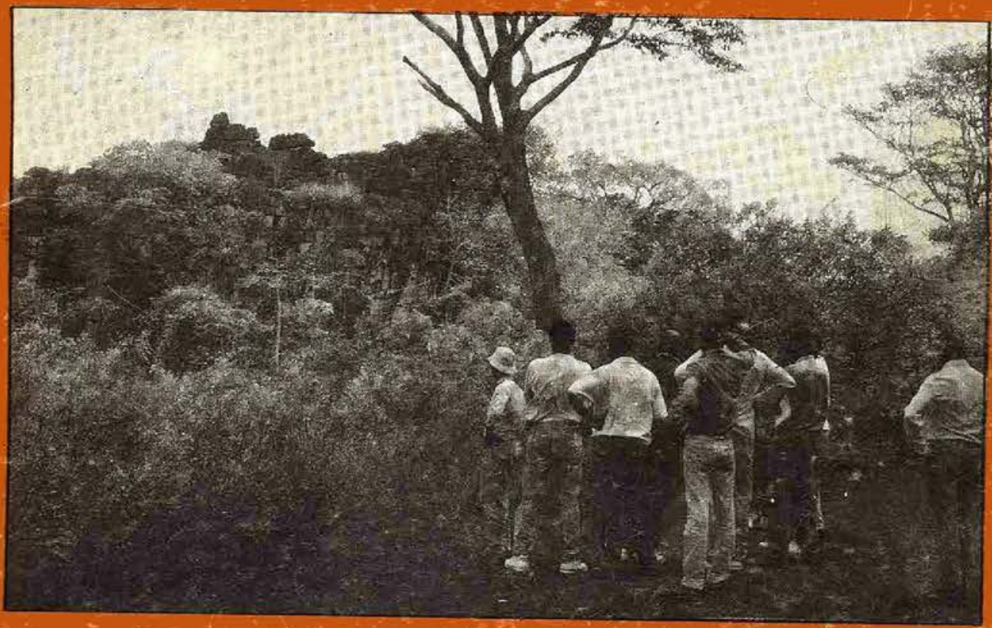
Proceedings of the Fifth Conference on the Geology of Kenya

on

# GEOLOGY FOR SUSTAINABLE DEVELOPMENT



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Edited By: Dr. Norbert Opiyo-Akech

# GEOLOGICAL SOCIETY OF KENYA



## Proceedings of the Fifth Conference on the Geology of Kenya on GEOLOGY FOR SUSTAINABLE DEVELOPMENT

Edited By: Dr. Norbert Opiyo-Akech

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**CHAIRMAN WELCOMING ADDRESS**

Hon. John Sambu, Minister for Environment & Natural Resources,

Prof. F. J. Gichaga, Vice Chancellor, UON

Prof. S.O. Wandiga, DVC, (A&F)

Prof. O.K. Mutungi, DVC, (Academic)

Ambassador M. Okeyo, P.S. MENR

Prof. R.W. Mwangi, Acting Principal, CBPS & Dean, Faculty of Science.

Mr. Collins Owayo, Commissioner of Mines.

Distinguished guests

Distinguished conference participants

Ladies and gentleman

It is a special pleasure to me and the Executive Committee of the Geological Society of Kenya to welcome you to this Annual Conference. I am glad for this opportunity to express my gratitude to you for honouring us with your presence here.

It is a part of the embodiment of the constitution of the Geological Soceity of Kenya to arrange and promote discussions as well as exchange views on the state-of-the art in geology and allied professions in the forms of such conferences where papers are presented with the ultimate aim of contributing to the development of Kenya and the profession itself. Indeed the GSK considers such a conference to be one of the most important scientific activities for the future of mankind. We therefore hope that at this conference we shall continue to build upon past scientific achievements and set a pattern for the future while recognising that the geological sciences are now approaching a consistent comprehensive perception of mankind We therefore hope that at this conference we shall continue to build upon past scientific achievements and set a pattern for the future while recognising that the geological sciences are now approaching a consistent comprehensive perception of how the earth works.

We also recognise the complexity of the problems associated with development and the important role other sciences play in solving them. However, in a physical sense, our life is dependent on the use we make of the earth and its resources, and the geological sciences provide the key to understanding the many problems related to resource development and the preservation of environmental quality. In the light of these realities, my address will focus on:

**TOWARDS A SUSTAINABLE POLICY FOR MAXIMUM BENEFITS FROM THE GEOLOGICAL SCIENCES**

In discussing this theme, it is important to draw attention to some of the contributions the geological sciences have made and can make in solving problems associated with resource development. Coupled to this is the urgency to advance our knowledge of the potential national mineral resources. We have to appreciate this urgency in realization of the fact that Kenya's population will most likely hit 35 million by the year 2000. Such a population increase highlights the inescapable fact that we will progressively need more mineral fuel, geothermal and water resources in the yearsto come. And yet most of these resources are finite, at least within certain geographical confines. We must therefore put more concerted efforts in discovering new sources of minerals, water, geothermal and fuel resources, involving increased financial input and deployment of relevant qualified personnel. However, since increased exploitation of the resources has direct relation with utilization and environmental impact, we must therefore conduct our activities in an environmentally safe manner.

At the same time when confronted by these needs which cannot be long filled from present commercial sources, we cannot escape the crucial and urgent need to advance our knowledge about potential resources and our ability to discover them. We need to extend our exploration to the marine environment taking due advantage of the Convention on the Law of the Sea. We need to have inventory of the potential marine non-living resources within our national exclusive economic zone (EEZ).

At this point let me turn my attention to some of the ways in which geological sciences can contribute to the solution of our pressing needs and problems, realizing that one of the most urgent needs is for the development of additional supplies of minerals, mineral fuels, water and geothermal resources. These physical resources are essential for the industrial society. We need to recognise the various crucial roles that the different physical resources play in our life. For example industrial minerals play a very crucial role in our national development, yet there is a lack of an integrated policy on their exploitation and marketing. Allow me to say what is now almost a dictum; namely industrial minerals are the backbone of any national development programme, particularly in industrialization. However a sound exploitation of the physical resources, especially minerals must have a definite linkage between resources identification; prospecting and development; establishment of mines, and industries producing finished products. To make the linkage vibrant, the skills necessary at the various stages have to be judiciously blended. This also calls for Kenyans to be collaborative rather than be antagonistic in their professional endeavours, realizing that the ultimate goal is to maximise.the developmental achievements of Kenya.

We should therefore learn and accept that whatever is achieved within the various Kenyan institutions is positive and acceptable so long as it is for the benefit of this nation. Unfortunately, sometimes we have witnessed undesirable antagonisms or confidentiality in areas where the professionals should share knowledge and collaborate in achieving results.

Geological sciences have already played an important role in resource discoveries and development, but we must also admit that we are just beginning to develop capability to search effectively for mineral accumulations that are wholly concealed beneath the earth's surface. And we must also admit the paucity of detailed information on the geology of much of the subsurface. This is an area where a project like Kenya Rift International Seismic Project (KRISP) is of tremendous scientific value and should be strongly supported for its contribution to our better understanding of the subsurface geology in Kenya.

Another extremely important task for our geoscientists in the area of mineral resources is the appraisal of the magnitude of the potentiality of the physical resources. With our dependence on minerals, mineral fuels, geothermal and water resources, the consequences of failure to anticipate their shortages in time would be catastrophic. Indeed the problem of appraising potential resources is essentially dependent on the geological sciences as a service to mankind.

We may need to be reminded that the application of the geological sciences to construction and other engineering problems has a long history, however the future need in this area is enormous. It rises from three concerns. One is to reduce the cost of construction and other engineering works. The second is to reduce the hazards to mankind. And the third which is of tremendous concern today, is to maintain environmental quality. The application of geological knowledge in the appraisal of foundation conditions for engineering construction i.e. buildings, dams, highways, airports etc. can lead to significant savings in building and maintenance costs. Identifications of natural hazards; such as flood plains, seismically active areas potentially explosive volcanoes, global sea level rise, and potentially active landslides, can help prevent the terrible losses in life and property. Furthermore geological knowledge of the rocks at and beneath the surface provides the basis for determining the effects of liquid and solid waste disposal on the environment, especially groundwater supplies. Thus geological sciences in their present state are adequate to guide intelligent planning and decision making in many of our activities today.

Hon. Minister, in the foregoing I have outlined the challenges facing us today within the realm of the geological sciences. Our Kenyan geoscientists have strived to streamline their activities within the profession. We now have a Code of Professional Conduct which is enshrined in the total body of our constitution. The Kenyan geoscientists have gone further by proposing a Bill of Registration for professional geologists in order to regulate their activities and make them legally responsible for their actions. To this end Hon. Minister we require your support and assistance. The document for the Bill of Registration has been static in the Ministry of Environment and Natural Resources for a considerable length of time. Any professional worth his salt would agree wlth me that this Bill of Registration is a positive step in streamlining the activities of the professional geologists. It definitely cannot hurt anybody but to enhance development of the geological sciences in Kenya. We are therefore appealing to you to do all within your power to make this bill be enacted by Parliament. We are confident that you have the zeal and will to assist in the advancement of the geological sciences and the practising professionals in this field.

Again, I most heartily welcome you all to this conference

Thank you.

**Professor Isaac 0. Nyambok**
**CHAIRMAN, GEOLOGICAL SOCIETY OF KENYA**

## WELCOMING SPEECH BY PROF. F.G. GICHAGA, VICE-CHANCELLOR, UNIVERSITY OF NAIROBI

Hon J. Sambu - Minister for Environment and Natural Resources,

Ladies and gentlemen

It is my pleasure to welcome you to the University of Nairobi. We feel delighted that the University of Nairobi is associated with the hosting of this conference (Geological Society of Kenya (GSK) 93 5th Annual Conference on the Geology of Kenya).

Within the academic community of the University, it is our calling to promote the dissemination of knowledge and exchange of ideas. It is through such activities that we can facilitate the advancement of knowledge for the benefit of mankind, and in particular the development of our nation.

I note that the theme for this conference is "Geology for Sustainable Deve]opment". This is a very apt theme at times like these, when the world is faced with severe economic constraints. we need to look a new at our natural resources, and at the same time identify appropriate technologies which can increase output from the existing sources. Some of these challenges today require trans-disciplinary appproach and therefore scientists must increasingly talk. Our modern world is increasingly vulnerable to the vulgaries of nature, despite the more advanced technologies at our disposal.

It is important to consider the link between human action and the availability of natural resources, while also maintaining environmental quality. I am sure you are all aware that in order to have the sustainable development this link must be developed and nurtured.

Today policy makers and planners lack vital up-to-date and accurate information on the resources they manage. Planners, resource managers and policy makers require information on maps of critical habitat, soil types, population densities and projections, resource maps and hazard risk assessment. These are the kinds of challenges that you as geoscientists should provide answers to and we await the answers. As an engineer myself, I appreciate the interlink between our professions on the wise use of the earth and we should strive to strengthen it.

Hon. Minister, Mr. Chairman, with these remarks I wish to welcome all the participants in this conference to the University of Nairobi.

**PROF. F.G. GICHAGA,**
**VICE-CHANCELLOR, UNIVERSITY OF NAIROBI**

**ADDRESS BY HON. J.K. SAMBU, MP.,
MINISTER FOR ENVIRONMENT AND NATURAL RESOURCES.**

Mr. Chairman, Ladies and Gentlemen; I am happy to be with you here today during this occasion of the 5th Conference on the Geology of Kenya. I am aware that two of my predecessors have participated in the past conferences and I am therefore glad to continue the good trend they had set.

I understand that some of the contributors to this conference have come from outside our country. To them, I would like to extend a very warm welcome and a happy time during their stay in Kenya.

Ladies and Gentlemen, I note that the theme of the Conference is "Geology for Sustainable Development". This is indeed very appropriate for programmes aimed at economic development of the country.

I note that the geological sciences have made significant contributions to the solution of problems associated with the resource development. Bearing in mind that Kenya has definite national policies regarding the development of geological resources to enhance the economic and social advancement of its people, I am quite gratified to see that geologists of this nation are committed to finding solutions to achieve these national goals.

I believe that the theme of this conference calls for a concerted systematic search for and identification of geological resources which, among others, include minerals and fuels of value in the earth's crust, water and constructional materials; geologically stable sites for major structures as well as finding solutions to environmental problems including the provision of foreknowledge of some of the dangers associated with geological phenomena and natural hazards such as landslides, earthquakes, volcanic eruptions etc.

As a matter of fact, environmental geoscience should now become a very important subject as the world's attention is fully focused on conservation of the environment.

As you are aware, the Rio Earth Summit held in June 1992 made developmental funding contingent upon environmental conservation. Environmental conservation must now be incorporated in and form an integral part of any development project. I am, however, pleased to understand that your profession at the international level had recognized the pivotal role of the enviromnent and as a result launched the Co-Geoenvironment as far back as 1990. The Chairman of this body addressed the Rio Summit on its activities. We believe that your Society nationally will collaborate in any researches in this area so that any benefits will also acrue to the country.

More locally, the public and particularly the business community engaged in mineral and quarry rock extraction must be made aware, as part of geological advise and resource assessment, of the need to restore the surface of the land disturbed by its activities by progressively filling up and levelling excavations and planting restored surface with trees as they continue to extract and abandon exhausted areas, instead of leaving this to the very end of their beneficial operations when the costs of doing so would be exhorbitant.

Ladies and Gentlemen, the point I want to put to you is that your knowledge as professionals must be made available to our people and it has to be made available in simple language and at a cost our small-scale miners can afford.

There are mutual benefits to both parties. Increased mineral resources activities will mean more work for geologists.

Mr. Chairman, Ladies and Gentlemen, I know that apart from a few mineral resources such as common salt from the sea and trona from Lake Magadi, the majority of mineral deposits are non-renewable and are therefore liable to depletion. The rate of depletion of mineral resources depends on utilization management which, in turn, depends on how well the society understands the need for proper management of the resource.

Arising out of this fact, the geologists and other geoscientists therefore, have, a great task in not only discovering new sources of these materials but also of educating the public on the best and most economical ways of using them.

It must, therefore, I believe, be very interesting and encouraging to the mining industry and to the sectors that are involved with and consume minerals and other products of mining and indeed all other geological concerns, that a conference of this nature has been organized.

Since this is only the 5th Conference, it is my hope that you will continue with others in future.

However, much more important is how you can disseminate your deliberations, findings and the outcome of your individual and collective efforts to the consumer who will use them in his operations on the ground for the benefit of our nation.

Mr. Chairman, I understand that the Geological Society of Kenya currently has a membership of 205 and that it is growing at a rate of about 20 geologists per year, graduating from universities mainly from the University of Nairobi. This is a healthy and encouraging development, given that we are only at the end of our 3rd decade of independence and that at the time of independence in 1963, there were no Kenyan geologists.

I would wish to link this growth of indigenous professional development with the mineral development of our country - a responsibility bestowed on my Ministry through the Mines and Geological Department.

In 1963 at the dawn of independence, mineral production in the country was valued at about Kenya Pounds 2.5 million. Ten years later, in 1973, the production rose to Kenya Pounds 3.8 million.

Presently, 30 years after independence, the production has shot up to a value of over Kenya Pounds 50 million. This shows a tremendous growth in mineral resource activity which, now that there are so many geoscientists in the country, should not only be maintained but improved upon significantly.

I may also add here that, while at independence the emphasis was on metalliferous mineral products, the tpend has now shifted considerably towards industrial non-metallic minerals not only in Kenya but throughout the world.

As you have noted earlier, Mr. Chairman, thaL industrial minerals are the backbone of any national industrial development plan, your geoscientists must put the required emphasis on the development of our industrial mineral resources.

Small scale miners, usually engaged in production of industrial minerals, should therefore get professional know-how from geologists not only to improve on the efficiency of the industry and the quality of the commodities produced but also, as I have mentioned before, on the conservation of the environment and restoration of degraded lands.

Mr. Chairman, on the question of the Bill of Registration of Geologists as raised by the geologists, I wish to inform you that the draft Bill is now with the Attorney Generals's Chambers. After it has been examined, we shall take it to Cabinet for necessary approval, and, final drafting and publication into a Government Bill will follow thereafter. When enacted, the Law will enable the maintainance fo high standards in the profession and the nation will expect even better performance from the profession.

You, the geoscientists who are gathered here today and those who will be joining your society in later years must, therefore, work hard and prove your worth to the nation by producing positive results in your respective areas of research.

I take this opportunity to congratulate and thank the organisers and contributors to this conference and to wish the conference a thorough success.

**Ladies and Gentlemen, I now declare the 5th Conference on the Geology of Kenya formally open.**

Thank You.

**HON. J.K. SAMBU, M.P.,**
**MINISTER FOR ENVIRONMENT AND NATURAL RESOURCES**

**Statement fron UNESCO**

Thank you for inviting UNESCO to this conference.

Our Regional Office for Science and Technology for Africa(ROSTA) supports in its regular budget three major programmes:

1. The International Geological Correlation Proramme(IGCP);

2. Geology for environmentally sound development;

3. Natural Disaster Reduction;

Since the funds in the regular programme are very limited, it is the task of the Member States to create projects and submit them to Donor Agencies for funding. From the African Region the following project proposals have been submitted to UNDP for funding:

1. The establishment of a seismological network in Eastern and Southern Africa;

2. The establishment of a geological network in Eastern and Southern Africa for the environmentally-sound development of their mineral resources;

I hope this conference will encourage you to come up with some proposals in the field of high priorites (Environment, hydrogeology) and I wish you full success.

**Dr. H. Dreissle, Specialist in Earth Sciences.,**
**Nairobi, February 1993**

**Possible Contributions of Geology towards resolving/mitigating environmental problems.**

By Gerhart Schneider, UNEP

Mr. Chairman, Ladies and Gentlemen, I want to greet you on behalf of the United Nations Environment Programme.

Why is this conference relevant to the work we are doing at UNEP?

What contributions can be expected from Geologists when it comes to protection of natural resources?

One area within geology is of especial interest to us: Hydrogeology, the science dealing with groundwater. Groundwater is a crucial resource all over the world, and threatened by many human activities (Table 1).

Table 1 GROUNDWATER: Threats to its Quality/Availability

| | |
|---|---|
| I Agriculture | Fertilizers (Nitrate, Phosphate)<br>Manure (Nitrate, Phosphate)<br>Pesticides (org. chemicals/metabolites) |
| II Industry | Accidental spillages<br>Wide array of chemicals/heavy metals |
| III Landfills | Domestic/ind. wastes: heavy metals, wide range of org. chemicals,<br>microbial pathogens |
| IV Overdraft (various uses) | Intrusion of saltwater (coastal zones, arid and semi-arid areas),<br>'Mining' of fossil resources, especially problematic in shared aquifers |
| V Mining | Lowering of groundwater table, oxygenization of previously reduced material, release of toxic materials from heaps of overburden + tailings, (petro-) chemicals |

Apart from fertilizers, pesticides, industrial chemicals (including petrol products), groundwater quality often is threatened by overdraft: This is a peculiar problem in arid and semi-arid areas, and also in coastal zones. Usually saltwater intrusion, either from brackish aquifers or from the ocean, occurs, rendering the resource unusable. Sustainable use of groundwater can only be achieved by quite precisely calculating the rates of recharge, and adjusting the withdrawal accordingly. Such calculations and assessments can only be provided by (hydro-)geologists.

A tricky problem is the use of groundwater resources shared by different sovereign states. This, for instance is the case in the Arab Peninsula, where several quifers underly the areas of different states. Another example is the Nubian Sandstone Aquifer in North Africa, which is currently being developed by Libya. Those developments of shared aquifers, sometimes containing fossil water which is not being replenished, can bring neighbouring countries in serious conflict with each other. It is within UNEP's mandate to assist the concerned governments in settling conflicts about shared water resources, and it is only Geologists and especially Hydrogeologists who can deliver necessary baseline data for finding viable solutions.

Another hydrogeological phenomenon with important repercussions is the intrusion of saltwater into coastal aquifers, already a serious problem in many coastal areas. However, experts expect it to become even worse in the future, due to the expected climate change (and locally rising sea levels). For UNEP, 'Climate Change' issues as well as environmentally sound management of coastal areas have received high priority.

Another issue, closely related with geology as well as with environmental problems, is mining:

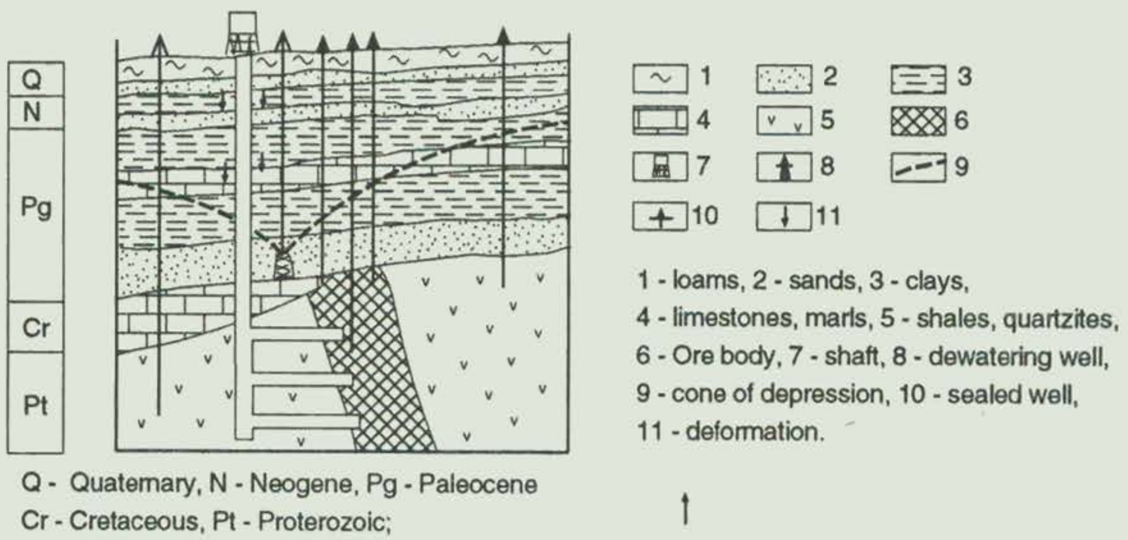


Figure 1: Schematic profile of a mine. (Redrawn from Mining and the Geoenvironment, Vol. II. UNEP/UNESCO 1991)

Figure 1 shows a schematic drawing of a mine. The mineral resource (ore body) is covered by several layers of tertiary sediments. In order to be mined, the area around the ore body has to be dewatered. The effects of this mine drainage, also schematically drawn and indicating only long-term trends, are shown in figure 2:

Development of the so-called cone of depression of the groundwater table possibly in a large area, leading to reduced spring flow, small river flow, and well yield, thereby negatively affecting other users in the region. Due to oxygenization of previously reduced material the mine drainage becomes more and more mineralized (and often more and more acid, if the reduced material is sulfidic). The question now is where this mine drainage water is pumped to, and whether it is treated. If just pumped into the nearest river, its water quality will deteriorate more and more.

Also the heaps of overburden, tailings, and other materials stored at the mining site can release toxic materials into the environment. Mining areas also can create problems of land subsidence, inflicting damage to buildings and infrastructure.

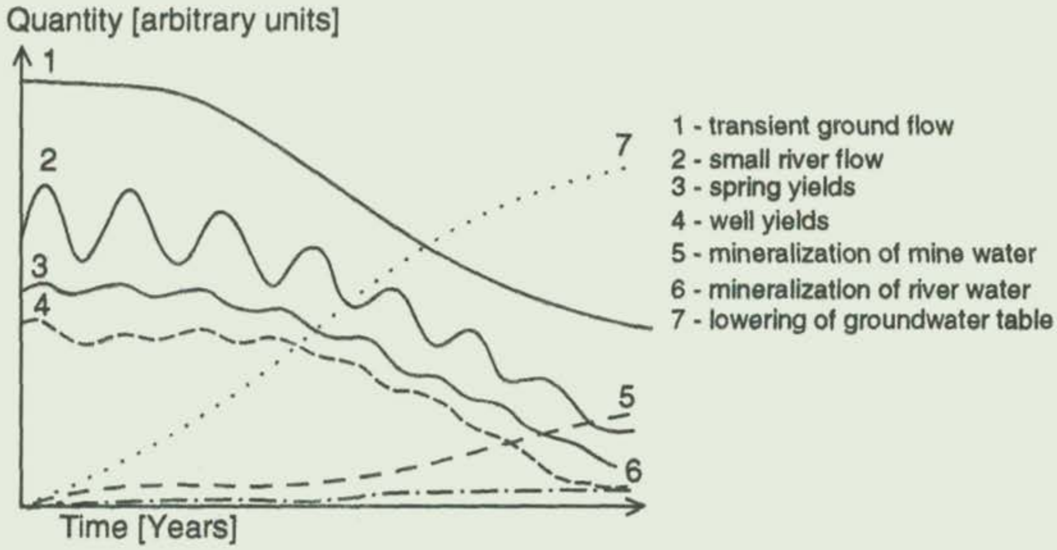


Figure 2: Long-Term Hydrological Effects of a Mine (Redrawn from Mining and the Geoenvironment, Vol. II. UNEP/UNESCO 1991)

In conclusion, tackling those environmental problems touched upon briefly (and certainly many more which were not mentioned) is only possible with the scientific advice and assessments provided by geologists. For this reason UNEP has taken a strong interest in this conference organized by the Geological Society of Kenya, and agreed to support the publication of the conference proceedings. We also want to draw your attention to the sample of recent UNEP/UNESCO publications in the field of 'Geology and Environment' exhibited here which might be of interest to you.

We wish you a fruitful conference, and hopefully this will become a regular annual event. Thank you.

# DISTRIBUTION OF ELEMENTS IN MINERAL-PAIRS FROM MOZAMBIQUE BELT ROCKS OF MATUU AREA, CENTRAL KENYA

S.J. Gaciri[1], R. Altherr[2], C.M. Nyamai[1] and E.M. Mathu[1]

[1]Dept. of Geology, University of Nairobi, Box 30197, Nairobi, Kenya
[2]Institute of Petrography and Geochemistry, University of Karlsruhe

**ABSTRACT**

*The composition of several mineral-pairs have been analysed using the camebax SX-50 microprobe with the aim of determining mineral phase stability and assemblage in gneisses from the Matuu area of Central Kenya. Garnet-biotite, garnet-clinopyroxene, amphibole-clinopyroxene and amphibole-biotite mineral pairs have been analysed for their bulk chemistries. Each mineral pair approaches chemical equilibrium and defines composition in which either the fluid content is nearly constant or the compositional range is narrow. The biotite in the gneisses show a narrow compositional range from Mg/Mg + Fe = 0.32 to 0.43. This is consistent with the assemblage amphibole + biotite + garnet. This amphibole calculated from the ($Fe^{+3}/Fe^{2+} + Fe^{3+}$) atomic ratio appears reasonable for hornblende while the clinopyroxene shows diopside composition. The garnet composition is almandine suggesting medium grade metamorphism for the gneisses.*

## INTRODUCTION

The Matuu area, located about 60 km north-east of Nairobi, Figure 1, is situated along the Thika to Garissa highway, and lies approximately at the intersection of latitude 1°10'S ; and longitude 37°30'E. It is predominantly underlain by rocks of the Pan-African Mozambique belt in central Kenya, which in this area, vary from medium to high grade gneisses and granulites, to intrusive granites, anorthosites, diorites and gabbros. The early geological works in the area, which date as far back as the last century, have been well documented by Fairburn (1963). Later works in the area by Biyajima et al. (1975), Mathu and Tole (1984), and Mathu et al. (1991), have mainly highlighted the complex geology, structures and tectonics of the area, with little or no emphasis on its metamorphism as based on the available geothermometers and geobarometers.

Studies on the metamorphism of the Kenyan Mozambique belt, have largely been based on petrography of the mineral phases. Very limited work has therefore been done on the quantification of the more precise original metamorphic conditions of this belt based on probe analyses of its geothermometers and geobarometers. Suwa et al. (1979) obtained temperatures of about 500 to 700°C in the Mbooni-Uvete area of Machakos district through petrographic studies. Later Miyake and Suwa (1985) carried out a probe analyses on the metamorphic conditions of these Mozambique belt rocks in the Mbooni-Uvete area, Machakos district and obtained more precise temperature (T°C) and pressure (P kbars) values of 540 + 40°C and 6.5 + 0.5 k bar respectively. The Mbooni-Uvete area lies approximately along the same longitude and metamorphic isograd as the Matuu area and it is of interest therefore to compare the metamorphic variations along this isograd. The aim of this paper therefore is to determine the more precise P/T values of metamorphism for the Mozambique belt rocks in Matuu and other adjoining areas as this also has a bearing on their economic implications. For example, a lot of garnets have been noted in the area but their gem quality value is largely controlled by both the metamorphic conditions and other factors. Furthermore, it is only through such studies that the entire gem and industrial mineral potential of this belt will be fully realized.

## GEOLOGICAL SETTING

### Petrology and Petrography

The major geological rock units identified in the study area (see Fig. 1) are the biotite gneiss, granitoid gneisses, hornblende gneiss, gabbroic and porphyritic granites.

Aerially, the biotite gneisses are the most widespread rocks in the study area. In outcrop, the biotite gneisses are medium to coarse grained, mesocratic and well foliated with colour banding or mineralogical layering of feldspar and opaque minerals. Localised occurrence of garnet and/or sillimanite bearing biotite gneisses particularly along the shear zones have been mapped under this rock unit. Petrographically, the rock consists of plagioclase ($An_{22-24}$), orthoclase, microline, quartz, biotite, sillimanite, garnet and accessory ilmenite and muscovite. Also noted to occur within this rock unit are amphibole-bearing mafic enclaves (disrupted dykes?) which have biotite-rich margins, suggesting that small-scale mobility of alkalies and fluid phases took place during metamorphism.

The mafic hornblende gneiss is a minor but widespread component, with the largest mass occurring at the NE section of the study area. The rock consists essentially of hornblende and plagioclase, (i.e. is amphibolite); pyroxene is also present locally. In other instances, granoblastic mafic amphibolite gneiss occurs as narrow discontinuous bands within quartzo-feldspathic gneisses. The bands probably represent metamorphosed and deformed mafic dykes. Hornblende, andesine, biotite and epidote are the typical minerals, with clinopyroxene and rare garnet occurring locally.

Granitoid plutons in the study area represented by the granitoid gneisses, gabbroic and porphyritic granites which cover about 30% of the total survey area. Their relative voluminous occurrence in this area demonstrate the importance of crustal accretion (for anatexis) during the Mozambique orogeny as demonstrated clearly by Suwa et al. (1979) in Machakos area, central

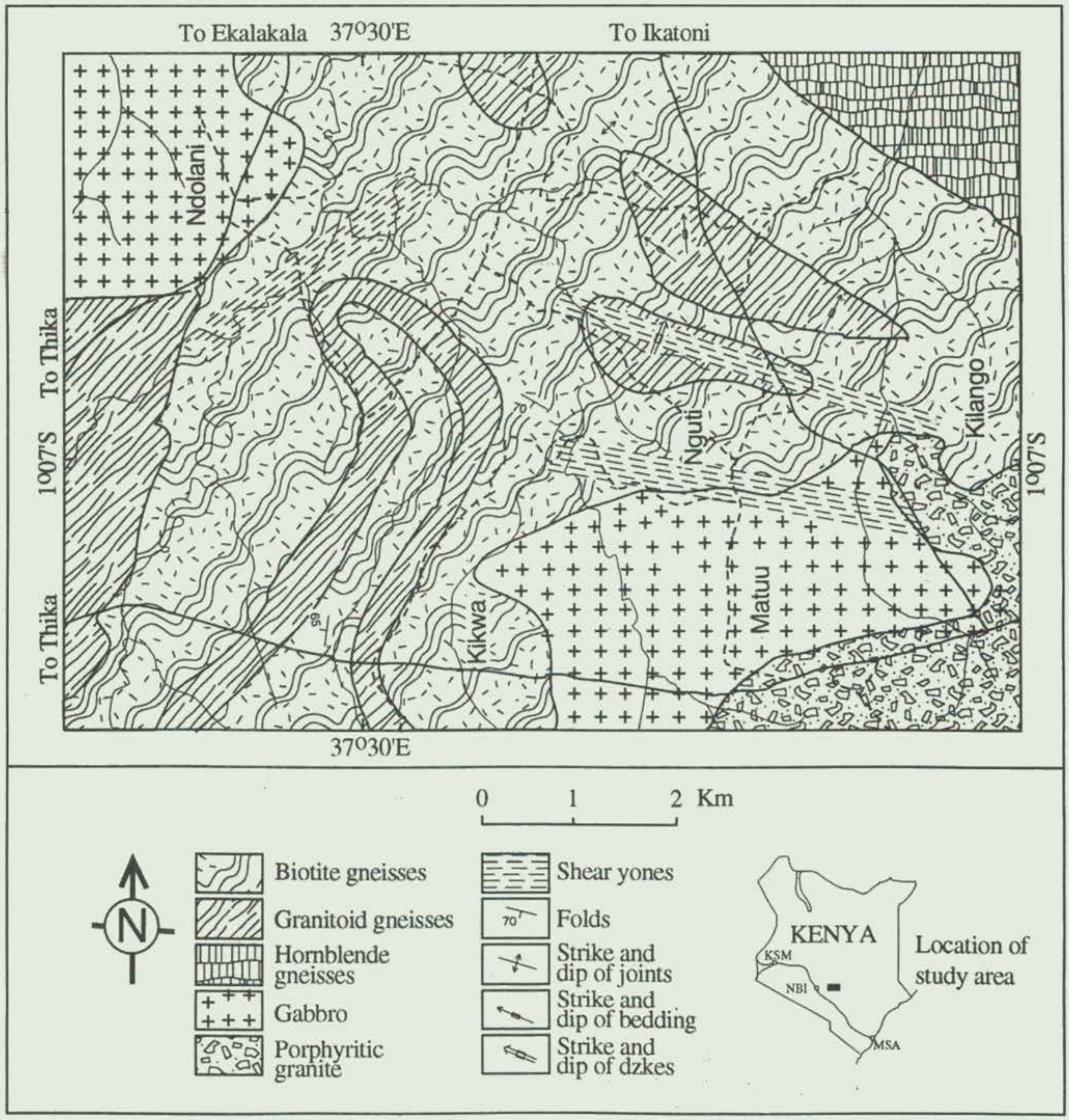


Figure 1. Map showing the location (inset) and the Geology of the study area.

Kenya. The granitoid gneiss is an equigranular, medium to coarse grained with faint foliation nature. It consists essentially of quartz, microcline, plagioclase, biotite, and sometimes muscovite and hastingsitic amphibole, with minor amounts of apatite, epidote, sphene, zircon and opaque minerals. Antiperthite and perthite textures are common.

The coarse grained porphyritic granite consists of potassium-feldpar porphyroblasts studded in a medium grained matrix of quartz, plagioclase, microcline, biotite, epidote and muscovite with minor amounts of apatite, sphene, zircon, calcite and opaque minerals.

Surface outcrops of the gabbroic rocks in the study area were relatively rare and this rock unit was mapped largely by inferences based on soil types. Field evidence showed that the black-cotton clayey soils were underlain by the gabbroic rock. The two major gabbroic representative plutons noted in the survey area occur slightly north of Matuu town and Ndalani area. The rock is medium grained, melanocratic and consists essentially of pyroxene, calcic plagioclase and hornblende.

**Structures**

The general structural trend in the area varies from NNW-SSE to NW-SE direction with localised concentric trends around granitoid intrusions. The dip is predominantly to the west with angles varying from 50° to the vertical. The mineral lineations are mostly parallel to the regional structural trend. The foliations are well pronounced in the hornblende and biotite gneisses and vary in degrees on the outcrop scale with mafic and felsic bands of 3 to 5 cm thickness to small scale segregational banding in hand specimen.

On an outcrop scale, isoclinal, open and overturned folds are a common feature in the survey area. The observed cleavage patterns and boudins along with thinning of incompetent layers suggest severe strains to have affected the area. The orientations of the isoclinal fold axial planes suggest compressive forces acting on a south westerly direction. Three generations of microfolds $F_1$, $F_2$, and $F_3$ were noted to occur in the study area with $F_2$ being more prominent. These structures suggest a complex tectonic history of the region with at least three phases of deformation.

Mafic dykes, mainly of gabbroic composition occur sporadically in the study area. In particular, a dyke swarm around Kilango school average about 200 m in width (with individual dyke thickness ranging from 0.3-3.0 m) and trends in N20°W direction with a vertical dip. A number of shear zone occur in the study area. A major characteristic of these shear zones is the intimate occurrence of the almandine garnet porphyroblasts with growth concentrated along the biotite rich layers. Competent mafic lensoidal layers that have undergone ductile deformation and associated with rotated boudins and displaced micro-faults define a dextral sense of shear.

### Metamorphism

The occurrence of the mineral assemblages quartz-muscovite-sillimanite-biotite-garnet and the hornblende-plagioclase-pyroxene-garnet with some of the rock units in the study area give an insight of the P/T conditions that affected the area. Clearly, the high grade amphibolite and locally granulite facies appears to have their imprints in the survey area. This high grade metamorphism is further alluded to by the poor preservation of relict structures, abundant microfolds and the intensity of the shear zones.

## ANALYTICAL METHOD

The minerals were analysed on polished thin section, with a CAMEBAX SX50 electron microprobe (Institute of Petrography and Geochemistry, University of Karlsruhe). The probe has four wavelength dispersive spectrometers with accelerating voltage of 15 KV. The spot analyses were about 2-3 um in diameter with the electron beam at 1 um in diameter. The area for re-integration was about 50 um x 50 um. The data were collected on an electron probe micronanalyser using an online data reduction system currently in use at the University of Karlsruhe.

## MINERAL CHEMISTRY AND ASSEMBLAGES

Detailed analysis of bulk composition and of co-existing mineral associations have been utilized for petrological interpretation so as to understand the history, conditions and timing. For example micas are useful indicators of phases of metamorphic rocks which contain them while chlorites can be very helpful in understanding the metamorphic history of an area.

### Amphiboles

The composition of amphiboles is consistently calcic. The structural formulas based on 23 oxygens and 15 cations are presented in Table 1. The resulting $Fe^{3+}/Fe^{2+} + Fe^{3+}$ atomic ratios are reasonable for hornblende structure while the Si cations range from 6.15 to 6.71. The Ti content in the hornblende is comparatively lower than in the co-existing biotites but nevertheless the degree of metamorphism appears to be amphibolite facies. The (Ca, Na, K) exceeds the theoretical maximum of 2.000 cations per formula unit. Na invariably exceeds K in all the samples analysed.

| | Table 1. Rep. Amphiboles. | | | Table 2. Rep. Biotites | | | |
|---|---|---|---|---|---|---|---|
| | 50 | 58 | 64 | GB1 | 58 | 64 | 85 |
| $SiO_2$ | 46.24 | 43.39 | 40.00 | 35.77 | 35.55 | 35.47 | 36.51 |
| $TiO_2$ | 0.72 | 1.64 | 0.78 | 2.33 | 5.38 | 2.30 | 3.33 |
| $Al_2O_3$ | 8.88 | 10.27 | 12.28 | 17.48 | 14.02 | 15.60 | 18.39 |
| $Cr_2O_3$ | 0.04 | 0.06 | 0.02 | 0.01 | 0.06 | 0.01 | 0.03 |
| $Fe_2O_3$ | 2.82 | 4.90 | 6.71 | 3.13 | 3.39 | 3.53 | 2.76 |
| FeO | 11.96 | 13.15 | 15.53 | 15.95 | 17.29 | 18.00 | 14.06 |
| MnO | 0.25 | 0.28 | 0.51 | 0.03 | 0.09 | 0.37 | 0.10 |
| MgO | 12.61 | 10.32 | 7.38 | 10.82 | 10.64 | 10.48 | 9.66 |
| CaO | 12.45 | 11.61 | 11.65 | 0.08 | 0.03 | 0.08 | 0.12 |
| $Na_2O$ | 1.08 | 1.35 | 1.36 | 0.13 | 0.13 | 0.11 | 0.19 |
| $K_2O$ | 1.08 | 1.12 | 1.36 | 9.32 | 9.46 | 9.24 | 9.32 |
| $H_2O$ | 2.02 | 2.01 | 1.95 | 3.96 | 3.94 | 3.90 | 3.99 |
| Total | 100.12 | 100.10 | 99.53 | 99.01 | 99.98 | 99.09 | 98.46 |
| Formulas based on 23 oxygens | | | | Formulas based on 11 oxygens | | | |
| O | 23 | 23 | 23 | 11 | 11 | 11 | 11 |
| Si | 6.745 | 6.473 | 6.151 | 2.711 | 2.706 | 2.727 | 2.747 |
| Ti | 0.081 | 0.185 | 0.090 | 0.133 | 0.308 | 0.133 | 0.189 |
| Al | 1.562 | 1.808 | 2.225 | 1.561 | 1.258 | 1.414 | 1.631 |
| Cr | 0.005 | 0.008 | 0.002 | 0.000 | 0.004 | 0.001 | 0.002 |
| $Fe^{3+}$ | 0.316 | 0.550 | 0.777 | 0.178 | 0.194 | 0.204 | 0.156 |
| $Fe^{2+}$ | 1.487 | 1.643 | 1.997 | 1.015 | 1.101 | 1.158 | 0.885 |
| Mn | 0.032 | 0.036 | 0.066 | 0.002 | 0.006 | 0.024 | 0.007 |
| Mg | 2.773 | 2.298 | 1.691 | 1.222 | 1.208 | 1.202 | 1.083 |
| Ca | 2.029 | 1.858 | 1.919 | 0.006 | 0.003 | 0.006 | 0.010 |
| Na | 0.313 | 0.391 | 0.407 | 0.020 | 0.019 | 0.017 | 0.027 |
| K | 0.200 | 0.214 | 0.268 | 0.902 | 0.918 | 0.906 | 0.895 |

### Biotite

The chemical compositions of biotites are given on Table 2. The Mg/Mg + Fe ratio varies from 0.47 to 0.51 while the Si; Al ratio is around 2.20:1. This composition is consistent with biotites in meta-granitic rocks (Hoshino, 1986). The Ti content of the biotites is indicative of high grade rocks. The composition on assemblage is from garnet + biotite + muscovite to biotite + amphibole + orthopyroxene.

## Pyroxenes

Pyroxenes are calculated on the basis of six oxygens and four cations Table 3. Present in samples 47Z and 50 are clinopyroxenes of diopside composition. The orthopyroxene is richer in iron and magnesium and is indicative of hypersthene. The orthopyroxene has a higher Fe/Mg ratio than the co-existing hornblende. The assemblage of the clinopyroxene are garnet + clinopyroxene and amphibole + clinopyroxene + epidote.

Table 3. Rep. Pyroxenes.

| | 47Z(cpx) | 50(cpx) | 58(opx) |
|---|---|---|---|
| $SiO_2$ | 47.95 | 52.11 | 50.54 |
| $TiO_2$ | 0.38 | 0.11 | 0.07 |
| $Al_2O_3$ | 4.71 | 1.61 | 0.45 |
| $Cr_2O_3$ | 0.02 | 0.01 | 0.03 |
| $Fe_2O_3$ | 5.45 | 3.06 | 1.00 |
| FeO | 7.79 | 6.35 | 30.73 |
| MnO | 0.69 | 0.31 | 1.37 |
| MgO | 9.10 | 12.44 | 15.54 |
| CaO | 23.74 | 23.93 | 0.47 |
| $Na_2O$ | 0.56 | 0.63 | 0.02 |
| $K_2O$ | 0.01 | 0.01 | 0.01 |
| $H_2O$ | 0.00 | 0.00 | 0.00 |
| Total | 100.40 | 100.57 | 99.82 |
| Formulas based on 6 oxygens | | | |
| O | 6 | 6 | 6 |
| Si | 1.826 | 1.942 | 1.973 |
| Ti | 0.011 | 0.003 | 0.002 |
| Al | 0.211 | 0.070 | 0.021 |
| Cr | 0.000 | 0.000 | 0.001 |
| $Fe^{3+}$ | 0.156 | 0.086 | 0.029 |
| $Fe^{2+}$ | 0.248 | 0.198 | 1.003 |
| Mn | 0.022 | 0.10 | 0.045 |
| Mg | 0.515 | 0.691 | 0.904 |
| Ca | 0.968 | 0.956 | 0.002 |
| Na | 0.041 | 0.045 | 0.001 |
| K | 0.000 | 0.000 | 0.000 |

Table 4. Rep. Garnets

| | GB1 | 47Z | 85 |
|---|---|---|---|
| $SiO_2$ | 36.44 | 37.58 | 36.75 |
| $TiO_2$ | 0.01 | 0.36 | 0.02 |
| $Al_2O_3$ | 20.95 | 16.19 | 21.11 |
| $Cr_2O_3$ | 0.01 | 0.02 | 0.03 |
| $Fe_2O_3$ | 2.14 | 9.72 | 1.59 |
| FeO | 35.33 | 4.26 | 31.37 |
| MnO | 1.85 | 2.59 | 5.50 |
| MgO | 3.06 | 0.51 | 2.91 |
| CaO | 0.66 | 29.18 | 1.02 |
| $Na_2O$ | 0.01 | 0.01 | 0.05 |
| $K_2O$ | 0.02 | 0.01 | 0.02 |
| $H_2O$ | 0.00 | 0.00 | 0.00 |
| Total | 100.48 | 100.43 | 100.34 |
| Formulas based on 12 oxygens | | | |
| O | 12 | 12 | 12 |
| Si | 2.940 | 2.945 | 2.954 |
| Ti | 0.000 | 0.021 | 0.001 |
| Al | 1.992 | 1.496 | 2.001 |
| Cr | 0.001 | 0.001 | 0.002 |
| $Fe^{3+}$ | 0.130 | 0.567 | 0.088 |
| $Fe^{2+}$ | 2.384 | 0.279 | 2.108 |
| Mn | 0.125 | 0.172 | 0.379 |
| Mg | 0.367 | 0.059 | 0.361 |
| Ca | 0.057 | 2.450 | 0.088 |
| Na | 0.002 | 0.002 | 0.007 |
| K | 0.002 | 0.000 | 0.002 |

## Garnets

The garnets analyses are calculated on the basis of 12 oxygens as shown in Table 4. The garnets that are in the assemblage of garnet + biotite have the composition of almandine while the garnets in the garnet clinopyroxene assemblage is glossularite. The distribution coefficient $K_{D2}$ = (Fe/Mg) gar/ = 0.440 and agrees with the (Fe/Mg)cpx exchange reaction Mg-garnet + Fe-clinopyroxene = Fe-garnet + Mg-clinopyroxene. Other mineral phases during the analyses include epidote, sphene, magnetite, ilmenite, apatite, and plagioclase. Of these epidote gives phases of hornblende + clinopyroxene + epidote.

The temperatures and pressures of metamorphism of the Matuu rocks as estimated from the co-existing mineral phases are consistent with amphibolite facies. A similar behaviour has been noticed by Stephenson (1977) in Western Australia. The estimated temperatures are between 550° and 880°C while pressures are between 2 and 10 kb.

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# GOLD MINERALIZATION IN THE KARROO SYSTEM OF KENYA

F.R. MURUGA
Mines and Geological Depart., MENR, P.O.Box 30009, Nairobi

**ABSTRACT.**

*This report gives an account of gold occurrence in the sedimentary rocks of the Kenya Coast Province which is underlain by the Permo-Triassic sandstone formations of Taru, Maji ya Chumvi, Mariakani and Mazeras collectively known as Duruma sandstones of the Karroo System. Of the four formations its only the Maji ya Chumvi one which has visible fossils mainly confined in what is preferably called the Fish bed of the formation. Extensive geological mapping has been conducted in the zone lying between Sabaki River and the southern tip of Vanga in the Republic of Kenya. North of the Sabaki River the terrain is underlain by thick sediments of quarternary and recent ages and the detailed geological exploration presently conducted there is by the oil exploration companies. Thus the zone south of Sabaki River which comprises Kilifi and Kwale administrative districts is the area which has been more closely examined in detail and has been found to contain various minerals of economic importance comprising lead, zinc and barytes. At present mining in the coastal Karroo system is found in Kilifi District at Vitengeni, Bamba and Kinagoni. In Kwale District mining of barytes has been attempted at Lunga Lunga but the grade did not encourage further mining.*
*Sighting of a gold speck on Jombo Hill in South Coast was reported in 1893 but this has not been followed by anything more sifnificant. Some of the manganese ore from Mrima Hill in South Coast has yielded 0.5 dwts.*
*Recent mineral exploration by the Mines and Geological Department has located some areas in the coastal region with interesting gold geochemical anomalies some of which are associated with quartz veins in the sandstones. The department is conducting more work in the south coast for the precious metal and the related minerals.*

## INTRODUCTION.

The sandstone formations of the Karroo System in the coastal region of Kenya have been found to have concentrations of minerals of economic significance such as manganese and sulphides comprising galena, pyrite and sphalerite. Sulphates of barium and calcium have also been found in association with the metal sulphides with barytes being mined at various localities. Rare earth oxides together with niobium are moderately concentrated in residual soils from Mrima Hill carbonatite plug. Of the precious metals it is only silver which has been reported as recovered as a by product of the lead extraction of galena mined at Kinangoni of Kilifi District. The same mineral association of the sulphides is expected in the sandstone formation.

