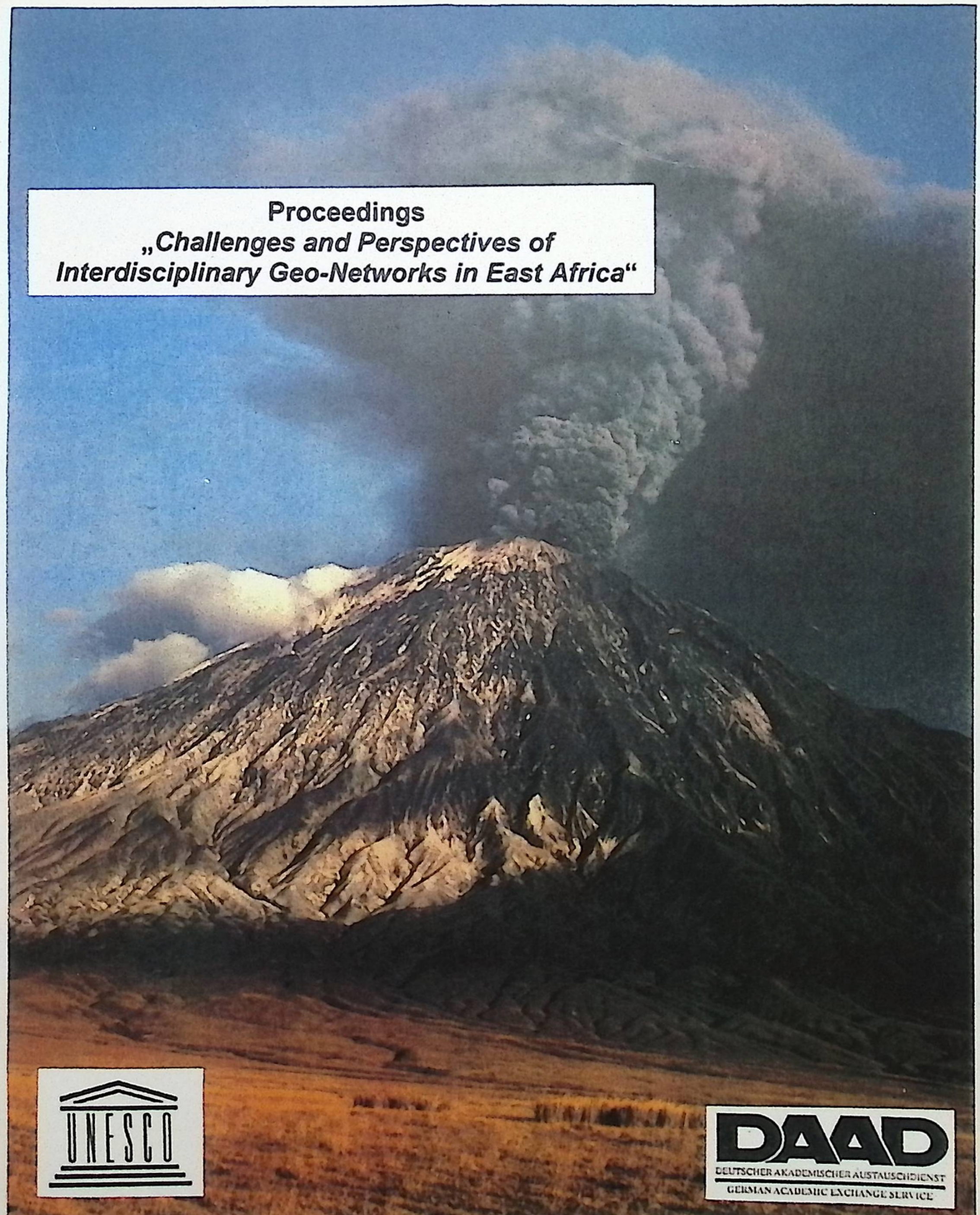
# documenta naturae no. 136

München 2001




**Proceedings**
***„Challenges and Perspectives of Interdisciplinary Geo-Networks in East Africa"***

**DOCUMENTA NATURAE**

**Nr. 136 2001**

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**ISSN 0723-8428**

**Herausgeber der Zeitschrift Documenta naturae im**
**Verlag (Publishing House) Documenta naturae - München (Munich)**
Dr. Hans-Joachim Gregor, Daxerstr. 21, D-82140 Olching
Dr. Heinz J. Unger, Nußbaumstraße 13, D-85435 Altenerding
Priv.-Doz Dr. Diethard H. Storch, Sägematte 2, D-79183 Waldkirch

Die Zeitschrift erscheint in zwangloser Folge mit Themen aus den Gebieten Geologie, Paläontologie (Lagerstättenkunde, Paläophytologie, Stratigraphie usw.), Botanik, Anthropologie, Domestikationsforschung, Vor- und Frühgeschichte u.a.

Die Zeitschrift ist Mitteilungsorgan der Paläobotanisch-Biostratigraphischen Arbeitsgruppe (PBA) im Heimatmuseum Günzburg und im Naturmuseum, Im Thäle 3, D-86152 Augsburg

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Überweisung des Heftpreises erbeten auf das Konto 1548460 bei der Sparkasse Fürstenfeldbruck (BLZ 700 530 70) - Inh. H.-J. Gregor.
Bestellungen: bei Buchhandlungen und den Herausgebern (s.o.)



Gestaltung: Juliane Gregor und Hans-Joachim Gregor

Umschlagbild: Eruption des Vulkans Oldoinyo Lengai im Jahre 1966
**München 2001**

| Documenta naturae | 136 | 1-184 | Munich 2001 |
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**Andrew Muwanga, Rolf Kohring, Thomas Schlüter,**
**Dirk Hollnack and Andreas Schumann (eds.):**

# Proceedings of the workshop on

# *„Challenges and Perspectives of Interdisciplinary Geo-Networks in East Africa“*

## (October 1999, Kampala)

Title - Eruption of volcano Oldoinyo Lengai in 1966. This is the only active volcano with a carbonatitic lava composition. It is also worshipped by the Masai tribe as the "Mountain of God".

**Munich 2001**

## CONTENT

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| Documenta naturae | 136 | 5-6 | Munich 2001 |
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**Preface**

Dirk Hollnack, Rolf Kohring, Andrew Muwanga, Thomas Schlüter and Andreas Schumann

These papers are the repository of the proceedings of a "Workshop on Challenges and Perspectives of Interdisciplinary GEO-Networks in East Africa", which was held in Kampala, Uganda, from 25 to 27 October 1999. The workshop was attended by about 30 participants - mostly geoscientists - working in East Africa, i. e. Kenya, Tanzania and Uganda.

Financial support to organize this workshop was mainly provided by the German Academic Exchange Service (DAAD), Makerere University and UNESCO contributed to a lesser extent. For several decades DAAD has sponsored capacity building and research activities in East Africa, and as a result there are currently more than 50 former DAAD scholars with a geoscientific background working in these three countries. The aim of the workshop was to evaluate

- Recent scientific links and research activities among East African geoscientists
- Possibilities of initiating interdisciplinary projects with African and international partners
- Problems related to the acquisition and realization of research programmes in East Africa
- The influence of DAAD sponsorship on the individual and scientific career of the committed earth scientists, and
- The impact of former DAAD scholars for capacity building within geological institutions of East Africa

The oral presentation of scientific papers and their discussion occupied the first part of the workshop. Some of the full papers, which were subsequently submitted and peer reviewed, are included in these proceedings. The second part of the workshop was dedicated to working group discussions on recent scientific links, research activities and possibilities, problems of initiating research projects in Africa with African and international partners, and on the influence of the DAAD sponsorship on individual careers and its impact for geological institutions in East Africa. Resulting from these discussions and following long deliberations a constitution of the East African Geo-science Network (EAGN) was adopted by the plenum of the workshop (p. 0), forming an integral part of these proceedings.

It is hoped that both the scientific and the technical papers of these proceedings will therefore contribute to a better public awareness of the problems with which geoscientists in East Africa are sometimes confronted.

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## Obituary

The entire Council and Membership of the Geological Society of Uganda (GSU) with deep sorrow announce the death of **Mr. Saul Mboijana**. Mr. Mboijana served the Society as President from 1990 up to June 2000. He died at Mulago Hospital on 25$^{th}$ April 2001 and was buried at his ancestral home in Kabarole District on 27$^{th}$ April 2001.

Mr. Mboijana was among the pioneer students of the Department of Geology at Makerere University. He graduated with a BSc. Degree in 1972. He later embarked on a one-year postgraduate course in Applied Geology. Immediately he completed his studies, he joined the Geological Survey and Mines Department. He worked as a Geologist but later rose through the ranks to become the Commissioner of the same Department.

By the time of this death, he was the Director of the Directorate of Energy and Mineral Development. We shall all emulate the legacy he has left with us in the profession.

May Saul's soul rest in eternal peace.

Dr. Erasmus Barifaijo
President, GSU

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## The Constitution of the East African Geo-science Network (EAGN)

(First proposed draft, 2nd Febr. 2000)

### Contents



### Introduction

In October 1999 East African geo-scientists from Kenya, Tanzania and Uganda met at a DAAD-workshop on „Challenges and Perspectives of Interdisciplinary Geo-Networks in East Africa" in Kampala, Uganda.

During the workshop it became obvious, that the geo-scientists of the region lack interregional co-operation, although the geology and geo-science related problems of the region are similar.

At the end of the workshop the participants founded the „East African Geo-science Network" (EAGN)

### Article 1 Name

The East African Geo-science Network (EAGN).

### Article 2 Nature

EAGN is a non-governmental, academic, independant and non-political network.

### Article 3 Language

The official language of the Geo-network shall be English.

### Article 4 Justification

East African scientists recognised, that there is no organised collaboration in geo-sciences within East Africa so far. A lot of independent research has been done which could be of mutual benefit to other scientists within the region. Communication facilities and the lack of a regional databank comprising addresses of geo-scientists, publications and research activities, were identified as major reasons why research and geo-science related activities were carried outin an „isolated" manner. The collaboration and communication will be greatly enhanced through the Geo-science Network.

### Article 5 Aim

The aim of EAGN is to promote geo-sciences relatied activities within East Africa and to become an umbrella under which geo-scientific information is stored and disseminated.

Special objectives

During the workshop and a meeting of the EAGN-representatives at „Hotel Africana" in Kampala at the 28th October 1999 the following specific objectives were formulated:

- to foster the development and co-ordination of geo-scientific research in East Africa and its sustainability
- to improve geo-scientific education in East Africa
- to facilitate the publicity and dissemination of scientific results to governments and public
- to promote a sustainable management of earth resources
- to endeavour to create awareness and advice on mitigation of natural hazards

**Article 6 Activities**

EAGN-members should contribute to the successful establishment of the Geo-network in being active members:

- to bring together scientists of the region to formulate and conduct joint research projects
- to provide platforms for exchange of information
- to organise seminars, meetings and workshops
- to facilitate the dissemination and publication of research results
- to facilitate the exchange of academic and technical staff
- to publish a newsletter
- to sensitise the public through mass media, public lectures, exhibitions etc.
- to create a data base (addresses, scientific specialisation, research activities, publications)
- to open up linkages to related organisations and companies in public and private sector

**Article 7 Structure of EAGN**

The major concern of EAGN is to establish a network through computer based communication technology (e-mail, internet, websides).

The permanent bureau will be at the Department of Geology at Makerere University in Kampala, Uganda.

Executive committee / Elections

The executive comprises of four EAGN-members which will be elected every three years:

- one chairman (executive)
- three country representatives (one from Kenya, one from Tanzania, one from Uganda)

Functions of executive members

**The chairman**

- to co-ordinate EAGN activities
- preside over all meetings
- preside over meeting of the executive committee
- represent the association whereever necessary

**Country representatives (function in their countries)**

- to co-ordinate EAGN activities in their countries and with the secretariat
- preside over EAGN meetings in their countries

- make decisions on behalf of the executive committee, in line with this constitution and report to the executive committee within a week
- responsible for money of EAGN
- keep financial accounts of EAGN
- be in charge of all records of subscriptions, donations and grants to the EAGN
- report on their functions to the secretariat every six month and the General Assembly once a year

**Duties of the executive committee**

- responsible to the General Assembly
- deliberate on all matters that effect the members and resolve on measures taken by the General Assembly
- have powers to deal with matters pertaining to EAGN and report thereon to the General Assembly
- carry out the decisions and programmes of the General Assembly resolved at a general meeting
- initiate policies and carry them out after approval of the General Assembly
- have powers to deal with emergencies pertaining to EAGN and report thereon to the General Assembly
- assist EAGN members in fulfilment of any projects which are deemed by the General Assembly
- being treasurers of EAGN and report to the General Assembly after every year
- be responsible for the correspondence of EAGN
- keeping records of all activities of EAGN
- co-ordinating EAGN activities
- keep in regular and close contact with each other

**Resigning**

- if the chairperson is resigning she/he should inform the executive committee members, who will nominate one among themselves to act before any chairman is elected at the next General Assembly
- if a country representative is resigning she/he should inform the secretariat and the other executive members and the EAGN members in the respective country will nominate a replacement

## Article 8 Membership

Every scientist dealing with geo-science related work may become a member of EAGN and is requested to fill in a standardised form with his address, publications and research activities.

## Article 9 Ethical standards

All members participating in EAGN shall conduct its affairs in accordance with the constitution, and shall pay specific attention to the following:

- show utmost faith in all matter
- not to use EAGN facilities or influence to further private gains or interests at the expense of the association
- not to conduct themselves in a manner prejudicial to the interest of the EAGN

## Article 10 Fees

### Membership

Membership is free of fees, but members may donate any amount to EAGN. Members of Tanzania should donate their money to the Tanzanian representative, members of Kenya should donate to the Kenyan representative and Ugandans to the Ugandan representative.

### Income

Any requests should be charged.

- Single customer requests

E-mail requests: each customer will have an account and be charged by 0,5 US $ for each e-mail or 1 US $ per page of information which will be sent via mail (via letter). After half a year the country representatives will send bills to every customer. The customer will send the amount in cash or as a check to the country representative. Customers who are not paying their duties may not have any longer access to EAGN facilities.

- Packages

Scientists who are engaged in an international research project may get access to EAGN facilities for a whole year by paying 300 US $ to EAGN. This should be accompanied by a list of participating scientists. This money will be shared between the three EAGN offices in East Africa. Thos applies also for requests from other orhanisations or companies which might be in need of EAGN facilities.

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| Documenta naturae | 136 | 11-12 | Munich 2001 |
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## Course of the Workshop

Dirk Hollnack and Andreas Schumann

In March 1998 a workshop on "Challenges and Perspectives of Universities in Africa" took place in Kampala, Uganda, which was initiated by several German development and donor agencies (DAAD, GTZ, CIM and DED). It became obvious during the deliberations that scientific co-operation among East African countries do either not exist at all, or are only in an initial stage. It was therefore envisaged to implement research projects on a more international basis. The geo-sciences may in this context serve very well, because geological structures are not limited by political borders.

This led to the idea of creating a platform for the exchange of information and experiences among geoscientists from the different East African countries. As a starting point it was decided to organize a geo-workshop with delegates from Kenya, Tanzania and Uganda. Since about 50 active geoscientists in these countries are former DAAD scholars, the German Academic Exchange Service was asked to assume the auspices and sponsorship of such an event, which eventually was agreed to.

As a result the "Workshop on Challenges and Perspectives of Interdisciplinary GEO-Networks in East Africa" was held from 25 to 27 October 1999 in Kampala, Uganda, and attended by about 30 participants from Kenya, Tanzania and Uganda. The workshop programme was divided into two main parts:

a) oral presentations, and

b) group work.

For the first part of the workshop programme the invited delegates were asked to give an oral presentation on their present research projects. These topics represented a wide spectrum of geoscientific research and disciplines. For the second part of the workshop programme the participants were separated into two groups to discuss the following topics: a) Recent scientific links, research activities and possibilities, problems of initiating research projects in Africa with African and international partners, and b) The influence of the DAAD sponsorship on individual careers and its impact for geological institutions within East Africa.

The results of the two working groups were presented and discussed during the final panel session. It became obvious that insufficient communication facilities are a major reason for the lack of cooperation among East African geoscientific working groups. To take remedial action it was decided to found the "East African Geoscience Network" (EAGN), with the intention to:

a) promote cooperation between the member departments,

b) facilitate the exchange of staff and of students,

c) consult each other during the process of modernization of coursework studies,

d) facilitate concerted action for the promotion of geosciences in the region,

e) develop common research projects, and

f) set up a data base for addresses, recent research activities and publications.

Apart from these conclusions the workshop had also some other positive side effects, and a number of in-region activities have already commenced since then:

a) a student field excursion took place in December 1999, with participants from Austria, Kenya, Tanzania and Uganda, which was mainly organized by Prof. Sospeter Muhongo (Department of Geology, University of Dar es Salaam),

b) The Geological Society of Uganda has been revitalized after years of dormancy (June 2000), and

c) with funds from DAAD and BMZ the EAGN office at the Department of Geology, Makerere University, has been equipped with electronic facilities (September).

A Regional International Conference on the Geology of East Africa will be organized by the Geological Society of Uganda (GSU) in conjunction with the Geological Society of Africa (GSA), with organizing committee members from Kenya, Tanzania and Uganda. The venue will be in September 2001 in Kampala, Uganda.

The current issue of Documenta Naturae presents selected full papers of the participants at the Kampala workshop, which give an overview about some actual geoscientific research activities of East African geoscientists. The editors thank DAAD and UNESCO for shouldering the printing costs of this issue.

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| Documenta naturae | 136 | 13-14 | Munich 2001 |
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## „Workshop on Challenges and Perspectives of Interdisciplinary Geo-networks in East Africa“

### - Opening address -

Saul A. Mboijana (†)
former Director of Energy and Mineral Development, Uganda

H.E. The German Ambassador the Hon. Klaus Holderbaum,
The Head of the DAAD Regional Officer for Africa, Mr. Jacob,
The Dean of the Faculty of Science, Makerere University, Prof. S. Luboobi,
Organisers of the Workshop,
Distinguished guests,
Workshop participants,
Ladies and gentlemen,

It is my special honour and rare privilege to welcome you all to this important workshop which is organised by the German Academic Exchange Service, which for a number of years, has sponsored the education of geo-scientists in East Africa region.

I am informed that one of the main targets of DAAD is to promote academic cooperation among German and East African institutions of higher education. This is clearly demonstrated by the visible sizeable attendence of the workshop from Kenya, Tanzania and Uganda who have been the beneficiaries of this effort.

I am further informed that the intention of this workshop is to enable you to evaluate and take stock of:

- Recent scientific links and research activities
- possibilities of initiating interdisciplinary projects with African and international partners
- the influence of DAAD sponsorship on the scientific career, and
- to discuss problems related to acquisition and realisation of research programs in East Africa.

These issues are very important indeed for geoscience development in the region and Africa as a whole. For this reason I wish to take the opportunity to show our gratitude to the organisers of this workshop for having selected Kampala as the venue for this important consultation.

We are all aware that the East African region is not yet industrialised. This means that for the foreseeable future we shall rely mainly on our natural resources for social development and economic growth. Knowledge of the region's geoscience data and mineral resources in particular, will play a major role in this endeavour. Therefore we see geoscienctific research net-working for the region will go a long way towards achieving this objective.

Economic history shows that the present day developed economies of the world used mineral resources as a springboard for their development. Developing countries ought to borrow a leaf from the experience of the developed countries as a strategy for economic growth.

It is apparent that there is a missing link between the political and the economic asipiration of our governments and our academic research institutions. I want to suggest that our research in geoscience should not only remain academic, but also be applied in contributing to the growth of our economies.

The challenge before us at this geo-science workshop is to try and translate our geo-scientific findings into applicable uses to benefit our region and Africa as a whole in our effort to attain economic growth and development.

I note with satisfaction that the issues to be discussed in the workshop concern not only geo-education or a demonstration of academic excellence per se, but also concerns geo-scientific co-operation and net-working within the region, Africa and the international organisers.

Let me take this opportunity to appeal to you that at the end of this workshop you come out with a „DAAD-Uganda plan of action", which among other activities, should foster continued integration and co-ordination of cross-boarder geo-science research and mineral development of East Africa - being well aware that geology transcends political boundaries.

I thank you for the honour of be able to give this opening address to a workshop of such distinguished geo-scientists.

I wish you fruitful deliberation.

Thank you.

Saul A. Mbojana

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| Documenta naturae | 136 | 15-17 | Munich 2001 |
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# Review of the strategies for the development and utilisation of mineral resources of Africa

Saul A. Mboijana (†)

## Introduction

The countries of Africa have been ardently searching for strategies and policies aimed at reviewing economic growth, reducing over-dependence on imports of consumable items and industrial raw materials, in order to free their industrial infrastructures from merely assembling semi-finished products that have no positive gain to the economy in terms of technology transfer, self-reliance and sustainable development.

From the time human beings first used flint to make fire, stone implements to hunt, containers to collect water or salt to preserve food, minerals have been and continue to be one of the essential elements in the development of society. Minerals have historically had such an impact on development of society that even in the days of ancient history minerals were used to calibrate the time scale for various epochs. That is why the important land-marks of history are called mineral types and/or geological events like stone age, bronze age, Paleozoic, Mesozoic, Cambrian etc. Despite some substitution by plastic, the use of minerals continues to grow and a significant number of developed economics have used minerals as a basis for their development.

Africa has realised now, more than ever before, that the need to develop and utilise their mineral resources maximumly for socio-economic development is real and urgent. For this reason a series of regional conferences of Development and Utilisation of Mineral Resources in Africa have been held in recent years and hosted by various countries of Africa under the auspices of the ESA in Addis Ababa, Ethopia. The very act of holding of these conferences on Development and Utilisation of Mineral Resources of Africa, reaffirms Africa's special concern and determination to work towards finding and defining common strategies that could enable these countries to fully benefit from exploitation of the abundant mineral resources of the continent.

## Mineral endowment

Africa has a sizeable endowment of various mineral commodities. This includes a number of major world mineral commodities which have limited geographic and national distribution. Most notable amongst the commodities with such a limited distribution include cobalt, phosphate, tungsten, chromium, beryl, columbite-tantalite to name a few. In future this limited distribution may be a source of concern for world mineral demand for these rare commodities. Africa's strategies for development and utilisation of such strategic commodities has to take this into consideration. The sooner appropriate measures are taken to produce finished products of these mineral commodities now, the better for the future of the continent.

We recognise that there is an urgent need to develop Africa's agriculture and preserve the environment. The mineral industry and the production of phosphate fertilisers in particular is an essential input into that sector. Africa is endowed with phosphate fertiliser deposits that have in some cases been identified and evaluated. With co-operation of the Preferential Trade Area States (PTA) and the Eastern and Southern Africa Common Market (COMESA), it is planned to jointly develop these deposits to meet the fertiliser needs of the sub-region. Already a donor's conference organised by PTA was held some time back and pledges to start the regional project made. When this project is implemented, it will help increase sub-region's agricultural production. A similar mode of development based on iron ore deposits for an integrated iron and steel industry for the sub-region is being considered to utilise the available resources of iron ore and coal in the various member states. These efforts needs further consolidation to ensure meaningful development and utilisation of the sizeable mineral endowment of Africa.

## Need for a wider market and integrated sector development

The Eastern and Southern African sub-region member states met some few years ago to establish a common market - the Common Market for Eastern and Southern Africa (COMESA) to foster better economic growth in all aspects of their economy. This was a step in the right direction by the political leaders. With the establishment of COMESA, member states should be encouraged further to focus attention to new strategies, policies and programmes to enable the region derive greater value from exploitation and processing of its natural resources, including minerals, and market them through the sub-regional and intra-regional trade for mutual development. A wider market base such as COMESA is necessary for the effective utilisation of minerals and other commodities produced in the region. Minerals, which transcend political boundaries should be seen to play a major role in this regional co-operation effort.

It is important to focus on integrated development of the mineral resources of the region in order to ensure the acquisition of upstream and downstream process technologies in the sector Maximum impact will result from mineral development if and when upstream and downstream industries in the sector are developed in the region. This will ensure transfer of technology and the initial sure steps to a degree of self-reliance and sustainable development.

## The next steps

Quite a number of specific and general recommendations have been made after every regional Conference on Developmen and Utilisation of Mineral Resources in Africa. Several conferences have already been held as pointed out and corresponding reports of deliberation and appropriate recommendations made. The recommendations have been widely published, and there is no need to repeat them in this paper.

This paper is meant to recommend urgent follow-up action to be taken by member states to jointly or individually start implementing these recommendations. The steps already taken by SADC, COMESA, PTA, ECOWAS, GEODESA and ESMARDC to implement some of these recommendations are highly commendable and should be fully supported by all members of these groupings. Our organisation as earth scientists - the Geological Society of Africa - has an important role to play.

As far as previous Mineral Conference recommendations are concerned, Uganda has embarked on the first steps towards their implementation within the overall country's economic strategy. The government has realised economic activity and an Investment Authority was set up to focus on attracting private investment in all sectors of the economy. The various investment laws were consolidated into an Investment Code, under the Uganda Investment Authority (1991) in order to streamline bureaucratic procedures by establishing a one-step investment shop. This move has been adopted to encourage investment in activities that use Uganda's mineral resources which is one of the major inputs in order to achieve social economic development.

Countries of Africa have to set up fiscal and legal frameworks geared to create a conducive environment in which private investors are assured of guarantees which will safeguard normal commercial operations. This is particularly necessary for the mining sector for the required risk investment capital. Our countries should be encouraged to continue to be active co-operating members of regional and sub-regional institutions in order to improve the contribution of minerals to the economic and social advancement of the African region. Geological Surveys of Africa should ensure research collaboration with universities and other international research Organisations in order to fully develop and utilise the mineral resources that have so far been identified in the region.

## Conclusion

Having started this paper by pointing to the ardent search the countries of Africa have so far undertaken to develop strategies and policies to review general economic growth, reduce over-dependence on imports, and forge self-reliance and sustainable development, the major elements of the role of minerals in improvement of the economy has been separately considered by individual countries. There is therefore the need for the Member States to try and bring the separate elements together. It has to be borne in mind that the concept of sustained development, especially when based on minerals, requires a long-term view. We are all aware that mineral exploration and development takes a long time to bear fruit and, probably more so, in developing countries where lack of appropriate technology and limited financial resources are major factors of constraint. The impact of the use of minerals on degradation of the environment is well known. But minerals are also a critical element for industrial development and agricultural inputs as fertilizers to feed the increasing population. It is also to be noted that where there is waste as a result of mining, processing and utilisation of minerals, this should be as benign as possible implying an added cost. The geologists must be prepared to play a role from the point of view this problem, because there is likely to be a need for minerals with new specifications which might render to known commodities uncompetitive worldwide. Hence the need for us to develop a wider market for our products of the continent.

Whilst there are many other serious issues impacting upon the sustainable use of mineral resources, there is every reason to believe that solutions will be found, not least by the geologists. Some of those to be kept in mind in seeking these solutions are as follows:

- While we plan for regional growth of mineral utilisation, we must mutually work to minimise its impact on the environment.
- The sustainability of the sector depends on an extraordinarily complex interplay of factors affecting the availabilty and use of the minerals. Geoscience is a key to this understanding and this will require better surveying, monitoring, modelling and documenting of the resource.
- The most people today, the important mineral business is to earn foreign exchange for their countries, without regard to the related benefits like availability of metals, good soils, building materials and a secure place to live. There must be deliberate attempts by scientists, educators and political leaders in the region to try and correct this concept. Geological educators must be prepared to venture a bit outside the traditional approach to geological education, in particular placing more emphasis on other social benefits of the science.
- Interdisciplinary and effective net-working, including development of enabling mineral legislation by politicians, are essential to the future of the mineral contribution to the socio-economic development of the continent.
- A narrow short-term, market-driven approach has for long underlain many development problems for the sector. A broader-term, market-driven approach on a regional basis may provide solutions through intra/inter-regional trade.
- Political structures in the region must develop a culture of proper natural resources accounting, in particular in the ever-sensitive area of minerals. Appropriate returns and accountability to the public and the rights of indigenous people must be guaranteed. Technical advisers must be prepared to communicate and speak out on such important issues.
- Finally it may be pointed out that politics is short-term, whereas resources and environment issues are long-term and are the insurance for posterity. Short-term desires have often undermined long-term objectives for sustainable development.

### Ackowledgements

A direcor of mineral development of a country has the rare opportunity to keep in contact with a variety of activities from Surveys of other countries and from investment companies. The information accessed in this way is varies and diverse. One wishes to share most of it with colleagues and other beneficiaries but, due to many other demands of the director's office, time available is hardly enough to collate and disseminate this information. A lot of information presented in this paper has come from participation in conferences where different experiences of mineral resources development and utilisation were shared. I am most grateful to the organisers.

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| Documenta naturae | 136 | 18-20 | Munich 2001 |
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# Status of geological education in Kenya

T.C. Davies[1] and S.J. Gaciri[2]

**Abstract:** Kenya is a country of great geological diversity, with its broad range of ancient rocks, Tertiary extrusives bodies, varied sediments and mineral deposits. The country's geographical location is unique and its physiography characterised by a range of altitudes dissected by the Great Rift Valley, with its peculiar hydrological network. Again too, public infrastructure and private building construction and mining companies in the country are expanding and require a variety of geological inputs, from hydrogeology and groundwater engineering in the water sector, geotechnical assessments for often difficult foundation designs, to appraisal of aggregate reserves and marine investigations for land reclamation, port extensions and sewage outfalls. These reasons underscore the need both of providing a sound geological education and the prosecution of meaningful research in this subject area. This paper surveys the development of geological education in Kenya and emphasises the importance of fieldwork and palaeontolgy as essential pillars upon which an effective curriculum should be built.

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## Introduction

Formal geological education in Kenya began in 1961 with the setting up of a Department of Geology within the then Royal Technical College of East Africa which had since been reconstituted into the present University of Nairobi (UoN). The Department is a constituent of the Faculty of Science within the College of Biological and Physical Sciences. At present it is the only institution that offers a dedicated geology degree course and is also the major research establishment in the country in this field. It also offers M.Sc. and Ph.D. programmes in which the interdependence of teaching and research are emphasised as essential components of scholarship.

Other Kenyan institutions where significant geology teaching and / or research are undertaken at present are the Institute of Environment and Natural Resources at Egerton University and the Kenya Polytechnic; aspects of basic geology are also taught in most secondary schools around the country under a structured school programme referred to as the 8-4-4 system. Also involved in geology research and extension services are the Ministry of Mines and Geology (MMG), the Regional Centre for Surveying, Mapping and Remote Sensing (RCSMRS) and the Department of Resource Surveys and Remote Sensing (DRSRS) of the Ministry of Planning and Economic Development. The MMG is concerned mainly with large scale geological mapping and mineral exploration of the country, but also offers extension services in analyses of geological materials. The RCSMRS provides services in the application of remote sensing and geographic information systems. The DRSRS also applies remote sensing methods in various geological, hydrological and agricultural surveys and offers internship to senior undergraduate and postgraduate geoscience students. This institution is pioneering the inauguration of space science research in Kenya. Moi University, the nation's second oldest public university has recently identified the applied geological sciences as a major area for growth within the institution and, as part of this development has appointed a committee that is urgently working on the inauguration of this faculty in the 2000 / 2001 academic year.

## Curriculum development

The undergraduate syllabus at UoN is undergoing constant review, and training is supported by a wide range of modern teaching aids and research instrumentation including audio-visual equipment, microscopes, posters, models of various chemical compounds, a seismological network and other geophysical equipment, microcomputers, a terrameter, camping and other field gear, 4-wheel drive vehicles and equipment for rock cutting, polishing and mineral separation.

The considerable strides in the earth sciences over the last three decades have largely been taken into account in shaping the present day curricula at UoN as well as the other teaching establishments in the country. As a result, these curricula now have a pretty modern outlook, which however should not obviate the need to continue addressing outstanding and fundamental questions. For instance:

**1.** Is the relative proportion of fieldwork, laboratory work and theory appropriate? It does seem that geological fieldwork in African departments generally, has been under severe pressure for some years. This pressure is partly imposed by university accountants on financial grounds and partly by the advance of the subject led by ever improving geophysical and geochemical data, manipulated and displayed by computers.

Excellent geologists are needed by any emerging nation like ours; and it should be noted that, as in every science, observations are absolutely fundamental in geology. According to Sparks (1999), the unique and defining feature of geology would always be the observation of rocks, and ability to interpret these observations in terms of Earth history, Earth structure and dynamical processes. Geological observations involve description and quantitative documentation of rocks. Much of this observation must take place in the field at a very wide range of scales : from a whole planet, to what can be observed with a hand-lens, to an electron microscope image.

Of course, there are many remote and indirect methods of observing rocks, such as satellites and seismology (Sparks 1999). However it is doubtful that such images could be interpreted usefully without the observer having first-hand experience and knowledge of geology in the field.

**2.** What is the focus and eventual goal of the curricula? Do the course contents, structure and objectives as well as the variety of first degrees match the needs of the country?

If we want to locate possible gas or oil reservoirs and exploit them efficiently, find solutions to the safe disposal of hazardous, industrial and domestic wastes, build bridges, dams and buildings that do not fall down, anticipate and mitigate geological hazards, manage water resources responsibly and understand the consequences of human activity on the Earth's environment, then Kenya and East Africa will need a supply of highly trained geologists with strong field skills and knowledge.

**3.** The study of fossils also seems to have been marginalised by the more instrumentation-based branches of Earth sciences. It should be noted that palaeontology has relevance to the global environment in the future as well as in the past. The fossil record is the only direct evidence we have of how the Earth's biota has reacted to past regional or global environmental changes. Thus the record of global change is reflected not only in modifications of communities through time, but also in the originations and adaptations of individual organisms, along with their subsequent extinction (Cocks & Culver 1996). A geologist does not have to specialise in palaeontology to appreciate the importance such key topics as the origin of life, the origin of phyla, the origin of species and the origin of *Homo sapiens*. Finally, and perhaps most importantly, all geologists must realise that the future of palaeontology is closely connected to all of our futures (Cocks & Culver 1996). Only if we strive to understand the interactions of organisms and environmental change in the past can we hope to predict and therefore adapt to anthropogenically enhanced environmental change in the future. The future of palaeontology is indeed our own future.

**4.** Now, as far as examinations and testing of students' grasp of taught courses are concerned, our observations over the past decade precipitate certain fundamental questions which ought to be addressed. What teaching methods could be adopted to best inculcate in students the capacity to tackle 'analytical type' questions? Are examination questions set, always free from ambiguities that will mislead students?

There appear to be too many 'discuss' type of questions set by examiners in geology, which students usually take to mean 'write down everything you can remember from the relevant lecture'. They don't really discuss. More 'analytical' type of questions, requiring a problem-solving approach are desirable. This should be particularly so at the postgraduate level.

Finally, we could consider re-introducing oral examinations, especially at the final year level, that would enable examiners to establish whether a candidate actually misread a question, or was just simply off-track!

### Career opportunity for graduate geologists

From 1969 up until now, there have been nearly 600 graduates of the geology programmes at UoN of whom 60-70 percent have gained employment opportunities within the Civil Service of the Kenya Government, in the Ministries of Environment and Natural Resources, Energy, Water Development, and Agriculture. The others have gone on to work with various NGO's and parastatals, including (in the case of M.Sc. and Ph.D. geology degree holders), public and private universities countrywide and abroad.

### Conclusion

Several other pertinent aspects of the teaching of geoscience at UoN have recently been ably covered in a paper by Opiyo-Akech & Barongo (1999). The authors give vivid descriptions of course contents, entry requirements, mode of teaching and assessment, and staff development issues, and no attempt has been made to duplicate these in the present review.

It is noted that curriculum review should be a continuous process with a scope for incorporating changes and making modifications promptly, in line with global developments in academia in general and the earth sciences in particular.

The main methods of field geology are still the geological map, stratigraphic logs, structural sections, descriptions and measurements of the compositions and internal structures of rocks and the relationships between rocks of different age and type. The information and understanding that comes from field-based geological observation is essential to almost any commercial activity or environmental issue where the solid Earth is in some way important. But the solution to today's fieldwork debate lies largely in the reform of geology education, rather than in complaining about lack of resources.

The future of palaeontology will continue to include its essential basic work, the description of new faunas and floras (which many African geology students tend to find rather boring). Without this foundation, however, fundamental questions regarding the history of life on this planet cannot be addressed. The information that we glean from the fossil record, therefore, will be of increasingly greater significance as we try to predict how individual organisms, populations and entire communities will react to future environmental changes.

Finally, it is observed that there is the need to encourage a problem solving approach in students as well as develop their analytical ability, especially in field situations and when tackling examination questions.

In spite of the above observations, it is believed, that the study of geology in Kenya is at the forefront and is poised towards total address of the myriad geological problems that presently confront the country as well as increasing academic excellence.

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| Documenta naturae | 136 | 21-22 | Munich 2001 |
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# Geo-Networks in East Africa - a personal view

Walter Pohl

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Why did the organisers invite me as a speaker on this occasion ? - Apart from age, present position, or accidental availability, one reason could be that in the past I had the chance to do field work in East Africa and to co-operate with a number of East African geo-scientists. Let me present a list of my former activities in the region:

- Rwanda 1972-74: Mining Geologist with the Geological Survey
- Kenya 1975, 1977-1978: Mapping and prospecting in the SE (Coastal and Mozambique belts)
- Kenya 1979: Course „Structural Methods in Geological Mapping“
- Uganda 1984: UNESCO-Geotraverse in the SW (Kibara Belt)
- Uganda 1986: UNESCO-Geotraverse (Mashonga gold)
- Kibara Belt 1987-1991: UNESCO-IGCP Project 255 „Geological Evolution and Metallogeny of the Mid-Proterozoic Kibara Belt, Africa“
- Uganda 1995-1997: Co-operation with Makerere University in „Environmental Geology of Kilembe Cu-Mines“

Why co-operate in Geo-Networks ? - The idea to invest time and resources into a large project which is beyond control of individual persons or institutions may have negative connotations, too. However, the international trend is clearly towards co-operation, so what are the advantages?

- Goals of the participating institutions may be idealistic-political, practical and financial
- Idealistic-political rewards of co-operation may be simply enjoying scientific discovery, but also rising in public perception, and influencing public decisions
- Practical rewards are strengthening of single institutions by mutual assistance, at individual scale the furthering of careers
- Financial rewards result from the possible acquisition of large, well-financed projects
- Mutual assistance can be exchange of ideas and skills, help with technologies (laboratories, equipment, software, literature...), and hosting participating scientist

How to go about forming a successful co-operation:

- Identifying an attractive project idea
- Consider seriously the interest of all potential partners, of the public, and of society
- Check project idea against the rules of the potential supporting agency
- Consider carefully the choice of the ablest project leader/manager (overall and local)
- Insist on self-driven participants

Some rules of good practice in co-operation are as follows:

- Accept the leader's role
- Trust your partners, follow rules of good scientific conduct
- Always acknowledge the source of ideas or of data not your own
- Work to established time plans, report regularly and communicate frequently
- Establish rules of authorship early in the project
- Visit your partners as often as possible

**Conclusion**

Co-operation in networks should be centred around successful research projects. This success cannot be ordered from top down. It will result from the effort of individuals who agree to work towards a common goal. For this, they must be prepared to give up part of their freedom. This will only be attractive, if the rewards are shared justly by all participants.

| Documenta naturae | 136 | 23-26 | Munich 2001 |
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# Prospects of Interdisciplinary Geo-Networks in East Africa

Andrew Muwanga

Keynote Address to the
„DAAD-Workshop on Challenges and Perspectives of Interdisciplinary Geo-Networks in East Africa",
Kampala, Uganda, 25 to 27 October 1999

**Abstract:** Geology is a relatively young department in Makerere University. It only became a fully fledged department in the Faculty of Science in August 1969. It is the only academic institution in the country that teaches geology and related disciplines, and it is also charged with spearheading research. It was considerably affected by the political and economic turmoils of the 1970s. The department was then largely manned by expatriates, and when they left there were only a few Ugandans available to take their places. The staffing has now considerably improved. This has been mede possible through training, staff exchange and other forms of cooperation with international organisations of which DAAD has been a key player. Although there has been considerable cooperation between the department and partners abroad, there has been very little interaction with sister institutions in the region. As the world is becoming a global village, there is now a great need for forgoing a closer cooperation within and outside the region by building interdisciplinary geo-networks. These will facilitate identifying of areas of joint research, coordination of teaching of geosciences within and outside the region, poling human and physical resources for optimum utilisation and promotion of the use of modern communication and information technology for easy and efficient access to information. To fulfill these efforts some support from international organisations such as DAAD and UNESCO in terms of materials and human resources is needed.

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## Introduction

I would like to take this opportunity to welcome all the invited guests and participants to this workshop and to thank DAAD for organising this important workshop, the first of its kind held in Kampala. As this may be the first encounter with most of us, allow me to briefly outline the history of the department. In terms of Makerere history, geology is a relatively young department in the university. It started as a sub-department in the Department of Geography in 1968 and only became a fully fledged department in the Faculty of Science in August 1969. It is the only academic institution in the country that teaches geology and related disciplines, and it is also charged with spearheading research.

The political and economic turmoils of the 1970s and early 1980s found it still in its infant stages and thus affected the department considerably. At the height of the crisis, the department was manned mainly by expatriates and only a few Ugandans had embarked on postgraduate training. After the expatriates had left the country, the department was transferred into the hands of young but dedicated graduates who were themselves seeking opportunities of post-graduate training. Partly because of the uncertainty then, a few of those who managed to get chances of going out for further training never returned.

The 1980s saw some improvement in the status of the department. Four lectureres have completed their doctorates, two others are almost ready. This may seem modest compared to our sister universities in the region, but it is no mean achievement for a department with the history we have gone through.

I would like he to recognise the role DAAD in particular and some other German organisations in general have played in the support of the department.

- We have had two members of staff trained in Germany - one M. Sc. candidate and one PhD, the presenter of this address.
- One technician was trained in Hannover at the BGR in the early days of the department.
- A long-term Senior Lecturer is currently sponsored by DAAD (one of the organisers of this conference). Several short-term lecturers/professors have been sponsored by DAAD at the hour of need. One of them, Prof. Dr. Walter Pohl from Braunschweig, is with us attending this workshop.
- Prof. Dr. Thomas Schlüter was in the department for six years sponsored by CIM.
- Projects are being initiated in collaboration with TU Braunschweig and University of Hamburg with the aim to achieve linkages with DFG and other organisations.
- One PhD candidate was supported by Volkswagen-Stiftung. This also included a computer donation and some accessories as well as laboratory equipment and exchange of staff from Germany.

From the foregoing, it can be seen that we have had a good interaction with our partners abroad, but it has not been the same story within the region. Possibly because of the turbulent history we have gone through, which also created a gap in academic growth between us and our sister institutions, our linkages with Kenya and Tanzania have been minimal.

In the mid 1980s, we had two staff members on training for MSc Programmes in Nairobi. It was also during the same period that the UNESCO sponsored IGCP Project on the Kibaran Belt commenced, in which geoscientists from Kenya and Tanzania participated. Apart from these activities, external examiners from the East African region were also recruited.

There is a great need to forge close cooperation within and outside the region - defined as geo-networking. We should explore areas in which we can initiate joint projects, considering that the world is becoming a global village. The most beneficial projects are those with an interdisciplinary approach.

### Potential Areas of Geo-Networking

The following are some of the areas that could be considered for networking:

- To identify projects that can be carried out jointly within a network. In Uganda, there are many geoscientific areas, which have either received little attention or where research has only recently began. From a regional/international approach the following projects may benefit:
- The interaction between the environment (groundwater, soil, etc.) and human activities (mining, industry, etc.) - this requires an interdisciplinary approach.
- The study of natural hazards such as landslides, floods, earthquakes and mitigation against them
- The identification of sites of geological interset due to their uniqueness, and seeking ways of their conservation (= geoconservation)
- The contribution of geology to agriculture (= agrogeology)
- The use of GIS in the study of various applied geoscientific problems

These are areas that require the cooperation of geologists, chemists, engineers, planners, historians, etc.

There are also some purely academic research projects which require attention, but have not been adequately carried out in Uganda. These are cross-border research areas, some of which are currently under more extensive investigation in Kenya or Tanzania. These include:

- Differentiation of the largely unknown Archaean Basement Complex in central and northern Uganda.
- A better understanding of the Neoproterozoic Mozambique Belt and the Aswa Shear Zone in eastern Uganda.

To carry out such projects and to improve teaching and research within the region, it is also necessary to critically look at the following points:

- To locate subject specilists at regional and international levels to support and coordinate projects aimed at establishing or strengthening inter-regional or international networks to reduce the gap between East Africa and other regions by solving key regional development problems in earth sciences and related disciplines.
- To identify institutions to form networking centres of excellence to respond to the most pressing needs in terms of training, research and teaching. These institutions in the region could identify specific areas of expertise in which they excel and contribute to a regional skill-sharing network. This can also involve putting laboratories in a network such that we can utilise jointly facilities within the region and reduce costs of purchasing new and expensive equipment.
- Information sharing and staff exchange to reduce costs. Student numbers have grown especially with the partial liberalisation of university education. The student population growth has not necessarily corresponded to the availability of funds. The consequence has been slashing of research funds including subscription to journals. With networking, the little available information and human resources can be pooled to have a multiplier effect on the institutions concerned. Costs could also be reduced with the availability of internet services.
- Operation of networks will inevitably require use of new information and communication technologies. The different regional institutions are at various levels of development in this area. The Department of Geology at Makerere University had in October 1999 no direct e-mail contact and no access to the internet. Much as we had to struggle to raise funds internally to achieve this goal, the hurdles were great. Using new and modern information and communication technology also enhances regional and international cooperation and cuts costs of travelling, telephone, fax, etc. This can also allow distant co-supervision of students, also reducing costs.
- This would avoid duplication where experience from projects elsewhere can be used to boost the capacity in another institution where it has not been carried out before. In Tanzania, for example, significant work has been carried out on effects of artisanal gold mining in the environment, particularly the effects of mercury, which are also of interest for us here. In Makerere, we have done some work in environmentally related problems, e. g. petrology, palynology, geochemistry of volcanic terrains, which we are ready to share with our partners in the region.

## Conclusions

On behalf of the Department of Geology, I end by thanking the organisers (DAAD) for having chosen Uganda to host this important workshop. It is my sincere hope that this workshop will come out with strong resolutions to lay a strategy for the implementation of geo-networks, which should include among others:

- To identify disciplines of cooperation and research that can link up with the geosciences.
- Coordination of teaching of geosciences research activities within and outside the region.
- To consider the conceptof regional centres of specialisation for a long-term human resource development strategy.

- To pool available manpower for efficient utilisation to avoid duplication of efforts, reduction of training costs and develop institutional capacity including staff exchange, resaerch and teaching.
- To promote the use of modern communication and information technology for easy and efficient access to information.

It is my sincere hope that we shall have fruitful deliberations and formulate resolutions that will lay the foundation of a regional geo-network.

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| Documenta naturae | 136 | 27-37 | Munich 2001 |
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# Geoscience research in Kenya

T.C. Davies[1] and Th. Schlüter[2]

**Abstract:** Recent and ongoing geoscience research in Kenya cover a wide spectrum of topics relevant to the country's development and the continued quest for solutions to the rising incidence of geo-hazards. In recent years, effort has focussed on the themes: seismology, mass-movements, volcanism and geothermal research, the impact of mining and mineral processing and the management of water resources. Most geoscience research done in the country is thus inevitably environmental. The results of these studies are contained in published works in various scientific journals or documented in unpublished works or institutional reports. The Geological Society of Kenya holds an annual conference at which results of recent geoscience research are presented and summarised in a proceedings volume. Similar conferences covering aspects of the earth sciences are also held occasionally by other institutions in the country. In this paper only a proportion of the mass of recent literature on the more important geoscience research activities is highlighted. The interdisciplinary aspects of these researches are emphasised throughout, as well as collaborative efforts with counterparts in the East African Region and elsewhere.

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## Introduction

### Geography and Physiography

The Republic of Kenya lies astride the equator on the eastern side of Africa (Fig. 1). It is bounded approximately by latitudes 5°30´N and 4°30´S by longitudes 34°00´E and 42°00´E. The population of Kenya was projected at 30 million by 1996 (Central Bureau of Statistics, 1994). Climate and vegetation are variable due to the varied relief of the country from zero to 5,000 metres in altitude. Over three quarters of the country is covered by loam soils, which are particularly well-developed in the semi-arid and desert regions. A wide variety of crops, depending on their ideal climatic and soil conditions, are grown in the different parts of the country. The economy and industry of the country are heavily dependent on tourism and agriculture. Power is largely hydroelectric but is supplemented by geothermal electric power exploited mainly in the Naivasha area.

### Geology and Stratigraphy

A summary of the geology of Kenya is given in Fig. 1. The major rock types include: the Archaean-Palaeoproterozoic granite-greenstone terrane found in western Kenya around Lake Victoria, the Neoproterozoic Kisii Group (formerly the Kisii Series), the Mozambique Belt and the Upper Palaeozoic to Mesozoic Karoo sediments of coastal and northeastern Kenya.

Younger rocks are represented by Tertiary and Quaternary sediments in eastern Kenya and the coastal strip bordering the Indian Ocean. A generalised succession of these major rock types is indicated in Tab. 1. A number of poorly resolved stratigraphic and structural relationships are currently being researched by among others, one of the research groups at UoN, the 'Committee on Kenya's Stratigraphy and Nomenclature' under the leadership of Dr. D.W. Ichang'i. Collaborative studies between another of the UoN's research groups and other overseas institutions, notably in Tanzania, Germany, the U.S. and Japan are aimed at unravelling the structure and evolution of the Mozambique Belt (e.g. Mathu, 1992; Nyamai et al., 1993; Hetzel & Strecker, 1994, etc.)

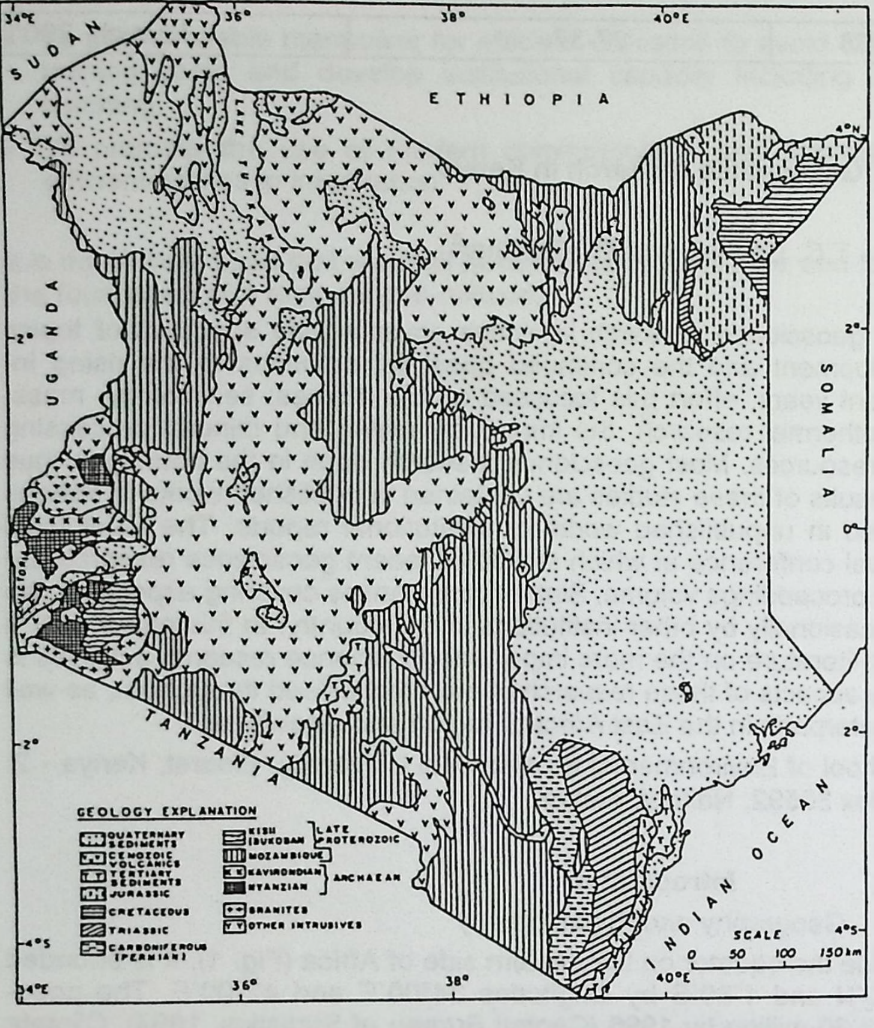


**Fig. 1:** Simplified geological map of Kenya showing the major rock units (modified from EAEP Limited, 1991).

| Era | Rock formations | Age | Major rock types |
|---|---|---|---|
| Cenozoic | Oloronga Beds<br>High Magadi Beds | Quaternary sediments | clays, diatomites, shales, silts |
| | Magarini Beds | | |
| | Fundi Isha Beds<br>Faratumu Beds | Tertiary sediments | sands, marls, clays, conglomerates, limestones |
| | East African Rift System lavas and pyroclastic flows | Tertiary and Quaternary | basalts, phonolites, trachytes, nephelinites, tuffs, agglomerates |
| Mesozoic | Maheran Series | Upper Cretaceous | siltstones, sandstones, limestones, shales |
| | Mandera Beds<br>Mazeras sandstones | Jurassic | coarse grits, feldspathic sandstone, sandy shales |
| | Mariakani sandstones<br>Maji ya Chumvi Beds | Permo-Triassic | flaggy sandstones (fine-grained), micaceous shales, mudstone, shales, sandstones |
| Palaeozoic | Taru grits | Carbo-Permian (?) | grits, shales |
| | Lower Palaeozoic is not represented | | |
| Precambrian | Mozambique Belt | Neoproterozoic (~0.75-0.45 Ga) | schists, gneisses, marble, amphibolites, migmatites, granitoid gneisses |
| | Kisii Series (the Bukoban) | Neoproterozoic (~1.0-0.8 Ga) | rhyolites, basalts, quartzites, conglomerates |
| | Mumias, Maragoli, Oyugis, Wanjare granites | Palaeoproterozoic (~1.8-2.4 Ga) | granites, granodiorites, leucogranites |
| | Kavirondian Group (formerly System) | Archaean (~2.5-2.8 Ga) | shales, mudstones, greywackes, phyllites, conglomerates |
| | Nyanzian Group (formerly System) | Archaean (~2.8-3.1 Ga) | basalts, andesites, dacites, agglomerates, andesitic tuffs, rhyolites |

**Tab. 1.** Generalised sequence of the geology of Kenya.

Modified from Cole (1950), Haughton (1963), Saggerson (1972) and Cannon et al. (1981).

## Seismology

Kenya is a country of high seismicity, with most activity centred along the Kenya Rift which runs north-south through central Kenya; but there is a network of other faults of high seismic potential (Dindi, 1994). Two strong events, one in Subukia in 1928 and the other in Homa Bay in 1965, both on the western Rift Valley, underscore the need for accurate seismic monitoring.

**Tab. 2.** Location and operation times of stations within the University of Nairobi seismic network Source : Hollnack (1996).

| Name | Code | Working Period | Latitude | Longitude | Elevation (m) |
|---|---|---|---|---|---|
| Nairobi | NAI | since 1963 | 1.274 S | 36.804 E | 1692 |
| Langata | LAN | Feb 94-Jan 95 | 1.377 S | 36.773 E | 1707 |
| Magadi | MAG | since Feb 94 | 1.918 S | 36.287 E | 660 |
| Kibwezi | KIB | Apr 94-Aug 94 since Jun 96 | 2.340 S | 38.046 E | 775 |
| Olkaria | OLK | Mar 95-Nov 96 | 0.888 S | 36.324 E | 1751 |
| Olkaria West | OLW | since Nov 96 | 0.886 S | 36.264 E | 1780 |
| Kilima Mbogo | KMBO | since Sep 95 | 1.135 S | 37.234 E | 1950 |

## The KRISP International Seismic Project

It is no surprise that among the Department of Geology's (UoN) research projects, that of seismology is the main one comprising largely of the Kenya Rift International Seismic Project (KRISP). This project was begun in 1990, although continuous observation of the seismic activity in the country started way back in 1963, when one of the World Wide Standardised Seismograph Networks (WWSSN) was installed in Nairobi. The KRISP was inaugurated through an agreement of cooperation between UoN and the University of Karlsruhe, Germany and is mainly funded by the GeoForschungsZentrum (GTZ) of Potsdam, Germany, with UoN providing personnel and office facilities.

The field campaigns of KRISP were conducted in 1985, 1989-1990 and 1993-1995, and were divided into refraction seismic experiments and temporary established earthquake networks. The main results of these investigations are given in KRISP Working Party (1991), Achauer et al. (1994), Keller et al. (1994), Prodehl et al. (1997) and Hollnack & Stangl (1998). The initial experiments indicated that the magnitude and extent of seismicity in Kenya was much greater than was previously indicated when the WWSSN was the only work station in use. The KRISP therefore sought the acquisition of a permanent seismological network. By 1996, a data centre and five digital portable seismograph systems of the MARS-88type (Lennartz Electronics) had been established (Hollnack & Stangl, 1998; see Tab. 2). The old WWWSSN station has also been updated with a modern IRIS / GEOFON system in 1995. Under the project it is envisaged that more stations will be installed to cover a larger area of the country.

The International Programme for Physical Sciences (IPPS) of Uppsala University has also been supporting the seismological activities at UoN for many years. The support has been mainly in the form of training of staff and technicians attached to this project. The Geology Department at UoN also has links with the University of Cape Town, South Africa, in the field of training and research in seismology. The International Global - Biosphere Programme (IGBP-START) Secretariat and the Regional Office of the Global Seismic Hazard Assessment Programme (GSHAP) are also based within the Department.

In 1997, the Geology Department (UoN) hosted and jointly organised the First Regional International Training Course on Seismology and Seismic Hazard Assessment with the (GFZ). The major topics of this course were prediction research on earthquakes and volcanic eruptions, collection of first-hand data about damages, vulnerability, aftershocks or post-event activity and seismotectonic conditions.

## Monitoring and Seismic Impact Mitigation

Seismic research to date has focussed on seismic monitoring which has contributed to the establishment of the seismological network (op. cit.). Since 1996, therefore, a continuous and complete observation of the seismic activity in Kenya and adjacent areas became possible. As the network continues to be improved, the formulation of possible methods of earthquake prediction and the setting up of early warning systems would become a reality. Monitoring so far has included cataloguing, identification of possible indicators, modelling, and the construction of hazard potential maps. Refraction experiments performed along and across the Rift have greatly improved the local crustal velocity models. Once the reconfiguration and extension of the national seismological network is completed, a more accurate location of earthquake epicentres would be possible.

Background information on the distribution of earthquakes, mechanisms and mode of energy release, earthquake quantification and the negative effects of earthquakes are important if the impact of earthquakes in our everyday lives is to be fully appreciated. Accurate monitoring of earthquakes enables parameters such as maximum ground accelerations and magnitudes to be determined. These parameters can then be used for seismic zoning purposes and the preparation of seismic hazard maps, which are useful for the enforcement of legislation on earthquake resistant structures as well as for raising the level of preparedness for possible major events in the future. The existing building code although useful, was based on information on felt earthquakes rather than on instrumental data and is hence rather subjective and of limited reliability. This code is in the process of revision based on the extended instrumental data network recently acquired by the KRISP team. With the great dedication displayed by this team in nearly a decade of seismic research, great strides will continue to be made in addressing other outstanding concerns in seismology in Kenya.

### Water quality and management of water resources

About 83 percent of the country falls within arid and semi-arid lands (ASAL). An important question in water management therefore is: are we optimising the use of the limited supply of ground- and surface water for domestic, industrial, agricultural and other uses? Some aspects of the hydrochemistry of Kenyan waters have already being researched and documented (e.g. Gaciri & Davies, 1993; Davies, 1996a) but there is still the need for further surveillance and testing of water management strategies.

Since the quality of our water supplies has direct and major implications for human health, the urgency of adopting practical guidelines for protecting water supplies from various pollutants cannot be over-emphasised. Undesirable impacts on the country's water resources are due mainly to anthropogenic causes, including improper waste disposal, mining and mineral proceesing (e.g. Davies 1994; Ogola, in press) agricultural activities, industrial emissions (sugar, paper, coffee, leather industries, etc.) and these issues are now being addressed (e.g. Ngecu & Gaciri 1999). The impact of solid waste disposal on the water resources of the City of Nairobi is the subject of an ongoing European Union funded research project by a team from the School of Evironmental Studies (SES), Moi University working together with some overseas counterparts (Davies et al., 1998).

One should not also overlook the possible health impacts of abnormal concentrations of trace elements and other chemical species arising from natural geochemical processes. In this connection, mention could be made of high fluoride waters in and around the Rift valley resulting from the hydrogen fluoride volcanism accompanying Rift formation (e.g. Gaciri & Davies, 1993), researches by Mustapha et al. (1999) on radon occurrences in the country, and a recent collaborative effort between SES, the TH Huxley School, Imperial College and the Technical University of Berlin in studying the distribution of arsenic in the groundwater system of western Kenya in relation to geology, nutritional status and epidemiology of arsenicosis.

### Geothermal energy research in Kenya

Geothermal energy for electricity generation is likely to become increasingly important in Kenya in the future. Numerous centres of thermal activity exist in the country, particularly within the Rift valley, but aridity and, consequently, unavailability of water is a constraint to development of large-scale natural hydrothermal systems (Tole, 1996).

Geothermal resources in the islands of Lake Turkana, and those close to other Rift lakes are currently being investigated for their exploitative potential as they do not suffer from the constraints of water shortage (Dunkley et al., 1993). Research carried out on the Olkaria fields to date (e.g. Tole, 1990) shows that environmental problems can be adequately addressed, though constant monitoring is necessary. Hydrogen sulphide emissions preclude the setting up of permanent residences within a 5-km radius of geothermal power stations. Trace elements and radiation from geothermal fluids need to be monitored with respect to their impacts on plants and animals. Impacts on the local hydrology also require close observation. Multistage uses of goethermal fluids will greatly increase the benefits derived from this resource.

Tole (in press) has also been assessing the potential of Kenya's geothermal energy resources for other uses apart from electricity generation. Local inhabitants for instance go to worship and offer sacrifices at geothermal sites, particularly when afflicted with ailments that are difficult to cure. At Lake Bogoria Hotel for instance, natural hot water is directed towards a swimming pool, in which tourists often bathe to cure some of their ailments. Such curative properties are highly valued in several countries including Iceland and China. Tole (in press) argues that Kenya should develop its geothermal systems for balneological uses in order to bolster tourism, and enhance the health of its people.

**Mining and mineral processing**

Exploitation of geological resources is widespread in the country and includes quarrying of dimension and ornamental stones, mining of industrial minerals such as fluorite, evaporites (soda ash, trona, gypsum) as well as gemstones and aggregates (Mathu, pers. comm.). Much of the research and exploration however, is for metallic minerals yielded by the Nyanza greenstone belt (e.g. Pickford 1982), where the Migori segment for instance, reveals massive sulphide deposits in close proximity to the Macalder and Lolgorien volcanic centres, and gold mineralisation throughout the belt (Ogola, 1987; Ichang'i & MacLean, 1991; Ngecu, 1993).

The potential for petroleum deposits lies in the sedimentary formations of the coast and offshore, as well as in northeastern Kenya. Recent press coverage was given to exploration work for oil, commissioned by the Kenya Government but the results are yet to be publicised.

Much of the research carried out to date on mining and mineral processing by the UoN and other institutions in the country has centred on environmental impacts. The effects of fluorite mining on the waterways of the Kerio Valley area of western Kenya is reviewed by Gaciri & Davies (1993) & Davies (1994). Other studies have included the effect of dust produced during processing of diatomite at Kariandusi near Gilgil in Central Kenya and asbestos (Davies, 1996b), the pollution of waterways and the atmosphere by Hg, which is used for amalgamating gold in the alluvial gold workings in the Greenstone Belt of western Kenya (Ogola, in press), and the effect of escaped volatiles and spent liquor in the processing of trona at Lake Magadi.

**Mass movements**

Most research on mass movements in Kenya have been in the areas of landslides and soil erosion. The majority of slides, it seems are the result of a combination of factors, the most important of which are, steep topography, a volcanic soil type of high sorption capacity and unacceptable land-use practices; but the immediate trigger has always been heavy rains. Davies (1996c), Ngecu & Mathu (in press) and Ngecu et al. (in press) have summarised much of the documented studies in this field. The effects of landslides to the Kenyan economy is enormous and include deaths of humans and animals, and destruction of fertile farmlands and infrastructure (Davies & Nyambok, 1993).

Kenya's soil erosion problems are aggravated by a semi-arid climate over much of its interior, the cutting of forests for fuelwood and charcoal-making, and poor land management and agricultural practices. Soil erosion increases from higher surface runoff and surface exposure, filling rivers with sediments.

Recent researches on soil conservation in Kenya include the works of Hedfors (1981), who gave an evaluation and economic appraisal of soil conservation and Okeefe, (1983), who considered the causes, consequences and remedies of soil conservation in Kenya. Fahlen (1985) presented an evaluation of soil conservation practices in Nyeri District, whereas Mbegera et al. (1992) focussed on training and extension in soil and water conservation.

