these increase with decomposition grade. Saturation moisture content increases from 0.2 % in grade II material to 21 % in garde VI material and quick absorption index from 0.22 % in grade II material to 4.65 % in grade IV material (Tab. 3).

Sample	Grade	SHV	Mineral specific gravity g/cm³	Dry bulk density ϱ d g/cm³	Saturated bulk density ϱ sat[a] g/cm³	Saturation moisture content Sat.m.c%	Quick absorption index Iqat %	Effective porosity neff %	Slake durability index Id_2 %	Point Load strength index Is 50 MPa	Uniaxial compressive strength dry UCS_d MPa	saturated UCS_s MPa
T1a	II	56	2.68	2.65	2.61	0.20	0.22	1.12	99.3	6.046	94.32	64.49
V8b	II	54	N.D.	[a]2.56	2.57	0.57	0.48	[b]1.69	N.D.	5.797	78.66	N.D.
V6g	II	52	2.58	2.52	2.57	0.58	0.51	2.30	N.D.	5.964	81.62	N.D.
V2a	II	52	2.56	2.53	2.56	0.45	0.34	1.16	99.1	5.257	77.41	59.16
T4b	III	40	2.64	2.58	2.57	0.73	0.54	2.41	98.8	3.648	65.18	39.81
V3c	III	36	2.60	2.51	2.55	1.48	1.34	3.24	97.2	3.662	67.72	N.D.
V6d	III	32	2.61	2.48	2.51	3.21	3.00	5.33	97.9	4.021	48.24	13.20
T2b	III	30	N.D.	[a]2.52	2.54	3.41	N.D.	[b]3.93	N.D.	2.151	47.40	40.61
V5a	IV	22	2.44	2.26	2.34	3.96	3.45	7.82	80.8	0.884	17.10	N.D.
T2c	IV	18	2.56	2.38	N.D.	N.D.	4.65	18.31	76.6	0.310	10.94	N.D.
V5b	IV	<10	-	[c]1.89	-	-	-	N.D.	-	-	-	-
T5a	IV	<10	-	[c]1.93	-	-	-	N.D.	-	-	-	-
V4b	V	0	2.54	1.98	-	-	-	28.60	-	-	-	-
V8a	V	0	2.34	1.91	-	[c]21	-	22.21	-	-	-	-
T5b	V	0	-	[c]1.92	-	-	-	N.D.	-	-	-	-

a - obtained by caliper method
b - obtained by water saturation
c - obtained by shear box test

N.D. - not determined
\- - method used not applicable for such material

Tab. 3: Summary of test results.

Grade	SHV	Mineral specific gravity g/cm³	Dry bulk density ϱ d g/cm³	Saturated bulk density ϱsat g/cm³	Saturation moisture content %	Quick absorption Iqat %	Effective porosity neff %	Slake durability index Id_2 %	Point Load strength Is(50)MPa	Uniaxial compressive strength dry UCS_d,MPa	saturated UCS_s MPa
II	52-56	2.56 - 2.68	2.52 - 2.65	2.56 - 2.61	0.20 - 0.58	0.22 - 0.51	1.12 - 2.30	99.1 - 99.3	5.2 - 6.0	77.4 - 94.3	59.1 - 64.5
III	30-40	2.60 - 2.64	2.48 - 2.58	2.51 - 2.57	0.73 - 3.41	0.54 - 3.00	2.41 - 5.33	97.2 - 98.8	2.1 - 3.7	47.4 - 67.7	13.0 - 4.0
IV	18-22	2.54 - 2.56	2.26 - 2.38	* 2.34	* 3.96	3.45 - 4.65	7.82 -18.31	76.6 - 80.8	0.3 - 0.8	10.9 - 17.1	N.D.
V	0	2.34 - 2.54	1.91 - 1.98	N.D.	N.D.	N.D.	22.2 -28.6	-	-	-	-