## GEOLOGICAL SETTING

The Kenya coastal strip approximately 65km wide is underlain by predominantly palaeozoic and mesozoic sedimentary formations of the Karroo System. To the west of the sedimentary formations, the Pre-Cambrian Mozambiquian system forms a fault contact. The PreCambrian system comprises schists, gneisses, quartzites, charnokites and crystalline limestones. The sedimentary formations of the Karroo System in Kenya are four: namely-Taru, Maji ya Chumvi Mariakani and Mazeras. The four formations are Permo-Triassic in age and each of them has its own unique characteristic features.

The Taru Formation is a coarse grained arkosic sandstone of Permo-Carboniferous age. The Maji ya Chumvi Formation is composed of beds of fine-grained silstones and shales. The fish bed of the Maji ya Chumvi formation is the one mainly fossiliferous with fish fossils and it is also in the same bed that mineralization traces of copper, lead and barytes has been found

The Mariakani Formation as at Kokotoni, is usually massive and fine-grained characterized by mottling. The formation is mainly arkosic with quartz, feldspar and mica. Unlike the Maji ya Chumvi no mineralization has been reported in both Mariakani and Taru formations. Fossil wood has been found in some parts of the Mariakani Formation but it is possible that the erosion of the younger Mazeras Formation left behind the fossils.

The Mazeras Formation is characterized by silicified fossil wood. The Mazeras Formation is composed of quartz and feldspar grains coarser than those in both Mariakani and Maji ya Chumvi Formations but less coarse than those grains that compose the Taru Formation. Unlike the other three formations the Mazeras Formation has had more tectonic changes which have been accompanied by faulting and hydrothermal mineralization.

The four formations of the Karroo System are conformable to each other and their mode of deposition was variably marine, shallow water, lacustrine to fluvio-deltaic.

To the east, the Mazeras formation is unconformably overlain by the jurassic Kambe limestones which in turn is overlain by recent formations of shales, sands and coral limestones.

Coast parallel faults are extensively developed in the directions of NNE-SSW to NE-SW with the major ones bordering the Mazeras Formation and the Kambe Formation for a long distance along the coast. Cross cutting the major coast parallel faults, minor faults and fractures in other trends are also well developed and most of them are younger than the major parallel faults.

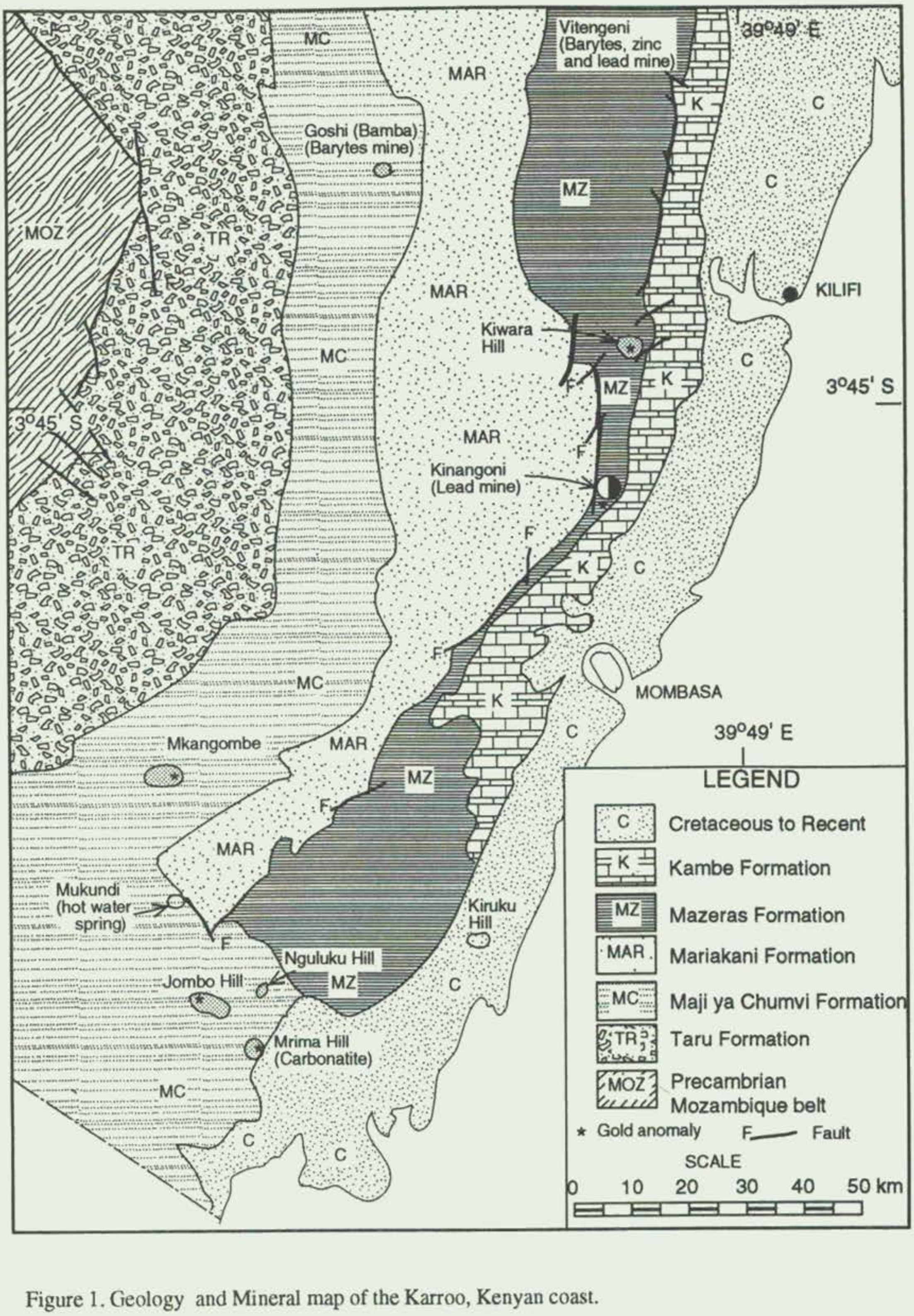



Figure 1. Geology and Mineral map of the Karroo, Kenyan coast.

Intrusives in the Palaeozoic and Mesozoic sediments of the area are few in number which include the alkaline complex of Jombo Hill and the carbonatite intrusion of the Mrima Hill. Both Mrima and Jombo Hills are located in the South Coast where basic dykes form satellites of the Jombo alkaline intrusion.

The mineralization of lead, zinc, barytes in the Karroo System represented by Kinangoni, Vitengeni, Lungalunga and Bamba appears to be controlled by the fault structures treading NNE-SSW to NESW. Similarly related to the faults are the major geochemical anomalies in mainly the Maji ya Chumvi and the Mazeras Formations.

The Permo-Triassic sedimentary formations of the Kenya Coast are correlated to the Karroo system of Southern Africa but the Kenyan formations are of much finer grains in general than their equivalent rocks in other parts of the African Karroo trough.

## GOLD IN THE PERMO-TRINSSIC FORMATIONS.

### Jombo Hill

In the coast region of Kenya a gold speck was found at Jombo Hill in 1893 (Geological Survey of Kenya Report No. 24). This finding never raised anything more than just historical interest. Jombo Hill is an alkaline intrusion in the Maji ya Chumvi sandstones in the south coast. It is strange, however, that a gold speck should be found in the alkaline complex where no other minerals have been found yet but there may be quartz veins in the hill which have not been identified which may have introduced the gold speck in the area.

In 1990, 20 soil samples for geochemical analysis were collected from 20 different localities on Jombo Hill for which trace gold was determined. The samples were prepared by nitric-aqua-regia digestion method and gold was determined by Fire Assay-Neutron Activation Analysis (FA-NAA). The analytical results showed that the gold content was less than 5 parts per billion in each of the samples. The geochemical results of the gold do not give any hope of finding gold mineralization in the Jombo Alkaline complex and it is not possible to pin-point the source location of the gold speck as its map grid-reference is not available.

### Mrima Hill

Mrima Hill situated also in the South Coast is a good mineral prospect with manganese, iron ore, radioactive minerals, niobium and rare earth elements. Some of the manganese ore from the hill has yielded 0.8gm per ton. The hill is a carbonatite intrusive in the Maji ya Chumvi Formation. In 1990 soil 20 samples were collected from the hill and determined for trace gold in the same way as for Jombo Hill. The gold content here proved to be higher than in the alkaline complex with a maximum concentration of 64ppb. The rest of the samples had concentrations of 45ppb, 13 and less than 6ppb. Since Mrima Hill has a large host of different minerals it may at one time attract mining of at least one of the minerals and in the course of it gold will have more exploration done on it. The area of Mrima Hill may be extended to include Kiruku and Nguluku Hills which are close to one another and have also shown strong geochemical anomalies of the precious metal.

### Mkangombe Area

In the same year, soil geochemical sampling was conducted over a small area called Mkangombe lying to the west of Kinango town. The area is within the Maji ya Chumvi Formation and it is intruded with a quartz vein treading north east south west. Associated with the vein on the surface are galena crystals, malachite, chalcopyrite and azurite. forty soil samples were collected from the area and were analyzed in the same way as for Mrima and Jombo Hills. The highest gold content from the analytical results was 407ppb from one sample whereas the other samples ranged in content from less than 4ppb to 2Oppb. With the quartz vein any high gold geochemical concentration may be expected. A Mines and Geological Department diamond drill core from the area at a depth of 60 metres showed a presence of a band approximately two metres thick with massive sphalerite, chalcopyrite, quartz and pyrite. It will be interesting to know the chemical gold content of the core samples after laboratory tests.

The surface trace of the quartz vein is about 5 kilometres long continuously and where the vein is not projecting out of the ground it is represented by quartz float strewn all over.

### Kinangoni Area

Kinangoni area is known for lead mining for the last twenty years. In the year 1990 forty soil samples were collected from the area and on chemical analysis it was found that the trace gold content varied between 3Oppb and lppb. The Kinangoni lead mine is in the Mazeras Formation in North Coast and it has a hydrothermal mineralization within a fault that separates the two formations of Mazeras and Kambe limestone. The same faulting continues northwards to Vitengeni where another mining is conducted for barytes, lead and Zinc.

## CONCLUSIONS

The four areas Jombo Hill, Mrima Hill, Mkangombe and Kinangoni were selected for mineral exploration in 1990 as they were known to have surface indications of mineralization and eventually turned out to have polymetallic anomalies. During the survey of 1990 the soil samples collected were 120 and nearly 30% of them indicated less than lppb. According to the frequency distribution of gold values 100, 20 and 4ppb were chosen for the threshold to differentiate anomalous Au values. The gold values above 20ppb were regarded as distinctively anomalous and those between 4 and 20ppb as possibly anomalous. Only three samples indicated outstandingly high values: 30,64 and 407ppb from Kinangoni, Mrima Hill and Mkang'ombe respectively.

With continued mineral exploration there is a possibility of locating economic concentrations of gold in association with quartz veins and the sulphide mineralizations commonly found in the sandstone formations of the Kenya Karroo system. In the event of locating economic gold mineralization in the coastal region comparative notes will be made on the gold bearing greenstone belt of Western Kenya and the gold bear Mozambiquian belt in West Pokot District.

# MICROCOMPUTER BASED ANALYSIS OF ELECTROMAGNETIC PROFILING DATA FROM TROPICAL GEOLOGICAL ENVIRONMENTS

J. O. Barongo
Department of Geology, University of Nairobi. P.O.Box 30197, Nairobi

## ABSTRACT

*Traditionally, electromagnetic data collected along a profile for the purpose of detecting mineral conductors in the ground have been interpreted manually with the use of characteristic curves prepared mostly from laboratory scale modelling. With the advent of microcomputers and recent availability of solutions to electromagnetic problems that have been difficult to find, it is possible to carry out interpretation faster and more accurately on a personal computer without resorting to manual techniques. Data obtained over tropical weathered terrains can also be computationally handled with the use of suitably designed filters to reduce the effect of weathering.*

*In this paper, procedures on how to interpret horizontal loop electromagnetic (HLEM) data from tropical weathered environments using Fourier transformation and damped least squares inversion are presented. It is found that results obtained through these techniques are superior to those obtained through manual procedures.*

## INTRODUCTION

The horizontal loop electromagnetic method (HLEM) is one of the most effective geophysical methods used to explore for conductive mineral deposits, particularly massive sulphides. The method is known by this name because the loop transmitting the primary or 'source' electromagnetic field is held horizontally during field operation. Similarly, the loop used to receive the secondary electromagnetic field induced in the underground conductor is also held horizontally. The instrument utilising these two loops is operated along traverse lines (the survey grid) established over the mineralised terrain. The data obtained are hence referred to as 'electromagnetic profiling data'.

For a period of more than three decades since the development of the HLEM method, explorationists have used and continue to use characteristic curves developed largely from laboratory scale modelling to interpret HLEM data. This practice has persisted for that length of time because such curves are easier to obtain, especially in simple cases such as conductive plate models in free space, in the laboratory than through numerical computations. However, great efforts in geophysical research have now made it possible to obtain solutions to Maxwell's equations for at least simple electromagnetic models such as 'thin conducting plate in free space' (e.g., Annan, 1974). In this regard, the program PLATE for calculating the free air electromagnetic response of a thin conducting plate which was documented by Dyck et al. (1980) using algorithms developed by Annan (1974) is now widely used to calculate the theoretical electromagnetic response of a conducting thin plate model simulating an ore deposit (e.g. massive sulphide) embedded in a non-conducting host rock.

In this study, use was made of the program PLATE to generate synthetic electromagnetic profiling data over a thin conducting plate model in free space. Interpretation of these data using Fourier transformation and inversion methodologies is described. Application to data taken from tropical geological environments is demonstrated.

## INTERPRETATION USING CHARACTERISTIC CURVES

Figure 1(a) shows a simple diagram to illustrate the electromagnetic coupling between a transmitter loop, an underground conductor and a receiver loop. The underground conductor which may be a mineral deposit is embedded in a non-conducting host rock but beneath a conductive weathered layer. This conductor has no physical contact with the layer. Figure 1(b) illustrates the HLEM response profiles along traverse lines over the mineralised terrain. The conductor trace shown in the figure coincides with the negative maximum amplitudes of the response profiles. Figure 2 shows the characteristic curves known as 'phasor diagrams' (Grant and West, 1965) commonly used to interpret the depth and quality (i.e., conductivity-thickness product) of the underground conductor. The interpretation procedure which is well documented in Barongo (1987) is to measure the negative maximum amplitudes of the in-phase (real) and out-of-phase or quadrature (imaginary) components of the response profiles and to plot them on one of the 'phasor diagrams' corresponding to the 'approximate' dip. To be able to find the 'approximate' dip, one has to use other geophysical means such as the vertical loop electromagnetic (VLEM) method (Grant and West, 1965; Telford et al., 1990) or drilling. This is one of the great disadvantages of this procedure. From the plotted point, one can calculate the depth and conductivity-thickness product of the underground conductor.

## FOURIER TRANSFORMATION METHOD

This technique involves transforming data from its time or space domain to the frequency or wave-number domain and then carrying out the analysis in the new domain. The results are obtained in the old domain. The procedure is analogous to that of performing multiplication or division of numbers in the logarithm domain and expressing results in the standard domain through a simple anti-logarithm operation. The general scheme

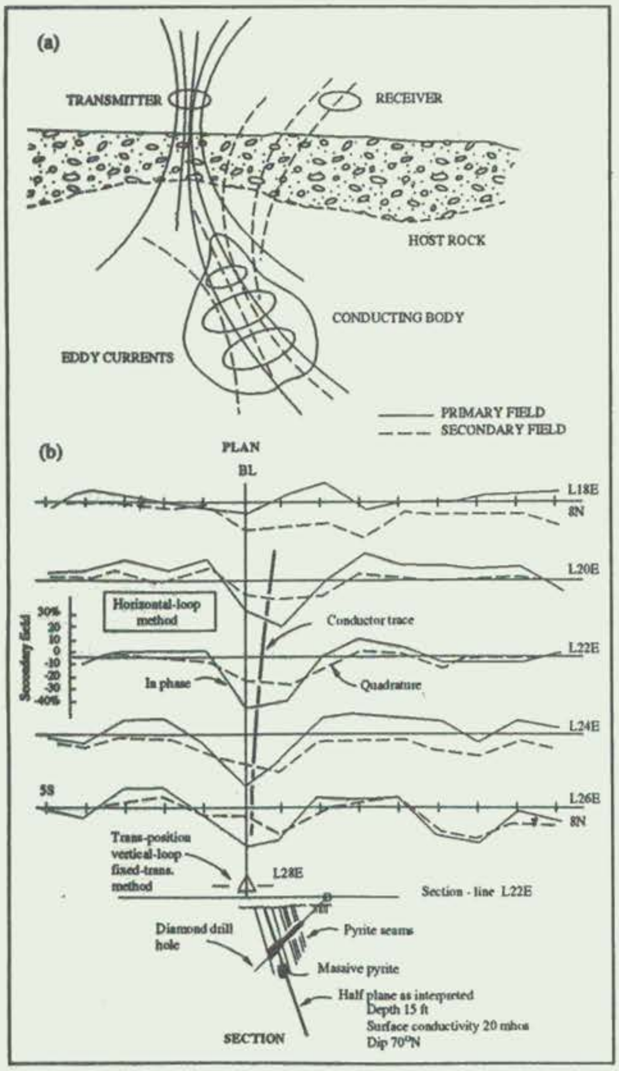



Figure1. (a) Electromagnetic coupling between a transmitter loop, an underground conductor and a receiver, and (b) HLEM responseprofile over mineralised terrain.

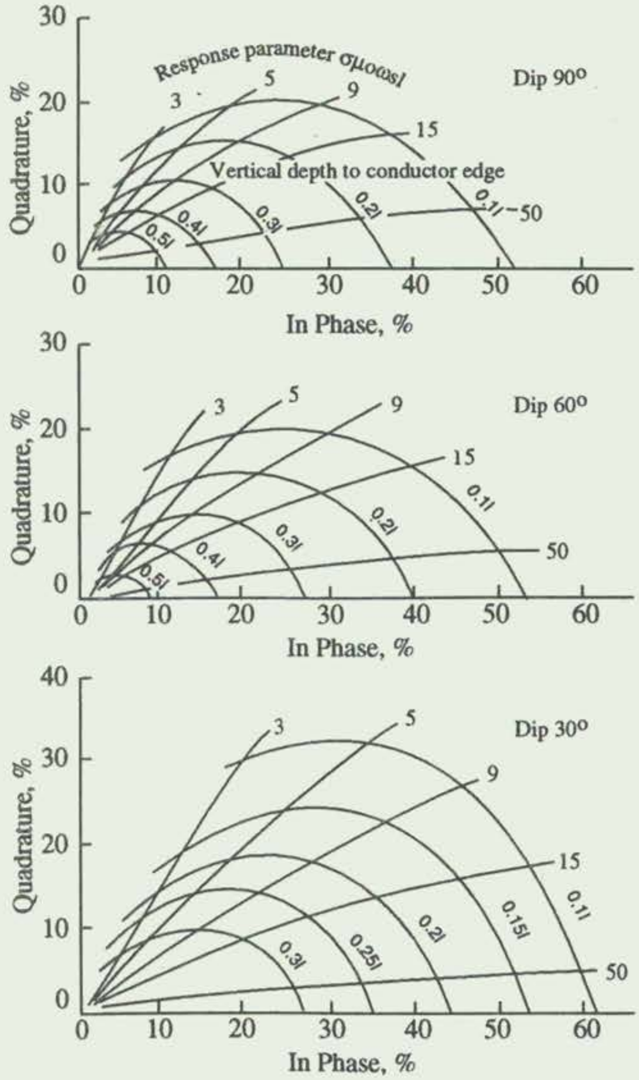
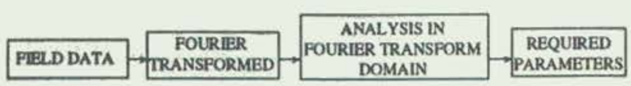



Figure 2. Phasor diagrams (after Grant and West, 1965)

of Fourier transformation is as follows:-




FUNCTION

f(x)

FOURIER TRANSFORM

$$f(k_x) = \int_{-\infty}^{\infty} f(x)\, e^{-ik_x x}\, dx$$

where

$k_x$ = wave number
= 1/profile length

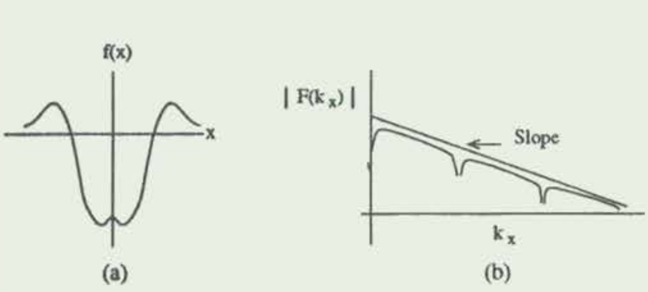


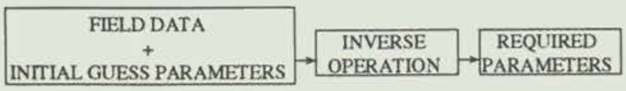

Figure. 3. Electromagnetic response of a long current-carrying wire (a) and its Fourier transform (b).

To determine the values of the required parameters such as depth to the top edge, dip and conductivity-thickness product of the underground conductor through the Fourier transformation method, an analytic function of a model simulating a thin conducting plate in free space must first be used. This is so because it is through the Fourier transform of the analytic solution that such parameters can be explicitly expressed in the wave number domain. After such expressions have been obtained, it is then possible to apply them directly to the plate model as well as field data. In this study, the electromagnetic response of a long conducting wire model in free space carrying an electric current was used to simulate that of a thin plate model (Telford et al., 1990). It is not possible to derive the theoretical response of such a plate analytically. Annan (1974) obtained a numerical solution. The simulation makes use of the assumption that a thin conducting plate of long strike and depth extents in free space which has an electric current induced in it by an alternating magnetic field has that current concentrated along its top edge.

Figures 3(a) and 3(b) show the electromagnetic response of such a wire and the corresponding Fourier transform of that response, respectively. From the analysis of the Fourier transform, the slope of the graph directly gives the depth to the wire (or, in the case of thin plate, depth to its top edge). The conductivity-thickness product can be obtained through nomograms developed in the wave number domain. Although it is not possible to find a way of determing the dip of a thin plate-like conductor through the wire model, it is, however, be possible to do so through nomograms developed from the Fourier transform of the numerical solution of the plate model.

## DAMPED LEAST SQUARES INVERSION

The least squares inversion technique is a direct method of analysing data using standard methods of numerical analysis. It is similar to that of solving a system of simultaneous equations. The scheme is as follows:-




Consider a system of simultaneous equations:

$$
\begin{array}{l}
ax_1 + bx_1^2 + cx_1^3 + \ldots\ldots\ldots\ldots + kx_1^n = y_1 \\
ax_2 + bx_2^2 + cx_2^3 + \ldots\ldots\ldots\ldots + kx_2^n = y_2 \\
\quad\vdots \\
ax_m \;\; bx_m^2 \;\; cx_m^3 + \ldots\ldots\ldots\ldots + kx_m^n = y_m
\end{array}
\qquad (1)
$$

In matrix form, this system of equations becomes

$$
\begin{bmatrix}
x_1 + x_1^2 + x_1^3 + \ldots\ldots\ldots\ldots + x_1^n \\
x_2 + x_2^2 + x_2^3 + \ldots\ldots\ldots\ldots + x_2^n \\
\vdots \\
x_m \;\; bx_m^2 \;\; x_m^3 + \ldots\ldots\ldots\ldots + x_m^n
\end{bmatrix}
\begin{bmatrix} a \\ b \\ \vdots \\ k \end{bmatrix}
=
\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}
\qquad (2)
$$

If we denote the matrix elements in the first and second matrices on the left hand side of (2) by **A** and **p**, respectively and that on the right hand side by **d**, we have

$$[\mathbf{A}][\mathbf{p}] = [\mathbf{d}] \qquad (3)$$

where **[A]** and **[d]** are known while **[p]** is unkown. To solve for the unkown matrix **[p]**, (3) can be written as

$$[\mathbf{p}] = [\mathbf{A}]^{-1}[\mathbf{d}] \qquad (4)$$

Methods of solving (4) for simple linear cases are well documented in standard texts on numerical analysis (e.g., Forsythe et al., 1977). Unfortunately, most geophysical problems involve equations that are non-linear. Therefore, in order to apply ordinary linear inversion algorithms to such problems, their non-linear functionals must first be linearised about parameters for which the solution is sought. This is normally done through Taylor's series expansion (Barongo, 1989). In this case, matrix **A**, also known as 'Jacobian matrix', has as its elements the derivatives of the model data with respect to parameters to be solved. Since **A**, in most cases, may not be square, it may not be possible to compute its inverse $\mathbf{A}^{-1}$. This inverse must be changed to the following form:

$$(\mathbf{A}^T\mathbf{A})^{-1} \qquad (5)$$

where $\mathbf{A}^T$ means transpose of **A**.

In all cases involving inversion of geophysical data, more generalised inverse operators, $(\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T$ for overdetermined problems (more data than unknown parameters) and $\mathbf{A}^T(\mathbf{A}^T\mathbf{A})^{-1}$ for underdetermined problems (less data than unknown parameters), are used. Since in the present study we are dealing with an overdetermined problem, (4) should be modified to

$$[\mathbf{p}] = [(\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T][\mathbf{d}] \qquad (6)$$

To stabilise the generalised inverse matrix $[(\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T]$ which is usually unstable, a constant value known as 'damping constant' or 'Marquardt parameter' (Marquardt, 1963) must be used to prevent division by the very small eigenvalues of the matrix that may arise. This type of inversion procedure is hence called 'damped least squares inversion' (see Barongo, 1989 for details). A FORTRAN program for carrying out least squares inversion of electromagnetic profiling data on an IBM compatible PC which can be applied to practical data was written. Initial guess parameters for depth, dip and conductivity-thickness product are used as input to the program and parameters representing the solution to the problem are obtained as output together with the statistical appraisal of the solution.

Table 1 demonstrates the type of results obtained using synthetic data of a wire model. In this case, initial guess parameters for depth, dip and conductivity-thickness product were 40 metres, and 0.35 Siemens per metre, respectively, and 20 metres,and 0.20 Siemens per metre were obtained as output. The output results were the actual parameters used to compute the theoretical response of the wire which was used in the inversion.

## EFFECT OF CONDUCTIVE WEATHERED LAYER

The effect of the conductive weathered layer on the electromagnetic field is to attenuate and rotatate the field (Parasnis, 1979). In other words, provided the underground conductor is not in galvanic contact with the weathered layer, the primary electromagnetic field reaching the conductor beneath the layer is weaker than at the transmitter. Also the secondary field reaching the receiver on or above the ground surface is weaker than at the conductor. Through the use of the computer, and in this case the microcomputer, it is possible to design filters to deconvolve this effect (e.g., Ferneyhough, 1985). While such filters have not been incorporated in this study, research is going on and will be incorporated in a future paper. Instead, the effect was handled, to a limited extent, manually.

Table 1. Inversion of HLEM data due to a horizontal wire

| ITERATION | MARQT CONST. | CHI-SQUARE VALUE | %RMS |
|---|---|---|---|
| 1 | .10E+04 | .18E+06 | .42E+02 |
| 2 | .10E+04 | .18E+06 | .42E+02 |
| 3 | .10E+03 | .17E+06 | .41E+02 |
| 4 | .10E+03 | .17E+06 | .41E+02 |
| 5 | .10E+02 | .12E+06 | .35E+02 |
| 6 | .10E+02 | .93E+05 | .30E+02 |
| 7 | .10E+01 | .54E+04 | .73E+01 |
| 8 | .10E+01 | .13E+04 | .36E+01 |
| 9 | .10E+00 | .13E+02 | .36E+00 |
| 10 | .10E+00 | .31E+00 | .56E-01 |
| 11 | .10E-01 | .92E-04 | .96E-03 |

CONVERGED WITHIN CHI-SQUARE TEST. END ITERATION

TRUE MODEL PARAMETERS USED TO GENERATE OBSERVED (SYNTHETIC) DATA

| PARAMETER | TRUE VALUE |
|---|---|
| 1 | 0.25 |
| 2 | 20.0 |

INITIAL GUESS MODEL PARAMETERS

| PARAMETER | INITIAL VALUE |
|---|---|
| 1 | 0.35 |
| 2 | 40.0 |

INVERSION MODEL PARAMETERS

| PARAMETER | INVERSION VALUE |
|---|---|
| 1 | 0.25 |
| 2 | 20.0 |

INVERSION MODEL PARAMETERS AND STATISTICS

| PARAMETER | FINAL SOLUTION | STANDARD DEVIATION | RESOLUTION |
|---|---|---|---|
| 1 | 0.25 | .11E-02 | .99E+00 |
| 1 | 20.0 | .11E-02 | .99E+00 |

PARAMETER CORRELATION MATRIX, LOWER LEFT HALF

| | | |
|---|---|---|
| 1 | 1.00 | |
| 2 | -.46 | 1.00 |
| | 1 | 2 |

FINAL MODEL DATA AND STATISTICS

| SPACING | OBSRVED DATA | CALCULATED DATA | ERROR | WEIGHTS | INFORMATION |
|---|---|---|---|---|---|
| -150. | 4.2 | 4.2 | .0 | .18E-02 | .10 |
| -140. | 4.9 | 4.9 | .0 | .24E-02 | .10 |
| -130. | 5.7 | 5.7 | .0 | .33E-02 | .10 |
| -120. | 6.8 | 6.8 | .0 | .47E-02 | .10 |
| -110. | 8.2 | 8.2 | .0 | .68E-02 | .10 |
| -100. | 10.1 | 10.1 | .0 | .10E-01 | .10 |
| -90. | 12.5 | 12.5 | .0 | .16E-01 | .12 |
| -80. | 15.4 | 15.4 | .0 | .24E-01 | .15 |
| -70. | 18.0 | 18.0 | .0 | .33E-01 | .24 |
| -60. | 15.7 | 15.7 | .0 | .25E-01 | .38 |
| -50. | 0 | 0 | .0 | .10E-17 | .00 |
| -40. | -18.8 | -18.8 | .0 | .36E-01 | .39 |
| -30. | -26.2 | -26.2 | .0 | .69E-01 | .25 |
| -20. | -27.1 | -27.1 | .0 | .74E-01 | .17 |
| -10. | -26.7 | -26.7 | .0 | .71E-01 | .14 |
| 0. | -26.5 | -26.5 | .0 | .70E-01 | .13 |
| 10. | -26.7 | -26.7 | .0 | .71E-01 | .14 |
| 20. | -27.1 | -27.1 | .0 | .74E-01 | .17 |
| 30. | -26.2 | -26.2 | .0 | .69E-01 | .25 |
| 40. | -18.9 | -18.9 | .0 | .36E-01 | .39 |
| 50. | 0 | 0 | .0 | .10E-17 | .00 |
| 60. | 15.7 | 15.7 | .0 | .25E-01 | .38 |
| 70. | 18.0 | 18.0 | .0 | .33E-01 | .24 |
| 80. | 15.4 | 15.4 | .0 | .24E-01 | .15 |
| 90. | 12.5 | 12.5 | .0 | .16E-01 | .12 |
| 100. | 10.1 | 10.1 | .0 | .10E-01 | .10 |
| 110. | 8.2 | 8.2 | .0 | .68E-02 | .10 |
| 120. | 6.8 | 6.8 | .0 | .47E-02 | .10 |
| 130. | 5.7 | 5.7 | .0 | .33E-02 | .10 |
| 140. | 4.9 | 4.9 | .0 | .24E-02 | .10 |
| 150. | 4.2 | 4.2 | .0 | .18E-02 | .10 |

FINAL SOLUTION EIGENVALUES

1.21 .74

## APPLICATION TO PRACTICAL DATA

In 1977, Terra Surveys Ltd. of Ottawa, Canada, conducted a combined magnetic and electromagnetic airborne survey in Western Kenya (Fig. 4) for the purpose of delineating underground conductors indicative of massive sulphides (Hetu, 1978). In 1978, the Kenya Mines and Geological Department started a ground follow up of the airborne anomalies using various geophysical instruments among which was the Apex MaxMin Horizontal Loop Electromagnetic (HLEM) System (Macharia and Barongo, 1982). Some of the HLEM anomalies obtained in that follow up were subjected to the interpretation techniques developed in this study. The results were obtained faster and were less ambiguous than those obtained through the conventional manual procedures. Figure 5 shows one of the field examples and the result obtained for depth using the Fourier transformation method.


Figure 4. Areas surveyed by Terra Surveys Ltd. of Canada, 1977

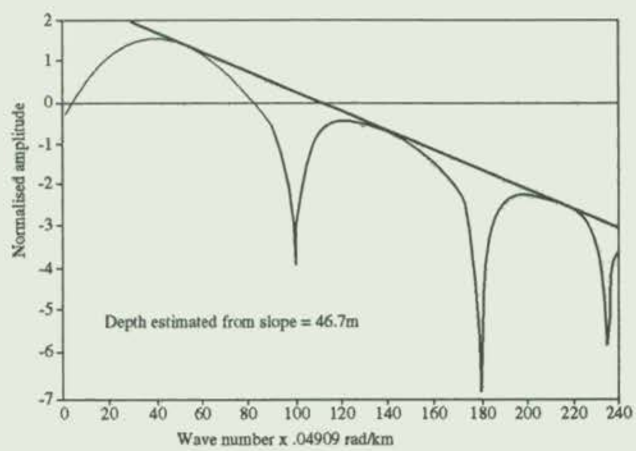



Figure 5. Depth results using the Fourier transformation method.

## CONCLUSION

The interpretation methodologies developed in this research when applied carefully should be a great contribution to the needs of the geophysical interpreter who would like to obtain results that are reliable faster. They should be able to improve the quality of interpretation and lead to a better and faster way of discoverying mineral deposits.

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# A 2D P-WAVE REFRACTION MODEL FOR THE CRUSTAL STRUCTURE BETWEEN LAKE TURKANA AND CHANLER'S FALLS BASED ON KRISP90 DATA


E. W. Dindi

Department of Geology, University of Nairobi, P.O.Box 30197, Nairobi.



**ABSTRACT**

*In this study, the high resolution refraction and wide-angle reflection data collected under the auspices of the Kenya Rift International Seismic Project in 1990 (KRISP90) were analysed and modelled to yield a P-wave velocity crustal model of the section between Lake Turkana and Chanler's Falls. Analysis of the data involved phase correlation and derivation of lD velocity depth functions for each shot and profile direction. These led to the initial model which was refined by 2D-ray tracing. Both phases and amplitudes were brought into agreement in the final 2D model and the corresponding synthetic seismograms computed. It is concluded from the study that the upper crust along this profile is heterogeneous with the section near Chanler's Falls exhibiting the strongest velocity gradients. The strong gradients could be due to intrusions of basic rocks in this section. The Moho shallows gently northwestwards from 35 km near Chanler's Falls to less than 29 km at the southeastern shore of Lake Turkana. The sub-Moho velocity of about 8.0 km/s obtained from the modelling suggests the existence of a cooled or normal mantle beneath the profile. This value contrasts remarkably with that of 7.5 km/s- 7.7 km/s reported along the axial zone of the Kenya Rift Valley and suggests that the abnormal mantle is confined to the Tertiary rift zone.*


## INTRODUCTION

In the months of January and February 1990 a high resolusion seismic refraction and wide-angle seismic reflection experiment was conducted in Kenya under the auspices of the Kenya Rift International Seismic Project, (KRISP90). The project was aimed at a detailed study of the shallow and deep structures of the Kenya Rift Valley and its flanks. The array used consisted of 5 profiles designated A, B, C, D and E (Fig. l). Profile E, trending at an oblique angle to the Kenya Rift Valley is the subject of the present study. The section studied is about 300 km long.

The geology indicates that the profile is located on metamorphic rocks of the Mozambiquan belt. Only in the first 30 km from shot point LTS are sediments and volcanics significant. The sediments are part of the lake sediments of the Lake Turkana and are estimated to be about 3 km thick (Dunkelmann, 1989). The volcanics belong the Tertiary age and occur as basalt flows and cinder cones. Sporadic occurrence of volcanics is also reported in the Laisamis (LAI) area (Hackmann, 1 986).

Four shot points namely Lake Turkana South (LTS), Ilaut (ILA), Laisamis (LAI) and Chanler's Falls (CHF) were used for this study. The charges used were 375 Kg, 900 Kg, 900 Kg, and 2000 Kg respectively. Recording was done using 206 stations equipped with 2 Hz geophones. An average spacing of 1.5 km was used. Timing was done using master clocks with built in receiver for Moscow time signal. Because of difficult terrain and accessibility problems, recording station offset of upto 1 5km on parts of the profile were inevitable. All the playback records for the four shots were usable. The best record section was that of LTS (see fig. 2) this having been an underwater shot. CHF was second best in quality on account of the large amount

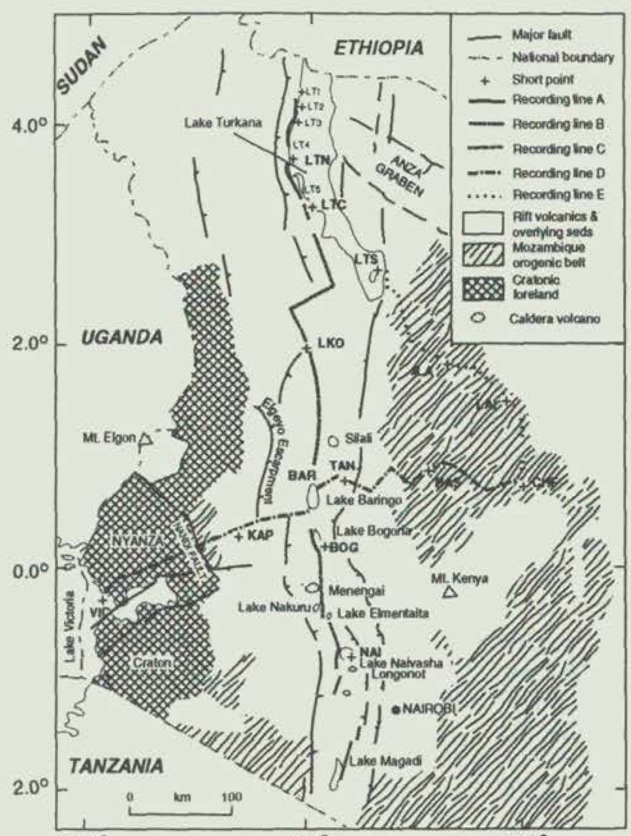


Fig. 1. KRISP90 Location map (from KRISP Working Group, 1991 )

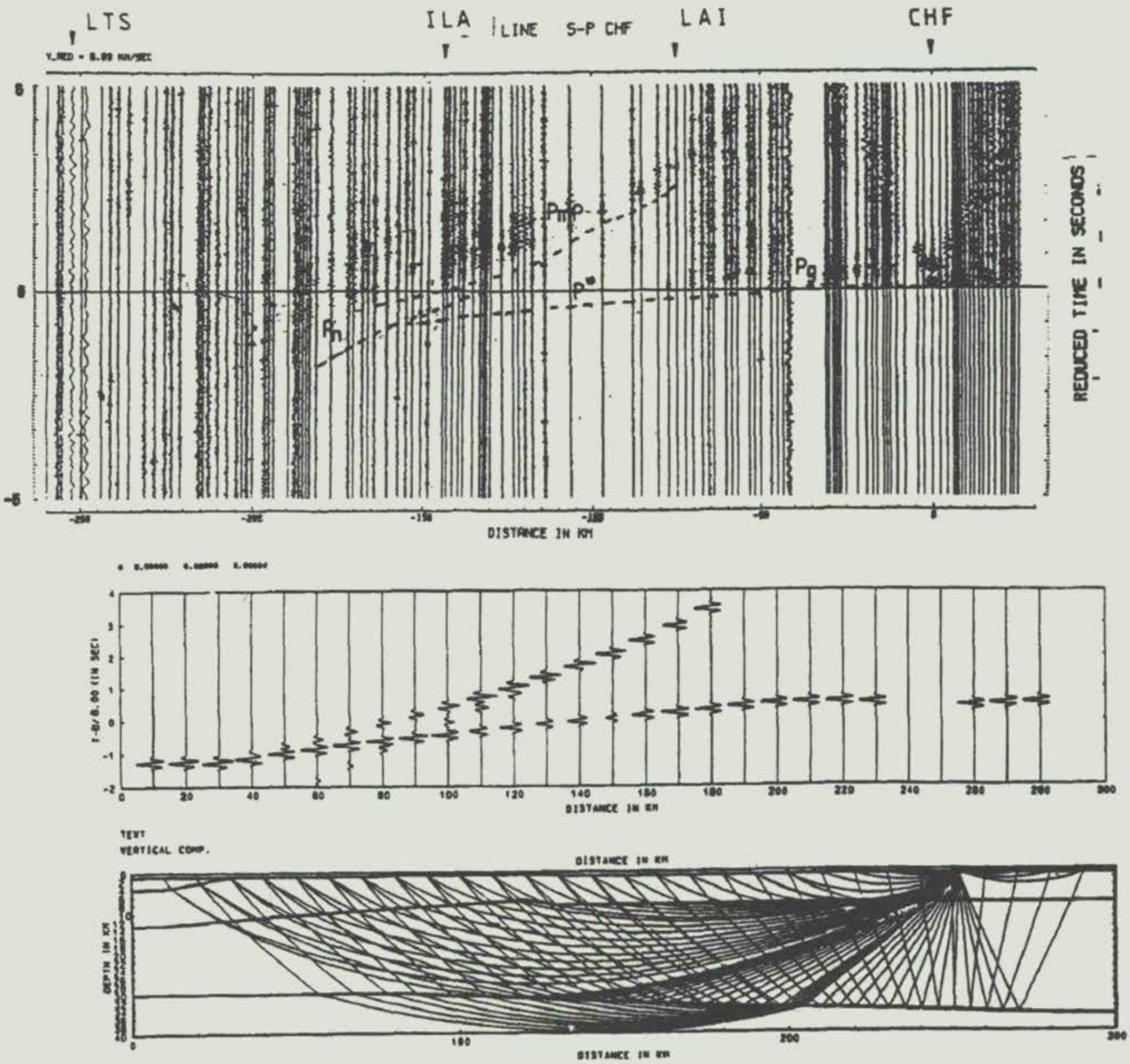


Fig. 2. Record section, synthetic seismograms and ray diagrams for S-P LTS

of charge used. The data analysis involved phase correlations and development of one dimensional velocity - depth functions leading to an initial 2D model. The correlated section for LTS and CHF are shown in figs. 2 and 3. The symbols used are Pg, P*, Pn for refractions in the upper crust, lower crust and at the Moho respectively and PmP for the Moho reflection. The detailed description of the correlations that led to the initial model have been presented elsewhere (Prodehl et al., 1992) and are therefore not included here.

## P-WAVE VELOCITY CRUSTAL MODEL

The 2D ray tracing was done using the package BEAM87 (Cerveny et al., 1977). Both lateral and vertical velocity variations were allowed. As the start model suggested varying thicknesses for the various layers, it was necessary to smoothen the velocities to obtain isolines of velocities. The modelling was continued until the best fit between the calculated and the correlated travel times was obtained. Velocity gradients were also improved until a reasonable agreement of amplitudes was obtained. The final P - wave velocity crustal model is shown (Fig. 4). The correlated section and synthetic seismograms corresponding to the model for the shot points LTS and CHF are shown in figs. 2 and 3.

The upper crust is considered to be comprised of metamorphic rocks of the Mozambiquan belt have velocity in the range 5.8 to 6.1 km/s. The velocity gradient varies laterally. It is strongest in the Laisamis area where a value of 0.08 km/s/km is obtained. The average gradient in the rest of the section is about 0.04km/s/km. The relatively strong gradients in the Laisamis area are attributed to basic intrusives in the region. The first 30 km are underlain by the sediments of the Lake Turkana. The model suggests a rapid increase in the velocity of sediments from 3.6

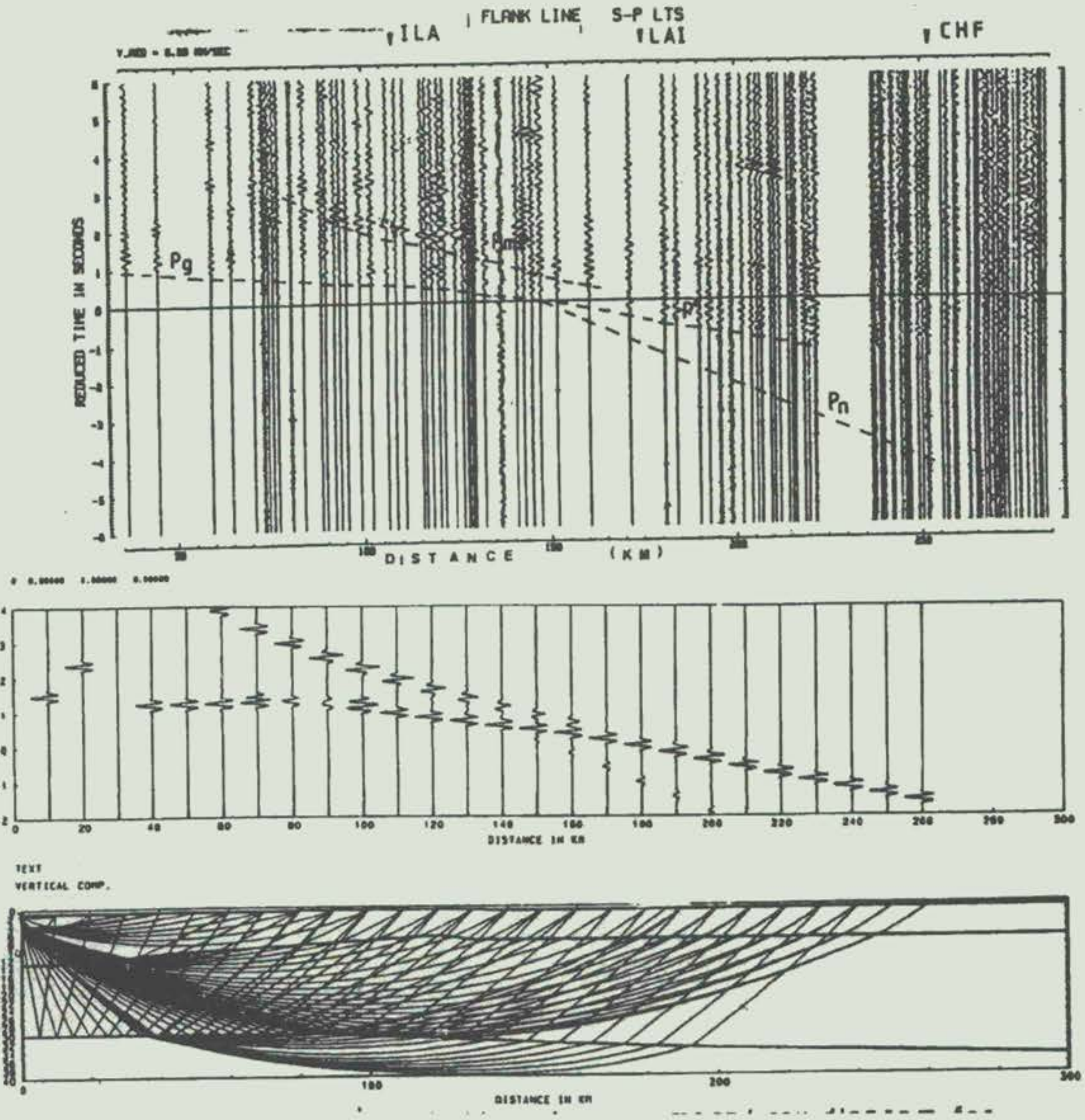


Fig. 3. Record section, synthetic seismograms and ray diagrams for

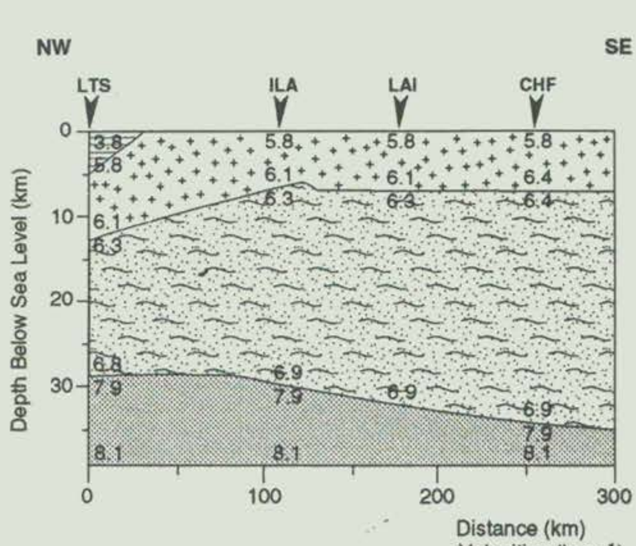


Fig. 4. P-wave velocity depth model for the section between Lake Turkana South and Chanler's Falls.

km/s at the top to 3.9 km/s at a depth of about 3 km giving a strong gradient of 0.1 km/s/km. A general thickening of the upper crust towards the northwest is indicated. The boundary between the upper and the lower crust occurs at an average depth of 7 km. This discontinuity is well defined except to the southeast where it appears fictitious. The thickness of the lower crust varies from 7 km near Lake Turkana to 12 km near Laisamis. It shows lateral variation in velocity with relatively strong gradients of 0.03 km/s/km in the northwest but weak gradient of 0.02 km/s/km in the southeast. Generally the lower crust shows a more homogeneous lateral velocity distribution than the upper crust. The model indicates a variation in thickness from 17 km in the northwest to 28km in the southwest.