Data accrued up to 1986 were reviewed at a Workshop held that year on 'Soil and Water Conservation in Kenya' (Thomas et al., 1986). Kilewe et al. (1989) are considering the role of agroforestry practices in soil erosion and conservation.

In November, 1992, the African Academy of Sciences in collaboration with the Ugandan Council of Science and Technology organised an international workshop in Kampala, Uganda, on 'Capacity Building in Soil and Water Management and Forestry Research in Africa'. The 1992 Workshop brought together African scientists with different levels of experience of academic life in different fields of soil and water research and agroclimatic zones for vital vertical and horizontal interaction.

## Flooding

Flooding can be looked at from the geoscientific point of view. It is a subject that is still underesearched in Kenya, but one that should be of great concern, especially because it can lead to an array of water-related and communicable diseases. Among the important documented studies on flooding in Kenya are the works of Obuodha (1975) and Krhoda (1992), who described the hydrology and flood management strategies in the City of Nairobi.

In 1990, the Kenyan Government, under the auspices of the Ministry of Housing and supported by other public institutions, held a symposium in Eldoret on 'Natural Disasters and Disaster Management', in which the subject of flooding was a key issue on the agenda. It was clear from the proceedings of this meeting that the rising frequency of flood hazards in the country calls for a re-assessment of riparian policies, especially with regard to flood-resistant design to avoid or minimise exposure to floods.

## Medical geology

Geomedical research in Kenya, as in other developing countries, is still in its infancy, although a significant amount of data already exists in certain aspects of the subject. The biggest advances to date have been with the halogens, fluorine and iodine but data interpretation and identification of meaningful correlations between geochemistry and epidemiology are hampered by the use of non-multidisciplinary approaches (Davies, 1996b).

To emphasise the effectiveness of the interdisciplinary approach as well as review recent advances in this important subject area, the first 'East and Southern Africa Regional Workshop on Geomedicine' was convened in Nairobi in June, 1999. Significant data were presented among others, on the occurrence of radon in Kenya and its health implications, and the health consequences of geophagy, a phenomenon believed to be widely practised by pregnant women in Kenya.

Additional information is needed on the behaviour of certain nutritional and toxic elements in various environmental media (soils, plants, natural waters and sediments). Indeed, one of the resolutions of the above-mentioned Workshop was an advocacy for further research on speciation, bioaccessibility and bioavailability of trace elements in soils, plant materials, and in humans and animals (Davies & Schlüter, in press).

## The International Decade of the East African Lakes

The International Decade of the East African Lakes (IDEAL) is a ten-year international programme of research on the large lakes of the East African Rift Valley. The Rift Valley lakes are among the oldest on Earth and are vital resources for East Africa.

The IDEAL programme was formulated in Bern, Switzerland, in 1990 and is now reaching its terminal stages (Johnson & Odada, 1996). The primary goals of the project are: (i) to obtain long, high resolution records of climatic change in tropical East Africa; and (ii) to provide a comprehensive training programme for African students and scientists that will result in collaborative efforts between African and northern hemisphere limnologists and palaeolimatoogists; and provide the scientific infrastructure within East Africa to carry on the proper monitoring and guardianship of the East African lakes after the termination of IDEAL.

Several valid and exciting aspects of research on the large East African lakes are recognised, such as trends in variation of mineral composition, e.g. Schlüter (1993), but the main focus of the IDEAL project is on the study of the lakes as archives of environmental and climatic dynamics. With an increased understanding of how large lakes at low latitudes respond to climatic forcing, it should be possible to decipher the long records of climatic variability stored in the sediments of these complex natural systems. These records it is hoped, will make a major contribution to the study of global climatic change.

### Remote sensing and geographic information systems

In Kenya, these technologies continue to be applied in various disciplines such as forestry, agriculture, hydrology and environmental geology, and important contributions are already being made especially in the domains of natural resources management and environmental monitoring (Legge; pers comm.). Based on remote sensing techniques, Gaciri (1992) has attempted the generation of a lineation map of the country by drawing up a correlation between lineaments and known geological data.

The Regional Centre for Surveying, Mapping and Remote Sensing is fully fitted with facilities for the collection and processing of remotely sensed data and runs occasional courses targeted at environmental educators and certain extension officers from the government ministries. The SES at Moi University, similarly runs programmes in remote sensing and GIS at both M.Phil. and D.Phil. levels and will soon start a diploma programme in environmental information systems for extension workers and government officers.

### Environmental impact assessment

Issues related to land and water are at the forefront of the country's development goals. On account of the value of these resources, the assessment of the impact on them of constructional activities related to various projects now constitutes a crucial dimension of the government's environmental policy.

The National Environment Secretariat (NES) was set up in 1974 in the context of Kenya's preparation for the United Nations Conference on the Human Environment. The emergence and development of NES is detailed in Hirji & Ortolano (1991). During the late 1970's, NES began to promote successfully a national environmental impact assessment (EIA) requirement that was intended to apply to all major projects, both public and private.

The key to NES's success in implementing EIA requirements was its ability to use the legislatively based authorities and sactions to force project proponents to conduct EIA. A good illustration of how NES influenced a major private undertaking is that of the Leather Industries of Kenya, one of the first projects to come under EIA requirements. A full account of the environmental impact statement is given in Hirji & Ortolano (1991). Other documented accounts of EIA conducted as a means of monitoring the behaviour and amounts of water and air pollutants from mining, industrial and waste disposal activities include those of Sakari (1990), Davies (1993, 1994), Masibo (1993) and Owuor (1993). A project to be launched shortly on the environmental impact of vehicular lead emissions in the City of Nairobi, is being developed by SES, Moi University and the British Geological Survey, with funding from DFID. Another European Union project on the development of guidelines for the investigation, evaluation and reduction of environmental problems caused by mining sites in western Kenya is due to be launched in January of the year 2001, as a collabrative effort between the Kühn Environmental Consultancy in Germany, Makerere University and Moi University.

### Palaeontology

Although palaeontology, as subject tends to be squeezed within the confines of the geology degree structure of African geology departments for various reasons (see Davies, this volume), research in the subject nevertheless has a bright future in Kenya. In this connection, mention could be made of the eminent contributions of Martin Pickford and Mary Leakey (National Museums of Kenya) over the last two decades on fossil preservation in the Nyanza Rift (e.g. Pickford, 1984; 1986) and Northern Kenya, and those of Maitima on pollen analysis in the central Rift Valley (e.g. Maitima, 1988), among several others.

Microfossils have taken centre stage in the part of modern palaeontology research because many of them have evolved at high rates and because only they can be recovered in great abundance from the small chips of the average exploration well. The National Oil Corporation of Kenya (NOC) as well as foreign exploration consortiums assessing the petroleum potential in offshore and northern Kenya are employing micropalaeontology in their work. Another nearby example is the use of fossil diatoms in working out the palaeolimnology of Lake Rukwa in Southwest Tanzania (Haberyan, 1987), where a 23.1 m sediment core from the lake records 13,000 years of climatic change in five diatom assemblage zones.

## Conclusion

In Kenya, geoscience research mainly involves the examination of interaction between geological processes and the natural environment, including seismicity, continental rifting, geothermal energy development, mineralisation and mining impacts, landslides, soil erosion, and reactions within the hydrological system to provide clues for proper water resources management. This is in response to the global call for environmental protection and the need for averting future geo-hazards of the kinds we have witnessed in the country over the last few years. Useful palaeontological work is also going on at institutions outside the universities.

Must of the geoscience research carried out in Kenya is quite rightly interdisciplinary, involving collaboration between Kenyan geoscientists and their counterparts in the region and farther afield. We continue to see the tremendous opportunity for East African geologists to work within interdisciplinary scientific projects, as was revealed in recent seminars in Nairobi, such as the 'International Geosphere / Biosphere Meeting', 'Workshop on Conservation of Geological Sites in East Africa' and the 'East and Southern Africa Regional Workshop on Geomedicine'. It is surely only a matter of time before there is a similar growth in researches that span the wide gap between the geosciences and humanities in universities.

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| Documenta naturae | 136 | 39-49 | Munich 2001 |
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# Geological Heritage in East Africa - its Protection and Conservation

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**Abstract:** In contrast to Europe and North America, where geologically significant monuments, i. e. natural sites (= geosites) and rare and valuable specimens - fossils, minerals, meteorites, etc. - are often already under active protection and conservation, geoconservation in Africa has a generally poor record. A first workshop on „Geosites and Geoconservation in East Africa" was therefore organized and held in Nairobi in February 1999, with the aim to sensitize participants from various geological institutions in the region on the subject and to prepare an inventory of those sites that are in urgent need for protection and conservation. A list of the most important geosites as presented by the participants of the workshop is here given.

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## Introduction

UNESCO's Division of Earth Sciences provides its 186 Member States with support in the areas of sustainable management and development of the Earth's mineral and energy resources, hazard mitigation and the safeguarding of monuments. The Division's annual regular budget of US $ 1.1 million in the year 2000 covers, among other things, international co-operation in geoscience, and research and training programmes. As a logical extension of existing national and international initiatives for the conservation of nature, UNESCO has decided to launch the Geopark Programme, with the aim to protect and conserve the geological heritage of selected monuments and areas. In addition to expertise in the field of pure and applied academic earth sciences, the organization places at the programme's disposal its world-wide scientific and political network, and the fruit of 50 years of public relations. Although measures to protect our environment are not lacking, few of these recognize the value of conserving the environment's memory inscribed in the rocks and landscapes we have come to acknowledge as our geological heritage. In response to the perceived need, UNESCO has adopted a new policy whereby enhancing the value of sites that are key witnesses to the Earth's history goes hand in hand with the creation of employment and local economic development (Eder & Patzak, 1999).

## Geoconservation in the East African Context

On the African continent it is only South Africa where the Conservation and Environment Committee of the Geological Society of SouthAfrica has worked towards the protection of important geological sites (= geosites) (Viljoen & Reimold, 1999). Most African countries contain innumerable geological sites that deserve not only attention but full protection. However, efforts yet done are not very promising. In East Africa - here defined to include Kenya, Tanzania and Uganda - some of its geological monuments are already covered by protection, either as national monuments (e. g. Mbozi Meteorite in Tanzania and Olorgesaillie Prehistoric Site in Kenya), as part of nature or game reserves (e. g. Olkaria Volcanic Field being part of Hell's Gate National Park in Kenya), or as World Heritage Sites (e. g. Ngorongoro Crater in Tanzania). Some of the potential geosites are not specifically protected but still in quite good condition. Others have already been threatened by deterioration or are at least strongly endangered. The vast majority of potential geosites is for the public, however, completely unknown.

Since 1996 the International Union of Geological Sciences (IUGS) and UNESCO have been sponsoring the global GEOSITES project (Wimbledon, 1996, Wimbledon et al., in press). This is currently focused mainly in Europe, where an active European Association of geoconservationists has been operating and organizing annual conferences and workshops and publishing brochures. GEOSITES is aimed at compiling a global inventory of important geological sites of both scenic and scientific value. This includes both unique/remarkable sites (for instance Laetoli Fossil Site with its 3.6 Ma old hominid footprints would be unique) and typical sites (for instance stratotype exposures, which are representatives of individual formations, e. g. Ngong Escarpment with its strongly alkaline lavas). In order to implement the above mentioned concepts and aims of geoconservation, the first international workshop on "Geosites and Geoconservation in East Africa" was organized by the National Museums of Kenya (NMK), in co-operation, with technical assistance and financial support from UNESCO. This workshop took place at NMK Headquarters in Nairobi from 18-19 February 1999. Resource people were drawn from relevant academic institutions in East Africa that are concerned with geoscientific research, exploration, exploitation and conservation. These included the National Museums, University Departments of Geology and Geological Surveys and Mines Departments of Kenya, Tanzania and Uganda. Altogether about 40 participants from Kenya, Tanzania, Uganda and Somalia attended the technical sessions of the workshop and after lengthy deliberations the following resolution was adopted by the plenum of the workshop:

It is noted that the concept of geoconservation as outlined by the International Union of Geological Sciences (IUGS) is of great significance for the protection of unique geological monuments, and should therefore be implemented in East Africa. This task should be left to specialists in the respective countries of East Africa. It is recommended that National Geosites Committees should be formed, composed of representatives of the respective Geological Surveys and Mines Departments, the Departments of Geology of the respective universities, the National Museums and Antiquities Departments of Kenya, Tanzania and Uganda, under consultation of Wildlife Organizations and other relevant bodies. The aims and tasks of these national committees will be to identify geosites in the respective countries that conform to the accepted international criteria of nominating geosites. The national governments, through the National Committees, should be responsible for funding during the process of identification and conservation of identified geosites in the respective countries.

### Short outline of the tectono-stratigraphic history of East Africa

The regional geology and stratigraphy of East Africa can be broadly subdivided into the Precambrian history, for which diagnostic fossils are not available, and the Phanerozoic history, datable by fossil or isotopic means. The Precambrian of East Africa is composed of rocks of igneous, sedimentary and metamorphic origin, which vary in age from Paleoarchean to Neoproterozoic. Generally the Paleoarchean nuclei incorporate Neoarchean greenstone belts, both of these assemblages being surrounded by Paleo-, Meso- and Neoproterozoic mobile belts of various grade of metamorphism. The ancient cratons representing the early sialic crust are recognizable by their stability and lack of involvement in tectonothermal events during the last 2500 Ma. The Tanzania Craton and the Gneissic-Granulitic Complex in Uganda are of Paleoarchean age, representing continental crust during the development of the Nyanzian and Kavirondian Greenstone Belts of Neoarchean age. Both the original cratons and the greenstone belts acted as cratonic area during the development of younger, ensialic mobile belts such as the Paleoproterozoic Ruwenzori Fold Belt and the Mesoproterozoic Kibaran Belt. Other Paleoproterozoic mobile belts along the Tanzania Craton are named Ubendian and Usagaran Belt, respectively. The highly metamorphic and deeply eroded Neoproterozoic Mozambique Belt trends N-S through Tanzania and Kenya and a marginal portion of NE Uganda. This belt exposes migmatitic gneisses, amphibolite-facies metasediments and sometimes granulite-facies rocks. A number of well-authenticated ophiolites are known. The Neoproterozoic Bukoban System rests partly on the Tanzania Craton and exhibits predominantly sedimentary rocks, sometimes containing stromatolites (Schlüter et al., 1996).

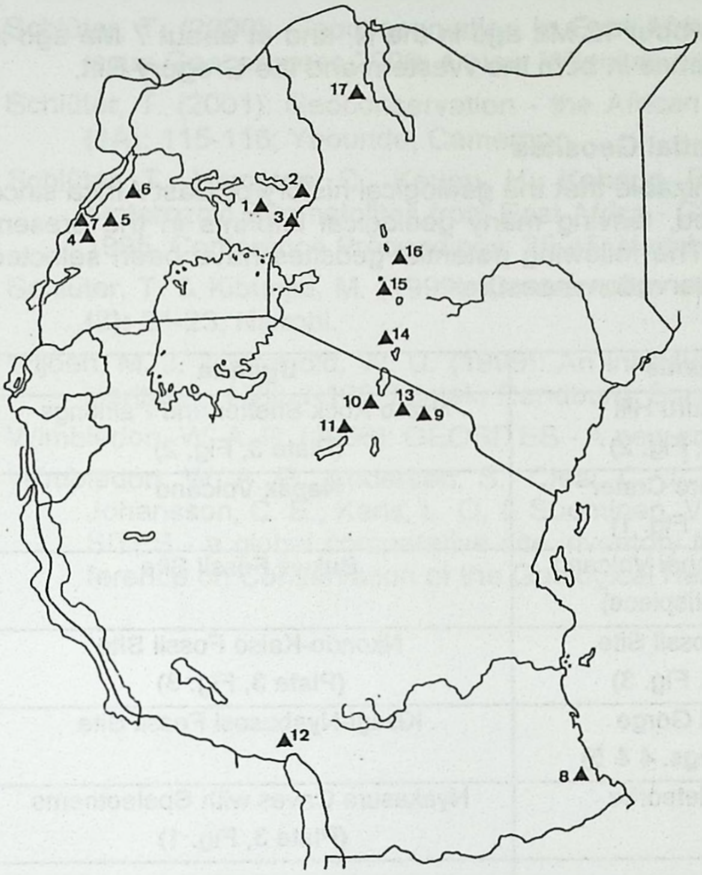


**Fig. 1:** Locality map of proposed geosites in East Africa. **1:** Nyero Rock Shelter and Paintings, **2:** Napak Volcano, **3:** Bukwa Fossil Site, **4:** Nkondo-Kaiso Fossil Site, **5:** Kisegi-Nyabusosi Fossil Site, **6:** Nyakasuro Caves with stalactites and stalagmites formed by carbonatites, **7:** Kibiro Hotsprings with travertine and sulphurous fumes, **8:** Tendaguru Dinosaur Hill of late Jurassic age, **9:** Ngorongoro Crater, **10:** Oldoinyo Lengai, the only active volcano with carbonatitic lava composition, **11:** Laetoli Fossil Site, **12:** Mbozi Meteorite, **13:** The Olduvai Gorge, **14:** Magadi-Natron Basin, including Olorgesaillie Fossil Site, **15:** Nakuru-Naivasha area, including Suswa and Longonot Volcanoes and the Lake Naivasha Geothermal Field, **16:** Maralal-Baragoi Area with Precambrian rocks of the Mozambique Belt, **17:** Lothagam Fossil Site with exceptional mammalian and hominid fossils of Pliocene age.

There is no evidence of Cambrian, Ordovician, Silurian and Devonian rocks in East Africa. The subsequent sedimentary units of the Upper Carboniferous to Triassic depositional megacycle are in Africa collectively referred to as Karoo deposits (Karoo Supergroup). In East Africa the Karoo basins extend in a NNE-SSW direction from Mozambique in the S to Kenya in the N. The Ruhuhu Basin, the Luwegu Basin and the Mombasa Basin are the most prominent units of the Karoo Supergroup. Smaller troughs occur as remnants along the NW-SE trending graben system of Lake Rukwa in Tanzania, and a few others are embedded in the Palaeoproterozoic Buganda-Toro System of southern Uganda. Widespread tillites at the base of the Karoo rocks indicate a glaciation that occurred from late Carboniferous to early Permian.

The cover of predominantly marine formations was initiated by a transgression of the sea that took place from Lower to Middle Jurassic times. No prominent tectonic event heralded this transgression. Only minor unconformities are present in NE Kenya between the Triassic succession and the Middle to Upper Jurassic limestones. This sequence was deposited on a continental margin, which was of low relief and was steadily tilted and possibly warped. Subsequent marine deposits of Cretaceous, Tertiary and Quaternary age are often well developed along the coast of Kenya and Tanzania.

The volcanically and seismically active East African Rift System lies atop a broad intracontinental swell, the East African Plateau, and consists of two branches, the Western Rift and the Gregory or Kenya Rift. These two rift valleys are in general infilled by sediments and water bodies. Volcanism is widespread and the tectonic structures are similar regardless of the nature of the infill. The Gregory Rift is preferentially located around the Tanzania Craton margin, following the trend of the Neoproterozoic Mozambique Belt. However, each graben sector of the Gregory Rift shows a different tectonic and magmatic history, and there have been problems in interpreting correctly the complexly interacting sequences of faulting, uplifting, volcanism and sedimentation at these local levels. Apparently the rift development was propagated from N to S. The Gregory Rift was initiated around Lake Turkana about 33 Ma ago and major faulting began in the central part of the rift at about 16 Ma ago. In the southern part of the rift, volcanism commenced at ca 15 Ma ago, and rifting followed at about 10 Ma. During rift evolution, volcanism tended to migrate towards the axial zone and the mafic eruptives became more silica-saturated. In the Western or

Kenya Rift, initial volcanism commenced at about 12 Ma ago in the N, and at about 7 Ma ago in the S. Volcanic activity continues to historic times in both the Western and the Gregory Rift.

## Potential Geosites

From the previous chapter it is clearly recognizable that the geological history of East Africa since early Precambrian times was very diversified, leaving many geological imprints in the present landscape that urgently need preservation. The following potential geosites have been selected and proposed as primary targets for geoconservation measures:

| Kenya | Tanzania | Uganda |
|---|---|---|
| Ngong Escarpment (Plate 1, Fig. 1) | Tendaguru Hill (Plate 2, Fig. 2) | Nyero Rock Shelter and Paintings (Plate 3, Fig. 2) |
| Olorgesaillie Prehistoric Site (Plate 1, Fig. 2) | Ngorongoro Crater (Plate 2, Fig. 1) | Napak Volcano |
| Lake Magadi Basin (Plate 1, Fig. 5) | Oldoinyo Lengai Volcano (see frontispiece) | Bukwa Fossil Site |
| Lake Naivasha Basin (Plate 1, Fig. 3) | Laetoli Fossil Site (Plate 2, Fig. 3) | Nkondo-Kaiso Fossil Site (Plate 3, Fig. 3) |
| Longonot Volcano | Olduvai Gorge (Plate 2, Figs. 4 & 5) | Kisegi-Nyabusosi Fossil Site |
| Olkaria Volcanic Field (Plate 1, Fig. 4) | Mbozi Meteorite | Nyakasura Caves with Speleothems (Plate 3, Fig. 1) |
| Menengai Crater | | |
| Siambu Ophiolite Complex | | |
| Lothagam Fossil Site | | |

## Conclusion

There is around the world now a broad public awareness of the necessity for the conservation of nature. Reports about air and water pollution, soil degradation, disappearing rain forests and the extinction of species have increased our perception of the urgency of conserving the natural environment. The need to conserve natural resources and biodiversity is now generally accepted. However, it is less obvious to many people that conservation of geological features is of similar importance. The prevalent notion that these features are inherently robust, less vulnerable to destruction and therefore not threatened, is not true. A geological monument is an asset that, once lost, cannot be replaced. Additionally, as well as being a fundamental part of the natural world, geological monuments and landforms have had a profound influence on society and civilization, and continue to do so. Our use of the land, for agriculture, forestry, mining, quarrying and for building homes and cities is intimately related to the underlying rocks, soils and landforms.

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**Plate 1:** Potential geosites in Kenya

**1:** View to the Ngong Hills

**2:** Olorgesaillie Fossil Site with large stone tools

**3:** View to Lake Naivasha

**4:** Olkaria geothermal Field

**5:** View to Lake Magadi

**6:** Participants of the workshop on "Geosites and Geoconservation", being held in Nairobi in February 1999.

**Plate 2:** Potential geosites in Tanzania

**1:** Ngorongoro Crater

**2:** A mounted brachiosaur from Tendaguru, exhibited in the Museum of Natural History, Berlin

**3:** Mary Leakey observing excavations at Laetoli

**4:** View to Olduvai Gorge

**5:** Skull of *Australopithecus* ("*Zinjanthropus*") *boisei* from Olduvai Gorge.

**Plate 3:** Potential geosites and geoscietific monuments in Uganda

**1:** Nyakasura Caves with a large stalacmite

**2:** Nyero Rock Shelter with Paintings

**3:** Kisegi-Nyabusosi Fossil Site

**4:** Sipi Falls in Kapchorwa District in eastern Uganda (not mentioned in text)

**5:** Murchison Falls at Lake Albert in western Uganda (not mentioned in text).

## Plate I

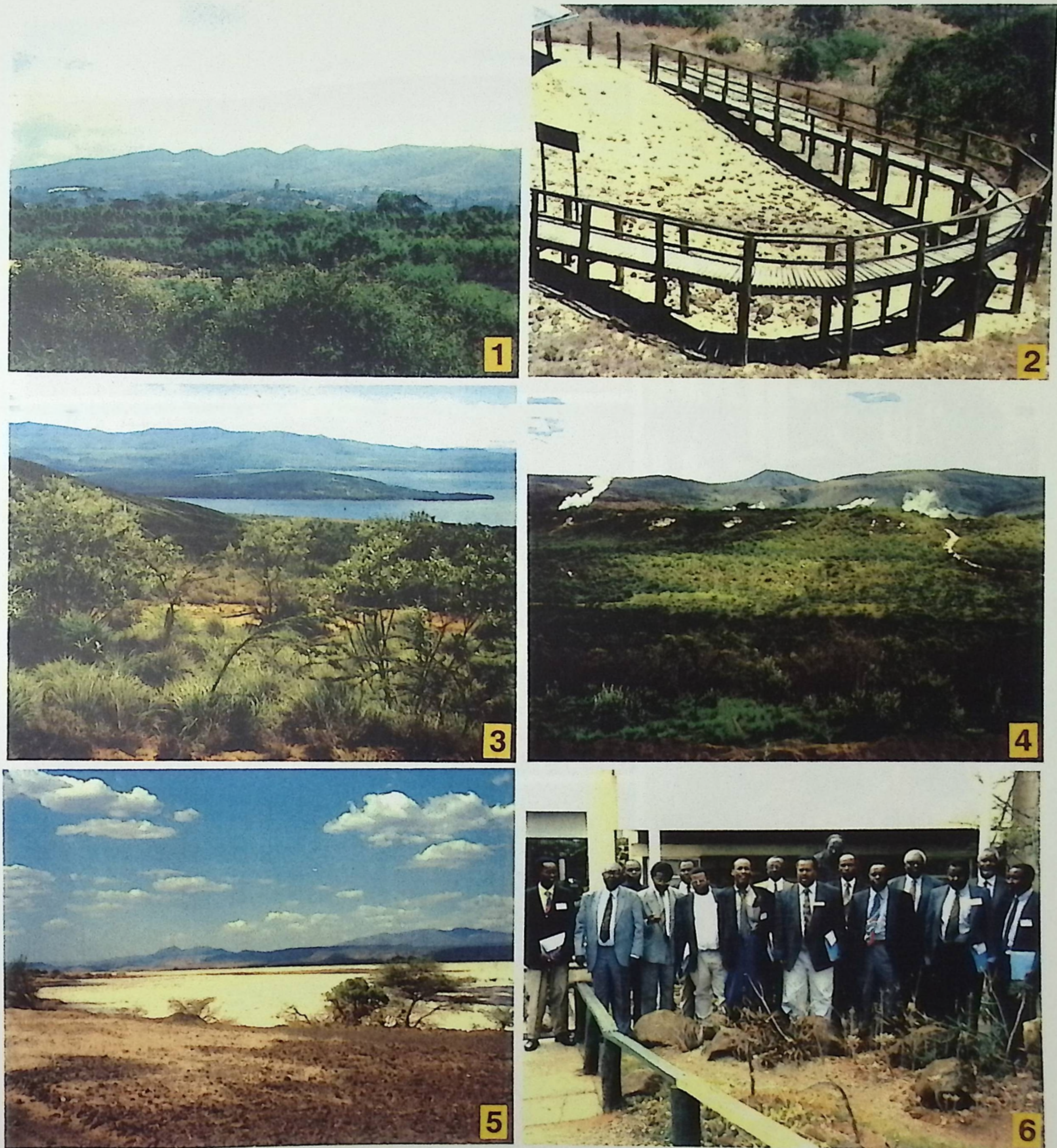

**Plate II**

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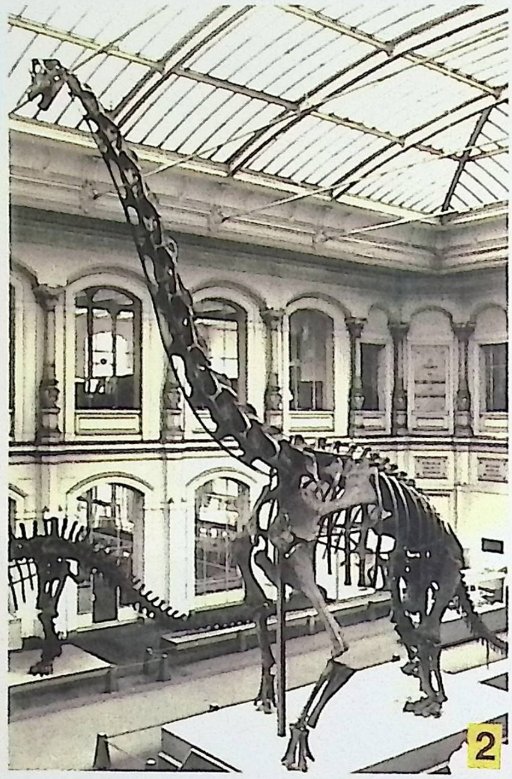

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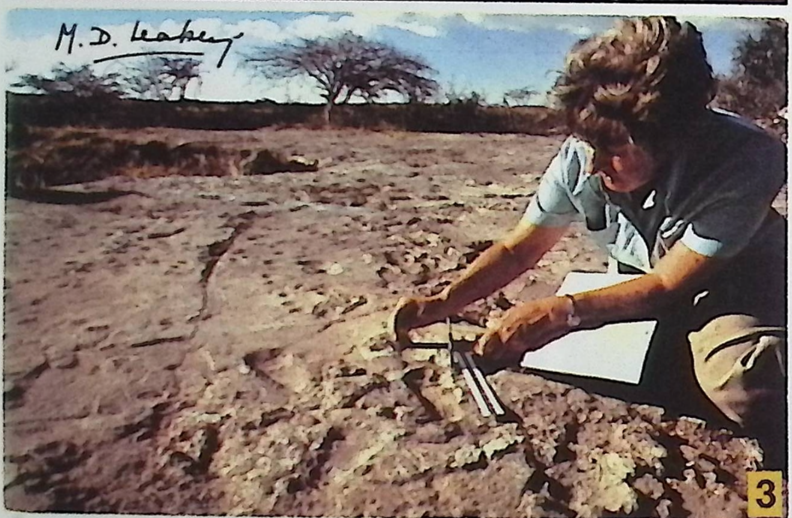


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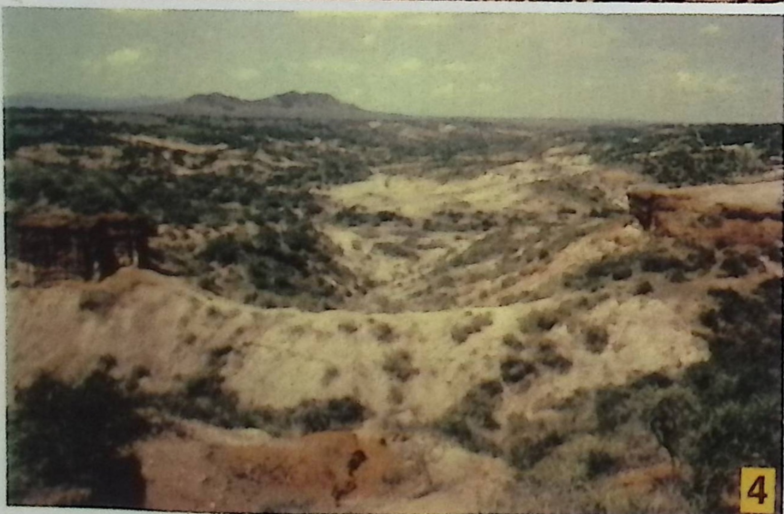

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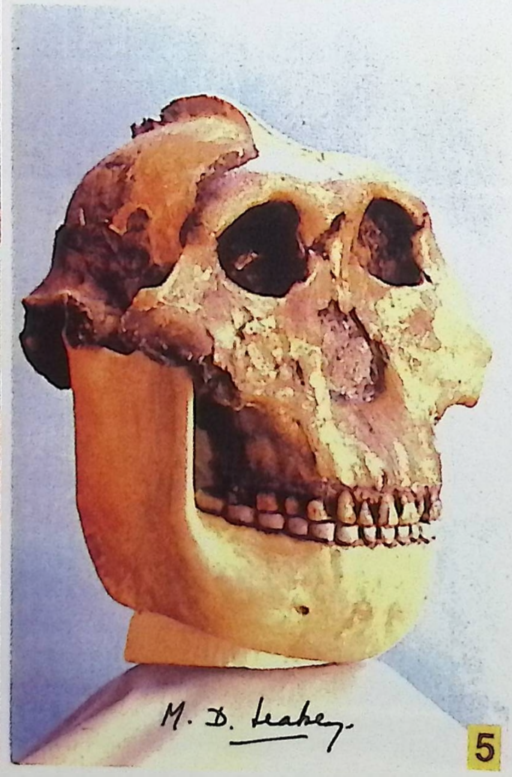


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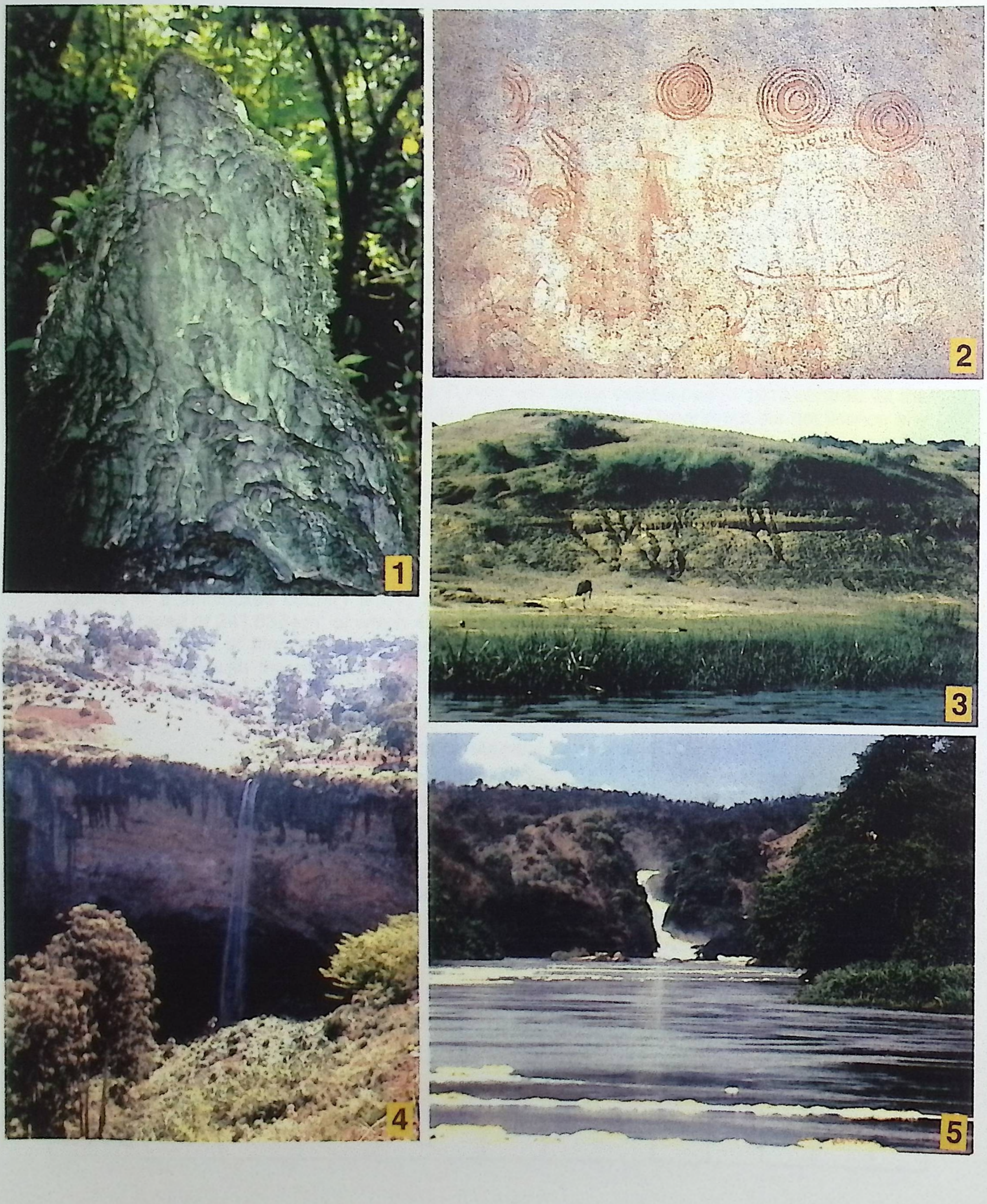
## Plate III



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# Mining and the current mineral target areas of Uganda

Erasmus Barifaijo and Fred Kabanda

**Abstract:** Uganda has a long geological history with rocks dating from the Archean to Recent. Rifting that started in the Tertiary up to Quaternary is the most spectacular geological feature. It opened up a graben that is approximately 570 km long and 45 km wide in the western part of the country. The Ruwenzori horst block that rises up to 5,109 metres (Margherita peak) in the midst of this rift valley, the alkaline rift volcanism and mineralisation of huge copper-cobalt deposits pose many challenges. Uganda's mineral exploration ventures started in 1908 with copper in the Ruwenzori mountains. Effective mining and production began in 1927 for a variety of minerals and in 1930 to 40s, it was a mining bonanza in Uganda but the sector plummeted to an all time low in the 1970s. The current investment and promotion drive in the mining sector in quest to revive the exploitation of the Ugandan minerals both metallic and industrial has produced positive results. The Department of the Geological Survey and Mines established in 1919 controls all the aspects of the mining sector through the Mining Act. In 1986 the Department did not licence any investor but the investors steadily increased after creating awareness and in 1995 alone the Department licenced 85 investors.

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## Background

Uganda is a landlocked country sitting atop the East African platform of the African plate. It covers an area of 241,638 km$^2$ of which 43,042 km$^2$ are swampy and under water. It is connected to the Indian port of Mombasa in Kenya by both rail and road networks. Steamer ships also connect Uganda with the port towns of Kisumu and Mwanza on Lake Victoria in Kenya and Tanzania respectively.

## The Department of Geological Survey and Mines

The Department of Geological Survey and Mines (DGSM) was started in 1919 as a Government organ to carry out mineral exploration and direct exploitation ventures (Mboijana & Byamugisha, 1997; Hadoto & Byamugisha, 1988). It now operates under the Directorate of Energy and Mineral Development (DEMD) of the Ministry of Energy and Minerals Development.

In the period 1992 to 1995 the Department under the auspices of a UNDP-funded project No. UGA/89/001 generated mineral targets (Hester & Boberg, 1996; Prast, 1996). The authorities at the DGSM work hand in hand with the policies of the Uganda Investment Authority (UIA) and the regulations of the investment code. The number of exploration licences issued during the period 1966 to 1995 are as shown in Tab. 1.

**Tab. 1:** Number of exploration and mining licenses issued from 1966 to 1995. Data from Mboijana & Byamugisha (1997).

| Years | 1966-71 | 1972-79 | 1980-85 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of liceneses | 6 | 5 | 3 | 0 | 3 | 7 | 6 | 4 | 4 | 58 | 39 | 42 | 85 |

In the period 1950 to 1970, the mining sector accounted for 30% of the country's earnings after cotton and coffee (Hester & Boberg, 1996) but only contributed less than 1% of the Gross National Domestic Product in the 1980s period because of the then political turmoil.

In the past ten years the DGSM has participated in other professional projects. These are:

a) The GIS computer centre project, GARS which was sponsored by Belgium Government. This was intended to equip the Department with computers and software to store and retrieve geochemical and geophysical maps as well as texts.

b) The Geothermal project that was funded by UNDP, OPEC and Iceland Government Phase one was completed in 1994 and Phase II in 1996.

c) The pozzolana cement project on volcanic ashes was financed by IDRC of Canada and executed by DGSM staff.

d) Upsala University of Sweden under the International programme in Physical Sciences helped in setting up the National Seismological Network.

e) Under UNDP project UGA/89/001, work was done and updated for the Kilembe Cu-Co deposits, Muko iron ore, phosphates and iron ore potential in the eastern Uganda carbonatite ring complexes (UNDP 1992).

f) Other projects where participation was involved were: gold exploration in Karamoja, Buhweju, Kamalenge and Busia, gypsum occurrences in Kibuku, Bundibugyo district and gemstones.

## The Geology Department at Makerere University

The Geology Department's main office and some staff offices and laboratories are housed on the ground floor of the JICA Building. The rest of the offices, laboratories and lecture rooms are on the first floor of the Mathematics Building and the workshop is adjacent to this building in the faculty of Science.

Geology in the University was started as a Sub-Department of the Department of Geography. It became a fully-fledged Department of Geology in the Faculty of Science in August, 1968 (Tosson 1975). The pioneer students of the Department got their degrees in 1970 and the first post-graduate student registered in 1971. The Department started to provide service courses for students of Agriculture in 1970 and Civil Engineering in 1972 and is still maintaining the culture but has also added the students of Surveying, Architecture and M.Sc. students of the Institute of Environment and Natural Resources.

The Department normally enrolls about 30 first year students, about 10 of whom are females. In the second and third years there are about 15 students for each year and the females are about 5 in each of those years (Barifaijo 1999). Entry requirements are two or higher Principal passes at advanced level in Chemistry and either Mathematics, Physics, Biology or Geography.

## Geology of Uganda

The rocks of Uganda range in age from the Archean to Recent (MacDonald 1966). The Archean occurs in the southern part of Uganda (Fig. 1) and is composed predominantly of granitic rocks and gneisses as a continuation of the Tanzanian craton called the Basement complex. The Basement complex occurs mainly in central, eastern and northern Uganda. Archean greenstone belts consisting of Nyanzian metavolcanic rocks and overlying Kavirondian sediments which are well-developed in Kenya and Tanzania also spill over into southern Uganda. The Archean belts have been modified by many subsequent orogenic events. These include high grade metamorphism along mobile belts, deposition of sedimentary rocks, intrusion of granites and other igneous rocks and rifting in Tertiary to Recent. The rifting was followed by alkaline volcanism and sedimentation in the formed grabens. The characteristics and associated mineralisation (Galimaka 1991; Morgan 1973) of each of these systems are summarised in Tab. 2.

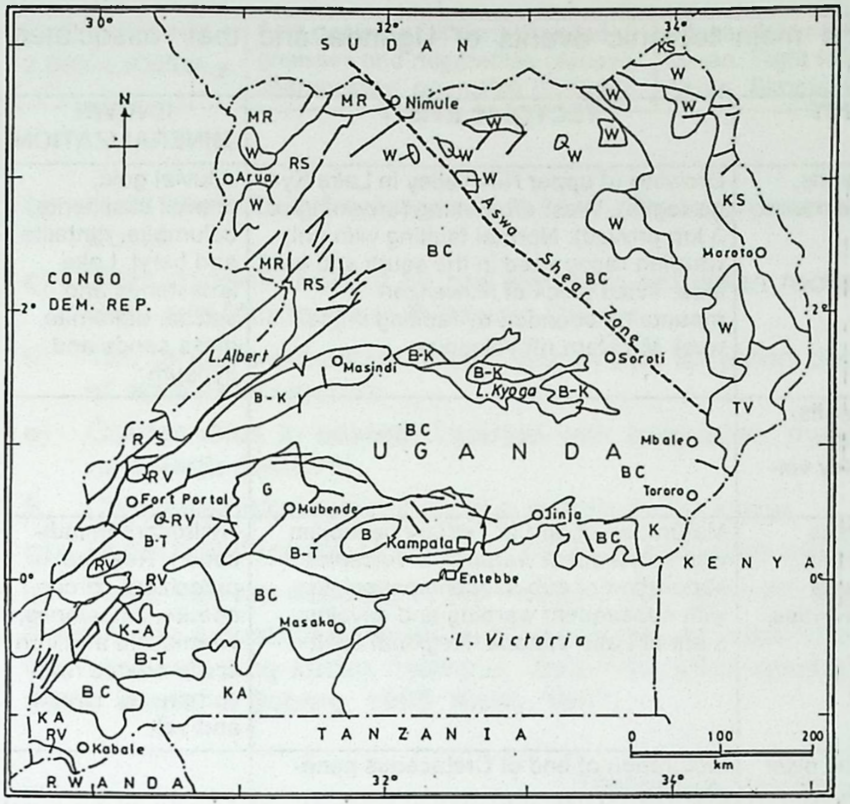



Fig. 1: Geology of Uganda (modified from MacDonald, 1966).

Legend

**RV** - Rift valley Volcanics. **RS** - Rift sediments. **TV** - Tertiary Volcanics. **G** - Granites

**PROTEROZOIC**: **B** - Bukoba Series. **B-K** - Bunyoro-Kyoga Series. **K-S** - Karasuk Series. **MR** - Mirian Gneisses. **K-A** - Karagwe-Ankolean System (Kibaran fold belt). **B-T** - Buganda-Toro System (Rwenzori fold belt).

**ARCHEAN**: **A** - Aruan Gneisses. **W** - Watian Gneisses. **BC** - Basement Complex. **K** - Kavirondian System. **NZ** - Nyanzian System.

- - - Tectonic fault, shear zone

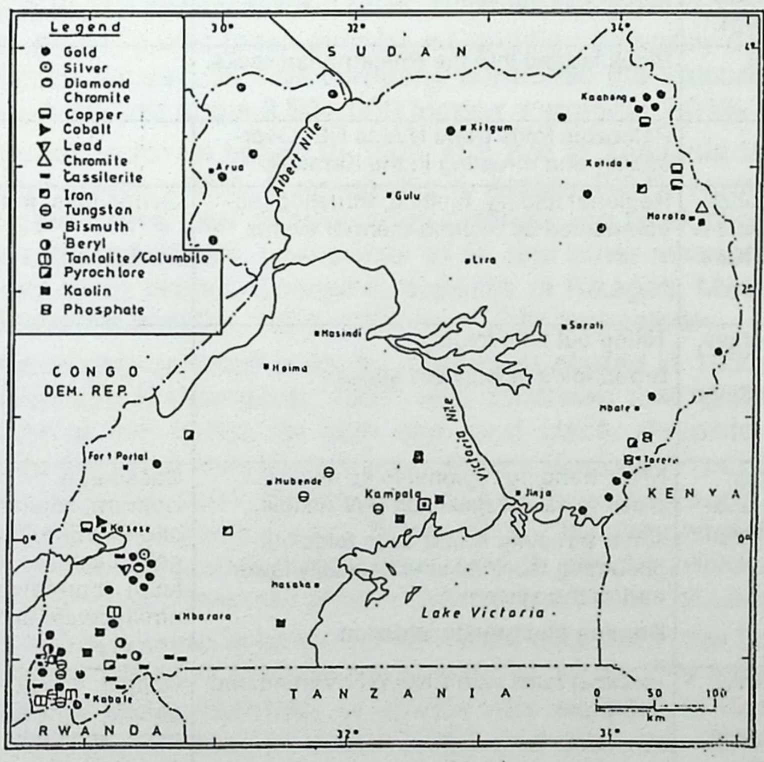



Fig. 2: Mineral occurrences in Uganda (after Prast, 1996).

## Mining in Uganda

The mineral deposits occur in discrete provinces (Hester & Boberg 1996; Prast 1996; Mboijana et al. 1997) in Uganda (Fig. 2) and these are:

a) Copper-cobalt sulphide deposits in a sedimentary-metamorphosed sequence in the Ruwenzori mountains especially at Kilembe.

**Tab. 2:** Lithostratigraphical units and main tectonic events of Uganda and their associated mineralisation.

| SYSTEM / AGE | LITHOLOGICAL UNIT | TECTONIC EVENT | KNOWN MINERALIZATION |
|---|---|---|---|
| Recent | Soils, swamps, alluvial sands, riverine and lacustrine sediments | Drowing uf upper Nile valley in Lake Kyoga region. West rift faulting (drowning of 3 km proved). Normal faulting with only warping recognized in the south and east side. Tilted block of Ruwenzori mountains bounded by faulting in the west. Western rift volcanics. | Alluvial gold, detrital cassiterite, columbite, tantalite and beryl. Lake limestones and calcite, diatomite, glass sands and gypsum. |
| Pleistocene | Swamps and alluvial deposits. Alkaline lava and pyroclasts (Semliki series, W rift valley volcanics) | | |
| Tertiary | Argillaceous and arenaceous terrestrial sediments with thin lignite bands. Alkaline lava & pyroclasts (Elgon-Bugishi series, Kisegi and Kaiso beds). | Maturation of end of Tertiary peneplain with subsequent warping. E volcanics. Maturation of sub-Miocene peneplain with subsequent warping and development of Lake Victoria. Regional uplift. | Hydrocarbon indication. Residual pyrochlore, zircon, apatite, limestones, vermiculite and iron ore in eroded ring complexes. Lignite and salt. |
| Cretaceous to Jurassic | Not represented, except the older carbonatic complexes of E Uganda (Tororo, Bukusu, Sekululu and Budeda) which are thought to be Cretaceous in age. | Maturation of end of Cretaceous peneplain. Erosion, deposition and peneplanation during the Jurassic. | |
| Karoo (Carboniferous) | Shales (partly carbonaceous), grits (Entebbe and Bugiri) | Block faulted into the Precambrian rocks. | |
| Paleozoic | not represented | Paleozoic folds trend NW to NE. Overfolding and thrusting in the Karasuk. | |
| Mozambique belt Upper Precambrian 450-650 m.y. | Quartzites, crystalline limestones, amphibolites, pelitic shists. Acid & basic gneisses (Madi sereis, Karasuk series). | Regional folding, faulting, thrusting, accompanied by tectono-thermal events. | Gemstones, marble |
| Bukoban Upper Precambrian 800 m.y. | Sandstones, shales and dolerites, conglomerates, arkoses and silicified rocks (Mityana and Singo series). | Tilting but little folding. Broad folds in Bunyoro series. | |
| Karagwe-Ankolean Precambrian 1,000-1,400 m.y. | Shales, phyllites, schists, grits, quartzites, conglomerates, sandstones and mudstones (Buhweju group, Kyoga series). | NNW trending regional folds and NE cross folds in Kigezi and SW Ankole. Minor thrusting broad open folds but becoming isoclinal in tectonically lower part of the system. Doming and granite intrusion. | Cassiterite, wolfram, columbite-tantalite, beryl, gold, bismuth, niobium, tourmaline, amblygonite and iron ore. |
| Buganda-Toro Precambrian 1,800 m.y. | The most extensive of the cover formations. Slates, phyllites, schists, quartzites, amphibolites, basic volcanics and gneisses. (Bwamba pass, Kilembe series and Toro quartzites, Iganga schists). | Isoclinal folds with ENE-WNW trend and N-S trend. | Copper, cobalt, galena, gold, iron, mica, sphalerite and lead. |
| Kavirondian and Nyanzian Precambrian 2,700-3,000 m.y. | Conglomerates, greywaxkes, shales, and agglomerates (Samia series). Basic to acid volcanics, banded ironstones and sediments (Bulugwe series). | Isoclinal folds with dominantly E trend. Slight metamorphism. Isoclinal folds in Nyanzian system with SE trend. Granite intrusion. | Gold |

| | | | |
|---|---|---|---|
| Gneiss complex 2,000-2,6000 m.y. | Acid gneisses (Mirian). Banded gneisses and migmatites (Aruan), charnockites, granulites (Watian). | Intense folding NE recumbent folds in Mirian. Tight folding with N-S axes in the Aruan. Simple E-W folds in the Watian. | Dimension stone Kaolin |

b) Gold deposits in fractures within the Archean greenstone belts and related sediments around Busia.

c) Gold deposits hosted by the Karagwe-Ankolean rocks in southwest Uganda between Buhweju and Mashonga in Bushenyi District.

d) Tin, tantalite-columbite, beryl, lithium and tungsten deposits in the Karagwe-Ankolean rocks of southwest Uganda.

e) Carbonatites in eastern Uganda with magnetite, pyrochlore, zircon, apatite, limestone and rare earth elements.

f) Chromite-nickel platinum group metals in Karamoja.

g) Lead-zinc deposits at Kitaka in the Buganda-Toro system.

h) Muko iron ore deposits in the middle Proterozoic Kibaran (Karagwe-Ankolean) rocks.

Among the industrial minerals are; limestones at Hima in western Uganda, rock salt at lake Katwe, clay including kaolin, feldspar, diatomite, silica (glass) sand and dimension stone (Mathers, 1994; Hester & Boberg, 1996; Katto, 1997).

## History of Mining

Copper was first recognised in the Ruwenzori mountains in 1908 by an Italian expedition. Tanganyika concessions Ltd in 1926 discovered copper mineralisation in the Kilembe deposit. The property was taken over by a Canadian company called Frobisher Ltd. in 1949 which formed Kilembe Mines Ltd. This company controlled the Falconbridge Mines Ltd. More exploration work was done and about 9,964,000 tonnes averaging 2.01% Cu were discovered (Maviri, 1994).

Production for tin began in 1924 at a site in Tanzania less than 1km at the border with Uganda (Byamugisha, 1988; Byamugisha & Alaba, 1997). Numerous prospects of both cassiterite and tungsten were later discovered in Uganda and production began in 1927. The mining used to be done by individuals. Low prices of tin and other minerals kept the production low until when the mines were closed. Economic deposits of Kikagati, Mwerasandu, Kaina and Nyamaherere were discovered in 1925, 1926, 1927 and 1928 respectively.

Gold mining on small scale by individuals started in 1930s (Hester &. Boberg, 1996; Prast, 1996; Tuhumwire & Nyakaana, 1997) and continued until World War II. Mining resumed with the gold boom of the 1970s for both vein and placer deposits up to the present day. The first gold production was from Kinkizi in southwest Uganda. Production from Buhweju, Mashonga and Tira was started in 1934. Gold mining activity by underground methods was resumed at Tira, Busia at the beginning of this year by Busitema Mining company. The list of the industrial minerals that are still being exploited include sands, gravel, clay for bricks and roofing tiles, limestones for cement at Tororo and Hima and glass sands on the shores of Lake Victoria.

Phosphates used to be mined from the Busumbu in the Bukusu carbonatite complex from 1945 to 1965 and Sukulu complex from 1964 to 1978. The export statistics for Busumbu indicate that nearly all the concentrate of apatite was exported to Kenya. Production of phosphate rock was remarkably constant at about 3,000 tons per year (Atkinson & Hale, 1993). When the bigger Sukulu phosphate deposits were discovered and with commencement of production in 1965, work at Busumbu was stopped. From 1955-1974, 15,000 tons per year of apatite grading 40-41 wt% $P_2O_5$ were produced but production declined thereafter and ceased in 1978. All of the concentrate was converted to single superphosphate (SSP) grading 24% $P_2O_5$ with 22% water soluble $P_2O_5$ and it used to be exported to Kenya.

## Future Prospects in Minerals and Mineral-related Investment

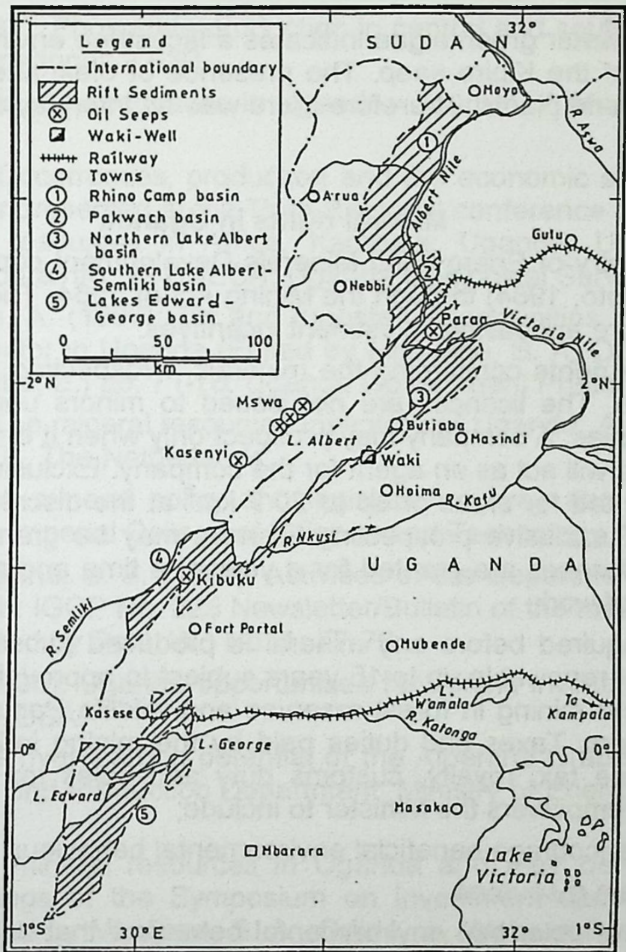
Before the UNDP project UGA/89/001 expired in 1996 (Mineral Investment Promotion Project) a number of potential economic minerals were identified (Tab. 3) to include; copper-cobalt at Kilembe Mines, carbonatites in eastern Uganda, gold in Busia, Buhweju, Kigezi, Karamoja and Mubende-Kiboga area, nickel at Kafunzo in southwestern Uganda, platinum and chromite in Karamoja, tin and tungsten in southwestern Uganda, gemstones in Karamoja, evaporites in the rift valley, columbite-tantalite and beryl in southwestern Uganda and fossil fuel in the rift valley.

**Tab. 3:** Identified mineral targets of Uganda and their location.

| MINERALS | LOCALITY | PROSPECTS |
|---|---|---|
| Copper & Cobalt | Kilembe, Kasese District | There is still more Cu-mineralisation in the vicinity of Kilembe mine at Bukangama and Nkenda. A concentrate of iron sulphides weighing about 1.1 mill t and containing about 1.4% cobalt was stockpiled at Kasese. Some of this pyrite was left in the footwall of the mine due to selective mining. Cobalt prices are now attractive. The pyrite could be used for producing sulphuric acid. The reaction between $H_2SO_3$ and limestone at Hima could be used for production of gypsum to be consumed during cement manufacture at Hima. |
| Carbonatites | E & NE Uganda | At Sukulu there are 230 mill. tons of proven phosphate material averaging 13.1% $P_2O_5$. Rock phosphate still occurs at Busumbu mine and is more suitable for direct use as it is more soluble. Sovite production for cement still exists at Tororo where Portland cement manufacturing is still in progress. Pyrochlore occurs in sub-commercial quantities at Napak, Tororo & Lolekek. The Sukulu soils average 0.2% $Nb_2O_5$. Vermiculite occurs at Namekara in the Bukusu complex with 0.15 mill t of proven ore. Large flakes reach 4-5 inches and the ore is available up to 50 ft deep. Baddeleyite (zircon ore) occurs in the Sukulu complex. There are also anomalous concentrations of Cu, Ti, V, zinc, Mb, Co, Ni & chrom in the Bukusu complex which is the largest in Afriica |
| Gold | a) Busia goldfield | The four areas with anomalous gold are: Tira mine area, Bukade-Makina area, Osipiri area and Bude-Kitoja area (all in the Nyanzian greenstone belt). |
| | b) Buhweju-Mashonga, Bushenyi | Prospective areas are at Buckley's reef, Bisya, Kampono, Kanyambogo, Kitaka and Mashonga - all in the alluvium of up to 1000 ppb gold. |
| | c) Kigezi | Occurrences are around Kanungu. |
| | d) North Karamoja | There are 5 known occurrences of gold between Kaabong and the Kenyan border. |
| | e) Mubende-Kiboga | Gold occurs roughly at the headwaters of the Mpongo river in the sapropelite. Some of the places are in Kamalenge. |
| Nickel | Kafunjo, Ruhama Ntungamo district | An established belt of rocks with commercial tonnages of Nickel values strikes northward from Tanzania and Rwanda into southwestern Uganda. |
| Platinum | Lolung-Nakiloro in Karamoja | About 4 penny weights (DWT) per long ton of these group of metals are reported but require follow-up work. |
| Chromium | Nakiloro, Karamoja | Occurs in parts up to 35 by 20 m of outcrop. It is a discontinuous zone of ultramafic rocks of serpentinite and talc schists. The results range from 3.25 - 59.8 dwt. |
| Tin & Tungsten | SW Uganda in Ankole & Kigezi | Small scale mining is still recommended for Kirwa, Bjordal, Mwerasandu & Kikagati. Related minerals requiring reappraisal are columbite/tantalite deposits in Ntungamo district and in former Kigezi and beryl in Ankole, Kigezi & Buganda region. |
| Gemstones | NE Uganda & N Karamoja | Gem quality garnets, ruby, sapphire and amethyst have been found by individual miners but there has been inconsistent exploration effort. These are found in granulite rocks. |
| Gypsum | Kibuku, in Bundibugyo | Deposits of gypsiferous clays up to 6 m thick crop out over 2 $km^2$ at Kibuku within the rift sediments. On average clays contain 10% gypsum providing total reserves of 1.2 mill t. Small showings occur at Kashasha river, Kanyatete & Lake Mburo. |
| Rock salt and Trona | Lake Katwe, Lake Bunyampaka, Lake Albert | Occurs in crater lakes and around hotsprings. Lake Katwe contains 10 mill t of mixed chlorides and ammonium salts. |
| Vermiculite | Namekara (Mbale) | More than 150,000 t have been delineated, it is high grade quality, yellow to lustrous bronze |
| Mica | Labwor Hills (Kotido) | 15,000 kg of cut mice were produced in 1940s of 0.61 m and 15.24 m width and up to 800 m long. It still exists. Several pegmatites elsewhere are intact such in the Mwerasandu quartz veins. |

| | | |
|---|---|---|
| Graphite | Mubuko River & Kigorobya (Hoima) | Occurs in crystalline quartz as bands from 15.24 cm to 17.28 cm. Several thin bands occur within shear zones in gneisses and granulites of Karamoja region. |
| Diatomite | Panyango, Atar & Parembo (Nebbi) | Occurs in Tertiary to Quaternarsy rift sediments.100,000 t of good to moderate quality diatomite occur at Panyango. |
| Silica sand | Shores of Lake Victoria | Important deposits of glass sand (> 99% $SiO_2$) occur at Diimu, Bukakata, Kome Island and Nalalumi Bay with resources of several million t. |
| Clays | Mukono, Namanve & Kajansi | Millions of t. Hydrothermal clays (kaolin) occur at Mutaka (Bushenyi district), Kobi (Rakai district) and many other places. |
| Dimension stone | All over the country | Got from dolomitic marbles in Karamoja and from granite, gneisses and basic rocks. |

**Fig. 3:** The Albertine Graben in Western Uganda (after Kashambuzi, 1997).




**The Hydrocarbon potential of the Albertine Graben**

The first evaluation of Uganda's hydrocarbon potential was by Wayland (1925) in the Albertine graben (Fig. 3). The Albertine graben stretches from the border with Sudan in the north to south of Lake Edward a distance of approximately 570 km and is averagely 45 km wide. Mapping reveals typical rift block faulting and reservoir sandstones. The sedimentary thickness in the graben exceeds 4,000 metres. Eighteen wells drilled by the African-European Investment company between 1936 and 1940 showed signs of presence of oil with some free oil being recovered on test.

Detailed gravity and aeromagnetic maps of the Albertine graben do exist and have been used in basin depth estimates. The aeromagnetic survey of 1983 indicated five major sub-basins and these are: Packwach, Rhino camp, Northern Lake Albert, southern Lake Albert to Semliki basins and Lake Edward-George basin (Kashambuzi, 1997).

**Tab. 4:** Summary of oil seeps in the Albertine graben (after Kashambuzi, 1997).

| **Country** | Uganda | Uganda | Uganda | Uganda | DRC | DRC |
|---|---|---|---|---|---|---|
| **Place** | Paraa | Waki | Kibuku | Kibiro | Kasenyi | Mswa |
| **No. of oil Seepages** | 2 | 1 | 1 | 1 | 1 | 3 |

The substantial portion of the Albertine graben sediments are of continental origin. There exists 9 confirmed oil seeps (Tab. 4) in the Albertine graben (Fig. 3) which is a manifestation of mature organic rich source rocks. The surface oil seeps occur further downstream near Lake Albert. Another seep is at Kibuku on the banks of the Kibuku stream. Oil seepages and gas seeps also occur at Kibiro. Other seepages are reported at Kasenyi and Mswa on the western shores of Lake Albert in the Democratic Republic of Congo (DRC). Sub-surface seepages occur near Kibiro and at Waki.

The presence of fresh water green algae indicates a lacustrine environment. This was especially found in the kerogen of the Kibiro seep. The presence of oleanane for the Kibiro seep means contribution by higher land plants. Therefore there was an interplay of both lacustrine and estuarine/bay environments.

### Mineral rights in Uganda

The DGSM of the Ministry of Energy and Minerals Development controls most of the aspects of the mining sector (Hadoto, 1984) through the Mining Act of 1964. The Mining Act is presently under revision to offer more appeasing investment incentives.

The state owns all the rights concerning the minerals. Prospecting may be done by individuals holding a valid licence. The licences are not issued to minors under 18 years, undischarged bankrupts or to companies. A company may prospect only when it employs at least one individual with such a licence and will act as an agent for the company. Exclusive prospecting licences for a single mineral are granted for areas of up to 20.7 $km^2$ at the discretion of the Commissioner of DGSM. Larger special exclusive prospecting licences may be granted at the discretion of the Minister. Prospecting licences are granted for a year at a time and must be accompanied by an approved programme of work.

A mining licence is required before any mineral is produced for sale. A mining lease may be granted up to 21 years, renewable up to 15 years subject to approval by the Commissioner of the DGSM. Prospecting and mining in forest reserves and wildlife Parks require special permission from respective Ministers. Taxes and duties paid by the mining industry are; corporate income tax, dividend remittance tax, royalty, customs duty and sales tax. The National Environment Statute of 1995 (§ 94) empowers the Minister to include;

a) Tax incentives to encourage beneficial environmental behaviour
b) User fees for certain resources
c) Tax disincentives to deter bad environmental behaviour that depletes a resource or causes pollution.