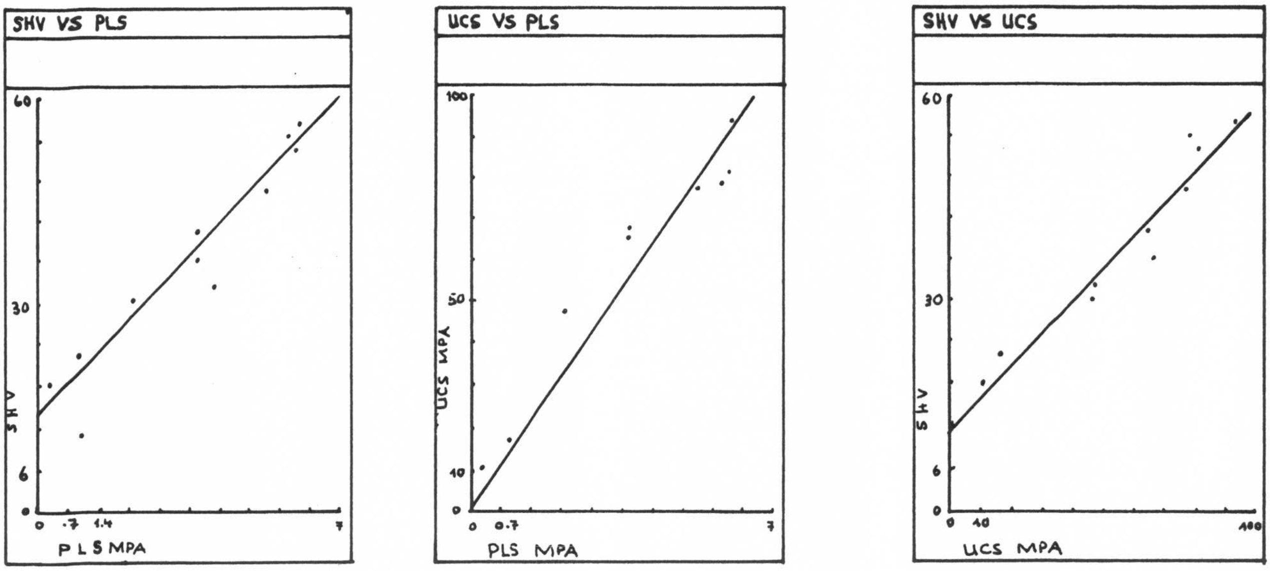
Tab. 4: Summary of results for different grades.

3.2.4. Porosity

Porosity increases from 1.12 % in grade II material to 28.6 % in grade V material (Tab. 3). Porosity increases as a result of alteration of feldspars to clay minerals.

3.2.5. Slake Durability Index

This decreases only from grade II to III. A significant decrease is observed between grades III and IV which marks the transition from sound rock to an intermediate material between sound rock and weak rock. It should be noted that only materials in the upper strength range of grade IV were tested. Slake durability index can thus be used to characterise sound rock from weak rock (grades III and IV).



Text-Figs. 3: SHV versus PLS, 4: UCS versus PLS, 5: SHV versus UCS.

3.2.6. Point Load Strength

There is a gradual decrease in point load strength from 6.0 MPa in grade II material to 0.3 MPa in grade IV material.

3.2.7. Uniaxial Compressive Strength

Uniaxial compressive strength decreases from 94 MPa in grade II material to 11 MPa in grade IV material (Tab. 3). Saturated uniaxial compressive strength follows the same trend.

Uniaxial compressive strength and point load strength are influenced by physical properties of the material like bulk density, saturation moisture content and porosity.

4. Interrelatiuonships between Index and Strength Tests

4.1. Point Load Strength and Schmidt-Hammer Value (SHV)

The relationship is linear (Text-Fig. 3) with an intercept of the schmidt-hammer value axis. The line should pass through the origin but it is not possible to test very weak rocks and granitic soil with the schmidt-hammer. Materials with SHV < 16 were not tested for point load strength - they were too weak.

4.2. Point Load Strength and Uniaxial Compressive Strength

Point load strength has been used as an index test (e.g. FOOKES et al. 1971) and the relationship is linear (Text-Fig. 4). Portable equipment which can be carried to the field is available.

4.3. Uniaxial Compressive Strength (UCS) and Schmidt Hammer Value (SHV)

SHV was used to characterise grades II to IV materials in the field and its plot with SHV (Text-Fig. 5) shows a linear relationship. DEERE & MILLER (1966) found a good relationship between UCS and a product of L-SHV and unit weigth. Although the graph (Text-Fig. 5) shows some scatter, given that the SHV is a quick field test, it can be reliably used to characterise the decomposition/alteration grade.

5. Conclusion

A field description method and classification of weathered rocks proposed by HENCHER & MARTIN (1982) has been used in this study of hydrothermally altered granite from St. Austell, SW England. Laboratory tests were carried out on representative samples and some relationships were established. The following conclusions are drawn:

1. Careful and qualitative description distinguishing grades of material decomposition on the basis of simple index tests can be used for a quick engineering assessment of rocks. This can be particularly useful in countries with inadequate laboratory facilities.

2. The N-Schmidt hammer value and slake test are the most useful field index tests for differentiating between decomposition grades.

3. Relationships established in 4 are linear thus those tests (schmidt hammer value and point load strength) can give a reliable basis for assessing material strength.

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