The Moho is modelled as a first order discontinuity at a depth of 35 km in the southeast shallowing to less than 29 km under LTS. Data from other KRISP90 profiles (Prodehl et al. 1990) suggest a rapid shallowing of the Moho northwest of LTS. to 23 km west of Lake Turkana. In the section northwest of LTS the Moho is accompanied by a transition zone in the range 19 km - 23 km. In the area of the present study however, a first order

Moho discontinuity with velocity jump from 6.8 km to 7.9 km/s is favoured. The gradients in the upper mantle are low in the northwest 0.02 km/s/km increasing to 0.04 km/s/km in the southeast. Low to large amplitude Pn arrivals are therefore to be expected.

**DISCUSSIONS**

The proposed model suggests that strongest hetereogeneities occur in the upper crust. These variations suggest a strong modification of the basement along the profile and favour presence of basic intrusives within the basement. This behaviour climaxes in the area between Laisamis and Chanler's Falls where strongest gradients occur. This may be related to intrusives which may have resulted in the injection of basic bodies in the upper crust. The existence of volcanics as well as a shield type volcano in this region (Hackmann et al., 1990) lend support to this. Gravity and magnetic data in parts of this region are anomalous and both suggest presence of intrusives in shallow depths (Dindi, 1992). Isolated occurrences of basic intrusives have been reported in the region and may reflect existence of larger ones at depth. The occurrence of the Conrad discontinuity at an average depth of only 10 km is unusual and may reflect the nearness of the Kenya rift valley. The lower crust shows more uniform behaviour with relatively low gradients. However in the Lake Turkana area the gradients increase. This increase is in line with results of the western side of the lake where transitional Moho with top and bottom of transitional layer at l9km and 23km is favoured by the modelled high resolution data (Gajewski et al., 1993). It is apparent that in the region under Lake Turkana a very rapid shallowing of the Moho occur in the northern direction. The shallowing of the Moho towards Lake Turkana seems to be related to the Kenya Rift Valley.

Elsewhere it is also observed that the crustal thickness reverts to normal at the flanks and away from the Kenya Rift Valley(Prodehl et al., 1991). Indeed the gradual shallowing may be due to the fact that the profile runs oblique and not perpendicular to the main rift. If the behaviour of the Moho below Anza graben is similar to that at the shoulders as is likely to be the case on account of the close proximity of the profile to the axis of Anza Graben (Dindi, 1992;1993) it will tend to suggest that the Moho shallows northwards under Anza graben. However the observed rapid change along the profile running normal to the to Kenya Rift Valley, stresses that such generalization should be treated with caution. However the Moho depth at the shoulder of the most developed section of Anza graben is about 35km and Pn velocities are normal suggesting that no anomalous material occur below Anza. This is in line with Bosworth's structural model (Bosworth, 1990 ) which favour cooling of anomalous mantle below rift with age.

It of interest here to compare the features of the present model with those of another model presented for the same profile (Prodehl et al. 1992). The latter model had the advantage of using additional data from shot Lake Turkana Central (LTC). Further, S- wave velocities and special filters were used in sections where the P-wave arrivals were weak or unclear. Despite these differences in the data used, the two models share many features. The latter model however attributes the speeding up of waves in the LAI and CHF areas to a thin high velocity wedge interpreted as a sill. The model also includes a transition zone of maximum thickness 9km before the Moho.

**CONCLUSIONS**

The results of interpretation and modelling of the section between Lake Turkana South and Chanler's Falls show that it is characterized by heterogeneities in the upper crust. These seem to favour presence of intrusives in some sections of the profile. In the sections where such intrusives are envisaged to occur the data indicate strong velocity gradients. There are so far no indications of anomalies mantle at depth nor of excessive thinning of the crust. One possible explanation for the normal mantle velocities and limited thinning may be that with age cooling has occurred and the velocities reverted to normal. An interesting observation is the gradual shallowing of the Moho towards Lake Turkana. It is however suggested from this study that the shallowing is due to the influence of the Kenya Rift Valley to which the present profile is obliquely oriented.

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# GEOCHEMICAL STUDY OF WATER - ROCK INTERACTION OF OLKARIA GEOTHERMAL FIELD

GACHIGUA M.W.
Mines and Geological Depart., MENR, P.O.Box 30009, Nairobi.

## ABSTRACT

*The Olkaria Geothermal Field is located within the eastern arm of the Great African Rift. The fleld lies about 120 Km north-west ofNairobi and about 10 Km south of Lake Naivasha.(Fig. 1). It is one of many active geothermal areas occurring within the Kenyan Rift Valley which extends from Lake Turkana in the north to Lake Magadi near the KenyanTanzania border in the south. However it is the only geothermal field that has been developed with a power station. The station generates 45 MW. The study of hydrothermal alteration of the Olkaria Geothermal Field was carried out by use of geothermal fluids from Olkaria East production wells and drill-core rock samples from well 601 (which lies about 5 Km from Olkaria East production wells). Lake Naivasha waters were also included in this study for comparison with the geothermal waters. The stability relationship between the thermal waters and the co-existing minerals with which the waters equilibrated was represented on log activity-activity diagrams. The diagrams indicate the type of minerals the Olkaria geothermal waters equilibrated with before being discharged onto the surface through the wells. Chemical geothermometers were found to be affected by dilution and boiling in the upflow zones. The Olkaria geothermal fluids were found to equilibrate with albite and K-feldspars at 200-300°C. Therefore the Na-K geothermometer may be used to estimate the reservoir temperature. The silica geothermometer may also be used.*

## Introduction

The Olkaria Geothermal Field covers an area of about 4 Km2. The paper discusses the waterrock interaction based on geothermal fluids ( collected from 16 wells) and four drill-core rock samples collected from well OW 601 (Fig. 2). Geothermal power is the cheapest form of energy for sustainable development in that it has very little environmental impact and displaces no communities as is the case with the constmction of large dams for generation of hydroelectricity. The water-rock interaction at Olkaria was studied due to the problem of low permeability that occurs in all geothermal areas. The low permeability restricts the water-rock interaction and can seal up the production wells.

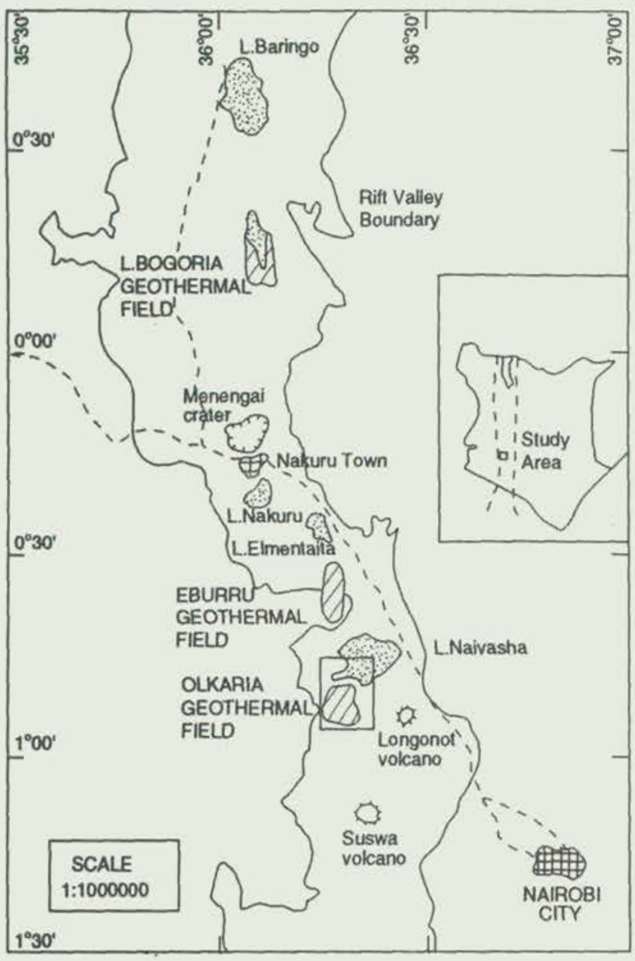



Figure 1. Location of study area.

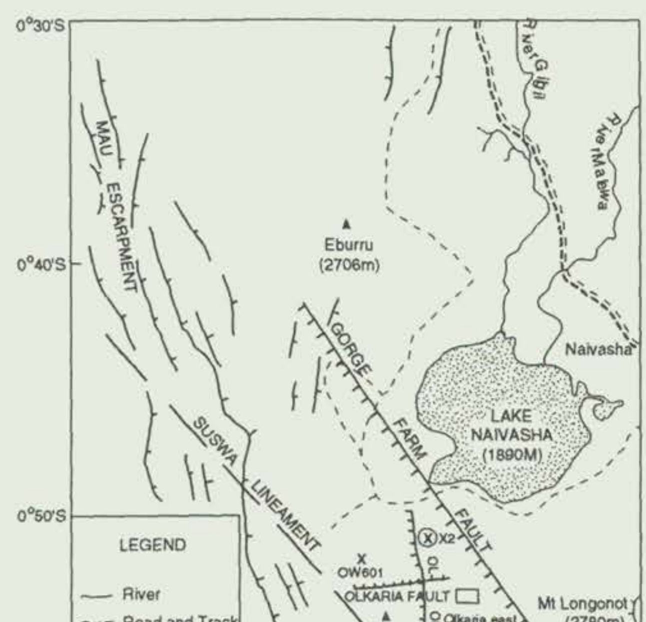



Figure 2. Geological struct ures of the Lake Naivasha area.

## Geology

The surface geology of the Olkaria east production area is composed of volcanic tuffs and sediments, otherwise the only rock exposures in this area are on the cliff on the SE facing 01 Njorowa Gorge where columnar comendites are exposed.

## Sampling methods

Water samples were collected from the weirboxes at ambient pressures (0.8 bars). Three water samples were collected from each of the 16 wells. One sample from each well was acidified with HCl to a pH of about 2-3 so as to conserve the unstable constituents in the water in preparation for later analyses. The acidity also prevents the adsorption of the metal cations onto the walls of the sampling bottles. All the other samples were filled in airtight bottles to prevent oxidation of hydrogen sulphide to sulphates, thus giving false values which would not be representative of the original hydrogen sulphide concentration in the natural waters. A blank was provided for both the acidified and the untreated samples using distilled water. In addition two samples were collected from Lake Naivasha (10 Km from Olkaria Geothermal Field) and treated as above.

Table 1 *Analytical Methods used for water samples*

| System | Elements determined |
|---|---|
| Inductively Coupled Plasma Atomic Emission Spectrometry (TCP-AES) | Na, K, Ca, B, $SO_4$ |
| Graphite Furnace Atomic Absorption Spectrometer | Mn |
| Spectrophotometry | SiO2, H2S |
| Fluorimetry | Al |
| Titration with HCI using pH to mark end point | CO2 |
| Ion Selective Electrode | Cl |

## Water -rock system

The main process affecting the distribution of minerals and solutes in a geothermal system is the gradual conversion of mineral phases which are thermodynamically unstable under geothermal conditions to a stable assemblage. The conversion of unstable primary minerals to stable secondary minerals is an example of an irreversible reaction. In a closed system, distribution of the components is given by mass balance:

$$Fluid_{initial}, + \text{Primary phases} \rightarrow Fluid_{final} + \text{Secondary phases}$$

At any intermediate stage during this process, the composition of the fluid changes and is likely to reflect the effects of earlier formation conditions and increasingly those approaching equilibrium. The approach to this equilibrium is greatly complicated by temperature gradients and generally interrupted when the fluid reaches the surface. The aim of this paper is therefore to evaluate the temperature (pressure) at which the Olkaria geothermal fluid and minerals that were analysed equilibrate. This objective was reached by use of log activityactivity diagrams and chemical geothermometers.

## Logarithmic activity- activity phase diagrams.

These are used to show the relationship between minerals and fluids and to permit the comparison with alteration mineral assemblages observed in geothermal systems. They play an important role in evaluating the mineralogical effects of cooling or boiling of hydrothermal solutions, and also form the basis for chemical geothermometry. The thermodynamic equilibria therefore provided the bases necessary in studying the above relationship. Most alteration reactions whose products were observed in the drill-cores involve alumino-silicate minerals. These are examples of incongruent mineral solubility or hydrolysis reactions in which alumina is conserved in the solid phases. In constructing the log activity diagrams, the calculation of equilibrium constants play a great role. The presence of albite

Table 2 *Results of the fluid samples.*

| Well No. | pH/20°C | Na | Li | K | Mg | Ca | Fe | Mn | $SiO_2$ | $SO_4$ | $H_2S$ | $HCO_3$ | $CO_2$ | Cl | Al | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 8.70 | 576.7 | 1.004 | 115.2 | 0.083 | 1.865 | 0.025 | 0.010 | 748.00 | 17.343 | 0.437 | 976.0 | 55.00 | 720.0 | 0.964 | 6.871 |
| 5 | 6.07 | 2.847 | 0.008 | 3.621 | 0.073 | 1.858 | 0.299 | 0.022 | 5.143 | 7.817 | 0.343 | 122.0 | 44.00 | 1.6 | 0.523 | 1.045 |
| 7&8 | 8.23 | 617.3 | 1.010 | 104.80 | 0.667 | 1.0.23 | 0.201 | 0.011 | 697.00 | 7.535 | 0.640 | 976.0 | 60.30 | 940.0 | 0.935 | 9.082 |
| 10 | 8.66 | 698.9 | 1.325 | 126.90 | 0.087 | 2.854 | 0.328 | 0.011 | 631.90 | 49.697 | 0.530 | 732.0 | 84.90 | 1025.0 | 0.208 | 15.730 |
| 13 | 9.89 | 419.6 | 0.655 | 49.69 | 0.079 | 2.081 | 0.853 | 0.039 | 718.00 | 41.919 | 0.234 | 2196.0 | 177.76 | 380.0 | 2.391 | 3.659 |
| 15 | 8.76 | 1123.0 | 2.446 | 192.4 | 1.293 | 5.665 | 3.369 | 0.024 | 728.90 | 73.528 | 0.950 | 1220.0 | 102.08 | 1072.0 | 3.041 | 24.870 |
| 16 | 8.44 | 499.0 | 1.038 | 70.59 | 0.047 | 0.716 | 0.082 | 0.005 | 551.31 | 13.571 | 0.530 | 732.0 | 69.10 | 800.0 | 0.846 | 7.156 |
| 18 | 8.70 | 914.2 | 2.087 | 155.50 | 0.042 | 1.540 | 0.028 | 0.005 | 1017.17 | 11.987 | 1.334 | 1098.0 | 90.64 | 1399.0 | 0.266 | 26.170 |
| 19 | 8.59 | 394.1 | 0.754 | 59.64 | 0.051 | 0.536 | 0.143 | 0.005 | 598.32 | 14.047 | 1.022 | 976.0 | 92.00 | 580.0 | 1.409 | 10.830 |
| 20 | 8.95 | 606.7 | 1.265 | 103.70 | 0.074 | 1.320 | 0.133 | 0.007 | 747.91 | 5.392 | 0.640 | 854.0 | 59.80 | 1030.0 | 0.806 | 12.560 |
| 21 | 9.55 | 474.0 | 1.072 | 59.91 | 0.050 | 1.648 | 0.203 | 0.014 | 559.85 | 71.822 | 0.593 | 1708.0 | 158.00 | 680.0 | 0.855 | 5.812 |
| 22 | 9.69 | 432.0 | 0.468 | 40.71 | 0.046 | 1.018 | 0.025 | 0.006 | 448.73 | 18.675 | 0.437 | 2196.0 | 234.08 | 300.0 | 0.422 | 2.081 |
| 23 | 9.44 | 383.3 | 0.751 | 48.55 | 0.022 | 0.741 | <0.01 | 0.004 | 632.51 | 27.232 | 0.733 | 732.0 | 182.60 | 350.0 | 0.839 | 3.258 |
| 24 | 8.62 | 627.7 | 1.233 | 115.5 | 0.092 | 2.256 | 0.167 | 0.014 | 769.28 | 26.594 | 0.733 | 732.0 | 73.90 | 1030.0 | 1.134 | 10.110 |
| 25 | 9.21 | 53.94 | 1.024 | 88.27 | 0.066 | 1.128 | 0.077 | 0.007 | 670.98 | 34.300 | 0.874 | 976.0 | 79.20 | 820.0 | 0.680 | 6.875 |
| 26 | 9.18 | 306.50 | 0.658 | 48.29 | 0.045 | 1.149 | <0.01 | 0.004 | 653.88 | 5.823 | 0.624 | 1464.0 | 102.00 | 340.0 | 1.019 | 2.742 |
| Lake Naivasha | 9.29 | 57.33 | <0.01 | 28.10 | 7.064 | 11.28 | 0.166 | 0.106 | 32.62 | <0.01 | 0.450 | 1830.0 | n.d | 12.2 | 0.266 | 0.076 |

Concetratins are expressed in $mg l^{-1}$

.Table *3 Results of the drill-core rock samples*

| | Primary Minerals | Secondary Minerals |
|---|---|---|
| Alkali Rhyolites sample 49875 | Alkali feldspars, aenigmatite, amphibole pyroxene= aegirine | Chlorite |
| sample 49877 | Alkali feldspars, pyroxene = aegirine - augite, amphibole = arfvedsonite | Carbonate = siderite |
| sample 49876 | | K-feldspar, albite, apatite. chlorite carbonate = calcite |
| Alkali Basalt sample 49878 | plagioclase feldspars, pyroxene = augite, | opaques, biotite chlorites, carbonate = calcite |

*The Joel JXA-SOA Electron Microprobe was used in the determination of the mineralogy of the drill-core rock samples*

and potassium feldspars, for example, suggests that equilibrium may be reached between the geothermal fluids and feldspars as shown in the reaction:

$$NaAlSi^3O^8 + K^+ \rightarrow KAlSi^3O^8 + Na^+$$
(Albite) (K-feldspar)

Provided the solid phases are pure, the equilibrium constallt, K, can be represented as:

$$K = {}^aNa^+/{}^aK^+$$

where a= activity (effective concentration of respective species $Na^+$, $K^+$ in this case) Conventionally, the log activity - activity diagrams have their axes, log values of respective cation/proton ratio. These are temperature dependent and unique for different mineral reactions. For the above reaction, the equilibrium constant is related to the Gibbs Free Energy change of the reaction which is given as:-

$$\log K = \log {}^aNa^+/{}^aH^+ - \log {}^aK^+/{}^aH^+$$

Gibbs Free Energy, ~G°, is related to K by:

$\Delta G^\circ = -RT\ln K = -2.303RT \log K$ where, R = Gas constant and T = Temperature in degrees Kelvin.

The equilibrium constant can be calculated from the reactions of minera]s if the thermodynamic data is available.The reactions below give the mineral reactions for which the calculation have been performed for $Na_2O - K_2O - Al_2O_3 - SiO_2 - H_2O$ system, and temperature range from 100-300°C at 1, 16 and 86 bars respectively . Pressure has very little effect on mineral dissolution provided ]iquid water is stable (Helgeson, 1969). The value of (aK-feldspar/aalbite) was computed from the microprobe data and log K was computed by the use of the "SUPCRT" program (Helgeson at al, 1978).

Assuming concentration to be a good approximation of activity, log aK-feldspar/aalbite is 0.03, for the alkali feldspars and this approaches the log activity ratio of pure end -members, which is zero.Table 4 shows the results of two alkali feldspars with almost similar compositions, with log aK-feldspar/aalbite = 0. The log activity - activity diagrams (figs 3a, b and c) show the relationships between minerals and the interacting fluids in the Olkaria Geothermal Field.Although only feldspars (albite and K - feldspar) were analysed, fig 3a, b &c suggested that the fluids may have been in equilibrium with a range of minerals in the Na20 -K20 -Al203 -H20 system

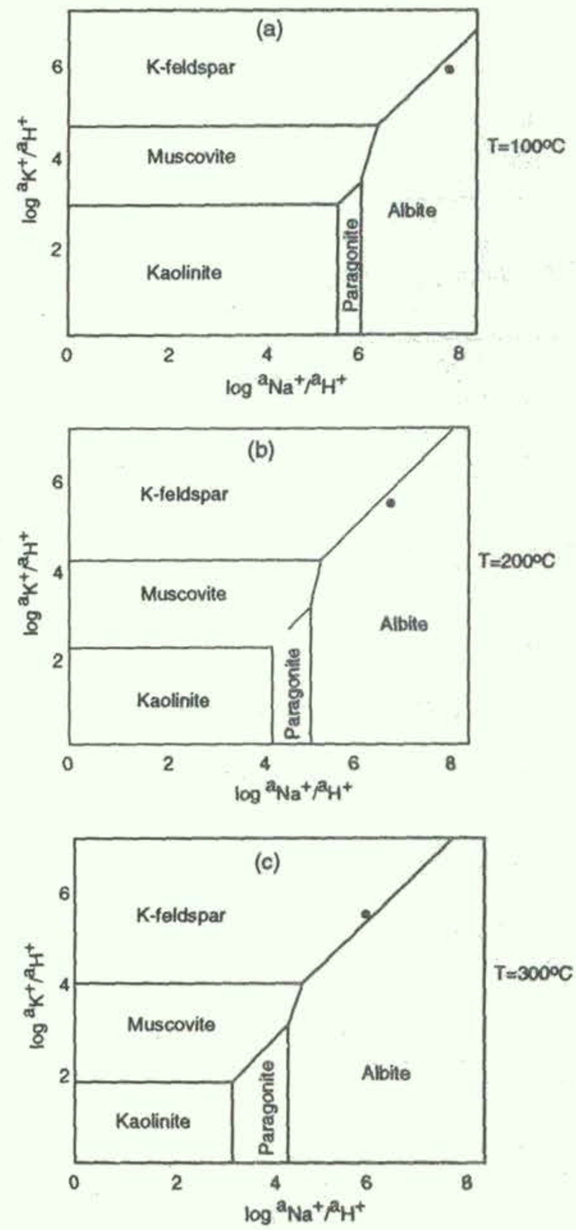



Figure 3a,b,&c Phase diagrams for sodium and potassium in terms of ion activity ratios in presence of quartz (solid cycle is the plot of Olkaria Geothermal Field Water Composition)

*Table 4.*

| Sample | 49875 | | 49877 | | 49876 (i) | | 49876 (ii) | | 49878 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | % oxide | Formula (8 oxygen) | % oxide | Formula | % oxide | Formula | % oxide | Formula | % oxide | Formula |
| Si | 67.638 | 3.012 | 66.943 | 2.995 | 68.382 | 2.986 | 63.789 | 2.980 | 52.171 | 2.390 |
| Ti | 0.033 | 0.001 | 0.035 | 0.001 | 0.029 | 0.001 | 0.035 | 0.001 | 0.095 | 0.003 |
| Al | 18.051 | 0.971 | 18.811 | 0.992 | 19.813 | 1.002 | 18.133 | 0.998 | 29.246 | 1.579 |
| Cr | n.d | - | 0.009 | <0.001 | 0.015 | <0.001 | 0.025 | 0.001 | 0.028 | 0.001 |
| Fe | 0.574 | 0.041 | 0.539 | 0.020 | 0.022 | 0.008 | 0.181 | 0.007 | 0.819 | 0.031 |
| Mn | 0.012 | <0.001 | 0.024 | <0.001 | 0.0.052 | 0.002 | 0.032 | 0.001 | 0.054 | 0.002 |
| Mg | 0.016 | 0.001 | 0.041 | 0.003 | 0.079 | 0.005 | 0.059 | 0.031 | 0.053 | 0.004 |
| Ca | 0.009 | <0.001 | 0.005 | <0.001 | 0.029 | 0.001 | 0.040 | 0.002 | 12.544 | 0.616 |
| Na | 6.553 | 0.566 | 6.614 | 0.574 | 11.208 | 0.947 | 0.450 | 0.041 | 6.124 | 0.367 |
| K | 7.000 | 0.398 | 7.276 | 0.416 | 0.154 | 0.009 | 16.920 | 1.009 | 0.261 | 0.015 |
| Ba | 0.077 | 0.001 | 0.025 | n.d | 0.024 | <0.001 | - | - | 0.021 | 0.008 |
| Sum | 100.446 | 4.965 | 100.318 | 5.002 | 100.009 | 4.982 | 99.664 | 4.965 | 99.416 | 5.008 |

Table 5. Silicate-Water Reactions for $Na_20 - K_20 - Al_20_3 - SiO_2 - H_20$ system

1. $2KAl_3Si_30_{10}(0H)_2 + 3H_20 + 2H^+ = 2K^+ + 3Al_2Si_20_5(0H)_4$
   *(muscovite)* *(kaolinite)*

2. $KAl_3Si_30_{10}(0H)_2 + Na+ = NaAl_3Si_30_{10}(0H)_2 + K^+$
   *(paragonite)*

3. $2NaAl_3Si_30_{10}(0H)_2 + 2H^+ + 3H_20 = 3Al_2Si_20_5(0H)_4 + 2Na^+$

4. $3NaAlSi_30_8 + 2H^+ = NaAl_3Si_30_{10}(0H)_2 + 6SiO_2 + 2Na^+$
   *(albite)* *(quartz)*

5. $3NaAlSi_30_8 + 2H^+ + K^+ = KAl_3Si_30_{10}(0H)_2 + 6SiO_2 + 3Na^+$

6. $NaAlSi_30_8 + K^+ = KAlSi_30_8 + Na^+$
   *(K-feldspar)*

7. $2KaAl_3Si_30_{10}(0H)_2 + 2H^+ + 3H_20 = 2K^+ + 3Al_2Si_20_5(0H)_4$

Considering equation 6

$K = ({}^aNa^+/{}^aK^+)\ ({}^aK\text{-feldspar}/{}^a\text{albite})$

$\log {}^aNa^+/{}^aK^+ = \log K \log {}^aK\text{-feldspar/aalbite}$

**Chemical Geothermometry**

As the deep water ascends towards the surface, it dissolves some constituents such as silica and alters the primary minerals to secondary minerals, the constituents of which reflect the reaction temperature and chemistry.The geothermal waters may mix with shallow cold waters, loose heat by conduction, boiling or by combination of the three processes. Nevertheless, the chemistry of geothermal water and gases may be used to evaluate underground fluid temperatures by applying various geothermometers (Arnorson, 1985) provided the rate of reaction between this water and the minerals in the upflow is sufficiently slow so as to re-equilibrate when exposed to lower temperatures.Although all cation ratios are potential geothermometers, silica, Na-K and Na-K-Ca geothermometers are mostly used.The silica geothermometers is controlled by solubility of quartz (Kennedy, 1950, Moray et al, 1962), or chalcedony (Fournier, 1993). The Na-K-Ca, geothermometer is based on the partitioning of Na, K, and Ca in the relevant silicate exchange equilibrium and is applicable in calcium-rich waters with low or moderate reservoir temperatures (Fournier & Truesdell, 1973).The Na-K geothermometer is based on the temperature dependence of partitioning of Na and K between alkali feldspars. It is applicable for temperature > 100°C because equilibrium between feldspars and solution may not be attained at lower temperatures (Ellis & Mahon, 1977).However the use of chemical geothermometers in determination of reservoir temperatures is so far mostly based on experience obtained in very active geothermal fields.

*Table 6: Equations expressing the Temperature Dependence of the shown Geothermometers (concentration (mg $^{-1}$))*

| | | |
|---|---|---|
| (a) Quartz,- no steam loss, TQC, t°C | $= \frac{1309}{5.19 - \log SiO_2}$ | = 273.15, t = 0-250°C |
| (b) Quartz,- maximum steam loss, TQA, t°C | $= \frac{1522}{4.69 - \log SiO_2}$ | = 273.15, t = 0-250°C |
| (c) Chalcedony, TCH, t°C | $= \frac{1032}{5.75 - \log SiO_2}$ | = 273.15, t = 0-250°C |
| (d) Na/K (Truesdell), TNaK-We, t°C | $= \frac{855.6}{\log(Na/K) + 0.8573}$ | = 273.15, t > 150°C |
| (e) Na/K (Fournier), TNaK-F, t°C | $= \frac{1217}{\log(Na/K) + 1.483}$ | = 273.15, t > 150°C |
| (f) Na-K-Ca, TNaKCa, t°C | $= \frac{1217}{\log(Na/K) + b\,[\log(\sqrt{Ca/Na}) + 2.06] + 2.47}$ | |

where $\beta = 1/3$ if $t > 100°C$ and $[\log(\sqrt{Ca/Na}) + 2.06] < 0$
and $4/3$ if $t < 100°C$ and $[\log(\sqrt{Ca/Na}) + 2.06] > 0$

## Discussion

The equilibrium relationship between the alteration mineralogy and the reservoir fluids of the Olkaria geothermal field was evaluated to yield temperatures ranging from 100-300°C Wells 5 and 25 gave unreasonably high temperature estimates (Table 7). This may be due to ion exchange reactions with clay minerals particularly where deep reservoir temperatures are < 200°C. At low temperatures calcite solubility is relatively high, and the fugacity of CO2 in the solution may significantly affect the results given by the Na-K-Ca geothermometer, yielding lower than that of the reservoir. This is because of the continuous reaction of geothermal fluids with the host rocks at low temperature in the upflow zones. The average temperatures of TQA, which represents the reservoir temperatures is lower than that of Na-K geothermometers (Table 7). This may be attributed to cooling in the feeding aquifer and thus yielding lower temperatures than the reservoir. Lake Naivasha waters are not in equilibrium with albite and K-feldspar and therefore gave the unrealistic geothermometric temperatures. The presence of chlorite in the drill-core rock samples suggested reservoir temperature ranges of 200-300°C (Table 8). High fugacities of CO2 explains the presence calcite in the drill-cores.

$$CaC0_3 + 2H+ , CO_2 + H_20 + Ca$$

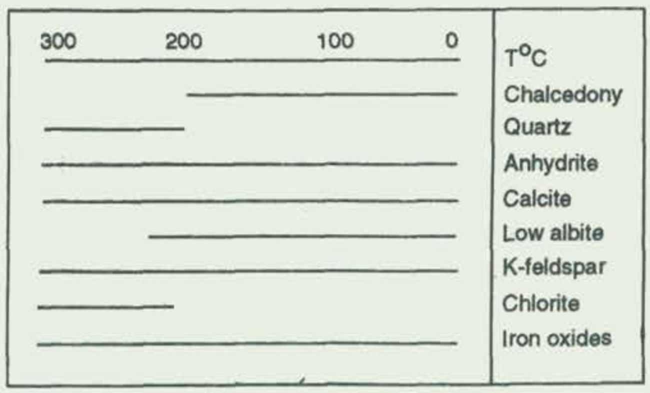
and therefore nullifies the application of Na-K-Ca geothermometer on the Olkaria geothermal waters. Albite and K-feldspar are abundant in Olkaria Geothermal area and hence the application of Na-K geothermemeter in the determination of the reservoir temperature. The Microprobe analyses indicated an enrichment of K+ in the reservoir rock and a depletion of Na+ from these rocks. Assuming equilibration of the feldspars with reservoir fluid, there would be dilution of K+ rather than Na+ from the reservoir fluid. The geothermal water showed high concentrations of Na+ and low concentration of K+. This suggested that the above equilibrium was reached in the study area. Assuming the reservoir temperature ranges from 200-300°C, then at 100°C, this reservoir fluid becomes saturated with amorphous silica through adiabatic cooling. This was confirmed by the presence of chalcedony at ~0°C (weirbox water temperature). The average power output in other producing wells of the world such as Wairakei Power Station (New Zealand), Mori Power Station (Japan) are different, and some are much higher than that from Olkaria (45MW), i.e 192MW and 50MW respectfully. This may be due to the very high Na content o~ the lavas, comedites and pan~ellerites in Olkaria Geothermal Field.

*Table 7.*

| Sample | TQC | TQA | TCH | TNaK-F | TNaK-We | TNaKCa β=1/3 | TNaKCa β=4/3 |
|---|---|---|---|---|---|---|---|
| 2 | 284 | 250 | 285 | 285 | 277 | 206 | 162 |
| 5 | 183 | 171 | 162 | 608 | 860 | 272 | 62 |
| 7&8 | 246 | 242 | 271 | 267 | 252 | 200 | 122 |
| 10 | 276 | 221 | 237 | 274 | 262 | 198 | 108 |
| 13 | 286 | 252 | 288 | 232 | 207 | 172 | 86 |
| 15 | 279 | 246 | 278 | 268 | 254 | 172 | 99 |
| 16 | 260 | 232 | 254 | 249 | 228 | 196 | 133 |
| 17 | 325 | 281 | 337 | 267 | 253 | 200 | 122 |
| 19 | 268 | 232 | 265 | 255 | 237 | 196 | 136 |
| 20 | 291 | 255 | 294 | 268 | 254 | 200 | 122 |
| 21 | 261 | 233 | 256 | 238 | 214 | 206 | 100 |
| 22 | 241 | 217 | 231 | 212 | 181 | 200 | 99 |
| 23 | 273 | 242 | 271 | 238 | 215 | 200 | 110 |
| 24 | 294 | 257 | 297 | 276 | 264 | 198 | 108 |
| 25 | 279 | 247 | 279 | 686 | 1058 | 196 | 277 |
| 26 | 277 | 245 | 276 | 261 | 242 | 198 | 102 |
| * Lake Naivasha | 85 | 88 | 53.8 | 409 | 466 | 155 | 57 |
| Average | 270 | 239 | 268 | 256 | 256 | 201 | 118 |

* Not included in the average NA-K geothermometric temperatures for well 5 and 25 are meaningless and thus not included in the average results

*Table 8 Distribution or minerals in geothermal systems with wnich the waters equilibrate. (Arnorsson ĕt al. 1983a)*




## Conclusions

It was established that chlorites and calcite were not in equilibrium with the reservoir fluid. Calcite could have been a product of another process inherent of geothermal activity such as boiling. However thermodynamic data for chlorites were not available. The leaching properties of the reservoir rocks was found to dominate the Olkaria Geothermal field composition. A reservoir temperature range of 200-300°C was predicted for the Olkaria Geothermal field assuming no analytical errors. Mixing of the geothermal water and surface waters was found to occur giving hybrid fluids (Gachigua, M.W.,1988). It was concluded that, the use of thermodynamic evaluation of reactions among hydrothermal minerals and then co-existing fluids is a valuable means of describing and interpreting the chemical characteristics of the hydrothermal fluids associated with a given mineral assemblage. Mixing of these fluids with cold groundwater, conductive cooling and boiling should be taken into consideration because of the role these processes play in the chemical composition of the fluids and their host rocks in the upflow zones.

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# THE IMPACT OF MINERAL DEVELOPMENT IN KENYA

T.C. Davies.
Dept. of Geology, University of Nairobi, P.O.Box 30197, Nairobi.

## ABSTRACT

*In this article some of the more important mineral resources of Kenya are discussed in the light of the possible effects that their development has on the population. The objective here is to raise an awareness and thus stimulate research on problems pertaining to the impact of mining of Kenya's minerals (including quarrying, treatment and processing of ores) on the environment as a whole.*

*The variety of mineral resources in Kenya is large but they contribute relatively little to the economy of the country. Kenya is largely an agricultural country; and this, coupled with problems of ore beneficiation, low ore reserves and transportation, mineral development in the country has been rather slow. Nevertheless, the continued search for minerals as well as ways of making their exploitation viable, has opened up wider and wider stretches of the country to development. As a result, people can now find work near to their homes, thus enabling them to sell farm produce easily and improve their standard of living by means of the cash received.*

*Undesirable effects of the mineral industry, on the other hand, include among others, health problems; discolouration of the teeth seen in people living in the vicinity of the fluorite occurrences in the Western Province and in areas near the hot springs, is well known. Patterns in peculiar disorders in people living near the carbonatite occurrences are beginning to emerge (e.g. at Homa).*

*Several instances of potential environmental degradation due to mining activities in Kenya are highlighted in this paper and recommendations for land reclamation and health protection are advanced.*

## INTRODUCTION

The mining industry in Kenya is not large, but its effect on the environment is significant. The suite of minerals is quite varied; metals include gold, silver, copper and zinc whereas industrial minerals range from talc and gypsum to dolomite. In general, it appears that the precious metals like gold, silver and copper are confined to the Precambrian rocks in Western and Northwestern Kenya . Potential for petroleun deposits lie in the sedimentary formations of the coast and offshore as well as in Northeastern Kenya. Other minerals commercially exploited include fluorite, trona and various building stones. A simplified geological map of Kenya including the chief mineral occurrences is given in Figure 1.

The last two or three decades have witnessed a rapid development in the mining industry in Kenya, in consonance with the country's strides in national reconstruction. Additional bases of industrial and mining undertakings have brought with them a number of social and economic benefits but also environmental problems which have aroused the attention of the community. Some of these problems can be illustrated by looking at a few selected mines.

## THE MACALDER MINE

The Macalder Mine is situated some 18km from Lake Victoria and about the same distance from the Tanzania border. It lies between the Kuja and Migori Rivers. The mining operations probably began in 1941, initially on the gold-bearing weathered ore or gossans by open-cast methods up to a depth of 30m. Later, underground workings reached a depth of 130m. Some 220,790 tonnes of ore were treated and 33,563 ounces of gold and 39,329 ounces of silver recovered between 1941 and 1949.

The deposits are found in fractured zones occurring in Precambrian rocks of the Nyanzian System. These include sediments, volcanics and other igneous bodies and are intruded by large granite bodies. The contact zone between the granites and other rocks is highly fractured and sheared and carries the gold - silver - copper - lead mineralisation.

Estimated reserves of all types of ores in 1951 were in excess of 1.5 million tonnes containing about 2 percent copper, 2.5 percent zinc, more than 2 dwt per tonne of gold and about 1.5 ounces per tonne of silver.

The processing consisted of crushing and milling the ore with lime to the required fineness, flotation in organic liquids and the dried ore passed to an oxidising reactor at 700 C. Air is blown at sufficient pressure to keep the ore particles suspended so that sulphides were converted to water soluble sulphates. Copper is precipitated in iron scrap. Zinc and iron - bearing solutions pass to the tailing dam as waste.

The calcined residue containing gold and silver, is removed by dissolving in lime and sodium cyanide. After filtering the solution, gold and silver are precipitated from solution by adding zinc dust and lead nitrate.

Gold was similarly mined from the Migori Mine, but by 1969, the operations had ceased.

During the mining operations, groundvater of highly acidic and corrosive nature had to be pumped out at a rate of about 10,000 gallons per hour.

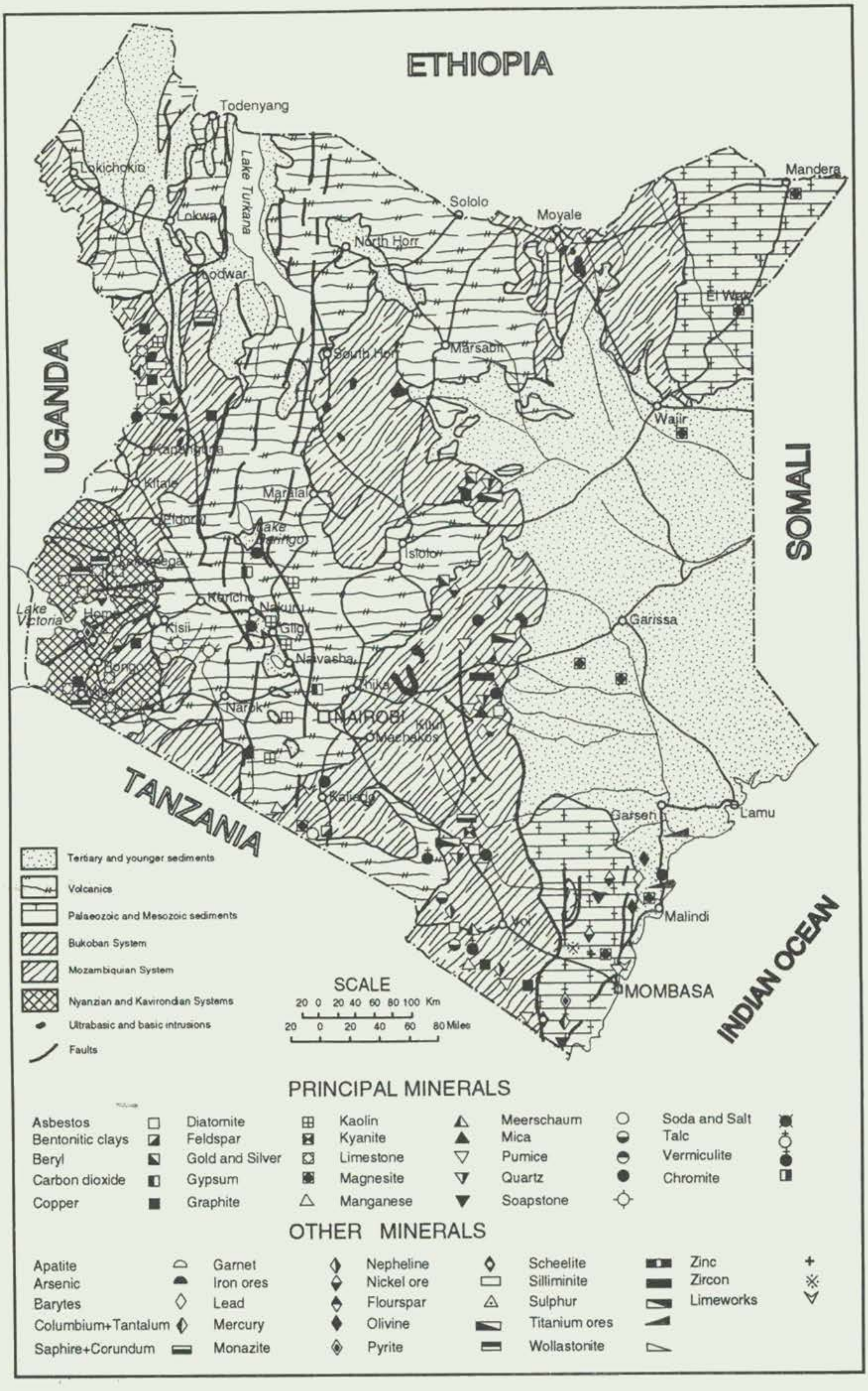


Figure 1. Generalised Geological and Minerals Map of Kenya (modified after Survey of Kenya, 1962, 1969; Ministry of Energy and Regional Development of Kenya, 1987).

Mining and processing of the ores have led to considerable environmental degradation. The entry of corrosive acid solutions into the adjacent water systems has resulted in untold damage to the ecosystem. Fish have been reported killed in the Migori River. It is possible that the method of solid waste disposal employed degraded the stream and rivers. The mine tailings are put on a fault belt only a few tens of metres away from a natural drainage channel. The precise relationship between the tailings and pollution of the Migori River is not yet understood, nor is the effect of the geology of the area on pollution. A lot of research is required in order to decipher the mechanisms by which pollutants enter the waterways, with a view to recommending pollution control measures.

## THE KINANGONI LEAD-SILVER MINE, COAST PROVINCE

Kinangoni Hill lies about 23km north of Mombasa; access is via an all - weather road from Mazeras to Kaloleni. The hilly areas forming the Coastal Range are underlain by the Mazeras Sandstones, and at the foot lie faulted Jurassic limestones. The contact zone between these two types of rocks along the coast, show scattered evidence of mineralisation of lead - zinc - silver and barium minerals. At Vitengeni, north of Kilifi, a baryte mine is in small-scale production.

The principal ores at Kinangoni consist of lead - silver minerals which the Ministry of Mines and Energy estimated to have about one million tons of possible reserve. The average grade of the ore is estimated to be about 9 percent lead and 6 ounces per tonne of silver.

The deposits were exploited for some time before mining activities were terminated. The concentration and beneficiation were carried out using sea-water which was later released. The waste tailings which were leached by surface precipitation also entered the local drainage. Both these waters were reported to contain high concentrations of ore-metals.

## THE FLUORITE MINE, KERIO VALLEY

The Kenya Fluorite Company Mine (KFC) is situated approximately 400km by road north-west of Nairobi (Fig. 1). Access is gained through the town of Eldoret to Nyaru at an altitude of 2,700m at the top of the Elgeyo escarpment and on the western edge of the Kerio Valley. The Kerio Valley which is part of the Great Rift Valley is for the most part semi-arid and undeveloped. It is inhabited by simple herdsmen and others engaged in subsistence farming on the slopes of the escarpment. The KFC is the only well developed project in the Kerio Valley and as such is bringing some measure of prosperity and improved living standards to the local inhabitants through the support it gives to the local economy. Commercial production at the factory began in 1974. The maximum capacity was indicated as being about 230,000 tonnes of fluorite per year representing at least K£ 4 million in export value. Different grades of fluorite are produced at the factory, mainly for use in steel and aluminium industries and also in the production of glass. The fluorite is exported mainly to Japan, the United States, Germany and the former Soviet Union.

### Water Supply

The factory is sited close to the ore deposits in the Valley, about 1km upstream of the confluence of Kimwarer/Mong Rivers. Water for industrial purposes is diverted from the Mong River and pumped through a pipeline to the factory. A micro-strainer has been used at the pumping station for the pre-treatment. Water for domestic use on the factory is drawn from the Kimwarer River and filtered, chlorinated and distributed.

### Ore Crushing

The ore is crushed at different sites - one about 6km from the factory and the other at the factory. The crushing is done in a crusher-jig. The crushed ore is ground in three grinding mills one operating with iron bars and the other two with iron balls.

### Extraction

Extraction of the fluorite is achieved by froth flotation using an oleic acid collector and soda ash to modify the pH (approximately 10.3). Clean water is essential for producing a high grade concentrate and liberal quantities of water are added to every stage of the cleaner circuit. Regrinding the cleaner tailings is also important for producing a high grade concentrate. At the end of the process, the waste water contains gangue minerals as well as soda ash, resulting in a pH in the range of 9.5 to 10.

Samples of effluent collected in 1975 and analysed at the Government Chemist Laboratory in Nairobi showed that the effluent is highly coloured and contain a high concentration of fluoride.

### Waste water Treatment and Disposal

Sedimentation of the effluent is carried out in large ponds which occasionally become filled up with sediment. There is a tendency for waste to be discharged into the Kimwarer River, causing gross pollution.

Various chemical methods have been tried in an attempt to lower the pH of the effluent and reduce its solid content and concentration of dissolved fluoride which could be as high as 60ppm. None of these methods has however proved to be absolutely satisfactory; pollution of Kerio Valley continues.

### Environmental Impact of the Fluorite Mine Factory

From existing evidence, it is clear that the factory effluent causes gross pollution of the rivers in Kerio Valley. The fluoride level in particular is much beyond the internationally acceptable level for drinking water purposes (Gaciri and Davies, 1993). People living in Kerio Valley are known to be using the water of the Kerio River for domestic, fishing and livestock watering. For sometime now, there has been a lot of public concern over the pollution problems of the Kerio River. For example, some Kerio Valley farmers have complained that the water had caused several miscarriages among their livestock. However, no serious scientific investigation has so far been carried out on the overall impact of the Fluorite Mine Factory on the ecology of the Valley.

## LAKE MAGADI

The Magadi Soda Lake is situated about 210km south-west of Nairobi, Lying at an altitude of 605m it occupies the deepest graben in the Rift in the area. The rainfall on average is about 38cm and the temperatures are generally high, between 95°F and 105 °F in the dry season. The rocks in the area are alkaline lavas; the ground water is also alkaline. These conditions as well as an arid landscape naturally degrade the environment.

The highly alkaline lake water continuously precipitates the mineral trona or soda-ash, together with minor quantities of other salts, including common salt, sodium bicarbonate and sodium fluoride. Soda-ash contains 97.55 percent $Na_2C0_3$ and is used in the manufacture of chemicals, glass, caustic soda, soap and cleansers.

Another similar but larger alkaline lake, Lake Natron, is situated farther south, with its northern end in Kenya.

The soda deposits of Lake Magadi are virtually inexhaustible in that the rate of soda input from leachings of the surrounding rocks and alkaline warm - to hot - springs exceeds the rate of extraction.

The crude trona is mined by mechanical dredger and is crushed through different sizes, washed and the slurry conveyed through a pipeline to the ash plant where dehydration, additional crushing and calcination in rotary kilns take place. Water and carbon dioxide gas go out of the chimney. For washing of the trona, alkaline spring water is used.

It is obviously necessary to evaluate and monitor the environmental impact of the Magadi Lake.

## OIL

No economically viable oil deposit has been discovered in Kenya to date. The country therefore depends on oil imports. The only conceivable kind of pollution that could be related to the oil industry is that of oil spillage. The Kenya Ports Authority has the equipment to deal with small oil spills of less than 5O tonnes at sea.

The refinery at Mombasa discharges some sulphur dioxide into the atmosphere, as well as other products of combustion. Some solid hydrocarbon sludge is left after refining, which has to be disposed of. Effluent water from the refinery is treated before being discharged. The possibility of fires also exists.