### Conclusion

Uganda is one of the three East African countries and has a variety of rocks ranging in age from Archean to Recent and their associated mineralisation. More than 75% of the country is covered by Precambrian rocks. These include highly metamorphosed granulites and gneisses to metasedimentary rocks and unmetamorphosed sandstones and shales. These are intruded by granites and granitoid rocks in certain areas. The Paleozoic is not represented in Uganda apart from three isolated Karoo deposits along the northern margin of Lake Victoria. Tertiary volcanics occur in eastern Uganda and are mostly represented by alkaline ring complexes including carbonatites. Quaternary to Recent alkaline volcanics and sediments occur in the western branch of the East African rift system.

The mentioned rocks are a vanguard of certain minerals which include; copper-cobalt, gold, tin, tungsten, columbite-tantalite, beryl, amblygonite (lithium ore), gemstones, chromite-nickel, evaporites and an assortment of industrial minerals. The country's mining history starts from around 1927 to the present time. There was a decline in the 1970s up to early 1990s due to political strife but it is now on the rise. The investment incentives in minerals are attracting more investors in the mining sector plus the recent mineral investment promotion drive undertaken by the Department of Geological Survey and Mines which has created an atmosphere of awareness. Mining contributed about 30% of the country's export earnings from 1950s to 1970s but now it contributes less than 1% of the National Gross Domestic Product. It is hoped that with the increasing new investment in the mining sector the old glory will be rekindled.

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# Siting for disposal of municipal solid waste in greater Kampala, Uganda

Michael Biryabarema

**Abstract:** A number of baseline spatial data were used to find, as an initial process, suitable dumping sites in Kampala municipality and surrounding areas. These data included landforms, soils, geology, landuse, rivers, wetlands, open water, roads and population density. After evaluation of the above spatial data in Kampala specific criteria were used to isolate appropriate dumping areas at this stage by overlaying them in a Geographic Information System (GIS). Data analysis showed that there is nothing like an ideal location for dumping in Kampala and surrounding areas. The footslopes and pediments which were found to be relatively most appropriate because of their correct angle of slope and soil types do contain important regolith aquifers. The trade-off requires adequate site preparation in the construction of the landfills and detailed survey of groundwater so that locations could be preferred where the resource is of less importance in terms of quality and quantity. The relatively better areas all fall in the surrounding districts of Mpigi and Mukono

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## Introduction

**Background:** The population of Kampala, the capital and main commercial city of Uganda, is estimated at 1,143,000, in 1999, based on the 1991 National Census population of 780,000 and a growth rate of 4.9% per annum. During the last two to three decades the infrastructure of the city was only marginally ameliorated while the population grew rapidly. Construction and industrial sectors have also grown rapidly in the last decade. The average annual rates of growth for the two sectors are 23.5% and 12% respectively (The State of the Environment Report for Uganda, 1996). One of the aspects of planning that is facing Kampala City Council (K.C.C) authorities is the adequate disposal of domestic, industrial and commercial wastes. The waste disposal system of the city is under increasing strain and there are frequent conflicts between the city authorities and the residents close to the disposal sites. Liquid effluent is discharged into Lake Victoria while solid wastes, prior to 1996, were being disposed of at various sites in and around the city in open dumping. The geologic and hydrogeologic environments of the sites were not studied in detail before dumping. Preventative measures to protect soil, groundwater and surface water from contamination by these wastes did not exist. Therefore, the extent of the resulting health hazard to the population is largely unknown. Since 1996, about 45% of the solid waste from Kampala City is disposed of at the first engineered landfill at Mpererwe, about 1½km north of the city. According to construction specifications 70-80% of the leachate is to be contained consequently reducing the potential contamination of the soil and water environment. During the design about 20% of the leachate was expected to disperse into groundwater and surface water and was expected to cause no serious water contamination. A ground monitoring plan had been envisaged and new locations for water supply boreholes for the communities with a population totaling 2460 persons to safer places had been planned.

With increasing environmental awareness of communities and the desire of the concerned authorities to dump the municipal solid waste appropriately there is a need to map out areas relatively more suitable for such dumping. Location of appropriate areas would have a twin advantages of scientific qualification for a site and the attendant less elaborate and hence less costly preparation of the site. The subject of this paper is to discuss the potential locations that should be investigated further as possible dumping sites relatively more suitable in Kampala and surrounding areas. According to EPA (1983), when discussing site evaluation and selection of options for land application of municipal sludge, careful identification, evaluation and ultimate selection of land application sites can prevent future environmental problems, reduce monitoring requirements, minimize overall programme costs and moderate or eliminate adverse public reaction. According to Environmental Resources Limited (1990) and The State of the Environment Report (1996), the Kampala municipal solid waste is composed of: vegetable matter (73.8%), tree cuttings (8%), street debris (5.5%), paper (5.4%), metals (3.1%), sawdust (1.7%), plastics (1.6%) and glass (0.9%). Solid waste generation is estimated at an average rate of 0.8 kg per capita per day and Kampala City Council spends US$ 3.4 per capita in solid waste delivery at the disposal site in Mpererwe (The State of the Environment Report for Uganda, 1996) with a delivery cost standing at US$13 per tone. Of an estimated 20,000 tones of waste expected to be generated per month, an average of about 9,000 tones are received at Mpererwe landfill, accounting for 45%. The rest is disposed of at temporary locations or left unattended to. The data on the current waste deliveries is courtesy of the engineer in charge of the Mpererwe site.

## Geology and Geomorphology of Kampala and Surrounding Areas

The geology of Kampala city and surrounding areas is presented in Fig. 1. The city is underlain by Precambrian basement of granites and granite gneisses, Buganda Toro quartzites, schists, phyllites, and amphibolites, and by Pleistocene to recent alluvium and lacustrine deposits. The city is situated on a succession of moderately sized hills nearly of the same height. They are often flat topped and laterite capped. There are also are broadly rounded hills and of lower altitudes with slope averaging 5-7%, rising above wide valleys originally filled with papyrus swamps, high grass or forest, now largely reclaimed by development in urbanization and alluvium and lacustrine landforms associated with Lake Victoria. Relief amplitude is moderate, about 180 m between hill tops and valleys and East-West through Kampala, hill tops lie consistently between 1300-1318 m and have uniform angles of slope, an upper slope at 24°-27° flattening to a long "pediment" or piedmont slopes of 5°-7° (Pallister, 1959). Flatter profiles are found to the north of Kampala, where 3°-4° slopes are common. An West-East topographic profile through Kampala city, is presented in Fig. 2. Typical profiles have been discussed by Pallister (1942), who described an upper surface capped with laterites and associated with it, a more or less pronounced scarp, a steeply sloping surface, a lower surface (usually covered by laterites), and finally a lower scarp overlooking a wide flat bottomed valley which may be choked by papyrus. The gradients are so slight that heavy rain usually produces temporary standing water or swamps.

At the base of most slopes in Kampala, at the swamp level, exist springs which are the main source of water supply for numerous households who have no access to tap water. Water ercolates through soils and the bedrock beneath forming a water table. On reaching the valley alluvium the water is forced to emerge as springs. There may be two possibilities; (i) water flowing through the soil over the impervious rock as throughflow and emerging at the base of the slope as springs or (ii) groundwater table sloping beneath clayey sediments of the valleys and partly emerging as springs at the base of the slope The latter is the most plausible.

## Siting of Municipal Solid Waste

Authors like Petts & Eduljee (1994), Daniel (1995) and others have outlined the criteria employed in site selection for dumping. According to Daniel (1995) factors that must be considered when siting landfills include; e.g. proximity to waste generators, availability of transport systems to carry waste to the site, climate, geology, hydrogeology, surface hydrology, proximity to transport networks, demographics, land use, impacts on local community. The geologic and hydrgeologic issues include definition of sub-surface stratigraphy, identification of background water quality and geochemical conditions, determination of the properties of major sub-surface units with particular emphasis on hydraulic conductivity, geochemical attenuation characteristics and strength, evaluation of availability of construction materials like clay for liners and granular material for drains and analysis of the probable performance of the site including assessment of probable groundwater impacts and analysis of the stability of the facility. For the infrastructure and land use/land cover, issues involve creating sufficient buffer zones that will ensure their protection.

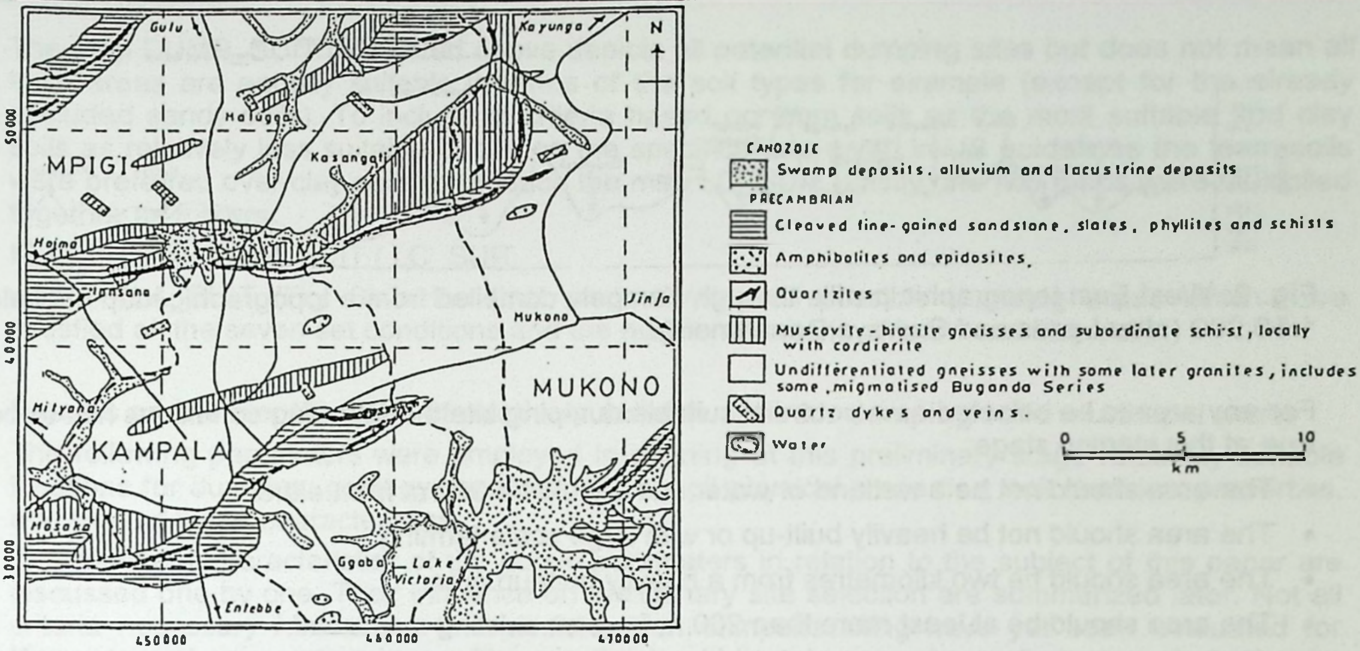


**Fig. 1:** The geology of Kampala area (after Uganda Geological Surveys and Mines, 1962).

Choice technology may improve a relatively naturally unsuitable site into a more appropriate dump site. This, however, in a poor country like Uganda may be too costly considering the big volume of waste to be dealt with. Favourable natural conditions needing less elaborate site preparations to minimize costs of landfill construction and subsequent management should be sought.

## Methodology

Preliminary work on the process of identification of relatively suitable waste disposal sites for municipal solid waste in Kampala has involved; (i) a qualitative description based on the physical parameters of geology, geomorphology and hydrogeology of Kampala and (ii) the overlaying of some of the information of the physical environment and infrastructure and land use patterns in a Geographic Information System (GIS) to come up with a derivative map outlining at this stage the areas that could be investigated further.

## Geology, Geomorphology and Hydrogeology

Part of the investigation to identify the relatively safer areas for disposal sites of municipal solid waste involved; (i) description of the geology and geomorphology of Kampala area from existing maps, aerial photographs and field work (ii) chemical and physical analysis of the regolith/ sediment samples underlying the Kampala area and (iii) description of hydrogeological characteristics. The qualitative assessment of the potential sites based on these parameters are presented later.

### Overlaying Some Baseline Data Using GIS

GIS (Geographical Information Systems) has been identified as a useful tool to derive information from existing data. This spatial data analysis is often referred to as GIS modeling. It has been used in numerous applied studies. For example Hiscock et al. (1995) applied it in the study of groundwater vulnerability assessment in Midlands and Northeast of England by overlaying information on solid geology, Quaternary drift, soil cover and came up with a derivative map indicating areas of extreme and high groundwater vulnerability.

In this Kampala case, a number of baseline spatial data were used to identify at a preliminary stage potential suitable dumping sites in and around Kampala. Data layers used in the GIS modeling included the following; land use/land cover, contours, geology, soils, rivers and roads.

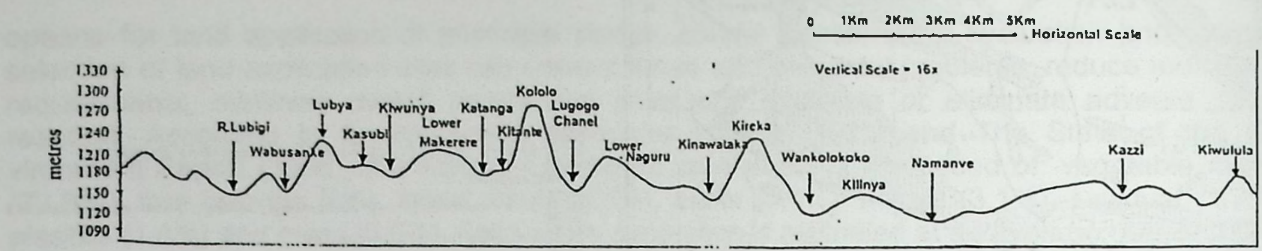


**Fig. 2:** West-East topographic profile through Kampala compiled from a topographic map of scale 1:50,000 (after Lands and Surveys Department).

For any area to be selected as a potential suitable dumping site the following conditions had to be true at this starting stage;

- The area should not be a wetland or water.and should be 300 m from either
- The area should not be heavily built-up or with large scale farming.
- The area should be two kilometres from a heavily built-up area.
- The area should be at least more than 200 m from an existing main road.
- The area should be at least 200 m from an existing stream.
- The area should not be covered by sands
- The area should avoid quartzite.
- The slope angle should be 2 - 12%.
- Loam soils were preferred over clay soils

ArcView GIS (with spatial analyst module) was used for the GIS modeling.

All the shape (vector) files were converted into grid (raster data format) before the GIS modeling. The following intermediary maps were derived from existing data sets before the GIS modeling:

(i) Suitable Land Cover Types (LUC_SUIT), prepared by isolating, open water, wetlands, built-up areas and large scale farmlands

(ii) Suitable Low-Populated Areas (POP_SUIT) prepared by isolating all heavily built up areas which represent densely populated areas. The resulting map was used to produce a buffer zone of at least 2km from the built up boundary.

(iii) Suitable Buffer Zone from Major Roads (ROAD_SUIT) prepared by creating a buffer zone of at least 200m on either side of the major roads of Kampala and surrounding areas.

(iv) Suitable Buffer Zone from Rivers (RIVER_SUIT) prepared by creating a buffer zone of at least 200m on either side of the rivers in Kampala.

(v) Suitable Soils (SOIL_SUIT) prepared by eliminating highly sandy soils, considered unsuitable due to their high permeability

(vi) Suitable Rocks (GEOL_SUIT) prepared by isolating quartzite rocks at this stage due to their high degree of fracturing and the overlying stony soils, highly permeable soils.

(vii) Suitable Slope Gradient (SLOPE_SUIT) prepared by selecting the slope angles of 2%-12% from digitized contours of Kampala area, the angles recommended in the US guidelines. The US guidelines for siting criteria for waste disposal used are after Cheremisinoff (in Petts & Eduljee, 1995).

Since all the maps prepared in (i) - (vii) are binary maps, the suitable dumping sites were derived using the "Map Calculator Module" in ArcView as follows:

DUMP_SUIT = LUC_SUIT ( POP-SUIT ( ROAD_SUIT ( RIVER_SUIT ( SOIL_SUIT ( GEOL_SUIT ( SLOPE_ SUIT.

where DUMP_SUIT represents all potential dumping sites in Kampala and its surroundings.

The map DUMP_SUIT calculated above depicts all potential dumping sites but does not mean all such areas are equally suitable in terms of the soil types for example (except for the already excluded sandy soils). To include in criteria based on loam soils as the most suitable and clay soils as relatively less suitable based on the specifications given in US guidelines the loam soils were preferred over clay soils to produce the map LC_SUIT. Lastly, the two maps were multiplied together as follows:

KLA_SUIT = DUMP_SUIT ( LC_SUIT

where KLA_SUIT (Fig. 6) is the final map showing all possible dumping areas which have satisfied all the seven set conditions and the additional criteria of loam and clay soils.

**Results on the identification of relatively suitable sites for dumping solid municipal waste**

The following parameters were employed in defining at this preliminary stage relatively suitable locations for dumping; geology, landform types, soil physical properties, soil chemical properties, and ground water characteristics.

The pertinent characteristics of the above parameters in relation to the subject of this paper are discussed one by one. Their influence on preliminary site selection are summarized later. Not all criteria necessary for making final decisions on dumpsite siting have yet been evaluated for Kampala and surrounding areas. The results should be taken as of a preliminary nature, that is, as a part of a process to solve this problem

Geology

The geology underlying Kampala area has already been discussed. The important geologic features considered in disposal site mapping at this stage are the highly fractured quartzite rocks and the overlying stony permeable soils and areas of shallow impermeable outcrops that would give rise to poor drainage. The detailed mapping of the all rocks and the nature of associated structures would be necessary to understand better the full extent of the influence of this factor in dumpsite selection in Kampala

Landform Type

Landform type affects the amount of runoff and flooding, the two factors which would influence the degree of erosion and potential runoff of the dumpsite material into the drainage system and on infrastructure and other facilities. Landform facets identified on recent unrectified aerial photos of Kampala are employed in this discussion. These are; plateau surfaces, steep slopes associated with the laterite plateaus, middle slopes, footslopes or pediments, valleys and lake terraces.

Soil Physical Properties

The soils of Kampala lack extreme properties and the most common clay mineral is kaolinite (Fig. 3). Plots of plasticity indices and liquid limits are indicated in Fig. 4. The most important groupings of soils in Kampala are:

(i) the deeply weathered mantle on the slopes with high percentage of fines by weight developed argillites of Buganda Toro System

(ii) stony soils developed on quartzites that are highly permeable

(iii) the valley alternations of clayey silts and clayey sands in various combinations overlying saprolite. The sands are well graded and always contain a proportion of clay.

(iv) the development of undulated laterites on tops of hills and lateritic gravel soils at various slope angles in the profile.

(v) very shallow soils where the outcrops are close to the surface.

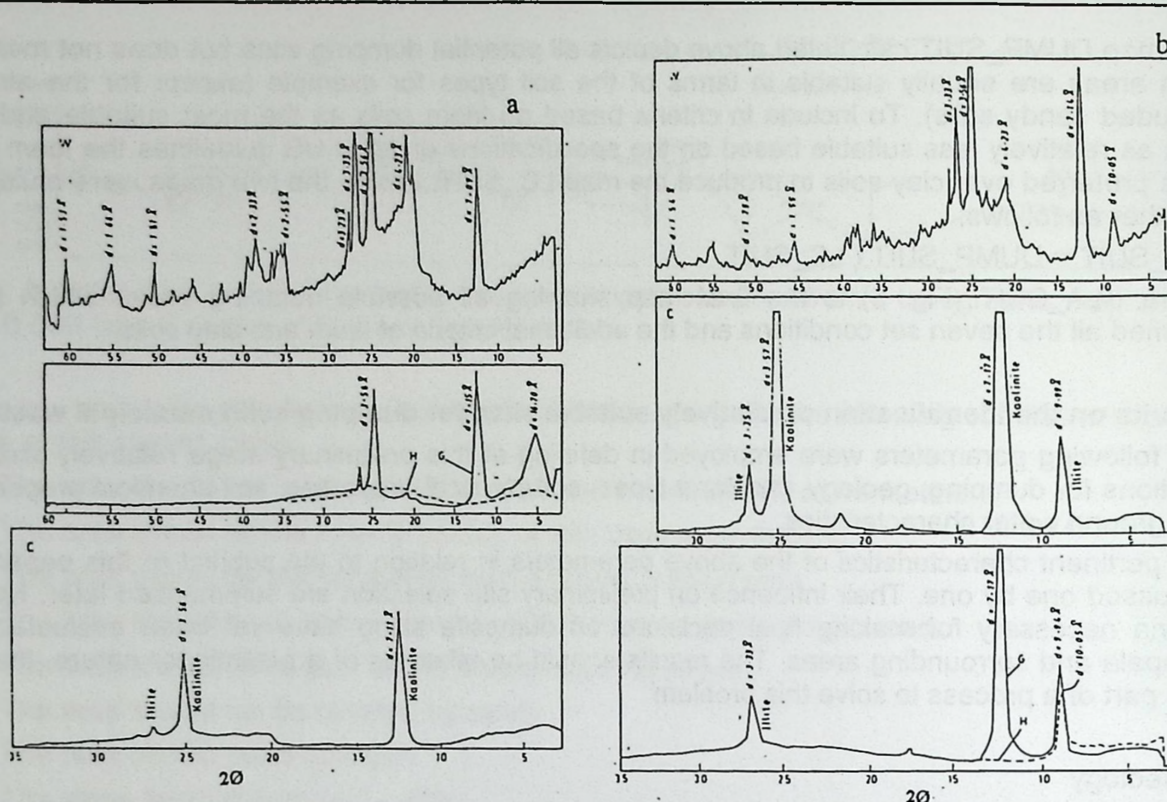


**Fig. 3:** Diffractograms for two representative soils from Kampala: saprolitic soil derived from granite gneiss (a) and an alluvial sediment (b): diffractograms for the total fine fraction (W), untreated clay fraction (C), clay fraction treated with glycol (C), and clay fraction heated to 550° C (H).

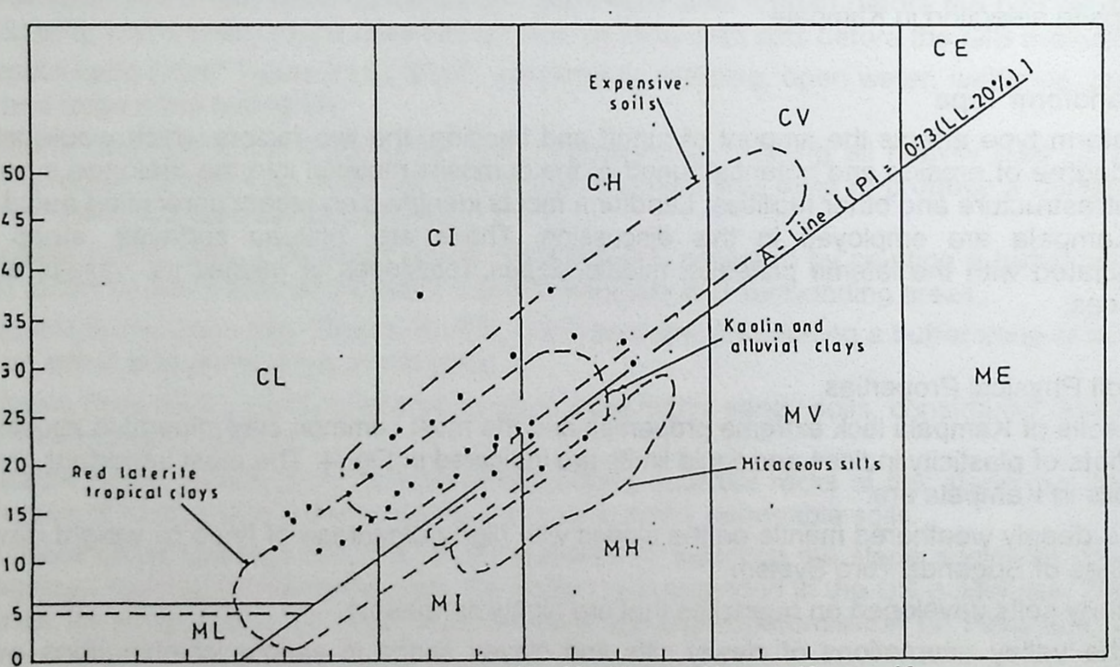


**Fig. 4:** Plasticity chart for Kampala soils (based on BS 5930, after Anon. 1981). Sections for clays and silts of various plasticity rates are inserted. The encircled (dashed) zones and their indicated soil types are after Hunt (1984).

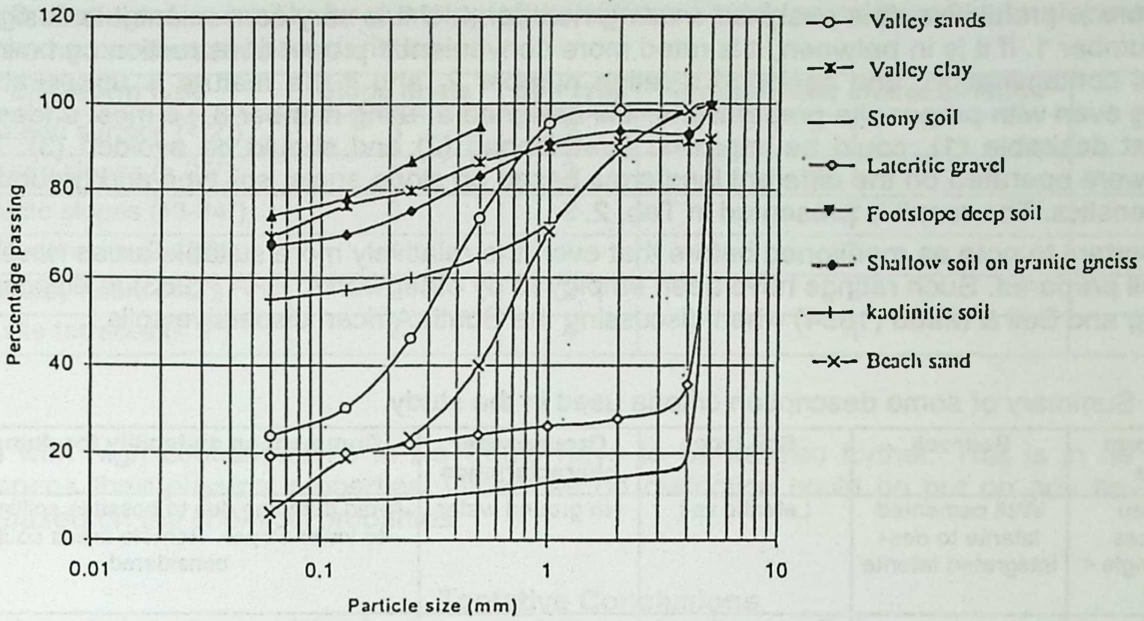


Fig. 5: Particle size distribution within the coarse fraction in various Kampala soils

(vi) well sorted beach sands mapped on the shores of Lake Victoria and possibly characterising the old beaches. The sands are underlain by a paleosol possibly overlying an even older beach sand.

The grain size distribution within the coarse fraction of the various described soils of Kampala are indicated in Fig. 5.

Groundwater Characteristics

One of the most important considerations in safe dumping is the protection of groundwater. Although this study has not included detailed study of bedrock aquifers whereby the analysis would include the long term safety of these deep aquifers, it is nevertheless crucial because it has considered spring water, a major source of potable water for thousands of families in Kampala and its periphery.

From existing borehole records, the thick overburden contains important aquifers in the saprolite because of their good transmissivity. These are reported by (Howard et al. 1994) to be hydraulically connected to unweathered rock aquifers implying a possible deep well contamination in the long term from the contaminated regolith aquifers.

Drilling up to 9 m in Wakaliga Valley revealed a dry soil/regolith profile. Most of the valley floors may be devoid of shallow groundwater. However, sand lenses as shallow groundwater aquifers exist on the fringes of some valleys. This has to be investigated at every possible site.

Drilling of shallow observation wells in Port Bell revealed the presence of a perched aquifer of well sorted beach sand overlying a paleosol acting as a confining bed to the aquifer. These beaches are close to Lake Victoria which is the source of piped water in Kampala City. Dumping on the terraces may not only affect the small aquifers but also the lake water. It should be avoided.

Based on the parameters of geology, landforms, soils, and groundwater, specific criteria were employed to rate various landfacets for their potential as municipal waste dumping sites. The criteria used and the description of suitability or unsuitability for each considered landfacet are summarised in Tab. 1.

If some of the above features are rated depending on their effect on suitability for dumping, a derivative picture on the relative suitability comes out. This is based on the following rating:

If a feature is prohibitive, it is assigned a rating number 4. If it is very convenient it is assigned a rating number 1. If it is in between, it is rated more convenient if proper construction can minimise potential contamination, and assigned a rating number 2, and if the feature is undesirable for dumping even with proper site preparations, it is assigned a rating number 3, i.e most undesirable (4), most desirable (1), could be improved (conditional) (2) and should be avoided (3). These ratings were operated on the different landforms based on slope angle, soil type and groundwater characteristics. The result is presented in Tab. 2.

It is important to note as mentioned before that even the relatively more suitable areas have to be very well prepared. Such ratings have been employed by other works: EPA (1983) in disposal site mapping and Bell & Maud (1994) when discussing the South African dispersive soils.

**Tab. 1:** Summary of some description criteria used in the study.

| Landform type | Bedrock | Soil type | Groundwater characteristics | Comment on suitability for dumping |
|---|---|---|---|---|
| Plateau surfaces (slope angle < 2°) | Well cemented laterite to des-integrated laterite | Lateritic soil | No ground water | Avoid dumping due to possible spilling over to lower slopes. Remote areas could be considered |
| Steep slopes (slope angle > 25°) | | Deep weathered saprolitic soils with high clay content | Not very important | Avoid dumping due to high runoff and erosion |
| Middle slopes (slope angle 13-24°) | Quartzite bedrock to be avoided due to high fracturing | Deeply weathered and partly residual soils | Possibly important | Could be avoided due to the angle of slope that can cause high runoff and erosion. With cautious measures and proper management could be considered |
| Pediments (slope angle 2-12°) | Avoid quartzite bedrock due to the gravely soils being highly permeable | Deep brown residual soils | Very important but very common springs of potable water quality | In terms of the angle of the slope and sopil characteristics it is the best. However, locations should be based on the trade off the groundwater situation |
| Valley floors (slope angle< 2°) | Alluvial sediments and beach sands | Alternation of clayey sands and clay silts and sandy soils with underlying beach sands | In some valleys swampy surfaces exist on dry soil profiles while small perched aquifers exist on fringes of some valleys and in beach sands | - The sandy locations should be avoided<br>- Valleys with small aquifers would have to be mapped and avoided<br>- The alternation of clayey silts and sands without groundwater in the regolith would be very important but the potential for flooding and nearness to surface streams would have to be worked out |

Soil Chemical Properties

Deposition of material highly loaded with pollutants will change the physical chemical equilibrium of the environment and may lead to the releasing of natural chemical parameters in the environment. Therefore, soils without anomalously high metal concentrations should be not preferred as bases for the disposal sites.

The issue of the chemical parameters is not so important because the Kampala soils do not contain anomalous values (Tab. 3).

The exception is in the laterites where Fe is highly concentrated. However, iron is not considered a contaminating metal. Relatively speaking shallow soils on granite gneisses are rich in major elements, top soils and clay layers in the valleys contain relatively high concentration of heavy elements, deeply weathered soils are depleted of major elements and laterites are rich in Fe, Al, and occasionally Na and a range of heavy metals but depleted of other major elements. Stony soils are poor in all heavy and major elements. Based on the chemical properties the most crucial criteria may be the influence of Na on the dispersive characteristics of the soils.

Tab. 2: Rating of suitability for dumping of the different land facets based on a slope angle, soil type and groundwater characteristics.

| Landform type | Slope angle | Soil type | Groundwater characteristics | Total |
|---|---|---|---|---|
| Plateau surface (< 2°) | 3 | 2 | 1 | 6 |
| Steep slopes (> 25°) | 4 | 2 | 1 | 7 |
| Middle slopes (13-24°) | 3 | 2 | 2 | 7 |
| Pediments (2-12°) | 1 | 1 | 3 | 5 |
| Valley floors (< 2°) | 2 | 2 | 2 | 6 |
| Lake terraces (< 2°) | 2 | 4 | 4 | 10 |

Soils with high concentrations in Na would have to be studied further. This is in as far as it influences their physical properties. Otherwise no restriction could be put on any environment now based on the chemical properties.

## Tentative Conclusions

Based on the considered criteria the first observation is that there is no such a thing as a location that is very suitable when the criteria are considered. However, in consideration of relative suitability the two most important possibilities are: (i) the pediment have the correct angle (2-12%) and the correct soil type but also does contain important regolith aquifers (ii) most of the valley floors may have no shallow groundwater, are sufficiently impermeable, but their slight slope angle, the possible activity of some clays, the poor drainage and the nearness to the surface streams are also a hindrance.

These observations are meaningful if (i) they are taken as preliminary to more comprehensive studies (ii) representing generalisations over a more complex situation. This means that detailed studies would always be required for each specific situation.

(iii) a need for proper development of each site is born in mind. The environments identified as most suitable are only in relative terms and irresponsible dumping would cause adverse effects in those environments.

## GIS Modeling for Location of Suitable Dumpsites

Suitable site selection is a process of mapping different criteria. These criteria have to be overlain to come out with a product that satisfies all the input data/conditions. According to Petts & Eduljee (1994), Geographical Information Systems (GIS) can handle many overlays and can accommodate varying degrees of constraint by generating a final map with numerical or shape intensity.

A number of baseline spatial data were overlain in a GIS System and used to find, as an initial process, suitable dumping sites in and around Kampala. The data layers used in the GIS included; contours, geology, landuse/landcover, soils, rivers and roads.

Normally, the design has to follow the regulations or guidelines that place limits to the physical characteristics of the site. A list of conditions set to select the potential sites for dumping in Kampala area were described earlier under methodology.

The list is not exhaustive but represents a starting point in the process of identifying most suitable areas for siting of municipal waste disposal systems. The final output map (Fig. 6) shows areas and their relative suitability for municipal waste dumping. Most suitable areas are located to the Southeast of Kampala and to the Northwest. The relatively suitable areas occur mainly to the Northeast of Kampala. If other criteria would be overlaid, the mapped areas could possibly shrink further. What is very clear is that Kampala district has run out of suitable dumping areas and may have always to negotiate with Mpigi and Mukono Districts for provision of such sites.

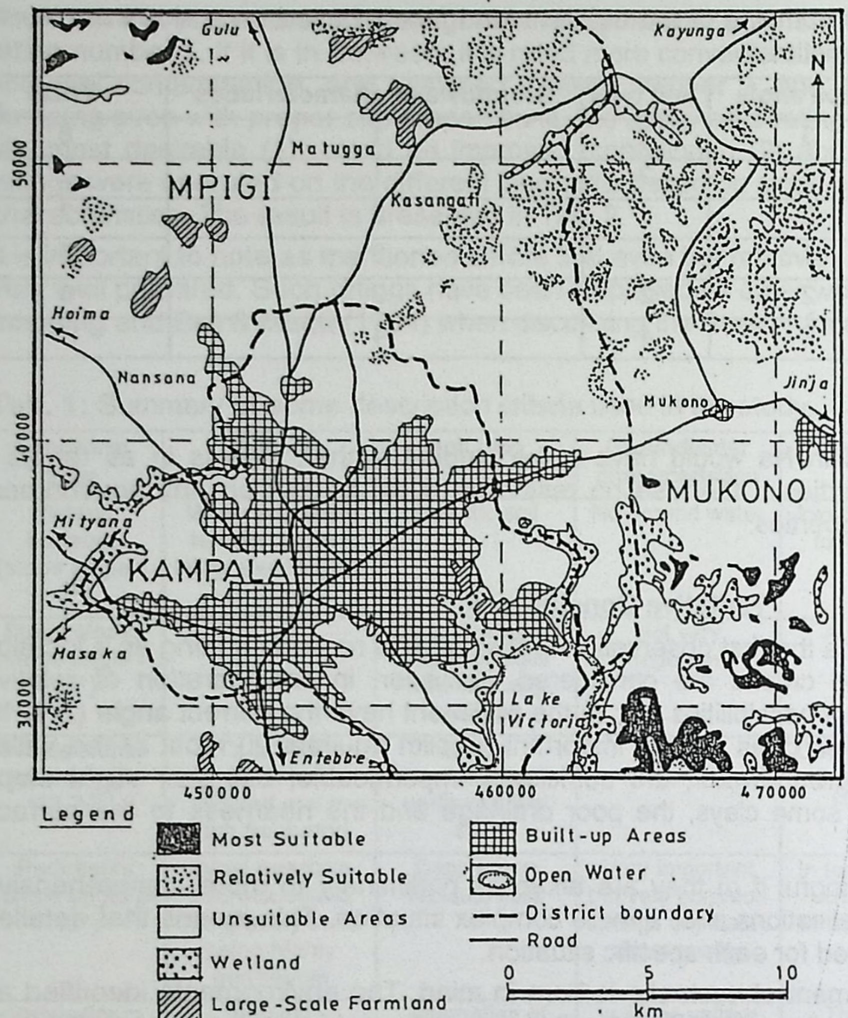


**Fig. 6:** Final output map indicating areas of relatively higher suitability for initial consideration for municipal solid waste dumping in Kampala and surrounding areas.

**Tab. 3:** Ranges and mean concentrations (ppm) of some trace and major elements determined in Kampala soils using ICP (inductively coupled plasm). Number of soils samples analysed is 44.

| Metal | Range | Mean | Metal | Range | Mean |
|---|---|---|---|---|---|
| Zn | 12.1 - 77.7 | 51.00 | Y | 1.1 - 31.6 | 12.04 |
| Pb | 5.9 - 70.2 | 28.04 | Zr | 6.0 - 135.0 | 56.09 |
| Co | 0.6 - 26.6 | 7.46 | Fe | 0.37 - 35.14 % | 9.51 % |
| Ni | 2.7 - 46.0 | 14.07 | Mg | 1.0 - 5521 | 399.93 |
| Cr | 21.4 - 911.3 | 133.00 | Al | 0.44 - 6.93 % | 2.48 % |
| Cu | 8.2 - 173 | 32.35 | Ca | 22 - 2097 | 515.46 |
| Sc | 0.4 - 37.5 | 10.34 | Na | 0 - 2280 | 679.75 |
| Yb | 0.4 - 9.8 | 3.81 | K | 41 - 6844 | 476.5 |

## Final Recommendations

No environment has been found to be ideal for dumping of municipal waste in Kampala and surrounding areas even at this preliminary stage. This means that every location chosen as relatively suitable, the following may have to be done: (i) further criteria would have to be considered and even an improvement of the suggested ones: specific criteria will have to be designed by the National Environment Management Authority, (ii) site preparation to improve the permeability of the underlying soils and hence the protection of groundwater and soil (iii) containing the solid waste and waste water from spreading and to (iv) monitoring the possible spread of the pollutants in the surrounding groundwater.

No spread of the dumpsite metal pollutants have occurred in the soil profiles around the studied old disposal sites in Kampala. However, the erosion into surface channels is a common phenomenon. Even the initial problems with Mpererwe landfill is the leachete flows into the surface stream affecting livestock. The short and long term effects of dumpsite on the environment need to be monitored continuously for pollution from disposal sites lasts for a very long time.

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# Engineering classification of the soils of Rwanda

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**Abstract:** A reconnaissance soil survey based on the underlying bedrock was carried out to begin a process of the engineering classification of the soils of Rwanda. Soils on most of the major rock groupings were sampled and their index properties of particle size distribution, atterberg limits and maximum densities and corresponding optimum moisture contents (for selected few samples) were determined and employed in soil classification. The Unified Soil Classification System (USCS) was used. However, comparisons with the British Soil Classification System (BS5930: 1981) was also included. The soils of Rwanda do not possess extreme properties. The highest plasticity index (PI) determined was 25.22% and the highest liquid limit (LL) determined was 57.18% and the later soil had a moderate plasticity index of 14.75%. Based on the United States Army Engineers Waterways Experimental Station (USAEWES), all the soils of Rwanda have a swell potential of < 0.5%, classified as low. Most of the soils plot close to the A-Line of the plasticity index chart indicating common mixtures of clays and silts in their fine fractions. They are largely of intermediate behaviour. The classes are CL, MH, GCL, GC, GM, SM, SC and others that can be described as gravel-sand-silt-clay mixtures. High values of dry density (d) are associated with gravely sandy soils, silty sands and laterites.

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## Introduction

Soils are very important in engineering either as foundations on which structures are built or as construction materials which can be borrowed from one site to another. They are also modified into specific construction objects like bricks and tiles. Knowledge of the physical characteristics of the soils helps in determining their suitability for any desired use. Therefore knowledge of the engineering characteristics of soils in a locality is very desirable. This report arose from the need to begin to compile the necessary data on the engineering character of the soils of Rwanda. This preliminary work involved a sampling principal based on the underlying bedrock. Soil samples were collected on all the major rock types in the country and it is reasonable to say that the data represents an important contribution to the process of building data bases on the engineering properties of the soils of Rwanda.

Bell (1983) states that although soils contain materials of various origin, for purposes of engineering classification it is sufficient to consider their simple index properties which can be assessed easily such as their particle size distribution, the consistency limits and density. Therefore engineering soil classification involves grouping different soils into classes of similar physical properties and appearance. This classification should to a limited level provide the engineering performance of a soil in regard to a particular engineering project.

## Rocks and Soils of Rwanda

### Rocks

Soils develop from the weathering of rocks. In engineering terms they mean materials that can be easily excavated and represent weathering products at various stages of disintegration and transformation. As already mentioned one of the conditions that determine the rate of weathering and the type of the products is the type of the parent rock. In less advanced weathering, the products and their characteristics are diagnostic of the parent material. But even in highly leached weathering products the parent material may bear some influence, albeit very reduced and subdued by other factors that influence the type and the rate of weathering. Soil sampling was based on the assumption that the physical characteristics of soils to a certain extent, are influenced by the parent material (bedrock). It is, therefore important to present the major rock types of Rwanda as a background to the sampled soils. The geologic map of Rwanda (Fig. 1) shows the presence of the following rocks and sediments;

a) alluvium of the valleys of Holecene to Pleistocene age,
b) Quaternary volcanic rocks of Birunga Chain and Tertiary Volcanic rock of Cyangugu. These are largely lavas, breccias and tuffs,
c) Pre-Cambrian Kibaran rocks of mica schists, phyllites, quartizites and sandstones, quarto-mica schists and meta-quatzites in various stratigraphic associations. Mylonites and quartz veins are associated with these rocks,
d) Associated with the metasediments of the Kibaran rocks are intrusive bodies (i) granitic rocks frequently rich in pegmatitic zones and (ii) narrow to wide zones of basis rocks falling in the category of dolerites, amphibolites and gabbros,
e) para gneisses and ortho gneisses,
f) Carbonate rocks: marbles, limestone/dolomites and travertine limestone

Soils

According to the soil map of Rwanda (Ministry of Agriculture and Animal Husbandry), the soils were classified based on the parent rock i.e. those derived from;

a) schistose formations, sandstone and quartzite
b) alluvial and colluvial sediments
c) organic soil,
d) calcareous rocks,
e) granite and gneisses
f) intrusive basic rocks of dolerites and amphibolites
g) recent volcanic rocks largely made of pyroclastics and lavas
h) association of volcanic rocks and Pre-cambrian rocks
i) Tertiary basaltic volcanoes (ancient).

The textural division and the soil taxonomy can be found on the above map. However, apart from the generalised clay content by weight, and the principle soil classification basing on the parent rock, the information provided is of less practical importance to the current objective of engineering soil classification. But the information is nevertheless relevant.

## Methodology

### Soil Sampling

The main aim of this project was to give in a very broad way the engineering classification of soils in Rwanda. The principle employed was the one based on the underlying bedrock. To limit the number of samples, the rocks were considered in their broader groupings rather than considering the smaller classes. It was assumed that at a sampling depth of 1 metre, where possible, the rocks do still have influence on the characteristics of those soils that result from their weathering. Even where the influence of the parent rock is strongly diminished like in most stable weathering products like laterites it was assumed to be a good guide. It is also reported that even in such more advanced weathering products the influence of the parent rock may still be relevant. Samples were collected from the west, east, central and southern parts of the country. It was possible to obtain representative samples on most rock types without going to the northern parts. This is possible because Rwanda is underlain largely by one system of rocks and associated structures i.e. the Kibaran metasediments and associated intrusive rocks. However, we missed sampling soils on the recent volcanics, which only occur in the northwestern part of the country.

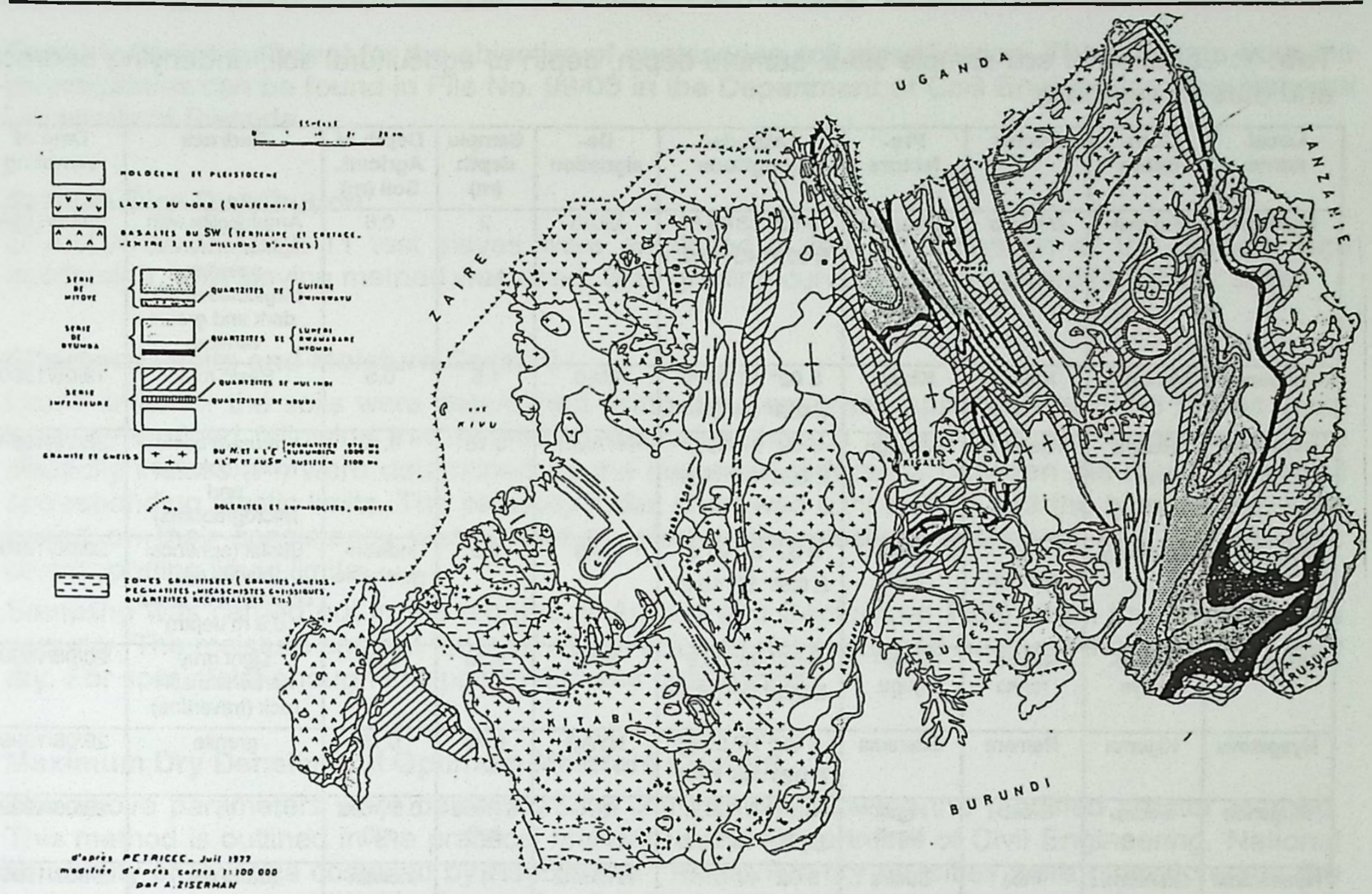



**Fig. 1:** A simplified geologic map of Rwanda (after Ziserman, 1977).

### Sampling Procedure

Where the depth of the soil permitted, soil samples were collected at a depth of 1 metre, well below the agricultural soil. This was made possible by pitting or from road cuttings. Field sample descriptions partly followed the procedure given by Anon (1981). A simplified description sheet was prepared and on it the following criteria were determined/described.

Date of sampling - Location: the local, commune, sector and the prefecture names - Longitude and latitude using a global positioning system (GPS) - Sample depth - Nature of soil (transported or in situ) - Depth of agricultural soil - Particle size/visual identification - Particle nature and plasticity - Compactness/strength - Structure - Colour - Underlying bedrock - Basic soil type

After the field description samples of about 30kg each were collected in sacks and carried to the laboratory for the determination of particle size distribution, Atteberg limits and maximum dry density and corresponding optimum moisture content. Locations, underlying bedrock, date of sampling and others are presented in Tab. 1.

### Laboratory Procedure

Soil analysis was carried out in the Department of Civil Engineering, the National University of Rwanda. The analyses carried out depended on the available facilities. There were no resources available to do more tests outside the University.

The following tests were done,

- particle size distribution within the coarse fraction of the soils the pipette or hydrometer apparatus for determining the particle size distribution in the fine fractions are not available
- Atterberg limits and
- compaction tests i.e. the determination of maximum dry density and corresponding optimum moisture content.

Tab. 1: Location of soil sample sites, sample depth, depth of agricultural soil, underlying bedrock and date of sampling.

| Local name | Com-mune | Sector | Pre-fecture | Latitude/ Longitude | De-signation | Sample depth (m) | Depth of Agricult. Soil (m) | Bedrock | Date of sampling |
|---|---|---|---|---|---|---|---|---|---|
| Mukingo | Kigoma | Mikingo | Gitarama | S 02° 18'06.8" E 029° 45' 46.2" | MUKI | 2 | 0.6 | Amphibolite with lighter minerals, possibly plagioclases and dark and green varietes | 29/08/1999 |
| Kimigenge | Mabanza | Kibirizi | Kibuye | S 02° o3' 31.4" E 029° 24' 35.4" | MAB | 1.5 | 0.5 | Basic rock | 19/08/1999 |
| Nyamu-rindira | Rukira | Ntaruka | Kibungo | S 02° 07' 39.2" E 028° 56' 15.9" | NYAMU | 0.15 | 0.10 | Intrusive basic rocks (dolerites and micrograbbros) | 28/08/1999 |
| Nyamu-tarama | Gishoma | Ga-shonga | Cyan-gugu | S 02° 37' 01.8" E 028° 56' 15.9" | GAS | 0.9 | indistin-guishable | Baslat (spherical blocks en-countered at about 0.9 m depth) | 20/08/1999 |
| Mashyuza | Nyaka-buye | Nyama-ronko | Cyan-gugu | S 02° 35' 06.9" E 029° 00' 58.6" | MAS | 0.30 | 0.30 | Light grey carbonate soft rock (travertine) | 20/08/1999 |
| Nyagatovu | Kigoma | Remera | Gitarama | S 02° 19' 58.8" E 029° 44' 53.4" | NYAG | 0.40 | 0.15 | granite | 29/08/1999 |
| Rugende | Gikoro | Gicaca | Kigali Ngali | S 01° 57'09.1" E 030° 14' 40.5" | RUG | 5 (road cut) | 0.5 (road cut) | | 29/08/1999 |
| Nyamirama | Gishamvu | Iriba | Butare | S 02° 40' 51.0" E 029° 43' 29.1" | NYAM 2 | 1 | indistin-guishable | quartz vein? | 24/08/1999 |
| Nyamirama | Gishamvu | Iriba | Butare | S 02° 40' 51.1" E 029° 43' 29.6" | NYAM 1 | 0.6 | - | Folded gneisses | 24/08/1999 |
| Migambi | Rukira | Rurama | Kibungo | S 02° 11' 48.2" E 030° 34' 53.6" | MIG | 3 | 0.5 | Soft shales | 28/08/1999 |
| Rwan-yanza | Kigembe | Nyaruteja | Butare | S 02° 48' 52.1" E 029° 43' 41.3" | RWA | 2 | very shallow | Mica schists with garnet (below a laterite) | 25/08/1999 |
| Kibingo | Gishamvu | Kibingo | Butare | S 02° 41' 29.7" E 029° 42' 49.1" | KIB | 1.6 | 0.4 | Mica schicts with muscovite crystals | 25/08/1999 |
| Kiyonza | Kigembe | Ngoma | Butare | S 02° 44' 20.8" E 029° 42' 04.8" | KIY | 6 | 1.5 | Laterite on mica schists | 24/08/1999 |
| Nyamirama | Gishamvu | Iriba | Butare | S 02° 40' 57.3" E 029° 43' 43.6" | NYAM 3 | 1 | 0.6 | Layered quartizite with mica specks | 24/08/1999 |
| Gakuto | Rukira | Gitwa | Kibungo | S 02° 09' 30.9" E 030° 36' 51.8" | GAK | 0.50 | thin | Laterite on a quartzitic sandstone | 28/08/1999 |
| Busonga | Kigoma | Mpanga | Gitarama | S 02° 18' 14.0" E 029° 44' 41.8" | BUS | 0.40 | 0.30 | Alluvial clay | 29/08/1999 |
| Akanya-mirama | Gishamvu | Kibingo | Butare | S 02° 42' 34.7" E 029° 42' 43.9" | AKA 2 | 0.26 | 0.25 | Alluvial fine sand | 24/08/1999 |
| Akanya-mirama | Gishamvu | Kibingo | Butare | S 02° 42' 34.7" E 029° 42' 43.9" | AKA 1 | 0.28 | 0.25 | Alluvial gravelly sand | 24/08/1999 |
| Nyabi-kenke | Kigembe | Karama | Butare | S 02° 45' 40.6" E 029° 43' 54.4" | NYAB 1 | 1.00 | thin | Peat (largely formed of semi-decomposed plant matter) | 25/08/1999 |
| Nyabi-kenke | Kigembe | Karama | Butare | S 02° 45' 40.6" E 029° 43' 54.4" | NYAB 2 | > 1.00 | thin | Clayey sand | 25/08/1999 |

These tests are sufficient for the objective of engineering soil classification. The raw data from the investigations can be found in File No. 99/03 in the Department of Civil Engineering, the National University of Rwanda.

**Particle Size Distribution**

STANDARD ASTM E-11 test sieves were employed in the determination of the particle size distribution. Wet sieving method was used. Size grading curves were prepared for all the soils.

**Atterberg Limits and Moisture Content**

Liquid limits for the soils were determined using the Casagrade apparatus and the plastic limits were determined following the method of fracturing threads of soil of 3 mm in diameter. The plasticity indices (PI) were determined as the numerical difference between the liquid limits and corresponding plastic limits. The plasticity index chart was constructed and the types of the soils based on their consistency were found by plotting the plasticity indices of soils versus their corresponding liquid limits.

Sampling was carried out in the months of August and September 1999 when the weather was very dry. The moisture content for most of the soil was not measured because the soils were very dry. For soils moist enough this parameter was determined.

**Maximum Dry Density and Optimum Moisture Content**

The above parameters were determined by compaction following the modified proctor method. This method is outlined in the practical manual for the Department of Civil Engineering, National University of Rwanda compiled by Nsabimana (1984). The dry densities were plotted versus the moisture contents and the maximum dry density and the corresponding optimum moisture contents for soils were determined.

**Soil Classification**

As mentioned before soils are classified based on easily determined soil properties of particle size distribution, Atterberg limits and density. Several systems of soil classification are in use.

Two of the most widely used ones are the Unified Soil Classification System (USCS) and British Soil Classification System, BS5930: 1981. The soil classes given in this report are based on USCS but comparisons based on BS5930:1981 are frequently provided especially concerning plasticity properties. Field description of soils was largely based on the comprehensive field description of soils after Anon (1981).

**Discussion of results of the investigation**

Particle Size Distribution

The results of the particle size distribution are presented as grading curves (Fig. 2). Grading curves for related soils were grouped together. This relationship was largely based on similarity of bedrock. Soils also related by being products of advanced weathering like laterites, though originating from different bedrock and others related in terms of the transport and deposition like alluvial sands and gravel were grouped together. These groups include soils developed on;

a) basis rocks; amphibolites, dolerites, gabbros and basalts - b) travertine limestone - c) granites and granite gneisses - d) shales and mica schists - e) quartzites

a) laterites - b) red tropical soils - c) alluvial sediments

The following observations are made from the grading curves;

a) soils developed on basic rocks have a high fine fraction, with the highest fraction >85% by weight of fines associated with the amphibolites of Mabanza, Kibuye and the basalts of Gishoma, Cyangugu.

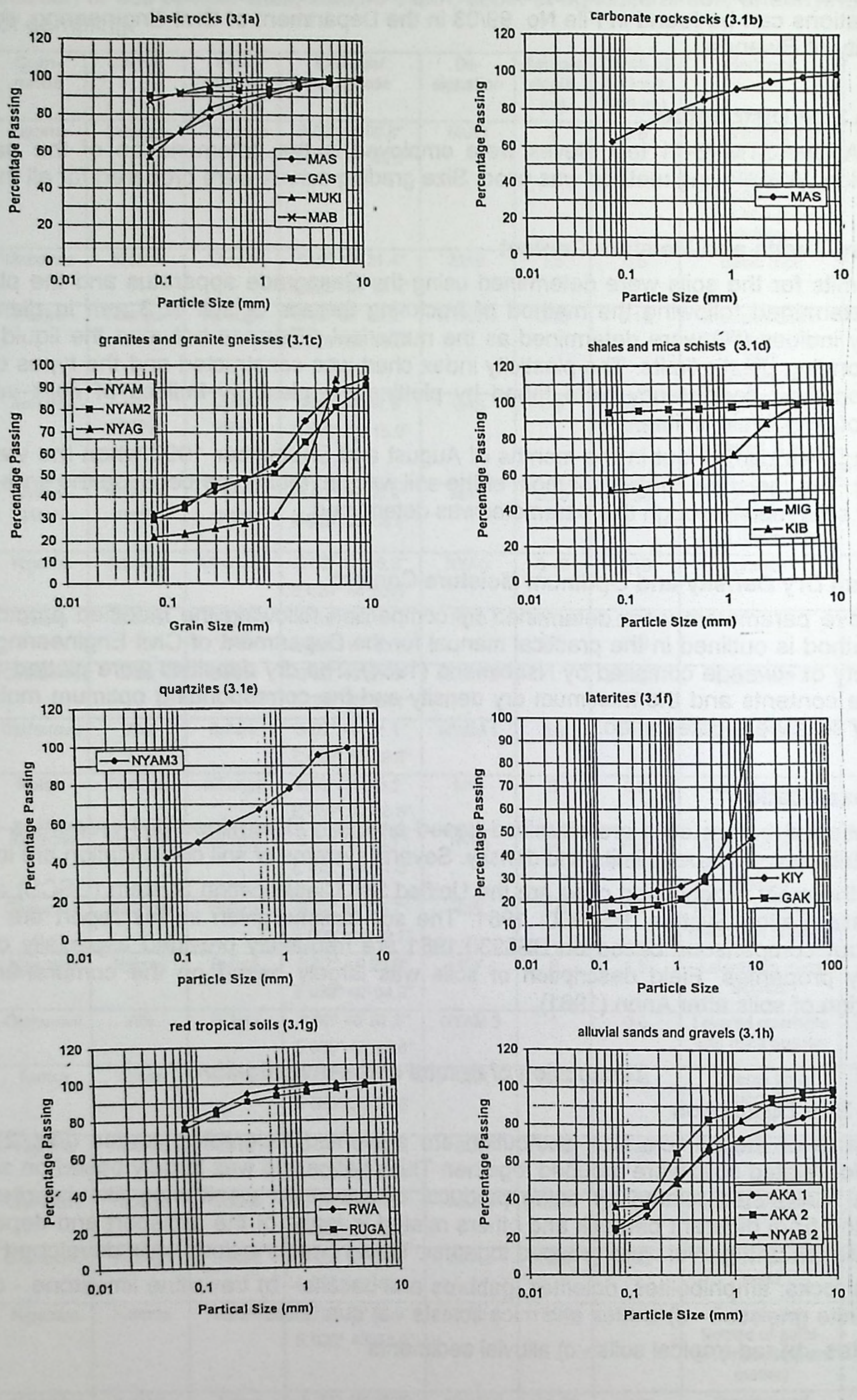



**Fig. 2:** Particle size distribution in the soils of Rwanda. The underlying bedrock is indicated where applicable, otherwise the typical soil type is indicated.

**Tab. 2:** Percentage by weight of particle sizes in the three classes of gravel, sand and fine fractions, Atterberg limits, moisture contents for few samples and predicted swell potentials are indicated. G = Gravel - S = Sand - F = Fines - MC = Moisture Content.

| Sample | % G | % S | % F | LL | PL | PI | MC | Potential swell (O'Neill & Poormoayed, 1980) |
|---|---|---|---|---|---|---|---|---|
| MUKI | 3.50 | 39.04 | 57.46 | 32.50 | 31.05 | 1.45 | | < 0.5 (low) |
| MAB | 1.50 | 11.55 | 86.95 | 46.00 | 24.32 | 23.85 | | < 0.5 (low) |
| NYAMU | 18.5 | 23.65 | 57.85 | 43.00 | 24.32 | 18.68 | | < 0.5 (low) |
| GAS | 5.00 | 4.85 | 90.15 | 57.18 | 42.43 | 14.75 | | < 0.5 (low) |
| MAS | 6.00 | 31.54 | 62.46 | 54.50 | 36.47 | 18.03 | | < 0.5 (low) |
| NYAG | 50.00 | 28.45 | 21.55 | 41.80 | 24.03 | 17.77 | | < 0.5 (low) |
| RUY | 16.00 | 39.29 | 44.71 | 37.40 | 28.37 | 9.03 | 5.735 | < 0.5 (low) |
| RUG | 3.00 | 21.47 | 75.53 | 32.12 | 20.80 | 11.32 | | < 0.5 (low) |
| NYAM 1 | 28.00 | 40.25 | 31.75 | 40.20 | 26.04 | 14.16 | | < 0.5 (low) |
| NYAM 2 | 37.00 | 33.37 | 29.63 | 34.00 | 24.75 | 9.25 | 7.58 | < 0.5 (low) |
| MIG | 2.5 | 3.25 | 94.25 | 38.00 | 22.47 | 15.53 | | < 0.5 (low) |
| RWA | 1.00 | 19.35 | 79.35 | 45.85 | 25.29 | 20.56 | | < 0.5 (low) |
| KIB | 15.5 | 33.16 | 51.34 | 38.20 | 20.47 | 17.73 | | < 0.5 (low) |
| KIY | 69.00 | 10.71 | 20.29 | 30.95 | 24.13 | 6.82 | | < 0.5 (low) |
| NYAM 3 | 7.00 | 50.62 | 42.38 | 40.70 | 31.01 | 9.69 | | < 0.5 (low) |
| GAK | 72.00 | 13.75 | 14.25 | 40.45 | 30.51 | 9.94 | 12.34 | < 0.5 (low) |
| BUS | | | | 48.20 | 22.98 | 25.22 | 45.50 | < 0.5 (low) |
| AKA 1 | 22.5 | 53.42 | 24.08 | | | | | |
| AKA 2 | 6.0 | 68.59 | 25.41 | | | | | |
| NYAB 1 | | | | | | | 534.43 | |
| NYAB 2 | 10.00 | 53.45 | 36.55 | 23.50 | 14.97 | 8.53 | 23.84 | < 0.5 (low) |

The amphibolites of Mukingo, Gitarama with presence of lighter minerals, possibly plagioclases or rhyolites and the dolerites and micro grabbros of Rukira, Kibungo have a relatively lower fine fraction of about 57% by weight and the next bigger percentage falling within fine sands.

b) shallow soils developed on the travertine limestone of Nyakabuye Cyangugu, possess a high percentage of fines, about 62% by weight. The remaining is largely composed of sand fraction in all sizes

c) relatively shallow, saprolitic soils developed on granites and granite gneisses are composed of atleast about 70% by weight of sand and gravels the rest fall in the fine fraction and are possibly mainly silts and kaolin

d) saprolitic soils in shale as indicated by those in Rukira, Kibungo are mainly fines with a percentage weight >90% by weight. Some mica schists like those at Kigembe, Butare have also a high percentage of fines at about 80% by weight. Mica schists with large crystals of muscovite possess a relatively lower percentage of fines, at about 50% by weight like that in Gishamvu, Butare.

e) soils developed on quartzite rocks contain more than 50% by weight of gravel and sands. The fine fraction may be largely made up of silt. The presence of the clay fraction may occur where the quartzites are interlayered with relatively thin layers of shales.

f) laterites or lateritic gravels are composed of about 70% by weight of gravel size and bigger particles. The grading curves compare well with concretionary gravels described by Gidigasu (1976). They are typically gap graded, missing or with very little sand fractions. The concretions tend to be cemented together in some laterites while the fabric is loose in others.

g) The deeply weathered red tropical soils have a fine fraction of at least 75% by weight with the remaining portion being largely made up of fine sands. According to Anon (1990) these are ferruginous and aluminous and clay soils which are frequent products of weathering in tropical latitudes.

h) The alluvial granular soils are mainly made up of well sorted sands (poorly graded) with at least 54% sand by weight to gravely sands with about 20% gravel and 50% sand by weight.

**Atterberg Limits**

Plastic limits (PL), liquid limits (LL) and plasticity indices (PL) for plastic soils were determined to facilitate in soil classification. Results indicate plasticity indices between 6.82% (laterite on mica schists) and 25.22% (alluvial clay). Some sample are non plastic. Non plastic soils include alluvial sand and gravely sands and a laterite formed on quartzite (GAK). Percentage by weight of particle sizes in the three classes of gravel, sand and fines, their corresponding Atterberg limits and swell potentials are compiled in Tab. 2.

Based on the plasticity index classes provided bu Anon (1979) the highest values of 18%-25.22% (highly plastic) correspond with alluvial clays, soils formed on basic rocks and a deeply weathered red tropical soil. However, The saprolite soil on the amphibolite rock at Mukingo has a very low plasticity index (1.45%) possibly due to a rather low weathering stage. The constituent rock minerals have not yet decayed into clay minerals but its soil structure is loose

Intermediate values of plasticity indices (10-17.77%) correspond with some granites and granite gneisses, shales and mica schists. Low values of <10% correspond with soils formed on some granites and granite gneisses, quartzites, alluvial clayey sands and laterites.

Soils of Rwanda do not possess extreme properties. The highest plasticity index recorded is 25.22% and the highest liquid limit recorded is 57.18% and the latter soil has a much reduced plasticity index of 14.75% (Tab. 2).

Based on the United States Army Engineers Waterways Experimental Station (USAEWES) classification of potential swell based partly on the liquid limit (LL) and plasticity index (PI), all the soils can be said to have a swell potential of <0.5 which is classified as low (Tab. 2).

A comparison between percentage fines and plasticity indices (Fig. 3) reveal that generally increases in percentage fines correspond with increases in plasticity indices indicating the importance of clay in the fine fraction. Others like soils developed on the basalt (GAS) and on travertine limestone (MAS) indicate a discrepancy, which could be due to a high percentage of silts in the fine fraction.

High percentage fines corresponding with relatively low plasticity indices may represent high silt content in the fine fraction or differences in clay types very conspicuous in soils developed on basalts (GAS), travertine limestone (MAS) kaolinitic soil developed on granite (RUY) and on the soil developed on soft shale (MIG). Low percentage fines corresponding with relatively high plasticity indices represent relatively high clay content in the fine fraction conspicuous examples being soil developed on intrusive basic rock (NYAMU) and on some granites (NYAG).

A plot of plasticity indices (PI) versus the liquid limits (LL) in a plasticity index chart was prepared and is presented in Fig. 4. Depending on the relative plotting position, the soil samples can be classified, based on the various ways the chart has been used in the past.

The demarcations of various plasticity descriptions presented in the chart are after the British System (BS5930:1981).

From the chart the following observations have been made. The studied soils fall mainly in 5 groups based on the BS5930: 1981;

a) clays of intermediate plasticity representing alluvial clays, soils developed on some basic rocks, some mica schist and red tropical soil

b) clays of low plasticity representing a clayey sand close to the region of mixed samples.

c) silts of high plasticity representing soils developed on the basalt and travertine limestone

**Fig. 3:** Comparison between plasticity indices and percentage fines by weight of the soils of Rwanda.

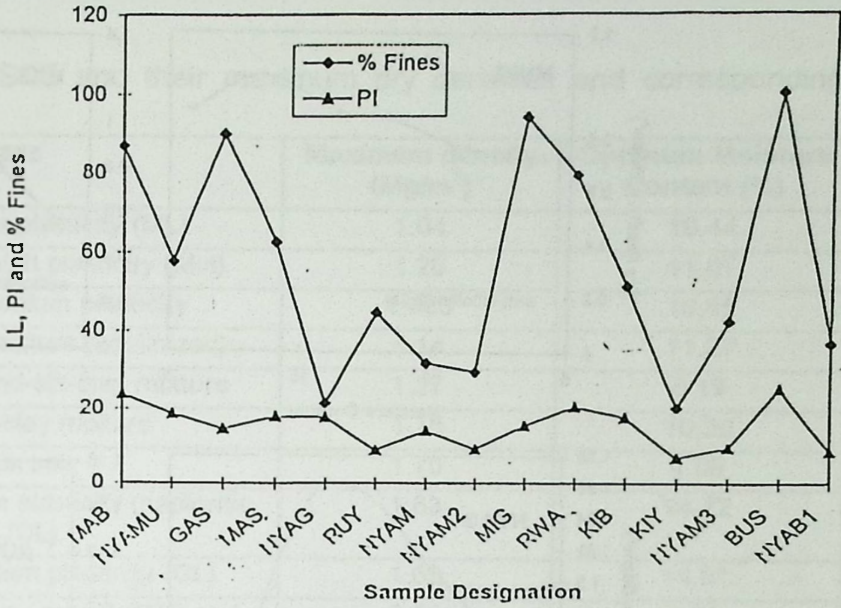
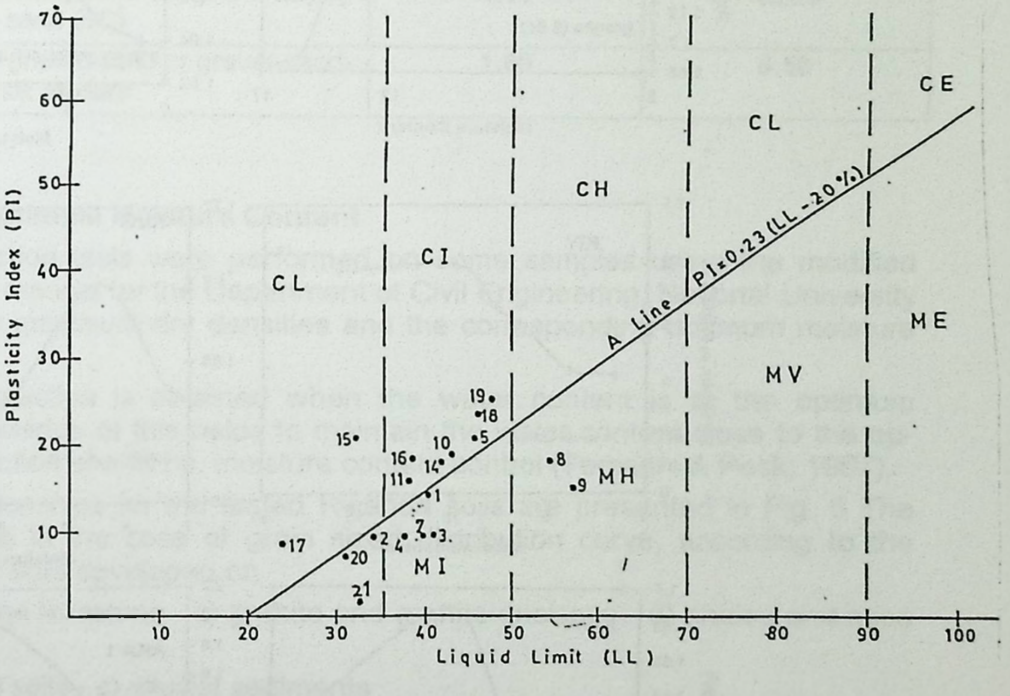



**Fig. 4:** Plots of the soils of Rwanda on the plasticity index chart.

**1** = NYAM1 **2** = NYAM2 **3** = NYAM3 **4** = RUY **5** = RWA **6** = KIB **7** = GAK **8** = MAS **9** = GAS **10** = NYAMU **11** = MIG **14** = NYAG **15** = RUG **18** = MAB **19** = BUS **20** = KIY **21** = MUKI




d) silts of intermediate plasticity representing soils developed on granite gneisses, granites and quartzites

e) silts of low plasticity representing soils developed on granite gneisses and some laterites.

It is important to note that most of the soils plot close to the A–Line indicating less extreme properties and the common mixtures of clays and silts in the fine fraction. They are of intermediate behaviour and can be described as clayey silts or silty clays (within the fine fraction)

**Soil Classification**

After the determination of the particle size distribution and the Atterberg limits, the soils were given classification symbols based on the Unified Soil Classification System (USCS). For comparison purposes, mention of the plasticity classes based on BS593:1981) are mentioned.

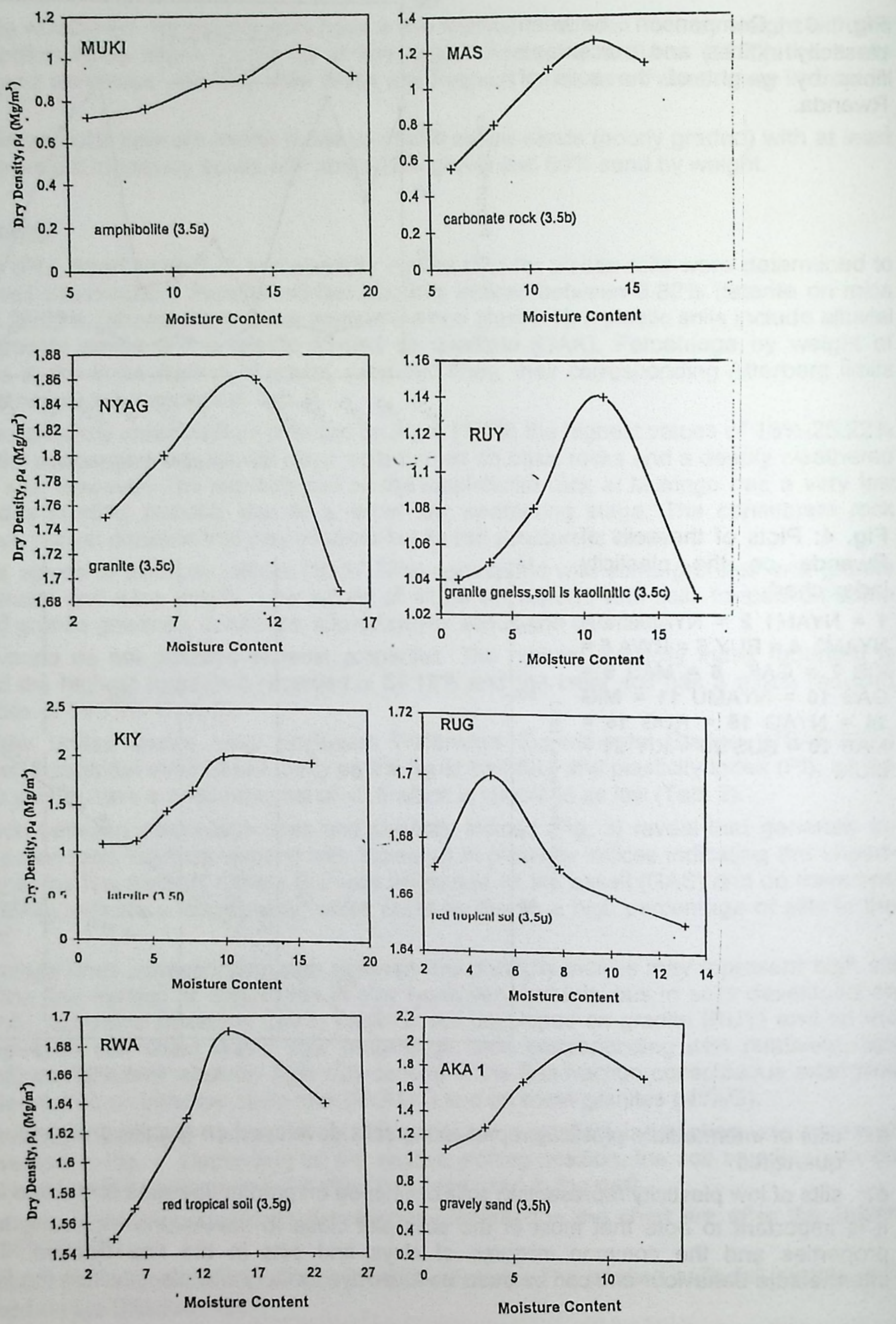



**Fig. 5: Moisture content- dry density curves for some soils of Rwanda.**

**Tab. 3:** Soils classes based on USCS and their maximum dry densities and corresponding optimum moisture contents.

| Soil sample | Soil Class | Maximum density ($Mg/m^3$) | Optimum Moisture Content (%) |
|---|---|---|---|
| MUKI | Silty soil of very low plasticity (ML) | 1.04 | 16.44 |
| MAS | Inorganic silty soil of high plasticity (MH) | 1.26 | 11.07 |
| NYAG | Clayey gravel of medium plasticity | 1.863 | 10.85 |
| RUY | Gravel-sand-silt-clay mixture (kaolinized) | 1.14 | 11.27 |
| MYAM2 | Well graded gravel-sand-silt-clay mixture | 1.27 | 8.19 |
| NYAM | Gravel-sand-silt-clay mixture | 1.78 | 10.20 |
| RUG | Red tropical soil | 1.70 | 4.99 |
| MIG | Inorganic clay of medium plasticity (saploritic material) (CL) | 1.63 | 14.72 |
| RWA | Inorganic clay of medium plasticity (CL) | 1.69 | 14.91 |
| KIY | Borderline between clayey gravel (GC) and silty gravel (GM) | 2.00 | 9.97 |
| NYAM 3 | Borderline between silty sand (SM) and clayey sand (SC) | 1.11 | 12.79 |
| AKA 1 | Non plastic poorly graded sand or gravel-sand-silt mixture | 1.99 | 8.50 |

**Maximum Dry Density and Optimum Moisture Content**

As mentioned earlier, compaction tests were performed on some samples using the modified proctor method outlined in the manual for the Department of Civil Engineering, National University of Rwanda, to determine their maximum dry densities and the corresponding optimum moisture contents.

The greatest degree of compaction is obtained when the water content is at the optimum moisture content and the knowledge of this helps to maintain the water content close to the optimum value during the compaction of a fill i.e. moisture content control (Terzaghi & Peck, 1967).

Moisture content-density relationships for the tested Rwanda soils are presented in Fig. 5 The curves have been grouped as in the case of grain sized distribution curve, according to the underlying bedrock. These are soils developed on

1. a) basic rocks - b) travertine limestone - c) granite and granite gneisses - d) shales and mica schists - e) quartzites
2. a) laterites - b) red tropical soils - c) alluvial sediments

The maximum dry density values and corresponding optimum moisture contents for the tested soils and the soil classes based on the Unified Soil Classification System are presented in Tab. 3. High values of dry densities given by previous workers like Terzaghi & Peck (1967) and Berry & Rheid (1987) indicate highest values for well graded sand, well graded silty sand, well graded sand with a small percentage of clay. The results obtained in the current work broadly agrees with the previous works. High maximum dry densities >1.8 correspond with silty gravel/clay gravel, and gravel-sand-silt mixtures.

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| Documenta naturae | 136 | 85-92 | Munich 2001 |
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# Some Aspects on the Seismic Risk in East Africa

Dirk Hollnack

**Abstract:** The Geology Department of the University of Nairobi started to build up a seismological network including six digital stations in 1990, mainly located in the southern part of the country. Between 1993 and 1999 the network detected about 9500 local and regional events, of which more than 7000 could be located. In general the magnitudes are quite small. Only two earthquakes with magnitudes (ML) larger than 5 (5.0 and 5.4) occurred, both in remote areas. For 56 events magnitudes between ML 4.0 and 4.9 were calculated. These results do not point to a high seismic risk, but historical data indicate that earthquakes of magnitudes up to 7 are possible.

A recent earthquake series at Lake Magadi (South Kenya) shows that the seismic risk potential is not only related to high magnitude earthquakes. In May and June 1998 more than 3000 events with magnitudes up to ML 4.1 occurred at the north-eastern edge of Lake Magadi. This activity caused a system of surface cracks which can be followed for several kilometres and openings of up to 35 cm. Additionally, information about historical earthquakes starting from 1880 as well as events from temporary networks are available. The picture of the seismic activity arising from this data-base is completely different from the one given by world-maps of the earthquake activities. On the basis of this set of data a seismic energy map for Kenya and adjacent regions is given. These investigation indicate an increased seismic risk potential for Kenya and its neighbouring countries, which proofs the need for a more detailed and continuous observation of the seismicity.

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## Introduction

Africa on its whole does not belong to the prominent seismic regions of the world. Other natural hazards, mainly floods and droughts, cause much more loss to life in Africa than seismic hazards. From world-maps, showing the distribution of major earthquakes determined by the global networks (Fig. 1), it becomes obvious that stronger seismic events are concentrated in the eastern part of Africa. This activity is mainly related to the East African Rift System (EARS), which splits in its central part into a western and an eastern branch. While the continuation of the western branch is marked by epicentres of prominent earthquakes, the eastern branch seems to be nearly free of seismic activity. This holds especially for Kenya which covers the major part of the eastern branch, also known as Kenya or Gregory Rift.

Less than 200 earthquake victims are reported for the Sub-Saharan part of the continent. This might lead to the impression that a seismic risk for Africa is not existing. One of the most hazardous earthquakes in Sub-Sahara Africa was the Tooro event (Uganda) of 20 March 1966 in which 160 people were killed, 1300 people injured and 7000 buildings were destroyed or damaged (Midzi et al., 1999). With a magnitude of about MS 6.1 this event does not belong to the strongest known earthquakes in eastern Africa which indicates that more factors than energy release have to be taken into to account to evaluate the seismic hazard potential. Pointing out some of those aspects is not meant as an earthquake prediction. The target is make aware of an existing hazard potential and the need to improve preparedness.

## The Database

Maps showing the global seismicity are limited to major earthquakes, normally starting from magnitudes of 4.5 or 5.0. For a more detailed view on the seismic activity in East Africa the region

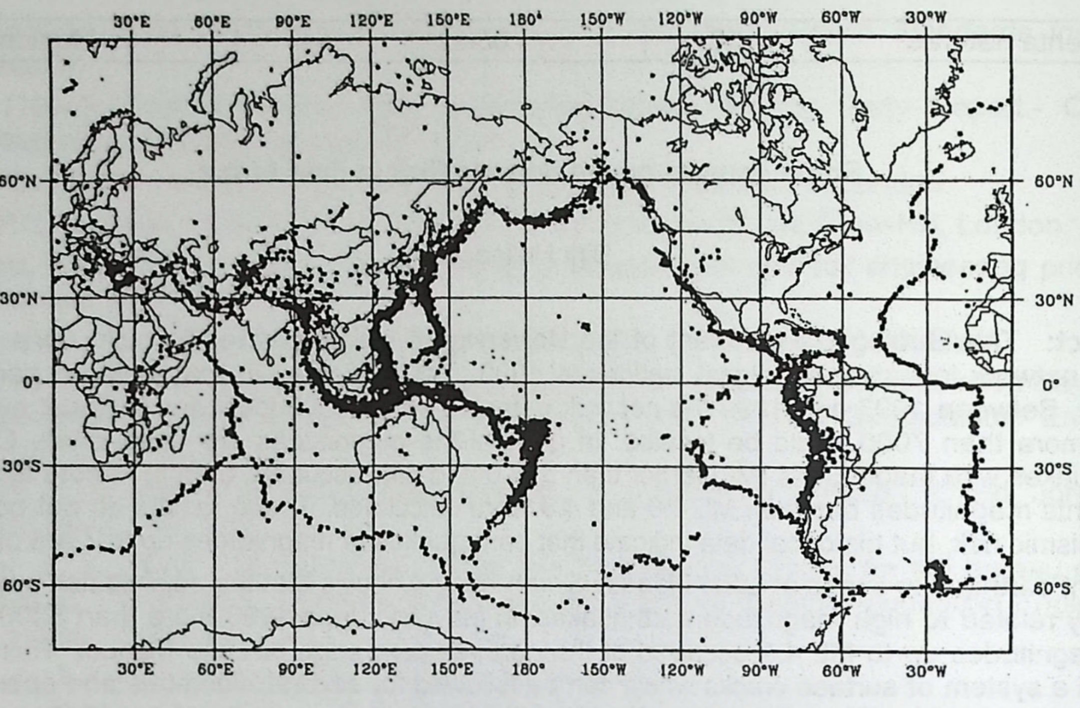



**Fig. 1:** Map of global shallow seismicity (U.S. Geological Survey), 1963-88, M > 5, depth < 70km [Bolt, 1993].

between latitudes 10°N to 10°S and longitudes 20°E to 50°E was selected (Fig. 2). All available earthquake information, historical as well as instrumental, were used to build up a database for this area. The focal parameter are taken from six main sources:

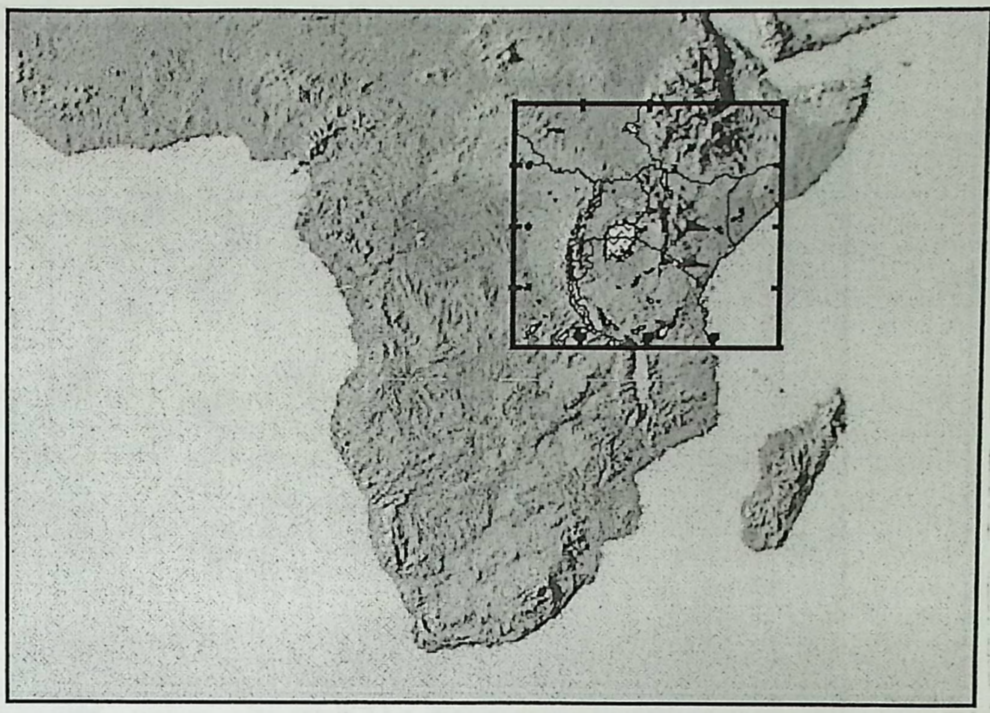
- Sha (1986), PhD Thesis
- Iranga (1991), Seismological Report
- Midzi et al. (1999), GSHAP Report
- USGS, NEIC database of the world-wide network
- ESARSWG Bulletins
- UoN Seismological Network

The studies 1-3 are themselves based on data-collections from different sources (i.e. Båth, 1975; Maasha, 1975; Ambraseys, 1972; Loupekine, 1971; Rodrigues, 1970) to give a comprehensive picture of the seismicity of a certain area of investigation. While Sha (1986) mainly concentrated on Kenya, Iranga (1986) covered Tanzania and wide parts of the western branch and Midzi et al. (1999) includes the whole region of the East African rift system.

Sources 4-6 are based on instrumental observations of different station networks. The USGS/NEIC (United States Geological Survey / National Earthquake Information Centre) catalogue includes station-readings from all over the world and starts at magnitudes of about 4.0 to 4.5. The ESARSWG Bulletins (East and South African Regional Seismological Working Group) are a compilation of earthquakes with magnitudes larger 3.0 recorded by stations in East and South Africa, including the University of Nairobi (UoN) seismological network which is fully operational since 1995 and mainly covers the southern part of Kenya. Since this time the earthquake observation for the EARS by the UoN network is complete for magnitudes of $M_L$ = 2.8 (Hollnack & Stangl, 1998). The distribution of active stations within the area of investigation is shown in Fig. 3.

The resulting database is made up of 9338 localised events and covers a time-period from 1841 until October 1999. At the current state the database has weak points, some of which have to be accepted as permanent:

**Fig. 2:** Relief map of Africa showing the area of investigation (Long.: 20°-50°E, Lat.: 10°N-10°S).



- Incompleteness: It is believed that all known major earthquakes (magnitude > 5.5) are included, but existing observations of some medium sized events are probably and numerous small events are definitely missing.
- Heterogeneous observation sensitivity in time and space: The distribution of earthquake-stations in East Africa is very uneven (Fig. 3). Therefore micro-seismicity of wide region remains unobserved. In addition to this, even permanent stations were not operational for longer time periods because of financial or political reasons.
- Missing ore unsure focal parameter: This mainly holds for historical events. In many cases focal time and location of the epicentre are only guessed. Details on focal depths are normally missing until 1966 and magnitude calculations are based on estimated intensities until 1954.
- No uniform magnitude scales: The data sources used for the present study are giving homogeneous magnitudes but they are using different scales. These values are not yet unified which has to be kept in mind for the later discussion on the seismic energy.

### Epicentral Distribution and Seismic Energy Release

The epicentral distribution of all earthquakes (Fig. 4) clearly shows a concentration of seismic events along both rift branches. While the shape of the western branch is quite well copied by epicentres, the activity related to the Gregory Rift is much more scattered. The northern part of the Gregory Rift, with the exception of a few events at Lake Turkana, seems to be nearly free of earthquakes. To eliminate the influence of the station-distribution, only events with magnitudes larger 4.9 are plotted in Fig. 5. The picture remains similar for the western branch. However, the number of large events in the Kenyan part of the Gregory Rift is significantly smaller than in the Tanzanian part which points to different energy release characteristics. This impression is strengthened by a seismic energy map (Fig. 6) which is based on the moving block method of Båth (1982). For this map the total seismic energy was computed for squares of 0.5° x 0.5° by summing the energy of each earthquake within the block borders. Afterwards the resulting energy was reconverted into a local magnitude and the block were moved by 0.25° to obtain some overlap and smoothing. The resulting energy map shows that energy release in the southern (Tanzanian) part of the Gregory Rift is higher than in the northern (Kenyan) part.

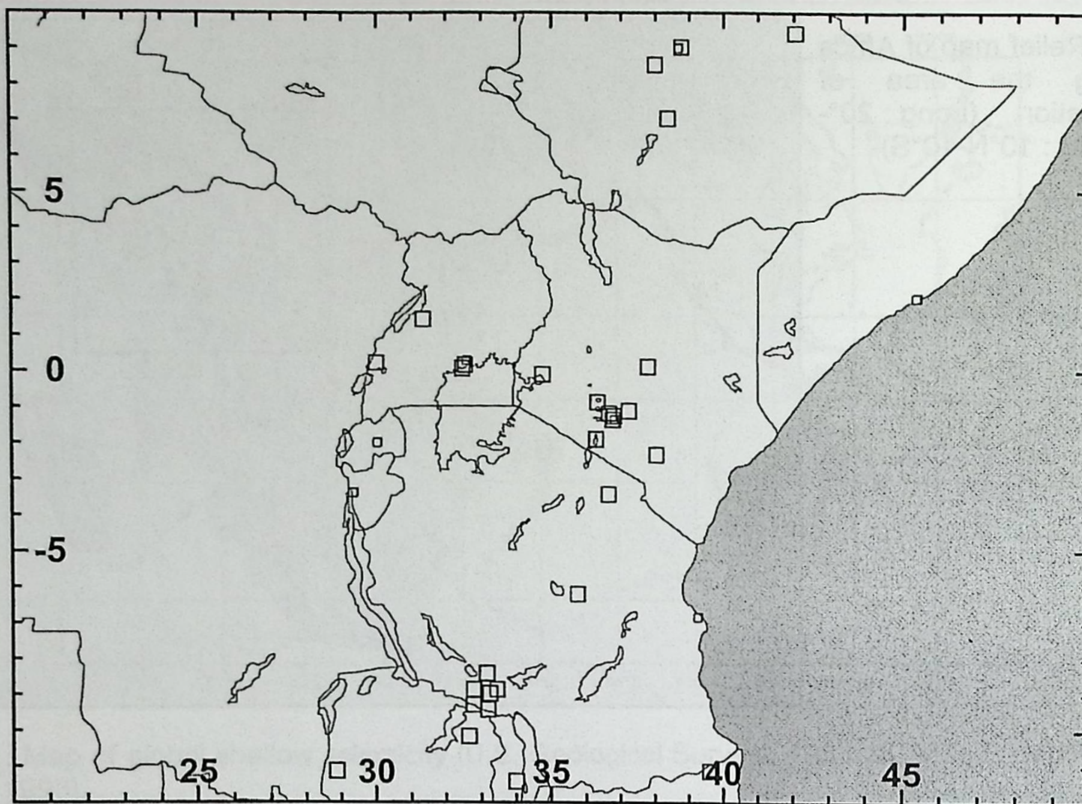



**Fig. 3:** Distribution of permanent earthquake-stations (large open squares) in the are of investigation.

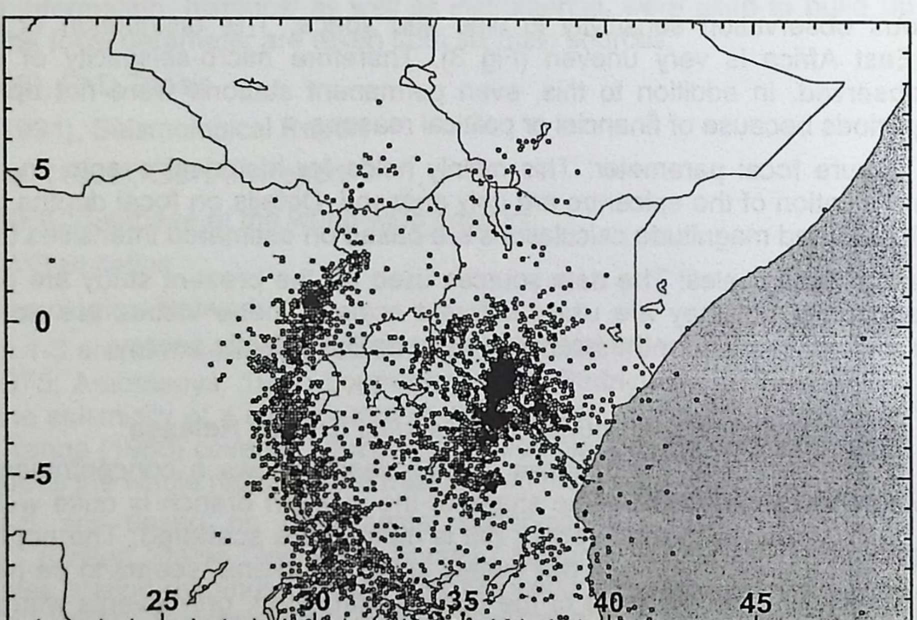



**Fig. 4:** Epicentral distribution of 9338 earthquakes between 1841-1999.

On the whole 15 events are given with magnitudes larger than 6 and more than 450 with magnitudes between 5.0 and 5.9 (Fig. 5). The largest earthquake occurred in 1990 in south Sudan with a magnitude of about 7.4. But earthquakes can be already destructive from magnitudes in the range of 5 which have already occurred in nearly all parts of the central EARS. Compared to this number of potentially destructive earthquakes the amount of reported hazards for East Africa is very small. Main reasons for this might be the following:

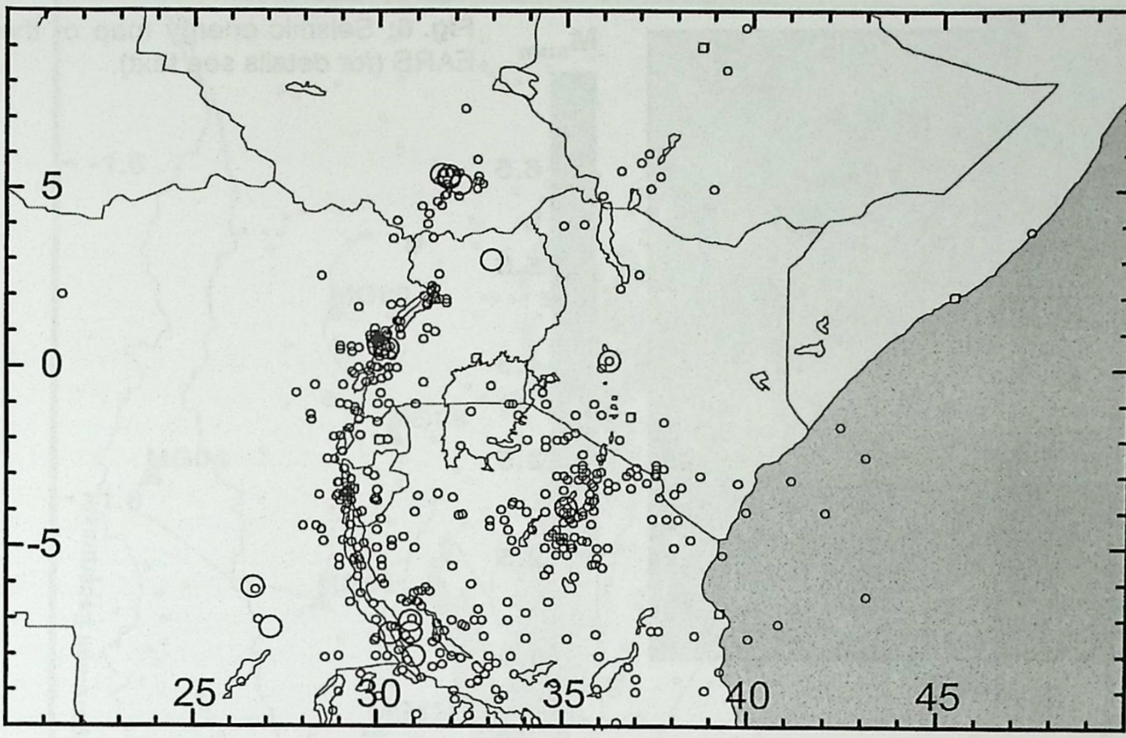



**Fig. 5:** Epicentral distribution of major events. Small circles: magnitudes 5.0-5.9; large circles: magnitudes > 5.9.

- No large basins with deep sedimentary cover which could cause an amplification of destructive frequencies.
- Most of the major earthquakes occurred in remote areas.
- The traditional buildings are made of very light materials.

But increasing population and urbanisation during the last decades leads to a higher hazard risk. The traditional light, flat buildings are more and more replaced by several storey houses constructed of bricks and concrete. The consequences of this changes might become obvious by the example of the Subukia Valley earthquake on 1928 January 6. A detailed analysis of this event and the amount of related damages is given by Ambraseys (1991). With a magnitude of $M_s$ 6.9 this is the strongest known event in Kenya.

The earthquake was associated with a 38 km long surface break and a maximum throw of 240 cm, an indication for a very small focal depth. Compared to the high magnitude damages are quite small and no victims are reported. In 1928 the focal area was sparsely populated and Nakuru was a village, but meanwhile it is the third largest town in Kenya. A return of the Subukia event would hit Nakuru with an intensity of about VII to XIII on the MSK-scale which would in all probability cause a disaster.

## The Magadi Project

But not only large magnitude earthquake can cause destruction. Between November 1997 and June 1998 a seismological station network was run at Lake Magadi (south Kenya, about 70 km sw of Nairobi). This field-experiment was part of a joint project between the UoN Geology department and the Geophysics Department of the University of Aachen (Germany). On the whole more than 5500 earthquakes were recorded, including a swarm activity lasting from May to June 1998. The locations of the stations and the epicentres of 1077 localised events are shown in Fig. 7. A detailed description of the investigations and results is given in Ibs-von Seht et al. (2000).

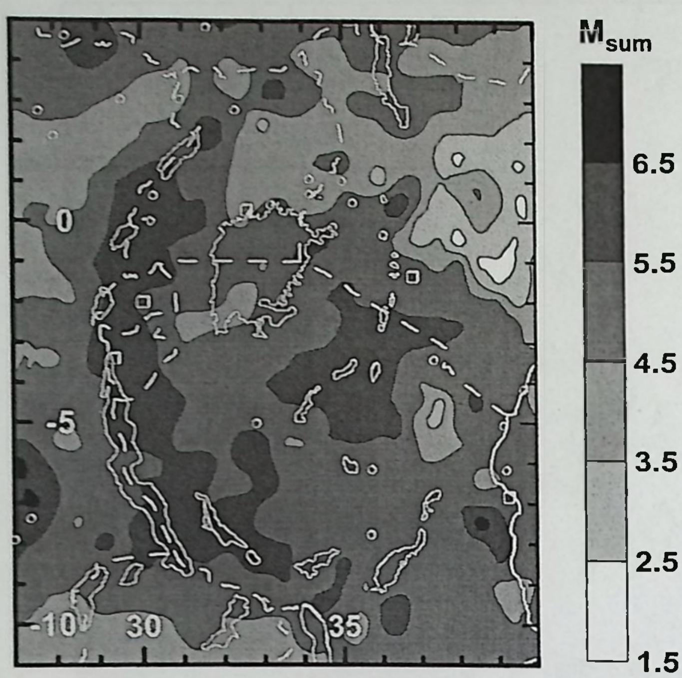



**Fig. 6:** Seismic energy map of the central EARS (for details see text).

For the present study it is of importance that a surface crack opened during the swarm activity although the largest event had a magnitude of only 4.1. The crack was located just NE of Lake Magadi and could be followed for several kilometres. The surface opening reached up to 50 cm and possible consequences for high storey buildings or other sensitive constructions are easy to imagine.

## Summary and Conclusions

East Africa is a region of seismic risk potential. Major earthquakes can occur nearly everywhere in the region of the central EARS. Since focal depths are in general very small, also medium sized events can already cause surface or topography changes and are therefore a risk for sensitive constructions.

Because of growing population-density, urbanisation, changing building materials and rising number of sensitive constructions (i.e. high-storey buildings, dams, bridges, ...) the seismic hazards risk increases with time. On the other hand the seismic hazard risk seems to be underestimated. To acquire a better preparedness for earthquake hazards the following measures should be taken:

- More detailed observations and investigations of the seismicity (i.e. seismic risk maps) are required.
- The seismic risk has to be taken into account for future constructions.
- Emergency plans are necessary, especially for the large cities.

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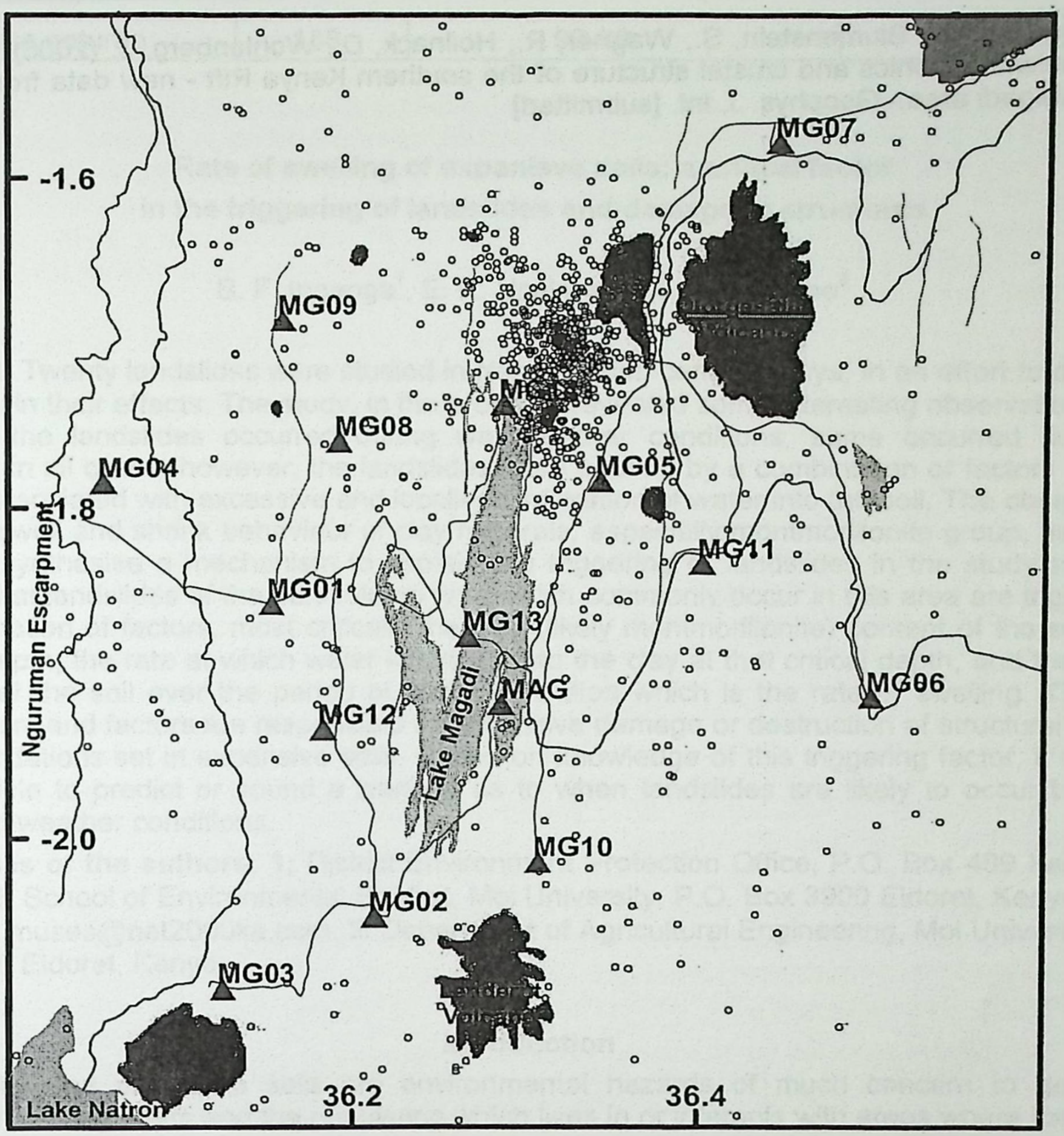


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| Documenta naturae | 136 | 93-98 | Munich 2001 |
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# Rate of swelling of expanisve soils: a critical factor in the triggering of landslides and damage to structures

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**Abstract:** Twenty landslides were studied in Nyeri district, central Kenya, in an effort to document and explain their effects. The study, in the process, revealed some interesting observations; while most of the landslides occurred during wet weather conditions, some occurred during dry weather. In all cases, however, the landslides were caused by a combination of factors but were always associated with excessive and localised infiltration of water into the soil. The observations, and the swell and shrink behaviour of clay minerals, especially montmorillonite group, have been used to synthesise a mechanism to explain the triggering of landslides in the study area. It is argued that landslides of the earth slump type which commonly occur in this area are triggered by a combination of factors, most critically the clay (likely montmorillonite) content of the soil at the critical depth, the rate at which water infiltrates into the clay at that critical depth, and the volume change of the soil over the period of water infiltration which is the rate of swelling. The same mechanism and factors are responsible for extensive damage or destruction of structural features with foundations set in expansive soils. Based on knowledge of this triggering factor, it may also be possible to predict or sound a warning as to when landslides are likely to occur based on observed weather conditions.

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## Introduction

Landslides and expansive soils are environmental hazards of much concern to geologists, geotechnical engineers and the population which lives in or interacts with areas where they occur. Landslides belong to the geological processes referred to as mass movement or mass wasting. Landslides result in human and livestock/animal fatalities and in the destruction of the landscape, structures, infrastructures and agricultural lands. Some of the effects of the landslides are direct and immediate while others are indirect and may be longer term. Damages caused by landslides are estimated in millions of dollars annually while fatalities due to the same around the world are in thousands of people (Kozlovskii, 1988).

The term "Landslides" is used generally for all mass movements down-slope. However, based on the mechanism of slide and the material involved, they are classified according to the shape of the slide surface as slumps or rotational slides and block glides or translational slides. Slumps or rotational glides move on curved, concave upward slide surfaces and are self-stabilising while block glides or translational slides move on inclined slide planes until they meet an obstacle or until the slope of the slide plane changes (Pipkin, 1994).

Causes of landslides are categorised broadly into two types as being due to internal (endogenic) factors and external (exogenic) factors (Alexander, 1992). Examples of internal factors commonly cited are increase in water-pore pressure or decrease in the cohesion of the slope material. External factors could be disturbances such as earthquake shocks, vibrations from vehicles and/or operation of heavy machinery in the vicinity, artificial increase in the slope angle, added weight on top of the slope and removal of lateral support from the toe of the slope (Alexander, 1992).

Expansive soils exhibit marked changes in volume when moisture is added to or removed from them. They are found in areas commonly associated with basic volcanics. Structures and infrastructures whose foundations rest in or above expansive soils suffer damages, often cracks and/or tilting due to vertical or lateral forces exerted on them by the unstable soils they are in contact with. Foundation engineers in some countries such as the USA have been subjected to lawsuits as a result of damages caused by expansive soils, to structures or infrastructures they put up (Chen, 1988). Swell-shrink in clay soils have caused losses of up to £ 2b in recent years in the United Kingdom while in the United States expansive soils give rise to higher bill for insurance claims than any other geohazard (Bell & de Bruyn, 1997).

This paper attempts to synthesise a mechanism for the triggering of landslides, based mainly on observations made on the earth slump type of landslides in Nyeri district, Kenya and on the known swell and shrink behaviour of clay minerals, especially montmorillonite which is presumed to constitute a significant proportion of the soils in this area.

## Previous studies on expansive soils and causes of landslides

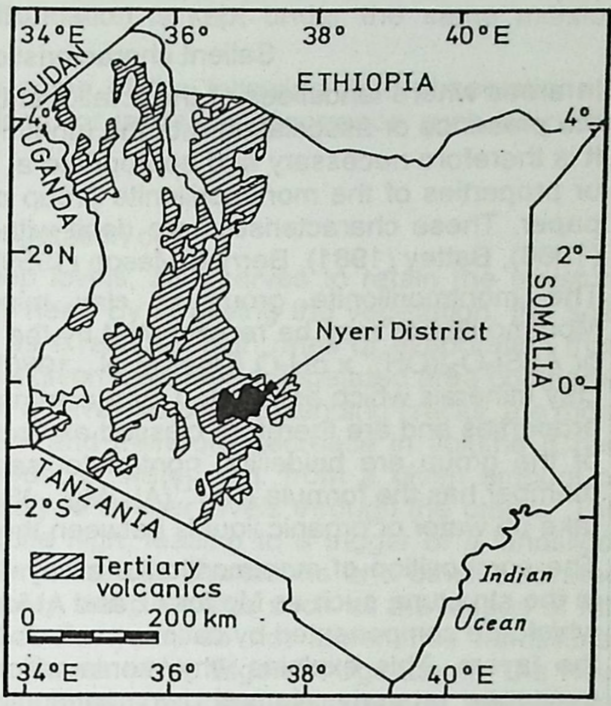
The problem of expansive soils was first recognised in 1938 by the US Bureau of Reclamation in connection with a foundation for a steel siphon at its Owyhee Project in Oregon (Chen, 1988). It was realised that damage caused to structures, hitherto attributed to foundation settlement, was actually due to heave by expansive soils. Since then, there has been a world-wide interest and research on expansive clays and shales. The first international Research and Engineering conference on expansive clays was held at the Texas A & M University in 1965. Since then, the International Conference on Expansive Soils has been held every four years (Chen, 1988). Research on expansive soils have focused mainly on their relationship to damage to structures and infrastructures. On the other hand, research on landslides have focused mainly on the mechanisms by which they are triggered. It has been recognised, both empirically as well as from deductive evidence, that landslides are triggered by a combination of factors which vary from human to natural. In standard texts on surface geological processes, e.g. Smith (1996), Pipkin (1994), Kozlovskii (1988), Montgomery (1992), Cooke & Doornkamp (1990), Keller (1982), and others, the factors are commonly cited as:

(i) increase in slope angle
(ii) high rainfall followed by increased water-pore pressure
(iii) removal of lateral support at the toe of the slope
(iv) added weight at the top of the slope
(v) earthquakes and other shocks and vibrations
(vi) removal of vegetation

## Some observations of landslides phenomenon in Kenya

Kenya has also had its shares of problems of landslides and expansive soils. The geology of central Kenya is dominated by the Rift volcanics and the volcanics associated with Mt. Kenya and the Aberdares mountain ranges (Fig. 1). These are, in many parts, composed of basic volcanic material. Weathering of these basic volcanic material, over the years, have produced deep profiles of soils rich in the montmorillonite group of clay minerals. High relief rainfalls associated with the windward sides of Mt. Kenya and the Aberdares have given rise to a dissected and rugged terrain of the Muranga and Nyeri districts of central Kenya. These two districts are also among the most densely populated in the country. Due to population pressure, the land is intensively cultivated, including the steep slopes (>30°) and settlements have often been built on terraces on these steep slopes. The combination of the steep slopes, high rainfall and poor land use practices, have resulted in frequent landslide occurrences, particularly in these two districts, many of which have resulted in heavy fatalities, and destruction of property and infrastructure in the recent past. In some cases the landslides were triggered by earthquakes (Inganga, 1995).

Fig. 1: Location of Nyeri District in Kenya, also showing the distribution of Tertiary volcanic rocks in Kenya (derived from Geology of Kenya, 1:3,000,000 compiled by Geology and Mines, 1977, and published by Survey of Kenya, Nairobi, 1985).




Damages to structures, particularly buildings and tarmac roads in many parts of Kenya where deep profiles of soils have developed from the basic volcanic material are common but systematic study has not been done to document these.

In Kenya, as in other parts of the world afflicted by frequent occurrence of this environmental hazard, studies have been conducted to try to understand the causes of landslides. Davies (1996) reviewed some of the most significant of these studies. Inganga (1995) studied 20 landslides in Nyeri district in an effort to understand their effects. The study revealed some interesting observations.

Although most of the landslides occurred during the rainy season and following intense rainfall, in at least three cases the landslides occurred during dry weather. In one such a case, water that was flowing through a narrow cemented irrigation channel which was constructed along a contour, leaked at one point and infiltrated to very deep (> 3 m) levels of the soil profile on the steep slope. A landslide resulted. In yet another case, water that had been stored in a tank on a ridge, leaked and flowed down slope but along the ridge. In an attempt to trap the water, one of the local residents dug a deep trench in the path of the water. Instead, the water infiltrated through the bottom of the trench to deeper levels of the soil profile and a land slide occurred on the slope immediately below the trench. In the third case, a landslide occurred on September 20, 1992, along the water pipe line that supplies Othaya town in Othaya division of Nyeri District. The pipe was damaged at that point. Although it could not be ascertained as to how the landslide was triggered, and although most observers claimed that the landslide broke the pipe, it is highly possible that a leakage in the pipe at that point could have instead triggered the landslide.

Many other landslides occurred on slopes that had been made nearly bare due to human activities such as cultivation, deforestation and terracing for construction.

In all cases, studies of the soils within the scars of the landslides, conducted by Inganga (1995), revealed high contents of clays, although the specific mineral types were not identified. It is highly probable that most of the clay is comprised of montmorillonite.

It was also interesting to note that actual field survey and interviews with the local residents and officials of the Mt. Kenya National Park and Aberdares National Park revealed no occurrence of landslides within the forested slopes of Mt. Kenya and the Aberdares mountains, in spite of the high rainfall and very steep slopes in these areas.

## Discussion

### Salient characteristics of the Montmorillonite group

In areas where landslides of the rotational type occur and in areas with expansive soils problem, the presence or association with the montmorillonite group of clay minerals has been recognised. It is therefore necessary and appropriate at this point to review some of the salient characteristics or properties of the montmorillonite group of clay minerals that are relevant to the theme of this paper. These characteristics are dealt with in many standard mineralogy texts, e.g. Deer et al. (1966), Battey (1981), Berry & Mason (1959) and many others.

The montmorillonite group of clay minerals belong to the layered or sheet silicates. Montmorillonite may be represented by the formula $Al_2Si_4O_{10}(OH)^2$ x $H_2O$ (Berry & Mason, 1959) or $Al_4Si_8O_{20}(OH)^4$ x $nH_2O$ (Deer et al., 1966). Chemical variations of this formula yield a group of clay minerals which are related by a common structure and by similarity of chemical and physical properties and are therefore classed as "montmorillonite group" (Deer et al. 1966). The members of the group are beidellite, nontronite, saponite, hectorite and sauconite. The montmorillonite member has the formula $(Na)^{0.7}(Al_{3.3}Mg_{0.7})Si_8O_{20}(OH)^4$ x $nH_2O$. All are swelling clays, i.e. they can take up water or organic liquids between their structural layers.

The composition of montmorillonite always deviates from the ideal formula through substitutions in the structure, such as Mg for Al, and Al for Si. This leads to a net negative charge on the layers which are compensated by cations such as $Ca^{2+}$, $Na^+$ and $H_3O^+$ (i.e. $H^+$ + $H_2O$) adsorbed between the layers. This explains why montmorillonite swells when immersed in water and its cation exchange property. Natural dry montmorillonite clays will have less than 15% water content. When exposed to moisture, the clay absorbs moisture up to 30% - this is near the moisture saturation point (Chen, 1988). Under natural conditions, the desiccation level or water content will depend on the ambient temperature and the availability of moisture.

### The rate of swelling of the clays as a factor in triggering of landslides: A theory

As noted earlier, some landslides occurred during dry weather but were associated with excessive infiltration of water into the soil at some localised point. Among the factors commonly cited as the contributors to landslide occurrence are steep slopes, heavy rainfall which then leads to increased pore-water pressure, removal of lateral support at the toe of the slope and added weight at the top of the slope.

Although many locations have a combination of the above factors at play at any one time, landslides may not occur at these locations. This has shed light on three parameters that, given the wrong combinations, might give rise to one of the most critical factors in the triggering of landslides. These parameters are: i) the clay (montmorillonite) content of the soil at a particular depth, ii) the rate at which water infiltrates into the clay at that depth, iii) the volume change of the soil over the period of water infiltration.

A given combination of these three parameters will result in a certain rate of expansion of the soil. For a given clay content of the soil there will be a maximum swell volume or expansion index. The volume change will depend on the initial moisture content of the soils and the amount of water/moisture available, but will reach a maximum when the liquid limit is reached or the supply of water stops. The initial moisture content of the clays which determines the volume change, in turn depends on temperatures that have prevailed in the area. Assuming availability of the critical water quantity to achieve the maximum volume change or the expansion index, the greater the volume change and the higher the rate of swelling to achieve that maximum volume, the greater the forces exerted laterally or vertically in unit time. Under these circumstances frictional forces or sliding inertia are easily overcome. An analogy may be drawn with the situation of applying stress to bend or stretch a semi-elastic material. If the stress is applied rapidly, the semi-plastic material easily breaks, whereas if it is applied slowly, the material may be able to bend or absorb much more stress and for a longer duration. This concept would also apply to the mechanism by which the expansive clays are able to cause extensive damages structures with foundations in soils rich in these clays. It is also common observation that even structures with foundations set in soils rich in these clays remain stable provided that the foundation is kept under the same moisture condition always; dry or wet.

The theory expounded above can help to explain some of the following field observations or landslide phenomena, assuming that other conditions for landslide occurrence such as critical slope factor and soil type, have been met:

Effect of removal of vegetation cover

Vegetation cover, although allows infiltration to deep levels, also serves to retain the moisture longer by shielding the ground from the direct sun's heat. By removing the vegetation, the soils are exposed to the heat and high loss of moisture as a result of high rates of evaporation from them. The desiccation level of the clays is higher at a given depth for a vegetated area compared to a bare area. The dryer the soil becomes, the more it develops deep-extending cracks, the more the montmorillonite minerals lose their water content and therefore decrease in volume (Chen 1988). Therefore, when subjected to a certain amount of water, e.g. from a given amount of rainfall, the bare soil will take in the water more rapidly to deeper levels through the cracks. The rate of expansion of the soil at this depth will be quite high, leading to a trigger of a landslide. Examples are the landslides which occur commonly in the tea plantations and other cultivated slopes (Inganga, 1995). Vegetated slopes, even in very steep terrains such as the slopes of Mt. Kenya which also receive a lot of rainfall much of the year, do not experience landslides. Landslides also recently affected very adversely, the slopes of Mt. Elgon in Uganda. In The New Vision of September 13, 1999 it was reported, one of the local residents of the slopes acknowledged that planting trees on the slopes was the only solution to ending landslides. He further commented that he noticed that the neighbouring Mt. Elgon National Park did not experience landslides because the trees had been preserved (The New Vision, September 13, 1999, p. 24 and 29).

Terraces, trenches and other localised infiltration points

These have one thing in common; they enable water to concentrate and then infiltrate rapidly to deeper levels of the soil profile, resulting in landslide by the same mechanism as the first case above. Examples are landslides that occur immediately below houses constructed on terraced surfaces, landslides such as those described earlier that were triggered after water leaked from an irrigation channel, a tank and the water pipe line that supplies Othaya town.

Long-term prevailing dry climate

The effect of long-term prevailing dry climate is linked to the situations in the first two cases above. A persistent hot and dry weather would give rise to a much desiccated soil condition. The desiccation level would be relative, varying from point to point depending on the vegetation cover and clay content of the soils at that point and the duration of the hot/dry weather condition. At the onset of the rainy season, the desiccation levels are at the highest. The first torrential rains yield so much run-off that much of it also infiltrates the already desiccated soil to deep levels through the cracks. At a point where the clay (montmorillonite) content is high, the volume change due to water absorbed would be very high and rapid, increasing the trigger potential of a landslide at that point. This would also explain why most landslides occur at or soon after the onset of the rainy season. As the rainy season progresses, the soils at deeper levels absorb moisture from above but at a rate that does not cause rapid changes in the volume of the soils.

**Conclusions and recommendations**

Based on knowledge of the rate of swelling of the soils as critical factor it may also be possible to predict or sound a warning as to when landslides are likely to occur, based observed long-term weather conditions prevailing in an area that is prone to landslides. The following signals in particular, could portend landslide danger in such areas: (i) Long persisting dry and hot weather. Temperature trends and precipitation should be monitored closely, especially during the normal "dry period" in landslide prone areas, (ii) High levels of desiccation as evidenced by deep-extending cracks in bare or cultivated grounds, especially when these occur on upper slopes. Residents should be educated to recognise these features and conditions that generally portend potential for landslide occurrence, (iii) Conditions which allow run-off or water from any other sources to accumulate and infiltrate at a point should be avoided at all cost, especially at points high on the slopes above settlements and other structures. As was noted before, landslides can also occur during dry weather, as such artificial channels for water and pipes should be made leak-proof.

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| Documenta naturae | 136 | 99-109 | Munich 2001 |
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# Use of statistical methods to predict availability of heavy metals in tailings and sediments in a former mine area (Uganda)

Andrew Muwanga

**Abstract:** The tailings and other wastes that were produced from the processing of sulphide ore in Kilembe, Uganda were dumped in a mountain valley close to R. Nyamwamba. This paper focuses on the of Cu, Co, Ni and Zn in the tailings and stream sediments (from R.Nyamwamba). The four metals occur in high concentration in the samples analysed.

The metal contents are high but may have low mobility hence not readily biochemically available. Statistical methods have been used to interpret their bonding forms and establish those that would be readily available. In the tailings Co, Ni, Zn are closely associated with Fe indicating that the three metals could be bonded on to Fe hydrous oxides and would not be readily available unless they are in the amorphous hydrous oxide phase which is relatively unstable. Cu on the other hand seems bonded to Mn hydrous oxides or in basic layer silicates. For the sediments, all the metals seem to be adsorbed on Mn/Al hydrous oxides or basic layer silicates. The bonding to basic layer silicates is by non-specific adsorption which would render the metals mobile by cation exchange. Metals adsorbed by Mn hydrous oxides can easily be released in a reducing environment. Thus Cu would be the most readily available metal from the tailings while all the metals could be easily mobilsed from the stream sediments.

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## Introduction

Copper mining in Kilembe, Uganda (Fig. 1) from strata-bound copper-cobalt ore between 1956 and 1978 left the area highly polluted with heavy metals. The mineralisation is associated with the amphibolites of the Kilembe Schist Group. The tailings and other mine wastes produced are the main sources of the heavy metals such as copper, cobalt and nickel which have been leached and dispersed into sediments and waters as well as soils in the river valley (Edroma, 1974; Bugenyi, 1979, 1982; Pohl & Muwanga, 1995; Muwanga, 1997 a,b). Although the heavy metal contents have been reported to be high, they may have low mobility and hence less biochemically available. Mobility is the ability of metals to change their speciation towards soluble phases. In order to predict and assess the availability of the heavy metals, it is important to define their bonding forms so as to estimate the easily available amounts. These can be done qualitatively using statistical methods (e.g. Schenk, 1995; Davies, 1997; Gaiero et. al., 1997) or quantitatively using sequential extraction (e.g. Tessier et.al., 1980; Foerstner & Calmano, 1982; Jacob et. al., 1990; Achilli et. al., 1997).

In this paper, statisical methods are being used to give an overview of the likely bonding forms using associations between the heavy metals (Cu, Co, Ni and Zn) which occur in high concentrations in Kilembe and adsorptive components in the natural environment. From these associations, the likely mobility/fixation of the metals is deduced. Adsorptive components include Al, Fe and Mn hydrous oxides, organic carbon and clay minerals (deduced from Al and Mg contents). Bonding to clay minerals is by non-specific adsorption and these can be easily released through cation exchange. Fe and Mn oxides are affected by reducing conditions and affect the behaviour of heavy metals. Under reducing conditions and a mild change in pH, metals adsorbed to these oxides can easily be released (Cambier et. al., 1999).

## Materials and Methods

### Sampling and Analysis

The geological setting of the study area (Fig. 1) has been described elsewhere (Muwanga, 1997). Tailings samples were collected from eight dump sites within the Nyamwamba river valley. The stream sediment samples were taken from various points within and outside the mine area (see Fig. 1). All the samples were air-dried and sieved. The tailings samples were sieved to 125 µm and the sediment samples to 63 µm.

The samples were digested with aqua regia and analysed for heavy metals using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES). Organic C was determined using the Carbon-Phase-Analyser (LECO RC 412) and pH was measured according to DIN 38414-5 (1981).

### Statistical methods

The data obtained from the analysis was statistically analysed using the conventional univariate and multivariate methods. The latter included Pearson correlation, cluster and factor analysis. Cluster analysis was used to define and group variables in associations. The method is based on the similarities of correlations using the mutually highest correlations as centres of clusters. The variables are classified into hierarchical groups and displayed as dendrograms so that relationships between the groups becomes evident. The statistical operation begins with the formation of the initial cluster by linkage of the two elements with the highest correlation coefficient. The linkage iterates to the most similar pair of elements which are clustered to the preceding correlation(s) (Swan et. al., 1995). The method may blur correlations. However, when considered together with the correlation matrix, the obtained groups can be interpreted in terms of their geochemical implications.

Factor analysis is used to elucidate the structure of the variance-covariance (correlation) matrix from a collection of multivariate observations. The R-mode factor analysis used in this study reduces the complexity of a given set of intercorrelated data by accounting for the observed correlation among the variables in terms of the fewest possible number of independent underlying factors (Davis, 1973). Each factor consists of (non-exclusive) loadings of the original variables which give a kind of attribute classification that can be correlated to meaningful geochemical processes or associations. The first factor describes the most important association of variances in the data, the second corresponds to the highest residual variance after removal of the first factor. The procedure continues until the total variance is accounted for.

The aim of the factor analysis is to summarise the sometimes highly complicated element relationship which is displayed in the original correlation matrix. The main scope is to minimise the number of factors to be used for interpretation. In this study, only factors with associated eigen-values exceeding unity and those that have more than one element associated with them and the associated elements showing high factor loadings were considered. To improve the inter-pretability of the results, the resulting variable-factor matrix was rotated using the Kaiser's varimax rotation model to maximise the loadings for each factor. The method changes the factor loadings so that the original variables are either near $\pm$ 1 or near zero. For each factor, there will be only few significantly high loadings and many insignificant loadings.

## Results

A total of 64 samples were analysed. The results were statistically treated to remove significant and highly significant outliers. A summary of the results is shown in Tab. 1. From the table, it can be seen that the tailings are highly loaded with metals Cu, Co and Ni which are associated in the sulphide ores. The major sulphides in Kilembe are cobaltiferous pyrite, chalcopyrite and pyrrhotite with minor amounts of linnaeite, pentlandite (sometimes containing Co) and siegenite (Bird, 1968; Davis, 1969). The pH is relatively acidic as a result of the acidity generated duting the oxidation of residual sulphides. This implies that metals can easily mobilised and eventually enter the ecosysytem.