The environmental effects of the effluents from the refinery should be carefully monitored and any necessary remedial measures should be identified.

## THE DIATOMITE MINES, KARIANDUSI

The Kariandusi Diatomite Mine near Gilgil is located in the Rift Valley Province of Kenya; 1t 1s situated at about 117km to the northwest of Nairobi along the Nairobi - Nakuru road.

The geology of the area consists of recent volcanics, stratified tuffs, tuffaceous gravel, diatomite and grey silts. Diatomite or diatomaceous earth has been formed by the skeletons of diatoms, microscopic organisms that lived in the great seas which covered the earth millions of years ago. Mining and quarrying of diatomite leads to emission of silica dust (diatomite is composed of 70 - 80 percent silica) which is the cause of silicosis with its associated lung disorders.

In the Kariandusi Diatomite Mine, silicosis and related lung disorders have been found in connection with mining, quarrying and calcining of diatomaceous earth. The extent of the problem is however unknown and a lot of research on the subject is warranted. It seems probable also that silicosis exists in the workers of other work-places, such as foundries, ceramic industries, quarries and some types of mining.

## CONCLUSIONS

Mineral resources are essentially non-renewable and, therefore, their exploitation should be properly planned so that when the mines are exhausted and closed down, alternative sources of employment are readily available to the people.

The life expectancy of mines should be carefully estimated and projections made, so that future difficulties can be anticipated.

Before the commencement of operations, information should be sought on the hydrology and geology of the area, problems of land degradation and reclamation, reforestation, water pollution from run off and processing operations and so on. A thorough analysis and assessment of this information should be undertaken and appropriate measures identified to counter the potential environmental hazards.

Finally, mention is made of the Bamburi Cement Factory, an industry that has shown exemplary awareness and responsibility in the preservation of the environment. Their dust suppression measures, the protection of workers in the asbestos works department and the rehabilitation of the quarries have been widely documented.

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# KILIMANJARO AND THE CHYULU HILLS: THEIR CONTRIBUTION TO THE ECONOMY OF KENYA

John M. Omenge
Mines & Geological Department, P.O. Box 30009, Nairobi.

**ABSTRACT**

*Kilimanjaro and the Chyulu hills are of national economic importance. Both are spectacular and large parts of the hills and the north-eastern slopes of the mountain abound in wildlife making the two landforms important for the tourism industry. The slopes and hills have water resources that serve Coast, Rift Valley and Eastern Provinces, and sources of unlimited quantities of aggregates and building materials. Irrigation utilizing the water yields produce for local use and export and sediments derived from the two form deposits of industrial minerals. Parts of the Kilimanjaro slopes with fertile volcanic soils are intensively cultivated for maize and beans sold to the National Cereals and Produce Board. The geology of both landforms, with its influence on the water resources, land use, origin of the industrial minerals and the nature and quantity of the aggregate and building materials found on them, needs to be understood.*

## INTRODUCTION

In East Africa, volcanic activity associated with the Rift Valley dates from Miocene to present day (Williams 1970). The volcanic occurrences (Fig. 1) include central volcanoes, such as Kilimanjaro, Africa's highest mountain, and shields built up of eruptive products of multiple vents, such as the Chyulu hills. Kilimanjaro has a base 100 Km long and 65 Km across, elongated WNW-ESE. It consists of three major volcanic centres; Kibo (5,895 m) in the centre, Mawenzi (5,148 m) in the east and Shira (4,005 m) in west and many smaller parasitic cones. All three major centres, and most mass of the mountain are situated in Tanzania, with only the middle and lower north-eastern slopes spilling over into Kenya. These slopes comprise lavas, locally with pyroclastics, debris-flow deposits, and fluviatile and lacustrine volcanic sediments. The age of these rocks is Pliocene to Recent.

The Chyulu hills, located 70 Km NE of Kilimanjaro, are constituted of Quaternary to Recent lavas and pyroclastics erupted from hundreds of vents making a pile up to 1000 m thick. The lavas and pyroclastics are erupted onto a dissected surface of Proterozoic metamorphic rocks, elevated inselbergs of which form inliers within the volcanics. Older lavas of Simba and Ngatatema occur just north of the Chyulu hills and rocks derived from Kilimanjaro on the south-west. The Yatta Plateau with Miocene phonolite capping lies 55 Km east of the hills.

Kilimanjaro and Chyulu hills contribute to the economy of Kenya in five ways. The slopes of the mountain situated in Kenya and the hills (1) have large volumes of groundwater, part of which is currently being exploited, (2) have sources of inexaustible quantities of aggregates and building materials, (3) source sediments forming deposits of industrial minerals, (4) are key parts of an important region for the tourist industry and (5) have fertile soils derived from the volcanics which receive high rainfall or are irrigated to grow produce for local use and export. The geology of both landforms influences all the above contributions.

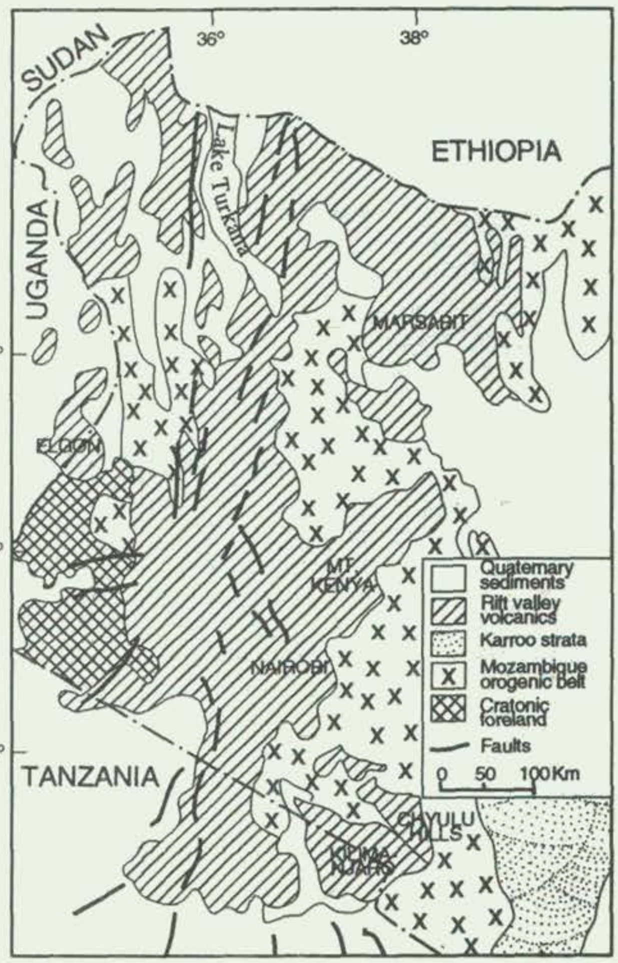


Figure 1. The distribution of the Rift Valley Volcanics in Kenya, northern Tanzania and eastern Uganda.

## GEOLOGY

### Kilimanjaro Slopes

The Kilimanjaro slopes form an arc-shaped area (Fig. 2) which straddles the Kenya/Tanzania border and extends from about parallel 3°30'S near Taveta in the south to parallel 2°37'S near Ol Tukai in the north, and from meridian 37°55'E at the Loolturesh river near Kitane in the east to meridian 37°06'E near Lake Amboseli in the west. These slopes are comprised of a sequence of lavas, locally with pyrocalastics, two debris-flow deposits and fluviatile and lacustrine volcanic sediments. These rocks are deposited on a dissected surface of the Proterozoic metamorphic rocks. Isolated cones of the Kilimanjaro lavas occur within the metamorphic rocks at Lorlawi, Mesanani, Timbila and Salaita. Williams (1972) designated the lavas and pyroclastics derived from Kilimanjaro the 'Kilimanjaro Volcanic Rocks'. An abbreviated form of this nomenclature 'Kilimanjaro Volcanics' has recently been used (Omenge and Okelo 1992) to describe the succession of lavas together with one of the debris-flow deposits. The distribution of these rocks is shown in Fig.2.

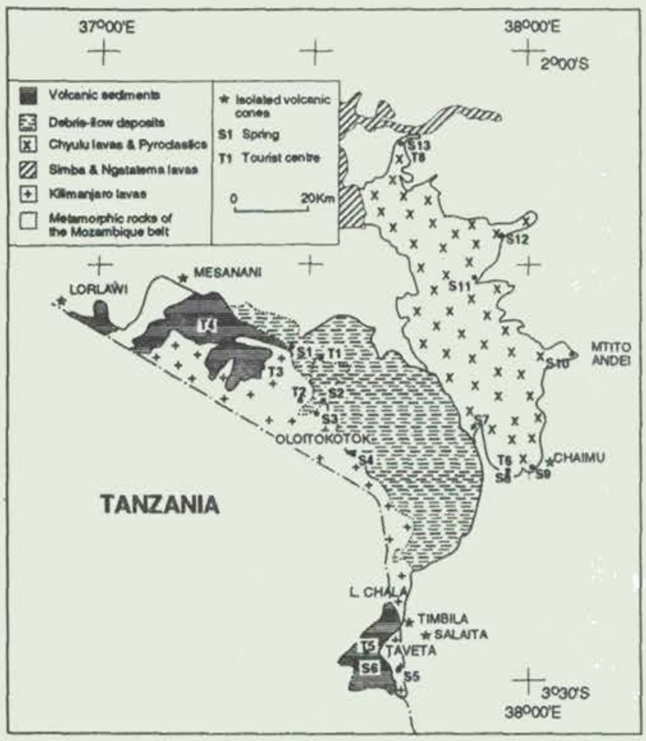


Figure 2. Distribution of rocks derived from Kilimanjaro, and Chyulu hills.

### *Lavas and Pyroclastics*

Lavas form a sequence of continuous and extensive flows derived from the three main centres of the mountain, the apparent order of activity of which was, first, Shira then Mawenzi, and finally Kibo. The occurrences in Kenya represent only the lower part of the sequence; the upper flows are found in Tanzania where the highest parts of the volcanic edifice are situated. Wilcockson *et al.* (1965) classified the succession in Tanzania into 'groups', including 'Ol Molog Group' (derived from Shira and lowermost), 'Newman Tower Group' and 'Mawenzi Group' (both derived from Mawenzi), 'Lent Group' and 'Inner Crater Group', the uppermost, (both derived from Kibo).

The earliest occurrences mapped in Kenya, are those south of parallel 3°00'S which Bear (1955) classified into two subdivisions of the 'Rombo Series'. These rocks are at least in part equivalent to the 'Newman Tower Group' and 'Mawenzi Group'. They also, together with adjacent metamorphics and intrusives, are subject of on-going work 'Rombo-Taveta Project' of the Mines and Geological Department (Siambi *et al.* 1993). Joubert (1957) studied the outlying occurrences of Kilimanjaro lavas west of meridian 37°00'E. Williams (1967, 1969) described the occurences lying between meridians 37°00'E and 37°30'E and classified them (Williams 1972) into seven 'groups' akin to those of Wilcockson *et al.* (1965). He noted that the oldest flows correspond to the 'Ol Molog Group' and the youngest, a small part of the 'Inner Crater Group'. The occurrences to the east of meridian 37°30'E and north of latitude 3°00'S have recently been mapped (Omenge and Okelo 1992) into two units as: 'Ilassit basalts' and 'Oloitokitok lavas', the youngest which corresponds to part of the 'Lent Group'. The Kilimanjaro slopes in Kenya therefore contain only the lower part of the Kilimanjaro volcanic sequence, with the uppermost units being equivalent to a small part of the 'Inner Crater Group'. These studies also show that the early flows of the sequence are mildly alkaline basalts and the upper flows much richer in alkalis but of more diverse compositions. The largest number of flows (representing the greatest thickness) of the sequence are of basalts. Other flows include nephelinites, tephri-phonolites and phonolites. Pyroclastics occur only as thin intercalations within the lavas. Parasitic cones situated on the flanks of the mountain have small agglomeratic flows, mainly olivine basalts. The isolated cones within the metamorphic rocks have limited flows ranging from analcime basanites to olivine basalts.

A K-Ar age determination for two early flows (olivine basalts) on the Kilimanjaro slopes gave c.1 Ma (Curtis, personal communication in Williams 1972). However this age is not reported in Evernden & Curtis (1965) who instead record three ages (0.51, 0.46 and 0.36 Ma) for rocks equivalent to younger flows in the succession. Wilkinson (1966) reports an age of 0.4 Ma for the 'Lent Group' in Tanzania. K-ar dates of c.0.25 Ma were given by Evans et al. (1971), also for rocks from the 'Lent Group'. Ages older than 0.25 Ma are therefore indicated for the bulk of the lavas in Kenya.

### *Debris Flows*

Two debris-flow deposits, one extensive and the other smaller scale and overlying the larger one, occur on the north-eastern flanks of Kilimanjaro (Fig.2). These deposits have been recently designated the 'Kuku formation' (larger deposit) and 'Kimana formation' (the smaller one), mapped and their characteristics described (Omenge & Okelo 1992). Both comprise materials derived from the older volcanics on the mountain. The extensive debris flow is characterised by hummocks which occur in several hundreds in an apparently haphazard, unpatterned manner. The hummocks are covered by thin soils with extensive spreads of boulders, a characteristic noted by Temperley (1960) when describing part of the deposit as a bouldery lahar. The boulders are of a number of lithologies, mainly olivine basalts. The deposit rests on a dissected surface of the Proterozoic metamorphic rocks, an inlier of which occurs at Losoito. Chyulu volcanics overlie the deposit on the east. The extent of the deposit east of longitude 37°30'E and south of latitude 3°00'S (marked with a dotted boundary on Fig.2) is unclear. Williams (1978) noted the considerable extent of the deposit and suggested an origin from the collapse of the old eruptive centre of Mawenzi.

The smaller deposit comprises two members; a muddy lahar (upper member) and unconsolidated fluvial clastics (lower member). The upper member is made up of multiple units of clasts with a wide range in size (0.2-3.0 m), often angular, usually lava fragments or pumiceous pyroclastics set in a pale coarse to fine-grained consolidated matrix. Crude inverse grading occurs. The lower member has normaly-graded rounded clasts also ranging in size. Cross-bedding, channelling and scouring and cobble lags occur and the material grades into a pale grey clay in the north. Six glacial periods have been recorded on the summit of Kilimanjaro (Downie 1964). The deposit is therefore probably due to glacial reworking of some of the volcanics and ablation of the ice caps leading to slumping from the upper slopes.

### *Lacustrine and Fluviatile Deposits*

Pleistocene age volcanic sedimentary deposits occur around Taveta and in the Amboseli basin. The deposits at Amboseli were first mapped by Joubert (1957) who designated them the 'Amboseli Lake Beds' and thereafter Williams (1972) used the same terminology. These authors describe in detail, among other things, the extent (areal and depth) and lithologies (clays, marls and silts) of the deposit and suggest a source as pyroclastics from Kilimanjaro outpoured into a lake. More coarser sediments (with conglomerates, gravels, and sands) mapped closer to the lava outcrops and regarded as a fluviatile facies of the lacustrine deposits, have similar characteristics to the smaller scale debris flow. The deposits extend into Tanzania and contain meerschaum, gaylussite and sepiolitic clays.

The deposit at Taveta extends into Tanzania (Wilcockson *et al.* 1965) and has been described as 'calcareous tuffaceous grits' by Bear (1955) who recognised the Chala crater as the most likely source. The sediments, partly water-lain and partly aeolian, overlie basalts in the crater walls. On the whole, the rock is poorly sorted and the fragments (partly volcanic and partly of metamorphics) are in places cemented by a calcareous matrix. Well-bedded horizons are sources of building stone.

## Chyulu Hills

The Chyulu hills are mainly constituted of lavas that are capped by pyroclastic cones to form a volcanic shield. The Shield is north-west/south-east oriented, some 80 Km long and 35 Km wide. Cones on the shield which erupted both lavas and pyroclastics are arranged in NNW-SSE or N-S chains forming a ridge along the axis of the shield. The lavas are tangential to the shield axis. There is an isolated cone with lava and pyroclastics within the Proterozoic metamorphic rocks at Chaimu in the SE of the main outcrop area (Fig.2). The area extends from about latitude 3°00'S at the Mzima springs to about 2°10'S NE of Kiboko, and from longitude 37°37'E to 38°08'E near Mtito Andei. The occurrence of the youngest eruptive products in the southern part of the hills indicates a SE migration of the volcanic activity with time.

### *Lavas and Pyroclastics*

Various studies have been carried out on the volcanics of the Chyulu hills. Saggerson (1963) mapped and described the occurrences north of parallel 2°30'S and west of Meridian 38°00'E. He delineated more than seventy individual lava flows of olivine basalt and distinguished them from the Lower Pleistocene analcime basanite and olivine basalt series of Simba and Upper Pleistocene olivine basalt series of Ngatatema and noted that the flows are pahoehoe, aa and blocky. The small occurrence to the east of Meridian 38°00'E and north of parallel 2°30'S was described by Walsh (1963) who identified the rocks as olivine basalts. Austromineral (1978) mapped some of the occurences east of longitude 38°00'E and referred to them as' Quaternary Basalts'. Wright *et al.* (1988), in a black and white geological map, show the distribution of all the occurences south of parallel 2°30'S. These occurrences were preliminarily classified by Wright and Parker (1985) into five broad subdivisions which were later (Wright and Gunston 1988) increased to seven. The seven subdivisions were recently designated (Omenge and Okelo, 1992) as: Oldoinyo Sambu and Elmau, Mzima, Iltilal, Kitane, Nooka and Leyenkati, Soitpus and Olokurto and Shaitani lavas and descriptions of the occurrences south of parallel 2°30'S and west of 38°00'E presented. Details of the petrology and chemistry of these lavas are also given in Fortey (1988). The bulk of the Chyulu lavas are alkali olivine basalts with exception of Mzima lavas, which are tholeeitic basalts, and Oldoinyo Sambu and Elmau lavas which are akin to lavas of Simba and Ngatatema.

The Mzima lavas overlie lake deposits located near Mzima springs. Two samples of these sediments, a calcareous tuffa and a shelly limestone, have given radiocarbon ages of c.26000 year BP (as reported in Wright & Gunston 1988). Charcoal from below lavas around Umani Springs gave a $^{14}C$ date of 480 +/- 200 B.P. (W-749, Saggerson 1963). The fresh appearance and almost complete absence of soil and vegetation on the youngest flows indicate very recent eruption: oral historical evidence points to an age within the last 100 years (Soper 1976). The lavas are therefore Recent in age.

### *Metamorphic rocks*

Inselbergs of Proterozoic metamorphic rocks occur as inliers on the western and eastern flanks of the Chyulu ridge and at the south-eastern extremity of the hills. Those for which detailed descrptions of occurrances and their lithologies are given in Omenge & Okelo (1992) and Saggerson (1963) include: Leyankati, Soitpus, Olokurto and Eldoinyo Longido (west flank), Nooka, Komboyo, Kenzili, Umani and Kibwezi (eastern flank) and Poacher's Lookout (southern extremity). Main lithologies are quartz-feldspar-biotite, hornblende-biotite and biotite-garnet gneisses.

## TOURISM

Kilimanjaro, rising 5000 m above the surrounding ground on average, dominates most of SE Kenya. Its highest peaks, perennially snow covered Kibo and rugged Mawenzi, together with the forest-clad middle slopes and the lower areas with hummocks of the larger debris flow are scenic. These receive heavy rainfall (Table 1). The lower slopes with lavas, characterised by rough topography of boulders and thick vegetation, are home of a variety of wildlife. A large part of these slopes together with the Amboseli basin fall into the Amboseli National Park. To the south the hummocky topography develops into a SE slope with the spectacular Chala crater. Five major tourist centres: Kimana (T1), Kilimanjaro Buffalo (T2), Amboseli Serena (T3) and Ol Tukai (T4) lodges and Chala hotel (Taveta) (T5) are located on the Kilimanjaro slopes.

Table 1: Average annual and quarterly rainfall for stations on the Kilimanjaro slopes and Chyulu hills (from Touber 1983 and Makin & Pratt 1984).

| Station | Elavation (m) | Period of record | Jan-Feb (mm) | Mar-May (mm) | Jun-Sep (mm) | Oct-Dec (mm) | Ann. total (Ave., mm) |
|---|---|---|---|---|---|---|---|
| 1 | 1432 | 1971-81 | 175 | 774) | 33 | 643) | 1625 |
| 2 | 1572 | 1975-82 | 60 | 441 | 154 | 454 | 1109 |
| 3 | 1845 | 1970-74 | 0 | 394 | 115 | 472 | 981 |
| 4 | 1790 | 1970-74 | 112 | 271 | 31 | 384 | 798 |

1: Oltiasika, Chyulu hills, western flank.
2: Chyulu 1, Chyulu hills, central ridge.
3: Outward Bound Mountain School, Kilimanjaro mid-slope.
4: Oloitokitok District office, Oloitokitok.

The Chyulu hills are also important for tourism is SE Kenya. Features that are attractive include the hundreds of closely spaced cinder cones, fresh lavas and pyroclastics, such as the Shaitani and Chaimu flows, and the spectacular Mzima springs. The high rainfall received on the hills (Table 1) enables formation of soil pockets on older lavas and pyroclastics which support plant growth. The hills are covered by vegetation ranging from grass with a few shrubs at the lower flanks to dense forest on the higher parts. A variety of game inhabit the hills, a large part of which falls into the Tsavo West National Park. Three important tourist centres are found on the hills namely; Kitane (T6), Kilaguni (T7) and Hunters Lodge (Kiboko) (T8).

## WATER RESOURCES

The Kilimanjaro slopes and Chyulu hills have water resource that are not only locally but also regionally important. Thes resources depend strongly on topography. The main inputs are from the high levels of orographic rainfall (Table 1) and, to a lesser degree, mist precipitation, on Kilimanjaro and the Chyulu hills. These infiltrate the permeable (mainly in the form of fissures) basalts which are the primary aquifers in both cases to form large underground reservoirs. The water comes out at springs and can be tapped in bore holes, wells and the crater Lake Chala.

### Springs

Springs occur at junctions of the Kilimanjaro basalt lava flow and those between the Chyulu basalts and the underlyin impermeable metamorphic rocks. These springs provide th base flows to the larger rivers and streams that supply water t the more arid parts of south-east and eastern Kenya, particularl the Tsavo/Galana system; water used locally and in distant centres. Principal springs on the Kilimanjaro slope include (Fig.2): Engumi (S1), Tikondo (S2), Emperon (S3), Loolturesh (S4), Njoro Kubwa (S5) and Kitovo (S6).

The Largest of these are Loolturesh (Nolturesh) springs, from which water is abstracted into three pipelines. The older (gravity fed) pipeline with a capacity of c.2.16 million litres per day distributes water to Sultan Hamud, Simba and Kiu. The newly constructed (the Nolturesh Water Project) pipeline has an abstraction rate of 150 litres per second and distributes water with the help of pumping stations to distant centres such as Mashuru, Ulu, Athi River, Machakos and Kajiado. A separate intake at the springs (the Oloitokitok water supply) abstracts 20 litres per second for use in the Oloitokitok area.

Springs which discharge from the Chyulu volcanics are situated on the lower parts of the eastern flank from north to south. The principal examples shown in Fig.2 include: Moilo (S7), Kitane (S8), Mzima (S9), Mangalete (S10), Umani (S11), Manoni (Chai) (S12), and Kiboko (Hunter's Lodge) (S13). The most importlant of these are the Mzima springs, of which flow values are estimated to C.4700 litres per second. 367 litres per second of these are piped to Mombasa. Flow rates for most of the other springs are quoted in Temperley (1960) and Wright and Gunston(1988).

### Lake Chala

In addition to the springs on the Kilimanjaro slope, fresh water is found in the crater Lake Chala, with a surface area of over 12 $Km^2$ and a depth below the water surface estimated (Bear 1955) at 80-90 m, shared between Kenya and Tanzania. This lake which has no surface inlet or outlet may well be the source of water for springs to the east and south of the crater. No abstraction is being made from the lake at present.

### Bore Holes and Wells

In the absence of springs, bore holes and wells provide the means for drawing water from aquifers. Several bore holes to obtain water have been drilled in the Kilimanjaro slopes especially in the NW and south. In the Chyulu hills several boreholes have been drilled in the northern parts. Details of location of the boreholes and analyses of the water, among other things, are presented in Williams (1972), Bear (1955), Saggerson (1963) and Walsh (1963). Most recently a bore hole was drilled at the Loolturesh springs to provide supplementary supply in case of fluctuation of the spring flow. Known wells include those at Iltilal near the Chyulu hills (Omenge and Okelo 1992).

## AGRICULTURE

The mid-Kilimanjaro slopes have fertile brown soils derived from weathering of lavas and receive high rainfall (see Table 1). These areas (around Oloitokitok) are intensively cultivated and maize and beans grown are sold to the National Cereals and Produce Board. Areas around Kimana have grey pebbly soils developed on the debris flow deposit which are irrigated with water from the Loltulelei stream and Tikondo spring (Njeru 1980, Mungai and Kanake 1978) to grow vegetables. Horticulture using irrigation is also practised near Rombo. Produce from these activities is mainly for export and sale in Nairobi and Mombasa. Further south, water from streams and springs on the Kilimanjaro slope irrigates plantations at the Taveta and Ziwani estates (Bear 1955) where sisal is grown for export. The Manoni springs in the NE part of the Chyulu hills provide water for the Dwaa sisal estate factory (Walsh 1963).

## BUILDING METERIALS AND AGGREGATES

### Aggregate

Lavas of the Chyulu hills and Kilimanjaro slopes are mainly basalts. All basalt lavas that occur on the two landforms are considered to be potential aggregate sources, with flow units that are well consolidated being most suitable. Whereas, most Chyulu lavas are not very well consolidated which limits them as potential sources of aggregate, the Kilimanjaro lavas in general are more massive flows and are therefore better suited for aggregate. Potential sources from these rocks are to be found at most stream cuttings on the mid-Kilimanjaro slopes and at the edges of individual lava flows. Most recently, aggregate from the flows were used to tarmac part of Oloitokitok-Taveta road. Studies carried out by the Ministry of Public Works (Onduto and Radier 1973) show that the lavas at Timbila hill and those downslope Chala crater on the east (Kirimeri River) are of 'surfacing quality' for road building and material of the volcanic sediment around Taveta suitable for 'road base'. Fresh (unweathered) quartz-feldspar-biotite gneisses on the metamorphic inliers could be used as alternative sources of aggregate, although the cost of crushing, and wear and tear on machines, is likely to be much higher than for basalts.

### Building and dimension stone

The volcanic sedimentary deposit at Taveta affords a good source of building stone on a regional scale. Quarries from where blocks are extracted by hammer, lever and chisel are situated along the Kenya/Tanzania border, NW of Taveta. The source extents into Tanzania (Wilkockson *et al.* 1965). However, the total volume of the building stone is unknown. Although in general Chyulu lavas are not well consolidated, the Mzima and Iltilal lavas have pronounced polygonal cooling joints which enables the rocks to be utilised for building. Blocks of these lavas have been used for walls of the Kilaguni and Kitani lodges and towns along Nairobi-Mombasa road. Pyroclastic bomb material of the Chyulu lavas makes good 'hard core' for foundations of houses. Massive blocks from the Kilimanjaro lavas and the debris-flow deposits make good building stone when split, and have been used for walls of Kimana, Kilimanjaro Buffalo and Amboseli Serena lodges and markets on the Kilimanjaro slope. Blocks of fresh (uweathered), locally rather flaggy quartz-feldspar-biotite gneisses form attractive walls, floors and pavements as has been demonstrated at most of the tourist lodges on the Kilimanjaro slope and Chyulu hills.

### 'Sand and Gravel'

Lack of consolidation of most Chyulu lavas makes them good sources of 'gravel' for all-weather roads. Lapilli from cinder cones, such as Chaimu, agglomeratic lavas of the subsidiary cones and fine-to very coarse-grained sand-grade material of the smaller scale debris flow when mixed with cement are used for making building blocks. Much of these materials are unconsolidated and easily won. Similar but reworked material may also be obtained from rounded fragments composed of vesicular basalt and pumice in streams. The finer-grade but clast-rich material scraped off the sides of hummocks of th larger debris-flow deposit and lapilli are also used for surfacin earth roads. Around Taveta, kunkar formed from weathering o agglomeratic lavas is mixed with sand and cement to make blocks for building.

## INDUSTRIAL MINERALS

Both the Chyulu hills and Kilimanjaro slopes are sources of materials forming deposits of industrial minerals. The occurrences include meerschaum, gaylussite and sepiolitic clays found in the Amboseli basin; the Ziwani and Lake Jipe clays, kunkar and industrial rock of around Taveta and kunkur and industrial rock of the northern parts of the Chyulu hills. Investigations carried out on the meerschaum reported in Williams (1972) indicate that the deposit has over 1 million tonnes of host rock with 225-340 g of meerschaum per tonne of host rock. Gaylussite occurs beneath the alluvium on dry Lake Amboseli. Investigations carried out by Matheson (1972) reveal that the reserves total over 3 million tonnes. Studies into the clays which occur at Amboseli reported in Williams (1972) only indicate that the sepiolite is contaminated in varying degrees by impurities including carbonate minerals but give no figures of the reserves. No detailed investigations have been carried out on the clay deposits found at Ziwani and near Lake Jipe. Pale grey clays, at present used solely as whitewash, occur in the northern part of the smaller debris-flow deposit, towards the base (Omenge and Okelo 1992). Bear (1955) and Saggerson (1963) report occurrences of kunkar and attempts to use Chyulu hills and Kilimanjaro lavas as pozzolana and for the manufacture of ceramics.

## DISCUSSION

Heavy rainfall, geology and unique physiography combine to make the Kilimanjaro slopes in Kenya and the Chyulu hills important landforms. Water resources found in these areas serve a large number of centres in southern Kenya. The unique physiography (rough lava country) and thick vegetation combine to provide good habitat for wildlife and these together with the beauty of the country make the two landforms important regions for tourism. Areas with thick fertile soils derived from weathering of the volcanic rocks on the mid-Kilimanjaro slope are cultivated for maize and beans consumed locally and for sale. Elsewhere in lower areas irrigation from the springs and streams produces fruits, vegetables and sisal used locally and for export. Industrial minerals formed from sediments derived from the volcanics are found in the Amboseli basin, near Taveta and in the northern parts of the Chyulu hills. Detailed investigations need to be carried out on some of these. Both the Chyulu hills and Kilimanjaro slopes abound in sources of aggregates and building materials which are likely to become increasingly important with time. Knowledge of all these resources is important both for District/Regional and National planning. The two landforms are therefore very important for the economy of Kenya.

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## Petrology of the gabbroic suite of rocks occurring South East of Mt. Kenya

J. O. Ochieng
Mines and Geological Department, P.O.Box 30009, Nairobi, Kenya

**ABSTRACT**

*Groups of basic igneous bodies of various shapes and sizes upto several kilometres long/wide, occur ubiquitously in the Kenyan Mozambique Belt (MB). Some of these are associated with dismembered ophiolitic complexes while others are sheet or lopolith intrusives with complex metamorphic history, having been affected by at the last structural/metamorphic events of the MB. Two groups of gabbroic rocks, about 50 Km apart, and which presumably belong to the latter category, occur S.E. of Mt. Kenya in Central Kenya. The suite ranges from layered anorthositic gabbros to orthopyroxene bearing varieties, occurring as discrete lenticular or elongate bodies, oriented mainly in the arc NW-NE, generally parallel or subparallel to the main gneiss trend. Mineralogy is invariably orthopyroxene, clinopyroxene, plagioclase, amphiboles and a host of accessory minerals (including clinozoizite, ilmenite, sphène, zircon, olivine, spinel). Corona textures are a prominent feature of these rocks mostly exhibited by pyroxene/iron ore (+/- spinel) surrounded by clinopyroxene (+/-spinel), hornblende (+/- spinel), magnetite (+/- spinel). Hornblende also occurs as pseudomorphs of large (upto 20 cm long) cumulus pyroxene crystals indicative of replacement of the latter in post magmatic metamorphism/cooling. These at places occur intergrown with equally large ilmenomagnetite of economic significance.*

### *INTRODUCTION*

The Mozambique Belt (MB) in Kenya is exposed mainly in the central portion of the country in a N-S elongation, beginning from the Tanzanian border and extending almost to the border with Ethiopia. This exposure is bordered to the east by sedimentary units, ranging in age from Carboniferous to Quaternary. The latter rest unconformably on the MB while the older sediments to the south probably have a tectonic contact.

To the west, the exposure is bound by the volcanics of the Rift Valley under which it disappears. Mt. Kenya volcanics form a circular feature in the MB, merging with the Rift volcanics to the west. Other relatively smaller exposures of the MB occur west of the Rift Valley in the south and central western parts of the country and also in the north east. Basic intrusives occur intermittently within the MB some of which have been associated with dismembered ophiolitic complexes. The majority are however considered to be sheet or lopolith intrusives with multifarious emplacement/metamorphic history. This paper looks at the petrology and spatial relations of two groups of the latter type of intrusives of gabbroic composition occurring south east of Mt. Kenya.

### *Location*

The intrusives occur in clusters of discrete or connected circular to lenticular bodies, the latter oriented generally in the arc NE-NW. Individual bodies range from a fraction of a kilometre to several kilometres in length and/or width. One group composed mainly of anorthositic metagabbros occur on the northern flanks of River Tana some 40-odd Km south of Embu town. The other group constituting mainly a gabbro-norite suite, occur about 60 Km NE of the first and extends northwards for over 50 Km. (Fig. 1).

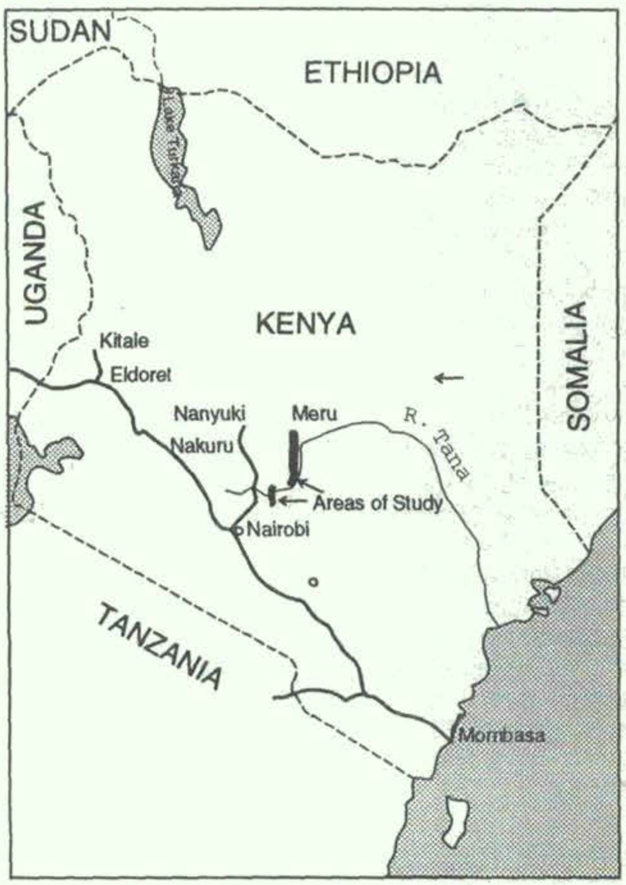


Figure 1. Location map of the gabbroic rocks

### *GENERAL LITHOLOGY*

The two groups, although showing considerable variations within themselves are believed to be of the same age and origin, but to have been modified by their post-emplacement metamorphic and deformational history.

The gabbro-norite suite is enveloped by granulitic dioritoid gneisses, composed of the mafic minerals hornblende, biotite and pyroxenes with quartz and feldspar forming an important component. These rocks also show local centimetre to decimetre scale compositional layering. Mosley (in press) lists features common to the two groups, and indeed to other bodies not covered in this study, to include:

(a) a composition of a range of anorthositic to ultramafic rock types layered on cm- to dm-scale;
(b) ortho- and clinopyroxene and hornblende mineralogy with calcic feldspars, much spinel and little or no garnet;
(c) corona structures;
(d) deformation by the Late Proterozoic phase of shearing, represented by boudins on all scales, from microscopic to regional, giving the lenticular shapes of the bodies.

## DETAILS OF LITHOLOGY

One of the bodies in the norite-gabbro suite, the Ntugi, is bordered to the south by finely banded gneisses in association with disrupted basic bands and lenses, which are offshoots of the main body. The basic bands vary upto 1.5 metres in thickness and variably have quartz in tension gashes. The bands increase in quantity and size towards the centre of the body, and the overview of the rock is a streaky heterogenous mafic gneiss with dark disrupted and folded basic lensoid boudins. Later dykes of a finer-grained dark rock with visible feldspar laths, randomly cross-cut the whole group. Medium- to coarse-grained, massive dioritoid gneiss with weak foliation traces, often grading into a dark, banded calc-silicate variety on one side and into a streaky coarse-grained gneiss with garnets on the other side is also present. The garnets are mostly concentrated within the margins of mafic pods in the rock. A homogeneously speckled variety contains distinctive mafic schlieren.

The central parts of the body incorporate websterites which continue to the northern foot hills where loose blocks *in situ* show igneous layering, mainly pyroxenitic cumulates and sub anorthositic couplets (upto 1 mm pyroxene and 30 cm pale anorthosite). Layering is also defined by coarse and fine bands ranging from mm to dm scale, often with gradational boundaries. In the finer-grained varieties, corona rimmed olivine and pyroxene megacrysts are in a grey anorthositic matrix. Some pyroxenitic cumulate layers have been altered to amphibolitic (hornblende and richterite) rich in ilmenomagnetite with low Cr and Ni and high V. The ilmenomagnetite occurs in discrete layers or intergrown with large (up to 20 cm) hornblende and richterite.

These layers are nearly vertical, striking 360°-040°, and have been worked for the ilmenomagnetite. The amphibole weathers to a pale green colour and with a marked schiller structure. The table below shows chemical analysis of the ilmenomagnetite:

Elsewhere in the area, the norites contain coarse and locally pegmatitic pyroxenites and pyroxene accumulations which are not commonly stratiform but possibly represent squeezed cumulate residual patches.

Table: Chemical analysis of the Marimante ilmenomagnetite. Figures in %.

| Sample number | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $SiO_2$ | - | - | - | - | 7.58 | 4.10 |
| $Al_2O_3$ | 1.80 | 1.80 | 4.10 | 4.10 | - | - |
| $Fe_2O_3$ | 31.20 | 31.20 | 54.50 | 52.80 | 48.41 | 58.61 |
| CaO | 0.14 | 0.28 | 0.36 | 0.37 | - | - |
| MgO | 0.52 | 0.94 | 2.00 | 2.10 | - | - |
| $TiO_2$ | 14.20 | 14.20 | 30.50 | 30.50 | 36.86 | 35.16 |
| $Na_2O$ | 0.54 | 0.97 | 0.02 | 0.01 | - | - |
| $K_2O$ | 0.10 | 0.12 | 0.03 | 0.09 | - | - |
| $V_2O_5$ | - | - | - | - | 0.84 | 0.88 |
| $V_2O_3$ | - | - | - | - | 0.67 | 0.70 |

The most common type is coarse-grained (3-4 mm) with 5-6 mm mafic patches exhibiting ubiquitous corona structures. The centres of these structures weather out easily leaving fairly reddened limonitic minerals with distinctive dark green fibrous rims which are spinel-hornblende simplectites. (Plate 1)

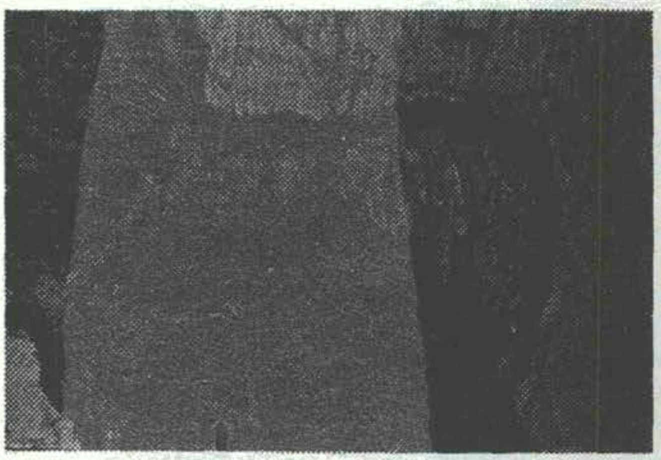

Plate 1: Orthopyroxene-hornblende-plagioclase reaction zoning. hbl/spinnel symplectite between hbl and plg.

Locally there are cumulate layers, usually not exceeding 20 cm, composed of pyroxene crystals upto 3 cm across which pass rapidly out into coarse to pegmatitic anorthositic gabbros.

Another large body of the suite, the Njunguni, is composed of rocks similar to those described above: coarse grained and massive with pyroxene crystals up to 5 mm, and prominent corona structures having limonitic or hollowed out centres. Outcrops are on the whole bouldery but lack the layering which is abundant in the Ntugi body and instead have medium-grained varieties with phenocrystic pyroxene crystals in a grey feldspar/pyroxene background.

In the anorthositic bodies on the northern flanks of the Tana, lithologic variants are distinguished by the felsic/mafic differentiation and also by the extent of shearing and metamorphism. Such compositional variation has been recorded for other anorthositic gabbros such as those of the Clinton-Colden hornblende gabbro-norite in Canada (Macfie, 1987). The shapes of the bodies are rounded in plan and are composed of dense, massive and locally layered anorthositic gabbro blocks. The rocks are characterized by abundant amphibolitic variants of mafic cumulates injected with late stage felsic veinlets giving rise to a patchy locally leucocratic gneiss appearance. As with the noritic suite farther to the north, the fringes of the bodies are associated with amphibolitic and ultramafic bands and pods with rare calc-silicate alterations. Feeble felsic mineral lineation and amphibolitised coarse pyroxenite cumulates are indicators of metamorphism but relict igneous layering is evident.

## PETROGRAPHY

Thin section studies show the plagioclase as ranging between oligoclase and bytownite (median $An_{60}$), a lot of it as inclusions in pyroxenes. Hornblende is mostly replacive of pyroxenes and forms an important constituent of the rocks. Some pyroxene-shaped cumulates are actually amphiboles. Primary hornblende is also present in some gabbros. Hypersthene is a major constituent, though not equally distributed. The most abundant pyroxenes are augite and diopside. Quartz is also found with the acid plagioclases in small amounts. Clinozoizite and zircon are present in some specimens. Iron ore is present in varying amounts throughout the slides.
Reaction zoning is a major feature of the rocks, exhibited in the following were noted (core minerals first):

1. Hypersthene-(magnetite)-(+/-)augite-hornblende-magnetite + plagioclase (see Plate 1)
2. Augite-hornblende and spinel
3. Olivine (+/-magnetite)-augite-hornblende with spinel ( Plate 2)
4. Olivine - hornblende ( Plate 3)

Pulfrey (1946) also lists the following additional sequences:
1. Hypersthene with a little spinel-hornblende with spinel
2. Hypersthene-hornblende
3. Hypersthene (+/-)spinel-augite and spinel-hornblende and spinel
4. Iron ore-hornblende.
5. Hypersthene - tremolite - hornblende

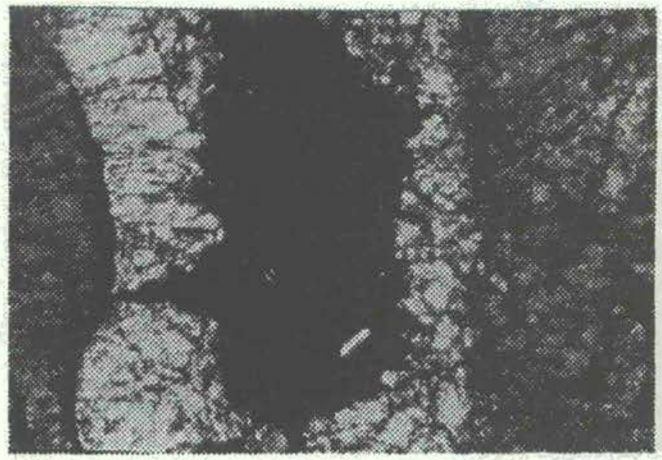

Plate 2: Iron ore-olivine-clionopyroxene-hornblende corona. Most of the olivine has been replaced by the ore.

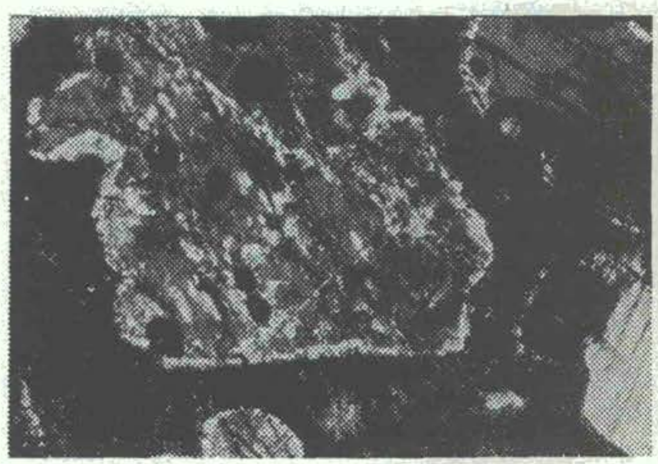

Plate 3: Olivine surrounded by hornblende

Olivine when present is partly altered to iron ore or hypersthene and indeed the hypersthene and iron ore cores could be wholly altered olivine. The anorthositic gabbros, despite exhibiting macroscopic lithologic variations, show a close microscopic similarity typified by completely pseudomorphosed original coarse pyroxene grains by fresh fibrous, medium grained dark green pleochroic amphibole crystals.

## DISCUSSION

Generally, the two formations are broadly concordant with the surrounding gneisses and clearly predate at least the last phase of tectonism and metamorphism in the Mozambique Belt which is believed to be 630-580 Ma based on Rb/Sr dates from areas farther to the north (e.g Hackman, 1988; Charsley, 1987; Key, 1987). The elongate shapes of the bodies and their alignment with the enclosing regional structural grain of the gneisses suggest compressional deformation during the regional MB Orogeny. This is evidence for at least synorogenic emplacement. Within the bodies, though, deformational structures are limited to the poorly exposed margins where faint foliation and shear textures are exhibited. Many of the bodies do not show any traces of deformation, but this is no evidence for post-deformational intrusion: some bodies behave as rigid blocks during deformation (Davidson et al, 1979). Evidence for pre-metamorphic/deformational intrusion is also found in the various lenses and bands of basic 'stringers' or offshoots from the main bodies which have been folded with the host rocks. Earlier authors (Pulfrey, 1946; Bear, 1958; Schoemann, 1951) classified these intrusives into several groups such as diorites, gabbros, norites, amphibolites, pyroxenites, perknites, bojites and hyperites The present study shows that the rocks are more or less similar mineralogically and texturally and are considered to be variations in a gabbroic suite. The rocks are thus interpreted as moderate to thick sheets intruded into the gneisses and boudinaged on a large scale during the last phases of the regional deformation. In regional context, these bodies may be related to similar ones farther north in the Chanler's Falls area (Williams, 1967), Barchuma-Kom area (Dodson, 1963), Laisamis area (Randel, 1970), Moyale area (Walsh, 1972), the area to the north east of Marsabit (Dodson, 1991) and Buna area (Williams and Matheson, 1991). On even a wider regional scale, Andreoli (1991) describes a series of anorthositic, gabbro-norite suites with similar mineralogy and featuring granulite facies assemblages, occurring in a roughly N-S linear belt from Mozambique to northern Tanzania. The suite in this study is therefore apparently a continuation of the series. Andreoli further suggests that these East African rocks have closest analogues in the Marcy massif of the Adirondacks. Many of the gneiss and migmatite formations enveloping the present intrusives are granulitic in appearance; garnets, hypersthene and plagioclase form common assemblages (Ochieng et al, in preparation). Further, occurrence of ilmenite with hornblende has been interpreted to represent granulite facies metamorphism (Mengel and Rivers, 1991).

The replacement of olivine by hypersthene together with the general corona sequences, little garnet and hornblende-spinel symplectites indicate moderate pressures post-emplacement, probably due to slow uplift. Grant (1986) has described corona textures, similar to the ones in this study, as having been produced by reaction between plagioclase and olivine + Fe-Ti oxides for metagabbros of the Central Gneiss Belt of Ontario, where ilmenite also forms cores. In the absence of corroborating analysis, the iron ore cores in this study, seen mostly as replacive of olivine, might as well be primary titaniferous oxides. Emslie (1983), on the Michael gabbros in Labrador, concludes that corona development was the result of subsolidus reactions during lower temperature re-equilibration on cooling at considerable depths.

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# THE KENYAN PROSPECTOR: HARDSHIPS AND SOLUTIONS

N.N. Kamundia
Mines and Geological depart., MENR, P.O.Box 30009, Nairobi

## ABSTRACT

*This paper highlights the problems the majority of indigenous Kenyan prospectors face, mainly due to their lack of understanding of technical and scientific laws governing mineral deposits. Their limitations are manifested at both the stages of prospecting and exploitation. An attempt is made to suggest assistance that can be given to the prospectors by professional geologists.*

## INTRODUCTION

### Problems met during prospecting stage

The need for professional assistance is brought out by erroneous practice:

(a) Staking Outside Reef

Due to lack of understanding of geological controls, a prospector who samples an alluvial mineral may stake his claim outside the in-situ ore body and include the placer in the centre of his claim (Fig.1).