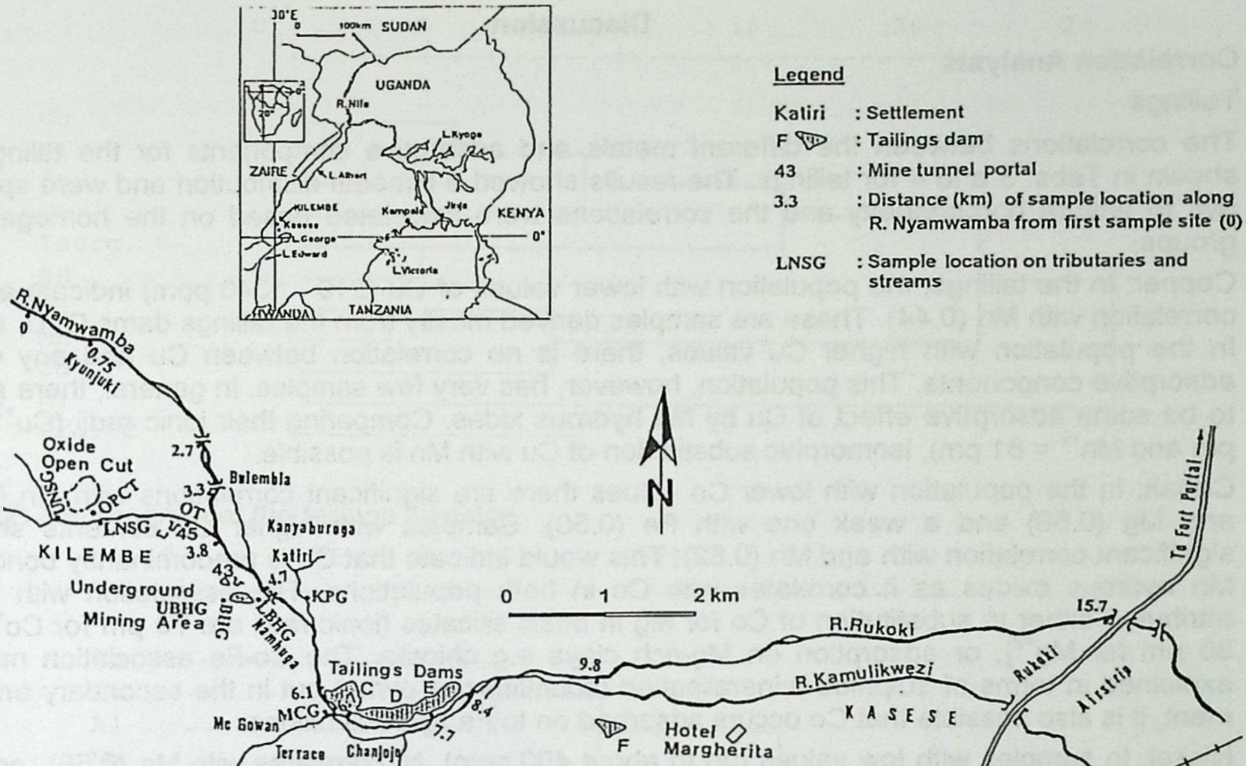


**Fig. 1:** Location map of study area and sample sites of stream sediments.

## Sediments

Tab. 2 shows the average metal contents and other parameters of sediments. Samples taken from upstream are comparable to "background" values obtained by earlier workers (e.g. Rose et. al, 1979; Clews, 1962). Therefore, samples taken upstream of the mining area can be taken to represent "background" values i.e. sediments that have not been significantly affected by mining operations.

The relative enrichments of the metals compared to upstream values are given in Tab. 2. Within the mining area, average Cu contents are 20 times above "background" levels followed by Co (8.4) and Ni (2.8). Zn which is very mobile in the weathering environment is not so strongly enriched in the sediments although it is also present in significant amounts in the tailings. Although Fe apparently shows a weak enrichment (EF 1.5), its concentration is much higher in samples from the mining area (ca. 4%) as compared to upstream samples (2.6%).

Stream sediments from tunnel portals have the highest concentrations of all the metals concerned. Since a limited number of samples was analysed, it was not feasible to carry out the statistical tests to eliminate extreme values, the results show a high scatter. For this reason, the enrichment ratios were based on the ranges of values and not on the means. The most highly enriched metals remain restricted to Cu, Co and Ni. Zn is enriched more in the tunnel drainage sediments than in the rest of the mine area. The material from the tunnel portals is mainly derived from sandfill material that was used for cut and fill stoping (Bird & Kottler 1969) and erosion products of the ore horizon and enclosing rocks. Visually, the sediments contain blue and greenish particles or aggregates. These are most likely secondary minerals such as malachite or copper hydroxides which are products of weathering of the sulphides (cobaltiferous pyrite, chalcopyrite, pentlandite and possibly traces of sphalerite).

## Discussion

### Correlation Analysis

Tailings

The correlations between the different metals and adsorptive components for the talings are shown in Tabs. 3 and 4 for tailings. The results showed a bimodal distribution and were split into two to ensure homogeneity and the correlations were calculated based on the homogeneous groups.

Copper: In the tailings, the population with lower values of Cu (210 - 1340 ppm) indicate a weak correlation with Mn (0.44). These are samples derived mostly from the tailings dams C, D, and E. In the population with higher Cu values, there is no correlation between Cu and any of the adsorptive conponents. This population, however, has very few samples. In general, there seems to be some adsorptive effect of Cu by Mn hydrous xides. Comparing their ionic radii ($Cu^{+2}$ = 87 pm and $Mn^{+2}$ = 81 pm), isomorphic substitution of Cu with Mn is possible.

Cobalt: In the population with lower Co values there are significant correlations with Mn (0.73), and Mg (0.68) and a weak one with Fe (0.50). Samples with higher Co contents show a significant correlation with and Mn (0.82). This would indicate that Co is predominantly bonded to Mn hydrous oxides as it correlates with Co in both populations. The association with Mg is attributed either to substitution of Co for Mg in basic silicates (ionic radii are 79 pm for $Co^{+2}$ and 86 pm for $Mg^{+2}$), or adsorption on Mg-rich clays e.g chlorite. The Co-Fe association may be explained in terms of sulphide mineralisation (cobaltiferous pyrite) but in the secondary environment, it is also possible that Co occurs adsorbed on to Fe hydrous oxides.

Nickel. In samples with low values (up to about 400 ppm), Ni correlates with Mn (0.55) and Mg (0.75). In samples with high values, Ni correlates only weakly with inorganic C. As discussed for Co, Ni also seems to be bonded to Mn or maybe either substituted for Mg in basic silicates or adsorbed non-specifically by Mg-rich clays. At high contents, Ni may form carbonates either from reaction with $CO_2$ or by reacting with carbonates from the tailings.

Zinc: At low values, Zn correlates with Fe (0.49), Mg (0.55), Mn (0.43) and inorganic carbon (0.50). At high values, correlation is only observed with inorganic C. Zn and Mg readily substitute for each other (ionic radii are 88 pm for $Zn^{+2}$ and 86 pm for $Mg^{+2}$). The same reasoning given for Ni is also applicable to Zn. In addition, it is also bonded to Fe hydrous xides. These are more stable than those of Mn.

The association to different components that may be important is controlling bonding of metals in the secondary environment are shown in Tab. 5. As seen in Tab. 2, the samples were divided into three populations. Those of samples from upstream of mine area and from tunnel portals were too few to obtain meaningful statistical tests. The coefficients presented here are based only on samples from within the mine area.

Copper nickel and zinc: These three correlate with Mn, Al and Mg. Cu and Ni correlate with Fe but Zn does not. Correlation with Mn is attributed to adsorption on Mn oxides/hydroxides while that with Al and Mg is linked to adsorption by clay minerals. Jenne (1968) states that Cu is readily adsorbed by Mn oxides/hydroxides and Ure and Berrow (1982) found that Cu can be readily adsorbed by clay minerals. Fe correlates weakly with Cu but more strongly with Ni. Fe and Ni are normally geochemically associated in basic rocks. Otherwise the association between Cu, Ni and Fe in the secondary environment is attributed to the adsorptive character of Fe oxides.

The correlation between Al and Mg further indicates the presence of clay minerals such as chlorite. Mn is also associated with the two elements which may be due ionic substitution. (crystal radii are $Mn^{2+}$ = 80 pm and $Mg^{2+}$ = 86 pm).

Cobalt: Co shows a slightly different behaviour from the other three metals. It is only associated with Mn and Al indicating that it may be adsorbed on to Al and Mn oxides hydroxides. Several authors (e.g; Jenne, 1968; Ure & Berrow, 1982; Smith, 1990) have reported strong adsorption of Co by Mn.

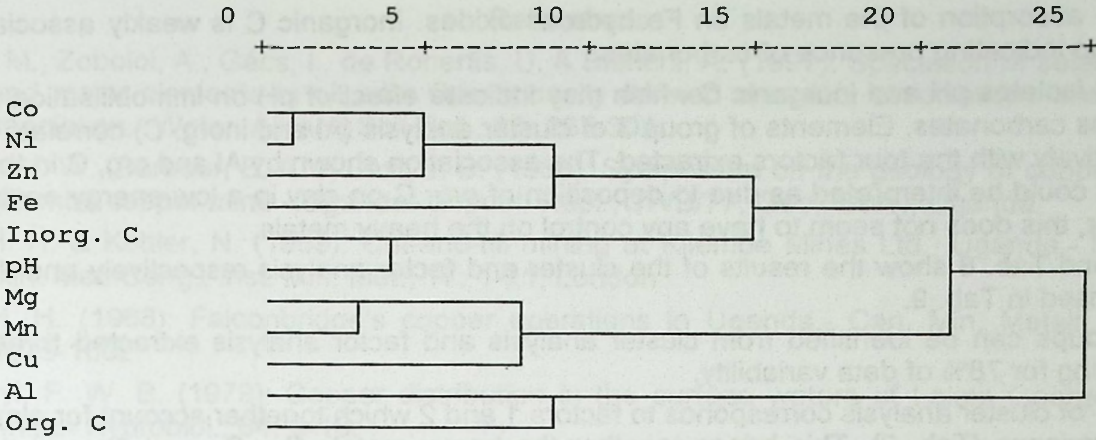


Fig. 2: Dendrogram of the tailings samples.

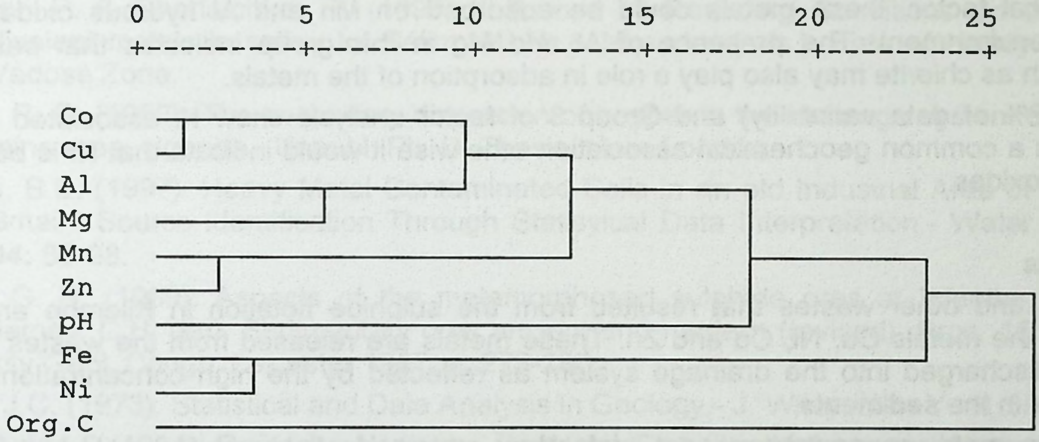


Fig. 3: Dendrogram of the stream sediments samples.

## Cluster and Factor Analysis

To group the variables into possible association that can be geochemically explained, cluster and factor analysis were carried out.

### Tailings

The dendrogram produced from the R-mode cluster analysis using the average linkage within the group is given in Fig. 2 and the results of factor analysis are shown in Table 6. The results from both are summarised in Tab. 7.

From cluster analysis, three variable associations can be established. Factor analysis extracted four factors with eigen values > 1.0 describing 89 % of data variability.

Factor 1 explains about 37 % of variance among the data. It brings together Cu, Mn, Mg and is similar to group 2 of cluster analysis. This is partly a lithologic factor related to mafic silicates in basic rocks that host the sulphide mineralisation in Kilembe. However, it could also be attributed to the adsorptive nature of Mn. Cu and Mn can subsitute for Mg in basic minerals e.g. amphiboles and mica but Cu can also be incorporated into Mn oxide lattices in the secondary environment.

Factor 2 accounts for 25% of data variability. Fe is correlated with this factor while Ni is only very weakly correlated. Ni is normally geochemically associated with Fe.

Factor 3 accounts for 16% of variance and is similar to group 1 of cluster analysis with the exception of Fe. The three elements (Co, Ni and Zn) are associated with sulphide mineralisation in Kilembe (Barnes et. al., 1959). In cluster analysis, Fe is correlated with this group indicating possible adsorption of the metals on Fe hydrous oxides. Inorganic C is weakly associated with this group indicating presence of carbonates.

Factor 4 isolates pH and inorganic C which may indicate effect of pH on immobilisation of heavy metals as carbonates. Elements of group 3 of cluster analysis (Al and inorg. C) correlate very low or negatively with the four factors extracted. The association shown by Al and org. C in the cluster analysis could be interpreted as due to deposition of org. C on clay in a low energy environment. However, this does not seem to have any control on the heavy metals.

Figs 3 and Tab. 8 show the results of the cluster and factor analysis respectively and these are summarised in Tab. 9.

Four groups can be identified from cluster analysis and factor analysis extracted three factors accounting for 78% of data variability.

Group 1 of cluster analysis corresponds to factors 1 and 2 which together account for almost 66% of the variance (Tab. 9). This brings together the heavy metals Cu, Co and Zn and the major elements Mn and Al. This has lithological implications in that the heavy metals in this group are associated with the sulphide mineralisation in Kilembe which occurs in the amphibolites. Besides the lithological factor, these metals could be adsorbed on Mn and Al hydrous oxides in the secondary environment. The presence of Al and Mg in this group indicates that basic layer silicates such as chlorite may also play a role in adsorption of the metals.

Factor 3 (12% of data variability) and Group 3 of factor analysis show Ni associated with Fe. Again this is a common geochemical association otherwise it would indicate that Ni is bonded to Fe hydrous oxides.

### Conclusions

The tailings and other wastes that resulted from the sulphide flotation in Kilembe are highly loaded with the metals Cu, Ni, Co and Zn. These metals are released from the wastes and are eventually discharged into the drainage system as reflected by the high concentrations of the same metals in the sediments.

Although the metal concentrations are high, they may have low mobility making them less biochemically available. Their speciation and hence mobility has been assessed by statistical methods using correlation cluster and factor analysis. There is a strong association of Co, Ni, Zn with Fe in the tailings showing the influence of the sulphide mineralisation on the mine wastes. This would indicate that they are bonded to Fe hydrous oxides. In this form they would be relatively stable if they are incorporated into crystalline lattices of the oxides. However, they would be unstable if bonded on to the hydrous amorphous state of the oxides and would hence be easily available. Cu is associated with Mn and Mg indicating that it is either adsorbed by Mn hydrous oxides or basic silicates such as chlorite by non-specific adsorption. These are unstable forms and it would mean that Cu would thus be readily mobilised from the tailings.

In sediments, the association between Cu, Co, Ni and Zn with Mn, Al and Mg indicates adsorption by Mn and Al hydrous oxides and basic layer silicates. The metals adsorbed by Mn hydrous oxides will be readily released in a mildly reducing environment and slight change in pH. Those bonded to basic layer silicates are easily mobilised by cation exchange.

In conclusion, Cu would be the most readily available from tailings while all the metals would be easily mobilsed from stream sediments by desorption or in a reducing environnment.

### Acknowledgements

The author is very grateful Prof. Dr. W. Pohl, Prof. Dr. D. Zachmann and Dr. J. Wolff of Braunschweig for their guidance during the research as well as the laboratory staff of the geochemistry laboratory in Braunschweig for their assistance in the analysis. The financial assistance of the DAAD who sponsored the research project is greatly acknowledged. Special thanks also go to the management and staff of Kilembe mines and colleagues in the Department of Geology, Makerere University for their co-operation.

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## APPENDIX

| | Flotation Tailings n = 49 | *Tolerable limits in soils (Kloke 1980) |
|---|---|---|
| Cu | 1725 ± 1302 | 100 |
| Ni | 405 ± 151 | 50 |
| Co | 983 ± 839 | 50 |
| Zn | 142 ± 49 | 300 |
| Cd | 3 ± 0.7 | 3 |
| Fe | 99678 ± 20096 | |
| Al | 65298 ± 4995 | |
| Mn | 1748 ± 380 | |
| Mg | 34316 ± 6948 | |
| | all metal values in ppm | |
| pH | 5.6 ± 1.4 | |
| org. C % | 0.35 ± 0.72 | |
| inorg. C% | 0.05 ± 0.06 | |

* Tolerable limits are given for comparison with soils.

**Tab. 1:** Trace and major element contents and other parameters (mean and standard deviation) of flotation tailings at Kilembe.

| | A Upstream (n = 14) | | | B Within mining area (n = 30) | | |
|---|---|---|---|---|---|---|
| Parameter | Mean | Std. dev. | Range | Mean | Std. dev. | Range |
| Cu | 57 | 23 | 26 - 101 | 1150 | 670 | 206 - 2264 |
| Ni | 29 | 4 | 22 - 35 | 81 | 26 | 47 - 144 |
| Co | 20 | 5 | 14 - 31 | 167 | 57 | 55 - 264 |
| Zn | 73 | 15 | 55 - 99 | 108 | 33 | 49 - 174 |
| Fe | 25796 | 2993 | 17260 -28820 | 39976 | 16148 | 21300 - 94200 |
| Al | 8872 | 1347 | 6902 - 11990 | 10726 | 3195 | 4300 - 18050 |
| Mn | 510 | 74 | 400 - 620 | 676 | 236 | 300 - 1420 |
| Ca | 2447 | 304 | 1946 - 2890 | 2455 | 949 | 1100 - 5180 |
| Mg | 4340 | 500 | 3200 - 5060 | 5719 | 2023 | 2700 - 12300 |
| org. C% | 1.8 | 0.7 | 0.8 - 3.7 | 1.1 (27) | 0.6 | 0.4 - 2.9 |
| inorg. C% | 0.02 | 0.01 | 0.01 - 0.07 | 0.01 (26) | 0.006 | 0.003 - 0.023 |
| pH | 6.6 (13) | 0.2 | 6.2 - 6.7 | 6.7 (26) | 0.5 | 4.8 - 7.2 |
| | C Tunnels (n =10) | | | Enrichment compared to upstream | | |
| Parameter | Mean | Std. dev. | Range | | Ratio B:A | Ratio C:A |
| Cu | 21850 | 11599 | 9071 - 41291 | Cu | 20 | 159 - 724 |
| Ni | 614 | 282 | 147 - 1025 | Ni | 2.8 | 5 -35 |
| Co | 2834 | 1454 | 394 - 5081 | Co | 8.4 | 20 - 254 |
| Zn | 699 | 321 | 129 - 1167 | Zn | 1.5 | 1.8 -16 |
| Fe | 132357 | 68538 | 67220 - 260820 | Fe | 1.5 | 2.6 - 10 |
| Al | 20680 | 10094 | 9300 - 40990 | Al | 1.2 | 1 - 5 |
| Mn | 4462 | 2215 | 2020 - 8100 | Mn | 1.3 | 4 - 16 |
| Ca | 7035 | 2074 | 3967 - 11300 | Ca | 1.0 | 1.6 - 5 |
| Mg | 6540 | 2276 | 3917 - 9458 | Mg | 1.3 | 1 - 2 |
| org. C% | 0.6 | 0.19 | 0.3 - 0.9 | org. C% | 0.6 | 0.1 - 0.5 |
| inorg. C% | 0.08 | 0.05 | 0.02 - 0.15 | inorg. C% | 0.5 | 6 - 7.5 |
| pH | 7.5 | 0.2 | 7.1 - 7.9 | | | |

**Tab. 2:** Statistical parameters of stream sediment samples from upstream, from within mining area and from tunnel portals. All metal contents in ppm. (n = number of samples). Ratios B:A and C:A are the relative enrichment within mining area and tunnel portals respectively compared to upstream values. Those for tunnels are given as ranges as the results were too few to carry out tests to establish a relatively normally distributed population.

| | Mn | Fe | Al | Mg | Org. C | Inorg. C |
|---|---|---|---|---|---|---|
| Cu (n = 37) | 0.44* | 0.10 | -0.08 | 0.28 | -0.15 | -0.38 |
| Co (n = 23) | 0.73** | 0.15 | -0.34 | 0.68** | -0.53** | 0.28 |
| Ni (n = 25) | 0.55* | 0.47* | -0.49* | 0.75** | -0.73** | 0.03 |
| Zn (n = 39) | 0.43* | 0.49** | -0.31 | 0.55** | -0.19 | 0.60** |

**Tab. 3:** Correlation between heavy metals and adsorptive components at low values of the heavy metals in tailings.

** 99% significance * 95% significance

| | Mn | Fe | Al | Mg | Org. C | Inorg. C |
|---|---|---|---|---|---|---|
| Cu (n = 12) | 0.15 | -0.16 | -0.33 | 0.04 | 0.14 | -0.01 |
| Co (n = 26) | 0.82** | 0.50** | -0.53** | -0.45* | 0.13 | -0.19 |
| Ni (n = 24) | 0.13 | -0.15 | 0.17 | 0.20 | -0.21 | 0.46* |
| Zn (n = 15) | -0.15 | 0.05 | 0.18 | -0.35 | -0.04 | 0.50** |

**Tab. 4:** Correlation between heavy metals and adsorptive components at high values of the heavy metals in tailings.

** 99% significance * 95% significance

| n = 26 | Mn | Fe | Al | Mg | Organic C |
|---|---|---|---|---|---|
| Cu | 0.79** | 0.56* | 0.78** | 0.79** | -0.26 |
| Ni | 0.64** | 0.63** | 0.69** | 0.75** | -0.46 |
| Co | 0.67** | 0.32 | 0.62** | 0.38 | -0.29 |
| Zn | 0.77** | -0.04 | 0.65** | 0.63** | 0.17 |
| Fe | -0.16 | 1 | 0.51 | 0.1 | -0.31 |
| Al | 0.69** | -0.17 | 1 | 0.67** | -0.14 |
| Mg | 0.74* | 0.10 | 0.87** | 1 | -0.12 |

**Tab. 5:** Correlation between heavy metals and adsorptive components in sediments

** 99% significance * 95% significance

| Variable | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Communality |
|---|---|---|---|---|---|
| Al | -0.630 | -0.899 | -0.118 | 0.055 | 0.829 |
| Co | -0.245 | 0.412 | 0.827 | 0.160 | 0.938 |
| Cu | 0.795 | -0.187 | 0.021 | -0.327 | 0.774 |
| Fe | -0.265 | 0.842 | 0.318 | 0.058 | 0.883 |
| Inorg. C | -0.174 | 0.141 | 0.241 | 0.893 | 0.906 |
| Mg | 0.876 | 0.343 | 0.124 | 0.149 | 0.923 |
| Mn | 0.921 | 0.008 | 0.027 | 0.059 | 0.853 |
| Ni | 0.103 | 0.421 | 0.842 | 0.249 | 0.959 |
| Org. C | -0.456 | -0.785 | -0.072 | -0.105 | 0.840 |
| pH | 0.121 | -0.081 | 0.084 | 0.944 | 0.919 |
| Zn | 0.267 | -0.082 | 0.912 | 0.068 | 0.914 |
| Eigen value | 4.03 | 2.70 | 1.76 | 1.24 | |
| Pct of var | 36.6 | 24.6 | 16.0 | 11.3 | |
| Cum Pct | 36.6 | 61.2 | 77.2 | 88.5 | |

**Tab. 6:** Varimax rotated factor matrix of tailings data.

| Cluster Analysis | Factor Analysis |
|---|---|
| Group 1. Co, Ni, Zn, Fe (inorg. C) | Factor 1. Cu, Mn, Mg |
| Group 2. Mg, Mn, Cu | Factor 2. Fe, (Ni) |
| Group 3. Al, Org. C | Factor 3. Co, Ni, Zn |
| | Factor 4. pH, inorg. C |

**Tab. 7:** Associations obtained from cluster and factor analysis for tailings data.

| Variable | Factor 1 | Factor 2 | Factor 3 | Communality |
|---|---|---|---|---|
| Al | 0.626 | 0.525 | -0.166 | 0.694 |
| Co | 0.850 | 0.183 | -0.130 | 0.773 |
| Cu | 0.779 | 0.230 | 0.150 | 0.682 |
| Fe | 0.106 | -0.046 | 0.922 | 0.864 |
| Mg | 0.558 | 0.506 | 0.203 | 0.609 |
| Mn | 0.696 | 0.202 | .0652 | 0.846 |
| Ni | 0.695 | 0.202 | 0.652 | 0.950 |
| Org. C | -0.663 | 0.542 | -0.182 | 0.768 |
| pH | 0.086 | 0.230 | -0.888 | 0.849 |
| Zn | 0.299 | 0.801 | -0.012 | 0.731 |
| Eigen Value | 3.92 | 2.63 | 1.21 | |
| Pct of var. | 39.2 | 26.3 | 12.2 | |
| Cum Pct | 39.2 | 65.5 | 77.7 | |

**Tab. 8:** Varimax rotated factor matrix of stream sediments data.

| Cluster Analysis | Factor Analysis |
|---|---|
| Group 1. Co, Cu, Zn, Al, Mg, Mn | Factor 1. Co, Cu, Ni, Al, Mg |
| Group 2. pH | Factor 2. Zn, Al, Mg, Mn, Org. C |
| Group 3. Fe, Ni | Factor 3. Fe, Ni |
| Group 4. Org. C | |

**Tab. 9:** Associations obtained from cluster and factor analysis for stream sediments data.

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| --- | --- | --- | --- |

# Landslides in Uganda - Documentation of a Natural Hazard

A. Muwanga, A. Schumann & M. Biryabarema

**Abstract:** Between November and December 1997 a number of hazardous landslides occurred in eastern and western Uganda. Well documented are the landslides in eastern Uganda, as these were the most disastrous ones. Anyway, so far no reliable data concerning the socio-economic impact are available. The same area was affected in August 1999 and a commission was set up to evaluate the costs of destroyed infrastructure and settlements.

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## Introduction

The El Niño phenomenon of 1997 contributed to the occurrence of several hazardous landslides in Uganda. The areas most affected were in eastern and western Uganda destroying plantations, houses and many people lost their lives. To understand the distribution pattern of landslides, the geology, morphology and climatic conditions of the particular areas should be considered. Landslides have been known to occur in the mountainous parts of Kabale, Rukungiri, Mbarara, Kasese, Bundibuyo, Kabarole and Mbale districts in Uganda. Fig. 1 shows the most affected area in Uganda.

## Geology, Morphology and Climate

### Central Uganda

The major part of central Uganda is covered by granitoid basement rocks (see Fig. 1) of Pre-Cambrian ages (Leggo, 1974; Schlüter, 1997; Schumann et al., 1999). Peneplanation and intensive chemical weathering during Cretaceous and Early Tertiary led to a flat uniform slightly undulating landscape of almost equal altitude (approx. 1100 m a.s.l.). As a relict of the former morphology ‚mesa' shaped mountains capped with duricrust appear occasionally. No disastrous landslides are reported from central Uganda.

### Western Uganda

The western limb of the East African Rift Valley and the Ruwenzori Mountains are the two major structural units in this part.

- The Rift Valley, which developed during the Mesozoic and Cenozoic is a depressional zone filled with up to 3000 m of young sediments. Several younger volcanic centres are associated with the formation of the Rift (see Fig. 1). Major rock types occur include alkaline basalts (Barifaijo 1999). Such centres are characterised by e.g. volcanic cones and stratovolcanoes, with steep slopes. The underlying basement rocks consist of Precambrian sediments and metasediments, partly mineralized (Muwanga, 1997).
- The Ruwenzories - a horst structure, developed during the phase of rifting - raise up to 5100 m a.s.l. Major rock types comprise Pre-Cambrian granitoids.The morphology is characterised by extremely steep slopes. Due to the altitude several different vegetation zones are found. The vegetation includes Sudanian herbaceous savannahs in the rift depression, Combratacea woodland above 2000 m, montane and bamboo zones up to 3000 m and an alpine belt above 3800 m. Above 3000 m, the mountain is ice-capped. (Ssemmanda, pers. comm.) In western Uganda several hazardous landslides occurred (Biryabarema, 1995).

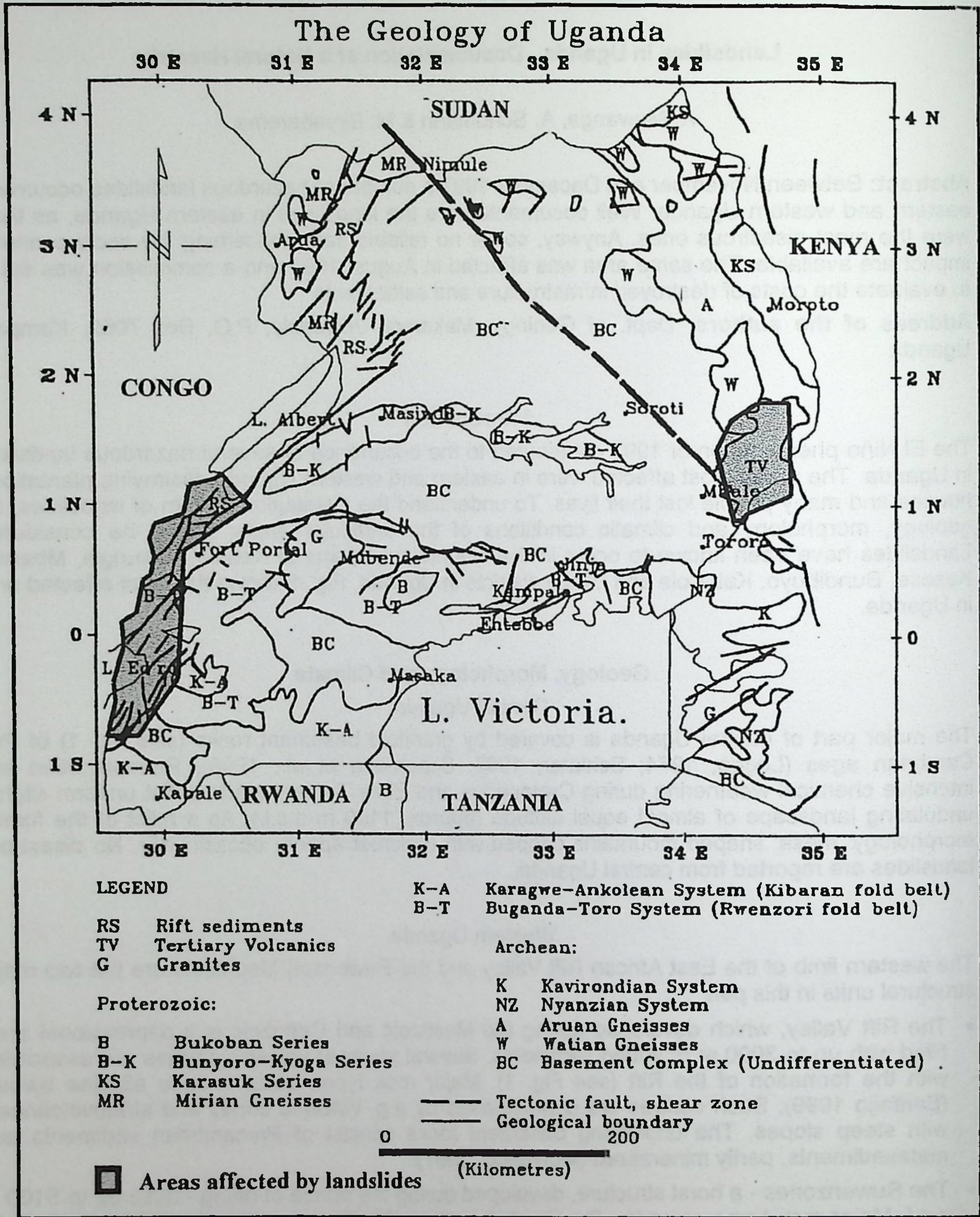


**Fig. 1:** Sketch map of the Geology of Uganda. Indicated are also areas more prone to landslides.

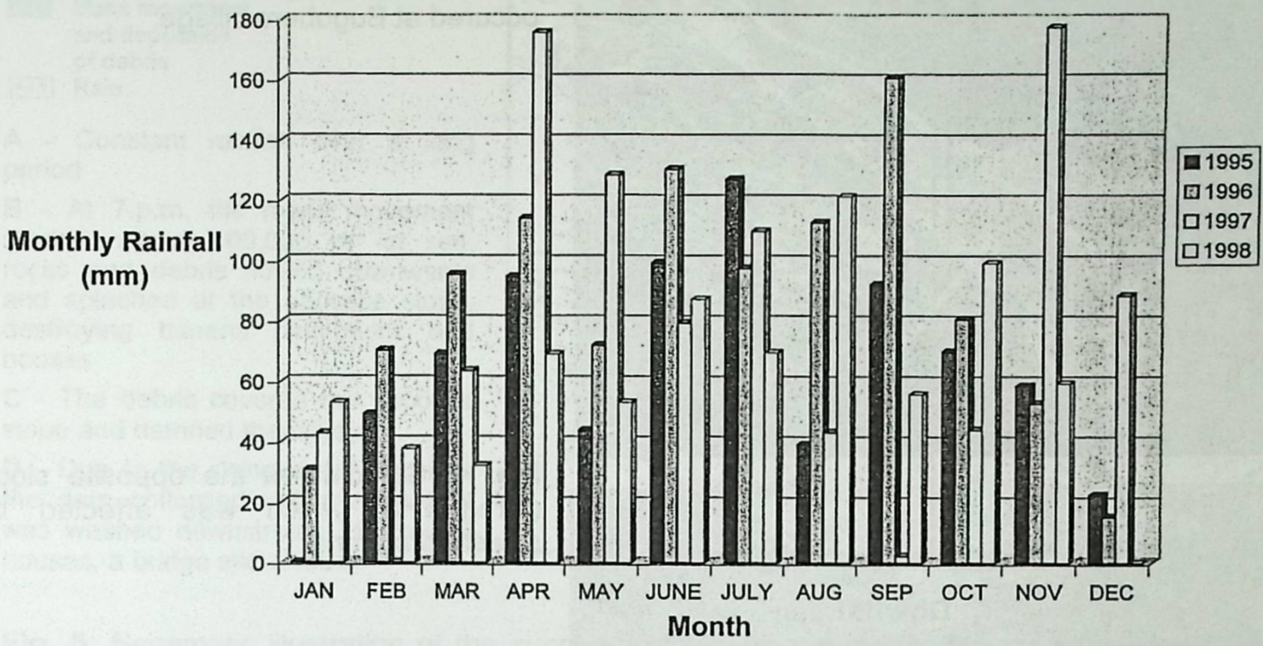


**Fig. 2:** Mean annual rainfall around Bududa (1995-1998).

- The area experiences two rainy seasons; March-May and September-November with average annual rainfall of 1530-2030 mm. With the exception of the densely forested lower parts of the Ruwenzories the major part of the area is deforested and cultivated (traditional food crops, like bananas, cassava, etc.).

Southern Uganda

The topography is predominantly mountainous and hilly with intervening areas of low relief variously occupied by granitic rocks or their metamorphosed equivalents. The latter have been intensively weathered producing morphological depressions.

In the extreme south-west, a large part of mountains are densely populated and under intensive pressure for cultivation making them vulnerable to landslides. Landslides are common in this area and although not discussed in this paper, several of them occurred during the El-Niño rains.

Northern Uganda

The relief is generally low and undulating, the monotony being broken by hills and inselbergs which are erosional remnants of old surfaces. Some mountains e.g. Napak and Moroto occur in the north-east. These are highly dissected with gentle slopes. No significant landslides have been reported in this area.

Eastern Uganda

The area east and north-east of Mbale is quite mountainous. Here are found a number of younger Tertiary volcanic centers including Mt. Elgon, which is a shield volcano with steep valleys and canyons at its foot hill. These different volcanoes are aligned almost parallel to the western limb of the East African Rift Valley (see Fig. 1), which is located in Kenya.

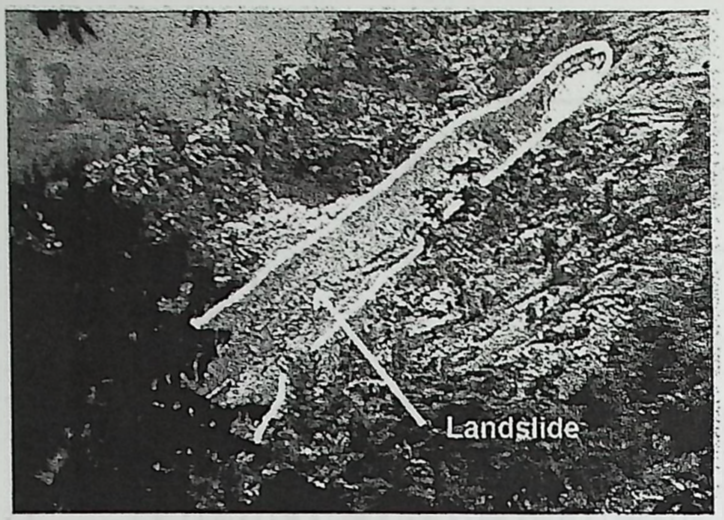


**Fig. 3:** View at the landslide which occured at Bugobero village.

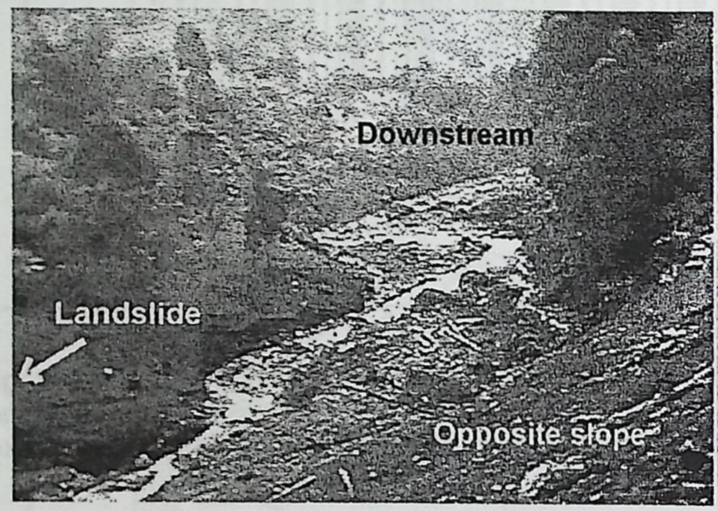


**Fig. 4:** Standing at the opposite slope (foreground) which was affected by splashed material.

**Examples of disastrous landslides in eastern Uganda in 1997**

The Mbale landslides were as a result of exceptional heavy rainfall (October-December 1997) associated with the phenomenon of El-Niño. The landslides occurred widely distributed in the Mount Elgon area but the most affected areas were the hills surrounding Bududa where several people died and homes and plantations were destroyed (Biryabarema & Schumann, 1998). Such mass movement of Mbale region occur in areas where the following factors have been recognized:

- Moderate to strong morphology (steep slopes, with slope angles above 25°)
- Deforestation
- A deep lateritic soil cover, which is no longer protected' by a forest (underlain by volcanic or granitic rocks)
- Heavy rainfall over a long period

Fig. 2 gives the rainfall in the area between 1995 and 1998. In November and December 1997 there was intense rainfall which coincided with the sever landslides described below. The slides are likely to be characterised by initial failure plane (slip surface) followed by complete mixing of the soil with water and flowing as debris flows. The materail carried (slide load) ranges from big boulders to fine fraction. Sometimes the current debris flows follow former channels and the load is additionally enriched enroute by detaching semi consolidated material of the previous hazard. The destruction by the landslide is a result of actual sliding, collision and deposition of material. The biggest and the most destructive landslide of the season was in Bugobero village in Bulucheke (see Fig. 3). The material that moved is estimated at 100,000 $m^3$.

Parent rock
Laterite
Mass movement and deposition of debris
Rain

A - Constant rainfall over a long period

B - At 7.p.m. the mass movement started. About 100.000 $m^3$ of soil, rocks and debris flowed downwards and splashed at the opposite slope, destroying banana plantations and houses

C - The debris covered the opposite slope and damned the valley

D - Due to the rising water pressure the dam collapsed and the material was washed downstream, destroying houses, a bridge and a road

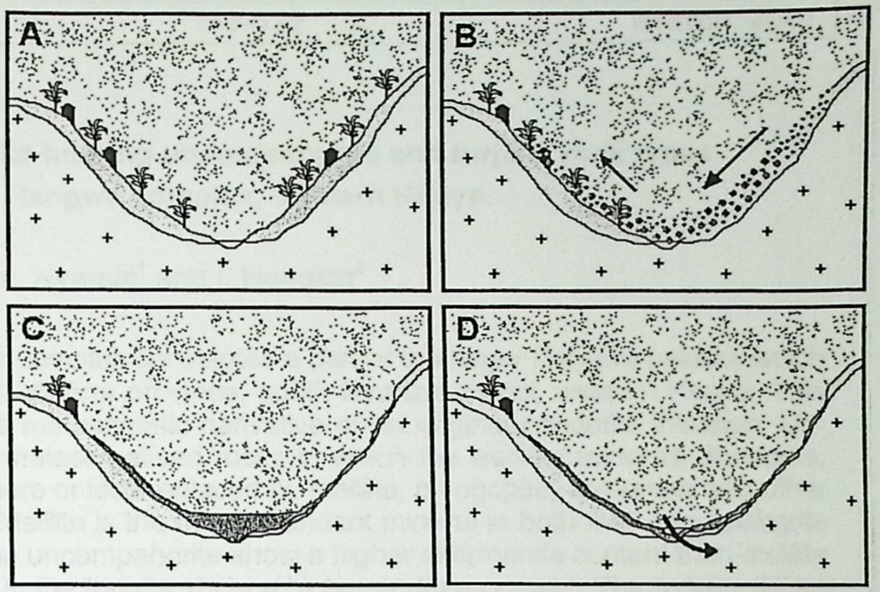


**Fig. 5:** Schematic illustration of the succession of events happened during the Bukobelo landslide.

It occurred at about 7 p.m. after it had been drizzling the whole day. The quiet soaking of the regolith led to progressive build up of the pore water pressures till cohesion was lost and the material flowed under gravity. A combination of a steep slope and near liquefaction gave rise to a high speed devastating earth flow. The impact with the valley floor gave a splash that covered part of the opposite slope (see Fig 4) and the lower part of the slide scar. The slide carried everything on its course, and five people died. On the opposite slope the splashed material destroyed plantations and houses completely, and two people died. A detailed description of this slides is given (see Fig. 5).

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| Documenta naturae | 136 | 117-132 | Munich 2001 |
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# Petrochemistry of the melilite-bearing uncompahgrite and turjaite rock types from south Rangwe complex, western Kenya

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**Abstract:** The uncompahgrite - turjaite complex constitutes a part of the larger Rangwe caldera which occurs in the Tertiary and Quaternary alkaline province, south Nyanza district, western Kenya. This alkaline complex is interpreted to be a metasomatic derivative of an original peridotite intrusion. Uncompahgrite and turjaite are strongly metasomatised rocks in which the earliest minerals (forsterite, diopside, magnetite, perosvikite) are more or less replaced by melilite, phlogopite, carbonate and other minerals. Melilite is further sericitized. Melilite is the most abundant mineral in both the uncompahgrite and turjaite. The melilite occurring in the uncompahgrite show a higher akermanite content than melilite in the turjaite. By contrast, the melilite in the turjaite show a higher sodium content. The turjaite differs from the uncompahgrite by containing nepheline, more phlogopite and apatite, and less diopside. Forsteric olivine ($Fo_{85}$) distinctly occur only in the uncompahgrite rock. The geochemical studies show that the turjaite is enriched in total alkalis, $Al_2O_3$ and $P_2O_5$, but depleted in CaO, $TiO_2$, and FeO relative to the uncompahgrite. The characteristic light REE enrichment in the rock sequences is in the order: ijolite < turjaite < uncompahgrite. The element distribution patterns within the rock types indicate a close genetic association between the uncompahgrite and turjaite. Microprobe analyses of the garnet crystals in both the uncompahgrite and turjaite show a strong andraditic affinity with possible melanite and schorlomite varieties. The ore minerals identified in the turjaite include pyrite, chalcopyrite, and magnetite.

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## Introduction

The primal petrochemical study that this paper addresses to is the melilite-bearing uncompahgrite and turjaite rock types from south Rangwe alkaline silicate complex. The study area, which occurs in western Kenya, covers an area of about 3 km$^2$. It is bounded between the latitudes 0° 32' S to 0° 37' S and longitudes from 34 7' 7" E to 34 10' 30" E (Fig. 1). The rock complex, which constitutes a part of the larger Rangwe caldera, is located in the central area of the very large Kisingiri volcanic complex in south Nyanza district, western Kenya. The uncompahgrite-turjaite complex was interpreted by Le Bas (1977) as a metasomatic derivative of an original peridotite intrusion.

The chosen area of study is at the centre of the Tertiary and Quaternary petrographic province which encompasses the eastern Uganda-western Kenya carbonatite-nepheline alkaline province. The Kisingiri volcanic complex (see Fig. 1) and its other closely associated array of volcanic structures (i.e., Mts. Elgon, Kadam and Napak) are characterised by carbonatite associations and composed dominantly of olivine-poor and augite-rich nephelinitic lavas (Le Bas, op.cit.). The large volcanoes along the Uganda-Kenya border and some of the carbonatite intrusive complexes have been dated and referred to by King et al. (1972).

The intrusion of the alkaline magma (e.g. uncompahgrite-turjaite) into the Precambrian basement (dated to about 2800-3000 Ma) is recognised as the earliest igneous event in the history of the Tertiary Kisingiri volcano. This event is envisaged to have been succeeded by a second episode that began with an extensive nephelinitic volcanism and ended with the intrusion of the Rangwe carbonatites.

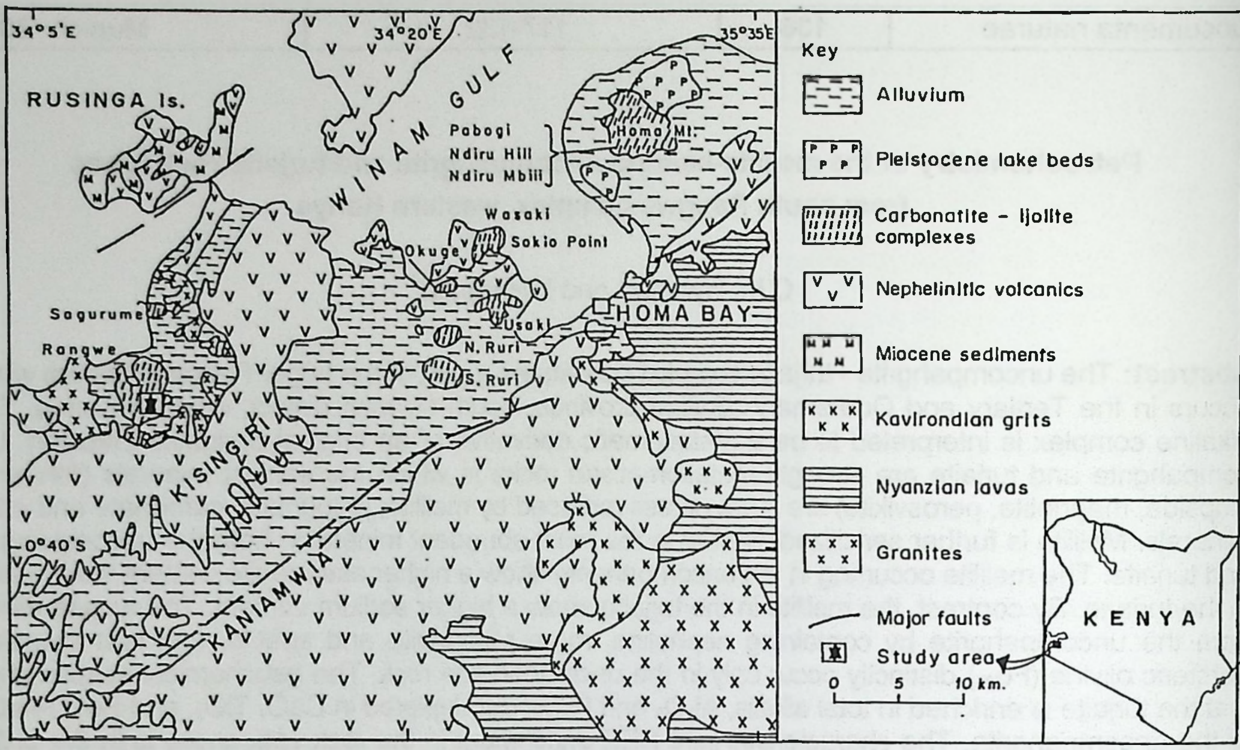



**Fig. 1:** General geological map of the regional survey area (modified after Le Bas, 1977). The asterisk (*) indicates approximate position of the uncompahgrite-turjaite alkaline silicate complex.

The Tertiary intruded alkaline silicate rocks, which presently are exposed on the south eastern flanks of the Rangwe caldera, are established to have formed as a layered silicate complex comprising mostly of the uncompahgrite and turjaite rock types (Findlay, 1967). The basement rocks, adjacent to these alkali silicate rocks, have been intensely fenitized by alkali metasomatic fluids.

Besides complementing the geological work already done by previous researchers in the survey area, the present study aims to offer a more detailed and systematic study on the petrochemistry of the rare melilite-bearing uncompahgrite and turjaite rock types. The results are aimed to establish possible mineralogical and chemical trends that may enlighten on their petrogenesis.

In order to achieve the above aim, a total of 33 representative rock specimens from the rock complex were sampled for mineralogical and geochemical studies.

## Analytical Methods

Major oxides and trace elements on whole-rock samples were analysed by X-ray fluorescence spectrometry (XRF) using a PHILIPS 1400 spectrometer at the laboratory of Rautaruukki Oy, Finland. The mineralogical studies were conducted at the Geological survey of Finland in Espoo. The minerals were identified by a PHILIPS PW 1730 X-ray diffractometer using a wide angle goniometer and a Debye-Scherrer camera (diameter 57.3 mm) when the mineral amount was small. The diffraction patterns were performed using Ni-filtered Cuk$_\alpha$ radiation, 40 KV, 20 mA, silicon standard, scanning rate 1/4°/min and a chart drive of 2 cm per degree. Mineral analyses were carried out with a JEOL JXA-733 electron microprobe equipped with three wavelength dispersive spectrometers (WDS) and one energy dispersive spectrometer (EDS). For most analyses, a focused electron beam (Ø = 1 µm) was used but for more delicate minerals (e.g. micas) a defocused beam of about 10 µm was used.

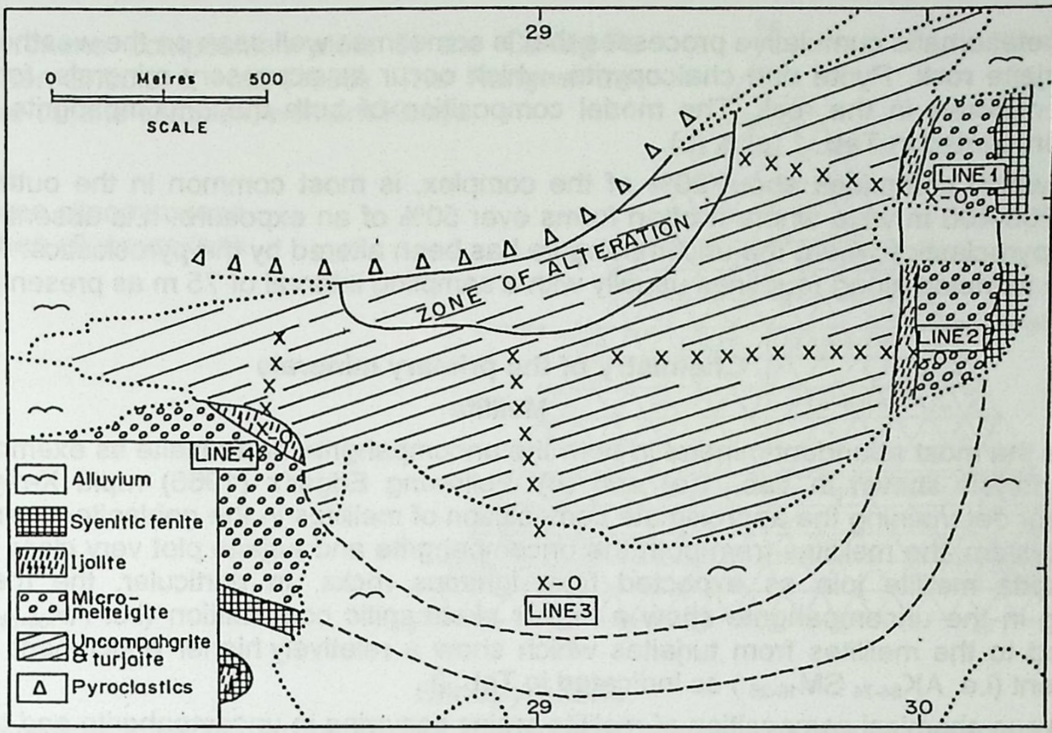



**Fig. 2:** A geological map of the south Rangwe uncompahgrite-turjaite rock complex (after Le Bas, 1977) with respective sampling lines.

Petrographic study of thin sections was done with the help of a Leitz polarising microscope. Modal composition was calculated by point counting method using a swift automatic thin section point-counter. One thousand points were counted on each thin section.

## Geology and Petrography of the South Rangwe uncompahgrite-turjaite complex

The south Ranwge uncompahgrite-turjaite complex is exposed on the south-east flanks of Rangwe caldera (Fig. 2). The complex is indicated in the gravimetric survey by Walker (1977) that showed the Rangwe caldera to be completely surrounded by heavier rock types (unlike other carbonatitic complexes in western Kenya), i.e., by the rock types occurring in the uncompahgrite-turjaite complex.

The complex can be divided into two groups based on rock type, age and structure. The earlier-formed group comprises uncompahgrite and turjaite bounded to the north by later pyroclastic rocks of the Rangwe caldera, and to the south and east by a later formed group of micro-melteigite which is in contact with fenitized basement (Fig. 2). The contact between micro-melteigite and uncompahgrite-turjaite is separated by a band of ijolite. Petrographic evidence indicates that the uncompahgrite-turjaite complex has formed from peridotite by metasomatic replacement. The inward-dipping layered shallow cone-structure of the uncompahgrite-turjaite complex suggests that the parent rock, peridotite, formed as a layered comulative deposit before being subjected to metasomatism.

The uncompahgrite rock consists mainly of melilite, magnetite, perovskite, phlogopite, olivine and diopside. The main mineral constituent is the xenomorphic melilite which forms about 64% of the rock, and appears to be enclosing all the other minerals except phlogopite. Sericite and carbonate occur as alteration products. The commonly coarse-grained turjaite differs from the uncompahgrite by containing abundant nepheline, distinctive large phlogopite crystals and by the absence of olivine. Other main minerals noted in the turjaite include melilite (averaging 5-6 mm in grain size), magnetite, perovskite, melanite and apatite. Based on the examination of two thin sections (L1-375, L2-800) apatite in turjaites occurs both as fine and coarse grained crystals. Together with abundant perovskite crystals and much coarser brown mica, they form an interstitial matrix to coarse grained nepheline and melilite grains. This interesting texture may originate from the pre-metasomatic cumulative processes that is sometimes well seen on the weathering surface of the turjaite rock. Pyrite and chalcopyrite, which occur as accessory minerals, form the main sulphide minerals in the rock. The modal composition of both the uncompahgrite and turjaite rocks is presented in Tab. 1 (a) & (b).

Turjaite, which comprises about 30% of the complex, is most common in the outer concentric zone of 200-400 m wide where it often forms over 50% of an exposure. It is absent close to the Rangwe pyroclastics where the uncompahgrite has been altered by the pyroclastics. The complex has been sampled along four lines usually with a sampling interval of 75 m as presented in Fig. 2.

## Chemistry of the primary minerals

### Melilite

Melilite is the most abundant mineral in both the uncompahgrite and turjaite as exemplified by the modal analysis shown in Tab. 1(a) and (b). Following Edgar's (1965) rapid X-ray diffraction method for determining the approximate composition of melilites in the gehlenite-akermanite-soda melilite system, the melilites from both the uncompahgrite and turjaite plot very close to the akermanite-soda melilite join as expected from igneous rocks. In particular, the melilite grains occurring in the uncompahgrite show a higher akermanitic composition (i.e. $AK_{86-78}$ $SM_{14-22}$) as compared to the melilites from turjaites which show a relatively higher enrichment in the soda component (i.e. $AK_{84-74}$ $SM_{16-26}$ ) as indicated in Tab. 2.

The average chemical composition of melilite grains occurring in uncompahgrite and turjaite rocks are presented in Tab. 3. From the mean analyses it can be observed that the melilites in turjaite are slightly enriched in $Na_2O$ (av. 3.10 wt. %), FeO (av. 3.21 wt. %), $Al_2O_3$ (av. 4.58 wt. %) and depleted in MgO (av. 8.96 wt. %) as compared to the uncompahgrite $Na_2O$ (av. 2.78 wt. %), FeO (av. 3.01 wt. %), $Al_2O_3$ (av. 4.30 wt. %) and MgO (av. 9.67 wt. %) respectively.

### Perovskite

Perovskite, as a common associate mineral in melilite-bearing rocks, occurs in the uncompahgrite rock as subhedral to idiomorphic crystals with an average grain size of 0.8 - 2.5 mm in diameter. In a number of thin sections, perovskite, besides occurring as single grains, form a thin rim and infiltrate magnetite grains. This texture suggest that perovskite is a later phase than magnetite. Adjacent to this observed texture, abundant yellowish granules of fine grained perovskite grains occur within highly altered melilites, suggesting alteration of the latter to perovskite. This phenomenon may be analogous to that noted in a similar uncompahgrite rock from Iron Hill, Colorado where the alteration of melilite to perovskite by the action of residual magmatic fluid has been reported by Larsen & Goranson (1932).

Representative microprobe analyses of perovskite grains in uncompahgrite and turjaite are presented in Tab. 3. The analysis show perovskite in uncompahgrite is slightly enriched in $TiO_2$ (56.17 wt. %) and depleted in $SiO_2$ (0.04 wt. %) content in comparison to those occurring in the turjaite $TiO_2$ (54.35 wt. %) and $SiO_2$ (0.77 wt. %) respectively. The niobium content in perovskite - $Nb_2O_5$ (av. 0.96 wt. %) - reported in this study is higher than that reported by McCall (1958) - (av. 0.56 wt. %) - from a similar rock in the same locality, and are comparable to the niobium rich perovskite varieties that occur in the alkaline plutonic rocks of the Kola Peninsula (Afanassiev, 1939).

### Olivine

Olivine occurs characteristically in the uncompahgrite rock, often as relics which are seen as half-resorbed crystals in optical continuity. This feature indicates the former presence of more olivine rich rocks.

Microprobe analyses of individual olivine grains separated from the uncompahgrite rock (Tab. 4) show a high forsteritic composition of $Fo_{85}$ - $Fa_{15}$. These results suggest that the olivine grains are of an early phase as they fall within the forsteritic range of olivines crystallizing from basic-igneous melts $Fo_{88}$ - $Fo_{82}$ (Augustithus, 1978).

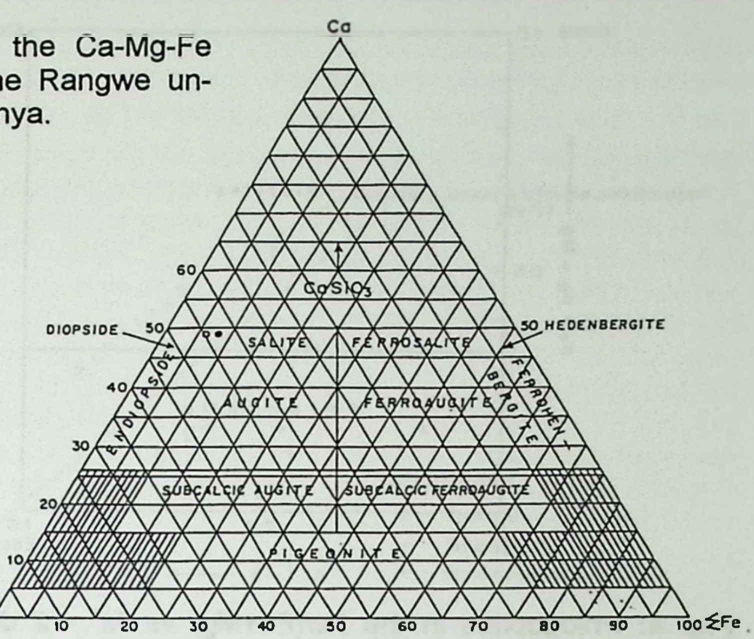



**Fig. 3:** Pyroxene composition plots in the Ca-Mg-Fe diagram after Gribble & Hall (1985). The Rangwe uncompahgrite-turjaite complex, western Kenya.

Explanation:
o Light green clinopyroxene
● Dark green clinopyroxene

### Clinopyroxene

The clinopyroxene in both uncompahgrite and turjaite occurs as short subhedral to euhedral prismatic crystals which are wholly enclosed by the xenomorphic melilite grains. After mineral separation followed by X-ray diffraction identification procedure, two varieties of diopsidic pyroxene were noted on the basis of their colour: light green and dark green crystals. Probe analysis of these two types of clinopyroxene grains are presented in Tab. 4, analysis 4 and 5.

The results show that relative to the light green crystals (with a structural formula $Ca_{48.9}$ $Mg_{44.9}$ $Fe_{6.2}$) the dark green crystals (with a structural formula $Ca_{49.3}$ $Mg_{43.3}$ $Fe_{7.4}$) are enriched by an average factor of 5 in $TiO_2$ and $Al_2O_3$. By contrast the light green crystals are enriched in relatively more MgO and $SiO_2$ than the dark green crystals. Although the light green crystals of south Rangwe are relatively enriched in MgO than the dark green crystals (Tab. 4, analyses 4 and 5), for calcic clinopyroxenes, the range in colours from black to pale green has previously been attributed to an increase in Mg content (Best, 1982). A compositional plot in the Ca-Mg-Fe triangular diagram (Fig. 3) after Gribble & Hall (1985) of the two types of clinopyoxenes are shown to be of diopsidic affinity.

Diopsidic pyroxenes occurring in the south Rangwe ultrabasic rocks are comparable in composition to other diopside bearing ultrabasic rocks such as those occurring in the olivine-melilite-nephelinite of d'Essey-la-cote, Meurthe-et-Moselle, France (Velde & Thiebaut, 1973), and the peridodite and olivine pyroxenites of the Duke Island ultramafic complex, Alaska (Irvine, 1974).

### Magnetite

Magnetite occurs both as anhedral granular to sub-idiomorphic triangular or rhombic crystals. The magnetite grains are wholly enclosed by melilite and occassionally are partially rimmed and infiltrated by a thin rim of perovskite and phlogopite mica. This texture suggests that some of the magnetite grains are of early crystallization phase.

Probe analytical results of the magnetite from both uncompahgrite and turjaite rocks show the uncompahgrite rock to be enriched in $TiO_2$ (av. 7.16 wt. %), MgO (av. 3.24 wt. %) and depleted in $FeO_{tot}$ (av. 82.01 wt. %) relative to the turjaite rock with $TiO_2$ (av. 3.95 wt. %), MgO (av. 1.45 wt. %) and $FeO_{tot}$ (av. 86.69 wt. %) respectively. The grains are interpreted to be of an high-temperature titano-ferrous variety (i.e ilmenite component in solid solution within the lattice of magnetite). Buddington et al. (1955) have emphasized firstly that the formation of most titaniferrous magnetite-ilmenite association takes place at magmatic temperatures and secondly that titanoferrous magnetite developes contemporaneously with the silicate phases.

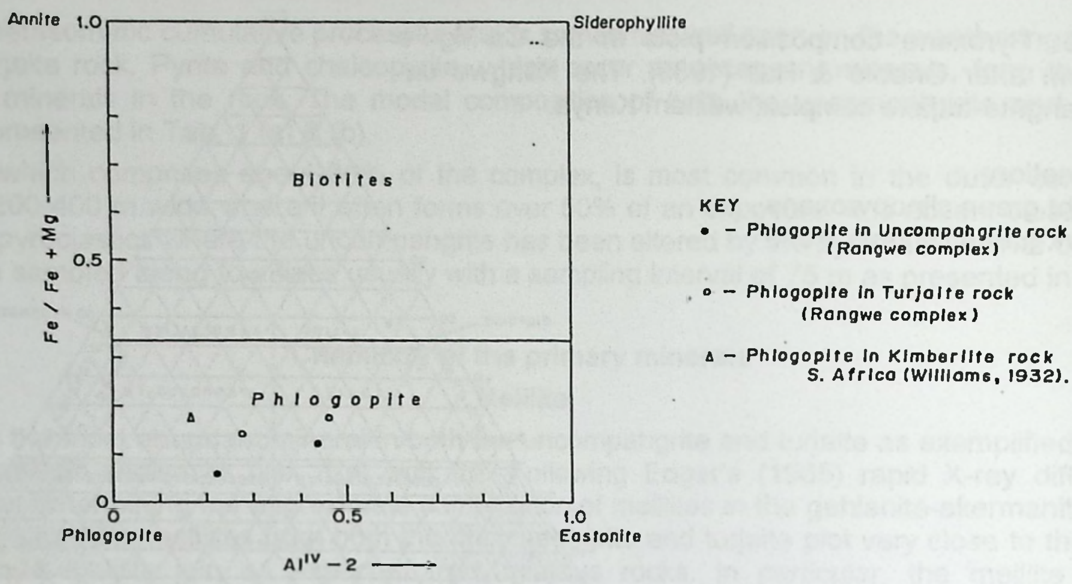



**Fig. 4:** Phlogopites in the Fe/(Fe+Mg) vs $Al^{iv}$ - 2 diagram after Azzouni-Sekkal & Boissonnas (1987). Rangwe uncompahgrite-turjaite complex, western Kenya.