(b) Dumping on lateral extension of the ore body (Fig.2).

(c) Staking Across Ore Body (Fig.3).

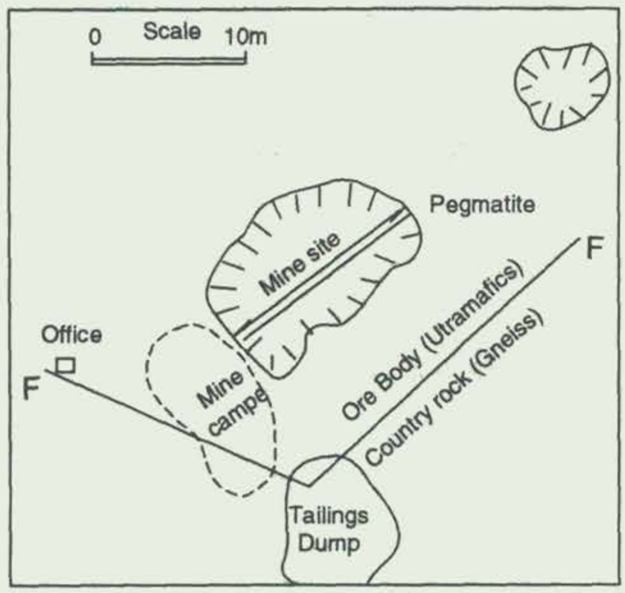


Figure 2. Dumping wrongly soted

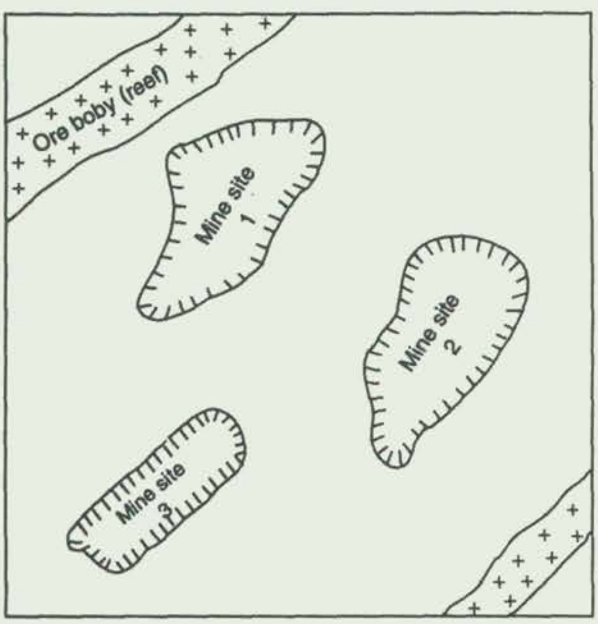


Figure 1. Staking Outside Reef (Plan view)

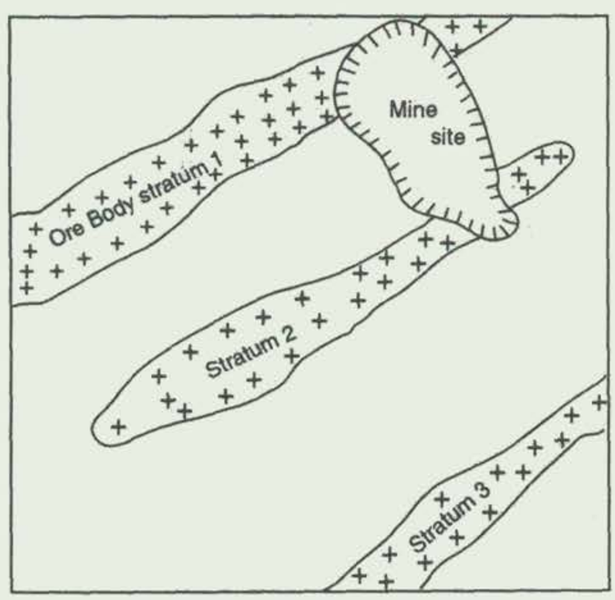


Figure 3. Mining across the strike (plan view)

(d) Wrong approach to concealed ore bodies (Fig.4).

(e) Failure to trace strike (Fig.5, Mine B).

Some claims are pegged parallel to existing ones without regard to the strike being followed by existing mine.

(f) Mining in Two-Dimension, down-dip (Fig.6).

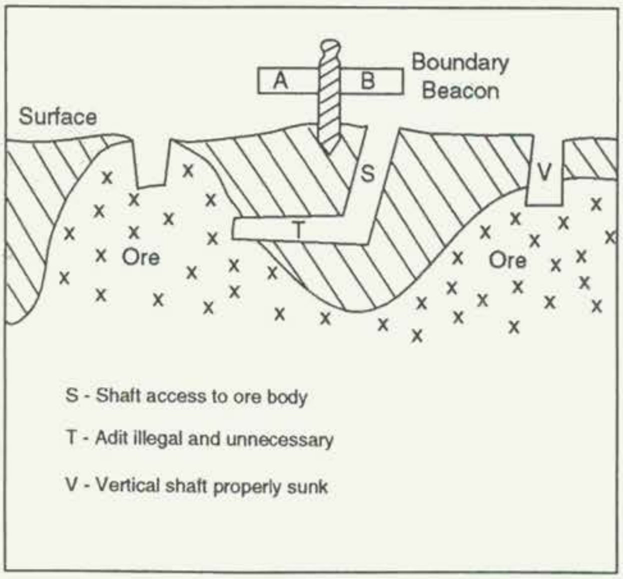


Figure 4. Wrong approach to concealed or bodies (section view)

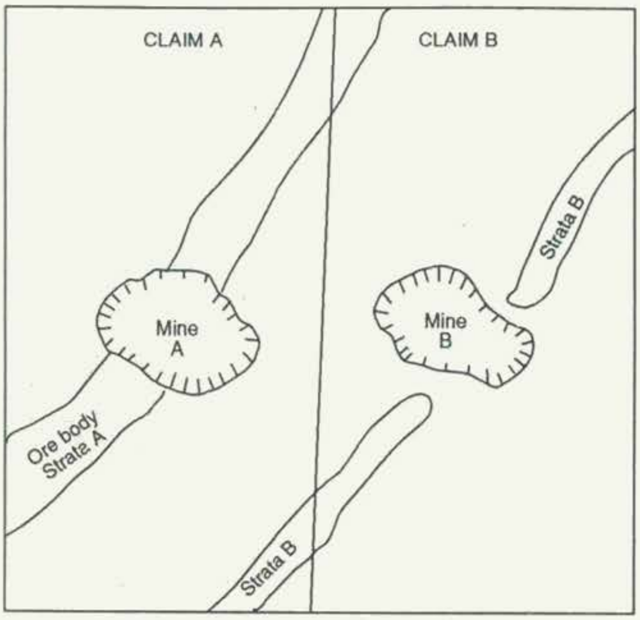


Figure 5. Failure to trace Strike (plan view)

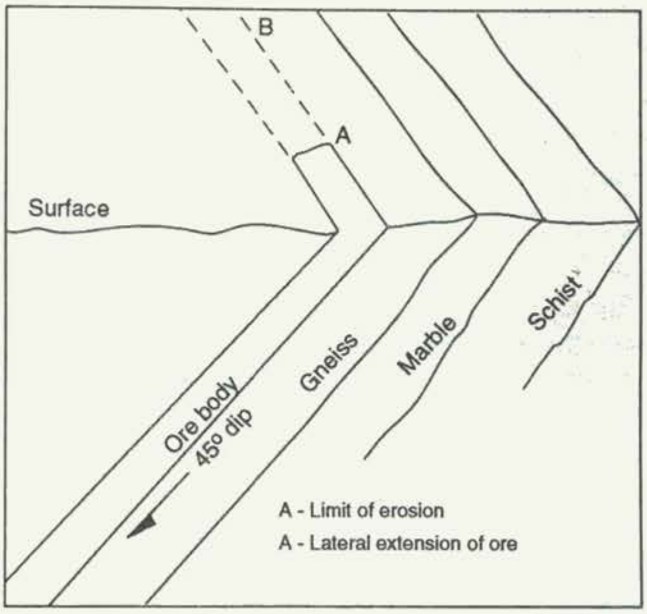


Figure 6. Mining in two dimensions down the dip (section view)

**Lack of knowledge about chemistry of minerals**

Some prospectors having obtained a chemical assay certificate showing presence of aluminium oxide, often reach the conclusion that the mineral assayed must be ruby. One prospector stunned the writer when he claimed that heating zircon (or silicon?) in sulphur gives "red mercury". The saga about red mercury has had its rounds in Nairobi and Mombasa for the last dozen years with some prosector alleging that it is used in the manufacture of "nuclear atomic bombs". Some claim it is produced from Zaire while others claim it comes from Europe. Some unsuspecting prospectors have fallen prey to the red mercury deals. Some prospectors paid as much as Sh.125,000 as down payment, for the seller never to be seen again.

**Lack of knowledge about physical properties**

Some prospector produced quartz (H7) and claimed it scratched diamond (H10). On the author's proof to the contrary regarding the relative hardness, the prospector claimed that the diamond I used for testing must be harder than his diamond that he has used over the years!

## PROPOSED SOLUTIONS

(a) During Prospecting and Pegging: A geologist becomes handy as he can identify the minerals found in the field. He will also be able to relate it genetically to the "mother-rock" or reef. Pegging will then be in accordance with the mineralisation and strike. It is common observation that after a prospector observes alluvial samples he engages the services of a sign writer whom he shows where to install the beacons he has written. In most cases the prospector will peg the area enclosing the alluvial samples site, rather than survey his stake after taking into consideration the strike and dip of the reef.

(b) During the compilation of Work Programme: The drawing of work programme is a very important step and, if drawn by "businessmen" or economists, it may have unbearable technical handicaps when considered against the licence conditions of EPL category of licences. It is also common knowledge that the sign writer referred to above is also asked to draw the programme of work. This work is best tackled by a geologist who understands the geology of the area under consideration.

(c) During establishment of mine site: many mine sites are wrongly established due to lack of knowledge by prospectors and it appears that mine sites within a claim are established haphazardly. If a geologist is involved, such cases as mining across the strike would be eliminated. A geologist will establish mine sites with regard to his geological mapping of the area.

(d) During the compilation of Mining Plans: For underground mining, a geologist becomes most important as he is capable of mapping the subterranean occurrence of ore bodies. He should be able to advise on the best method of underground access, after which a mining engineer will be needed to advise on mine support and sinking of underground ways.

(e) In grading of Gemstones: Some geologists will be able of grading gemstones into A 1-3 and B 1-3. This is the first step in gemstone evaluation. A geologist will find it easier as he can identify the minerals much faster using his knowledge in crystallography, cleavage, dichroism etc.

(f) During New Product Promotion: When a new gem is discovered, it will need promotion. An example in mind is the tanzanite which was discovered in 1967 and tsavorite. In both cases the geologist was involved in the identification before gemmologists took up the minerals for detailed descriptions which led to their final names. It is to be noted that gemological laboratories have geologists and geologists-turned-gemmologists in the staff complement.

## CONCLUSIONS

It is a well known fact that the geologists in Kenya have not had their profession sold to majority of prospectors. In fact only a handful of prospectors are or employ the services of a geologist. The majority, who are indigenous, consider geologists "white-collar prospectors" who have the academic excellence but who would not soil his hands in helmet-and-boots job.

It is high time that geologists sold their professionalism to the prospectors by such simple incentives as conducting on departmental basis rudimentary geological classes that will lead the prospector to know that mineral occurrences are based on a scientific discipline called geology.

# THE USE OF PHOTOGEOLOGY IN STUDYING LAND DEGRADATION: A KENYAN EXAMPLE.

A.O.Odawa
Mines and Geological Dept, Ministry of Environment and Natural Resources.

## ABSTRACT

*Soil erosion is a major cause of land degradation in Kenya. Some of the most affected parts of the country are situated within the arid and semi arid parts of northern Kenya. An integrated photogeological study was conducted for the Barsaloi area of Samburu District, Rift Valley Province, to detect soil erosion and to determine its possible causes. The study involved analysis of a multispectral Landsat TM satellite images interpretation of aerial photographs, and use of geological and topographic maps.*

*Interpretation of the satellite image was carried out to identify different lithologies together with their alteration and the various soils and vegetation by use of bands 7, 3 and 1. To reveal linear features like faults and rivers, edge enhancement was performed on single bands 4 and 5 using a high pass filter. The aerial photographs of the 1950's and compared with the 1986 satellite image, helped to detect changes. The geological and topographic maps were used to determine lithology, geomorphology and the drainage pattern. The combined results of the study show that the frequency of soil stability index values for the area tends to be normal and can therefore be described by the statistical parameters which are determined from spectral signatures.*

## INTRODUCTION

The aim of the project was to compare the capability of a Landsat Thematic Mapper (TM) imagery and aerial photographs to detect and/or predict the land degradation by soil erosion in the semiarid tracts of Barsaloi. The increased spatial and spectral resolutions of TM imagery was expected to provide a considerable improvement over the capabilities of its predecessor, the multispectral scanner (MSS) imagery .

The Barsaloi project area is bounded by latitude 1°22'N and 1°35'N. The area is drained by the Barsaloi and Masiketa rivers, which flow eastwards, joining just before they cut through the eastern hills to form the Milgis river. They are seasonal rivers.

## LANDFORMS AND SUSCEPTABILITY TO EROSION

### *Soil Structure*

The soil structure is the arrangement of the soil particles and the pore spaces between them. The content of clay, organic matter, calcium, magnesium and free iron oxide contributes to the aggregation of particles. Exchangeable sodium, Na, is a dominant factor in reducing aggregate stability. Aggregation increases the number of large pores and thus increases the infiltration rate. The soils in Barsaloi area are categorized according to the landforms where they occur. The ridge crests and upper slopes have reddish brown sandy loams with stones & boulders. River flats have brown to light brown sandy loams to sandy clay loam.

### *Lithology*

Susceptibility to soil erosion also depends on infiltration, which is related to the rock type. The infiltration rates which depend on the texture, determine the permeability within the soil profile (Arnett, 1976). Acid igneous rocks like granite, weather into Predominantly sandy material. Basic igneous rocks like basalt produce a residue which is predominantly clay. A Surface with different lithological variations will have different effects on the soil erosion on its surface.

The study area is composed of metamorphic basement rocks of the Siambu complex. The rocks are dominated by the banded mafic gneiss, mostly hornblende rich, with disrupted pods of metamafics and meta-ultramafics. The complex consists of a number of distinct metamorphic rocks, including altered sediments and igneous extrusive and intrusive phases (Key, 1987).

## LANDFORM MAPPING

### *Aerial photo-interpretation*

This was completed for the study area. The purpose of the interpretation was to map the landforms and the drainage patterns of the Barsaloi area. The drainage system was needed to help in the analysis of development of new streams in study area between the periods 1956 and 1984 when the aerial photos and landsat TM were taken respectively. The development of smaller streams would be associated to the work of rill and gully erosions. The higher ground slopes would be associated with sheet erosion.

***Image Processing***

The study area was a sub-scene of 512 x 512 pixels and was sectioned on the I²S screen into three as stable (area which supported vegetation), semi-stable ( area with little vegetation) and Unstable (area with no vegetation at all). The scene was displayed on bands 4, 3 and 2 in order to show vegetation and produce a vegetation index map. The bands were chosen because band 2 is designed to measure the visible green reflectance peak of vegetation vigour assessment. Band 3 is a chlorophyll absorption band, while band 4 is useful for determining biomass content and delineation of water bodies.

In order to map the soils, a three band image was displayed in bands 7, 3 and 1. Band 1 is good in differentiation of soil from vegetation whilo band 7 is good in discriminating rock types and for hydrothermal mapping.

***Edge Enhancement***

This is an effective means of increasing geometric detail in an image. It was done for the lineament discrimination and was carried out on single bands 4 and 5. A high pass filter, the laplacian was applied;

| | | |
|---|---|---|
| O | -1 | 0 |
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| O | -1 | 0 |

This high pass filter was to enhance directional features like faults and small streams and check for news developments due to gullying and/or rilling.

***Decorrelation Stretching***

This was done to detect any change on the terrain on land use. This method stretches the saturation while retaining the original hue relationships. It reduces atmospheric effects such as haze and back scatter on the image. This method revealed patches which looked like land under stress and were assumed to be areas where there is over-grazing and therefore soil erosion is beginning to take place. It was done on one image of bands 7, 3 and 1.

## METHODOLOGY

Pickup and Chewings in 1986 used a model for forecasting large scale patterns of soil erosion and deposition in arid grazing lands. They used the landsat MSS 4/6 and 5/6 band ratios and plotted their Mean against Variance for a number of pixels. Their study was on a flat area.

For this study, landsat TM data was used and therefore corresponding band ratios were applied as TM 2/4 and 3/4. The ratios were first displayed as single individual images. The ratio of two images were then "added" to form a final single displayable image on the screen. In order to get the stats file for specific areas within the image, blotching was completed for 29 grid cells. The stats file generated the Mean and Standard Deviations from which the Variance was calculated. The Variance was then plotted against the mean and the results compared with those of Pickup and Chewings (see figs. 1 & 2)

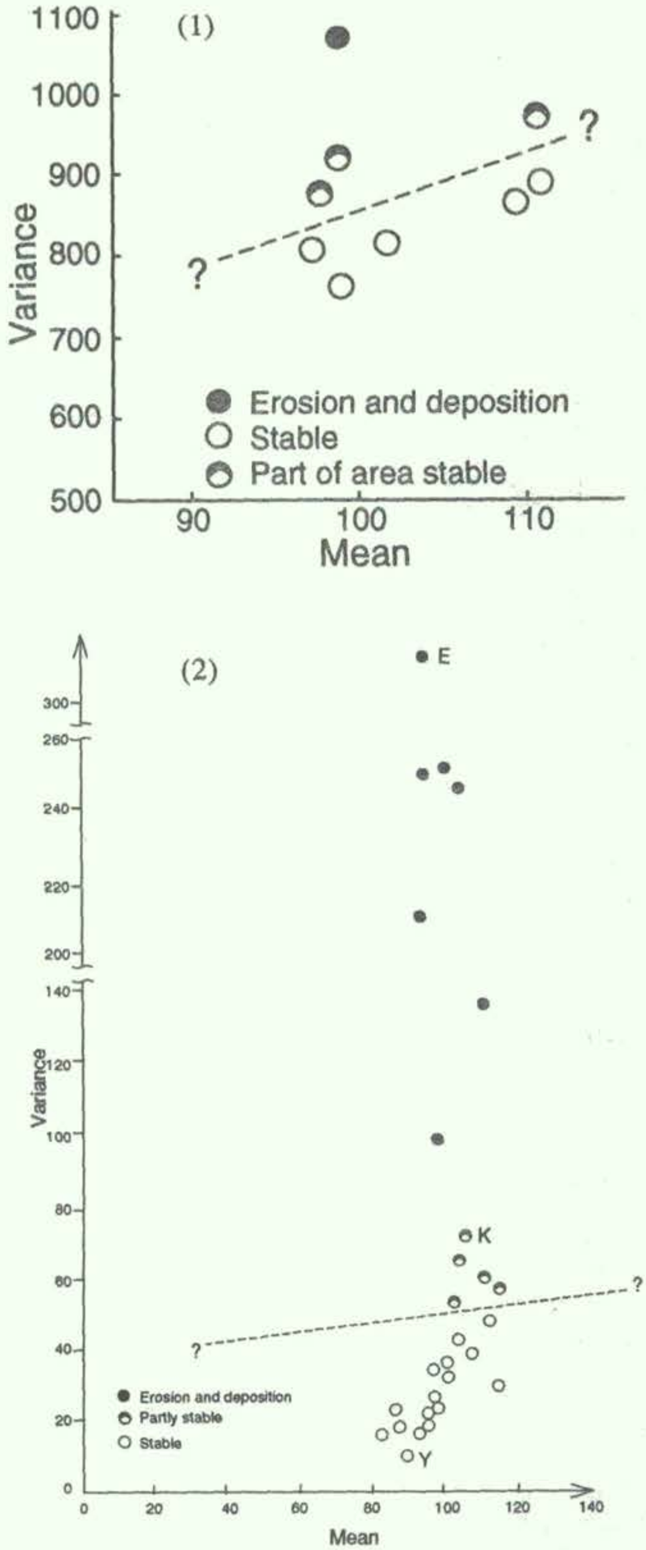


Figure 1 & 2. Mean and variance of soil stability index for nine 128/128 pixel areas in various states os stability. The broken line suggests the mean-variance relationship which forms the boundary between stable and unstable landscapes.

To test the reliability of the above results, a new approach was designed in which the training areas were selected to fall within the three earlier sections in the study area, stable, semi-stable and unstable (erosion & deposition) regions. The aim of training was to obtain decision rules for the classification of each pixel according to stability rules for the three selected training regions. For each region, spectral reflectance in the R (Red band) and IR (Infrared band) were recorded. This was completed for

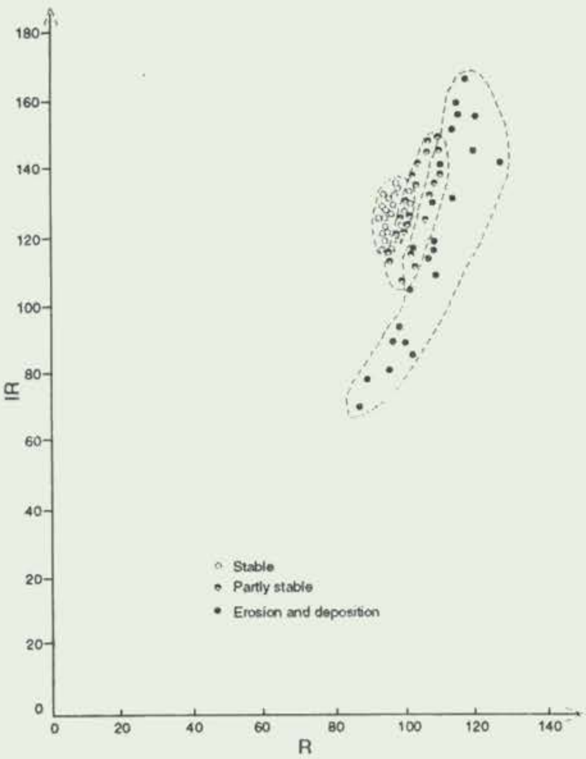


Figure 3. A plot showing the stability fields.

22 points. The values were then plotted IR against R in the feature space. This gave a scatter plot of 66 pixels (see fig. 3).

## RESULTS

The results showed that as in Pickup & Chewings study, the TM data, the areas with vegetation which was stable plotted lowest in the feature space. The areas where vegetation were scattered and some erosion was noticed, plotted in the middle while the area which supported no vegetation at all and had only deposition and erosional features plotted on top as in the Pickup & Chewings case.

In the verification of the results, again it came out that areas which are stable, pixels plotted closer together with minimum gap between them. Those in semi-stable and Unstable conditions, the gap between individual pixels increased as the tract moves from stable to unstable. Secondly as one moves from stability to unstable condition, the scatter-plot moves to the right with the stable condition on the far left while the unstable area (with deposition and erosion) on the far right. Thirdly, another revealing fact is that the tract becomes unstable as the scatter-plot moves away from the line of Greeness towards soil-line which is to the far right, (see fig.3). A soilline indicates droughtness or lack of vegetation.

## CONCLUSIONS

1.The Landsat TM data can be used in the study of detecting and/ or predicting land degradation by soil erosion.

2.Unlike the MSS data which Pickup & Chewings said could mainly work on a flat area, the TM data proved that it could be applied on rugged surface areas like Barsaloi which was hilly and sloppy (See DTM of the area, fig.4). A Digital Terrain Model (DTM) was generated from the digitized values of contours for Maralal toposheet.

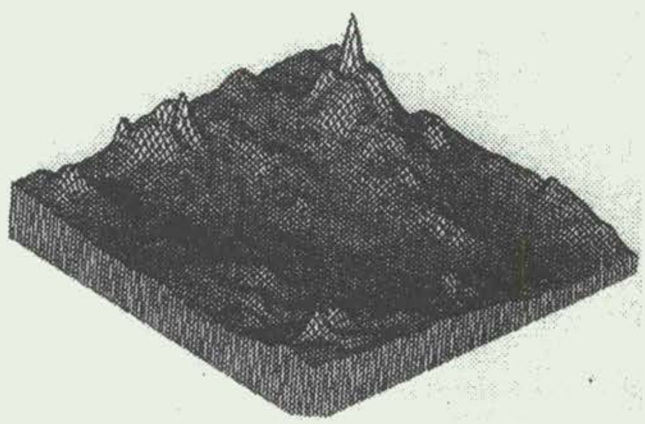

Figure 4. The DTM for the Barsaloa area (Site'2)

3. The results proved that integrated photogeology can be used to detect land degradation in an environmental study.

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# ENVIRONMENTAL IMPACT ASSESSMENT
# A CASE STUDY IN THE NAIROBI AREA

M.N. MASIBO
Mines and Geological Department, P.O. Box 30009, Nairobi

**ABSTRACT**

*The area studied is about 320 km² and includes Nairobi City, with a population of about two million people. The main rock types of the area are the Nairobi Phonolites, Nairobi Trachytes, Kerichwa Valley Tuffs and Athi Lake Beds. The area is drained by the Nairobi, Ngong, Mathare and Rui Ruaka Rivers all which flow roughly from west to northeast. A ground survey of the river courses revealed that Nairobi and Mathare Rivers were the most aesthetically polluted after they had flowed through the commercial and residential parts of the city. The Nairobi River received a treated sewage effluent at Kariobangi in the north east. The Ngong River received oily Industrial discharges around Enterprise Road at the Industrial area while the Rui Ruaka River received an alcoholic effluent from the Kenya Breweries factory at Ruaraka.*

*Chemical analysis by AAS for $Ca^{2+}$, $Mg^{2+}$, $Fe^{2+}$, $Si^{4+}$, $Cd^{2+}$, $Pb^{2+}$ and $Cr^{3+}$ and emission photometry for $Na^{+}$ and $K^{+}$ as well as electrical conductivity, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH and temperature measurements were carried out on samples of water from the rivers. The samples were collected once a month for five months at 30 stations situated in the upper, middle and lower reaches of the rivers. The results showed higher electrical conductivity, TDS, TSS and $Pb^{2+}$, $Cd^{2+}$ and $Cr^{2+}$ values for the Ngong River at the Industrial area. The Nairobi and Mathare Rivers had higher electrical conductivity, TDS and TSS values after they had flowed through the commercial and residential areas of the city, while the Rui Ruaka River had a higher TSS value after receiving the Kenya Breweries effluent at Ruaraka.*

*A correlation of geological information in core logs from Bore hole records for the Nairobi area showed that the main aquifer is constituted by the Athi Lake Beds occurring beneath the Nairobi Phonolites. The aquifer is shallower in the north-east and occurs at a depth of about 87m in the central region where it also tapers and terminates. Other minor sources of water occur in weathered zones at various levels represent contacts of lava flows. A survey of solid waste collection and disposal in the city area revealed that wastes were often left to pile up for long periods especially in the low income Eastlands and Kibera. These constituted an aesthetic and health hazard. The abandoned phonolite quarries at Dandora which comprise the main solid waste disposal sites for the city are situated within a residential area. A perennial pond in one of the quarries provides evidence of groundwater influent from the Athi Lake Beds exposed beneath the quarried phonolite. Continued dumping of wastes in these quarries therefore poses a danger of groundwater pollution. Air pollution was evident in smoke of burning wastes as well as bad smell emanating from waste dumps.*

## INTRODUCTION

### Location

The study area is about 320 km² and lies between latitudes 1° 12'S and 1° 19'S and longitudes 36° 45'E and 36° 58'E. It includes Nairobi city which has a population of about 2 million people ( Fig. 1 ).

### Physiography

The main physiographic units comprise the Kikuyu Highlands and Rift Valley flank in the west, the Ngong Hills in the south-west and the Athi Plains in the east. The maximum altitude is about 1800m in the west and drops gently to about 1500m in the east.

### Drainage

The Tigoni and Ondiri faults on the Rift Valley flank are reservoirs of groundwater. This water escapes through notches and fissures to the east, forming streams. The Tusoga springs from the Tigoni fault form the Rui Ruaka, Karura and Mathare Rivers while the Kikuyu springs from the Ondiri fault form the Nairobi, Ngong and Mbagathi Rivers.

### Geological Setting

The rock types of the area consist of alkaline lavas and pyroclasts extruded by fissure eruptions on the Rift Valley flank in the west from Mid-Miocene to the end of the Pleistocene Period ( Saggerson, 1991). They are represented by the Athi Tuffs and Lake Beds exposed in the north-east overlain by the Kandizi Phonolite, Nairobi Phonolite, Nairobi Trachyte, Kerichwa Valley Tuffs and the Limuru Trachytes and Quartz Trachytes towards the west ( Fig. 1 ).

### Hydrogeological Setting

The Athi Tuffs and Lake Beds overlying the Kapiti Phonolite constitute the main aquifer in the area. The aquifer crops out in the north-east , attains a thickness of about 305m near the Nairobi Railway Station and thins out towards the west, terminating in the Karura-Muthaiga area. It typically comprises layers of yellow welded tuff, grey pyroclastic beds, white fossiliferous beds, grey welded tuff and lower, grey pyroclastic beds with a yellow tuff band. A perched aquifer is formed by the Kerichwa Valley Tuffs Overlying the Nairobi Phonolite between Parklands and Nairobi South Estate. Other sources of groundwater occur within contact zones of lava flows representing old land surfaces.

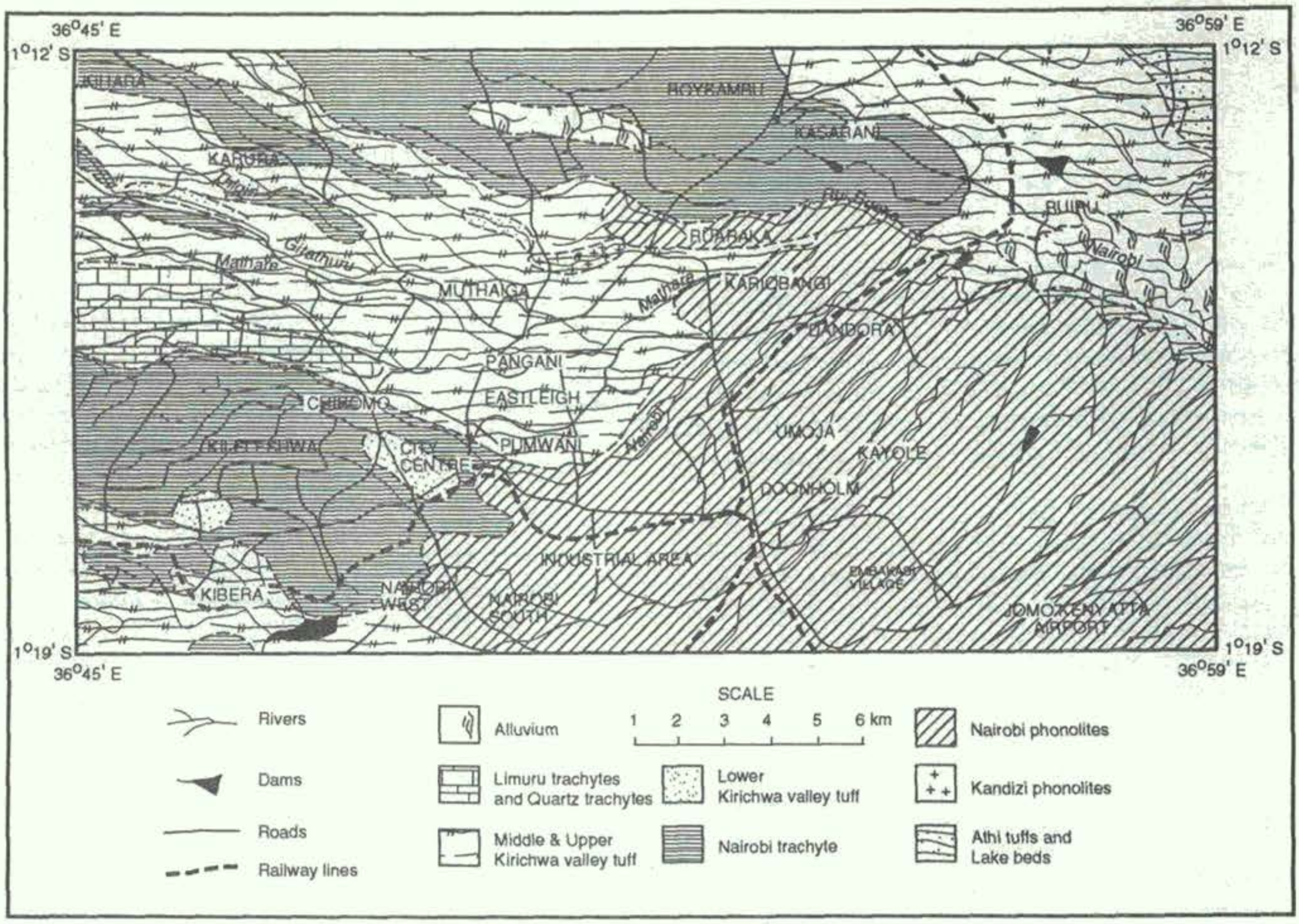


Figure 1. Location and Geology map of the Nairobi area.

**Waste Management in the City area.**

Waste management aims to provide hygienic, efficient and economic collection, transportation and treatment or disposal of solid wastes (UNEP, 1987). A good waste management Policy should protect health, prevent environmental degradation and maintain aesthetic standards. Like many cities in the world, Nairobi generates Industrial, commercial and domestic wastes; Most of these are generally transported from source areas to the disposal site at Dandora. The insufficient number of collection trucks causes wastes to remain in rotting piles for long periods especially in the low income Eastlands and Kibera areas. This means that insects have complete access for food and egg-laying, while rats and mice have free access to the food content. This leads to the proliferation of those insects and rodents which are disease vectors. Heat and humidity accelerate the decomposition of refuse giving rise to bad smell and ideal breeding sites for insects. In addition to endangering health, the solid waste piles constitute an aesthetic problem marring the beauty of the neighbourhoods and often block drains during periods of high run off. The abandoned phonolite quarries at Dandora which constitute the main solid waste disposal sites are situated within the kariobangi-Dandora residential areas ( Masibo, 1990 ). A perennial pond in an adjacent quarry provides evidence of groundwater influent from aquifers exposed by the quarrying excavations. Continued dumping of wastes in these quarries therefore poses a danger of groundwater pollution. The smoke from burning wastes and the stench emanating from the rotting piles pose a health risk to the area residents.

**Riverwater Pollution**

The continuing increase in socio-economic activities worldwide has been accompanied by an even faster growth in pollution stress on the aquatic environment (Chapman, 1992). In general, pollutants can be released into the environment as gases, dissolved substances and in particulate form. Pollution may result from point sources where the input is related to a single outlet such as a sewage disposal or diffuse (area) sources which may be due to a combination of many point sources such as agricultural and urban run-off, and waste disposal sites. A preliminary survey of rivers in the area showed that the Nairobi and Mathare Rivers were highly polluted as they flowed through the commercial and residential areas, the Ngong River as it flowed through the Industrial area, while the Rui Ruaka River received an alcoholic effluent from the Kenya Breweries factory at Ruaraka, imparting an alcoholic smell in the water for about 1 1\2 km downstream (Fig. 2).

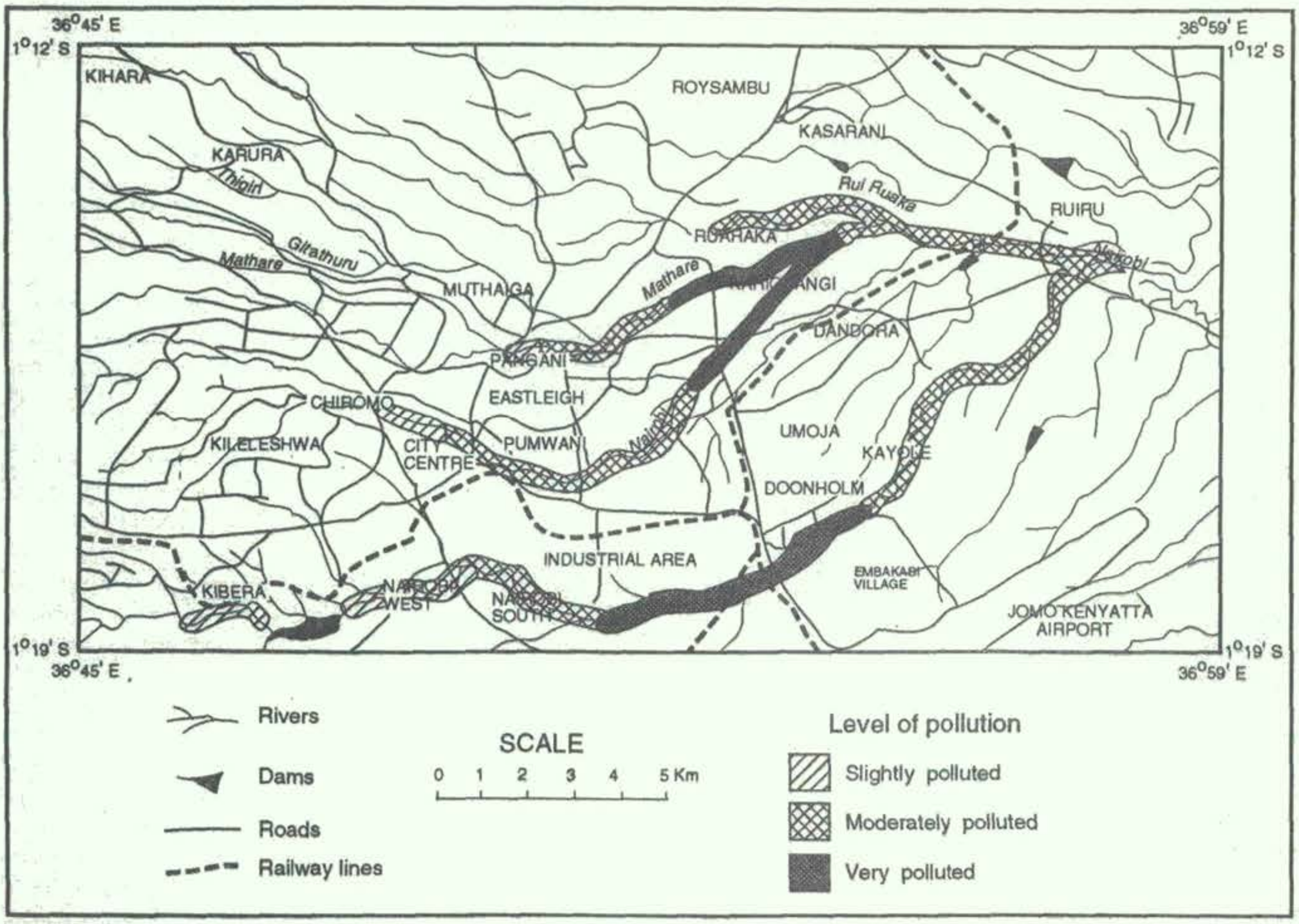


Figure 2. Map showing level of pollution in some Nairobi rivers.

**Riverwater quality monitoring**

On the basis of the preliminary survey, 30 sampling stations were set up in the upper reaches of the rivers to monitor the background characteristics, of the water in the middle reaches to monitor specific incidences of pollution and in the lower reaches to check the dilution due to self purification of the rivers.

**Water Sampling**

The water sampling was done in 500ml high density polythene bottles once a month for five months from November, 1987 to March, 1988. Two samples were collected at each station. One of the samples was preserved with one drop of conc.$HNO_3$ to prevent adsorption.

**Variables and analytical techniques**

The major ions $Ca^{2+}$, $Mg^{2+}$, $Fe^{2+}$, $Si^{4+}$, and the trace ions $Cd^{2+}$, $Pb^{2+}$ and $Cr^{3+}$ were analysed by Atomic Absorption Spectrophotometry (AAS). The ions $Na^{+}$ and $K^{+}$ were analysed by flame photometry using an electroselenium flame photometer. The Total Dissolved Solids (TDS) was analysed by evaporation to dryness and weighing of 50ml of filtered and preweighed water sample. The Total Suspended Solids (TSS) was measured by filtering 150ml of water sample through a filter paper using a suction pump. The electrical conductivity and pH were measured using an SMC1 Bibby stick meter and the PH meter respectively immediately the untreated samples were taken to the Laboratory. The water temperature was measured at the sampling stations by dipping a thermometer in the river water.

**Data Analysis and Presentation**

The results showed higher electrical conductivity, TDS, TSS and $Cd^{2+}$, $Pb^{2+}$ and $Cr^{3+}$ for the Ngong River at the Industrial area. The Nairobi and Mathare Rivers had higher electrical conductivity, TDS and TSS values after they had flowed through the commercial and residential areas of the city. The Rui Ruaka River had a higher TSS value after receiving the alcoholic Kenya Breweries effluent at Ruaraka.

**Seasonal variation of Water Chemistry**

The mean Total Cation Concentration, the TDS and electrical conductivity reached maximum levels during the driest month of January and dropped to minimum levels during the wetter month of March. The TSS on the contrary reached minimum levels in January and maximum values in March when there was an increased contribution of suspended matter from run-off water. The water pH and temperature had only slight variations about their mean values of 7.31 and 21.8°c respectively (Fig. 3& 4).

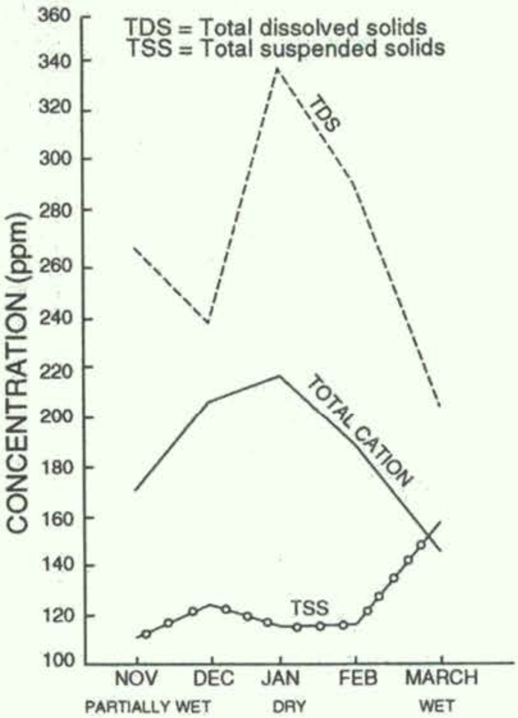


Figure 3. Graph showing the mean TDS and TSS and total Cations for rivers in Nairobi area.

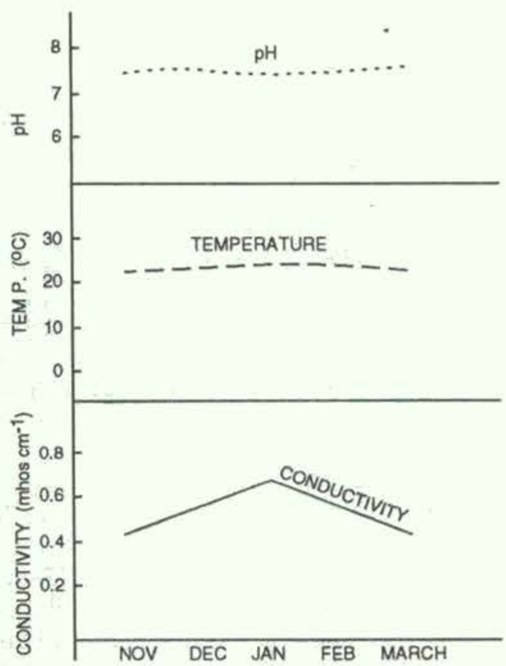


Figure 4. Graph showing the mean watertemperature, pH and electrical conductivity.

## SUMMARY AND CONCLUSIONS

The higher values of the heavy metal ions cd, Pb, and Cr observed at the industrial area were caused by discharges from industries. Anomalous values of $Pb^{2+}$ observed elsewhere in the city were caused by atmospheric fallout originating from exhaust fumes. The waste water from industries should be treated before releasing it into the rivers. The observed increase in Total Dissolved solids and electrical conductivity in the Eastlands residential areas along the Nairobi and Mathare Rivers was caused by storm water and untreated sewage. There should be regular inspection and repair of sewage lines in the city to stop overflows. Children, especially those living in slum areas were found to be very vulnerable to this health hazard. The continued dumping of solid wastes in the abandoned quarries at Dandora poses a danger of groundwater pollution. A similarly abandoned quarry adjacent to the site is fed by a perennial supply of groundwater. This implies that at these depths one or more aquifers were exposed by the quarry excavations. Noxious liquids from solid wastes may infiltrate into groundwater thus polluting it. Particularly at risk are the Athi Tuffs and Lake Beds immediately below the phonolite. These Beds constitute the main aquifer in the area.

The workers involved in waste collection should wear such protective items as hand-gloves and gumboots. There is evidence that when exposed to infection through unprotected handling of wastes, the workers suffer a higher than normal incidence of intestinal parasites. In India, a study showed that 94 percent of the refuse workers were infected with selected parasites as opposed to just over 4 percent in the control groups.(UNEP, 1987). When refuse is left uncollected during hot weather, fly breeding takes place. Flies are sometimes discovered breeding in solid wastes which have been neglected and left uncovered for more than forty eight hours. Insects such as flies and rodents are disease vectors. One way in which the problem of accumulating solid wastes can be alleviated is to create collection centres in residential, commercial and industrial areas, to which the wastes can be taken from source areas using hand carts, tractors or trucks. From these sites they can then be transported to the main disposal site. One advantage of this method is that when the trucks break down the source areas will continually be served and so indiscriminate dumping so common in the city can be prevented. Recycling of wastes can be made easier as the interested people will only have to go to the collection centres to do their selection. This eventually reduces the volume of wastes to be transported.

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# FLUID INCLUSION STUDIES ON AURIFEROUS QUARTZ FROM THE GREENSTONE COMPLEXES OF WESTERN KENYA

Jason S. Ogola
Department of Geology, University of Nairobi, P.O.Box 30197.

## ABSTRACT

*Three types of quartz were identified: early quartz, recrystallized quartz and late quartz. Brittle deformation which resulted into the formation of microfractures in quartz was multiphase in nature. Two types of microfractures were identified; internal and intergranular. Some of the early formed intergranular microfractures are healed by calcite. During microfracturing of early quartz, there was successive post-trapping modifications and leakages of earlier formed fluid inclusions in quartz, thus early quartz apparently lost nearly all of its primary inclusions and acquired new inclusions into its matrix.*

*Sulphide mineralisation is restricted to the recrystallized quartz, except in cases where mineralisation is either along the grain boundaries of early and recrystallized quartz or along the planes of unhealed late microfractures.*

*Microthermometric measurements of fluid inclusions in the Ramba, MK and Migori Hill deposits revealed the presence of inclusions rich in $CO_2 + CH_4(N2)$. The amount of $CO_2$ and $CH_4$ in the Ramba deposit was 19 mol% and 81 mol% respectively. Th plots of 110-170, 250-270 and 330-350°C were established in the MK and Migori Hill deposits while the Ramba deposit indicated Th values of 190-250 and 270-330°C. Sulphide mineralisation apparently took place at temperatures between 200 and 270°C.*

## INTRODUCTION

The greenstone belts of Kenya occupy the western part of the country and stretch for about 350 km from the south to the north (Fig.1). The main complexes are:

a) Migori greenstone belt, south of Lake Victoria.

b) Siaya greenstone complex, immediately north of Lake Victoria.

c) Kakamega greenstone belt, further north of Lake Victoria.

These complexes are known to be hosting gold-sulphide deposits. Gold mining in the greenstone units dates back to the early 1920's when there was gold-rush to western Kenya. Gold was first discovered in the Lolgorien area in the Migori belt in 1920 and mining was commissioned immediately. The renewal of interest in Kenya's gold possibilities was later created by the discovery of the Kakamega gold-field in 1929. Several prospects were successful in striking reefs. Mining at Rosterman mine in the Kakamega area was started in 1935 whereas in the Macalder deposit in the Migori complex, exploitation of gold and silver was started in 1936, initially for gold and silver, recovery of which was from the gossan and later of copper sulphide. Gold has also been obtained from surface rubbles and alluvium.

Currently, a new deposit at MK, 4 km south of Macalder mine is at the developmental stage. Development work is also taking place at the Ramba deposit in the Siaya complex. These activities have created the urgency for detailed exploration and mineralogical investigations of gold-sulphide localization in the greenstone complexes of western Kenya. There is dire need to ascertain the physical and chemical environments of mineralisition as well as establishing the mineral assemblages for purposes of ore reserves appraisal and assessment. The present work therefore is an attempt to investigate the physical and chemical nature of the mineralised solutions and conditions of mineralisation in these complexes.

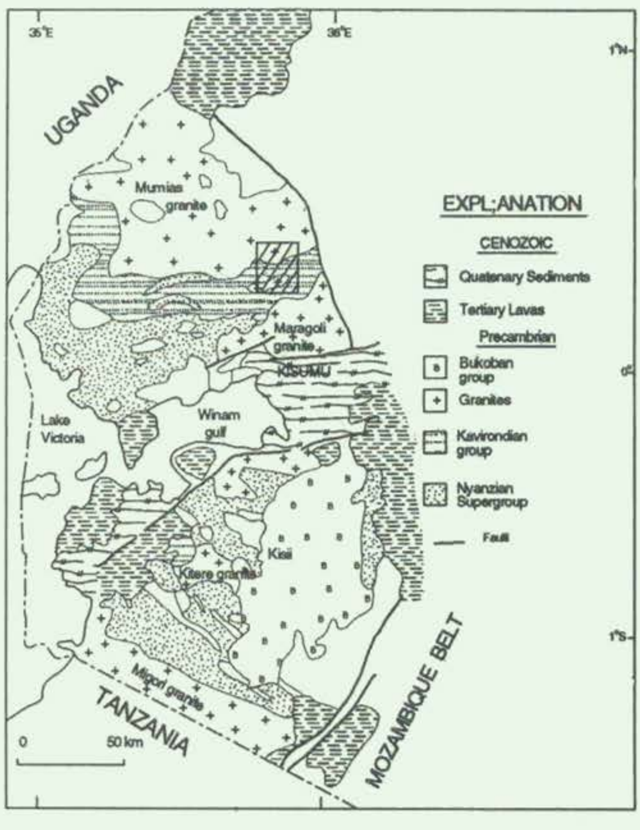



Fig. 1. The greenstone complexes of western Kenya

## GENERAL GEOLOGY

The greenstone complexes of western Kenya form part of the Nyanzian greenstone complexes which are genetically associated with the Tanzanian craton. The rocks of the Nyanzian Group represent the oldest supracrustal rocks in East Africa. These rocks were subjected to late orogenic processes which resulted into low grade metamorphism of greenschist facies. However, towards the base and along their contact with granite massifs, they were subjected to a higher grade of metamorphism of the epidote-amphibolite facies. Metasomatic processes in the Nyanzian greenstone complexes are evidenced by chloritization, sericitization, silicification and carbonatization of the rocks. Such alterations often accompanied sulphide mineralisation. A comparison of the altered and unaltered rocks in the Oyugis has revealed that hydrothermal alteration is attributed to the changes in the amounts of MgO, SiO2, CaO and to a lesser extent TiO2 and P2O5 (Omenda, 1990).

The rocks of the greenstone complexes of western Kenya are represented by mafic and felsic lavas and pyroclastics; metabasalt and pillow lavas, diorites, andesites and rhyolites as well as sedimentary units, mainly graywacke, banded ironstone and shales. The sedimentary rocks in places contain coarse to fine grained crystalline schists and phyllites, alternating with the volcanites. These rocks are unconformably overlain by those of the Kavirondian Group which are composed mainly of interbedded coarse grained sandstones, argillites and conglomerates. The rocks of the Nyanzian and Kavirondian Groups are intruded by the Migori, Kitere, Kilgoris, Oyugis, Seme, Asembo, Abiero, Abom, Maragoli and Mumias massifs as well as dolerites and pegmatites. Granites which intrude rocks of the Nyanzian Group are considered to be older than those intruding the Kavirondian complexes. Among the older granites is the Migori massif. Dolerites although widespread in the area, are limited in magnitude. Detailed geological work has been undertaken in this region among others by Combe (1929), Hitchen (1936), Pulfrey (1936, 1946), Shackleton (1946), Huddlestone (1954), UNDP (1969, 1988), Ichangi (1983), Cohen (1984), Ogola (1986, 1987), Omenda (1990), Opiyo-Akech (1992).

The Migori greenstone belt is situated to the southwest of Kenya, along the Kenya-Tanzania border. The belt extends in a northwest direction for a distance of 120 km. It varies in width from 5 to 10 km. The eastern wing of the belt is covered by the Tertiary volcanics; phonolites of the Isuria plateau. The southern and northern margins are occupied by the Migori granite and dioritic porphirites respectively (Fig.2).

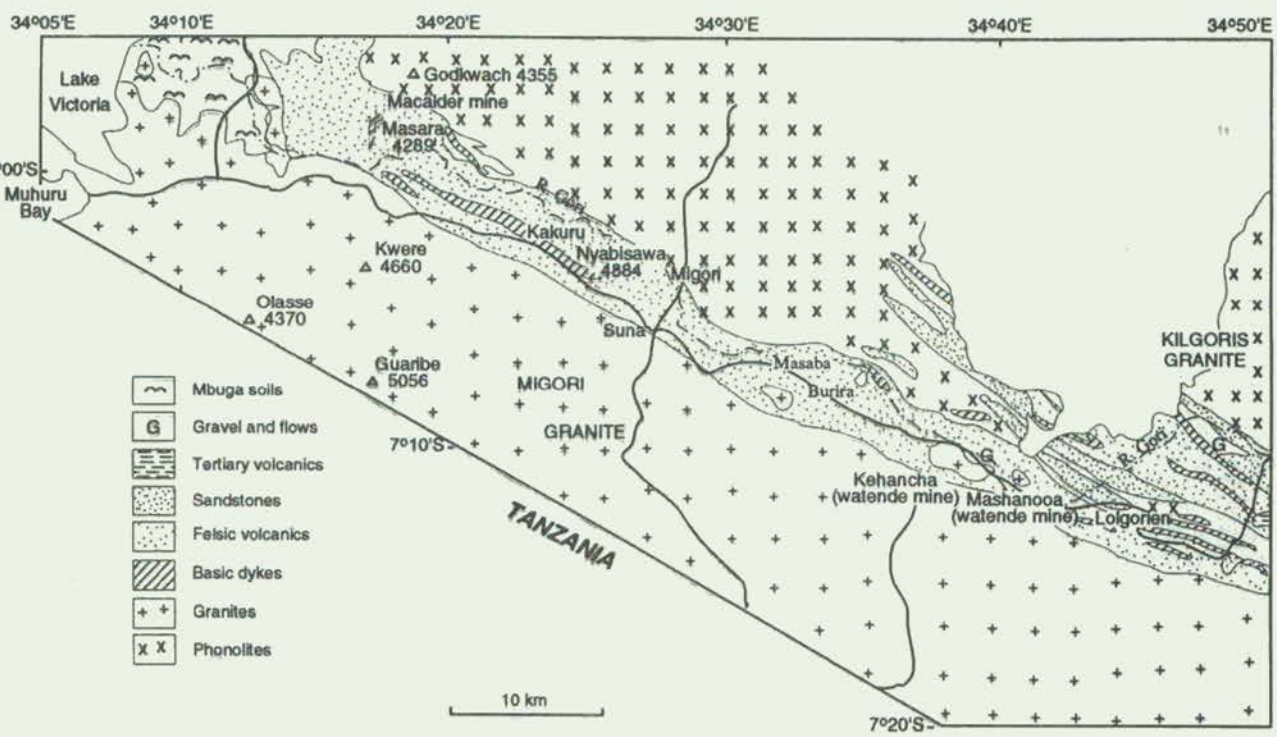



Figure 2. Geology of the Migori greenstone belt (after Shackleton, 1946).

The following succession is established:

a) Mafic volcanics, metabasalts and pillow lavas with layers of banded ironstone, thickness 1230m.
b) Intermediate to felsic volcanics; rhyolites and subfelsic lavas with layers of tuffs, agglomerates, thickness 15-200m.
c) Sedimentary units intercalated with volcanics; sandstones, andesitic tuffs, lapilli and crystalline tuffs, banded ironstone and tuffaceous and ferruginous shales, thickness 1540m.

The Archaean volcanism that deposited these rocks evolved from sub-aqueous and basaltic magma at the base of the succession along the southwestern margin of the belt, to partly sub-aqueous, partly sub-arial and andesitic along its northeastern margin (Hutchinson,1981). Sub-aerial volcanism took the form of andesitic lava domes; porphirites.

The Siaya greenstone rocks are associated with the granites of Asembo, Abiero and Abom. The rocks here consist of metabasalts, andesites and pyroclastic tuffs as well as rhyolites. These rocks are overlain in places by the Kavirondian conglomerates and Tertiary volcanics. Most of the auriferous quartz veins occur in close proximity to the major acid intrusions extending from the Abom granite in the northeast to the south through the diorite at Ramba to Asembo granite and southwestwards to Abiero granite (Pulfrey, 1938).

The Kakamega complex lies betwwen two granite batholiths; the Maragoli and Mumias granites. The Nyanzian rocks here are composed of metamorphosed and sheared volcanics ranging from metabasalts through andesites to rhyolites. The Kavirondian rocks which overlie the greenstones constitute a series of weakly metamorphosed sedimentary units varying from conglomerates, sandstones to mudstones.

## GOLD MINERALISATION

In the Migori greenstone belt gold mineralisation is found at Macalder, Migori Hill, Bushell, MK, Masara, Blackshalls Reef, Kihancha, Lolgorien Hill, Red Ray and Alfa Ray. The known gold occurrences in the Siaya complex include the Ramba and Ngiga prospects. Gold deposits occur in the Rosterman and Edsawa Ridge within the Kakamega area.

Gold occurs within quartz veins either in the metavolcanics or metasediments. The host rocks include metabasalts, rhyolites, diorites, andesites, banded ironstone, shales and the Kavirondian grits and mudstones. Gold mineralisation within granite is rare and has been observed only to the south of Kihancha and to the east of Lolgorien in the Kilgoris granite. Gold is mainly associated with sulphide minerals. In most cases, for instance in the Macalder, Mk and Ramba deposits, gold is emplaced along the microfractures of pyrite whereas in the Migori Hill, it occurs as inclusions in arsenopyrite. A weak correlation betwwen gold and copper had been established at the Macalder deposit (Ogola,1986). In the Kakamega area, gold is associated with silver and traces of scheelite had been recovered from gold cocentrates. Other associated minerals in this area include pyrite, chalcopyrite, arsenopyrite, molibdenite and traces of sphalerite and pentlandite.

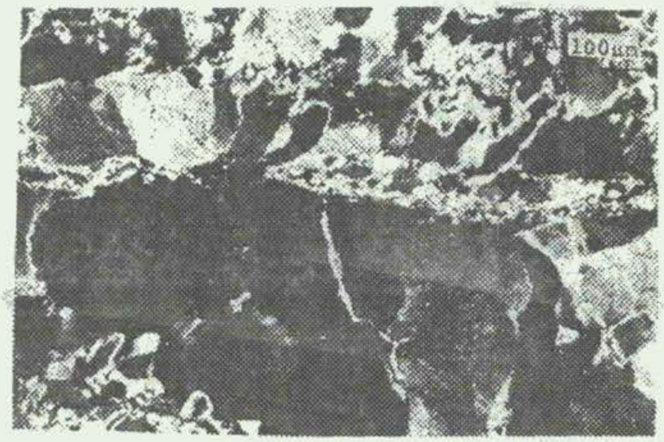
## MICROSTRUCTURAL ANALYSIS AND FLUID INCLUSION IDENTIFICATION IN QUARTZ GRAINS

### Microfractures in quartz

Thin sections from the gold-sulphide prospects of the greenstone complexes of western Kenya were investigated by means of transmitted light microscope (TLM). Three different types of quartz were identified in practically all prospects under investigation. These were early quartz, recrystallized quartz and late quartz. Associated with the late quartz is late calcite formation. The different types of quartz and their structural features are discussed below.

### Early Quartz

The matrix of early quartz under crossed nicols potrays the following textural variations: clear quartz and partially recrystallised quartz. Quartz occurs either as idiomorphic, anhedral or allotriomorphic grains. It was therefore possible to identify the crystallographic orientations of some of these grains along the C-axis under the TLM and correlate this to the existing microfratures within quartz. Partial recrystallization of quartz occurred along the grain margins and planes of microfractures (Fig.3). Individual quartz grains generally range in size from 0.2 x 0.08mm to 1.8 x 1.1mm. However, in some prospects, for

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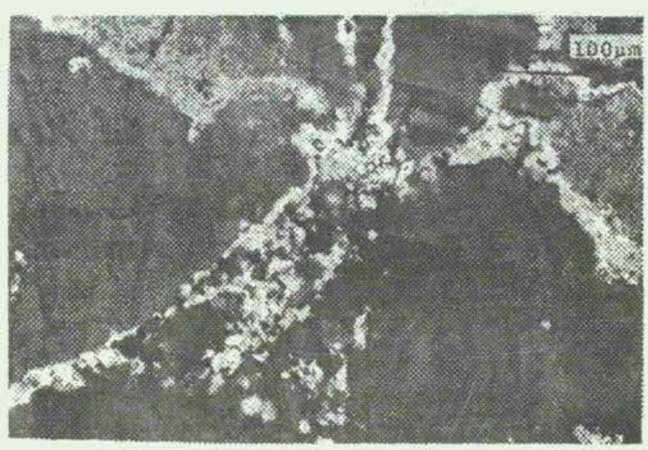



b

Figure 3. Recrystallization of early quartz in the KM deposit a) Recrystallization along a microfracture, b) Recrystallization of early quartz along the grain margins.

instance the MK deposit, allotriomorphic quartz grains are up to 7mm long and 2.6mm wide. The contacts of quartz grains are sharp and straight while idiomorphic grains fit into each other. This points to the fact that quartz was not subjected to rotational deformation. This is further supported by the fact that the crystallographic orientation of the C-axis of individual grains is quite consistent.

Different types of microfractures occur in early quartz, viz; internal and several phases of intergranular microfratures (Fig.4). Internal microfractures are more pronounced along the C-axis, although in some cases they are also well developed along other directions. For instance, in the MK deposit where brittle

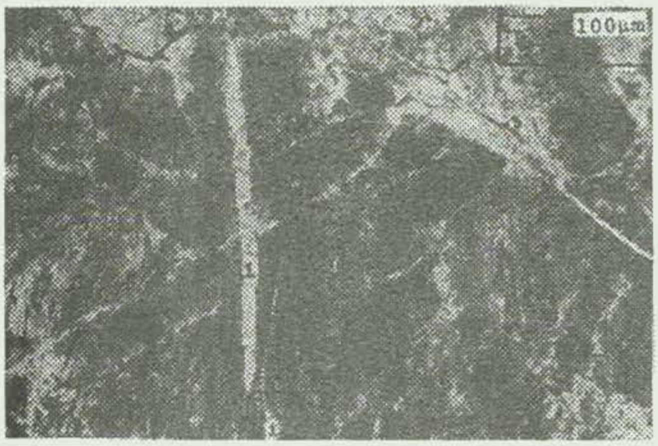



Figure 4. Microfractures in early quartz and recrystallized quartz in the Ngiga deposit. Three phases of microfracturing are noted; early (1), intermediate (2) and late (3). In places, microfractures of the 1st. phase are displaced by the 2nd. and both are healed by calcite.


Figure 5. Microfracturing in early quartz in the MK deposit. Brittle deformation resulted into intense microfracturing of quartz grains with orientation in different directions. At the centre is a calcite veinlet healing a late intergranular microfracture.

deformation of quartz was quite intense, microfractures with different orientations were developed (Fig. 5). This type of microfracturing may, however, be representing different phases of deformation, the sequential order of which is difficult to determine. In the Ngiga deposit, the microfractures are often continuous along the C-axis whereas the ones normal to them are generally broken (Fig. 6). The development of pronounced microfractures along crystallographic orientation of quartz grains in this deposit points to the existence of a uniaxial stress which was propagated roughly normal to one of the crystallographic axes at any given phase of deformation. Individual microfractures here are less than 0.02mm in width and are up to 0.6mm long.

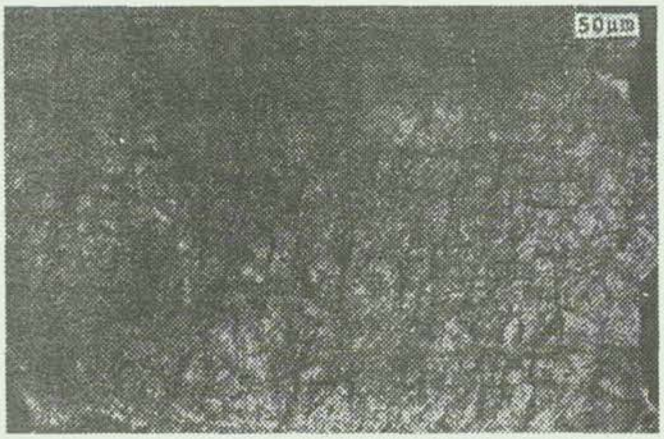



Figure 6. Microfracturing of early quartz in the Ngiga deposit. Quartz grains are fractured in two distinct directions corresponding to the crystallographic axes of the grains. Microfractures along the C-axis are continuous.

The second phase of deformation is represented by the presence of microfractures which have hitherto been healed. Such microfractures are straight and continuous, thus are intergranular. They have different orientations and are up to 3.5mm long and 0.02mm wide. Healing of these structures is often by calcite, although in some cases, healing was through recrystallization along their planes. Some of these microfractures have been dislocated by much later microfractures which are in turn healed by calcite (Fig. 4). In the Ramba deposit, the intergranular microfractures are well developed in two directions and they intersect each other at an angle of 56-50 degrees (Fig. 7). These quartz grains are allotriomorphic, thus it was not possible to ascertain the relative direction of the microfractures to the crystallographic orientation.

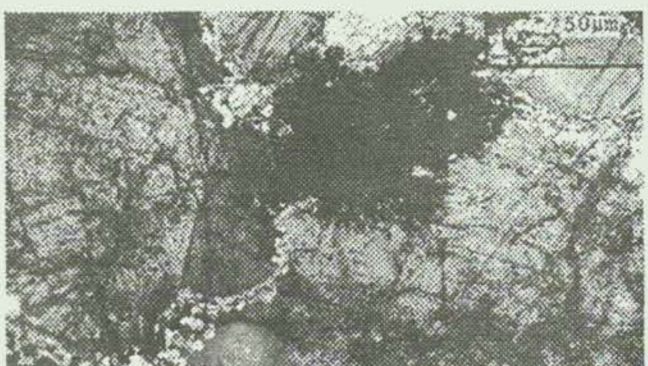



Figure 7. Microfractures in early quartz in the Ramba deposit. They intersect each other at 56-60 degrees and are over 4mm long and 0.004mm wide.

The final phase of brittle deformation of early quartz is represented by the occurrences of unhealed microfractures, some of which are extensive (Fig. 8). Sulphide mineralization and chloritization took place along the planes of these microfractures, some of which represent dendritic features (Fig. 9).


Figure 8. Late microfracturing in early and recrystallized quartz in the Ramba deposit. Individual microfractures are up to 20mm long and 0.1mm wide. They are often chloritized.

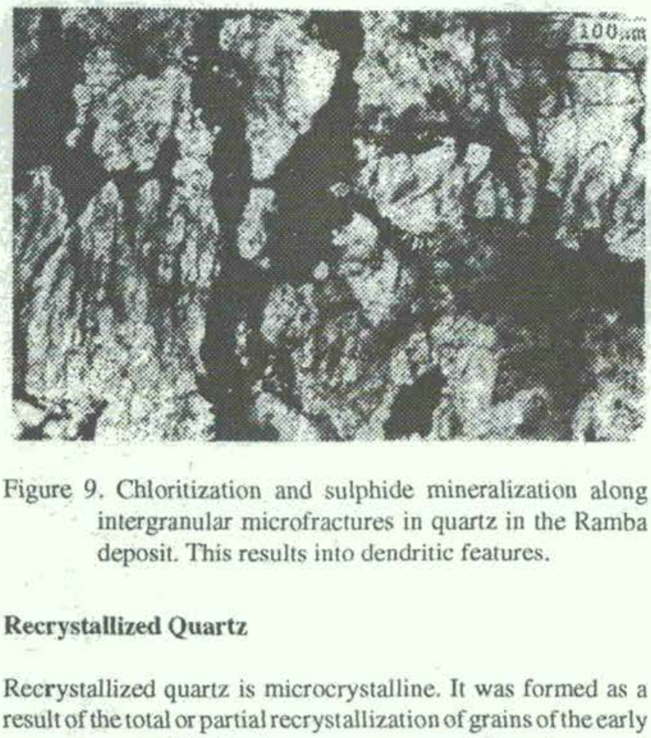



Figure 9. Chloritization and sulphide mineralization along intergranular microfractures in quartz in the Ramba deposit. This results into dendritic features.

**Recrystallized Quartz**

Recrystallized quartz is microcrystalline. It was formed as a result of the total or partial recrystallization of grains of the early quartz. Recrystallization in most cases started along the crystal margins and planes of microfractures in early quartz (Fig. 3). In some cases this process started from the central part of the grain and proceeded outwards. Recrystallization was progressive as is occasioned by diffusion and zonation of the quartz grains (Fig. 10). Recrystallized quartz occurs as granules of up to 0.04-0.08mm in diameter. They are well compacted and show extinction at different angles on rotation of the stage. Scanning electron microscopy (SEM) images revealed this variety of quartz as dark grey structures.

Recrystallization was closely associated with sulphide mineralization and hydrothermal alteration (Fig. 11). The latter process is evidenced by the presence of chlorite and in some cases, actinolite (Fig. 12). Sulphide mineralization was restricted to the recrystallized quartz except in cases where ore deposition and chloritization occurred along microfractures in early quartz (Fig. 9).


Figure 10 Progressive recrystallization of early quartz in the Ngiga deposit is characterized by zonation along the grain margins .

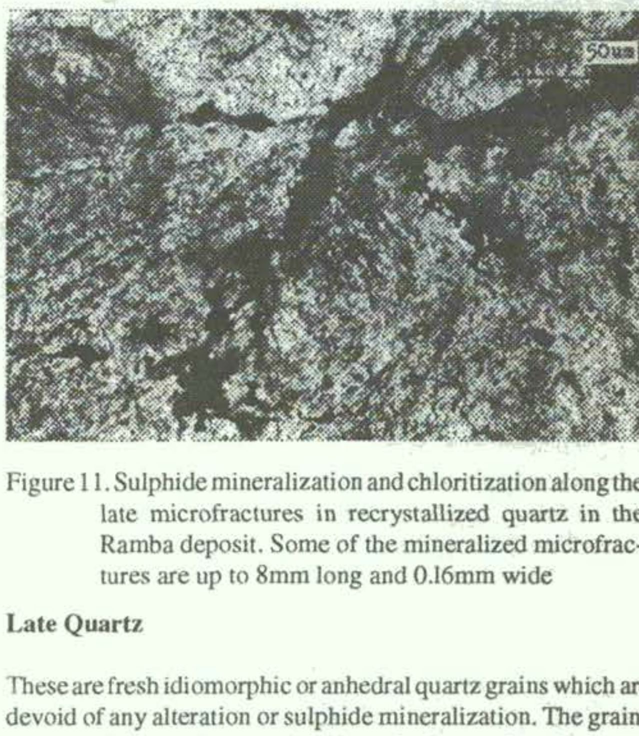



Figure 11. Sulphide mineralization and chloritization along the late microfractures in recrystallized quartz in the Ramba deposit. Some of the mineralized microfractures are up to 8mm long and 0.16mm wide

**Late Quartz**

These are fresh idiomorphic or anhedral quartz grains which are devoid of any alteration or sulphide mineralization. The grains are creamish grey in normal light and show a play of colours under crossed nicols. They vary in width from a few centimetres to large veins of up to 2-3m. Some of the veins, for instance in the Ngiga deposits were subjected to brittle deformation, resulting in the formation of unhealed microfractures of up to 2.6mm long. Microfractures are well developed along the crystallographic axes, thus they divide the quartz grains into uneven micro blocks. The formation of the late quartz apparently associated with calcite which seems to be penetrating into quartz and yet has a smooth contact with early quartz. Calcite veinlets have a distinctive creamish brown colour in normal light and creamish white under crossed nicols (Fig. 13).

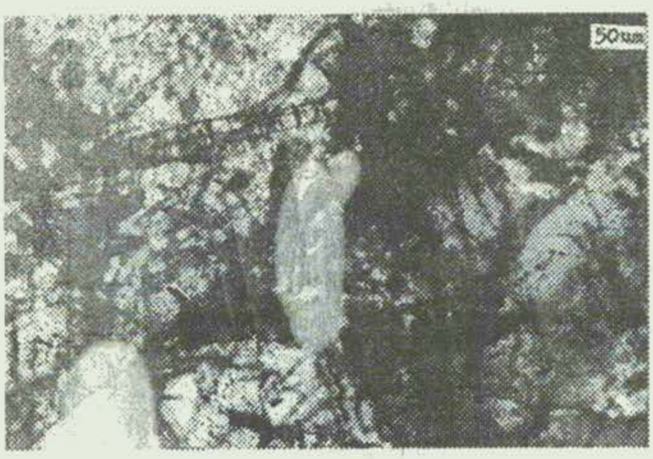



Fig... ...loritization and actinolitization of quartz in the ... deposit. Actinolite is needle-like. Hydrothermal ...ion followed sulphide mineralization.

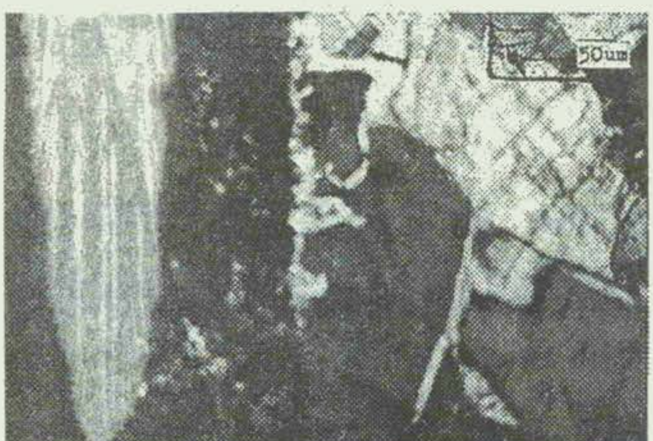


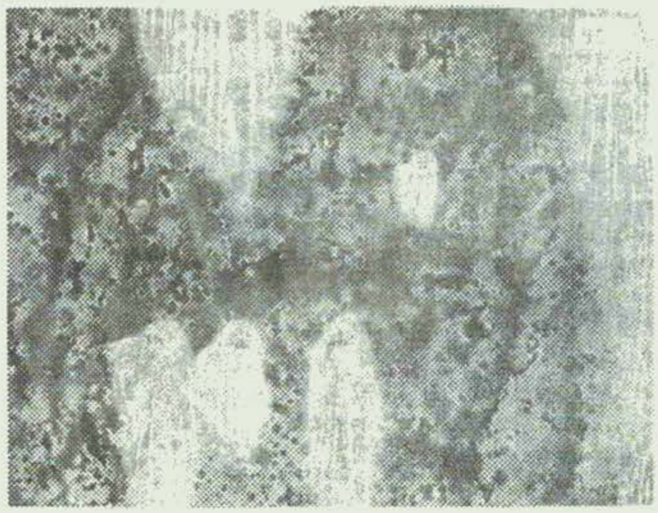

Figure 13. Formation of late quartz (light grey) in association with late calcite (white) within early quartz (dark grey) in Ngiga deposit.

## DISTRIBUTION AND OCCURRENCE OF FLUID INCLUSIONS

Fluid inclusions in early and recrystallized quartz were partly structurally controlled by microfractures.

### Inclusions in Early Quartz

Large and small monophase and multiphase inclusions were identified within early quartz. They form trails along the planes of microfractures in quartz and relatively large inclusions occurring either as clusters or as isolated inclusions within the matrix of quartz (Fig. 14). In the first instance, inclusions are aligned along the planes of microfractures and often criss-cross each other, repeating the pattern of internal microfractures, thus form chains and cells. Such trails terminate at the grain boundary. Commonly, the monophase liquid inclusions are more elongated along such planes. Multiphase inclusions consist of either L+V phases or L+V+D minerals with or without solid particles. Cases were also observed where the vapour bubble is missing, ... consists of either L+V or L+... minerals wi... Such inclusions commonly ... within the ... fractures which have either ... healed throu... and sulphide mineralization ... The margins ... quartz grains are generally ...



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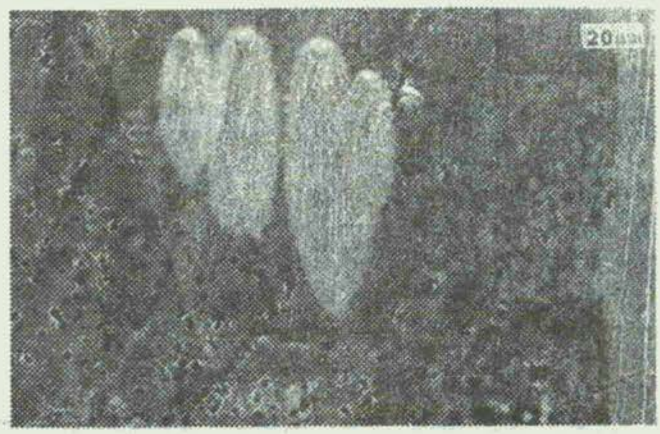


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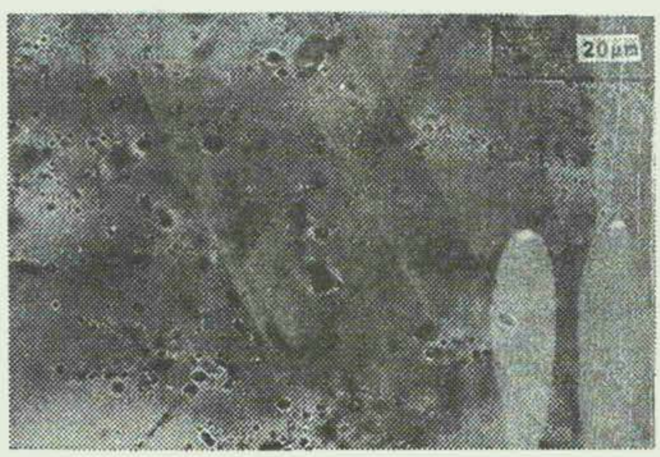


c

Figure 14. Trails of inclusions aligned to the microfractures in early quartz in the Ngiga deposit (a-b) and Ramba deposits (c). Inclusions are generally circular and small. Clusters and isolated inclusions occur in the quartz matrix.

inclusions. Relics of early quartz occurring within recrystallized quartz are characterised by high population of inclusions.

The distribution and nature of inclusions is not always the same within the prospects of the greenstone complexes. For instance, the Ngiga deposit which is located in the northern part of the complex, north of L. Victoria, has much higher population of three phase inclusions, in particular, the presence of daughter minerals and solid particles. On the other hand, the MK deposit, which is situated to the southern part, south of L. Victoria, is characterised by the dominance of two phase, L+V inclusions. The presence of inclusions composed of L+D minerals with solid particles is limited here (Fig. 15). In such cases, the liquid-vapour phases are quite rare and where they occur, the inclusions are relatively small, approximately 2µm and with bubble fillings of 10% or less. Large inclusions are often irregular while small ones are spheroidal, oval, cubic or rectangular Vapour fillings are generally 10-20%, rarely 30-40%, although some inclusions have bubble fillings of up to 70-80%. Some inclusions contain cubic daughter minerals which are up to 8mm. while the inclusion itself is up to 16-24µm. Conversely, some

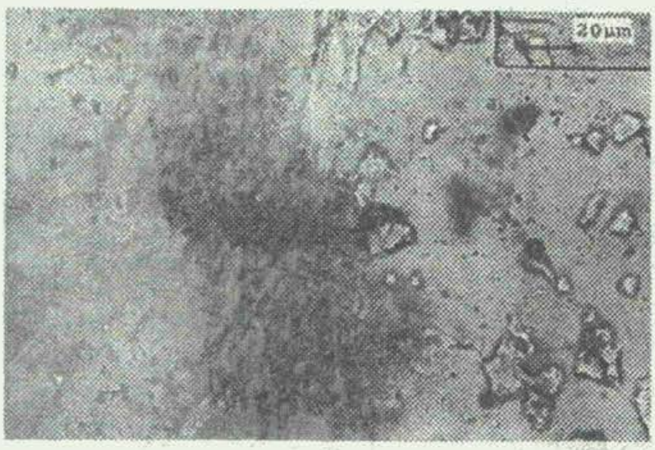


Figure 15. Late microfractures at the contact of early and recrystallized quartz. Early quartz is characterized by high population of inclusions. Some cubic inclusions contain cubic daughter minerals. Irregular inclusions show signs of leakages.

cubic liquid phases contain only solid particles.

**Inclusions in Recrystallized Quartz**

The population of inclusions within recrystallized quartz is much less and smaller in size than in early quartz. Here inclusions commonly form trails along the grain margins, thus the trails are circular, describing the granular nature of the recrystallized quartz (Fig. 16). The inclusions forming trails are often spheroidal. The size and form of inclusions forming such trails might have been controlled by the granular nature of recrystallized quartz combined by their compaction, forming a well intertwined matrix. Isolated inclusions are generally evenly distributed within the grains. These inclusions range from irregular, spheroidal, oval, rectangular to cubic. The contact of recrystallized quartz and early quartz is devoid of any inclusions.

Fluid inclusions are predominantly L+V phases, although liquid phases with solid particles are also present along microfractures where chloritization took place (Fig. 15). Such inclusions are generally large, irregular and even show signs of leakages. The irregular liquid phases often contain solid particles, the presence of which seems to have intensified with the intensity of chloritization and actinolitization along the microfractures. During these processes, remobilization of inclusions seems to have taken place, resulting into the escape of the vapour bubble and formation of large irregular liquid phases with either daughter minerals and with or without solid particles. The most affected were those inclusions which were within the environs of microfractures. Large irregular L+V phases were also encountered in recrystallized quartz. Some of these inclusions are up to 124µm across the long axis and with vapour bubbles of 6µm. Vapour fillings are 10-20%.

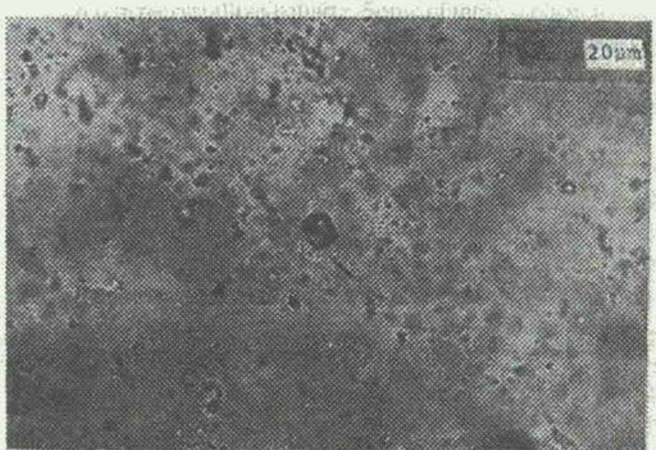


Figure 16. Trails of inclusions in recrystallized quartz in the MK deposit. Trails have either circular, cubic or rectangular shapes. Relatively large isolated inclusions occur within the grains. At the centre is cubic inclusion with vapour bubble.

Inclusions along the microfractures in early quartz which have hitherto been healed through recrystallization are principally the same as those in recrystallized quartz. The only exception here is that, the contact of early quartz and healed microfracture is aligned with either monophase liquid or L+V inclusions. Chloritization and sulphide mineralization took place along such contacts.

**Inclusions in Late Quartz**

Fluid inclusions in late quartz are considered to be secondary in relation to mineralized solutions. Formation of trails of inclusions along the microfractures in quartz here is pronounced whereas clusters and isolated inclusions are few. The inclusions are comparable to those occurring in recrystallized quartz, both in population and in size, although in this case, no trails are formed along the grain margins. The inclusions in late quartz are predominantly L+V phases. Vapour fillings are often less than 20%, rarely 50%.

## MICROTHERMOMETRIC INVESTIGATION

Microthermometric measurements were conducted on thin sections from the MK, Ramba and Migori Hill deposits by using the Linkam THM 600 Heating and Cooling Stage. A total of 110 measurements were made with a view to investigating the nature of mineralized solutions and their homogenization temperatures.

### Freezing

Freezing temperatures established the presence of $CO_2$-$CH_4$ inclusions in the above deposits. These inclusions occur as liquid monophase at room temperature. In the MK deposit, the Tm of the inclusions fall within -61 and -60°C. Three populations of $CO_2$-$CH_4$ inclusions were identified in the Migori Hill deposit. They showed Tm values of -65 to -64, -61 to -59 and -57 to -56°C. The Tm for the inclusions in the Ramba deposit were rather scattered: -83 to -82, -75 to -74 and -67 to 64°C.

A plot of the Tm vs. Th for the $CO_2$-$CH_4$ inclusions show lower Th-Tm values (Fig. 17). This suggests that the Th corresponds to the increase of $CH_4$ and possibly $N_2$ as the melting point and homogenization points of $CO_2$ are depressed. The increase of volatiles in the inclusions was variable from one deposit to another. For instance, the Ramba deposit in the Siaya greenstone complex shows a greater increase in the volatiles with a Th range from -49.3 to -44.5 while the MK deposit in the Migori complex indicates a range of -19.2 to -9.0 oC. Likewise, the Migori Hill deposit, occurring just at a distance of about 2km west of MK has two types of inclusions with Th values of -6.5 to 0 and 3.7 to 12.1 oC. This shows that the increase or decrease in the volatile component of the mineralized solutions might have varied within short distances. The Migori Hill is richer in gold-hosting arsenopyrite while the MK deposit is richer in pyrite and chalcopyrite. In the latter case, blebs of gold occur in the microfractured pyrite. Laser Raman microprobe analysis of inclusions in the Ramba deposit confirmed the presence of $CO_2$ and $CH_4$ with traces of $N_2$ (Fig. 18). Two mixtures with concentrations of 39 mol % $CO_2$ and 61 mol % $CH_4$ and 19 mol % $CO_2$ and 81 mol % $CH_4$ were ascertained.

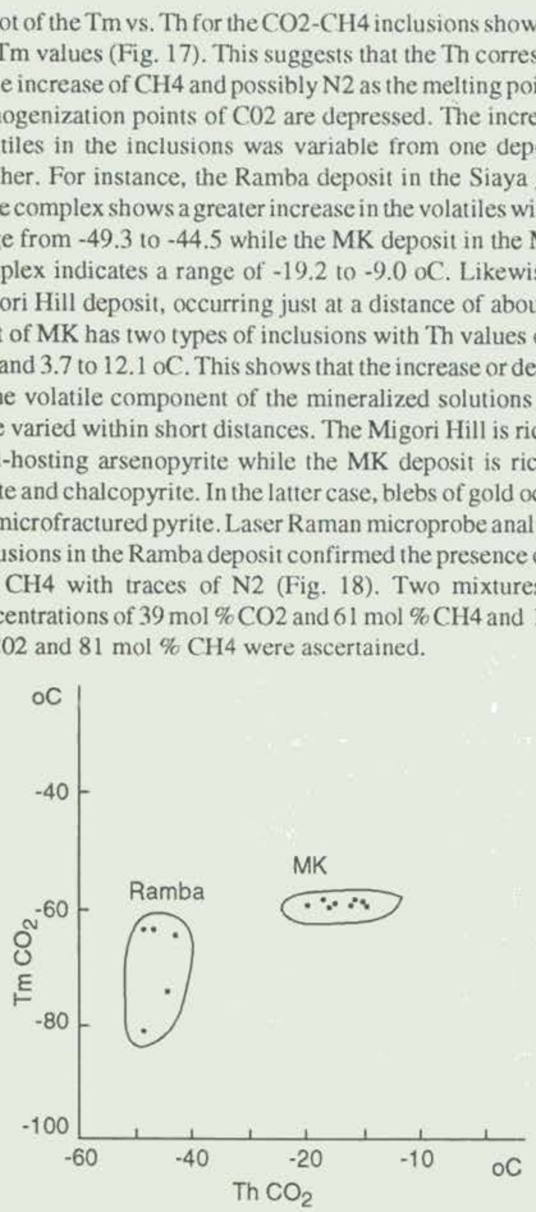


Figure 17. A plot of the Th vs. Tm for the $CO_2$-$CH_4$ inclusions in the MK and Ramba deposits

### Heating

Investigation of inclusions occurring as multiphase at room temperature revealed the presence of three distinct inclusion groupings in the MK and Migori Hill deposits. The range of the Th values are: 110 to 170, 250 to 270 and 330 to 350 oC. The Ramba deposit is characterized by the presence of two groupings with Th values of 190 to 250 and 270 to 330 oC. Th values above 270 oC were noted among the isolated inclusions in early quartz. These temperatures may be attributed to the primary inclusions in early quartz, thus they do not have any bearing to the actual mineralized solutions which resulted into the deposition of sulphide minerals. The different groupings of inclusions may be reflecting the different stages of fluid infiltration and subsequent deposition of sulphide minerals (Ogola, 1987a).

## DISCUSSION

Brittle deformation which resulted into the formation of microfractures in quartz within the greenstone complexes of western Kenya was multiphase in nature. At each phase, there seems to have been a uniaxial stress which acted normal to the quartz grains, resulting into the formation of microfractures along its crystallographic axes, thus at each stage, microfracturing was more pronounced in a given crystallographic orientation. At the same time, late microfractures forming in quartz seem not to conform to this general rule. Instead they are intergranular, unhealed and intersect grains obliquely, thus conform to no pattern. The source of tresses responsible for this type of deformation apparently is different from the first type. In the latter case, the stresses were at an angle to the quartz grains.

It is anticipated that during microfracturing of early quartz, there was successive post-trapping modifications and leakages of earlier formed fluid inclusions in quartz. In this way, early quartz apparently lost nearly all its primary inclusions and acquired new inclusions into its matrix and along the newly formed microfractures within it. Such inclusions now occur as trails, clusters or as isolated inclusions within early quartz. In principle, the inclusions occurring in early quartz and Recrystallized quartz are considered to be of the same generation. They are primary as far as quartz recrystallization and sulphide mineralization are concerned. In other words, they are secondary to early quartz, but primary to recrystallized quartz and sulphide minerals. Recrystallization process is likely to have been induced by the influx of mineralized solutions. However, ore depositional processes and hydrothermal alteration persisted for a longer period. This is supported by the following observations:

a) Sulphide mineralization is restricted to the recrystallized quartz. Noting that recrystallized quartz is well compacted, it would have been more difficult for mineralized solutions to penetrate it at a later stage than the tectonically disturbed early quartz.

b) Chloritization and sulphide mineralization took place along some of the late microfractures which developed both in early quartz and recrystallized quartz.

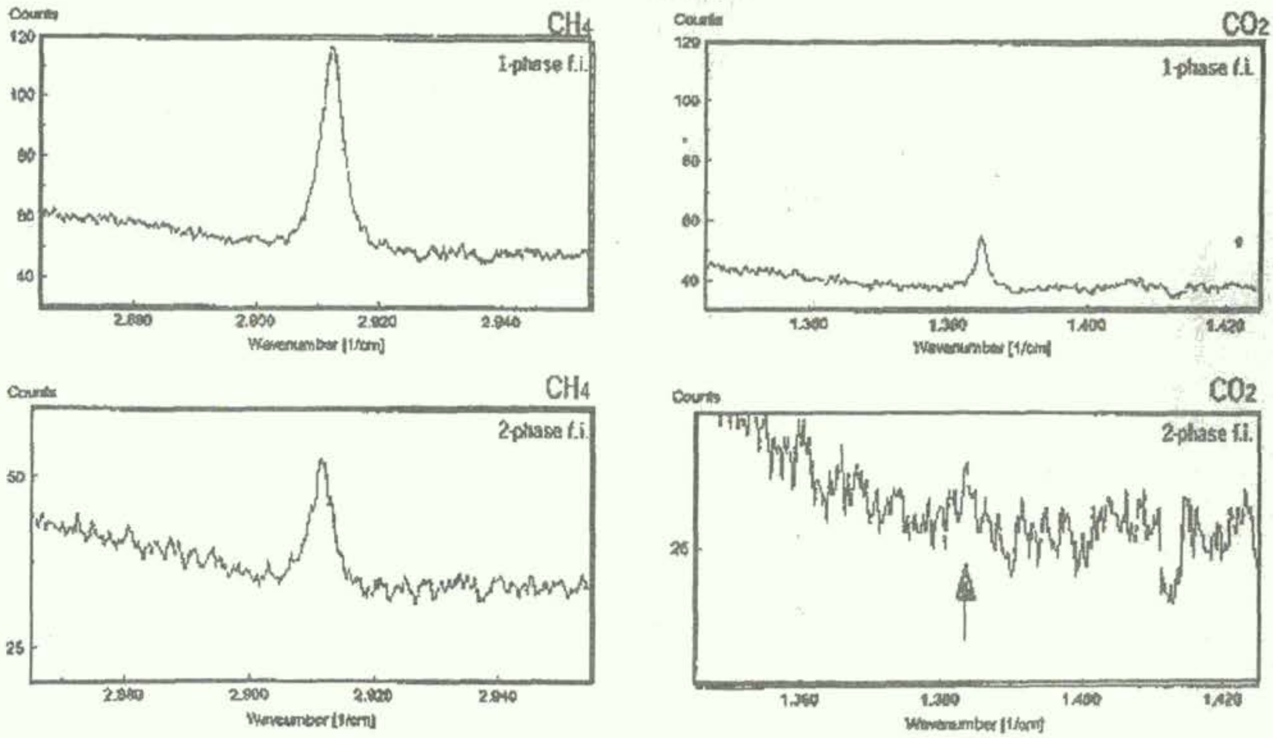


Figure 18. Upper spectra: 1-phase f.i. (39 mol% $CO_2$, 61 mol% $CH_4$), Lower spectra: 2-phase f.i., vapour phase (19 mol% $CO_2$, 81 mol% $CH_4$)

Preferential deposition of sulphide minerals in recrystallized quartz may further be explained apparently by the point that recrystallization process created an environment of chemical reactivation, thus exchange of ions favouring metasomatic process was possible.

The time interval between these processes was not investigated. But according to Boiron et. al. (1992), the chronology of ore deposition as well as the different stages of fluid migration and trapping in relationship to the deformational events are especially difficult to establish by using standard techniques. They assert that to decipher the time-space relationships between deformational events, mineral healing or crystallization, fluid trapping and ore deposition, it is necessary to develop a multidisciplinary approach leading to a complete characterization of the paleofluid pathways. In this respect, they do recommend optical and scanning electron microscopy methods of investigation.

Microthermometric investigations of fluid inclusions in the Ramba, MK and Migori Hill deposits revealed the presence of inclusions rich in $CO_2$ + $CH_4(N_2)$. The amount of volatiles in the inclusions varied from one deposit to another. Laser Raman microprobe analysis indicated the presence of 19 mol% $CO_2$ and 81mol% $CH_4$ in the Ramba deposit. Three inclusion groupings were identified in the MK and Migori Hill deposits. They showed Th plots of 110-170; 250-270 and 330350 degrees. The Ramba deposit indicated inclusion populations with Th ranges of 190 to 250 and 270 to 330 degrees. Higher homogenization temperatures above 270 degrees may be attributed to the primary inclusions in early quartz. Sulphide mineralization apparently took place at temperatures between 200 and 270 degrees. This is in agreement with homogenization temperatures at Macalder deposit in the Migori greenstone belt which indicated Th values of 246-270 degrees (Ogola, 1987a).

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# LITHOSTRATIGRAPHIC FORMATIONS OF THE ARCHAEAN SEDIMENTARY ROCKS OF WESTERN KENYA.

W. M. Ngecu.
Department of Geology, University of Nairobi, P.O. Box 30197,
Nairobi, Kenya.

**ABSTRACT**

*In the Archaean greenstone belt of Western Kenya, the lowermost Nyanzian volcanic rock suites are uǹconformably overlain by the sedimentary rocks of the Kavirondian Group. During a recent mapping exercise, the Kavirondian Group sediments were divided into four formations. The Shivakala Formation is the lowermost in the sedimentary sequences and consists of clasts supported polymictic conglomerates. The conglomerates show few scour marks, imbrication and crude graded bedding. The Igukhu Formation conformably overlies the Shivakala Formation and is composed of greywacke sequences which show graded bedding, soft sediment intrusions and preconsolidation folds. The Mroda Formation lies conformably above the Igukhu Formation and is composed of minor couplets of cross-stratified sandstones which are interbedded within greywacke sequences and mudstone sequences. This formation contains load structures, flame structures and ripple drifts. Mudaa is the uppermost formation and it is composed of thinly laminated mudstone beds which alternate with blocky almost structureless mudstones. Some mudstone beds persist laterally for several kilometres, grading into silty mudstone and finally greywacke beds.*

## INTRODUCTION

The studied area is an east-west striking basin structure which lies between the western slopes of Nandi Hills and Yala Town. The basin also lies between Maseno town in the south and Kakamega in the north. The structure is a part of the Archaean greestone belt of the Tanzania Craton (Fig. 1) which extends from northern Tanzania, through western Kenya to southeastern Uganda (Quennel et al. 1956). On the northern and southern margins of the basin structure are found early Proterozoic granite intrusions which are about 2450Ma (Cahen et al. 1984) and rocks of the Nyanzian system which are about 2700Ma (Cahen eta al. 1984).