### Phlogopite

The poikiloblastic phlogopite occurring in the turjaite rock are distinctive by their crystal size (ranging up to 2.5 cm) and strong pleochroism i.e., yellow and dark brown on their prismatic sections. Relatively large number of the phlogopite grains enclose some magnetite and apatite grains. In other instances, idiomorphic phlogopite laths forms a network occupying intergranular spaces between xenomorphic melilite grains. On the basis of this textural pattern, the phlogopite appears to be more dependent on a solution phase than on a direct crystallizastion from a wet melt phase. A plot of Fe/(Fe+Mg) versus $Al^{iv}$-2 diagram after Azzouni-Sekkal & Boissonnas (1987) discriminating between biotite and phlogopite (Fig. 4) show the characteristic mica occurring in the uncompahgrite and turjaite rocks to have a strong phlogopitic affinity. The mineral probe analyses show that the rim of the zoned phlogopite (Tab. 5, analyses 1 and 3) are relatively depleted in $TiO_2$ , FeO, BaO and enriched in MgO when compared with their core analyses (Tab. 5, analyes 2 and 4) of the respective individual grains. The compositional zoning could best be attributed to the marked compositional variance of Ti, Fe and Mg migration. The phlogopitic micas in the Rangwe complex rocks share a close chemical composition to that occurring in the kimberlitic rock from the Frank Smith mine, South Africa (Tab. 5, analysis 6)

### Garnet

In the uncompahgrite rock, garnet occurs as a minor component enclosed exclusively in late-stage nepheliniced veinlets. Probe analyses of these crystals (Tab. 6, analysis 1 and 2) show them to be of titanium rich andradite garnet species. Although the Ti-rich andradite varieties occurring in the Rangwe complex have previously been assigned the name melanite (Le Bas 1977), some of these grains have a titanium content that closely compares with that of schorlomite andradite species (Tab. 6, analysis 3). According to Huggins et al. (1977), structural and experimental evidence for melanite varieties indicates that the Ti is mainly in the octahedral position replacing $Fe^{3+}$, since the relative preference for the tetrahedral site must be in the order Al > Fe ⇩ Ti. However, in the present study the opposite might be the case (i.e., $Fe^{3+} < Ti$ , see Tab. 6, analyses 1, 2 and 3 for schorlomite varieties). Although the determination of Fe and Ti contents of garnet is possible using electron microprobe, the assignment of titanium to octahedral $Ti^{3+}$ requires the application of other research methods (e.g., Mössbauer spectroscopy and infra-red absorption spectra as suggested by Manning (1967). Based on the available data, the present study advances the possibility of schorlomite garnet varieties in the Rangwe alkaline complex similar to those observed in the Alnö alkaline complex, Sweden (Eckermann, 1974). This study calls for further structural mineralogical work to ascertain this possibility.

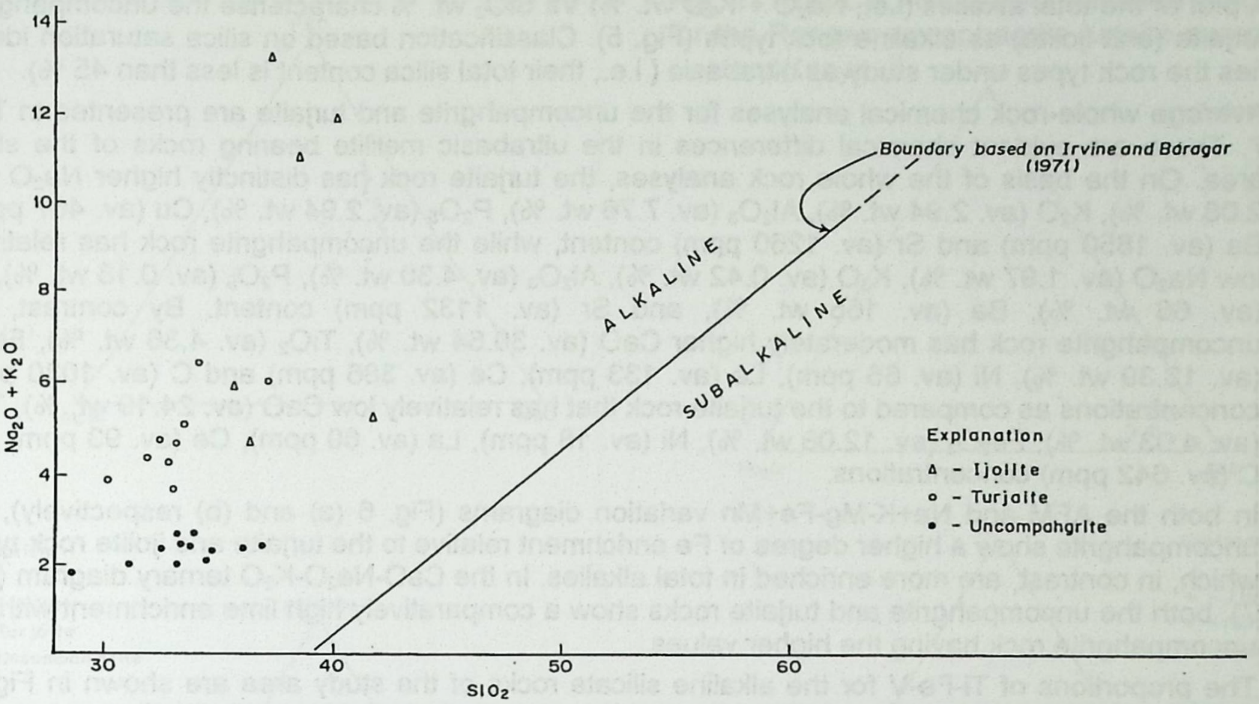



**Fig. 5:** A plot of the total alkalies (i.e., $Na_2O + K_2O$) wt.% Vs $SiO_2$ wt.% based on the boundary line proposed by Irvine & Barager (1971). Rangwe uncompahgrite-turjaite complex, western Kenya.

In the turjaite rock, garnet occurs as a major phase both as pale brownish irregular aggregates and as rims infiltrating perosvikite grains. This texture establishes a paragenetic sequence between the early phase perovskite and later garnet crystals. Allowing for atomic substitution known to occur between iron and aluminium in the Ca-rich ugrandite garnet series (Berry et al., 1983: 481), the analytical results indicate a garnet of strong andraditic affinity (Tab. 6 analyses 4 and 5). The Ti-rich andradite garnets occurring in the turjaite rock are comparable in mineral composition with the Ti-rich melanite garnet reported from Oldoinyo Lengai, Tanzania (Tab. 6, analysis 6).

### Apatite

Based on petrographic examination, apatite occurs as a major mineral in turjaite rock (Tab. 1(b)). It occurs as fine to medium grained crystals. Together with abundant perovskite and coarse brown phlogopite, they form an interstitial matrix to coarse grained melilite and nepheline grains. This very interesting texture, which also indicates a measure of paragenetic sequence, may have originated from the pre-metasomatic cumulate processes which is sometimes well preserved in the weathering surface of the turjaite rock.

In other instances, highly prismatic apatite grains that crystallized with an immense crystalloblastic force are seen traversing two or three phenocrysts of melilite, phlogopite and perovskite. This texture clearly indicates that some of the apatite grains are of post melilite-perovskite-mica blastogenic phase.

### Geochemistry of the alkaline silicate rocks

Whole-rock analyses of three rock types (i.e., uncompahgrite, turjaite and ijolite) were analysed with respect to their main components and trace elements. The ijolite rock, being in close geological association in space and time with the two major rock types under investigation (see Fig. 2), was included in this study for comparison purposes and to investigate if it exemplifies any genetic associations with the melilite-bearing rock types.

A plot of the total alkalies (i.e., $Na_2O + K_2O$ wt. %) Vs $SiO_2$ wt. % characterise the uncompahgrite, turjaite (and ijolite) as alkaline rock types (Fig. 5). Classification based on silica saturation identifies the rock types under study as ultrabasic ( i.e., their total silica content is less than 45 %).

Average whole-rock chemical analyses for the uncompahgrite and turjaite are presented in Tab. 7. There are evident chemical differences in the ultrabasic melilite bearing rocks of the study area. On the basis of the whole rock analyses, the turjaite rock has distinctly higher $Na_2O$ (av. 2.08 wt. %), $K_2O$ (av. 2.94 wt. %), $Al_2O_3$ (av. 7.76 wt. %), $P_2O_5$ (av. 2.94 wt. %), Cu (av. 467 ppm), Ba (av. 1850 ppm) and Sr (av. 1260 ppm) content, while the uncompahgrite rock has relatively low $Na_2O$ (av. 1.97 wt. %), $K_2O$ (av. 0.42 wt. %), $Al_2O_3$ (av. 4.30 wt. %), $P_2O_5$ (av. 0.18 wt. %), Cu (av. 66 wt. %), Ba (av. 165 wt. %), and Sr (av. 1132 ppm) content. By contrast, the uncompahgrite rock has moderately higher CaO (av. 30.64 wt. %), $TiO_2$ (av. 4.36 wt. %), $Fe_2O_3$ (av. 13.39 wt. %), Ni (av. 66 ppm), La (av. 133 ppm), Ce (av. 386 ppm) and C (av. 1030 ppm) concentrations as compared to the turjaite rock that has relatively low CaO (av. 24.19 wt. %), $TiO_2$ (av. 4.03 wt. %), $Fe_2O_3$ (av. 12.08 wt. %), Ni (av. 18 ppm), La (av. 60 ppm), Ce (av. 93 ppm) and C (av. 642 ppm) concentrations.

In both the AFM and Na+K-Mg-Fe+Mn variation diagrams (Fig. 6 (a) and (b) respectively), the uncompahgrite show a higher degree of Fe enrichment relative to the turjaite and ijolite rock types which, in contrast, are more enriched in total alkalies. In the $CaO-Na_2O-K_2O$ ternary diagram (Fig. 7), both the uncompahgrite and turjaite rocks show a comparatively high lime enrichment with the uncompahgrite rock having the higher values.

The proportions of Ti-Fe-V for the alkaline silicate rocks of the study area are shown in Fig. 8. From this diagram it can be seen that the variation of vanadium and iron with titanium appears to have an approximate linear chemical pattern within each of the rock types, i.e., the uncompahgrite, turjaite and ijolite. This chemical pattern, which is further illustrated in the V versus Fe and Ti Harker diagrams respectively (Fig. 9 (a) and (b)), infers a genetically closely associated rock types. The correlation coefficient (r) between V and Fe in the uncompahgrite and turjaite rocks is > 0.9. The correlation coefficient between V and Ti in the turjaite, ijolite and uncompahgrite range from 0.54 to 0.91

Distribution patterns for the light rear earth elements (REE) Ce and La within the rock types under study (see Fig. 10 (a) and (b)) show that:

(a) Ce is characteristically enriched in the uncompahgrite (av. 300 ppm) with a higher degree of homogeneity than either in the turjaites (av. 90 ppm) or the ijolites (av. 90 ppm).

(b) La follows a similar pattern as cerium (Ce) but with comparatively less enrichment in all the rock sequences from uncompahgrite, turjaite, and ijolite (i.e., av. 130, 60, and 10 ppm's) respectively.

## Discussion

Even though the agent causing metasomatism in the Rangwe complex has not been clearly defined, evidence suggesting that the transformation to uncompahgrite and turjaite was due to a reaction of the cumulative peridotite with its residual and lime rich fluids comes from:

(a) the low $^{87}Sr/^{86}Sr$ ratio of 0.703 obtained from olivine grains in the uncompahgrite (Rock, 1976) which imply that the crustal rocks did not contribute to the generation of this alkaline rock;

(b) presence of partly resorbed relics of peridotite

(c) presence of melilite in the uncompahgrite and turjaite has been taken to suggest that the original peridotite may have had kimberlitic parentage (Mitchell, 1972). In petrogenetic terms, melilites are individually associated with kimberlites (Ukhanov, 1963; Nixon, 1973), ijolites and carbonatites.

(d) the petrographic association of other kimberlitic minerals (forsteric olivine, diopsidic pyroxene, perovskite, phogopite and garnet) in the Rangwe uncompahgrite and turjaite further suggest their source rocks were of deep mantle origin.

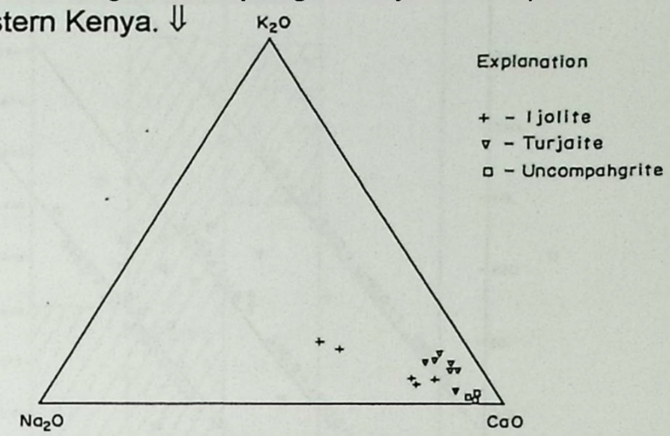
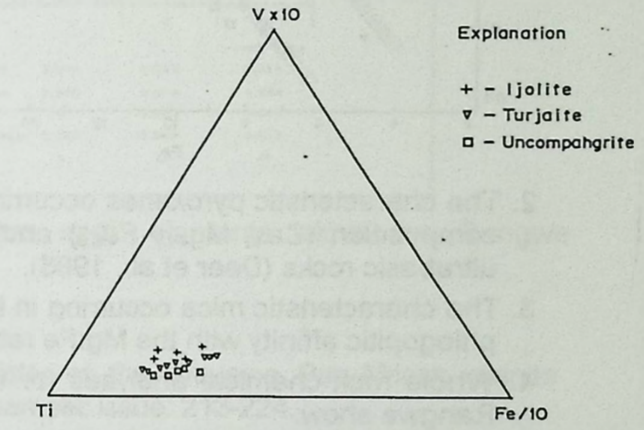
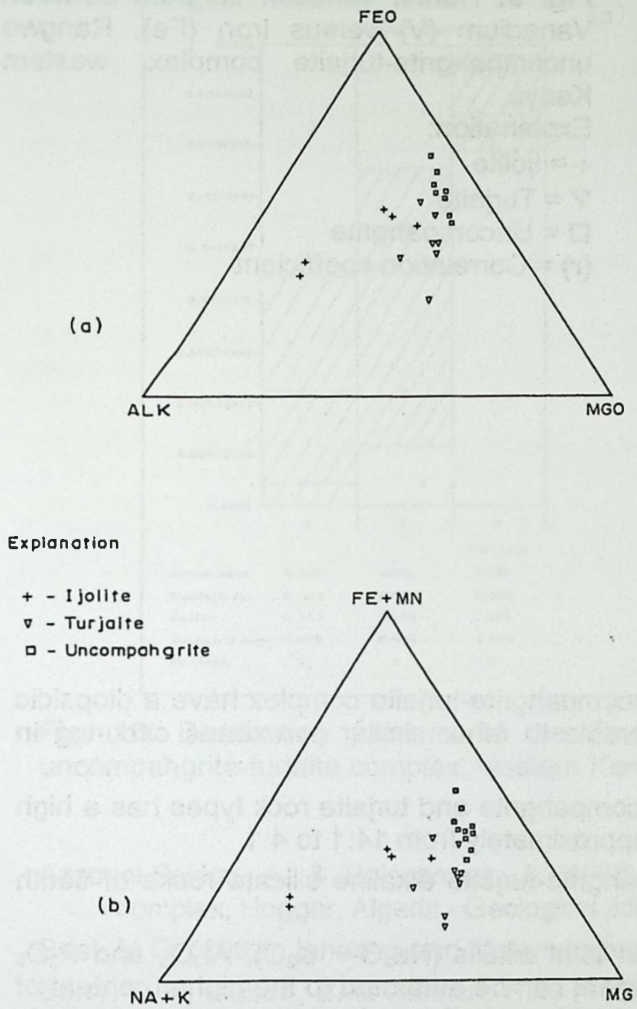



Fig. 7: The CaO-$Na_2O$-$K_2O$ variation diagram for the Rangwe uncophagrite-turjaite complex, western Kenya. ⇓




⇑ Fig. 8: The Ti-Fe-V variation diagram for the Rangwe uncompahgrite-turjaite complex, western Kenya.




⇑ **Fig. 6:** (a). The AFM and (b). the Na+K-Mg-Fe+Mn variation diagrams for the Rangwe uncompahgrite-turjaite complex, western Kenya.
Explanation for Figs. 6-8: + = Ijolite - ∇ = Turjaite - □ = Uncompahgrite

Melilites are known to be low pressure minerals, akermanite being stable in the presence of excess $CO_2$ and at less than 6 kbar pressure and between 1000 - 1400 C (Yoder, 1967). The trend frrom uncompahgrite to turjaite indicate that there is a significant variation in the composition of the melilites across the cluster of compositions at two-thirds akermanite and one-third soda melilite (see Tab. 2, this study; Le Bas, 1977) which is quoted by Yoder (1973) as being the normal field of igneous melilites.

The experimental evidence of Yoder (1967) appears to indicate that the uncompahgrite crystallized under comparatively low pressure, and that with continuing metasomatism, as the nature of the residual fluids changed and the temperature fell, nepheline became a stable phase and turjaite crystallized.

## Conclusions

The petrochemical study presented in this paper support a number of conclusions:

1. The relict olivine grains occurring in the uncompahgrite rock have a high forsteritic composition ($Fo_{85}$). This forsteritic composition closely matches that reported by Le Bas (1977) from a similar rock (i.e., $Fo_{84}$) from Kitunda area, south Rangwe.

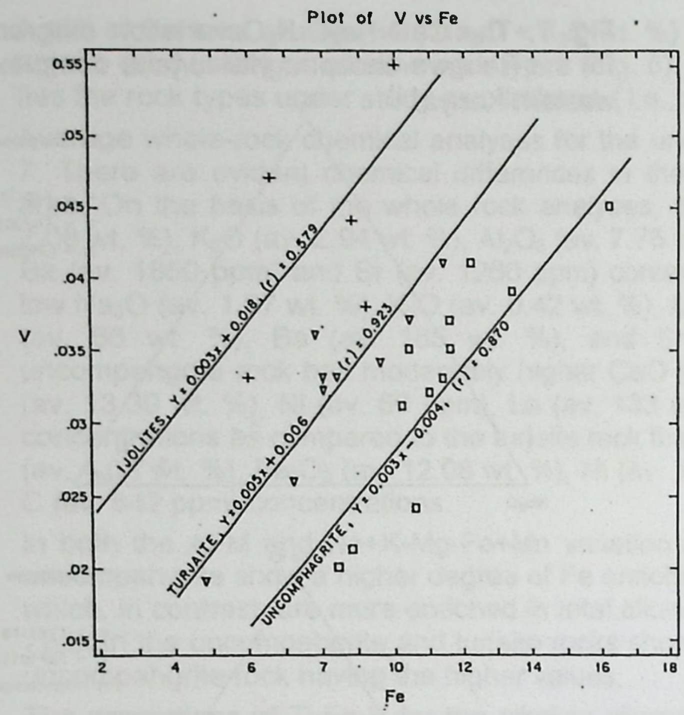



**Fig. 9:** Harker variation diagram between Vanadium (V) versus Iron (Fe). Rangwe uncompahgrite-turjaite complex, western Kenya.
Explanation:
+ = Ijolite
∇ = Turjaite
□ = Uncompahgrite
(r) = Correlation coefficient

2. The characteristic pyroxenes occurring in the uncompahgrite-turjaite complex have a diopsidic composition ($Ca_{49}$ $Mg_{44.7}$ $Fe_{6.3}$) and are comparable to other similar pyroxenes occuring in ultrabasic rocks (Deer et al., 1986).
3. The characteristic mica occurring in both the uncompahgrite and turjaite rock types has a high phlogopitic affinity with the Mg:Fe ratio ranging approximately from 14:1 to 4:1
4. Whole rock chemical analyses for the uncompahgrite-turjaite alkaline silicate rocks of south Rangwe show:

(i) that the turjaite is characteristically enriched in total alkalis ($Na_2O$ + $K_2O$), $Al_2O_3$ and $P_2O_5$ relative to the uncompahgrite rock. This enrichment can be attributed to the higher content of mica (mainly phlogopite) and apatite that occur in this rock. By contrast the uncompahgrite is relatively enriched in CaO, $TiO_2$ and FeO content which invariably can be attributed to its higher content in diopside, perovskite and magnetite as illustrated by its modal composition.

(ii) that there is characteristically light REE enrichment in the order: ijolite< turjaite < uncompahgrite.

5. Petrographic study has shown that the titanium rich andradite garnet in association with nepheline is a more stable phase in the turjaite rock than in the uncompahgrite.

## Acknowledgement

The senior author wish to thank Bo Johanson for his assistance in carrying out the mineral probe analyses at the Geological Survey of Finland. He also wishes to express deep gratitude to the Department of Mines and Geology through the Ministry of Environment and Natural Resources in Kenya, for granting him a study leave to carry out the research study in Finland. The research study programme was funded by the Finnish international Development Agency (FINIDA) through the Industrial minerals project.

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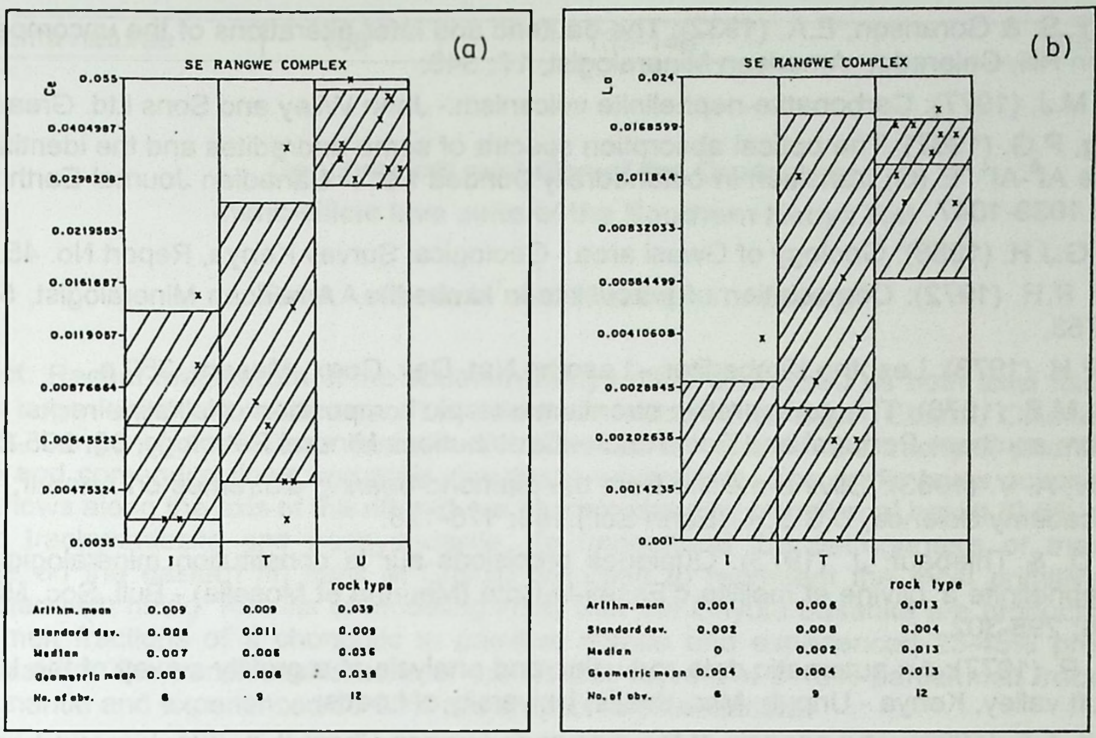


**Fig. 10:** Distribution patterns of the Ce and La rare earth elements within the Rangwe uncompahgrite-turjaite complex, western Kenya.


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## APPENDIX

**Tab. 1(a).** Modal composition of the Uncompahgrite rock from the south Rangwe alkaline complex, western Kenya. (Average of 4 samples based on point counter analyses of 1000 points).

| Mineral | Range (in volume %) | Average (in volume %) |
|---|---|---|
| Nepheline | - | - |
| Melilite | 61.2 - 70.4 | 64.2 |
| Diopside | 2.0 - 12.8 | 8.4 |
| Melanite | - | - |
| Olivine | 0 - 3 | 2 |
| Perovskite | 5.6 - 17.3 | 10.2 |
| Phlogopite | 1 - 4 | 3 |
| Apatite | 0 - 1 | 0.5 |
| Magnetite | 8.5 - 15.5 | 11.7 |

**Tab. 1(b).** Modal composition of the Turjaite rock from the south Rangwe alkaline complex, western Kenya. (Average of 3 samples based on point counter analyses of 1000 points).

| Mineral | Range (in volume %) | Average (in volume %) |
|---|---|---|
| Nepheline | 2 - 4 | 2.5 |
| Melilite | 43 - 58.4 | 46 |
| Diopside | 1.5 - 4 | 2.3 |
| Melanite | 0 - 2 | 1.2 |
| Olivine | - | - |
| Perovskite | 6.5 - 11.2 | 8.4 |
| Phlogopite | 15 - 40.3 | 25 |
| Apatite | 4 - 8.5 | 6.2 |
| Magnetite | 3 - 15 | 8.3 |

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# Geochemical evolution of the Quaternary mafic-silicic lava suite of the Southern Kenya Rift

Peter A. Omenda[1] and Elizabeth Y. Anthony[2]

**Abstract:** Recent magmatism in the southern Kenya rift is expressed as both axial fissure flows and as large low-shield volcanoes. The volcanoes include Menengai, Eburru, Olkaria volcanic complex, Longonot and Suswa and are characterized by voluminous trachyte, phonolite, pantellerite and comendite flows and their pyroclastic equivalents. The mafic lavas occur mainly as fissure flows along the axis of the rift and are characterized by transitional basalt (0-5% norm ne), basaltic trachyandesite and trachyandesite. To understand the petrogenesis of these lavas; basanite on the eastern rift flank at Chyulu are used to represent the most primitive magma associated with rifting. Results of modeling imply that the Chyulu basanite are products of 1-2% partial melt fractions of a chondritic to primitive mantle and experienced 25-45% pre-eruption crystallization. The transitional basalts of the rift axis represent 5-15% partial melt fractions of a similar mantle and experienced 60-80% pre-eruption crystallization.

Major and trace element models show that the pantellerite, trachyte and associated transitional basalt are co-genetic and the evolution was largely by poly-baric fractional crystallization processes. Suswa is in a transition zone where the lithosphere begins to thicken southward as determined from seismic and gravity studies. The thickness just north of Suswa is about 35 km but is about 70 km under Lake Magadi, <100 km south of Suswa. The volcano displays pre-caldera lavas of transitional basalt - trachyte association similar to the others in the rift. However, the evolution of the post-caldera phonolite - trachyte suite requires more alkaline parental magma. The contrasting magmatism of the volcano is related to the southward thickening of the lithosphere. Comendite at Olkaria volcanic complex are not part of the fractional crystallization evolutionary paths of the rift magmas but were generated by crustal anatexis. Partial melt models based on major and trace elements fail to generate the comendite from known Precambrian basement rocks and instead partial melting of syenitic pluton is proposed.

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## Introduction

The southern Kenya rift (SKR) is the region to the south of Menengai volcano and extending to the northern Tanzania border (Fig. 1). Detailed study was carried out in the sector between Elmenteita basaltic field in the north and Suswa volcano to the south and restricted to the rift graben floor. However, Chyulu volcanic field on the eastern flank of the rift has been used to aid in the understanding the nature of primary magmatism along the axis of the Kenya rift.

Magmatism associated with the Kenya rift has been studied in great detail over the years and in general, two lines of findings emerge with the first school of thought indicating that the mafic and silicic magmas are mantle derivatives with the silicic members being a result of protracted fractional crystallization processes (e.g. Gibson, 1972; Weaver et al., 1972; Barberi et al., 1975; Baker & Henage, 1977; Baker et al., 1977; Baker & McBirney, 1985; Baker et al., 1988). The second opinion is that the mafic lavas are of mantle derivation but contaminated with crustal materials during accent and that silicic lavas are either wholly crustal melts or combination of fractional crystallization and crustal assimilation (e.g. Davis & Macdonald, 1987; Macdonald et al., 1987; Black et al., 1997).

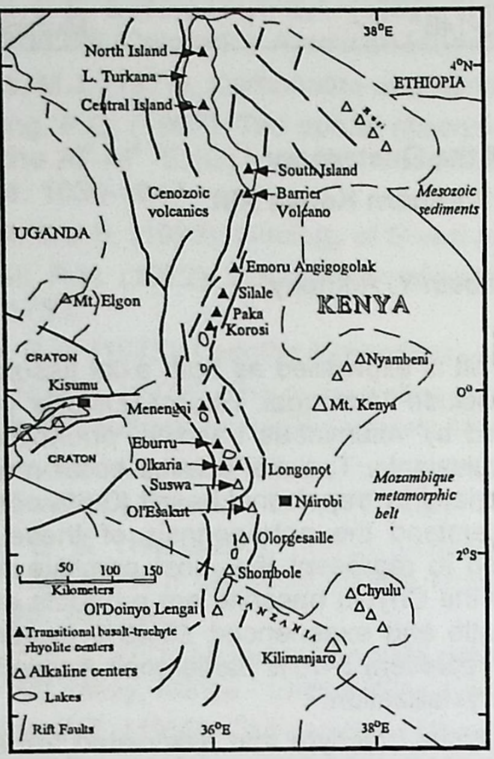



Fig. 1: Map of western Kenya showing the rift valley and the major Quaternary volcanoes in the axis of the rift and on the eastern flank including Chyulu

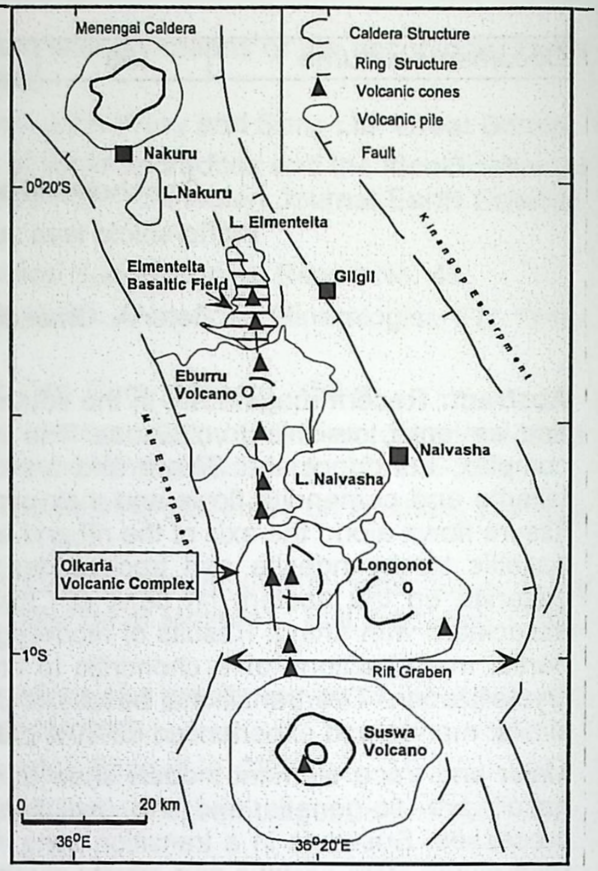



Fig. 2: Map showing the intra-rift volcanoes of the south-central Kenya rift

The main aims of in this study are to offer possible reasons for the occurrence of (1) phonolites at Suswa volcano since it is the only place where the lavas were erupted in the Kenya sector of the East African rift during the Recent times, (2) comendite at Olkaria and pantellerite at Eburru. Further, the relationships between the assemblages that built the volcanoes and the mafic lavas that are common in the low-lying grounds between the volcanoes are discussed.

## Geological setting

The evolution of the Kenya rift started during the late Oligocene - early Miocene with up doming associated with mantle upwelling. In the Kenya sector of the rift, the doming and subsequent collapse occurred along the contact of the Precambrian greenstone belt of the Tanzania craton and the Proterozoic Mozambiquan mobile belt (Baker et al., 1971, 1972, 1988; Baker & Mitchel, 1976; Baker, 1987; Shackleton, 1986; Smith & Mosley, 1993; Smith, 1994). Up doming was accompanied by extensive eruption of phonolite, basalt, basanite and their pyroclastic equivalents. Faulting associated with rifting commenced during late Miocene with half graben formation and the full graben formed during Pleistocene epoch. Faulting episode was accompanied by volcanism, which intensified during Pliocene - Pleistocene with the eruption of basalt, flood trachytes and tuffs.

During Pleistocene to Holocene epochs, volcanism moved to the axis of the rift with the formation of central volcanoes, most of which have transitional basalts and evolved lavas and pyroclastics (Williams et al., 1984). The volcanoes include Suswa, Longonot, Olkaria volcanic complex and Eburru (Fig. 2). The low-lying grounds between the volcanoes that include Elmenteita, Ndabibi and Tandamara, have fissure flows of basalt, trachybasalt, basaltic trachyandesite and trachyandesite. At the same time as the rift axial eruptions, volcanism occurred on the eastern flank of the rift at Chyulu, Nyambeni and Huri regions (Fig. 1). Volcanism in these areas was dominated by basanites and minor tholeiites (Goles, 1975; Class et al., 1994).

**Characteristics of the lava suites**

The volcanic centers under detailed discussion include the central volcanoes of Suswa, Olkaria, Eburru and Chyulu volcanic field on the eastern rift flank and fissure flows of Elmenteita, Ndabibi and Tandamara. Chyulu basaltic field lies on the eastern flank of the Kenya rift and about100 km from the edge of rift scarp. Volcanism in this area was structurally controlled with most of the centers lying along lines of weakness within the metamorphic rocks of the Mozambiquan mobile belt. The rock types are mainly basanites and minor tholeiites; however, the two are not readily identifiable in the field. The lavas are highly vesicular and phyric with large olivine phenocrysts. Several of the scoria cones associated with basanitic flows have mantle xenoliths, which vary in size from small to pea sizes and consist largely of olivine and pyroxenes (Goles, 1975; Omenge & Okelo, 1992).

Suswa is the most southern caldera volcano in the axis of the central Kenya rift (CKR) and probably the most petrologically and structurally interesting. The volcano has two calderas: large outer caldera (I) and inner caldera (II) with a resurgent dome surrounded by an annular trench. The shield volcano overlies a faulted trachyte formation of early Pleistocene age (Pre-Suswa Trachytes) and the volcano itself is built of two groups of vesicular trachytes (Early Suswa and Pre-Caldera Trachytes). The Pre-Caldera Trachytes are overlain by Syn-Caldera Trachytes that are highly vesicular and most of which qualify as agglutinates. The post-caldera magmatism changed from trachytic to phonolitic composition with the phonolites infilling the caldera floor and even overflowing the caldera walls to the east. Four distinct phonolite flows are identifiable, namely Ol' Donyo Nyoke (Pre-caldera II), Island Block, South Flank and Annular Trench (Post-Caldera II) Phonolites. Most of the phonolites are highly porphyritic with the phenocrysts being dominated by anorthoclase and minor aegirine and magnetite. The matrix contains glass, anorthoclase, aegirine, oxides and minor soda-minerals. Details are reported in Nash et al. (1969), Torfason (1987), Randel & Johnson (1991), Omenda (1994, 1997), Skilling (1988, 1993) and Macdonald et al. (1993).

Longonot caldera is located 20 km to the NNE of Suswa volcano and has a caldera of similar dimensions to that of Suswa. Longonot volcano largely erupted trachytes and their pyroclastic equivalent during the shield building and syn-caldera magmatic stages. However, the intra-caldera magmatism was mainly trachytic and the latest activities produced largely mixed basalt-trachyte lavas within the central crater and along linear fissures outside of the caldera floor (Scott, 1977; Scott & Bailey, 1984; Clarke et al., 1990). The volcano has a thick pyroclastic cover, which is associated with caldera collapse and post caldera volcanism.

Olkaria Volcanic Complex is one of the few areas within the Kenya rift floor with extensive rhyolitic volcanism. Olkaria area is characterized by comendite (rhyolite) lava flows and lava domes on a pyroclastic (ash) cover. Minor trachyte flows occur in the southern part of the field. Some of the lava domes describe a ring structure in the center of the volcanic field. The comendite consists of phenocrysts of arfvedsonite-riebeckite, quartz, sanidine, oxides, ±fluorite, and ±hornblende in a fine-grained matrix composed of the same minerals (Bliss, 1979; Bone, 1988; Clarke et al., 1990; Omenda, 1997, 1998; Marshall et al., 1998).

Eburru massif is the volcanic complex with the highest elevation (2700 masl) within the Kenya rift floor. The rocks forming the massif are mainly trachyte and pantellerite and their pyroclastic equivalents. However, basalts and tuffs occur in the subsurface as intercalations within trachyte and rhyolite flows. Syenitic intrusions were encountered from about 2041 m below the surface during drilling of geothermal wells in the area. The trachytes are porphyritic and consist of feldspar, aegirine, aenigmatite and oxides in a vitric groundmass. The pantellerites that are the youngest in Eburru are highly vitric and contain phenocrysts of quartz, aegirine, sanidine, aenigmatite and oxides (Sutherland, 1974; Omenda 1991, 1997).

Whereas the main volcanic centers experienced largely silicic magmatism during the period in review, the low-lying grounds between them had a change in volcanic style with the eruptions dominated by fissure flows of mafic and intermediate composition. Elmenteita basaltic field, which is located north of Eburru volcano, is characterized by basaltic, trachybasalt, basaltic trachy-andesite and trachyandesite flows. The lavas erupted through N-S fissures and the latest activity was probably contemporaneous or younger than the latest activity on Eburru.

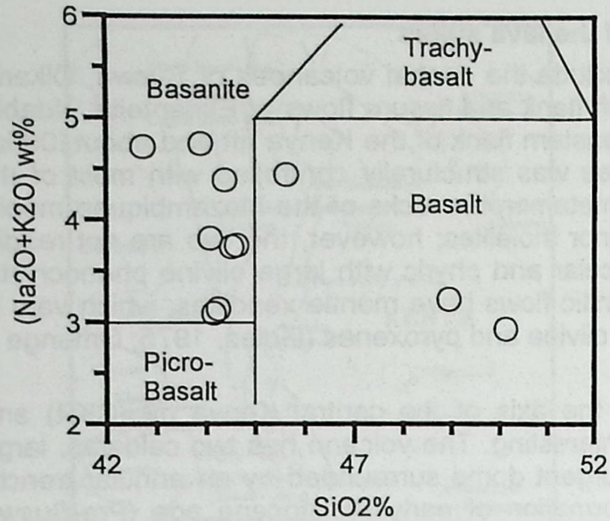



**Fig. 3:** TAS classification diagram of the basanites and tholeiites of Chyulu basaltic field.

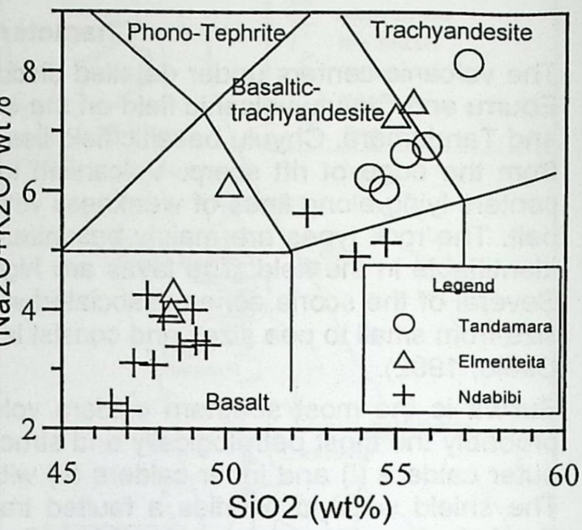



**Fig. 4:** TAS classification diagram for the mafic lavas of the rift axis at Ndabibi, Elmenteita and Tandamara basaltic fields.

Similar lavas occur in Ndabibi area, which is to the south of Eburru volcano but only basaltic trachyandesite and trachyandesite occur at Tandamara volcanic field, north of Suswa. The basalts contain phenocrysts of plagioclase, pyroxene and olivine in a fine-grained, vesicular matrix. The intermediate lavas do not have phenocrysts of olivine.

## Geochemical characteristics

### Chyulu

The lavas at Chyulu consist of basalts and basanites with Mg#'s of 57-74%; higher values being common in the latter group. The basanites are more under-saturated and plot in the alkaline field of Irvine and Baragar (1971) in contrast to the basalts that are sub-alkaline (Fig. 3). Detailed study indicates that the two groups of lavas are not part of the same liquid line of descent (Omenda, 1997) and thus, only the basanites will be considered further. The basanites may be considered primitive due to their high concentrations of transition elements, e.g., Cr (<940 ppm) and Ni (769 ppm), high Mg# (58-74%) and low $SiO_2$ (43.18-49.96%). The basanites also have high concentrations of incompatible trace elements, e.g., Zr (210-325 ppm), Nb (62-100 ppm). The basanites are nepheline normative (4.4-9.8%).

### Elmenteita Basaltic Field

The rocks occurring in this area consist of basalts, trachybasalt, basaltic trachyandesite, and trachyandesite. The rocks have medium to high $SiO_2$ (48-56%) contents in going from basalts to trachyandesite (Fig. 4), have low MgO (<6.5%), Mg# = 46-53% and are weakly hypersthene normative (0.8-5%) thus, qualify to be referred to as transitional basalts (Baker, 1987). Trace element data shows that even the most mafic of the basalts is depleted in transitional elements, e.g., Cr < 95 ppm, Ni < 55ppm and relatively low in concentrations of incompatible elements, e.g. Zr = 108-171 ppm, Nb = 28-43 ppm. Despite the lava flows being spatially and temporally associated, the scatter in trace element patterns as shown by the spider plots (Fig. 5) suggests that they are not comagmatic.

### Ndabibi Basaltic Field

The lavas in Ndabibi, according to TAS diagram (Fig. 4), consist of basalt and basaltic trachyandesite with $SiO_2$ lying within the range of 46.5-49%. Data from Davis & Macdonald (1987)

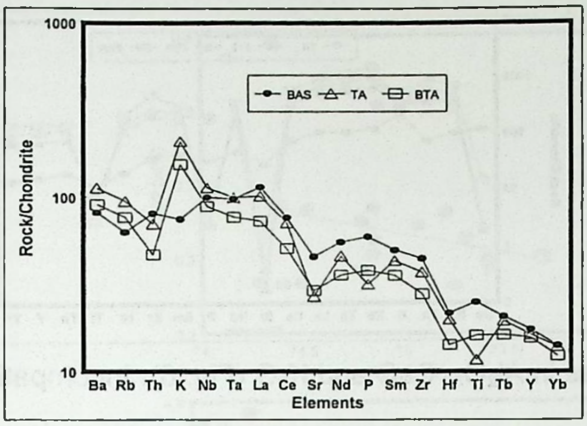



Fig. 5: Multi-element diagram of the basalts and intermediate lavas of the Elmenteita basaltic field.

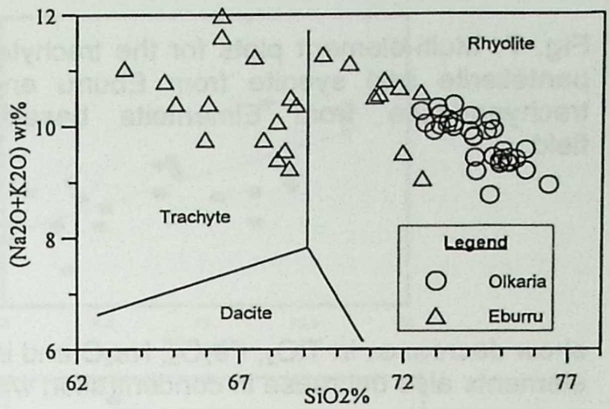



Fig. 6: TAS classification diagram for the Eburru and Olkaria rhyolites.

reveal that the rocks have medium to low MgO concentrations of 6.36-8.04%, low total alkalis (2.2-3.9%), high $Al_2O_3$ (15.48-15.11%), high CaO (10.18-12.31%) and high FeO (9.54-12.14%). Mg# varies between 48-59%. The rocks are highly depleted in compatible trace elements, e.g. Cr = 54-72 ppm, Ni = 20-34 ppm and are also low in the contents of incompatible trace elements, e.g. Zr = 64-124 ppm, Nb = 20-34 ppm. Major element variations indicate increase of $TiO_2$, $Na_2O$, $P_2O_5$ and $K_2O$ with evolution while CaO and $Al_2O_3$ decrease.

**Eburru volcano**

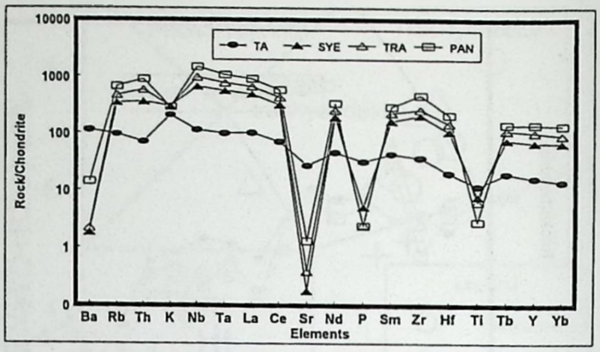
The trachytes and rhyolite that are associated with Eburru are highly evolved with some trachytes plotting close to the borderline between trachyte and rhyolite in the TAS classification (Fig. 6). The trachytes have high $SiO_2$ (63-69%), high $Fe_2O_{3(t)}$ (10.5-11.1%), $Na_2O$ (5.06-6.97%) > $K_2O$ (4.23-4.40%) and very low MgO (0.01-0.11%) and $P_2O_5$ (0.03%). The trace element contents of the trachytes show extreme depletion in the compatible elements, e.g. Cr = 0-9ppm, Ni = 0-6 ppm and strong enrichments in incompatible elements, e.g., Zr = 984-1053 ppm, Nb = 289-335 ppm. The syenitic intrusive has geochemical characteristics that are similar to those of trachytes.

The rhyolite in Eburru classify as pantellerite due to their high contents of FeO and high total normative femics (Di, Hd, En, Fs) and low $Al_2O_3$ as proposed by Macdonald and Bailey (1973). The rocks when compared to other rhyolite have low-medium $SiO_2$ (70.99-71.38%), high $Fe_2O_{3t}$ (8.58-8.86%), very low MgO (0.01-0.05%) and high alkalis $Na_2O$ (5.08-6.69%) > $K_2O$ (4.10-4.32%). The compatible trace elements are highly depleted in the pantellerite e.g. Cr = 2-12ppm, Ni = 0-4 ppm while the incompatible trace elements are highly enriched, e.g., Zr = 1700-1809 ppm, Nb = 468-523 ppm. Major element variations with $SiO_2$ show decrease in $TiO_2$, $Al_2O_3$, CaO, $Fe_2O_3$, $Na_2O$, and $K_2O$ from trachyte to pantellerite. Incompatible elements shows increase in concentration from trachyte to pantellerite while compatible elements are more depleted in pantellerite (Fig. 7).

**Olkaria volcanic Complex**

Total alkali-Silica classification diagram for the surface rocks at Olkaria show that they are mainly high silica rhyolite with $SiO_2$ = 72-76% (Fig. 6). The rocks qualify to be called comendite since $K_2O$ (4.53-4.90%) > $Na_2O$ (4.11-4.64%), have low $Fe_2O_{3t}$ (4.43-5.84%) and have high $Al_2O_3$ (10.58-11.49%). Other characteristics of the lavas include very low MgO (0-0.02%), low CaO (0.1-0.33%) and very low $P_2O_5$ (0%). Trace element patterns show extreme depletions in compatible elements, e.g. Cr = 0-9 ppm, Ni = 0-7 ppm while the incompatible elements are highly enriched, e.g. Zr = 1208-2111 ppm, Nb = 307-464 ppm. Variations of major elements variations with $SiO_2$

Fig. 7: Multi-element plots for the trachyte, pantellerite and syenite from Eburru and trachyandesite from Elmenteita basaltic field.




show decreases in $TiO_2$, $Fe_2O_3$, $Na_2O$ and increases in $Al_2O_3$, CaO and $K_2O$ (Fig. 8). Incompatible elements also decrease in concentration with $SiO_2$.

### *Suswa volcano*

The rocks associated with Suswa volcano include Early Suswa Trachytes, Pre-caldera Trachytes, Syn-Caldera Trachytes and Post-Caldera Phonolites. The oldest of these rocks overlie Plateau Trachytes. The Plateau Trachytes (Pre-Suswa lavas) are enriched in $SiO_2$ (62-66%) compared to the Suswa lavas (Fig. 9) but are closely matched by the Pre-Caldera Trachytes (59.28-60.80%) and Syn-Caldera Trachytes (58.55-61.14%). Phonolites have the lowest $SiO_2$ at 56.67-57.82%. Calculation of CIPW-norms indicates the Early Suswa and Pre-Caldera Trachytes as quartz normative (Q = 0.9-13) with the lower range common for the Pre-Caldera Trachytes. The Syn-Caldera Trachytes, in contrast, are weakly nepheline normative (Ne = 0-5.1) as is the case for the phonolites (Ne = 9.1-17.7). Major element variations show decrease in $TiO_2$, $Al_2O_3$, MgO, CaO, $Na_2O$ and $P_2O_5$ with $SiO_2$ from phonolite to trachytes indicating that the trachytes are more evolved than the phonolites.

Trace element contents of the Pre- and Syn-Caldera Trachytes are generally similar to the Early Suswa Trachytes in being depleted in the compatible trace elements e.g. Cr, Co, Ba and Sr and enriched in incompatible trace elements. However, multi-element spider diagram (Fig. 10) indicates that the Pre-Caldera Trachytes are more enriched in incompatible elements than the Syn-Caldera Trachytes and together with the fact that the Syn-Caldera Trachytes are ne-normative suggest that the two are not co-magmatic. The phonolites are enriched in incompatible trace elements and depleted in compatible elements; however, the degree of depletion is not as great as in trachytes. Plot of multi-elements shows that the concentrations of incompatible elements generally increase from phonolites to trachytes (Fig. 10). However, the older phonolites (Pre-Caldera II, e.g. samples 22,39) are more enriched in ITE than the younger phonolites (Post-Caldera II e.g. sample 49), thus suggesting the possible existence of a zoned magma chamber. The multi-element plot further indicates depletions in Ba, K, Sr, P, and Ti suggesting the influence of feldspars, apatite and Fe-oxides in the evolution of the lavas.

## Discussion

Characteristics of the Chyulu lavas on the eastern flank of the Kenya rift are here used to aid in the understanding of the geochemical evolution of the axial magmas of the Kenya rift. The basanites at Chyulu were chosen since they are the most primitive lavas associated with rifting in the southern Kenya rift. The Chyulu lavas are considered primitive due to their very high Mg#'s, very high content of transitional elements e.g. Cr, Ni, Co, and also the presence of mantle xenoliths and xenocrysts that are common within the lava flows. The mafic lavas at Chyulu and those within the axis of the rift are characterized by increase in $TiO_2$, $Na_2O$, $K_2O$, $P_2O_5$ and decrease in CaO with evolution. However, $Al_2O_3$ shows opposite trends where it decreases in the Ndabibi basalts and increases in the Chyulu basanites with evolution (decreasing Mg#). However, the Chyulu basanites are more enriched in $TiO_2$, MgO, $Na_2O$, $K_2O$ and $P_2O_5$ but lower in CaO and $Al_2O_3$. Trace elements concentrations are higher in the basanites than in the lavas of the rift axis at Ndabibi, Ol Tepesi and Elmenteita implying that either the sources for the magmas are different or the basalts of the rift axis are more evolved (Fig. 11).

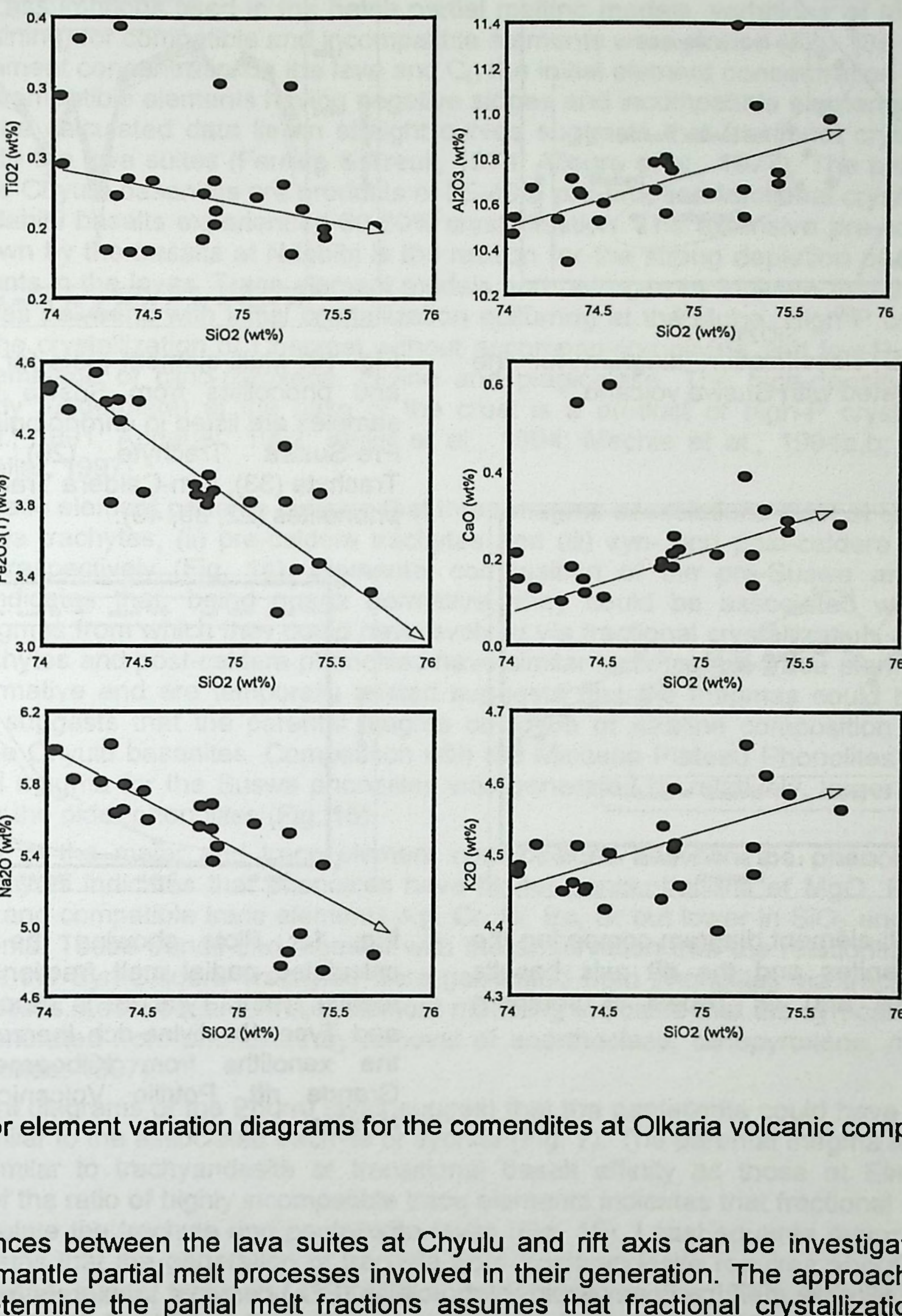



**Fig. 8:** Major element variation diagrams for the comendites at Olkaria volcanic complex

The differences between the lava suites at Chyulu and rift axis can be investigated by determining the mantle partial melt processes involved in their generation. The approach used in this study to determine the partial melt fractions assumes that fractional crystallization processes relate the lava flows in a suite. The main argument follows the findings of Roeder & Emslie (1970) that the ratio of $Mg/Fe^{+2}$ = 2.70 in mantle of Fo = 90. Taking the equilibrium constant of Mg/FeO in melt and solid to be 0.3 and assuming Rayleigh crystallization law, a regression between ln (Mg/Fe) and ln ($H^+$) can be generated. Extrapolation to mantle of Fo = 90 would generate the concentration ($C_{i,l}$) of element ($H^+$) in the initial melt. "$H^+$" is a highly incompatible trace element. The melt fraction "*F*" generated can then be obtained by assuming some initial concentration of the element, $C_o$, in the mantle (e.g. Minster & Allegre 1978).

In this study, four types of mantle were considered to be possible parental compositions: chondritic, primitive, olivine-rich and cpx-rich lherzolite (Long 1994, Omenda 1997). Results of the study indicate that basanites on the eastern flank at Chyulu are products of 0.7-2.4% partial melt fractions of chondritic to primitive mantle (Fig. 12).

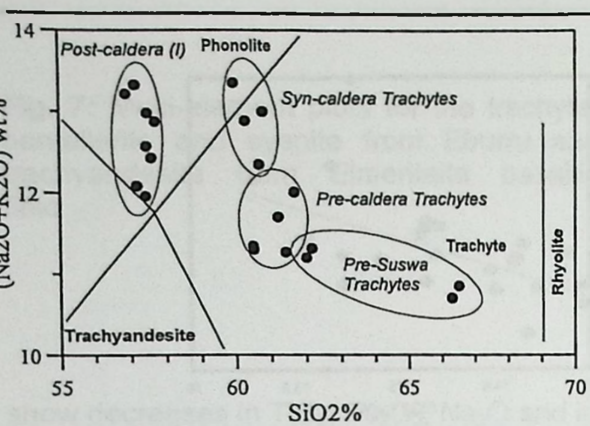



**Fig. 9:** TAS classification diagram for the lavas associated with Suswa volcano.

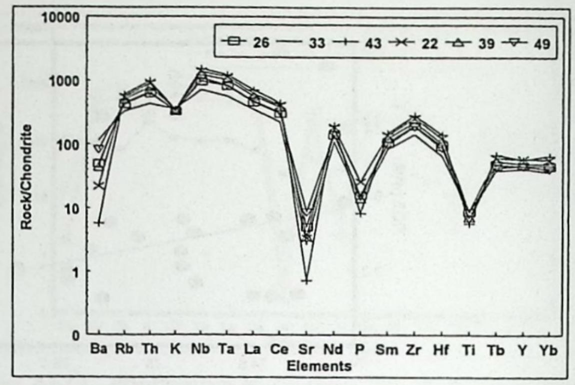



**Fig. 10:** Multi-element plots for the trachytes and phonolites from Suswa volcano. The samples are listed in chronological order from Pre-Suswa Trachyte (26), Pre-Caldera Trachyte (33), Syn-Caldera Trachyte (43) and phonolites (22, 39, 49).

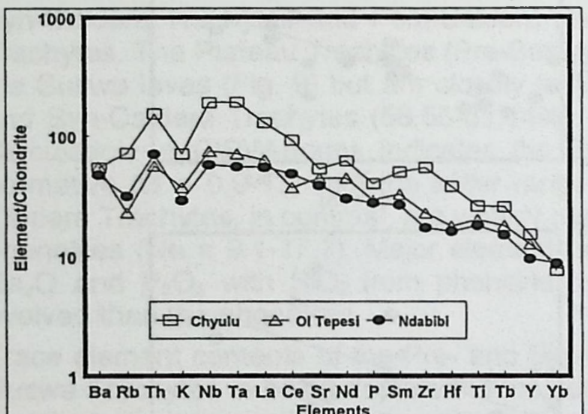



**Fig. 11:** Multi-element diagram comparing the Chyulu basanites and the rift axis basalts from Ndabibi and Ol Tepesi in southern Kenya rift.

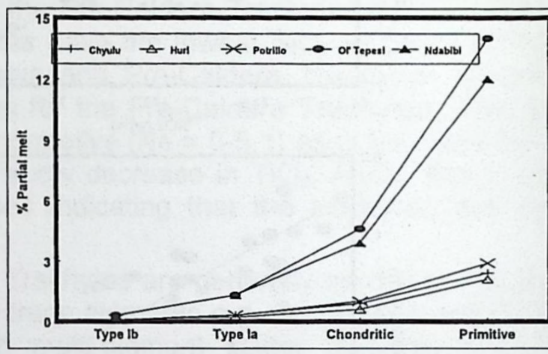



**Fig. 12:** Plots showing the variation of calculated partial melt fractions for various mantle types. Type 1a is clinopyroxene-rich and Type 1b olivine-rich lherzolite similar to the xenoliths from Kilbourne Hole, Rio Grande rift, Potrillo Volcanic field, New Mexico.

Since small alkaline melt fractions require high volatile ($CO_2$) contents to migrate implies that the basanites were generated from great depths, probably greater than 90 km in the mantle (Baker et al., 1995; Kinzler & Langmuir, 1995; Edger, 1987; Egger, 1976; Brey & Green, 1975). Thermo-barometry of the mantle xenoliths from Chyulu and seismic tomography indicate depth of partial melting to be greater than 100 km (Henjes-Kunst & Altherr, 1992; Ritter et al., 1995, 1997). In contrast, the primary magmas of the Kenya rift axis (e.g. Ol Tepesi and Ndabibi basalts) were produced from 5-15% melt fractions of chondritic to primitive mantle, respectively. The transitional character, high $SiO_2$ and high melt fractions imply that the primary rift axis magmas were generated from, relatively, shallow and volatile-poor source region of the mantle. The lower figure compares favorably with melt fractions determined by seismic studies (e.g. Mechie et al., 1994a). Lack of volatiles is also supported by the absence of mantle xenoliths in the rift axis lavas. The high concentrations of trace elements in the Chyulu lavas relative to those of the rift axis (Fig. 11) is related to the nature of the underlying mantle which is more depleted under the rift axis than under the eastern rift flank.

To test the assumptions used in the batch partial melting models, variations of $\ln C_l/C_{i,l}$ vs. F (% Liquid remaining) for compatible and incompatible elements were plotted (Fig. 13). In this case, $C_l$ refers to element concentration in the lava and $C_{i,l}$ the initial element concentration at source. The plots show compatible elements having negative slopes and incompatible elements positive slope and since the calculated data lie on straight curves suggests that fractional crystallization processes relate the lava suites (Ferrara & Treuil, 1974; Allegre et al., 1977). The plots further indicate that the Chyulu basanites are products of 25-43% pre-eruption fractional crystallization while those at Ndabibi basalts experienced 60-80% crystallization. The extensive pre-eruption crystallization shown by the basalts at Ndabibi is the reason for the strong depletion of the compatible trace elements in the lavas. Trace element models and petrography indicate that the evolution of the lavas was polybaric with initial crystallization occurring at the Moho. High-P crystallization is shown by the crystallization of Cr-spinel without accompanying olivine and low-P by the phenocrystic assemblage of clino-pyroxene, olivine and plagioclase. The high-density, high-seismic velocity body (underplate) at the base of the crust is a product of high-P crystallization (e.g. Green et al., 1991; Achauer, 1992; Keller et al., 1994; Mechie et al., 1994a,b; Simiyu, 1996; Simiyu & Keller, 1997).

Major and trace element patterns indicate that three magma associations exist at Suswa, namely, (i) Pre-Suswa trachytes, (ii) pre-caldera trachytes and (iii) syn- and post-caldera trachytes and phonolites, respectively (Fig. 14). Elemental composition of the pre-Suswa and pre-caldera trachytes indicates that, being quartz normative, they could be associated with transitional basaltic magmas from which they could have evolved via fractional crystallization. Since the syn-caldera trachytes and post-caldera phonolites have similar incompatible trace element ratios, are both ne-normative and are temporally related suggests that the magmas could be co-genetic. Ratio plots suggests that the parental magma could be of alkaline composition and probably similar to the Chyulu basanites. Comparison with the Miocene Plateau Phonolites indicates that the parental magma for the Suswa phonolites was generated by relatively, larger melt fractions than that for the older phonolites (Fig. 15).

Comparison of the major and trace element compositions between the phonolites and syn-caldera trachytes indicates that phonolites have higher concentrations of MgO, $Fe_2O_{3(t)}$, $Na_2O$, $Al_2O_3$, CaO and compatible trace elements e.g. Cr, Ni, Ba, Sr but lower in $SiO_2$ and incompatible trace elements. These trends and together with the observation that the relationships are linear indicate that the Syn-Caldera Trachytes were generated from phonolites via fractional crystallization processes. Least squares major element modeling indicates that the syn-caldera trachytes could be generated from phonolites by removal of anorthoclase, clinopyroxene, magnetite and apatite (Omenda, 1997).