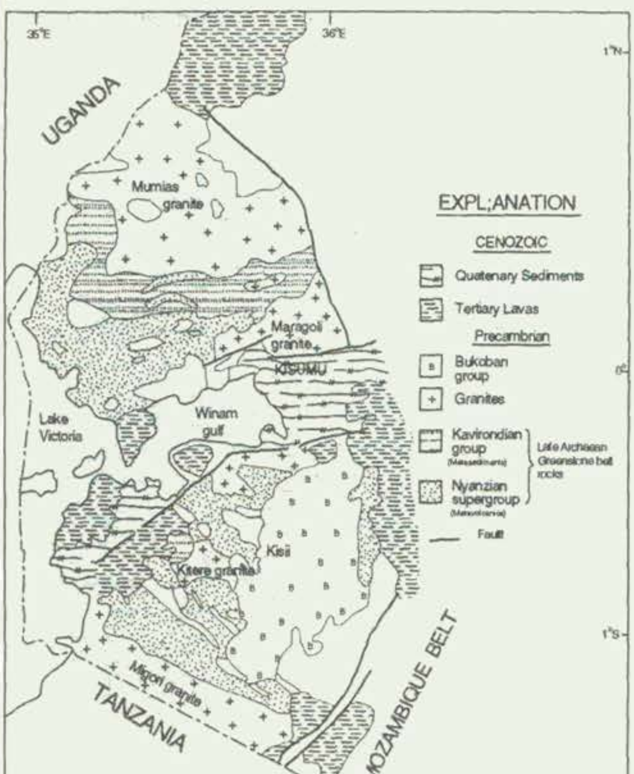


Figure 1. The Nyanzian Greenstone Belt in western Kenya (after Saunders, 1964)

The sediments of the Kavirondian Group contained in the basin consist of slightly metamorphosed rudites, arenites and argillites (greenstone facies) and the primary depositional structures in these rocks are often very well preserved. The sediments show variable petrographical and geochemical trends and differing primary depositional structures in different formations. It is therefore in the light of these attributes that the sediments have been divided into four formations. The formations include Shivakala Formation, Igukhu Formation, Mroda Formation and Mudaa Formation (Ngecu, 1992).

The secondary structures in the studied areas have been interpreted as east-west striking folds (Ichang'i, 1983; Opiyo-Akech, 1992). The Nyanzian volcanic rocks form steepily dipping monoclinal folds with the fold limbs being over 70 while the Kavirondian sediments are generally tightly isoclinally folded (Pulfrey 1936; Huddleston Iss4).

## REGIONAL GEOLOGY

The Archaean rocks of the greenstone belt in western Kenya are divided into two groups. These are the Nyanzian volcanic rocks and the Kavirondian Group. The Kavirondian Group consists of sedimentary rocks (conglomerates, greywakes and mudstones) which lie unconformably over the Nyanzian volcanic rocks (Pulfrey 1936; Stockley 1943; Huddleston 1954).

The volcanic and sedimentary rock sequences of the Tanzania Craton within the area studied have east-west strikes and are enclosed by massive granitoid rocks which are occasionally foliated at the margins. The granitoid rocks intrude both the volcanic and the sedimentary rock sequences (Fig. 2). Both types of rocks have also been intruded by dolerite dykes, pegmatites and giant quartz veins which were emplaced at different stages in the development of the greenstone belt.

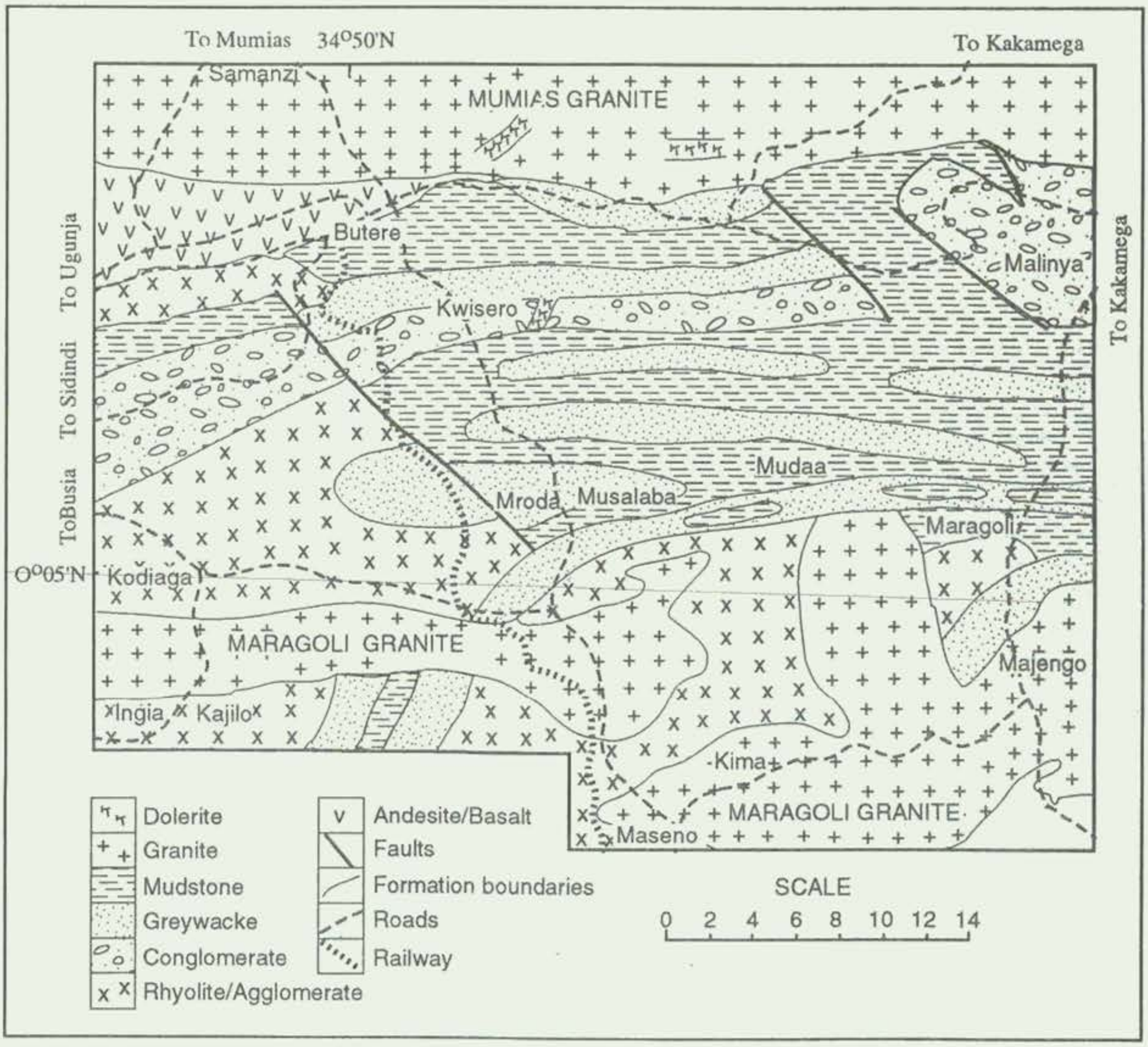


Figure 2. Geology of the Nyanzian greenstone belt in the area between Yala and Kakamega.

## FORMAL STRATIGRAPHIC TERMINOLOGY

The Kavirondian Group is proposed here as the formal name for the Archaean sediments of western Kenya. This name is preferred to the name "Kavirondian System" which was previously in use. This change is necessary because the term "Kavirondian System" implied that the boundaries between different lithological units were determined using chronostratigraphic cretaria which was not the case. The boundaries are actually diachronous and lithostratigraphic cretaria was used to define them.

During a recent study, the Kavirondian sediments were divided into smaller stratigraphic units using lithologic cretaria as recommended by International Stratigraphic Guide (Hedberg 1976) and North American Commission on Stratigraphic Nomenclature (1983). The sediments were divided into four formations which consequently form the Kavirondian Group. The formations were mapped in the area between the western slopes of the Nandi Hills and Yala town. The lowermost formation within the Kavirondian Group is the Shivakala Formation. It unconformably overlies the Nyanzian volcanic rocks (Huddleston 1954). The unit has been mapped in the area around the Shivakala market and its unit stratotype and the lower stratotype boundary have been designated on a major outcrop near Shivakala school. The formation consists of basal conglomerates interbedded with minor couplets of sandstones. The Igukhu Formation conformably overlies the Shivakala Formation and is composed of greywackes. The stratotype and the stratotype boundaries of this formation have been designated near Igukhu hospital which is about 800 metres from the banks of Yala river. The Mroda Formation rests conformably on the Igukhu Formation. This formation is composed of thin beds of sandstones which are interbedded with greywackes and mudstones. The stratotype and the lower stratotype boundary of the formation have been designated near Mroda school. The Mudaa Formation conformably overlies the Mroda Formation. The stratotype and the lower stratotype boundary of the formation is defined at Mudaa school. It is composed of thinly laminated mudstones which are sometimes interbedded with blocky mainly structureless mudstones.

## LITHOSTRATIGRAPHIC SEQUENCE SUBDIVISION

### Shivakala Formation:

The formation covers an area of about 15km in the Shivakala area. The stratotype of this formation is designated on a major outcrop which is about 260 metres thick near Shivakala School. The formation is composed of polymictic clast supported conglomerates which are intruded on the northeastern side by both the Kakamega Granites and Nyanzian andesites. On the northern side, the conglomerate sequence is intruded by the Mumias Granite and on the southern side the sequence forms a planar contact with sequences of greywackes and mudstones. Conglomerates consists of poorly sorted pebbles and boulders some of which measure up to 0.5 metres in diameter. The pebbles and clasts have basaltic, andesitic, rhyolitic and granitic compositions (Plate 1 and 2). The common sedimentary depositional structures in the conglomerates are scour marks crude stratification and imbrications.

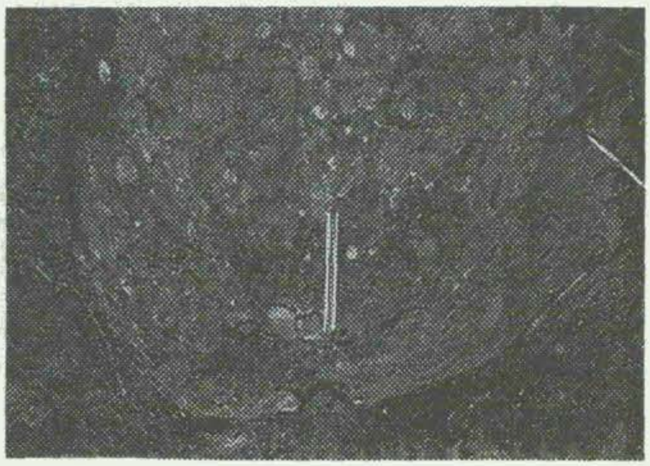

Plate 1

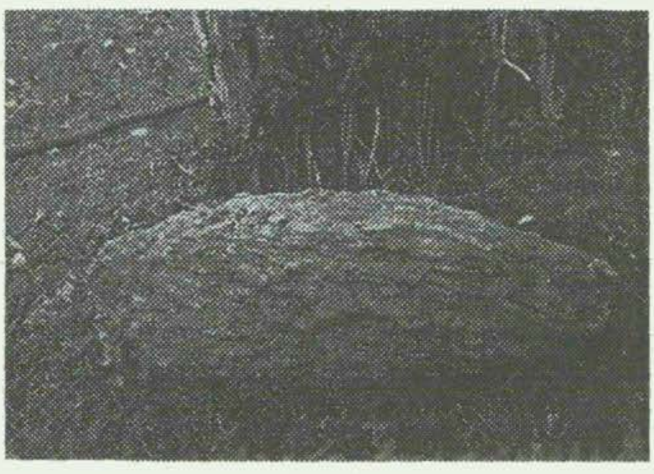

Plate 2

Plates 1 and 2 show clast supported polymictic conglomerates found at the stratotype of the Shivakala Formation. Note the crude imbrication on plate 1 along the ruler. On plate 2 imbrication is more distinct towards the front and crude stratification is observed from left to right.

### The Igukhu Formation

The stratotype of this formation is found at Igukhu hospital which is about 800 metres from the bank of the Yala river between Khayega and Chavakali markets. The greywacke found at Igukhu is dark grey and coarse grained. Clasts of quartz and feldspars in it are identifiable with the naked eye and their ratio is about 20:1. This type of greywacke is classified as quartz intermediate (Crook, 1974). The greywacke is generally thick-bedded and grades upwards into thin laminated beds of brown mudstone. The sediments at the base of the outcrop are rapid deposits which represent interval A of the Bouma Sequence (Bouma, 1962). Higher on the outcrop, smaller grains and parting lineations are observed. These sediments represent sedimentation under decreasing flow conditions (Interval B). The top of the outcrop is characterised by amalgamated fine silty deposits and mudstone beds (Intervals D and E) which represent the final fall-out of the turbidity current. The lower boundary of the Igukhu greywacke is often sharp although sometimes soft sediment intrusions are observed (Plate 3).

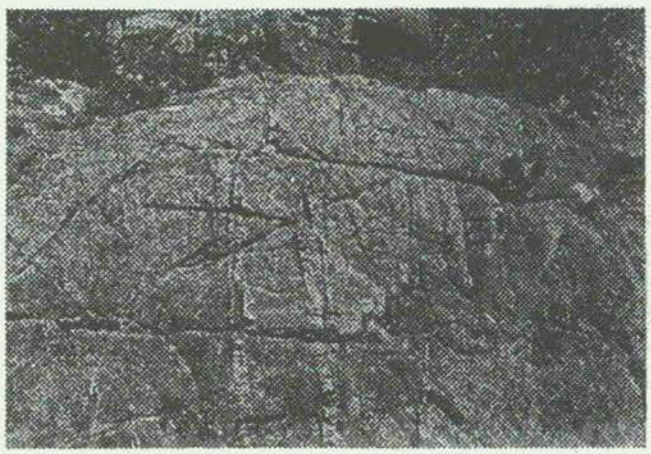

Plate 3

Another type of greywacke found in this formation at Kwisero contain less amount of quartz grains as compared to feldspars. The ratio of the two grain types is about 10:1. This greywacke contains higher mud fraction in its matrix and a lot of mudstone rock fragments. The quartz grains are moderately well sorted, sub-rounded and often fragmental. The average diameter of the grains is about 0.8 millimetres. Some quartz grains show rounded embayed outlines which are filled with felsitic material. The quartz also show distinct strain shadows.

Feldspar grains are generally anhedral and fragmented. Plagioclase feldspar is the common feldspars in the greywacke. Intraformational mudstone fragments which contain a lot of muscovite are common. Volcanic rock fragments constitute a minor fraction of the lithic component. The volcanic fragments are composed of felsic material which contain fine, lightly interlocked clasts which form a quartzo-feldspathic mosaic. The clasts have diffuse margins (Plate 4).

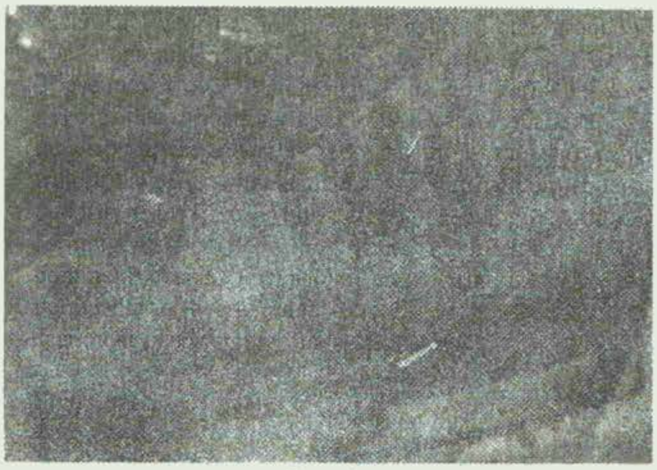

Plate 4

Plate 3 show the greywacke of Igukhu Formation stratotype. The base of the outcrop shows the Bouma interval (A) of coarse grains, followed by interval (B). Intervals D and E are not clear on the plate although they are represented on the outcrop. Plate 4 represent greywacke turbidite with base on the right side at top. Note the rock fragments near the pen, the fluxoturbidite on the middle left side, the soft sediment intrusions and slump structures on the extreme left.

## Mroda Formation

The formation consists of sandstones which appear as small interbeds within the greywacke and mudstone sequences. The stratotype of the formation is found near Mroda school. The stratotype covers an area of 6 km$^2$ and is about 17 metres thick. The sandstones are grey in colour on fresh surfaces and on weathering forms buff coloured soils.

The lithological boundaries of the sandstone beds are often gradational and therefore sometimes not easy to differentiate with greywacke facies in the field. On some outcrops however, the boundaries are sharp and their margins are marked by increased mica flakes along the bedding planes (Plate 5).

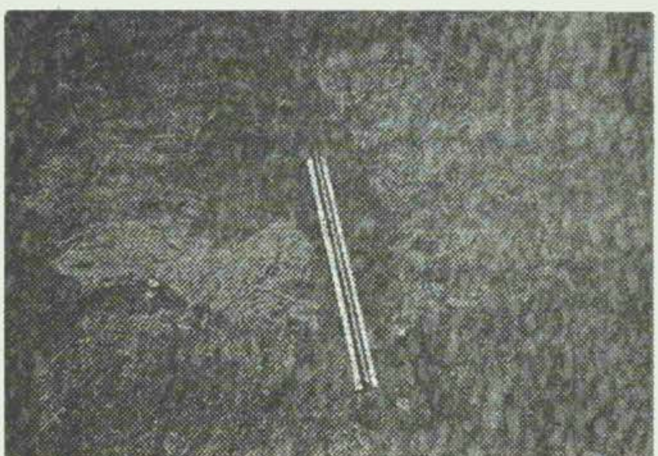

Plate 5

The sandstones contain fine well rounded quartz grains which attain diameters of up to 0.3 millimetres. The sandstones also contain up to 10% acid plagioclase feldspars. The matrix is composed of grains of quartz, feldspars, biotite, muscovite and chlorite. The rock fragments are generally absent in the sandstones. Plate 5 shows a band of sandstone at the base forming a sharp boundary with mudstones. Primary sedimentary structures are well preserved in the mudstones. Clearly visible are convolute laminations, graded bedding, slump structures and the fluxoturbidites along the river.

## Mudaa Formation

The stratotype of this formation is designated on a mudstone outcrop near Mudaa school. The lower stratotype boundary is within the interbeds of greywacke and mudstone and the upper stratotype boundary is intruded by giant quartz veins. The stratotype is about 80 meters thick (Plate 6).

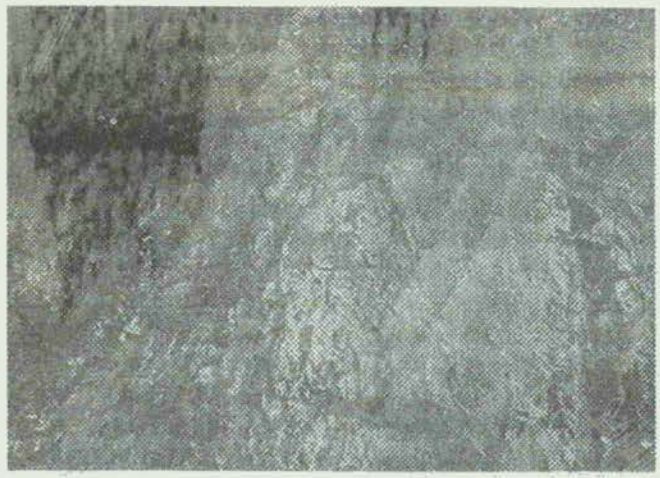

Plate 6

The mudstones are composed of minute grains of quartz, potassium feldspar and biotite. Other minerals found in the mudstones are sphene, epidote, chlorite and iron oxide. Most beds of the mudstones show graded bedding with bases which all are sharp and planar. Parallel laminations sometimes occur and some of them have been convoluted into small assymetrical folds and pillar structures (Plate 7). Mudstone beds which do not show parallel laminations, have ripple marks and tool marks (Plate 8).

Plate 6 is a blocky mudstone at the stratotype of Mudaa Formation. The mudstone is interbedded with thin beds of greywacke (next to the hummer). Plate 7 shows thin bedded mudstone which show Bouma intervals D and E. Assymetrical

Plate 7

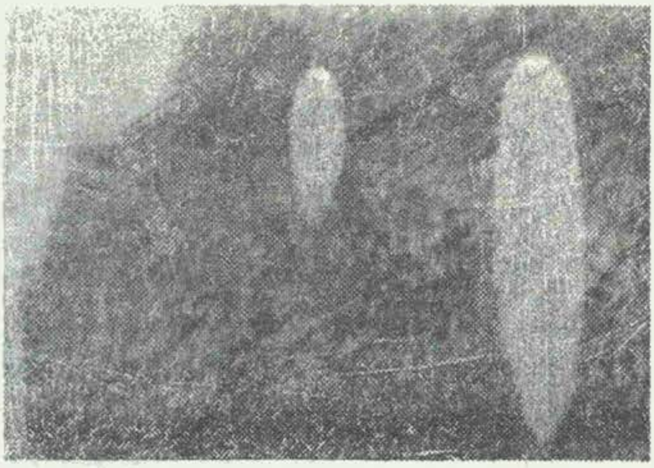

Plate 8

folds are also characteristic (next to the pen) and pillar structures on the left side of the photograph. Plate 8 shows blocky mudstone with characteristic ripple marks and tool marks (near the pencil).

## CHEMICAL ANALYSIS

In comparison with matrix of conglomerate from other Archaean terranes (Naqvi, 1977) the matrix of Kavirondian basal conglomerates is relatively more enriched in $SiO_2$. Similar chemical enrichment is observed in the elements Cr, Ca, Co, Mg and Fe and the $Na_20$-$K_20$ ratio is about 2:1.

The greywacke of western Kenya have relatively low $SiO_2$ compared with average sandstone (Pettijohn 1963). Conversely $Fe_20_3$, MgO and $A1_20_3$ are relatively high and the $Na_20$-$K_20$ ratio is within the range of 3:1.

The mudstones have even lower SiO2 values while A1203, MgO and $Fe_20_3$ are relatively high. The $Na_20$-$K_20$ ratio of mudstones is about 0.5.

The higher enrichment of the $SiO_2$ in the matrix of the conglomerates is probably an evidence of sialic rocks in the source area. The sialic crust is also evidenced by presence of tonalitic, granodioritic and trondhjemitic pebbles within the conglomerates. Enrichment of the ferromagnesian elements in the matrix would on the other hand appear to suggest simatic provenance of the matrix forming material. On some conglomerate outcrops such as the one found on the southern side on Got Regea, the pebbles are exclusively mafic and therefore a mafic rock terraine such as the older Nyanzian volcanic rocks is suggested as a second source of the matrix. However, high ferric iron ratio could also be a function of metamorphism (Pettijohn 1963).

The lower $SiO_2$ in greywacke as compared to an average sandstone is a reflection of "quartz intermediate" and "quartz poor" greywackes. Greywackes which contain 15% to 65% quartz as framework grains are called "quartz intermediate grewackes" while those which contain less than 15% quartz as flamework grains are called "poor quartz greywacke" (Crook, 1974). The two types of greywacke are derived from granitic and mafic source rocks respectively. The high ratio for greywacke is related to the high albite content in the feldspars of the sediment (Poettijohn 1963). The acid plagioclase in western Kenya greywacke supports this suggestion. The high $Na_20$-$K_20$ ratio in greywacke was also enhanced by the break down of intermediate and silicic volcanic rocks. It is believed that $Na_20$-$K_20$ ratio of most sediments which were formed prior to 2500 Ma is generally greater than 1 and the ratio is used to infer crustal evoluation and secular variation of the composition of sediments (Engel et al., 1974).

The mudstones are enriched in $K_20$ relative to $Na_20$. This indicates that the sediments retain only a small amount of detrital plagioclase. The enrichment of $K_20$ relative to $Na_20$ also increases with the maturity of the sediment.

## DEPOSITIONAL ENVIRONMENT

The polymictic conglomerates of the Shivakala Formation are interbedded with sandstones which show medium cross bedding. The conglomerates are supported by angular to subrounded clasts. The pebbles are imbricated and the upward fining of the boulders and pebbles is poorly developed. The deposits are diagnostic of predominatly stream flow-dominated alluvial fans and braided stream models (Rust et al., 1984; Mueller et al., 1987). Large subrounded clasts which are about 1 meter in diameter are common within the formation and they are characteristic of alluvial fan sedimentation. The angularity of some clasts is an indication of limited transport distance and therefore the provenance was partly close to the basin of sedimentation. Sub-rounded pebbles the other hand suggest long distance transport.

The thick repeated sequences of greywacke-mudstone in the studied area, resemble the Alpian flysch facies and the primary structures in the area are characteristic of sediements deposited by turb-dity currents. The base of the greywacke beds are generally sharp and the sequences grade upwards from coarse to fine grained argillaceous mudstones at the top. The beds are laterally continuous without pinching until they form amalgamated units with the preceeding beds and the paleo-current directions are consistent on most of the outcrops The sizes of greywacke units varies from thick beds, 15 centimeter to thin laminations. The thick beds resulted from amalgamation of several beds and they represent the more proximal turbidites. The finer grained thin beds with higher mud component represent the distal turbidites which marked low energy turbidity currents flow. Bouma intervals of internal sedimentary structures consists of basal coarse graded bedding interval A, a lower laminated bed interval B, a ripple laminated interval C, upper parallel laminated interval D and the pelitic E. These intervals occur partially or wholly in the beds of Kavirondian sedimentary sequences. On most of the greywacke outcrops, interval A is the most commonly represented at the base. Interval B is poorly represented or altogether lacking on most of the outcrops. This phenomenon may be due to combination of decreasing current velocity and grain size which may cause sedimentation to pass through to a lower flow regime bed form without the formation of the parallel laminated interval B (Walker 1965). The ripple laminated interval C is absent but interval D which indicate deposition in relatively low flow regime is common. The uppermost pelitic interval E always occur at the upper boundary of greywacke sequences where it grades from upper parallel interval with disappearance of the silty lamination which often terminate interval D.

## SUMMARY AND CONCLUSION

In the studied area, the Kavirondian Group sediments were divided into four formations, the Shivakala, Igukhu, Mroda and Mudaa. Petrographical studies of the Shivakala pebbles and chemical compositions of the matrix indicate that the sediments which make up the formation were derived from older volcanic and granitic rocks. Presence of quartzite and chert pebbles in the conglomerate also suggest intra basinal recycling of sedimentary rocks.

The primary sedimentary structures which occur on the formation include crude graded bedding and scour marks. Measurements of the apparent long-axes of the pebbles on the bedding planes and dip direction of their A-B plane where the plane project out of the rock surface, indicated that the pebbles are imbricated along their long axes. This kind of imbrication was interpreted to be as a result of fluvial flow since in fluvial situations, paleo flow is usually orthogonal to the statistical orientation of the apparent long axes. Fluvial deposition is also suggested by the angular to sub-rounded shapes of the pebbles.

Sedimentary structures contained in Igukhu, Mroda and Mudaa Formations are characteristic of turbidity current deposition. Walker (1967) compiled a number of cretaria proposed by various workers as indicative of the position of the locus of deposition relative to the source of the depositing turbidity currents. Indicators of distal deposition as opposed to proximal deposition, include thinner beds, fine grained beds, parallel sided regular beds, well-developed mudstone layers between greywacke beds, well graded beds, beds with sharp bases and tops which grade into fine sediments, the presence of abundant laminations and ripples, low sand to mud ratios and lack of scour, channels and composite beds.

The greywacke sequences at Igukhu are coarse grained, thick bedded (about 5 metres thick), show graded bedding and have about 10:1 sand-mud ratio. The sequences have therefore been interpreted as proximal turbidites. Greywacke with similar characteristics have been observed at Muruanda, Kwisero and Butere.

Sediments found at Mroda, Mudaa and Viyalo are fine grained, thin bedded, have sharp bases and low sand-mud ration (about 3:1). These sediments are frequently composed of mudstone alone and are interpreted as distal turbidites.

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# A RE-EVALUATION OF THE GEOLOGY AND TECTONICS OF THE GRANITOID PLUTONS AROUND KAKAMEGA TOWN, WESTERN KENYA

E.M. Mathu & I.O. Nyambok
Department of Geology, University of Nairobi, P.O. Box 30197, NAIROBI, Kenya.

**ABSTRACT**

*Two segments of major granitoid plutons, one located to the north and the other to the south of Kakamega town have been studied and their geology, geochemistry and tectonic evolution re-evaluated. The northerly located segment belongs to the Mumias granitoid batholith (MGB) while the segment to the south is a part of the Kakamega granite and Kakamega diorite, both referred to as the Kakamega granitoid pluton (KGP).*

*Whole rock geochemistry has revealed that these plutons are sub-alkaline and have a calc-alkalic affinity like their spatially associated greenstone belt metavolcanics. The MGB rocks classify as granites, granodiorites and tonalites while KGP rocks classify as granodiorites, tonalites, monzodiorites, diorites and gabbro-diorites.*

*The KGP is spatially associated with Archaean greenstone andesites, agglomerate, rhyolites and conglomerates and is interpreted to be an island arc pluton which tectonically uplifted the island arc volcanics in the course of its intrusion. Together with these arc volcanics, the KGP acted as a provenance for the high energy Kavirondian conglomerates and other clastic sediments which are considered to represent ancient fan models around the presumed island arc volcanoplutonic assemblage. Similar syntectonic granitoids are interpreted to be present within the MGB and could be represented by the existing granodiorite lithological units. However, most of the granitoid masses of the extensive MGB are interpreted to have been intruded after the Kavirondian sedimentation, hence resulting into the formation of the marginal metamorphic aureole around the batholith, which is also well marked in the Kavirondian metasediments. A similar lithotectonic evolutionary model is proposed for the Maragoli granitoid batholith, located to the south of the MGB, and possibly could be extended for other major granitoid bodies in the western Kenya region.*

## INTRODUCTION

Two major granitoid plutonic segments occur, one to the north and the other to the south of the Kakamega town in Western Kenya. The northern segment constitutes a part of the extensively large Mumias granitoid batholith (MGB) while the southern segment covers approximately a half of the total exposed area of the Kakamega granite and Kakamega diorite, Fig. 1 and 2. The Kakamega granite and Kakamega diorite (both referred to as the Kakamega granitoid pluton, KGP) grade into each other but are separated from the MGB by a narrow belt of the Archaean greenstone metavolcanics and metasediments.

Early geological work on these granitoid bodies for example, Huddleston (1954), did not pay much attention to their lithological variations and to a possible delineation of the lithological units found within these granitoid plutons. Although it is clear from the granitoid clasts in the Archaean greenstone belt conglomerates that some granitoids existed prior to the Archaean sedimentation, which is signified by the Kavirondian greenstone metasediments, identification and delineation of their type areas in the region has not yet been satisfactorily achieved. The main aims of this paper therefore are to reveal the geological nature of the MGB, to show that the KGP could be an island arc pluton of pre-Kavirondian and lastly, to propose that plutons syntectonic to KGP could be existing within the MGB and are possibly represented by the granodiorite lithological units within the MGB. It is evident from the metamorphic aureole around the MGB that most of the granitoid units within the MGB were intruded after the Kavirondian greenstone sedimentation.

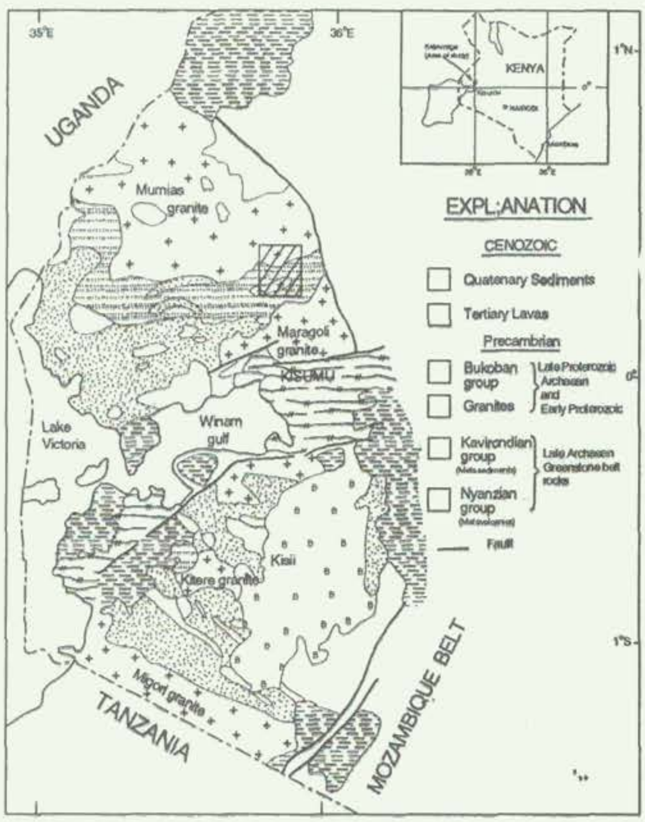


Figure 1. Map of western Kenya showing The Kakamega are (the shaded rectangle), The inset shows the location of Kakamega in Kenya.

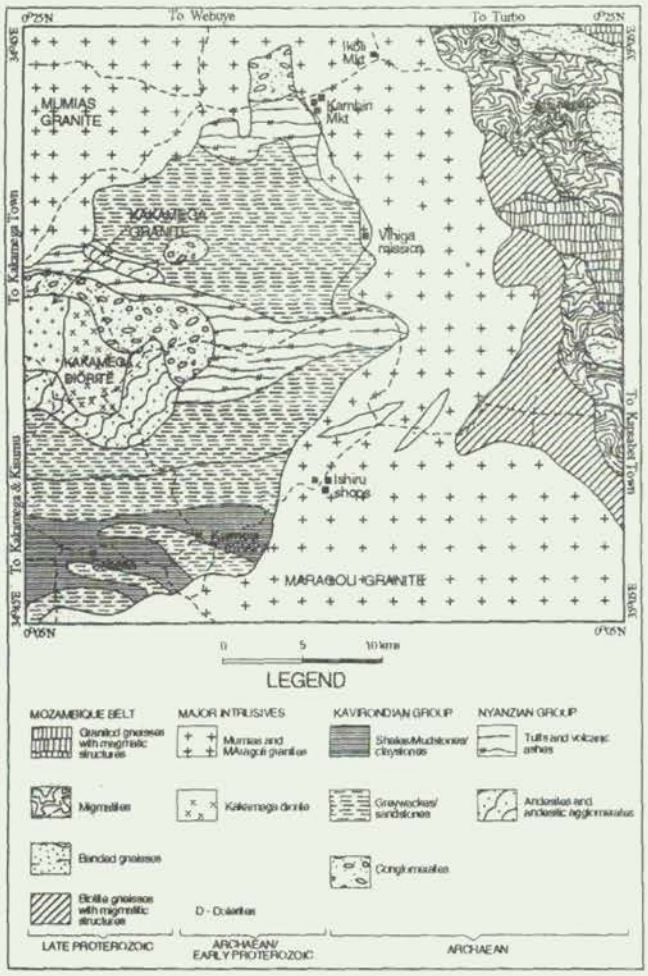


Figure2. Geology of the area around Kakamega town (inset rectangle in the NW corner)

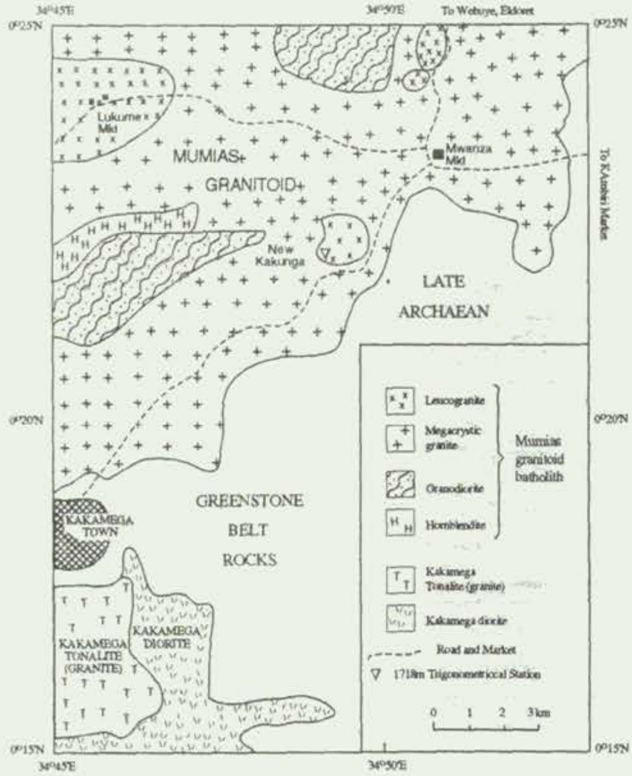


Figure 3 Geology of Archaean /Early Proterozoic granitoid bodies around Kakamega

## GEOLOGY

The mappable lithological units in the segment of the Mumias granitoid batholith (MGB) are hornblendite, granodiorite, megacrystic granite and leucogranite, Figures 2 and 3. The Kakamega granitoid pluton (KGP) on the other hand is basically composed of the granite and diorite. Further refinement of these petrographically identified litho-units have only been achieved through geochemical studies which is described in the subsequent section. Summarised petrographic characteristics of these lithological units, which demonstrate the composite nature of the MGB and KGP, are therefore described below. A summarised geology of the greenstone belt rocks around these plutons is also presented mainly because of its role in the tectonic evaluation of the plutons.

### Hornblendite

The hornblendite forms a narrow rock unit enclosed by the megacrystic granite within the MGB. It is very coarse grained, dark greenish black and has a highly interlocked matrix of randomly oriented large hornblende crystals which are about 1 to 2 cm wide and 2 to 4 cm long. The rock is approximately wholly constituted of hornblende crystals.

### Granodiorite

Granodiorite underlain areas within the MGB are characterised by a smoothly rounded, low-lying and undulating topography. The granodiorite has an equigranular, largely non-porphyritic medium texture, with an average grain size of 2 mm. The rock is composed of the following minerals in their approximate volume percentages, oligoclase 55-75%, hornblende 5 -20%, biotite 5%, microcline 7-10%, quartz 5%, accessory magnetite, haematite, sphene and apatite 5%.

### Megacrystic Granite

Within this unit, granite porphyry and biotite microgranite lithological units were also noted but at the scale of mapping, it was not possible to delineate them. The megacrystic granite is coarse grained, highly porphyritic with large phenocrysts (megacrysts) mainly of an oligoclase-andesine plagioclase and of microcline. These megacrysts are about 2 to 3 cm wide and 5 to 7 cm long and constitute upto about 25% of the total rock volume. They often portray simple contact twinning and oscillatory zoning. This rock unit is occasionally adamellitic with approximately equal proportions of solic plagioclase and potash feldspars. Its major composing minerals are microcline 40-60%, sodic plagioclase 15-45%, quartz 7-15%, hornblende 7%, occasional biotite 3% and accessory minerals, magnetite, sphene and apatite at about 3%.

### Leucogranites

Leucogranites are found as a major unit in the north-western corner of the MGB but also constitute the leucogranite dykes, largely within the megacrystic granite unit. Leucogranite grades from the megacrystic granite and the latter grades from the granodiorite. The leucogranites are largely non-porphyritic, have a medium equigranular texture with an average grain size 2 mm or less, and are rich in K-feldspars. The approximate mineralogical composition of these rocks are - microcline 50-80%, oligoclase, 10-25% and quartz 10-20% Biotite and haematite are the occasional mafic minerals present but constitute about 3% or less of the rock volume. Occasionally, leucogranites may contain quartz phenocrysts which are relatively much smaller in size than the feldspar megacrysts found in the megacrystic granite.

### Kakamega Granite and Diorite

Both the granite and the diorite grade into each other and are medium to coarse in texture with a grain size range of 1 to 3 mm. The granite is occasionally porphyritic and the phenocrysts are lath-like, ranging in size from 2 - 5mm wide and about 1 cm long. These phenocrysts are mainly of oligoclase or andesine composition. The composing mineral in the granite are approximately as follows - plagioclase of oligoclase composition ($An_{10}$-$An_{50}$), 30 - 60%, augite, hypersthene, hornblende and biotite , 10-20%, occasional microcline, 15-35%, quartz, 3-15% and accessory magnetite, 3%. Augite is usually the dominant mafic mineral present.

While the granite is medium to light in colour, the diorite is darker, often greenish gray to dark greenish gray. This diorite is both richer in mafic minerals and in calcic plagioclase and has the following approximate mineralogical composition - andesine, 60%, augite and some hypersthene, 30%, magnetite, 7%, and interstitial quartz, 3% which qualifies the rock to be a quartz diorite (tonalite).

### Mafic Xenoliths

These constitute other unmappable lithological units commonly occurring in the megacrystic granite. The xenoliths are black or dark greenish black, usually polygonal with sharp contact boundaries with the host rock. Occasionally, they are dappled with the feldspar phenocrysts which are also found in the host rock. The xenoliths have a medium to coarse, randomly oriented texture and are composed of oligoclase, 40 -60%, hornblende, 30%, magnetite, 15%, biotite and sphene, about 5%. When enriched in felsic minerals, quartz, 20% and microcline, 10%, are introduced into the rock matrix. Accessory haematite and apatite are other occasional minerals but constitute about 2%. Some xenoliths have lithological characteristics that clearly indicate their derivation from the greenstone belt metavolcanics.

### Greenstone belt rocks around the KGP and MGB

The greenstone belt rocks around the KGP and MGB, Fig. 2, include both the Archaean metavolcanics and metasediments, which will be simply referred to as volcanics and sediments. The volcanics include basaltic andesites, andesites, some dacites and rhyolites. Pyroclastic agglomerates, tuffs and volcanic ashes also occur as well as chert. These volcanics are calc-alkalic and from geochemistry are interpreted to be island arc volcanics. The sediments on the other hand include polymict conglomerates, greywackes, feldspathic sandstones, shales and mudstones. They are interpreted to be both shallow water deposits as well as deep water turbidite sequences.

## GEOCHEMISTRY

The geochemical nature of the MGB and KGP granitoids are indicated in Figs. 4,5 and 6 and Tables 1 and 2. Fig. 4 clearly shows that these granitoids plot in the sub-alkaline field. Their classification diagram, Fig. 5 based on De La Roches et al. (1980) shows that the MGB has rock units that vary from granodiorites, tonalites and granites, which compares fairly well with the petrographic classification used to describe the geology in the preceding section. The same diagram also shows a better classification refinement of the rocks of the Kakamega granitoid (KGP) pluton. Rocks of the Kakamega granite body classify between granodiorite, tonalite and monzo-diorite, while

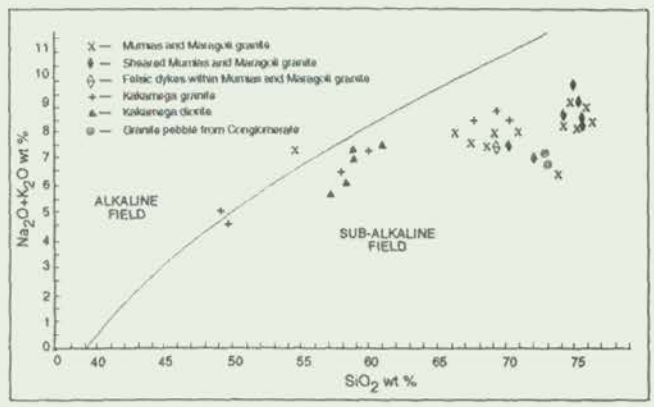


Figure 4. Silica versus Total-alkalis diagram for the plutonic and granitoid gneissic rocks from the Kakamega area.

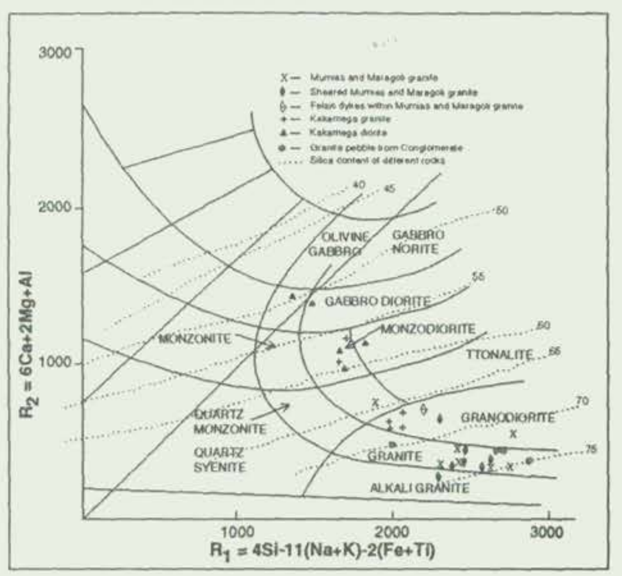


Figure 5. Classification of granitoids from around Kakamega andMaragoli using $R_1$-$R_2$ classification of De la Roches et al (1980)

those of the Kakamega diorite vary from monzo-diorite, diorite to gabbro-diorite.

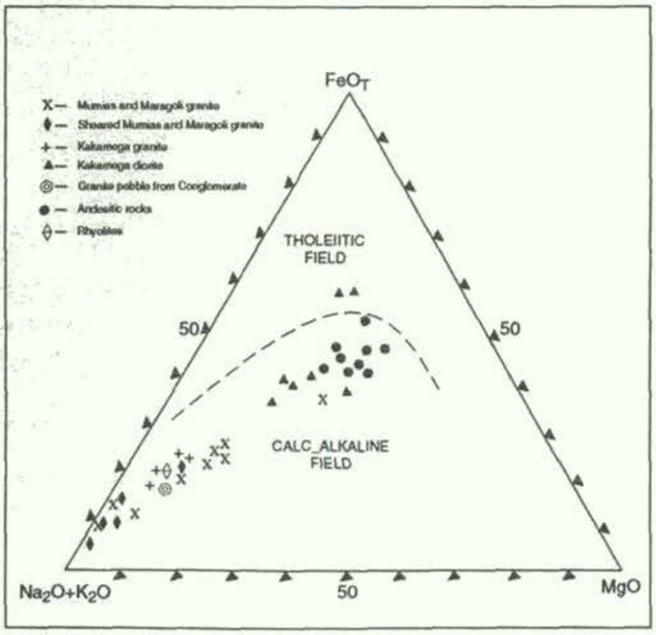


Figure 6. A Plot of putonic and volcanic rocks of the project area on the AFM diagram

A ternary AFM (where A= total alkali, ($Na_2+K_20$), F = total iron as ferrous, ($Fe0_T$) and M = Magnesium (Mg0)) diagram shows that these granitoids are calc-alkalic, just as the Archaean greenstone belt volcanics, also plotted in this diagram, Fig. 6.

Table1. Showing ranges for the major elements for the granitoids around Kakamega town and the Maragoli granitoids

| Major Element | (i) Mumias & Maragoli granitoids | (ii) Kakamega granite (granodiorite tonalite to monzodiorite) | (iii) Kakamega diorite (monzodiorite dioriite to gabbro-diorite) |
|---|---|---|---|
| $SiO_2$ | 66.37-75.51 | 57.87-69.32 | 49.29-61.15 |
| $Al_2O_3$ | 13.74-16.11 | 17.01-15.84 | 14.55-16.72 |
| $Fe_2O_3$ FeO | 1.01-3.72 | 7.60-2.48 | 15.23-6.15 |
| CaO | 3.34-0.86 | 5.93-2.40 | 8.64-4.78 |
| MgO | 1.98-0.18 | 4.06-0.94 | 4.70-3.00 |
| $Na_2O$ | 5.02-3.67 | 3.85-4.54 | 2.89-4.69 |
| $K_2O$ | 1.85-4.97 | 2.54-4.09 | 1.75-3.25 |
| MnO | 0.06-0.03 | 0.12-0.22 | 0.20-0.10 |
| $TiO_2$ | 0.50-0.03 | 0.71-0.22 | 2.45-0.59 |
| $P_2O_5$ | 0.24-0.03 | 0.36-0.12 | 0.35-0.21 |

Table 2. Major and trace elements of sample from the various granitoids around Kakamega town.