Multi-element diagrams of the Eburru lavas suggest that the pantellerite could have evolved from magmas similar to the associated trachyte or syenite (Fig. 7). The parental magma to the trachyte could be similar to trachyandesite of transitional basalt affinity as those at Elmenteita. The constancy of the ratio of highly incompatible trace elements indicates that fractional crystallization processes relate the trachyte and pantellerite lavas (Fig. 15). Least squares major element modeling indicates that the generation of trachyte from trachyandesite requires about 83% crystallization of olivine, augite, feldspars, magnetite and apatite (Omenda, 1997). Further crystallization of trachytic magma to produce pantellerite would be accompanied by about 23% crystallization with sanidine, aegirine, plagioclase and magnetite as the main solid phases removed. The model indicates that pantellerites are products of more than 95% pre-eruption crystallization of magma of similar composition as the Elmenteita or Ndabibi basalts.

Major elements data for the comendites at Olkaria show increase of CaO, $K_2O$ and $Al_2O_3$ with $SiO_2$; trends that are inconsistent with fractional crystallization processes (Fig. 8). Linear plots of highly incompatible trace elements for the rift related silicic lavas show the comendites at Olkaria falling on trends that are oblique to the general trends of the rift magmas (Fig.16). These patterns suggest that the comendites were not generated by fractional crystallization processes but by anatexis of appropriate crustal materials. The possible protoliths include Proterozoic metamorphic gneisses, which are the basement rocks in the region; down faulted late Oligocene to early Miocene rift related mafic to silicic lava flows; or plutons of intermediate composition and associated with the rift's evolved lavas. Gneisses are not possible source rocks since the comendites are

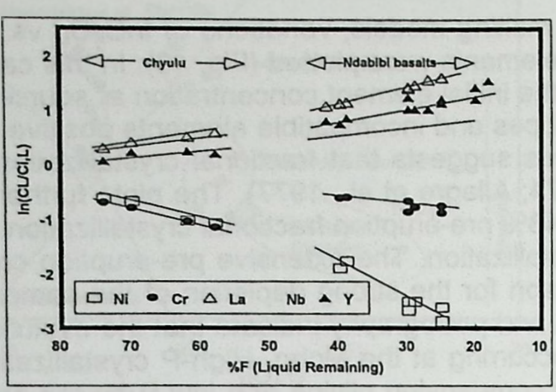



Fig. 13: Plots of modelled degrees of partial melt for the Chyulu basanites and basalts from the Ndabibi basaltic field.

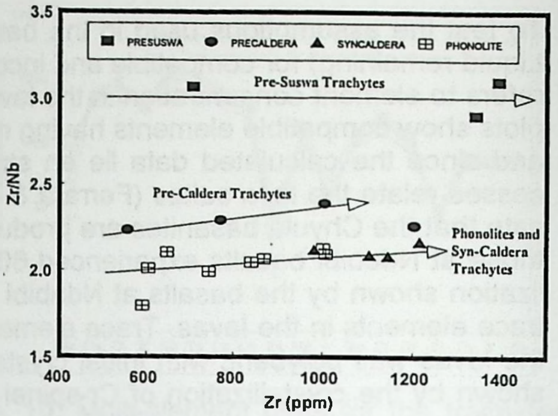



Fig. 14: Plots of Zr vs. Zr/Nb for the Suswa and Pre-Suswa lavas. The diagram shows distinct magmatic lineages for the various groups of the Suswa lavas.

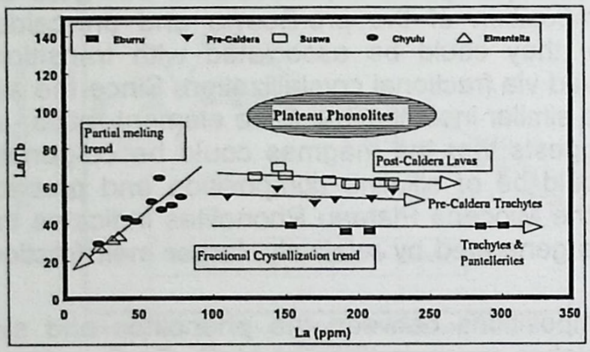



Fig. 15: Plots of La vs. La/Tb for the lavas from Chyulu, Suswa, Eburru and Elmenteita. The diagram shows that fractional crystallization processes relate the various lava suites.

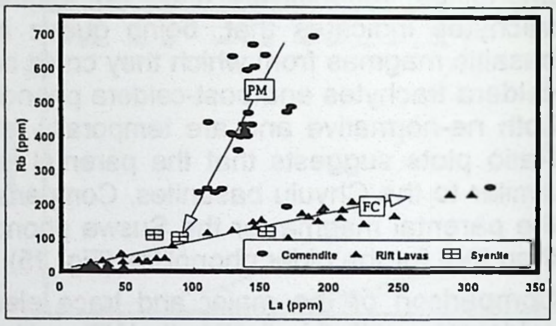



Fig. 16: Plots of La vs. Rb for all of the silicic lavas associated with the Kenya rift. The plots show that the comendites followed a different evolutionary path than the rest of the silicic lavas of the Kenya rift.

highly depleted in some elements, e.g. Ba and Sr that in turn are highly enriched in gneisses (Rooke, 1970; Gass, 1977; Ries & Shackleton, 1985).

Alternative to the gneisses are protoliths to the Olkaria comendites are the Miocene lavas and plutons. Since seismic and gravity studies along the rift reveal that the thickness of the lavas within axis of the rift is about 5 km (Simiyu et al., 1994; Simiyu, 1996) implies that it is unlikely that partial melting of these rocks would generate the comendites since very high heat flows would be required. Such amount of heat flow is not feasible at such shallow depths. An alternative is the syenitic plutons that are expected to be common under the Kenya rift. These plutons would be the equivalents of the abundant trachytic lavas. When the trace element concentrations of a syenite recovered at about 2400 m under Eburru volcano is plotted together with the rift lavas (Fig. 16), they fall close to the intersection of the comendite trend and that of the rift lavas. Partial melt models indicate that it is feasible to generate the comendites at Olkaria from a syenite similar to the one from Eburru by about 20-30% partial melting. A syenitic parent would thus explain the very low concentrations of Ba, Sr, MgO, Cr, Ni and enrichment in REE, HFSE, and Rb.

The variation in magmatic evolution from Eburru in the north to Suswa in the south can be explained by the variation in crustal thickness. Geophysical studies have shown that the Moho occurs at about 20-35 km in the north and central segments of the Kenya rift but deepens from about the latitude of Suswa volcano to about 70 km (Mechie et al., 1994b; Simiyu et al., 1995;

Simiyu, 1996; Novak et al., 1997). Great crustal depths under Suswa volcano would make it possible for the generation of alkaline magmas that would in turn produce phonolites.

## Conclusion

The study shows that there are three distinct magmatic suites associated with the Kenya rift, namely alkaline magmas of Chyulu and Suswa - basanite, phonolite, trachyte group; transitional basalt - trachyte - pantellerite group and anatectic comendites of Olkaria area.

The primary magmas were generated by 1-2% partial melt fractions under Chyulu and about 5% under the rift axis. The generated magmas experienced about 25-43% pre-eruption crystallization to form the Chyulu basanites and 60-80% to form the basalts of the rift axis.

The comendites at Olkaria were generated by 20-30% partial melting of syenitic plutons similar to the syenite under Eburru volcano.

Change in magmatic style at Suswa from transitional basalt character to alkaline is related to crustal thickening. The crust is more than 70 km thick under Suswa compared to 20-35 km to the north. The Pre- and Syn-Caldera Trachytes are comagmatic while the Pre-Suswa trachytes are related to the transitional basalts of the rift axis.

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# A first approach to a new understanding of the Ugandan Precambrian 'granite gneisses'

A. Schumann & P.K. Kulyanyingi

**Abstract:** Many efforts have been carried out to unravel the geological picture of the Precambrian history in East Africa. Unfortunately one piece of the puzzle is missing - the geology of the 'Central Ugandan Basement Complex', including the Aswa Shear Zone, which extends from the Sudan in the north through Uganda and Kenya. Recent studies carried out on the Central Ugandan Basement Complex (around Kampala and in Eastern Uganda) seem to support an origin of the granitoids, either by partial melting or anatexis of pre-existing sedimentary, metamorphic or plutonic protoliths rather than granitisation. The majority of the granitoids can be classified as per- to metaluminous monzogranites. The rocks exhibit I (A)- and S-type characteristics. Almost all analysed granitoids show a polyphase tectono-thermal overprint, as documented from their textures and age dating results. U-Th-total Pb age determinations using microprobe techniques on zoned zircons (from one locality) gave an oldest age of 2,59 ± 0,07 Ga for the core and 2.22 ± 0.08 Ga and 0.74 Ga ± 0.22 Ga for zircon mantle domains. Discrimination diagrams support a syn- to postcollisional tectonic setting during their emplacement.

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## Introduction

Two thirds of Uganda are occupied by Precambrian rocks known as the 'Basement Complex' ('BC'), which are believed to be the oldest, and mainly classified as granite gneisses. As frequently suggested, they originated by granitisation or migmatisation and may have partly suffered from retrograde amphibolite metamorphism (e.g. Leggo, 1974; Brinckmann & Gabert, 1977). Since the beginning of the 80s, no further studies have been carried out apart from some reports which are predominantly dealing with the economic potential of the 'BC' (e.g. Byamugisha, 1987). Previous results (Schumann et al., 1999) and data presented in this paper support a new and different understanding of the origin and 'history' of the 'BC'.

## Methods

Petrographic, structural data and samples have been collected during several field trips in 1998 and 1999. The petrographic microscope was used to determine the modal mineral content and to investigate structural differences of the rocks in thin sections. Ordinary thin sections have been done at the Department of Geology at Makerere University. Polished thin sections have been prepared to determine the chemical composition of zircons for age dating at the 'Mineralogisch-Petrographisches Institut' at the University of Hamburg by using a Cameca CAMEBEX automated electron microprobe with three wavelength dispersive-type spectrometers (detailed procedures are given in Geisler & Schleicher 2000). Whole rock chemical analysis for major and trace elements have been achieved by using a X-ray fluorescence unit (Philips PW 1480) at the 'Geologisch-Paläontologisches Insitut', at the University of Hamburg.

## Problems related to the granite gneisses of the 'Basement Complex'

Unlike other Precambrian units in Uganda such as the Watian (2.9 Ga), Aruan (2.55), Buganda Toro (1.8), Karagwe-Ankolean (1.0 Ga) and Mozambiquan (0.6 Ga), the so called granite-gneisses of the 'Basement Complex' have never been differentiated or subdivided. King & DeSwardt (1970) summarised some of the major problems related to the 'BC':

1) Poor outcrop situations and rarely exposed contacts between the granitoid rocks of the 'BC' and the other units mainly consisting of meta-sedimentary and high grade metamorphic Precambrian rocks.

2) Some rocks of the 'BC' form the base while others seem to be 'transgressive', lying on younger Precambrian cover formations. This indeed is contradictory to the name 'BC'. Many alternative names have been suggested, e.g. for the West Nile region, Groves (1935) called the basement 'Ugandan Charnockite Series', Petters (1991) used the term 'West Nile Gneissic Complex' and Schlüter (1997) suggested the name 'Gneissic Granulitic Complex' for the entire unit throughout Uganda

3) Textural differences among the granite gneisses, led to the differentiation between older foliated and younger non-foliated rocks, although Combe (1932) recognised, that the provisional assignment of all gneissose granites to the 'BC' was unjustified. He concluded that in the 'arena areas' of south-western Uganda, all granites which intruded in the anticlinal structures, whether foliated or not, post-date the Karagwe-Ankolean.

4) The origin of the granite-gneisses was mainly attributed to granitisation of meta-sedimentary parent rocks, although intrusive granites (generally those without foliation) and migmatites were also described.

## Results

### Field descriptions of the granitoids from around Kampala

The overall outcrop situation has to be regarded as poor, mainly due to an extensive lateritic weathering cover, but quarries offer the best exposures and some of them extend over several square kilometres. Fig. 1 gives an overview on the sample locations in and around Kampala.

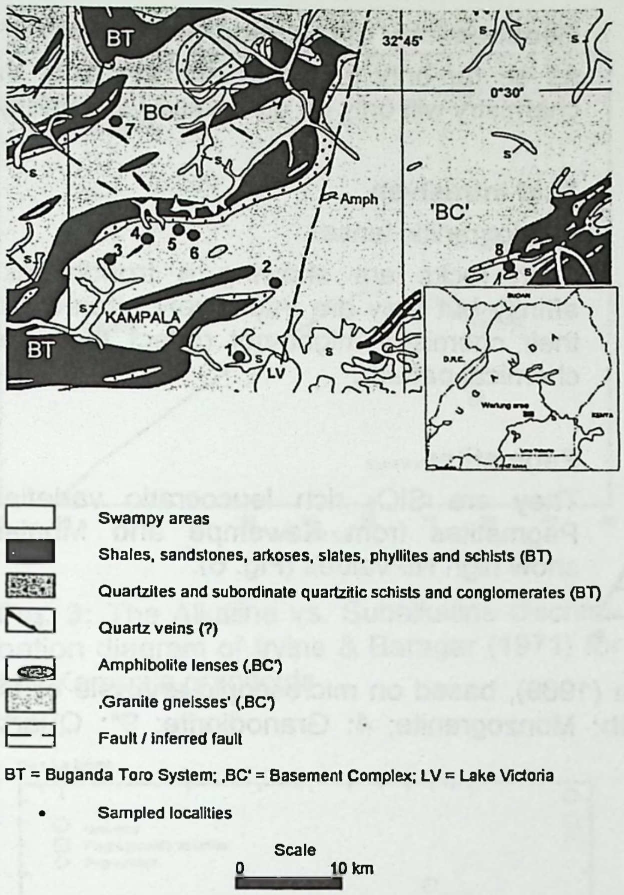
The granitoids show granular, often slightly cataclastic or foliated, partly proto-mylonitic textures; the latter especially appears along minor faults or shear zones. The degree of deformation may even change drastically within one outcrop like at Kawempe or Muyenga quarries. The major trends of the foliation range between NW/SE and almost E/W with varying dip directions generally at steep angles either towards the NE or SW. Less common are augen gneissic (Mattuga quarry) or migmatitic (Kulambiro quarry) textures. At Muyenga quarry, homogeneous granitoids appear side by side with inhomogeneous partly pegmatitic varieties exhibiting a migmatitic kind of texture, hence giving evidence for a partial melting process. Unfortunately the contacts between the homogeneous and inhomogeneous types are not yet exposed. Basic enclaves and/or schlieren may appear in the granitoids although not so frequent.

Minor intrusives are common. They are either dikes or dike like and are ultrabasic to acid in composition. Up to four different intrusive stages can be identified, e.g. at Mattuga quarry. Acid minor intrusives generally post-date the basic ones. The majority of the dikes are trending parallel and/or almost perpendicular to the foliation of the granitoids. Basic dikes are preferentially found within intensively foliated rocks and shear zones. The dikes are several centimetres to decimetres wide and extend from a few metres up to hundreds of metres. The contacts of the minor intrusives are generally sharp, either straight or curved and in some cases disrupted, indicating a synplutonic emplacement.

### Petrography

### Petrography of the granitoids

The granitoids are mainly monzogranites, and less common are granodioritic, syenogranitic and quartz-monzodioritic varieties (Fig. 2). At Kawempe quarry lenses of intensively altered plagioclase rich granitic varieties appear within the basic dikes or at the contact between the dikes and the monzogranite. The majority are leucocratic granitoids with biotite and subordinate amphibole (Mattuga, Nansana) as mafic constituents. Samples from Mbalala contain minor amounts of




garnet (< 2 wt. %). Subsolidus reactions are indicated by myrmekite, secondary albite and recrystallized quartz. The less deformed granitoids are medium grained with a granular allotriomorphic texture. Only plagioclases tend to exhibit a subhedral habitus. All rocks suffered at least weak alteration and deformation (Tab. 1, page 157). Common alteration products of plagioclase are sericite and muscovite while biotite alters to chlorite.

Less common secondary minerals comprise of epidote, carbonate and fluorite. The extent of this latest event of alteration seems to have never exceeded greenschist equivalent facies conditions. As mentioned earlier, the degree of deformation may change drastically within one outcrop. In all rocks quartz shows wavy extinction. Slightly cataclastic textures are widespread.

More pronounced deformational features are generally seen in or near shear zones or at contacts to basic dikes (e.g. Kawempe and Muyenga). In such zones quartz may be flattened and/or develop subgrains and/or recrystallise, biotite and feldspars may show kink bands.

**Fig. 1**: Geological sketch map of the Kampala area (modified after Brinkmann & Gabert, 1977). Sample locations: **1** Muyenga; **2** Nambole, **3** Nansana, **4** Kulambiro/Kulambiro Hill, **5** Cobla, **6** Kawempe, **7** Mattuga, **8** Mbalala

## Petrography of the minor intrusives

Quartz segregations as well as quartz veins are widespread. Acid pegmatites, consisting mainly of alkali feldspars and quartz, may form lenses, dikes or net veins. Cataclastic textures are common. The dark grey to blackish ultrabasic/basic dikes consist of green amphibole, twinned and untwinned plagioclase, and minor amounts of biotite and quartz. The ultrabasic rock from Kulambiro Hill is additionally bearing clinopyroxene and garnet. Amphiboles are generally well oriented. All minor intrusives are affected by alteration (Tab. 1, page 157). At Kawempe small lenses of intensively altered plagioclase rich granitoids occur in association with the basic dikes.

## Geochemistry

### Geochemistry of the granitoids

The granitoids are subalkaline varieties and meta- to peraluminous in character (Figs. 3, 4; Tab. 2, page 159) although the quartz-monzodiorites and the granodiorite from Nansana as well as the monzogranite from Mattuga plot almost on the boundary between the alkaline and subalkaline field. They also show the strongest metaluminous affinity. The samples from Nansana are additionally characterised by the highest REE (allanite is an accessory of these rocks) and Zr content (Figs. 5, 6). Geo-tectonic discrimination diagrams, which probably have to be handled with precaution for such Precambrian rocks, favour a syn- to post collisional setting during emplacement. The rocks from Nansana and Mattuga may be regarded as late-orogenic or within plate granites (Figs. 7, 8).

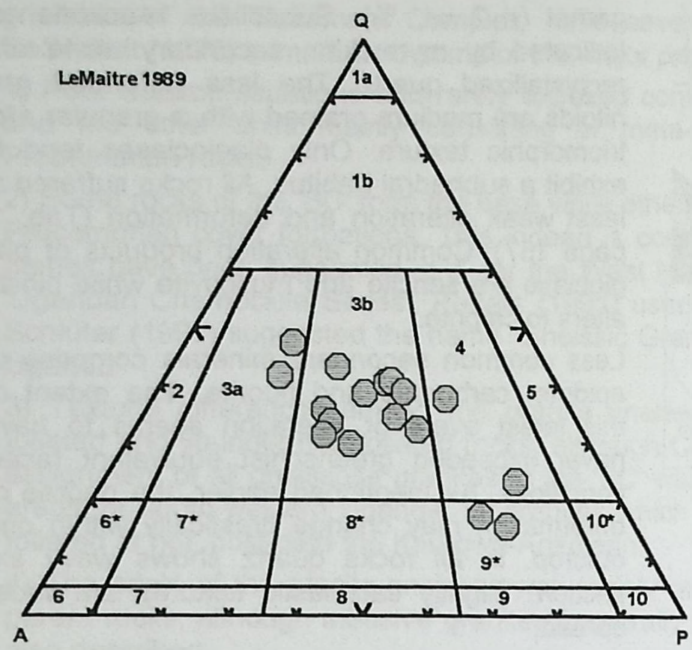



**Fig. 2:** Rock classification diagram after LeMaitre (1989), based on microscopic analysis of the Kampala granitoids (Fields: **3a:** Syenogranite; **3b:** Monzogranite; **4:** Granodiorite; **9*:** Quartz-monzodiorite)

### Geochemistry of the minor intrusives

As so far only few data are available the chemistry will only be discussed very briefly.

### Acid intrusives

Plagiogranitic lenses

Such rocks are showing a trondhjemitic affinity but they are intensively altered and their chemistry might not reflect their true chemical pattern.

### Pegmatites

They are $SiO_2$ rich leucocratic varieties. Pegmatites from Kawempe and Mbalala show high Nb values (Fig. 6).

### Basic to ultrabasic amphibolitic dikes

These dikes consist of basic to ultrabasic rock types and comprise subalkaline to slightly alkaline varieties (Fig. 9). They show an affinity of ocean floor basalts (Fig. 10), exhibiting characteristics of high-Fe-tholeiites, high-Mg-tholeiites, tholeiitic andesites and calc-alkali to alkali basalts (Fig. 11). Samples from Kulambiro contain quite high Cr values (Tab. 2; page 159).

### Age Determinations

U-Th-total Pb dating of zircons in a granitoid from Muyenga was done by using microprobe techniques (Geisler & Schleicher, 2000). The zircons in the granitoids are generally zoned and may show up to three different mantle domains.

Preliminary in situ U-Th-total Pb dating results and textural features of zircons (euhedral cores) in a syenogranite form Muyenga quarry (homogeneous variety) indicate a magmatic origin of these rocks but also show new zircon growth during later tectono-thermal overprinting. Cores of zoned zircons but also a single unzoned crystal have yielded an age of 2590 ± 70 Ma whereas small overgrowth rims gave ages of 2220 ± 80 Ma and 740 ± 220 Ma (Fig. 12). The youngest age, however, is somehow uncertain because only one spot could be positioned on this rim (Schumann, et al. 1999). Fig. 13 shows a compilation of age determinations on the Precambrian rocks of Uganda.

## Discussion

Within the investigated area, outcrop situations did not allow to apply field criteria to establish contact relationships among the different granitoids or between the granitoids and associated formations. In such cases age determinations might help to correlate these rocks and to complete the Precambrian stratigraphy.

Another subject of speculation was and is the origin of the granitoids. Granitisation has been regarded to be one of the major processes responsible for the widespread occurrences of the

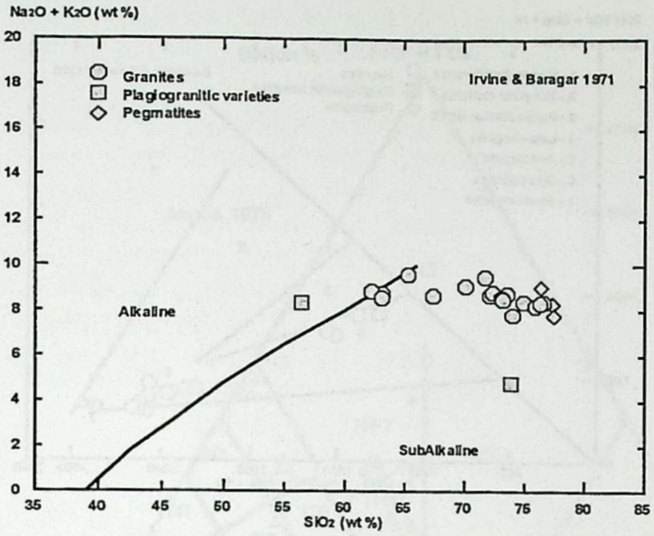



**Fig. 3**: The Alkaline vs. Subalkaline discrimination diagram of Irvine & Baragar (1971) for the Kampala granitoids

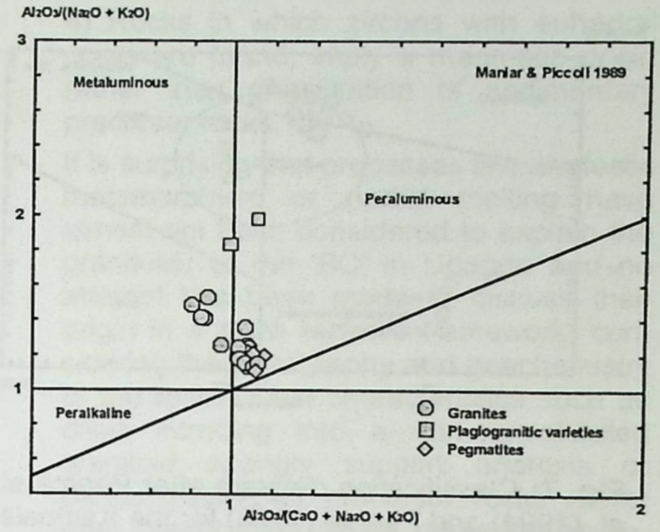



**Fig. 4**: ANK vs. ACNK diagram after Maniar and Piccoli (1989) showing the Kampala samples plotting in the metaluminous and peraluminous field.

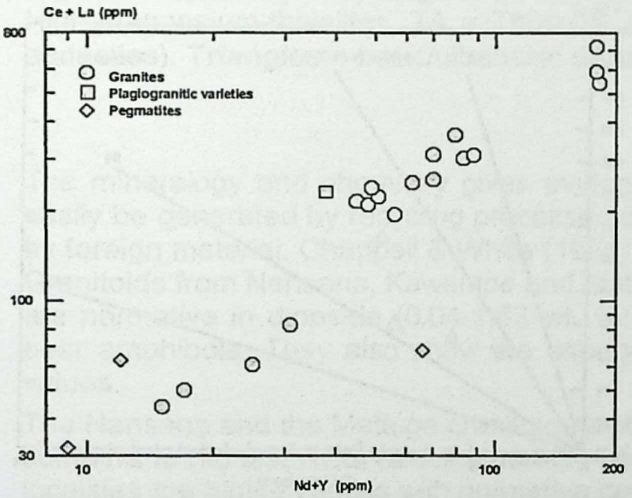



**Fig. 5**: Plot of Ce+La vs. Nd+Y of the Kampala granitoids

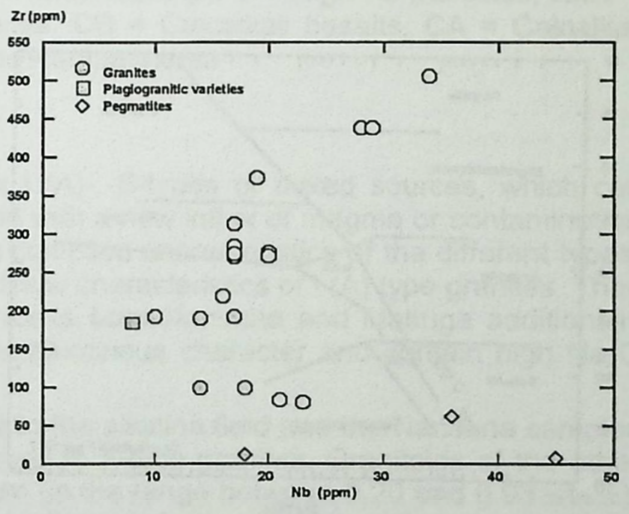



**Fig. 6**: Plot of Zr vs. Nb of the Kampala granitoids

foliated granitoids (e.g. King & DeSwardt, 1967; Leggo, 1974; Brinckmann & Gabert, 1977). In some cases granitisation was mentioned in conjunction with mobilisation and remobilisation of precurser rocks - mechanisms which are not compatible with granitisation, as granitisation refers to metasomatic processes whereby solid rocks are changed into rocks of granitic composition and texture without passing through a magmatic stage (Huang, 1962; Best, 1981). Pitcher & Berger (1972) already demonstrated that virtually all plutons are indeed magmatic and that granitisation if at all may appear at a very limited scale (Best, 1981). Pitcher (1993) added, that the process of metasomatic granitisation is decisively refuted by the simple geological observation that existing heterogenities such as stratification and clast form and size in metaconglomerates are preserved into very highest grade of metamorphism. Choosing granitisation as a process to explain the widespread occurrences of the 'BC'-granitoids in Uganda would necessarily fail, e.g.:

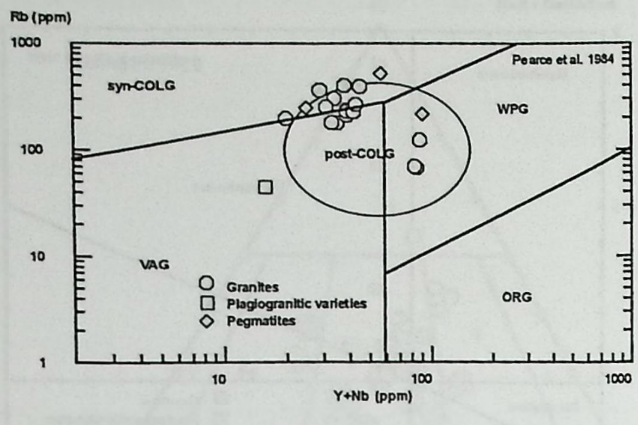



Fig. 7: Classification diagram after Pearce et al. (1994) and Pearce (1996) for the Kampala granitoids, discriminating the different tectonic settings (**syn-COLG:** Syn-collisional granites; **post-COLG:** Post-collisional granites; **WPG:** Within plate granites; **VAG:** Volcanic arc granites; **ORG:** Ocean ridge granites)

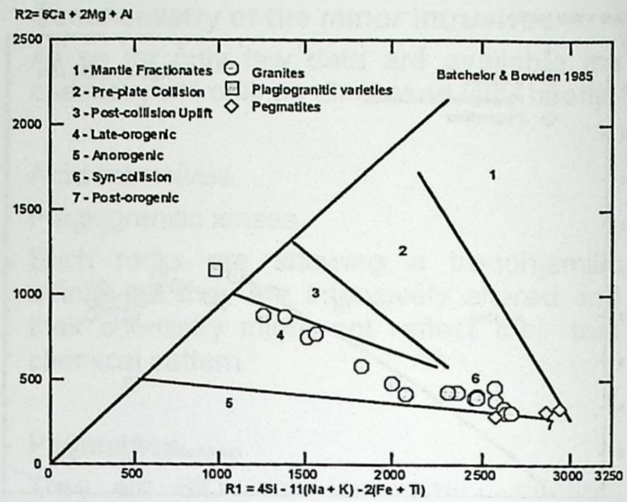



Fig. 8: R1 vs. R2 classification diagram after Batchelor & Bowden (1985) of the Kampala granitoids

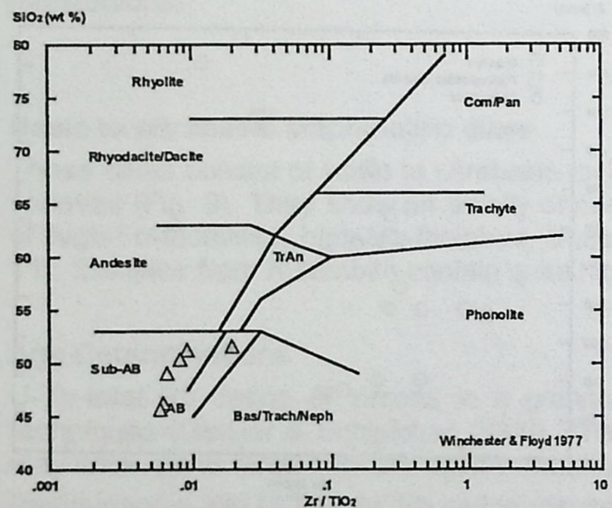



Fig. 9: Discrimination diagram of Winchester & Floyd (1977) showing the distribution of the basic/ultrabasic dikes in the respective field. **Sub-Ab** = Subalkaline basalts, **AB** = Alkaline basalts

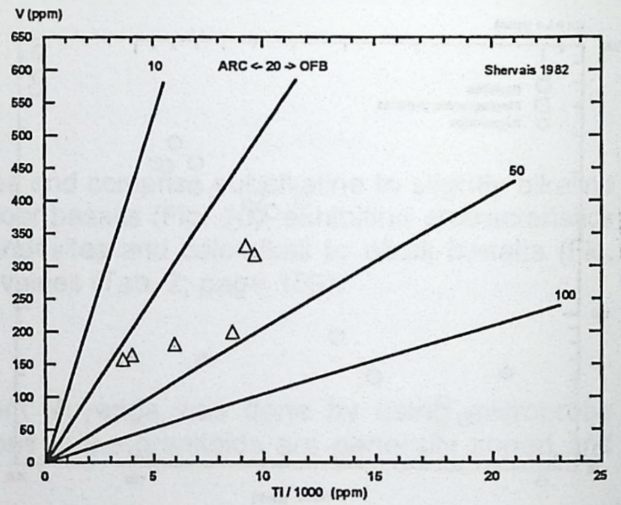



Fig. 10: V vs. Ti/1000 diagram (Shervais, 1982) differentiating between Arc and Ocean Floor Basalts; triangles = basic/ultrabasic dikes of the Kampala area.

1) The 'BC' covers an area of about 130000 square kilometres. The origin of such a huge rock mass can not be explained by metasomatism.

2) Relicts of stratification or banding of the parent rock are not obvious in the granitoids. In fact in most of the outcrops the degree of foliation (which has also been interpreted as a relict of sedimentary layering) may change drastically and can in many cases be related either to shearing or synplutonic deformation.

3) Some of the granitoids show macrotextures (such as disrupted dikes) which indicate an intrusion of dikes into a non-consolidated rock (e.g. at Mattuga), a phenomenon which might not be seen in a rock which is undergoing granitisation in a solid state.

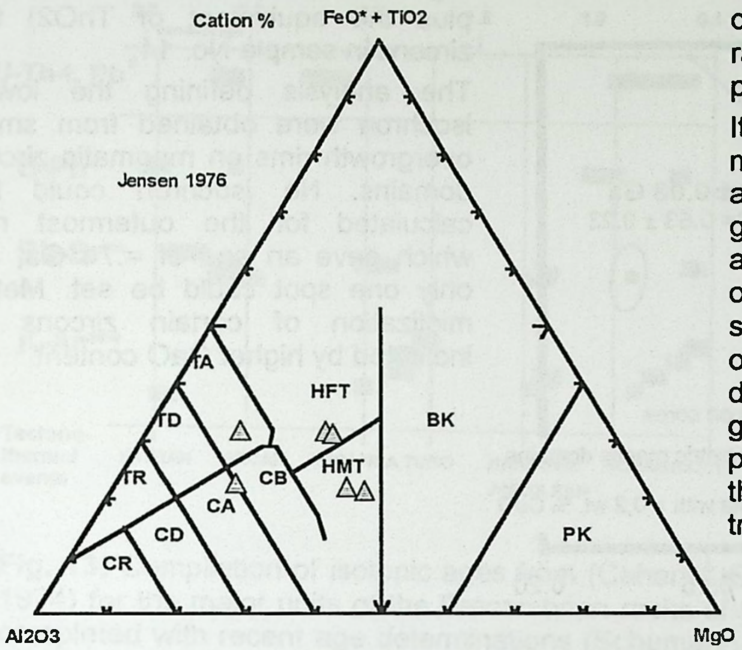



Fig. 11: Jenson's (1976) diagram for classifying volcanic rocks (**HFT** = High-Fe-tholeiites, **HMT** = High-Magnesium-tholeiites, **TA** = Tholeiitic andesites, **CB** = Calcalkali basalts, **CA** = Calcalkali andesites). **Triangles** = basic/ultrabasic dikes of the Kampala area

4) Rocks in which zircons with euhedral cores are found, imply a magmatic origin rather than granitisation of sedimentary precurser rocks.

It is surprising that processes like anatectic metamorphism or partial melting have almost not been considered to explain the granitoids of the 'BC' in Uganda and no attempt has been made to discuss their origin in a plate tectonic framework, considering the petrography and geochemistry of the rocks. Field characteristics such as dikes intruding into a non-consolidated granitoid strongly support anatexis or partial melting of precursor rocks rather than granitisation which demands an intrusion into a solid rock body.

The mineralogy and chemistry gives evidence for I (A)-, S-types or mixed sources, which can easily be generated by recycling processes coupled with a new influx of magma or contamination by foreign material. Chappell & White (1974) have compiled characteristics of the different types. Granitoids from Nansana, Kawempe and Mattuga show characteristics of I (A) type granites. They are normative in diopside (0.04-1.62 wt. %) and rocks from Nansana and Mattuga additionally bear amphibole. They also show the strongest metaluminous character and contain high $Na_2O$ values.

The Nansana and the Mattuga granitoids plot close to the alkaline field and the Nansana samples contain the highest REE values; characteristics linked to A-type granites. Granitoids of the other localities are biotite varities with normative corundum (in the range between 0.20 and 0.93 wt. %). These rocks plot in the peralumious field and generally contain lesser sodium than the previous group favouring an S-type origin. Muscovite or sericite are accessory constituents of all rocks and are regarded as secondary alteration products.

In the discrimanition digramms of Pearce et al. (1984) and Pearce (1996) most of the Kampala granitoids plot in the syn- and post-collisional field. According to Pearce (1996) post-collisional granites are the most difficult to classify as they have the greatest range of sources. Some may have subduction-like mantle sources and have many of the characteristics of volcanic arc granites on the diagram, whereas others have intraplate-like sources and have many of the characteristics of within plate granites on the diagram.

In addition, there is extensive interaction between the mantle derived sources and the crust which tends to move all compositions into the volcanic arc field. Pitcher (1993) summarized criteria of granitoid rocks in their respective contrasted tectonic niches. According to his classification the Kampala granitoids fit best in a scenery of oblique continental collision possibly followed by a post-closure uplift with a slight extensional force allowing the basic to ultrabasic tholeiitic dikes to intrude the granitoids.

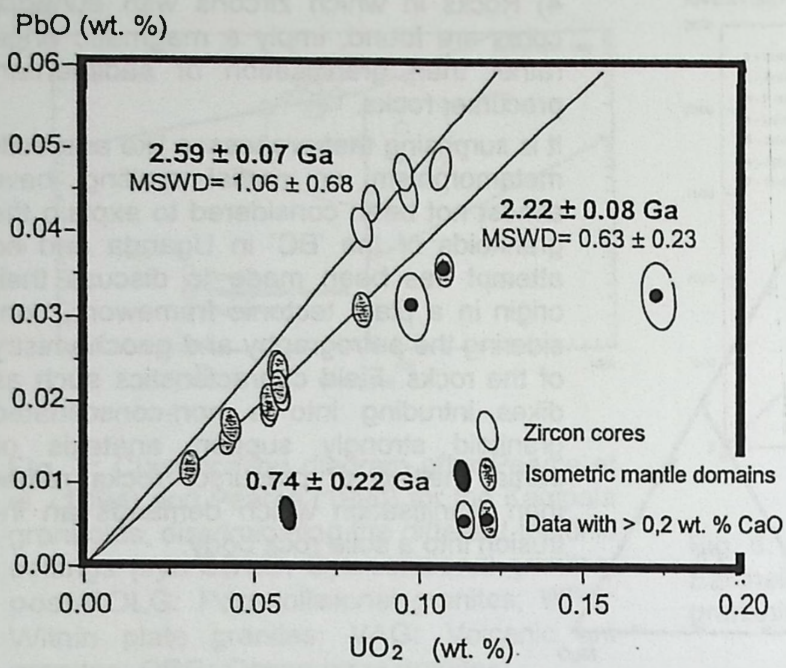



**Fig. 12:** Plot of PbO vs. UO2 (UO2 plus the equivalent of ThO2) for zircons in sample No. 14.

The analysis defining the lower isochron were obtained from small overgrowth rims on magmatic zircon domains. No isochron could be calculated for the outermost rim which gave an age of =.74 Ga, as only one spot could be set. Metamictization of certain zircons is indicated by higher CaO content.

## Conclusions

There is still a tremendous lack of information concerning the true structural and petrological patterns of so called granite gneisses of Uganda and more data have to be obtained in order to discuss these rocks in a regional context. This preliminary approach to unravel the picture of such granitoids favour a mobilisation of granitic magmas exhibiting I (A)- and S-type characteristics in a syn- to post-collisional environment. Evidence of recycling and or polyphase tectono-thermal overprinting of the granitoids is given by field observations and zircon ages.

## Perspective - Field results from Eastern Uganda

More field surveys, petrolocical studies and age determinations are necessary to unravel the entire picture of the 'basement' granitoids. Recent field studies in eastern Uganda (close to the towns of Ngora, Kumi and Soroti) are promising and allow to apply field characteristics as well as textural features to distinguish between different units within the 'Basement Complex'. A major criterion to distinguish between the older and younger granitoids in the area might be the assumed Mozambiquan age of the Aswa Shear Zone (Almond, 1969):

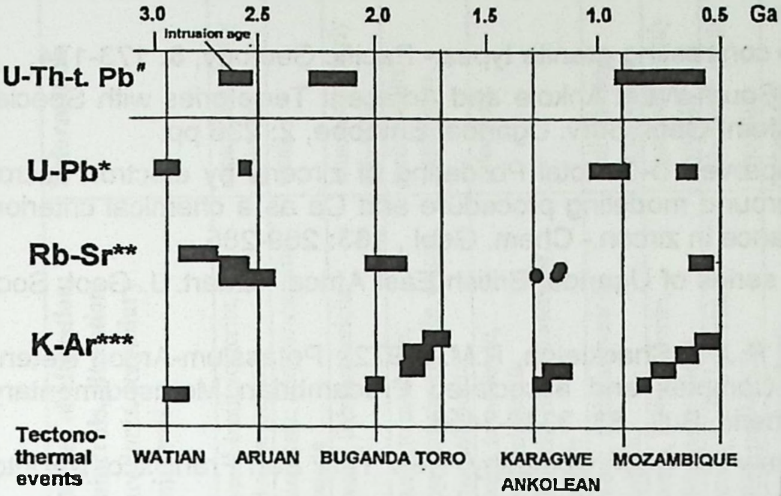
A) foliated granitoids (the foliation is almost trending NW/SE), affected by minor shear zones of the Aswa strike (NW/SE)

B) inhomogeneous, partly migmatitic varieties

C) granitoids exhibiting magmatic lamination and flow textures, less affected by minor shear zones of the Aswa trend

D) porphyritic granitoids, almost unaffected by minor shear zones of the Aswa trend

Within the investigated area the foliated granites seemed to be the oldest - indeed an observation which had already been discussed by King and DeSwardt (1967). They are clearly exhibiting minor shear zones trending NW/SE. Rocks of groups C and D are younger and field contacts between these groups suggest an almost similar age, due to their gradual contact relationships. The lack of obvious textural features linked to the Aswa trend implies a syn- to post-Mozambiquan age of such rocks. The age of the inhomogeneous, partly migmatitic rocks is uncertain because of their rare appearance and the lack of reliable field data.




It has however to be noted, that the Aswa Shear Zone might have developed along a reactivated, older fracture zone implying that the obvious minor shear zones in the granitoids of Eastern Uganda (may be even in the whole of Uganda) pre-date the Mozambiquan. So far the Mozambiquan event is well recorded in the granitoids of the 'BC' (Fig. 13) but it is uncertain, whether the Mozambiquan event in Uganda was intense enough to mobilise granitic melts, thus rocks lacking deformational features linked to the Aswa trend might even be older than the Mozambiquan.

**Fig. 13:** Compilation of isotopic ages from (Cahen & Snelling, 1966; Harper et al., 1972; Leggo, 1974) for the major units of the Precambrian rocks of Uganda. Redrawn after Leggo (1974) and completed with recent age determinations (Schumann et al., 1999), using U-Th-total Pb# dating of zircons by electron microprobe. U-Pb*: Zircon concordia method; Rb-Sr**: Whole rock isochron method; K-Ar***: Conventional biotite method. The length of the bars includes the error. No age limits are given for the circles. Due to the big error, the youngest age determined by the electron microprobe technique has to be handled with care.

## Acknowledgements

The authors are indebted to Prof. Dr. H. Schleicher, Dr. T. Geisler as well as to Mrs. B. Cornelisen ('Petrographisch-Mineralogisches Institut', University of Hamburg) for doing the microprobe analysis and age determinations, and Dr. B. Stütze and Mrs. E. Thun ('Geologisch-Paläontologisches Institut', University of Hamburg) for their assistance during the analytical stage of work (XRF-analyis). We thank Mr. P. Stutz ('Petrographisch-Mineralogisches Institut', University of Hamburg) for preparing polished thin sections and Mr. Wakyaya (Department of Geology, Makerere University) for preparing ordinary thin sections as well as Dr. A. Muwanga (Head of the Geology Department, Makerere University) for logistical support. This work was carried out with support from the German Academic Exchange Service (DAAD) and the German Technical Co-operation (GTZ), at the Geology Department at Makerere University (Project: PN 93.2254-06.200).

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**Tab. 1 (page 157 & 158):** Selected petrographic characteristics of the Kampala granitoids and associated rock types. *Poor outcrop situations or inaccessibility of the outcrop did not allow to recognize minor intrusives in any case

**Tab. 2 (page 159):** Major and trace element analyses of the Kampala granitoids and associated rock types (XRF analysis)

| Sample No; Locality | Rock type; grain size (fg = fine grained, mg = medium grained, cg = coarse grained) | Degree of foliation; macro-textural features | Dikes and minor intrusives in the granitoids* | Amphibole in the granitoids | Mantle domains around zircon cores in the granitoids | Degree of alteration; minerals, alteration products, secondary minerals | Deformation |
|---|---|---|---|---|---|---|---|
| 8 Cobla | Syenogranite, mg | weak to strong | pegmatites | - | 2 | weak; biotite/chlorite, fluorite, zoisite | cataclastic, partly mylonitic |
| 9 Kulambiro | Amphibolitic dike, fg-mg | moderate to strong, migmatitic | - | - | ? | moderate; feldspars/sericite, calcite | weak |
| 10 Kulambiro | Granodiorite, fg-mg | strong, migmatitic | pegmatites, amphibolitic dykes | - | 1 | weak; fedspars/sericite | cataclastic, partly mylonitic |
| 11 Kulambiro Hill | Garnet amphibolite, ?dike, mg | strong | - | - | ? | weak to moderate; pyroxene/amphibole, calcite, biotite/chlorite | well oriented amphiboles |
| 12 Kulambiro Hill | Monzogranite, mg | weak to moderate | amphibolitic ?dikes | - | 2, ?3 | weak to moderate, biotite/chlorite, ?fluorite,feldspars/sericite, calcite | cataclastic |
| 13 Muyenga | Amphibolitic dike, mg | strong | - | - | ? | weak, feldspars/sericite calcite | well oriented amphiboles |
| 14. Muyenga | Syenogranite, mg | weak to strong | pegmatites, amphibolitic dikes | - | 3, ?4 | weak, biotite/chlorite, feldspars/sericite | cataclastic, partly mylonitic |
| 15 Muyenga | Monzogranite, mg | weak to strong | pegmatites, amphibolitic dikes | - | 2, 3 | weak, biotite/chlorite, feldspars/sericite | cataclastic, partly mylonitic |
| 16 Nansana | Granodiorite, fg-mg | weak to moderate | - | + | 2, ?3 | weak to moderate, feldspars/sericite, ?mafic mineral/unknown alteration product | cataclastic |
| 17 Nansana | Quartz-monzo-diorite, fg-mg | weak | - | + | 1, ?2 | weak, feldspars/sericite; epidote | weak |
| 18 Nansana | Quartz-monzo-diorite, fg-mg | weak | - | + | 1, ?2 | weak, feldspars/sericite, epidote | weak |
| 19 Kawempe | Monzogranite, mg | weak | biotite nests, pegmatites, amphibolitic dikes | - | 1 | weak, feldspars/sericite | wavy extinction |
| 20 Kawempe | Plagiogranite, lense-like, fg-mg | strong | - | - | ?1 | moderate -strong, feldspars/sericite; epidote | cataclastic |
| 21 Kawempe | Amphibolitic dike, fg-mg | strong | - | - | ? | weak, feldspars/sericite | well oriented amphiboles |
| 22 Kawempe | Pegmatite, mg-cg | moderate | - | - | ? | strong, feldspars/sericite | cataclastic |
| 23 Kawempe | Plagiogranite, vein, mg-cg | strong | - | - | ? | strong, feldspars/sericite; chlorite, epidote | cataclastic |

| Sample No; Locality | Rock type; grain size (fg = fine grained, mg = medium grained, cg = coarse grained) | Degree of foliation; macro-textural features | Dikes and minor intrusives in the granitoids* | Amphibole in the granitoids | Mantle domains around zircon cores in the granitoids | Degree of alteration; minerals, alteration products, secondary minerals | Deformation |
|---|---|---|---|---|---|---|---|
| 24 Kawampe | Amphibolitic dike, mg | strong | - | - | ? | weak, feldspars/sericite | weak |
| 25 Kawempe | Monzogranite, mg | moderate | biotite nests, pegmatites, amphibolitic dikes | - | 1, ?2 | weak to moderate, feldspars/sericite | weak |
| 26 Kawempe | Monzogranite, mg | weak | biotite nests, pegmatites, amphibolitic dikes | - | 1 | weak, feldspars/sericite | weak |
| 27 Matuga | Monzogranite, mg | moderate, augen gneissic | pegmatite, amphibolite dikes | + | 1 | weak, biotite/chlorite | cataclastic, partly mylonitic |
| 28 Matuga | Pegmatitic monzogranite, mg-cg | weak | pegmatite, amphibolite dikes | - | 1 | weak. felspars/sericite, epidote | cataclastic |
| 29 Matuga | Amphibolitic dike | weak | - | - | ? | weak, feldspars/sericite | weak |
| 30 Nambole | Monzogranite, mg | weak | - | - | 2 | weak, biotite/chlorite | weak |
| 31 Nambole | Monzogranite, mg | weak-moderate | - | - | 1 | weak, feldspars/sericite, calcite, biotite/chlorite, fluorite | cataclastic |
| 32 Mbalala | Monzogranite, fg-mg | weak | pegmatite | - | ?1 | weak, biotite/chlorite, feldspars/sericite | cataclastic |
| 33 Mbalala | Monzogranite, mg | weak | pegmatite | - | ?1 | weak, biotite/chlorite, feldspars/sericite, fluorite | weak |
| 34 Mbalala | Monzogranite, mg | moderate | pegmatite | - | ?1 | weak, biotite/chlorite, feldspars/sericite | cataclastic, partly mylonitic |
| 35 Mbalala | Monzogranite, mg | moderate | pegmatite | - | ?1 | weak, biotite/chlorite, feldspars/sericite | cataclastic, partly mylonitic |
| 36 Mbalala | Pegmatite, mg-cg | weak | - | - | ? | weak, feldspars/sericite | cataclastic |

| S.N./Loc./R.T. | SiO2 wt. % | TiO2 | Al2O3 | Fe2O3 | MnO | MgO | CaO | Na2O | K2O | P2O5 | LOI | Cr ppm | Ni | Co | V | Cu | Pb | Zn | Rb | Ba | Sr | Ga | Nb | Zr | Y | Th | U | La | Ce | Nd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 KU Amph | 51.57 | 1 | 18.25 | 9.78 | 0.18 | 3.85 | 6.9 | 5.2 | 1.89 | 0.35 | 1.22 | 15 | 18 | 40 | 180 | 20 | 19 | 131 | 118 | 526 | 672 | 25 | 14 | 193 | 24 | 5 | 12 | 91 | 93 | 36 |
| 11 KU Amph | 51.24 | 1.44 | 16.44 | 13.54 | 0.19 | 3.21 | 9.47 | 2.97 | 0.56 | 0.19 | 1.07 | 13 | 28 | 54 | 199 | 67 | 4 | 135 | 30 | 121 | 255 | 22 | 17 | 132 | 32 | 1 | 0 | 66 | 9 | 4 |
| 13 TA Amph | 50.37 | 1.61 | 13.21 | 13.83 | 0.21 | 6.36 | 10.15 | 2.83 | 0.75 | 0.17 | 1.03 | 161 | 65 | 57 | 317 | 52 | 9 | 124 | 48 | 120 | 180 | 20 | 16 | 131 | 35 | 7 | 1 | 66 | 32 | 10 |
| 21 KW Amph | 46.26 | 0.67 | 16.11 | 11.88 | 0.18 | 9.75 | 10.25 | 2.07 | 0.85 | 0.06 | 1.46 | 451 | 273 | 72 | 164 | 48 | 5 | 119 | 48 | 141 | 243 | 17 | 6 | 41 | 17 | 1 | 0 | 67 | 6 | 1 |
| 24 KW Amph | 45.69 | 0.6 | 15.51 | 11.8 | 0.16 | 10.79 | 10.03 | 1.72 | 0.96 | 0.04 | 2.32 | 451 | 312 | 70 | 157 | 11 | 6 | 99 | 67 | 79 | 200 | 17 | 5 | 35 | 13 | 2 | 1 | 47 | 0 | 3 |
| 29 MT Amph | 49.07 | 1.54 | 13.14 | 13.95 | 0.24 | 6.77 | 9.74 | 3.3 | 1.06 | 0.12 | 0.98 | 178 | 64 | 60 | 331 | 17 | 19 | 125 | 38 | 100 | 217 | 20 | 12 | 101 | 30 | 4 | 2 | 47 | 20 | 11 |
| 8 CB GR | 74.92 | 0.21 | 13.01 | 1.53 | 0.03 | 0.24 | 1.03 | 3.36 | 5.03 | 0.04 | 0.46 | 0 | 0 | 22 | 12 | 2 | 34 | 44 | 299 | 452 | 131 | 13 | 16 | 219 | 18 | 53 | 11 | 113 | 103 | 27 |
| 10 KU GR | 67.47 | 0.48 | 16.19 | 3.1 | 0.04 | 0.82 | 2.07 | 4.59 | 4.05 | 0.16 | 0.47 | 7 | 5 | 30 | 46 | 16 | 28 | 71 | 177 | 982 | 488 | 20 | 17 | 313 | 18 | 16 | 6 | 110 | 85 | 38 |
| 12 KU GR | 73.59 | 0.2 | 13.47 | 1.61 | 0.02 | 0.26 | 1.09 | 2.93 | 5.8 | 0.05 | 0.63 | 0 | 0 | 23 | 20 | 6 | 28 | 43 | 195 | 1384 | 394 | 12 | 10 | 192 | 10 | 32 | 5 | 109 | 101 | 38 |
| 14 TA GR | 72.16 | 0.35 | 13.8 | 2.24 | 0.03 | 0.39 | 1.27 | 2.88 | 5.79 | 0.08 | 0.48 | 4 | 0 | 22 | 29 | 8 | 36 | 51 | 209 | 1069 | 225 | 16 | 19 | 373 | 20 | 36 | 1 | 139 | 172 | 50 |
| 15 TA GR | 72.41 | 0.3 | 13.87 | 2 | 0.03 | 0.36 | 1.28 | 3.27 | 5.52 | 0.07 | 0.39 | 1 | 5 | 41 | 23 | 17 | 30 | 59 | 236 | 943 | 213 | 19 | 17 | 284 | 22 | 33 | 5 | 114 | 142 | 48 |
| 16 NS GR | 63.16 | 0.51 | 18.8 | 3.03 | 0.02 | 0.3 | 4.54 | 5.69 | 3.04 | 0.08 | 0.47 | 5 | 5 | 33 | 36 | 2 | 15 | 14 | 67 | 911 | 653 | 20 | 28 | 438 | 57 | 45 | 4 | 263 | 279 | 125 |
| 17 NS GR | 65.36 | 0.54 | 18.17 | 1.66 | 0.02 | 0.05 | 3.65 | 4.48 | 5.1 | 0.1 | 0.5 | 5 | 1 | 33 | 34 | 11 | 10 | 10 | 122 | 1362 | 560 | 15 | 34 | 505 | 54 | 33 | 5 | 252 | 339 | 125 |
| 18 NS GR | 62.28 | 0.49 | 19.81 | 3.02 | 0.02 | 0.13 | 4.49 | 6 | 2.85 | 0.06 | 0.56 | 5 | 8 | 38 | 52 | 9 | 15 | 20 | 69 | 864 | 602 | 24 | 29 | 438 | 54 | 31 | 5 | 297 | 420 | 125 |
| 19 KW GR | 73.11 | 0.27 | 13.45 | 1.89 | 0.03 | 0.37 | 1.15 | 2.8 | 5.76 | 0.06 | 0.51 | 3 | 1 | 40 | 23 | 17 | 31 | 44 | 228 | 801 | 179 | 17 | 17 | 270 | 22 | 32 | 6 | 131 | 171 | 61 |
| 20 KW GRP | 73.94 | 0.17 | 14.78 | 0.73 | 0.01 | 0.52 | 3.54 | 4.18 | 0.57 | 0.01 | 0.74 | 3 | 7 | 40 | 13 | 8 | 16 | 15 | 43 | 147 | 524 | 7 | 8 | 182 | 8 | 13 | 2 | 102 | 129 | 30 |
| 22 KW Peg | 77.37 | 0.03 | 12.65 | 0.25 | 0 | 0 | 0.63 | 2.88 | 5.4 | 0.02 | 0.52 | 5 | 0 | 23 | 11 | 32 | 25 | 8 | 215 | 187 | 79 | 22 | 36 | 62 | 55 | 19 | 14 | 52 | 16 | 11 |
| 23 KW GRP | 56.55 | 0.13 | 23.2 | 1.41 | 0.03 | 1.24 | 5.83 | 6.61 | 1.68 | 0.01 | 2.82 | 33 | 37 | 13 | 16 | 2 | 16 | 37 | 129 | 164 | 853 | 20 | 0 | 23 | 1 | 0 | 3 | 92 | 0 | 0 |
| 25 KW GR | 73.23 | 0.28 | 13.24 | 1.89 | 0.03 | 0.37 | 1.08 | 3.04 | 5.43 | 0.06 | 0.58 | 3 | 0 | 38 | 26 | 10 | 34 | 34 | 246 | 741 | 177 | 13 | 20 | 276 | 22 | 35 | 3 | 119 | 131 | 40 |
| 26 KW GR | 74.03 | 0.18 | 13.46 | 1.52 | 0.02 | 0.18 | 1.72 | 4.05 | 3.75 | 0.03 | 0.66 | 0 | 3 | 36 | 18 | 1 | 30 | 30 | 179 | 288 | 140 | 17 | 14 | 190 | 19 | 46 | 10 | 103 | 121 | 32 |
| 27 MU GR | 63.09 | 0.69 | 16.37 | 4.75 | 0.07 | 1.68 | 3.4 | 4.1 | 4.46 | 0.34 | 0.71 | 16 | 14 | 28 | 67 | 20 | 35 | 91 | 225 | 1506 | 838 | 19 | 17 | 274 | 25 | 20 | 4 | 132 | 178 | 63 |
| 28 MU Peg | 77.46 | 0.04 | 12.37 | 0.38 | 0.01 | 0.02 | 0.84 | 3.21 | 4.57 | 0.01 | 0.57 | 1 | 0 | 21 | 5 | 1 | 62 | 24 | 246 | 15 | 51 | 18 | 18 | 12 | 7 | 4 | 13 | 32 | 0 | 2 |
| 30 NB GR | 70.15 | 0.3 | 15.01 | 2.21 | 0.05 | 0.48 | 1.49 | 4.02 | 5.05 | 0.07 | 0.68 | 5 | 13 | 39 | 15 | 14 | 41 | 55 | 264 | 979 | 306 | 19 | 20 | 271 | 23 | 35 | 11 | 167 | 195 | 56 |
| 31 NB GR | 71.78 | 0.18 | 14.51 | 1.51 | 0.04 | 0.33 | 1.07 | 3.66 | 5.82 | 0.06 | 0.8 | 0 | 2 | 26 | 11 | 17 | 26 | 44 | 251 | 578 | 200 | 17 | 17 | 192 | 14 | 17 | 3 | 110 | 130 | 35 |
| 32 MA GR | 76.39 | 0.05 | 12.65 | 0.8 | 0.04 | 0.04 | 0.54 | 3.84 | 4.5 | 0.01 | 0.5 | 0 | 0 | 49 | 8 | 5 | 51 | 42 | 396 | 12 | 18 | 16 | 21 | 83 | 17 | 21 | 17 | 50 | 0 | 0 |
| 33 MA GR | 75.93 | 0.08 | 12.87 | 0.77 | 0.04 | 0.08 | 0.72 | 4.1 | 4.09 | 0.01 | 0.56 | 0 | 0 | 37 | 0 | 6 | 60 | 41 | 390 | 158 | 77 | 17 | 23 | 80 | 22 | 34 | 37 | 58 | 25 | 9 |
| 34 MA GR | 76.64 | 0.03 | 12.85 | 0.69 | 0.08 | 0.05 | 0.47 | 4.12 | 4.23 | 0.01 | 0.36 | 0 | 0 | 23 | 8 | 3 | 39 | 17 | 362 | 3 | 17 | 16 | 14 | 99 | 15 | 25 | 10 | 44 | 0 | 0 |
| 35 MA GR | 76.35 | 0.05 | 12.8 | 0.62 | 0.03 | 0.05 | 0.5 | 3.79 | 4.53 | 0.01 | 0.46 | 0 | 0 | 45 | 5 | 4 | 42 | 24 | 398 | 27 | 27 | 16 | 18 | 99 | 20 | 26 | 18 | 61 | 0 | 5 |
| 36 MA Peg | 76.42 | 0.03 | 12.84 | 0.38 | 0.02 | 0.04 | 0.3 | 3.24 | 5.79 | 0.01 | 0.43 | 1 | 1 | 28 | 4 | 7 | 39 | 25 | 517 | 36 | 21 | 20 | 45 | 8 | 12 | 7 | 9 | 63 | 0 | 0 |

**S.N.: Sample Number; Loc.: Locality; R.T.: RockType**

**Localities: MU = Muyenga; NB = Nambole, NS = Nansana, KU = Kulambiro/Kulambiro Hill, CB = Cobla, KW = Kawempe, MT = Mattuga, MB = Mbalala**

**Rock Types: GR: Granitoids, GRP: Plagiogranites, Amph: Amphibolites, Peg: Pegmatites**

**Oxides in wt%, elements in ppm, Fe2O3 = Fe as total Fe**

| Documenta naturae | 136 | 161-183 | Munich 2001 |
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# History and Perspectives of Geological Research in East Africa

Thomas Schlüter

**Abstract:** The history of geological research carried out in East Africa, i.e. Kenya, Tanzania and Uganda, is presented. Since its beginning in the mid-19th century investigations spread into various directions, which were controlled by different scientific interests and by various economic demands. East Africa offers exciting research facilities in Precambrian and Phanerozoic geology both in pure and applied aspects. Since independence the three countries have produced their own geological manpower, which has enabled them to carry out indigenous research with the aim to contribute for poverty eradication and sustainable development of this part of the continent.

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## Introduction

The anglophone East Africa consisting of Kenya, Tanzania and Uganda covers an area of more than 1,750,000 $km^2$, which includes the highest mountains of Africa and some of the largest lakes on earth. Systematic geological surveying followed closely the geographical discoveries of the late 19th century, but even today its geological knowledge can not be compared with the attention that some areas in Europe witnessed. For instance the Harz (Hercynian) Mountains in the heart of Europe, cover an area of around 4,000 $km^2$.

A recent calculation indicated approximately 5,000 publications concerning their geology since Agricola's first descriptions of mining activities there in the 16th century (Mohr, 1993). Altogether there are approximately 7,000 publications on the geology of East Africa recorded - thus an area more than 400 times the size of the Harz Mountains is geologically documented by almost only the same number of publications as the tiny Harz Mountains. However, this meagre record is not a surprise considering that geological investigations started comparatively late, which had left East Africa scientifically more or less up to the end of the 19th century as a blank. A short historical review of early geological investigations will follow.

## The Search for the Sources of the While Nile: Repercussions in Geology

Up to the middle of the 19th century geographers and cartographers in Europe believed that all the important rivers of Africa originated from a single lake somewhere in central Africa. This legend had its roots in the writings of the ancient Greek Herodotus who had personally visited northern Egypt in the 5th century B. C. Although Herodotus made only references to even older citations he was however considered an authority on the source of the Nile. He even suggested that the Nile originated from melting snow-capped mountains somewhere in central Africa.

In the 2nd century A. D., the Alexandria based geographer and astronomer, Claudius Ptolemy produced his celebrated map of Africa, which was sometimes copied and is now preserved as a wall relief in a monastery of the Athos peninsula in northern Greece. On it one great lake with two N-S trending branches, placed side by side approximately at the 6th southern latitude, is shown to be watered by the Lunae Montes or "Mountains of the Moon" and forms the source of the Nile (Fig. 1a). In the 12th century, the Arab Al Idrisi was of the opinion that both rivers Nile and Niger were formed by the same lake somewhere in central Africa near the mysterious Mountains of the Moon (Fig. 1b). Other early maps such as that of the Dutch cartographer Dapper, show similar ideas (Fig. 2). Since that time European explorers developed activities in the search for the African drainage pattern.

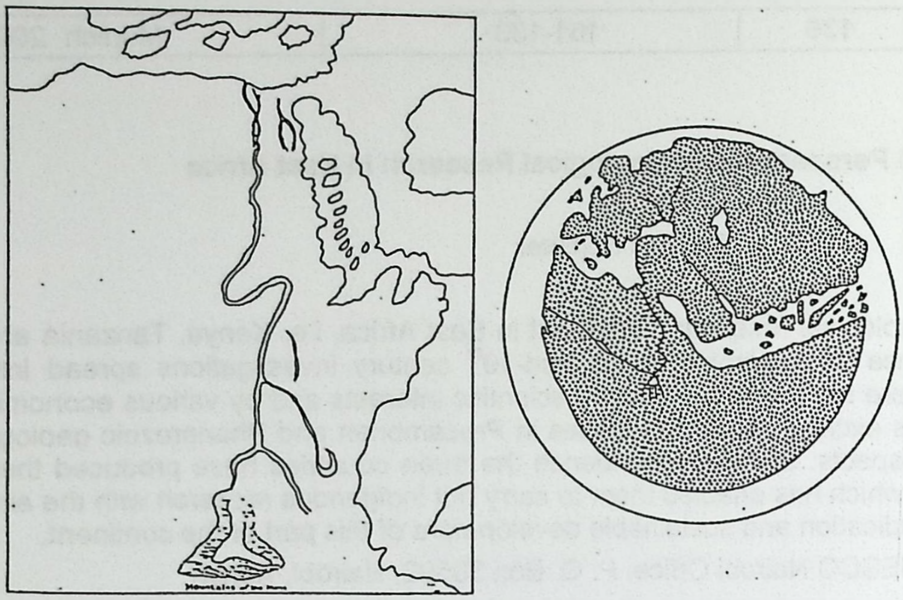


**Fig. 1:** Earliest sketch maps of Africa.

**a:** River Nile originating from a large lake in central Africa. After Ptolmy of Alexandria, Egypt, 2nd century A. D., from a wall relief in a monastery of Athos peninsula, Greece;

**b:** Outline of the world as known by the Arab Al Adrisi in the 12th century, from the the Atlas of African History (J. D. Fage, ed., 1982).

Around 1850 the two German missionaries Ludwig Krapf and Johann Rebmann reported about the possible position of a single great lake along the 10th southern latitude, but their map did not indicate an outflow of either the Nile or Zaire rivers. This map, together with the report of snow capped mountains along the equator, caused much curiosity and controversy in Europe. Krapf had to leave East Africa due to ill health in 1853, but he remains famous for his work on Swahili grammar and dictionary. His contributions on the geography including some remarks on the geology of East Africa were published in 1860.

The first detailed topographic maps of the East African hinterland were not even made until the 1860s when two amateur cartographers, T. Wakefield and Clemens Denhardt, both living in Mombasa, had questioned and investigated information from Arab traders. These maps were remarkably full and accurate, but poor on the locations of rivers and lakes. Above all, they failed to mention or depict the line of the Great Rift Valley at all.

During the mid-fifties of the 19th century Sir Roderick Murchison, who is also known as the founder of stratigraphy of the Early Palaeozoic in UK, was president of the Royal Geographical Society in London. Murchison was convinced about the long geological history of continental Africa, which he outlined in several articles since 1852. His position in the Royal Geographical Society enabled him to send out well-funded explorers with the aim to confirm his suggestions by doing fieldwork. In 1856 two British army officers, Richard Burton and John Hanning Speke, were picked to lead an expedition from Zanzibar to trace the source of the White Nile. Burton and Speke traveled inland along the trade route to Tabora and reached early in 1858 Lake Tanganyika. Only Speke decided to proceed from Tabora further north and found eventually the great lake which he named after his queen, Victoria - Nyanza. He was already convinced, though without sufficient proof, that this lake was the source of the White Nile. Burton who had remained in Tabora did not believe in him and therefore a strong argument between the two men arose. Another Royal Geographical expedition was therefore sent out in 1860, this time with Speke in command who was then accompanied by James Augustus Grant. This former major in the Indian army was loyal to Speke and had predominantly botanical and zoological interests. He was also a talented draughtsman.

Meanwhile the German Colonel Carl Claus von der Decken prepared his own expedition in Zanzibar. He was in search for the lost Dr. A. Roscher, a German traveler who had made some magnetic measurements near Lake Tanganyika in 1858/59 (Kersten, 1869). Roscher also drew a topographic map of the coastal area of the Rufiji delta. On it he marked, near the present city of Dar es Salaam, what he called "Kopalgruben" - best to be translated as small-scale mining pits of copal. Copal is a fossil resin similar to amber but generally younger in age. It often contains well-preserved inclusions, predominantly small insects. Before World War I the export of this then

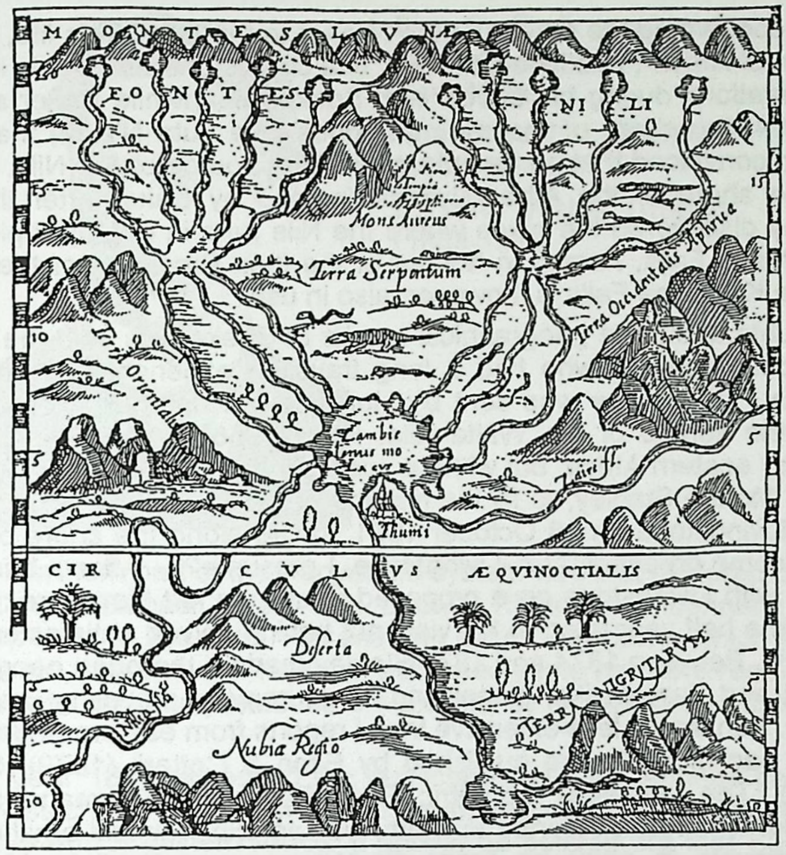



**Fig. 2:** A 16th century sketch map of the drainage pattern in central Africa. Most names are only tentative. From the Dutch cartographer Dapper.

Zanzibar or Gum copal named resin from German East Africa (DOA) to Imperial Germany played an economically important role because it was used in high grade varnishes. But due to the subsequent increase of artificial resins in manufacturing the knowledge of these deposits got almost lost in the 20th century (Schlüter & Gnielinski, 1987).

Von der Decken organized and led several expeditions to East Africa from 1860 to 1865, when he was finally killed in tribal clashes. He was sometimes accompanied by the young geologist Richard Thornton (1838-1863), and by O. Kersten who subsequently published the results in his own name or his data were compiled with editorial annotations (Kersten, 1869-1879) and transferred to other authors. To mention among this series of publications is the contribution of A. Sadebeck who gave the first comprehensive review on the geology of East Africa in 1879. This comprised an area running from Khartoum in the North to the Zambezi River in the South, including the first still fragmentary geological map of this region.. Additional geological results of von der Decken's travels during which he also reached Mt. Kilimanjaro, were published by Rose (1863) and Roth (1863), respectively.

Speke and Grant started out in the Summer of 1860 from Zanzibar and reached along the northern and western shores of Lake Victoria the border of the Buganda Kingdom where they had to wait up to January 1862 to get a permit to enter it. Leaving Grant behind, Speke then traveled east and came on 28th July 1862 across the place where the Nile leaves the lake, the former Ripon Falls, which are now ponded by the Owen Dam near the present town of Jinja. Grant rejoined him and together they traveled into a northern direction, only sometimes following the Nile. Almost 1000 km north from the Ripon Falls at the Sudanese town of Gondokoro, where an Austrian mission had been established they met in February 1863 Samuel Baker and his young wife Ruth who had organized their own expedition to go south and find Speke and Grant. Since for Speke the discovery of the source of the Nile now was settled he returned back to London. However, at home most people were not convinced and debated Speke's results with different arguments. One day before he was requested to defend his theories in a round table discussion of the British Association for the Advance of Science in September 1864, prominently against his strongest opponent, his former compatriot Richard Burton, he died in an accident from his own gun. Burton remained skeptical concerning the source of the Nile up to the end of his life, but his book "The Lake Regions of Central Africa", published in 1860, is a classic one and deals in large parts also with geological observations during his travels with Speke. Meanwhile Baker and his wife had reached, in March 1864, the shore of the still mysterious lake Luta N'zige, the today Lake Albert, and Baker was also convinced that he had discovered the source of the Nile. During their two weeks stay along the shore of the Albert-Nyanza (named by Baker after the late husband of Queen Victoria) they discovered the place where the Nile runs in mighty rapids into the lake, today still called Murchison Falls, named in honour of the then President of the Royal Geographical Society. The name Kabalega Falls is, however, also in use.

Among those who had their doubts about the geographical results of Speke was also the widely respected missionary Dr. David Livingstone who had a long traveling experience in southern Africa since 1849. Consequently, Livingstone was sent by Murchison in another expedition to solve finally the problem with the source of the White Nile. From 1866 to 1872 he traveled ceaselessly around in central and eastern Africa, but without success. It was left to the American adventurer and journalist Henry Morton Stanley, to fill the missing gaps. Well known in history is Stanley's meeting with the lost Livingstone on 18 October 1871, in Ujiji along the shore of Lake Tanganyika and his famous welcome greetings: "Dr. Livingstone, I presume?" - After a brief stay in Ujiji and fruitless discussions with Livingstone on a proposed return, he left him there. Livingstone died further south one and a half year later, in his view not having solved satisfactorily the problem of the sources of the Nile. Between 1874 and 1877 Stanley made a thorough geographic survey of Lakes Victoria, Albert and Tanganyika, completing his journey by traveling down the River Zaire to the Atlantic ocean. Similar but less extensive travel reports from eastern and central Africa with marginal geological background were published by Elton & Cotteril (1879), Giraud (1890) and Hildebrandt (1879). The somehow eccentric Emin Pascha, a German national formerly named Eduard Schnitzler who had converted to Islam, was an explorer and ornithologist accompanied during his last travels in 1890 by Franz Stuhlmann, a naturalist with wide knowledge in botany who drafted a rather accurate geological map of German East Africa (Stuhlmann, 1892, 1894, 1909).

### Early Geological Research

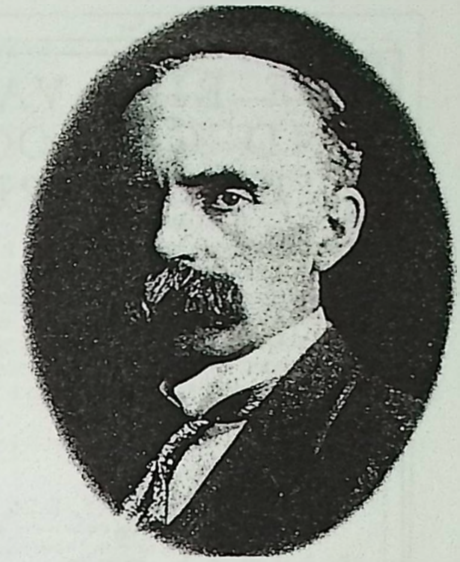
Most of the early geological surveys and accounts hail from coastal East Africa, because access was easier there than to the hinterland. Descriptions of various ammonite collections (Jones 1859; Beyrich, 1877, 1878; Marschall, 1878; Tornquist, 1879) or of the already mentioned copal deposits (Roscher in Kersten, 1869) were published in this early period. One of the first real geologists to travel in East Africa was the Scotsman Joseph J. Thompson (Fig. 3a) who just after the completion of his studies was supported by the African Exploration Fund Committee. In the late seventies he traveled from Mombasa to Lake Victoria via "Kilima Njaro", "Keri Nyanza" (Mt. Kenya) and Lake Baringo. In 1880 he presented in the journal Nature the first geological field account of a sector of the East African Rift system, that of Nyanza, in which he included three cross sections. His second journey took him in 1883/84 through Masailand (Thomson, 1885), across the Rift Valley and into western Kenya where he saw Mt. Elgon. As a result of his traverses Thomson postulated a zone of volcanism extending from the Cape to Ethiopia, roughly parallel to the Indian Ocean. From 1883 to 1886 the German naturalist Gustav A. Fischer mapped the rift grabens of southern Kenya and northern Tanzania (Fischer, 1884, 1885a, b). Notably a detailed geological map at a scale 1:50,000 of the areas where Fischer traveled is incorporated in his 1884 publication. Some of his rock collections were subsequently described by O. Muegge (1886 and see Fischer 1885b).

Since Mt. Kilimanjaro had been established as the highest peak of Africa, it also attracted extensive geological attention, which resulted in several petrographic publications on rock samples collected from there and its nearby surrounding (Bonney, 1885, 1886; Fletcher & Miers, 1887; Hatch, 1888; Hyland, 1889; Miers, 1886; Rose, 1863; Roth, 1863). Most of these articles are rather short and only concerned with the determination of the mineralogical composition of the respective rock samples.

**Fig. 3:** Early geologists carrying out research in East Africa.

⇦ **a:** Joseph J. Thomson (1853-1894)

**b:** John Walter Gregory (1864-1932). ⇨



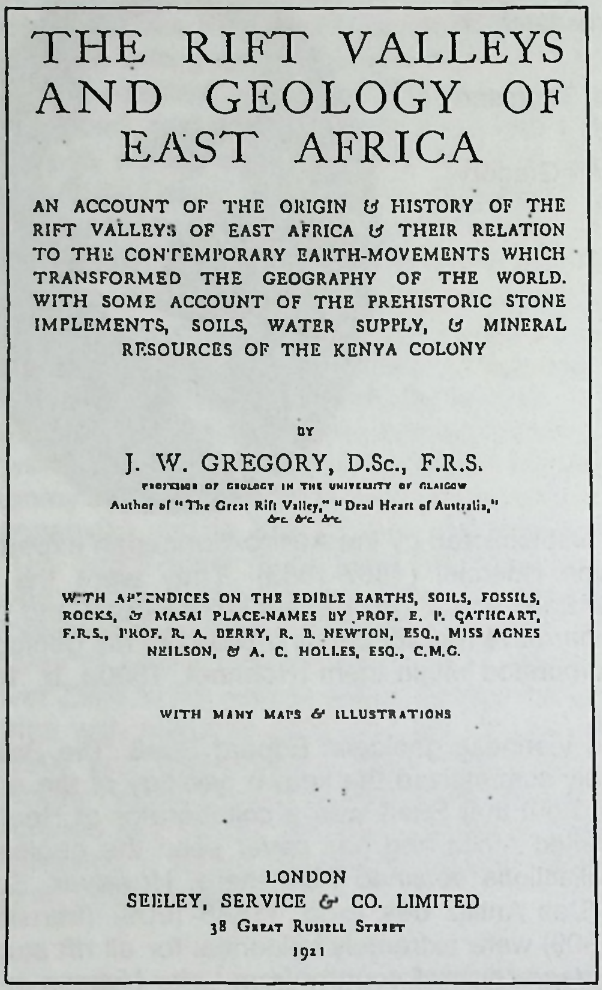
The northern part of the Kenyan rift system was first explored by the Austro-Hungarian expedition of Count Samuel Teleki and Ludwig Ritter von Hoehnel (1887-1888). They were the first Europeans to see Lake Turkana and Lake Chew Bahir which they named Lake Rudolf and Lake Stefanie, respectively. Hoehnel published some narrative reports on his travels but his geological accounts and interpretations are excellently incorporated within them (Hoehnel, 1890a, b, 1893, 1894).

The year 1891 witnessed the publication by the Viennese geologist Eduard Sueß "Die Brüche des östlichen Africa", a work that comprehensively summarized the known geology of the entire rift system of eastern Africa. It should be pointed out that Sueß was a collaborator of Hoehnel (Hoehnel et al., 1891) but that he has never visited Africa and has never seen the geological features which he interpreted from the data collections obtained from there. However, Sueß' articles and his subsequently published book "Das Antlitz des Erde" (1885-1909) (translated English version "The Face of the Earth", 1904-1909) were extremely influential for all rift studies of the following decades. Suess interpreted the depression of country from Lake Nyassa in the south to River Jordan in the north as a result of fractures caused by a series of earth movements. He used the term "Graben" to describe this phenomenon.

### The Golden Age of Gregory and his Contemporaries

Since the beginning of the 1890s another Scotsman, John Walter Gregory (1864-1932) (Fig. 3b), had a unique impact on the geological exploration of East Africa. After studying at London University, Gregory was appointed in 1887 as a palaeontological assistant at the British Museum of Natural History in Kensington. He was an ardent follower of Suess and agreed with him that there existed the so-called super-continent Gondwanaland, which broke up to form the present southern continents. The movements that pulled the continents apart, he believed, were also responsible for tearing at the fabric of Africa and causing the subsidence of the rift. However, it was still a theory, developed mostly from the explorers and travelers some years before. Therefore Gregory felt he must see the rift for himself and discover empirical evidence for his beliefs.

In 1892 Gregory took his chance. He heard about an expedition to investigate the least known portion of the Rift Valley only four days before it was supposed to leave England. After getting permission to vacate his post at the British Museum he set off with this expedition from the northern Kenyan coast along the Tana River then across Somalia. Unfortunately, the journey ended in a disaster, and after only six weeks in the field the party was forced to return to Mombasa due to malaria, dysentery and lack of food. Despite repeated discouragement from Europeans, who urged him not to venture into the little known territory of the hostile Kikuyu and Masai tribes, Gregory organized another expedition and left Mombasa on 23 March 1893, with 40 porters. On this second foray, instead of proceeding north along the swampy malarial Tana basin, Gregory struck northwest.



THE RIFT VALLEYS AND GEOLOGY OF EAST AFRICA

AN ACCOUNT OF THE ORIGIN & HISTORY OF THE RIFT VALLEYS OF EAST AFRICA & THEIR RELATION TO THE CONTEMPORARY EARTH-MOVEMENTS WHICH TRANSFORMED THE GEOGRAPHY OF THE WORLD. WITH SOME ACCOUNT OF THE PREHISTORIC STONE IMPLEMENTS, SOILS, WATER SUPPLY, & MINERAL RESOURCES OF THE KENYA COLONY

BY

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Author of "The Great Rift Valley," "Dead Heart of Australia," &c. &c. &c.

WITH APPENDICES ON THE EDIBLE EARTHS, SOILS, FOSSILS, ROCKS, & MASAI PLACE-NAMES BY PROF. E. P. CATHCART, F.R.S., PROF. R. A. BERRY, R. B. NEWTON, ESQ., MISS AGNES NEILSON, & A. C. HOLLES, ESQ., C.M.G.

WITH MANY MAPS & ILLUSTRATIONS

LONDON
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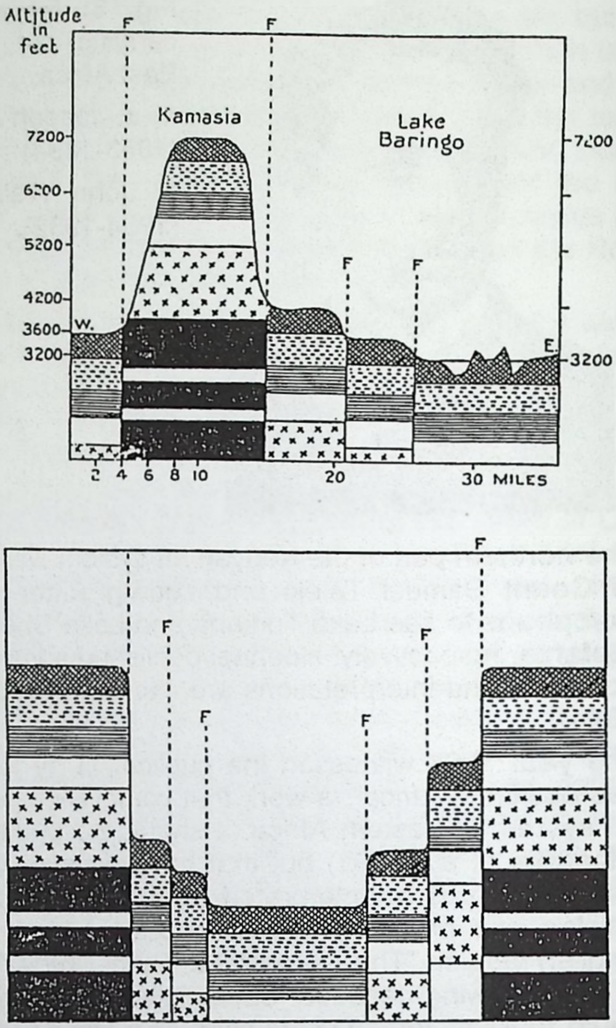



**Fig. 4:** Two cross sections showing Horsts and Grabens in the vicinity of Lake Baringo, Kenya. From Gregory, 1896.

This time he was better prepared. Immediately he started with geological fieldwork earning him the Kikuyu name "Mpokwa", which means "Loaded pockets" because he was always heavily weighed down with samples picked up along the way. Five weeks after the start of his second safari he came closer to the Rift Valley (Fig. 4) getting more and more impatient. He saw it initially at a point somewhere near the present town of Limuru in front of the great cone of the volcano Longonot. To the south he admired "the breached crater Doinyo Suswa", beneath him was "the dark sinuous line of flat-topped acacias that mark the course of the Guaso Kedong", and over in the west "the long, dull gray scarp of the plateau, which forms the western boundary of the valley". Descending the Rift Valley Gregory noticed former shorelines along the wall. He realized these were lake terraces, thus this valley had once been covered with water. Promptly he named this former huge lake after Sueß, the Austrian professor he so admired.

Gregory arranged a base camp in a small village at the southeastern end of Lake Baringo and set out from there on a series of rock-gathering excursions around the lake, taking samples of lavas and sediments all the way along. When climbing the tilted mountain block of Kamasia he noted that its strata were upturned. When the expedition continued northwards from Lake Baringo, it encountered starving villagers and there was a threat of mutiny. Eventually Gregory reached a point some 150 km south of Lake Turkana, but he had run out of regular supplies and was therefore forced to abandon his survey before even studying the nearby Elgeyo scarp.

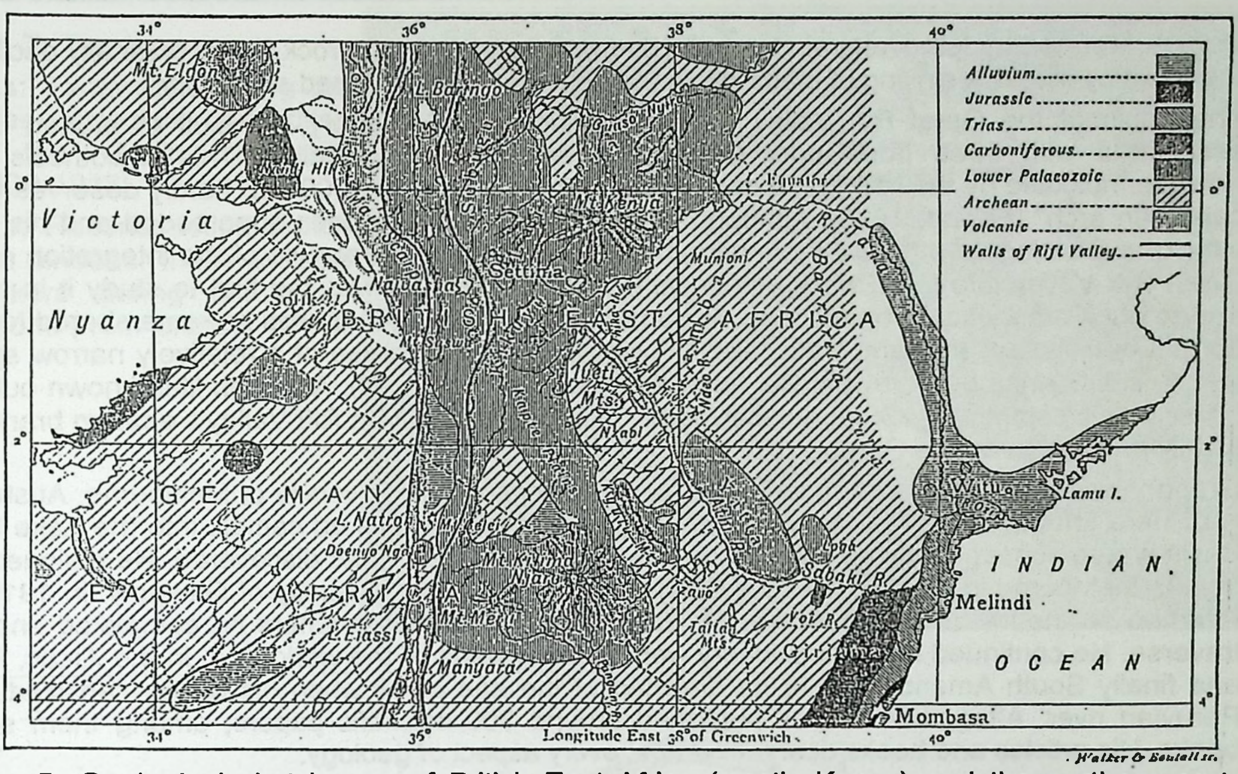



**Fig. 5:** Geological sketch map of British East Africa (mostly Kenya) and the northern part of German East Africa. Note the accurate extension of volcanic rocks in the eastern branch of the Rift Valley. From Gregory, 1896.

However, he still had time to observe Mt. Kenya and was therefore the first professional geologist to examine it from fieldwork. Other Europeans had already climbed much of it (see the summarizing reports of Mackinder, 1900 and Mackinder & Barbour, 1991) and collected rock specimens, but, in Gregory's view, unsatisfactorily. One of his important discoveries were some striae on rocks in the timberline area, from which he deduced that the mountain had been more widely glaciated in the past (Gregory, 1894).

Gregory returned to England having been only a few months in East Africa. Subsequently he wrote his book entitled "The Great Rift Valley - being the narrative of a journey to Mount Kenya and Lake Baringo", published in 1896 and a standard reference quotation (Fig. 5) at least up to 1921 when his second, more comprehensive work on "The Rift Valleys and Geology of East Africa" appeared. In addition to the information compiled in the 1896 edition the latter one gives a full account of the geological structure and history of the former Kenya colony, and it also includes summaries concerning the geology of the former Uganda protectorate and Tanganyika territory.

These two books mark milestones in the course of geological research carried out in East Africa. Gregory had seen before his journey to East Africa the lava fields of Idaho - he felt certain that he had also seen in East Africa "a plain of lava and not of alluvium". It ran over the land, and into the hollows of the mountains "just as the water of a lake follows the irregularities of its shore". Since he did not see signs of fissure eruptions he concluded a special type of plateau eruption had occurred whereby a sheet of lava was formed by numerous scattered cones, these appearing where lines of weakness crossed each other.

Gregory believed that the rifting was largely due to periods of volcanic activity followed by earth-movements, which restored equilibrium. He argued that, as masses of volcanic material had been piled up on the surface, and as the subterranean reservoirs had surely been emptied, the "upper layers of the earth's crust were therefore over-weighted". Hence a period of relative tranquility followed after each outburst while the land subsided to restore the better balance. "These valleys were not formed by removal grain by grain, by rivers or wind, of the rock which originally occupied them but by the rock sinking in mass, while the adjacent land remained stationary".

The origin of the Great Rift Valley was, in the opinion of Gregory, a result of arched uplift, associated with three post-Upper Cretaceous episodes of tectonism. This hypothesis was however ridiculed by the fact that a rise of only 1 km in a span of 1000 km "hardly deserves to be called an arch" (Shand, 1936). Although Gregory's notions have been superseded and his fixist view of explaining the rift valley formation has been abandoned because of the integration of the Great Rift Valley into the Earth's mid-oceanic ridge system, he was the first to study it in detail and to put it emphatically on the map. In geosciences Gregory will always be remembered for the correct definition of the term "Rift Valley", "using"...it..."in the sense of a relatively narrow space due to subsidence between parallel fractures" (Gregory, 1921: 18). Although little known outside his scientific community, Gregory received his memorial: The Great Rift Valley's eastern branch is widely referred to as the Gregory Rift.

Gregory was in 1900 appointed as professor of geology at the University of Melbourne, Australia. Also here known as a great organizer he led a group of students on camels into the Lake Eyre Basin where subsequently an important fossil vertebrate locality was discovered. He resigned his post in Melbourne in 1904 to take the Chair of Geology at the University of Glasgow. In 1919 he returned on the invitation of General Sir E. Northey to East Africa where he completed another traverse. He continued his expeditionary work in many parts of the world, e.g. in the Arctic, India and finally South America, where he drowned at the age of 68 when his canoe capsized in a Peruvian river. Altogether he has published around 300 scientific papers, among them some books. His articles and books deal with almost every aspect of geology.

Gregory was, of course, not the only scientist who contributed to the knowledge of East African geology during the decades from 1890 to the end of World War I. In former German East Africa that de facto became a German colony only in 1891, and then also included the former kingdoms of Rwanda and Burundi, vigorous geological investigations were initiated. Stromer von Reichenbach compiled in 1896 all the available data on the geology of the German colonies in his Ph. D. thesis, with special emphasis concerning German East Africa. The formal establishment of a German colony in East Africa opened also the way to prospect for exploitable resources in this region. G. Lieder (1892) gave the first summarizing report on the potential of economic minerals in German East Africa. The occurrence of gold was known because the Arab traders had brought it from the interior (Kuntz, 1909). In 1916 coins of endemic gold (15 rupies) were minted at Tabora in central German East Africa (Fig. 6). These served partially as an emergency currency when the colony's supply during World War I was totally cut from Imperial Germany and the surrounding British territories (Schlüter & Kohring, 1997).

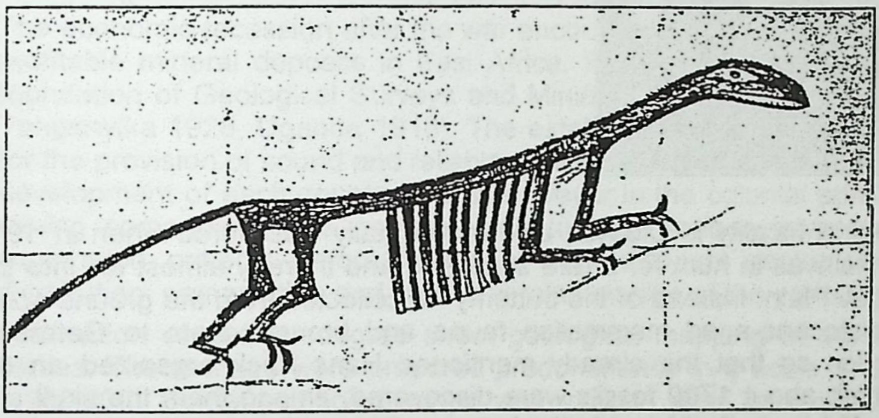

**Fig. 6:** Golden emergency coins of German East Africa from 1916, minted at Tabora and Lulanguru. After Schlüter & Kohring,(1997).

Large quantities of mica were estimated to occur near the Uluguru Mountains, just 150 km west of Dar es Salaam. The first diamonds were found in 1913 in an area, which became subsequently the Mabuki Mine in 1925. Altogether between 1884 and 1918 gold and mica worth around 1.4 million US $ were recovered under the German direction. Also coal deposits in the southwest of the colony were discovered but too remote for a systematic exploitation.

**Fig. 7**: Tendaguru.

**7. a**: Excavation during the palaeontological expedtion of the Berlin University (1909-1913).

**7. b**: Reconstruction sketch of a dinosaur made by local workers during the excavations (from Branca, 1914).



The end-nineties of the 19th century mark the period when geological investigations spread into various directions. Stratigraphical and palaeontological reviews were for example presented in separate articles by Potonie, Müller, Wolff and Weissermel in Bornhardt's classic book "Zur Oberflächengestaltung und Geologie Deutsch-Osafrikas" (1900), in which he also included four geological maps at a scale 1:500,000. Also Oppenheim (1916), Behrend (1918), Jäkel (1893), Futterer (1894), Hennig (1916), Menzel (1902), Scholz (1911), Dacqué & Krenkel (1909) and Krenkel (1910a, b, 1911) contributed with many detailed observations on the Phanerozoic cover formations of German East Africa.

The famous dinosaur-bearing locality Tendaguru (near Lindi in SE Tanzania) was accidentally discovered by a mining engineer, Bernhard Sattler, in 1906 who found an isolated fossil reptile bone. The first almost completely preserved skeletons of sauropods were subsequently dug out by Eberhard Fraas and later described by him as *Gigantosaurus robustus* and *G. africanus* (1908). These discoveries stimulated the Palaeontological Institute of the Berlin University to undertake research by funding a large-scale expedition in the area, which resulted in one of the most successful expeditions in the history of palaeontology. From 1909 to 1913 under the guidance of W. Janensch, E. Hennig and H. Reck the excavation of 225 t of dinosaur bones was achieved (Fig. 7a and b), brought by caravan to Dar es Salaam and then sent to Berlin. The best and most complete specimens are now exhibited in the Museum für Naturkunde in Berlin (Hennig, 1912; Branca et al.; 1914, Schuchert, 1918) (Fig. 7c). Some additional tonnes of the bone matrix were stored in the magazine of the museum, and it might be noted here that very recently a chemical dissolution of this material yielded the jaw of a tiny Upper Jurassic mammal, a discovery that followed after 80 years of dormancy (Heinrich, 1991).

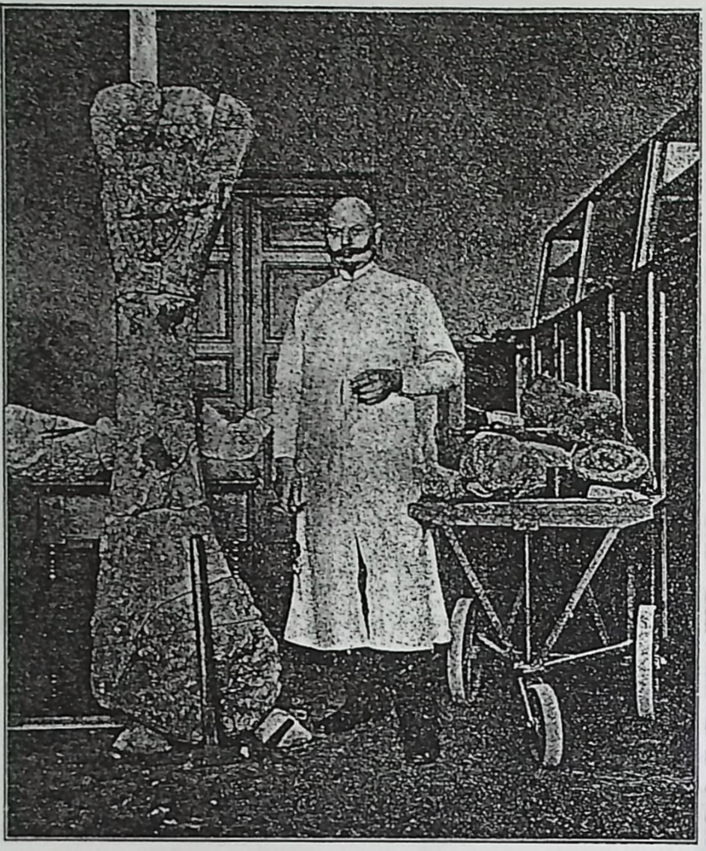


**Fig. 7. c:** Preparation of a dinosaur bone in Berlin (from Branca, 1914).

Another famous palaeontological locality is Olduvai, also accidentally discovered when in 1911 the butterfly collector Kattwinkel was in hunt for a rare specimen and thereby almost fell into the deep cut gorge in the Serengeti Plain. Instead of the butterfly he collected from the ground some washed out bones of a Pleistocene-aged mammalian fauna and brought them to Germany. These attracted much attention so that the already mentioned Hans Reck organized an expedition to Olduvai during which about 1700 fossils were discovered, among them the skull and skeleton of fossil man (Reck, 1914a, b; Dietrich, 1916). However, Olduvai is now more associated with the names of the palaeoanthropoligists Louis and Mary Leakey who started their excavations there in 1931 (Leakey, 1935).

Volcanism was another subject that has intensively been studied by German researchers in East Africa. The relationship of volcanism with the formation of the Great Rift Valley was clearly recognized since the end of the 19th century. The carbonatitic nature of the lava of the still active Oldoinyo Lengai, the holy mountain of the Masai tribe, was already observed by Fischer (1885) and subsequently confirmed by Reck and Schulze (1921). Other notable volcanological descriptions were made by Finck (1903, 1906), Goldschlag (1912), Mauritz (1908, 1911), Meyer (1900), Reck (1914b, 1915) and Uhlig (1904, 1908, 1909, 1911).

The three major islands in the Mozambique Channel opposite the coastal mainland, namely Zanzibar, Pemba and Mafia, attracted comparatively little geological attention, probably because they were only seen as remnants of elevated coral reefs by the early researchers. Therefore only a few references exist, for example, the earliest one of R. Thornton (1862) entitled "On the Geology of Zamzibar" describes a journey from Mombasa to Kilimanjaro, but does not mention Zanzibar at all! Smith (1887), Baumann (1891-1899), Bauer (1911), Crossland (1902, 1903) and Werth (1901, 1909, 1915) discussed some general aspects of the geological history of the archipelago, but it was Stockley (1928) and his co-workers (Stockley et al., 1927) who gave the first comprehensive account on its geology and palaeontology.

A curious scientific misunderstanding came up when the origin of Lake Tanganyika and its fauna were analyzed: The explanation of its geological history was dominated by the striking theory that the lake was the remnant of an ancient sea which was connected in Jurassic with the Atlantic across the Zaire basin (Hudleston, 1904). This theory was mainly based on the apparent marine ("thalassoid") relationships of some of its faunal members, especially the medusoid coelenterate ("jellyfish") *Limnocnida tanganyikae*. The most notable advocate of the idea was J. E. S. Moore (1904) whose discussion of the geological history of this lake and of the origin of its fauna in the wider setting of the East African lakes region was based on his expeditions in 1895 and 1898. It was finally Cunnington (1920) who refuted the theory and convincingly indicated that all the "thalossoid" species are related to freshwater forms found elsewhere in Africa from which they had diverged during a long period of adaptation to the special conditions in Lake Tanganyika. However, since most of the faunal components of Lake Tanganyika are endemic, it is conclusive that the lake for a long period was isolated from the faunas of rivers that were previously draining into the Zaire basin.

**Search and Perspectives for Economic Mineral Deposits and Energy Supplies**

World War I had to a certain extent clarified the political situation in East Africa because there was now no more direct competition between the British and the Germans after Tanganyika became in 1918 a mandate of the British Crown (Rwanda and Burundi went to Belgium). However, this apparent loss was in the German public during the twenties and thirties never accepted and for instance one of the leading experts in the pre war East African geology, Erich Krenkel, was - even in his scientific papers - an ardent representative of German ultra-nationalism with the aim to regain the former colonies (Krenkel, 1922, 1923).

The economic recession after the war encouraged in England the exploration and exploitation of profitable mineral deposits in East Africa. Systematic geological investigations began with the foundation of Geological Surveys and Mining Departments in the three countries (Kenya 1932, Tanganyika 1926, Uganda 1918). The establishment of these institutions was seen as a source for the provision of sound and reliable geological maps and as a basic prerequisite for the mineral development of each country. It was however in the colonial administration admitted that private mining companies were not expected to take serious interests in initiating detailed mineral exploration projects before having at their disposal geological maps indicating the nature, distribution, composition and structural relationships of the various rocks in the respective areas.

Publication of quarter degree sheet geological mapping at various scales began in the early thirties. These maps were prepared predominantly in a scale 1:125,000 or, in case of Uganda, 1:100,000. Some geological maps with various aims in a smaller or in a larger scale were sometimes also issued. The geological mapping of East Africa has not yet been completed and it has to be pointed out that the advent of independence of the three countries and the cease of publication of geological maps from there are almost coincident. For example, although about 80% of Tanzania is now geologically mapped, only 116 of the foreseen 322 map sheets have yet been published because there are presently no sources for printing available.

The search for economic deposits was for example wide open in the case of diamonds, which had already been found in northern Tanganyika in 1913. They were discovered near an area, which became the Mabuki Mine in 1925, but it was closed already in 1939. Nearby at Mwadui the Canadian geologist J. T. Williamson, a pathetic lonely figure, discovered in March 1940, a 2-carat octahedral diamond crystal. Immediately after the find he obtained an exclusive prospecting license for this area and began to build his own empire single handedly, which grew to become a township for several thousand employees and their families. The mine located on the largest known kimberlite pipe produced, in the fifties, about 500,000 carats per year, but after nationalization its production has greatly diminished.

Systematic mapping in East Africa yielded soon after its initiation some important information on metallogenic provinces and strata-bound deposits. For instance tin ore (cassiterite) occurs only in granitic intrusions in metamorphic areas of the Karagwe-Ankolean system. Mica is almost entirely found in pegmatites of the Usagaran and the Ubendian systems. Primary gold deposits ("reef gold") were only discovered in the Nyanzian and Kavirondian and partially in the Ubendian system. No major mineral occurrences are known from the Dodoman and the Bukoban system. However, there are surprisingly rich mineral deposits associated with post-Karoo (i.e. mainly Tertiary and Quaternary) volcanism as indicated by the already mentioned diamond-bearing kimberlitic pipes. Also the frequent carbonatites yield due to their particular composition pyrochlore/niobium, phosphate, iron and rare earth elements (REE). The salt and soda lakes with their abnormal concentration of various ions, especially in the Gregory Rift, have also contributed to some exploitable lagerstätten, e. g. Lake Magadi with its occurrence of trona.

Most of the commercial mines opened and operating in the thirties were small and controlled by individuals. Sometimes European farmers, administrators, businessmen and ex-soldiers rushed to assumed gold fields to individually pan there. During World War II the skilled German and Italian miners working in the larger companies were interned and the local labour force, which in Tanganyika had been approaching 30,000, just before the war, went down to about half. Another profound effect on the gold mining industry was the agreement to stabilize the war-torn economies of the Western Europe with the artificial fixing of the gold price at 35 US $ per ounce. In Tanganyika only the large reef gold mining companies survived by cutting costs, but even these, including Geita, Kibakari and Buhemba gold mines were forced to give up in the mid-sixties. The end of the colonial period was therefore characterized by the withdrawal of several mining concerns and after independence the young countries were confronted with the lack of profitable mining enterprises as well as skilled manpower to explore and exploit potentially rich deposits.

Tanzania is so far the only East African country where significant coal reserves have been discovered. These occurrences are known since at least 1896 (Bornhardt, 1900; Hasslacher, 1914). During the British colonial period much work was done in ascertaining the suitability of the territory's coal for industrial use. However, large scale coal exploitation was never possible due primarily to the remoteness of the deposits and lack of enough market to warrant special construction of the infrastructure to the coal deposits. The only coal mine during colonial times has been the Ilima colliery near Tukuyu in southwestern Tanzania, which operated privately from 1953 to 1971 and was then nationalized. At present nine known coalfields, mainly in the southern part of the Rift Valley but all of them related to the Permo/Carboniferous Karoo deposition, are estimated to contain about 1.2 billion tonnes of coal. Only the Chinese-built Cowrie Mine, northeast of the Kipengere Range is currently working, but at about 30% of its capacity. It is anticipated by the Tanzanian Government that the present annual production of about 45,000 tons could eventually rise to 300,000 tons by the year 2005.

The principle that some hydrocarbons (i.e. petroleum and natural gas) are less dense than water, and must therefore occur in sealed domes or anticlines, led to extensive geological mapping of exposed sedimentary structures in East Africa, later followed by predominantly seismic investigations. So far, the area of exploration has been concentrated in Kenya and Tanzania in the respective coastal basins, including off shore, whereas in Uganda the target area was the Lake Albert Rift Valley. An oil seepage near Kibiro in Lake Albert was known to local Africans for some time before it was first recorded by E. J. Wayland who visited the locality in 1919 and instigated the first geological investigations. The early history of oil exploration in the Lake Albert Rift Valley and of granting oil concessions was described by Wayland in 1925. However, although surface indications of the presence of oil and gas are found at several localities within the Lake Albert Rift Valley, and some seismic surveying and drilling has been carried out in potentially prospective fields, the recent ongoing exploration has never been successful. The same applies to the coastal basin of Kenya. In Tanzania, in an earlier survey, up to 1964, no reservoir rocks were observed. However, large deposits of natural gas were found at the Songo Songo Field about 300 km southeast of Dar es Salaam in the Indian Ocean. Exploration has recently also been undertaken on the internal sedimentary basins of the mainland of Tanzania between Lake Tanganyika and Lake Rukwa. No significant oil deposits were found.

Associated with rift structures are in East Africa most, if not all, of the geothermal resources, which can be sub-divided into those associated with young centres of volcanism and those located in non-volcanic areas. The earliest geothermal exploration was carried out at Olkaria in the central part of the Gregory Rift in Kenya near Lake Naivasha between 1956 and 1959, when two wells were drilled but failed to produce steam. In 1969, a reconnaissance geophysical survey in the area resulted in drilling of several new wells, which discharged steam. The first geothermal 15-Megawatt (MWe) turbo generator in Africa was installed in the late seventies and put into commercial production in July 1981. In 1985 the geothermal resources of Olkaria provided already 45 MWe of electric energy and, probably most important, the geothermal waste products have fewer environmental constraints than most other energy producing methods. A further 64 Mwe producing plant is expected to be added in 2002, and 56 Mwe in 2003, respectively (Omenda, 2000). Apart from Olkaria the following priority project areas for geothermal exploration and development in East Africa have been identified:

- The Suswa-Bogoria trend in central Kenya to develop power for the central Kenya grid.
- The Natron-Manyara trend in northern Tanzania to develop power for the Arusha-Moshi area.
- The Katwe area in western Uganda to develop power for the Kilembe/Kampala transmission line and possibly for chemical processing of the Katwe brines.

### The Precambrian is Dated

There is one aspect that was largely omitted by the pioneering geologists of the late 19$^{th}$ century almost up to the middle of the 20$^{th}$ century: The Precambrian basement comprises by far the largest share of rocks in East Africa, but the apparent monotony of its facies as well as the inability to date these formations sufficiently were probably the two striking reasons why comparatively few articles were published on it. Still in 1937 there was not a single comment made on the absolute age of these then so-called Archaeozoic and Eozoic groups. In fact, geologists of this time had no other tool than lithostratigraphic comparisons, which, of course, were not sufficient to correlate these formations precisely.

Arthur Holmes (1890-1965) whose book "The Age of the Earth" had already appeared in 1913 was a scientist who devoted a major portion of his career to the application of radioactivity in the solution of geological age dating. It is remarkable that his calculations and hence resulting definition of the so-called Mozambique Belt were based on less than 25 radiometric ages, when he gave his memorable address to the Association of African Geological Surveys at the International Geological Congress in London in 1948 (Holmes, 1951). He provisionally dated the Mozambique Belt to be approximately 1300 Ma old, an age today indicative for the predecessing Kibaran Belt, but at least much younger than the previously assumed Archaean age. Therefore, when Holmes defined the Mozambique Orogenic Belt as extending from south of the Zambezi River to the extreme north of Kenya, Uganda and Southern Ethiopia the stratigraphic and structural map of Equatorial and Southern Africa received a new face which basically still holds today (Daly 1988) (Fig. 8). In a compilation prepared by Arthur Holmes and Lucien Cahen (1912-1980) (Fig. 9), who was another father of Precambrian stratigraphy of Central and Eastern Africa, in 1954, the number of radiometric ages in Africa had grown to approximately 100, and by 1956 the same authors were able to list about 300 ages. In their summarizing book "The Geochronology of Equatorial Africa", Cahen & Snelling (1966) considered more than 550 determinations. During the early fifties, the K:Ar and Rb:Sr methods had been established on a virtually routine basis while the older U-Pb method had become even more firmly entrenched.

On the other hand it has to be pointed out that Cahen et al. (1984) in their famous and, currently probably most cited book on the Precambrian stratigraphy of Africa, were of the opinion that much of the former isotopic evidence was of relatively poor precision and that the data obtained for the variation of initial 87Sr:86Sr ratios through place and time with respect to Africa will probably soon become only of historical interest. Accordingly also the abundant U-Pb data achieved before 1984 should for similar reasons largely be ignored. Cahen et al. (1984) predict for future stratigraphic investigations isotopic variations of strontium, lead and neodymium, whereas they are skeptical about palaeomagnetic studies.

### The Postcolonial Development

Geological Education at the East African Universities

The independence of the three East African countries (Tanzania: 9-12-1961, Uganda: 9-10-1962, Kenya: 12-12-1963) gave way to indigenous exploration and exploitation of the mineral resources. Though the transition was relatively calm there was an obvious deficiency of academically skilled manpower to fulfil such jobs. From 1963 to 1970 there existed only one institutions of

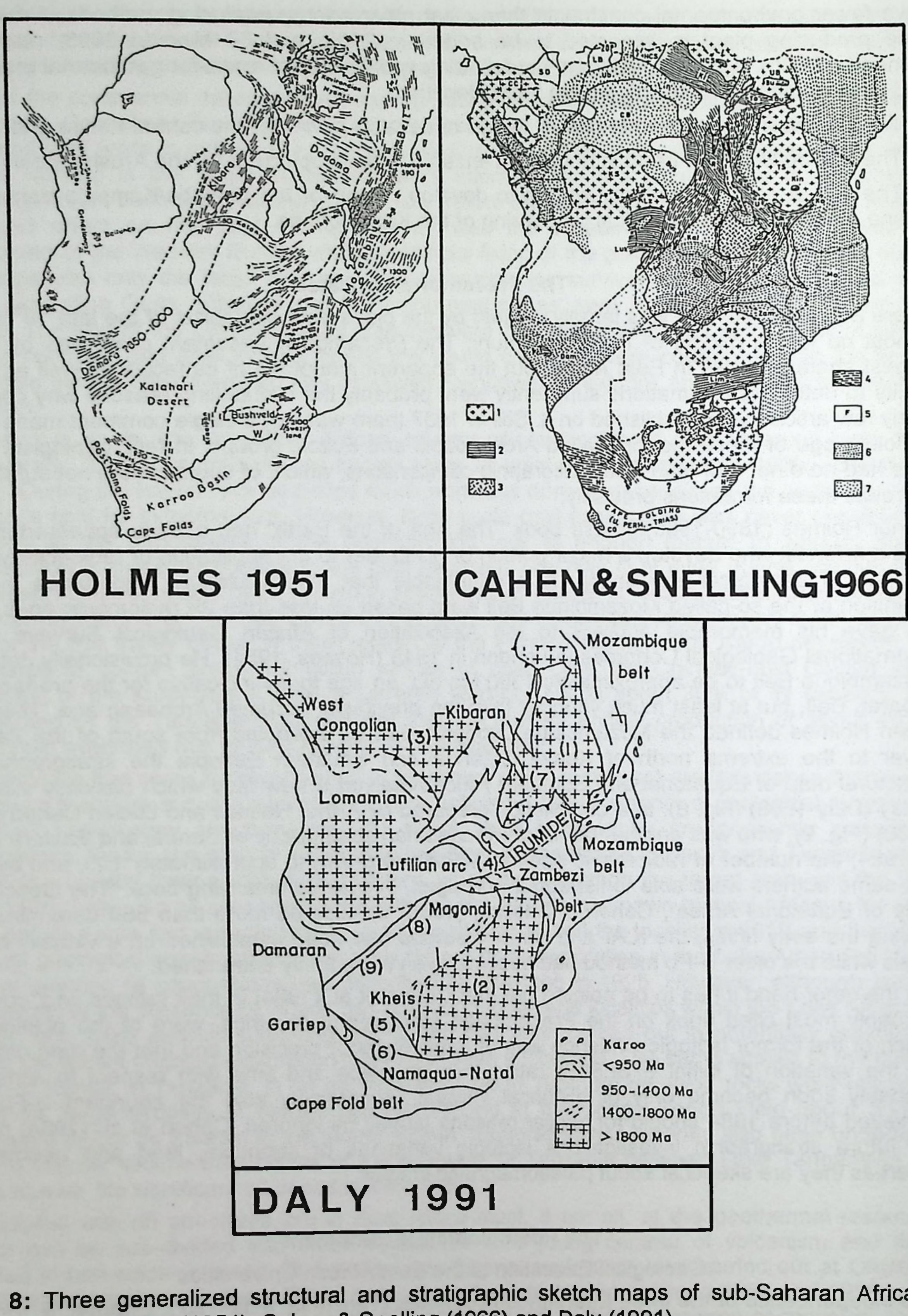



**Fig. 8:** Three generalized structural and stratigraphic sketch maps of sub-Saharan Africa as proposed by Holmes (1951), Cahen & Snelling (1966) and Daly (1991).

higher education in East Africa, the University of East Africa, which had its roots in the formerMakerere College in Kampala (already founded in 1922), the Nairobi University College (founded in 1956) and the University College of Dar es Salaam (founded in 1961).

In 1970 the University of East Africa was dissolved and each country set up its own university. Geology has been taught in Nairobi since 1961. At Makerere University geology was established as an academic discipline in a sub-department of the Department of Geography but became independent in 1968. At the University of Dar es Salaam a degree course in geology was introduced in 1974.

In their early phases these three departments were confronted with the various problems which all comparable institutions in developing countries face: Not enough teaching staff, heavy reliance on expatriates, no sufficient teaching facilities and no funds for research.

**Fig. 9:** Lucien Cahen (1912-1982).

Due to the political circumstances the situation in Uganda worsened in the seventies up to the early nineties, and as a result in 1994 neither a single Ugandan Ph.D.-holder in any field of geosciences was employed at the Department of Geology, Makerere University, nor at the Geological Survey and Mines Department in Entebbe. Since then the staff situation at Makerere has changed, after completion of almost half a dozen Ph. D. theses. Although a postgraduate diploma course in geology was already established in 1972 at Makerere, this programme was dormant for 20 years. It has recently been replaced by a M. Sc. Programme with course work, in which some students already graduated. A new building on the university campus for the Faculty of Science including the Department of Geology was provided through Japanese development cooperation in 1992 and helped to create a new physical infrastructure, thus probably contributing to a period of new initiatives. Presently there is only about 20-30%employment for graduates in geological jobs, which are offered by the government, parastatal organizations or in private industries.

At the University of Nairobi geology has the longest academic tradition in East Africa and over the years no major turmoil-affected teaching and research seriously. Although generally also short in funds a 4-year undergraduate programme has been regularly maintained. A Master of Science programme by coursework is normally offered for those who can afford the high costs. At the Department of Geology of the University of Nairobi most of the senior staff have been recruited from former students. The number of expatriates has been steadily reduced, only a few very specialized courses are sometimes offered under the scheme of development co-operation. A departmental newsletter with information about ongoing research activities is regularly issued.

The staff development programme at the University of Dar es Salaam took a slightly erratic course. Whereas there was in the seventies up to the mid-eighties a significant understaffing, the present condition is completely different. A well-funded development co-operation programme with Finland provided a new building for the Department of Geology on the university campus in 1985. Under the same scheme several junior staff members were assisted in completion of their Ph.D. thesis by studying in Finland. Simultaneously manpower support was also provided by German, British, Canadian, Australian and US government funds (scholarships for M. Sc. and Ph.D. candidates, expatriate contracts). Therefore now a comparatively small department with a regular undergraduate intake of about 20 students per year has presently an establishment of at least 12 Ph.D. holders - and further highly qualified members of staff are still expected after completion of their overseas studies. The University of Dar es Salaam funds come from the government and they are presently very limited, so it is rather difficult for individual members of staff to do independent research, especially when transport is needed in field oriented work. A Master of Science programme by coursework was introduced in 1988, but it can not be offered in every year mainly due to the high costs for potential candidates.

### Other Geoscientific Institutions

The Geological Surveys of the three East African countries maintained their status quo after independence. However, these during colonial times rather small but well-organized institutions now had a much lower scientific output than before. To a certain extent they turned into bureaucratic monsters since they absorbed almost all the jobless graduates of geology from the East African universities for which serious work was not available because funding by the respective governments became less and less. It did not help when the Geological Surveys were sometimes split of into new departments (e.g. Mining, Water, Petroleum), the number of employees increased, but the scientific and economic efficiency deteriorated because of the expanded administration, lack of funds and poor future prospects for the numerous staff members. The most prominent example is the already mentioned publication of geological maps, which almost ceased in the seventies and eighties and therefore left large parts of East Africa geologically uncovered (Fig. 10).

The small boom of exploitation of certain minerals during the early part of the twentieth century was followed by a sharp fall in production of them shortly after independence. The reasons were many, ranging from depletion of reserves, decrease in exploration activities and lack of investment; there were also political reasons. in Tanzania, the seventies, however, saw an increase in exploration activities following efforts by the Tanzanian government to revive the industry (Mutagwaba & Naiko, 1993). A government parastatal organization (the State Mining Corporation, STAMICO) was formed in 1973 to co-ordinate all mining activities in the country. As in many developing countries, efforts were put in to opening "large" (relatively speaking) mines, in the hope of earning the often-illusory foreign exchange and promoting development of an advanced industrial base. Whilst this saw an increase in a number of new mines being opened, several problems remained unsolved. One of the most obvious was the almost total collapse of the previously existing small-scale mining industry (Mutagwaba & Naiko, 1993).

### The Present State of Art in the African Context

The nineties, following the period of a so-called "lost decade" in the development of Africa, gradually provided a new approach to research: Since the departments of geology and the geological surveys of the East African countries had enough staff, they became also the partners with scientists from abroad who brought in diverse project proposals and the logistical support for them. Foreign donors involved in these activities are either from national universities or similar institutions in developed countries or from international organizations normally led by a team of outstanding scientists. "Geology for Development" was introduced as a major regional project during the UNESCO General Conference in 1980 and had the main objective to develop the knowledge of geological structures, mineral prospection and the exploitation of the mineral wealth of these countries. In the framework of "Geology for Development" the study of the Precambrian deposits was a major focus of research, because its various stratigraphic, structural, petrographic and exploration aspects, as well as its simultaneous effects of strengthening the intellectual and institutional capacities of the countries concerned, have a direct impact on the economic welfare of African countries.

Goals were set out for the education and training of African geologists on international training courses organized by UNESCO and funds for fieldwork with international participation were provided for work on "geotraverses". The latter aim incorporates multidisciplinary surveys through narrow corridors across two or three geological belts. It allows both demonstration and application of various research techniques and is especially suitable for the training of local geologists as well as for correlating the results achieved in different countries.

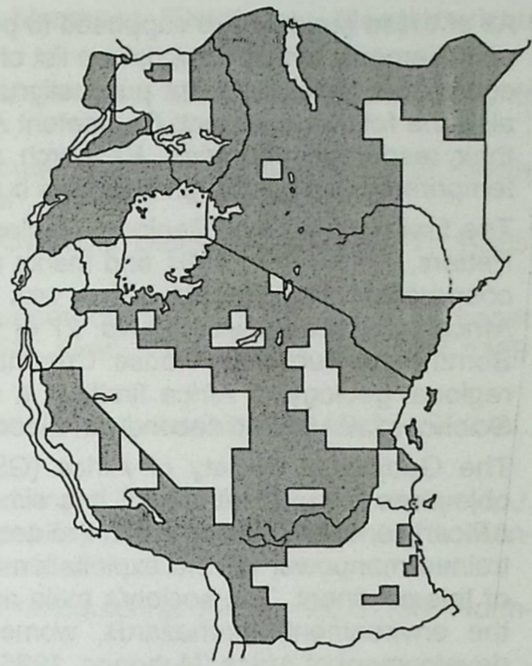


**Fig. 10:** Geological mapping coverage of East Africa (Kenya, Tanzania and Uganda), as completed and published in 1997. Maps were published in different scales, predominantly 1 : 125,000 for Kenya and Tanzania, and 1:100,000 for Uganda. However, some additional surveys and more detailed maps also exist.

Strengthening the infrastructure of African institutions, improving mutual scientific information, developing laboratory research in domestic laboratories and promoting collaboration with laboratories in developed countries are other milestones for which "Geology for sustainable Development", as the project has been renamed in 1990, is aimed to serve.

The international Geological Correlation Programme (IGCP) is co-sponsored by UNESCO and IUGS (International Union of Geological Sciences), the latter being a non-governmental, non-political and non-profit-making voluntary professional scientific association. IGCP has been operating since 1972 and aims to redefine and calibrate methods used in correlating geological relationships and events, to analyze the processes involved in major mountain-building orogenies, and to understand the formation and occurrence of mineral deposits in relation to such episodes. Among the approximately 400 research projects that have been sponsored from 1972-2000 under the auspices of IGCP, within the last fifteen years the following were of special relevance to East Africa:

**No. 227:** Magmatism and Evolution of Extensional Regions of the African Plate (Project Leaders: A. B. Kampunzu and R. T. Lubala, 1985-1989).

**No. 255:** Kibaran Metallogeny (Project Leaders: W. Pohl, J. Klerkx, D. P. M. Hadoto and A. Ntungicimpaye, 1987-1991).

**No. 273:** The Archaean Rocks of the Kasai Craton (Project Leaders: B. T. Rumvegeri and D. Kampunzu, 1988-1992).

**No. 302:** The Structure and Metallogenesis of Central African Late Proterozoic Belts (Project Leaders: M. Wendorff and W. M. Katekesha, 1990-1994).

**No. 348:** High-Grade Metamorphic Terranes in East Africa (Project Leaders: S. Muhongo and S. Berhe, 1992-1996).

**No. 363:** Palaeoproterozoic of Sub-Equatorial Africa (Project Leader: S. Master, 1996-1998).

**No. 413:** Understanding Future Dryland Changes from Past Dynamics (Project Leaders: D. Thomas and A. K. Singhvi, 1998-2002).

**No. 418:** Kibaran Events in Southwestern Africa (Project Leaders: R. M. Key and R. Mapeo, 1997-2001).

**No. 419:** Foreland Basins of the Neoproterozoic Belts in Central-to-Southern Africa and South America (Project Leaders: M. Wendorff and P. L. Binda, 1998-2002).

**No. 431:** African Pollen Database (Project Leaders: A. M. Lezine and A. Sowunmi, 1998-2002).

All of these projects are supposed to produce during their time of duration documentation of their achievements which comprises a list of actively participating countries, field meetings, workshops, conferences etc., relevant publications and the final report on the project. The projects indicate also the following aspect: Competent African geologists are aware of the geological problems in their respective countries. Research and the resulting publications are not only produced by temporarily visiting foreign scientists but now also by members of the local scientific community.

The first book on the "Regional Geology of Africa", written by the Nigerian geologist Sunday W. Petters, came out in 1991 and marks another milestone in the scientific achievements of mutual cooperation. The present author was able to publish in 1997 a book on the "Geology of East Africa", which appeared as No. 27 of the series "Beiträge zur regionalen Geologie der Erde" of Borntraeger Publishing House. Currently another project is aimed to compile the stratigraphy and regional geology of Africa firstly in a series of keynote articles in the Journal of African Earth Sciences (JEAS) and secondly in a book under the guidance of H. Kampunzu, Gaborone.

The Geological Society of Africa (GSA), which was already founded in 1973, has its main objectives recently redefined: It is aimed to promote the understanding of earth sciences in the African continent, and to assist the decision makers of African countries in the acquisition of well-trained manpower for the exploitation and sustainable management of the geological resources of this continent. The society's main activities shall concentrate on water, mineral raw materials, the environment, geohazards, women and earth science education for the socioeconomic development of Africa (Muhongo, 1996).

Although the mineral industry, at present, is practically insignificant to the economy of the three East African countries (mineral earning as percentage of GDP in Kenya: about 1%, in Tanzania less than 0.3% and in Uganda less than 0.1% in 1995), the interest in the geology of these countries has steadily increased as it is shown by the number of publications per decade. Exact data are difficult to obtain, but at least for Kenya about 60 publications per year during the eighties appear to be realistic. A few less are probably recorded from Tanzania, whereas Uganda counts for approximately 10-20 per year. Therefore as already mentioned in the beginning, altogether about 7000 geological publications on the geology of East Africa are now known - still a diminutive number and indicating a wide field for future research activities.

A final comment on geological research carried out in East Africa: Although in a western sense geological research apart from the last two decades was almost entirely based on the work of foreigners who traveled ceaselessly through the region and made their observations, it should also be pointed out that the indigenous people living there had their own ideas about the origin and formation of the landscape that sometimes sound like geological legends. For example, the Chagga people who have lived in the foothills of Mt. Kilimanjaro for over 200 years explain the history of the vast dome of the Kibo (5895 m) and the nearby smaller but jagged skeleton of the Mawenzi (5149 m) with the following story: One day Kibo was approached by Mawenzi. "Good day, friend, the fire in my heart has gone out". Mawenzi, having received fire and some bananas, carried them off, only to return, saying his fire had gone out again. After three gifts of fire and bananas Kibo lost patience and so beat up Mawenzi so that his battered profile still bears the marks of Kibo's pestle. That folk-lore has preserved a memory of Kibo's last puff of ash (about 200 years ago) is not unlikely, since the geological facts are strong enough.

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ISBN 3-86544-136-X

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