(i) Mumias and Maragoli granitoids

| Sample No. | 775B | 765A | 756A | 715 | 762A | 772 | 773 | 666A | 773D | 777 | 642 | 642 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 66.39 | 68.03 | 67.39 | 70.29 | 73.36 | 54.67 | 68.28 | 72.93 | 68.29 | 74.80 | 74.06 | 75.51 |
| $Al_2O_3$ | 16.11 | 15.39 | 15.39 | 15.18 | 14.56 | 14.46 | 15.60 | 14.50 | 15.57 | 13.74 | 13.81 | 13.83 |
| $Fe_2O_3^T$ | 3.54 | 3.47 | 3.72 | 2.36 | 1.40 | 0.09 | 3.14 | 2.61 | 3.13 | 1.25 | 1.52 | 1.01 |
| MgO | 1.06 | 1.81 | 1.98 | 1.30 | 0.59 | 5.63 | 1.61 | 0.83 | 1.64 | 0.24 | 0.27 | 0.18 |
| CaO | 3.34 | 3.21 | 3.16 | 2.59 | 1.50 | 7.00 | 2.92 | 2.40 | 2.92 | 0.94 | 0.99 | 0.86 |
| $Na_2O$ | 5.02 | 4.52 | 5.04 | 4.32 | 4.29 | 3.14 | 5.00 | 4.55 | 4.98 | 4.03 | 4.14 | 3.67 |
| $K_2O$ | 2.97 | 2.98 | 2.59 | 3.59 | 4.01 | 4.06 | 2.82 | 1.85 | 2.82 | 4.83 | 4.97 | 4.75 |
| $TiO_2$ | 0.50 | 0.37 | 0.44 | 0.25 | 0.20 | 1.60 | 0.37 | 0.23 | 0.37 | 0.13 | 0.16 | 0.13 |
| $P_2O_5$ | 0.21 | 0.15 | 0.24 | 0.08 | 0.05 | 1.20 | 0.20 | 0.06 | 0.21 | 0.00 | 0.03 | 0.03 |
| MnO | 0.05 | 0.06 | 0.05 | 0.04 | 0.03 | 0.14 | 0.05 | 0.04 | 0.05 | 0.03 | 0.05 | 0.03 |
| | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| Ba | 893 | 870 | 711 | 703 | 806 | 3190 | 779 | 558 | 775 | 693 | 398 | 723 |
| Cr | 42 | 61 | 32 | 23 | 16 | 153 | 36 | 21 | 42 | 20 | 2 | 19 |
| Zr | 145 | 124 | 150 | 96 | 104 | 192 | 137 | 106 | 142 | 100 | 134 | 92 |
| Sr | 890 | 676 | 851 | 551 | 401 | 847 | 832 | 193 | 838 | 191 | 126 | 190 |
| Rb | 70 | 95 | 93 | 106 | 113 | 89 | 81 | 57 | 85 | 221 | 389 | 177 |
| Y | 11 | 10 | 14 | 13 | 19 | 31 | 16 | 25 | 17 | 7 | 31 | 7 |
| Nb | 2 | 2 | 3 | 3 | 2 | 12 | 5 | 4 | 4 | 6 | 16 | 3 |
| Zn | 132 | 130 | 86 | 60 | 78 | 158 | 78 | 70 | 90 | 43 | 57 | 43 |
| Ni | 17 | 26 | 19 | 21 | 0 | 73 | 23 | 2 | 16 | 27 | 16 | 2 |
| V | 47 | 41 | 66 | 11 | 0 | 164 | 49 | 33 | 40 | 0 | 5 | 5 |

(ii) Kakamega granite —

| Sample No. | 551 | 558 | 559 | 729 |
|---|---|---|---|---|
| $SiO_2$ | 59.91 | 67.78 | 69.32 | 57.87 |
| $Al_2O_3$ | 15.84 | 16.01 | 16.04 | 17.01 |
| $Fe_2O_3^T$ | 7.11 | 3.42 | 2.48 | 7.60 |
| MgO | 3.64 | 1.32 | 0.94 | 4.06 |
| CaO | 5.10 | 2.57 | 2.40 | 5.93 |
| $Na_2O$ | 3.85 | 4.29 | 4.54 | 3.87 |
| $K_2O$ | 3.42 | 4.09 | 3.90 | 2.54 |
| $TiO_2$ | 0.65 | 0.31 | 0.22 | 0.71 |
| $P_2O_5$ | 0.36 | 0.14 | 0.12 | 0.29 |
| MnO | 0.12 | 0.06 | 0.05 | 0.12 |
| | 100.0 | 100.0 | 100.0 | 100.0 |
| Ba | 963 | 937 | 1051 | 859 |
| Cr | 109 | 25 | 27 | 124 |
| Zr | 181 | 170 | 133 | 158 |
| Sr | 640 | 634 | 646 | 699 |
| Rb | 147 | 159 | 156 | 81 |
| Y | 27 | 19 | 15 | 23 |
| Nb | 4 | 4 | 4 | 2 |
| Zn | 98 | 72 | 88 | 139 |
| Ni | 12 | 18 | 0 | 16 |
| V | 118 | 48 | 16 | 134 |

(iii) Kakamega diorite —

| Sample No. | 549 | 733 | 554 | 595 | 592 | 608 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 58.39 | 57.32 | 58.94 | 61.14 | 58.84 | 49.29 |
| $Al_2O_3$ | 16.72 | 16.13 | 16.36 | 16.65 | 16.51 | 14.55 |
| $Fe_2O_3^T$ | 7.76 | 7.76 | 7.55 | 6.15 | 7.74 | 15.23 |
| MgO | 3.94 | 5.38 | 3.49 | 3.00 | 3.33 | 4.70 |
| CaO | 5.97 | 6.65 | 5.36 | 4.78 | 5.14 | 8.64 |
| $Na_2O$ | 3.83 | 3.89 | 3.81 | 4.15 | 4.69 | 2.89 |
| $K_2O$ | 2.31 | 1.78 | 3.17 | 3.25 | 2.59 | 1.75 |
| $TiO_2$ | 0.70 | 0.74 | 0.84 | 0.59 | 0.74 | 2.45 |
| $P_2O_5$ | 0.26 | 0.21 | 0.35 | 0.19 | 0.30 | 0.29 |
| MnO | 0.12 | 0.12 | 0.11 | 0.10 | 0.12 | 0.20 |
| | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| Ba | 755 | 604 | 1037 | 880 | 769 | 513 |
| Cr | 96 | 160 | 98 | 88 | 74 | 59 |
| Zr | 170 | 146 | 209 | 213 | 203 | 199 |
| Sr | 592 | 618 | 563 | 600 | 516 | 210 |
| Rb | 80 | 47 | 124 | 119 | 89 | 65 |
| Y | 22 | 21 | 26 | 22 | 25 | 45 |
| Nb | 5 | 4 | 8 | 7 | 7 | 8 |
| Zn | 92 | 92 | 87 | 83 | 146 | 189 |
| Ni | 31 | 82 | 29 | 24 | 16 | 37 |
| V | 127 | 136 | 118 | 86 | 142 | 356 |

Table 1 and 2 gives the major element geochemistry of these MGB and KG rocks.

Table 1 shows that MGB pluton is richer in $Si0_2$, $K_20$ and $Na_20$ and poorer in $Al_20_3$ $Fe_20_3$ (total iron as ferric), CaO, MgO and MnO, $Ti0_2$ and $P_20_5$ as compared to the KGP. The KGP pluton on the other hand is poorer in alkali elements but richer in the other elements. The diorite in this pluton, however is the poorest in alkalis and richest in these other elements. This geochemical characterisation fairly complies with what has been realized from the petrographic studies.

## TECTONICS

The tectonic setting for these granitoid bodies as revealed by both the geologic and geochemical evidences is that the Kakamega granitoid (KGP) pluton could be representing an Archaean island arc pluton. The pluton is proposed to have been intruded after the island volcanism which occurred together with the volcanism of the other Nyanzian greenstone belt metavolcanics. However the intrusion of the pluton predated the sedimentation of the Archaean Kavirondian greenstone metasediments. Further, it is iproposed that similar syntectonically intruded granitoids as the Kakamega granitoid pluton, exist within the Mumias granitoid batholith (MGB). However, these plutons have not been identified and delineated within the MGB due to lack of both detailed work on the geological mapping within the granitoid bodies and inadequate geochronological dating within the batholithic plutons.

The consanguineous association of this ameboid shaped KGP with both the Archaean greenstone volcanics of possible island arc nature, together with the high energy Archaean greenstone clastic sediments and the occurrence of this pluton at the nuclear position of the entire rock assemblage, supports the proposition that the KGP was intruded as an island arc pluton. The pluton was intruded close to the end or after the island arc volcanism, hence resulting into a high tectonic uplift of the volcanics, which together with the pluton acted as the provenance for the derivation of the high energy clastic sediments that marginally surround this volcanoplutonic assemblage.

The high energy clastic sediments around the KGP and MGB show an inverted stratigraphy, where the conglomerates occur at the margin of the plutons and sediments. Farther away, from this margin, the conglomerates grade into greywackes and feldspathic sandstones of a possible shallow water sedimentation environment. Farther away southwards beyond the KGP into the Kaimosi area, the high energy rock assemblage gradually grades into a sequence of deep water shales and greywackes interpreted to be a turbidite sequence formed in a deeper forearc basin. It is therefore interpreted that the high energy clastic sediments constitute fan models formed by rivers debauching into shallow water marine environments. These rivers must have eroded this material from highly elevated sub-aerial areas. Iron rich chert has been noted occurring at the margin of the volcanics and the shallow water deposits, thus marking the separation boundary between the original sub-aerial and submarine environments.

## DISCUSSION

Geological and geochemical evidences indicate that the Mumias and Kakamega granitoid plutons had an epidosic history characterised by intrusions of pre- and post-tectonic age to the Archaean Kavirondian sedimentation. This evolution setting could be extended for the rest of Archaean - early Proterozoic intrusive granitoids in western Kenya. Both petrography and geochemistry have revealed that the early granitoids were alkali and silica poor but rich in mafic minerals. Their plagioclase was also more calcic while later granitoids were alkali and silica rich and their plagioclase was more sodic.

In the Archaean - early Proterozoic granite-greenstone and granulite-greenstone terrains, most of the granites have had a complex episodic evolution. In some of these terrains, the early granitoids were alkali and silica poor but rich in ferromagnesian minerals and calcic plagioclase. In the Svecofennian of the Fennoscandian Shield of Norway and Sweden, Andersson (1991) has documented about three felsic plutonisms and has given the early granitoids as of tonalitic-granodioritic compositions but the later granitoids were alkali rich with large K-feldspar megacrysts. Similarly, several episodic granitoid plutonisms in the Superior Province of Canada, have been documented by Card (1990). The early synvolcanic to synkinematic granitoid plutons are mainly quartz diorites, trondhjemites and granodiorites. The synvolcanics associated with these plutons are interpreted to be oceanic island arc and continental volcanics. Horneman et al. (1988) have also documented that the granitoids surrounding and intruding the Kuhmo greenstone belt in eastern Finland comprise of tonalites, trondhjemites, granodiorites and granites that were emplaced as several generations during the Archaean 2.6-2.9 Ga. Although no discrimination diagrams have been plotted for the granitoids around Kakamega town, the mineralogy of KGP compares with that of island arc granitoids as presented in Maniar and Piccoli (1989).

There has been a general notion among the Kenyan geologists to consider the Kakamega granite and diorite pluton to be an offshoot of the Mumias granitoid batholith. Available geological and geochemical evidence tend to negate this notion. Rather, it is considered that early mafic rich, alkali and silica poor granitoids existed as discrete small plutons that were later accreted together into one large Mumias granitoid plutonic body. This later granitoid plutonism was characterised by K-feldspar and silica enrichment and was responsible for the formation of the metamorphic aureoles around the batholiths. The KGP however, does not have any aureole around it which tends to support its pre-Kavirondian intrusion. Shiozaki (1983), through magnetic susceptibility studies on the Tanzanian cratonic granitoids in western Kenya noted that the susceptibility varied from low to high even within the same granitoid mass. Shiozaki (op. cit.) concluded that a probable multiple intrusion occurred even in a single intrusive body.

The following are therefore the major conclusions about the granitoids around the Kakamega town in western Kenya.

1. Two granitoid segments occur, one to the north and the other to the south of the Kakamega town. The segment to the north is a part of the Mumias granitoid batholith (MGB) and the one to the south is a part of the Kakamega granite and diorite, both called the Kakamega granitoid pluton (KGP).

2. The segment of the MGB has a heterogeneous lithology composed of hornblendite, granodiorite, megacrystic granite and leucogranite. The segment of the KGP is only composed of granite and diorite but geochemical classification has revealed it heterogenous lithological units too.

3. The hornblendite is almost wholly composed of randomly oriented, coarse, interlocked hornblende prisms. The granodiorite is composed of mainly oligoclase, hornblende and some biotite, quartz and microcline. The megacrystic granite is highly porphyritic with large alkali feldspar phenocrysts (megacrysts). Both K-feldspar and sodic plagioclase are dominant in the rock. Quartz and low contents of hornblende and biotite are present too. The leucogranites are dominated by K-feldpsars but also contain low amounts of sodic plagioclase and quartz. The Kakamega granite is mainly composed of oligoclase-andesine plagioclase, augite, some hypersthene, hornblende and biotite, occasional mi-

crocline, quartz and magnetite. The Kakamega diorite is predominantly composed of andesine, augite and hypersthene and magnetite and interstitial quartz.

4. The granitoids are sub-alkaline and have a calc-alkalic affinity. Classification based on De La Roches et al (1980) has shown that MGB contains granodiorites, tonalites and granites. The KGP pluton contains granodiorites, tonalite, monzodiorite and gabbro-diorite.

5. Geological and geochemical evidences have led to the interpretation that the KGP is an island arc pluton that was intruded before the Archaean Kavirondian greenstone sedimentation but post-tectonic to Nyanzian greenstone volcanism. Similar syntectonic granitoids to the KGP exist within the MGB but most of this batholith was intruded after the Kavirondian sedimentation resulting into a metamorphic aureole within these sediments.

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# THE LATE PROTEROZOIC YATTA SHEAR ZONE: A POSSIBLE LATERAL RAMP EXTENDING ACROSS THE KENYA RIFT

I.O. Nyambok[1], J. Chorowicz[2] and E. Mathu[1]

[1]Department of Geology, University of Nairobi P.O. Box 30197, Nairobi, Kenya.

[2]Department de Geotectonique, Universite Pierr et Marie Curie, 4 Place Jussieu, 75252 Paris, Cedex 05, France

## ABSTRACT

*In the Mozambique orogenic belt of the late Proterozoic, shear zones are observed to trend along the strike for long distances and often with wide zones of intense deformation. In Kenya, the shear zones appear to be reactivated frontal thrust imbricating ophiolites and crustal segments. This kind of shear zone is typified by the Yatta Shear Zone (YSZ). The YSZ is clearly recognisable near Thika and extends southeastwards for 300 kms. In studying the exposed section, LANDSAT-MSS and MOMS-01 satellite imageries were used for the regional interpretation and structural data taken across the YSZ. Both imageries were processed by stretching and thereafter produced as colour composite image, thus achieving high image resolution. From the study, it is apparent that the YSZ originated as a subvertical wall of a major lateral thrust zone during the Pan-Africa collision in which post-collisional reactivation was progressively transferred to the Mutito fault. To the northwest of Kenya, rift, the shear zones associated with ophiolites, mark major frontal ramps.*

## INTRODUCTION

In the late Proterozoic Mozambique Orogenic belt in East Africa (the Mozambique Belt of Holmes, 1951 shear zones are observed to trend for long distances along strike or at high angles with the belt, and coincide with wide (several kilometres) zones of intense deformation. In Kenya, parallel to the north-south trending Mozambique Orogenic belt, shear zones are interpreted by Shackleton (1986) to be reactivated frontal thrusts imbricating ophiolites and crustal segment. Shear zones extending across the Mozambique Orogenic belt may then represent reactivated lateral ramps. A possible example is the northwest-trending Aswa shear zone (Sanders, 1965; Hepworth, 1967), of which the Yatta shear zone in Central Kenya is considered to be the southeast extension (Fig. 1) (Chorowicz and Mukonki, 1979). In central Africa the large scale Proterozoic Mwembeshi shear zone is interpreted to have originated as a lateral ramp linking major frontal thrust zones (Coward and Darly, 1984). These types of shear zones are probably structures affecting different sections of the lithosphere that were easily reactivated by the extensional tectonic (Daly, 1986).

This paper examines the Yatta Shear Zone (YSZ) using satellite imageries and field observations. The aim is to interpret the Precambrian structure, and suggest whether the northwest extension of the YSZ played some role in the reactivation of the East African Rift.

## THE MOZAMBIQUE OROGENIC BELT IN KENYA

The Mozambique Orogenic belt runs northward for thousands of kilometres, from Mozambique to Ethiopia and gradually passes into the Arabian Nubian shield (Fig. 1). In Kenya, this belt is made up of medium to high grade metasedimentary rocks and granitoids (Shackleton, 1986), associated with dismembered medium to low retrograde metamorphic mafic-ultramafic and sedimentary-volcanic rocks clearly of ophiolitic affinity (Shackleton, 1977; Vearncombe, 1983; Key et al. 1989). The tectono-metamorphic history shows thrusting, folding and shearing typical of the Pan-African orogeny (Shackleton, 1986). According to Kennedy (1961) the term Pan-African Orogeny. restricted to about 500 Ma but is currently taken to include a much wider time-span namely an interval of 950 to 450 Ma (Kroner, 1985). Rocks from the Mozambique Orogenic belt generally yield a Pan-African age (Cahen et al. 1984). In north-central Kenya, however, Key et. al. (1989) have shown that rocks from the lowest stratigraphic unit are of Kibaran age (>1200 Ma). This fact can be taken as evidence that Pre-Pan-African crust may have been tectonically assembled together with younger late Proterozoic terrains; hence the polycylic character of the Mozambique belt recognised by Holmes (1951).

## THE GREGORY RIFT

In Kenya, the eastern branch of the East African Rift System is known as the Kenya Rift (Fig. 1, King, 1970). From Lake Turkana upto lake Bogoria, the Kenyan Rift has a north-south direction but then turns southeast to later re-orient in north-south direction from the Kedong Embayment and continues as far as Lake Magadi (Fig. 2). This curving (see the sketch map in Fig. 2) is part of a rift structure known as the Gregory Rift. In this sector of the rift, Cenozoic tectonic and volcanic features are well exposed. At a continental scale this sharp kink in the rift-trend coincides with the northwest-trending Aswa Shear Zone (Fig. 1).

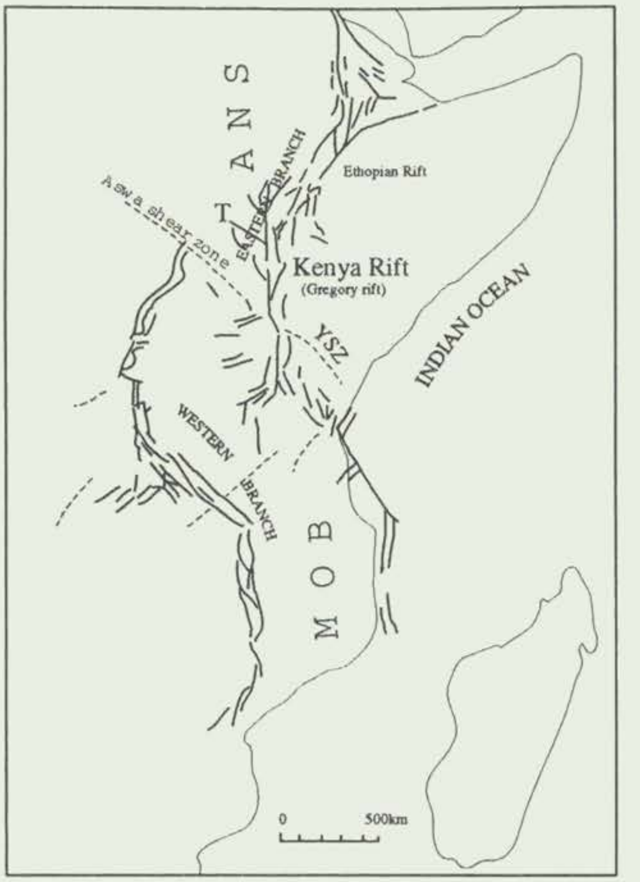


Fig. 1 - Cenozoic structural scheme of the East African Rift system (western and eastern branches) Key: YSZ = Yatta Shear Zone (the area of study); MOB = Mozambique Orogenic Belt; ANS = Arabian-Nubian Shield; T = Turkana lake

The main Cenozoic volcanic activity is centred in the Gregory Rift (Fig. 2). Pleistocene lavas occur also southeastward, along a fault zone which includes the Kilimanjaro (not shown in Fig. 2); other lava flows (Neogene phonolite) are exposed to the east of this trend, forming the Yatta Plateau. The Yatta Plateau is a narrow (2 to 3 kilometers wide) prominent feature, made up of Cenozoic phonolite, clearly visible on the satellite imagery (Fig. 3,4).

## THE YATTA SHEAR ZONE (YSZ)

The YSZ is clearly recognizable near Thika and extends 300 kms southeastward (Fig. 2). To study the exposed section, LANDSAT-MSS and MOMS-01 satellite imageries were used for the regional interpretation and structural data taken across the YSZ.

The LANDSAT-MSS image (path 179 and row 62, imagery taken on October 26, 1975 and February 11, 1976) were routinely processed by stretching and anamorphosis before generating color compositions (bands 4,5 and 7 respectively in blue, green and red). The space resolution of these data is about 80 meters (Fig. 3).

The MOMS-01 image (acquired from the Space Shuttle along the track STS-11 on February, 11, 1984, orbit n°11-62) has a space resolution of 20 meters and with a field of view of 138x92 km (Fig. 4). This sensor viewed the scene in two spectral bands (band 1: 575-625 nm, yellow-range; band 2:825-975 nm, near-infrared). After applying stretching to each MOMS-01 band, a color composite image was generated (band 1 in red and blue and band 2 in green). This process highlights areas covered by high vegetation (low topography) and areas with only bushes or bare soil cover (high topography). This permits appreciation of topographic variations and allows interpretation of continuous lines as structural trends (e.g. faults). In addition, iron-rich soil has a high reflectance value in the near-infrared range and this enables the detection of differences in rock composition (e.g. the folded amphibolite is shown in red-brown, Fig. 5).

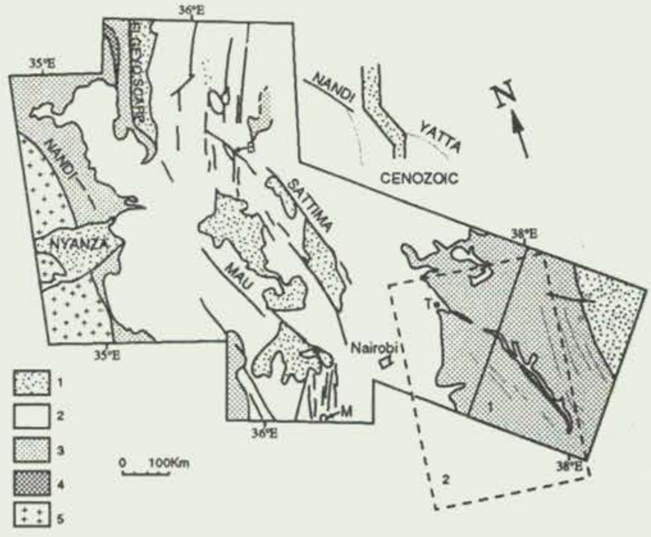


Fig. 2 - Geological map showing the Yatta Shear zone (south-east corner); the Cenozoic faults (Sattima, Mau); the frontal thrust zones of Pan-African terrains adjacent to the Tanzanian craton. The heavy (1) and broken (2) lines are respectively the areas covered by the MOMS-01 and Landsat-MSS imageries of Figs. 3 and 4. The structural sketch, outside the map, shows the bend of the Kenya Rift intersecting the YSZ and the Nandi scarp. Key 1: 1 =Recent sediments, 2= Neogene to recent volcanic rocks, 3= Rocks of the Mozambique Orogenic belt (4= ophiolite), 5= Archean rocks (Tanzania craton); B= Bogoria lake; M=Magadi lake.

## LANDSAT-MSS AND MOMS-01 INTERPRETATION

Because the interpretation from satellite imageries was not followed-up by ground checking the fault and foliation together with the fold-closure (all shown as dotted lines in Fig. 5) collectively represent the regional structural trend.

It is clear from Fig. 5 that the Yatta Plateau is the site along which two different structural trends intersect. The migmatitic gneisses which outcrop in the northeast side show a deviation in trend of as much as 30° from that of gneisses and amphibolites located in the southwest side. Since this feature is observed from an altitude of 900 kms, it must represent a large scale shear zone which roughly coincides with the Yatta Plateau. The sense of shearing (sinistral) can be deduced by observing the orientation of the structural trends.

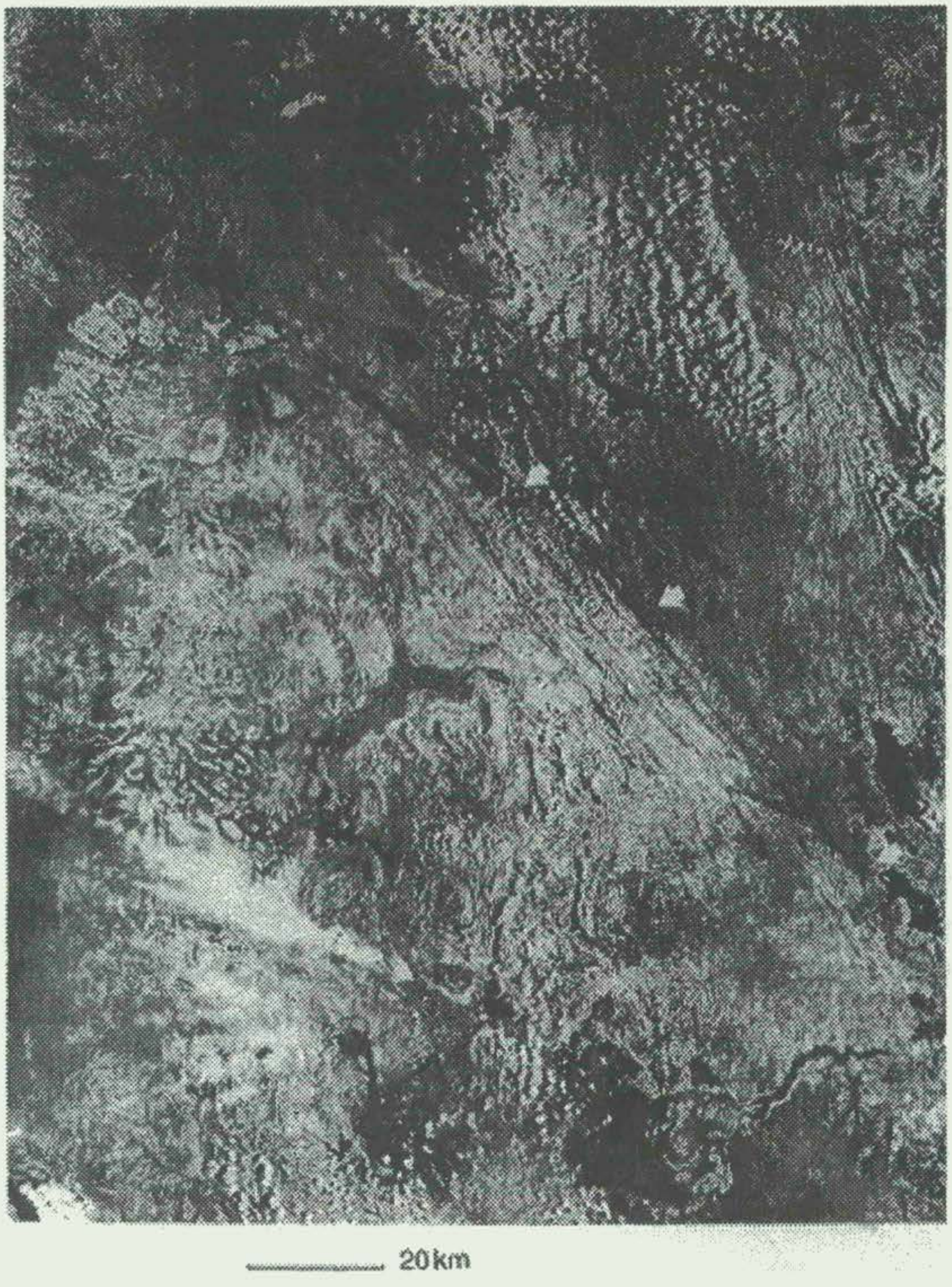


Fig. 3-LANDSAT-MSS imagery; the white arrows indicate the Yatta Plateau.

Along the southwest side of the Yatta Plateau, distinct structural feature can be detected. To the northwest, the structural-trend is constantly aligned with the fault zone, and no fold closure is observed at the scale of the map. On the contrary, in the southeast side, folds with axial trace progressively curving away from the fault zone are clear. Northwest of Simba-Kibwezi domal structures appear to have been affected by the proximity with the YSZ (Fig. 5). This observation confirms Baker's (1954) suggestion that the present shape of the concentric structures around these domes could have been the result of some rotation. Saggerson (1963) arrived at a similar conclusion by suggesting that regional folding was initially dominated by southeast-northwest compression which later changed, rotating anti-clockwise, to generate planar and linear fabrics, respectively striking and plunging towards north-northwest.

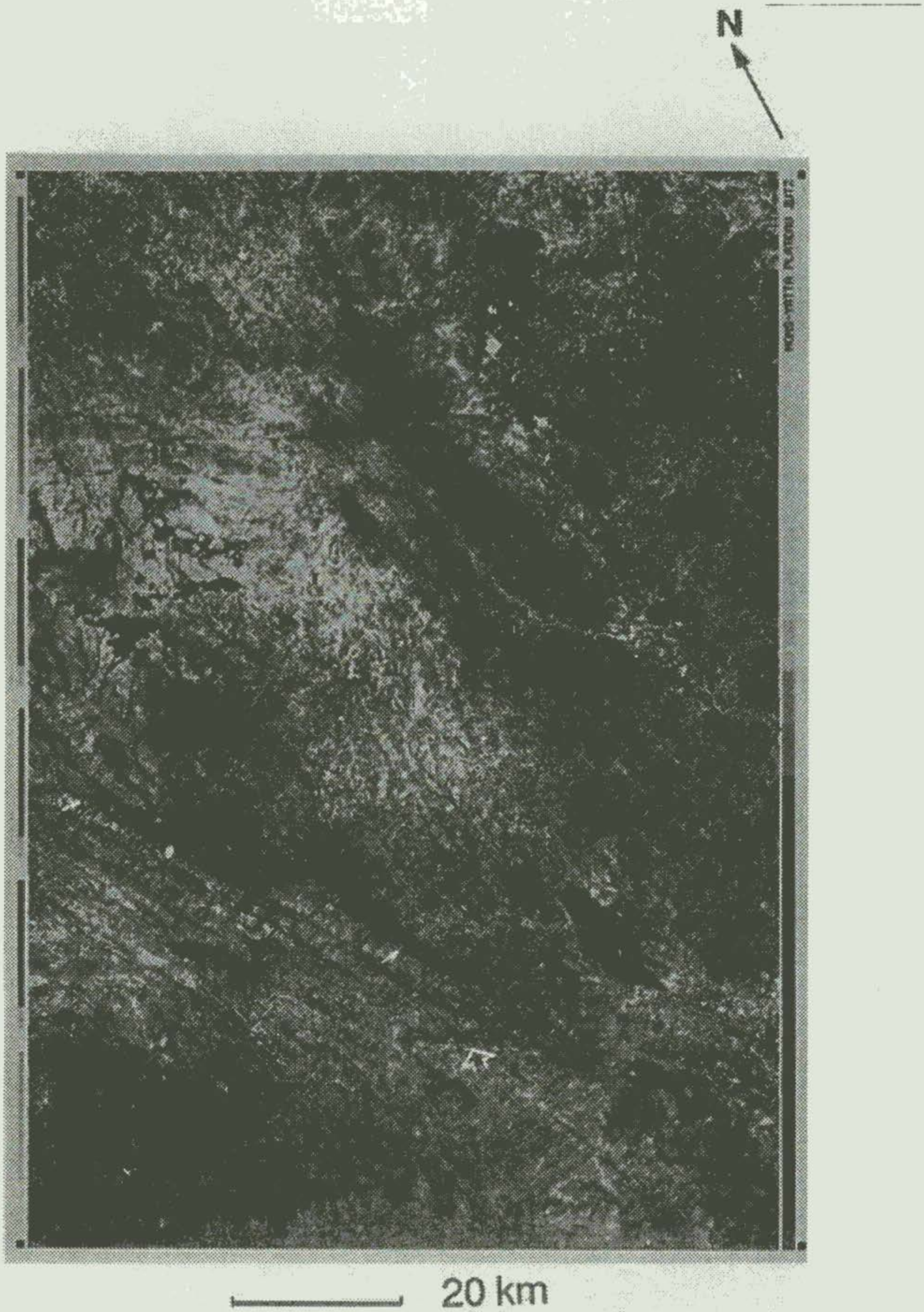


Fig. 4-MOMS-01 imagery; the arrows indicate the Yatta Plateau; the open white arrow highlights folding of amphibolite rocks close to the Yatta Plateau.

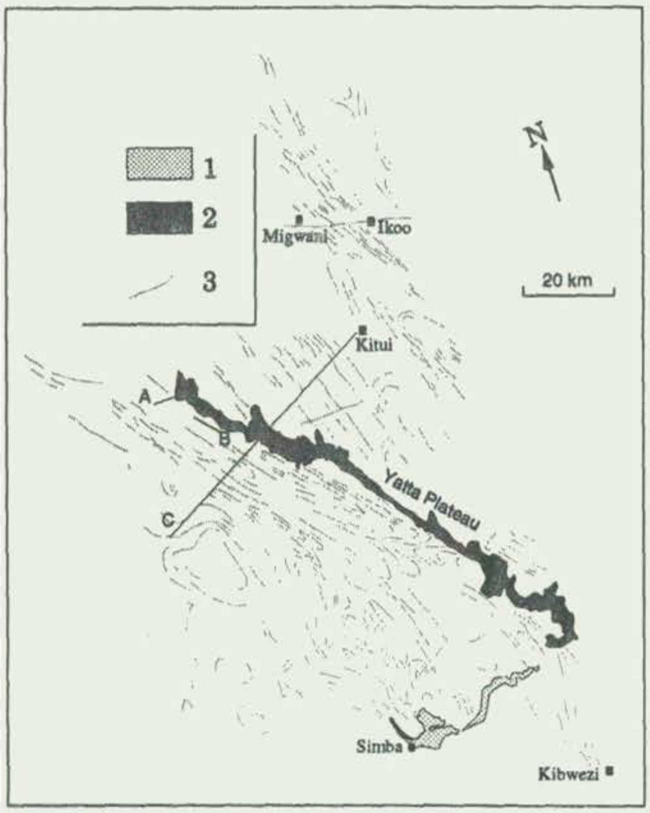


Fig. 5- The map shows structural trends (fault, foliation, fold) interpreted from both Landsat-MSS and MOMS-01 imageries; A,B,C are the localities where geotraverse were taken to make field observations and collect structural data.

To the northwest of the Yatta Plateau the structure is transected by the east-west trending Migwani-Ikoo fault (Sanders, 1954), and the north-trending Mutito fault (Sanders, 1954). Both faults are shown in Fig. 6a. Further east, the regional structure is dominated by folds of larger amplitude. It is safe to assume that since no major reworking of the Mozambique Orogenic belt occurred after Precambrian time all faults are at least of late Proterozoic age, but reactivated in the Quaternary (Mathu, 1992).

## ROCK-TEXTURES AND SHEAR STRUCTURES

Three (A,B,C) geotraverse were conducted across the YSZ (Fig. 5). Along the geotraverse-A (Fig. 7), muscovite-biotite gneisses and amphibolites occur. Rocks are sheared or show a wavy to sub-parallel foliation. The amphibolite (Fig. 9a) is predominantly composed of plagioclase (oligoclase to andesine) and hornblende; there are specks of quartz and sillimanite. Foliation is well defined by mafic minerals which display a preferred orientation, relic of pegmatitic veinings locally show itense transportation (Fig. 9b). In the muscovite-biotite gneiss, the micas have a preferred orientation and some muscovite grains display deformed kink-growth. There is also a general tendency of orthoclase to transform into microcline.

Along the geotraverse-B (Fig. 8), mylonitic quartzo-feldspathic gneisses (augen gneiss), amphibolites, and crushed (or milled) pegmatites occur. In the augen-gneiss, feldspar grains (porphyroblasts) may show rotation due to mineral growth during shear deformation, displaying characteristic pressure shadows or tail-like shapes. Mafic minerals are extremely fine grained and invariably aligned.

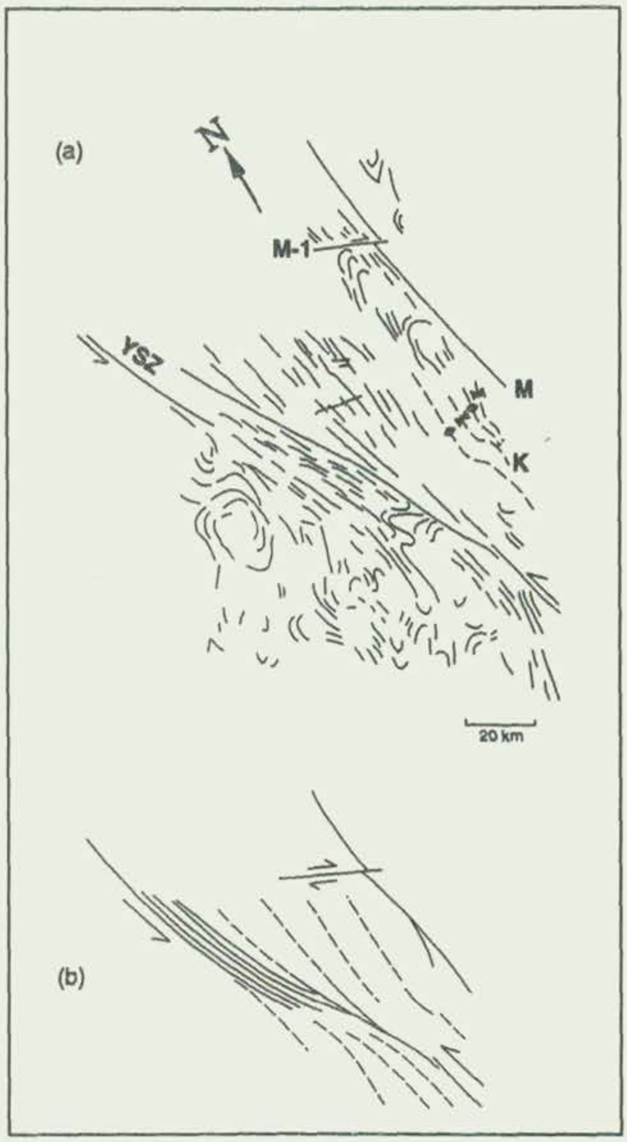


Fig. 6 (a) Interpreted structural map of the YSZ. (b) Simplified scheme of fault geometries (see the text for the explana-

Along the geotraverse-C (Fig. 8), mylonitic mica-schist and ultramylonitic amphibolite occur. Moving northeast, rocks appear increasingly sheared, and this indicates that the main fault plane coincide approximately with the trend of the Yatta Plateau.

The attitudes of linear and planar structures are given in Fig. 8 and are in agreement with poles to foliation planes and lineations taken by Saggerson (1963), close to the Yatta Plateau. Foliation planes (Fig. 8a) generally strike north to northwest and dip west. Mineral lineations, crenulation lineations, stretching lineations, and minor fold axes (Fig. 8b) have a similar trend and a moderate plunge (folds plunging in the opposite direction are also recorded). Poles to extensional fractures and tensional joints (Fig. 8c) are consistent with a northeast-trending extension. Mesoscale and microscale shear structures conform with the sinistral sense of movement deduced from satellite imageries.

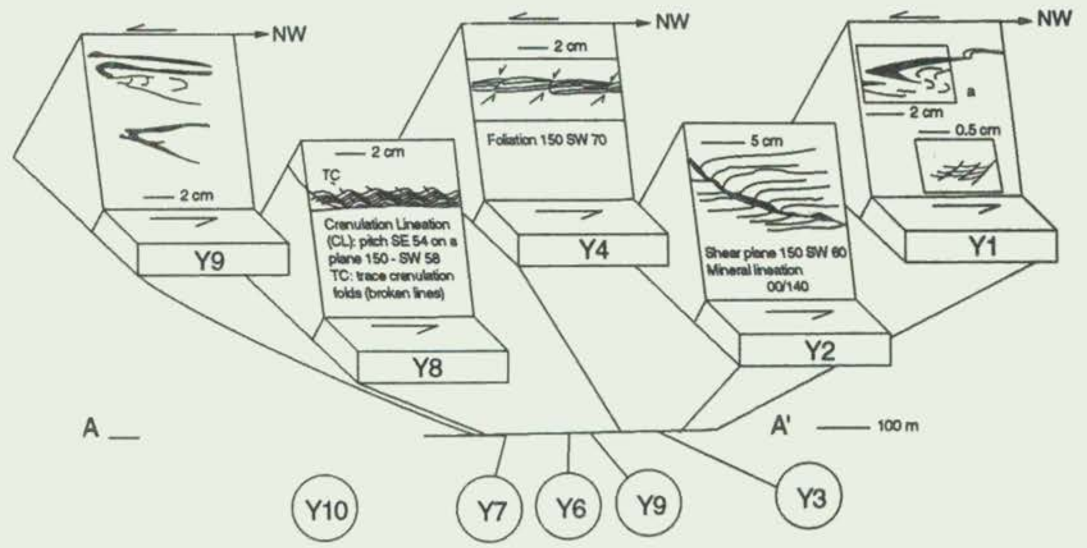


Fig. 7 - The map shows the field observations and the structural data collected across the YSZ (see Fig. 5 for the locality). In both Figures 6 and 7 planes are given as strike and dip, and lineations, otherwise specified, as plunge and trend; site of observatins are progressively labelled with the letter Y.

-Geotraverse A (along the Nditha river, a tributary of the Athi river). Y1= fine grained muscovite gneisses, (a) 3 mm thick, tightly folded quartz vein, parallel to a foliation spacing 0.5 to 1 mm, (b) S- and C-shear planes; Y2=shear plane filled with quartz - the lithology is similar to Y1; Y3=coarse and fine grained amphibolite bands; Y4=bands, up to 30 cms thick, of coarse feldspar gneisses and fine grained amphibolites Y6=gneisses with folded quartz bands folded, parallel to shear movement; Y7=mica-rich amphibolites; Y8=mica rich myloniates showing a distinct crenulation lineation; Y9= strongly sheared gneiss, showing folded quartz veins; Y10=less sheared, coarse grained amphibolites (probably a gabbro).

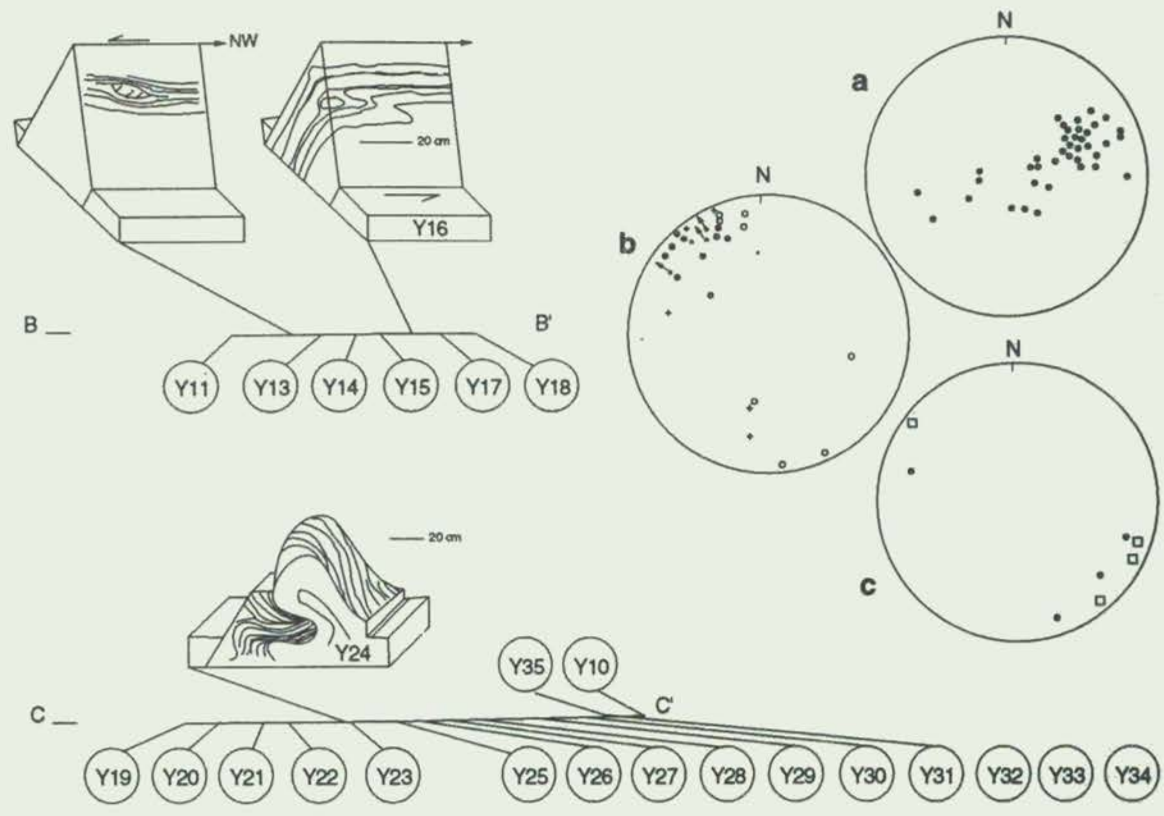


Fig. 8 - The ramp shows the field observations and the structural data collected across the YSZ (see Fig. 5 for the localities).

Geotraverse B (Syomunyu-Market, along the Athi river) Y11- mylonitic amphibolites, quartzo-feldspathic gneisses, and pegmatites; Y12=protomylonites with dismembered pegmatites showing tailing and C-shear planes; Y13=less deformed amphibolites; Y14=; Y15= fine grained gneisses showing kink-folds; Y16=bands of quartzo feldspathic gneisses and amphibolites; Y17=gneissic quartzite up to one meter thick; Y18=quartzo-feldpathic gneisses.

Geotraverse C (Machakos-Kitui). Y19 = fine grained granite gneisses but by pegmatitic veins, Y20=foliated biotite gneisses; Y21 = coarse grained (biotite) granite gneisses; Y22= slightly folitated biotite granite gneisses; Y23=strongly foliated biotite granite gneisses, showing stretching lineation; Y24=quartzo-feldspathic gneisse and amphibolites; Y25 = mylonitic gneisses and amphibolites Y26=as Y25 with dismembered pegmatitic veins; Y27=mylonitic amphibolites; Y28 = coarse grained amphibolites Y29 = foliated amphibolites, Y30, 31, 32 = mylonites and ultramylonites; Y33=mylonitic gneisses and deformed pegmatites, Y34, 35=foliated gneisses; Y36=coarse grained gneiss and amphibolite bands.

Stereographic plots (Figs. a,b,c) are equal area projections (a) 1= poles to foliation planes, (b) 2 = fold axis (open circle), mineral lineation (dot), stretching lineation (arrow), crenulation lineation (cross), (c) 3=extensional structures (dot), tension

## GEOMETRY OF THE YSZ

Low (R and P) and high (R' or antithetic) angle faults developed at 15° and 70° to the general shear trend (principle displacement zone with C-faults); all these faults are known as Riedel faults (Riedel, 1939). These fault-systems have been recognized in areas of brittle deformations (e.g. Tchalenko and Ambraseys, 1970), but can also form in brittle-ductile to ductile shear zones (Sylvester, 1988). Rock-textures in fault-zones of the YSZ show a mylonitic foliation (Figs. 9c,d), extensive annealing, and reduction in grain size (Figs. 9e,f). These textural characteristics develop in rocks under low strain rate and high recovery in a brittle-ductile regime (Wise, et al. 1984).

In Fig. 9a the YSZ northwest in 'en echelon' pattern of left-step-geometry. The Mutito fault trends north, parallel to the main structural trend. It is dextrally displaced by the east-southeast trending Migwani-Ikoo fault (Saggerson, 1957). Southward, a secondary north-northeast trending fault shows an aborted connection with the YSZ (Figs. 5,6). The failure to develop the link is replaced along the fault trajectory by the curving of earlier folding (Saggerson, 1957). This suggests that strain during shear development was taken up by bending the structure in the last stage of shear development. The evidence from satellite imageries is that the YSZ is the main structural trend. The Mutito fault developed later in response to regional changes in stress orientation which preclude deformation to continue along the YSZ. The issue, however, is whether or not the Mutito fault originated as Riedel fault of the YSZ.

A parallel structural alignment between the overlapping faults, is also evident in Figs 6a, whereby to the southwest side the structural trend curves away from the YSZ, and may be interpreted as the progressive disorientation of folding. Theoretical and experimental studies of strain conditions in left-lateral fault with step-geometry is trans-extensional between faults and trans-compressive in the outside region (Wilcox et al. 1973). The contrasting structural style in Fig. 6a is tentatively interpreted as the deep crustal level equivalent and compressional zones in high crustal domains.

## LATE PROTEROZOIC TECTONICS

Landsat-MSS and MOMS-01 imageries and field observations have unequivocabilly demonstrated the existence of the YSZ but the regional tectonic significance of this shear zone is interpretable only from indirect evidence. Stretching lineations can be used to indicate large scale plate mótions (Shackleton and Reiss, 1984).

In the frontal zones of the Mozambique Orogenic belt, north-west-to southwest-trending and eastward plunging of stretching lineations is taken to indicate westward collision. In central Kenya, north-south trending and plunging stretching lineations are considered to represent late shearing parallel to the belt (Shackleton and Reiss, 1984). If an Alpine-tectonic style is assumed (Shackleton, 1986), frontal and lateral ramps must then form the basic structural framework of Pan-African terrains. Local geology (Dodson, 1953; Sanders, 1954; Saggerson, 1957, 1963; Mathu and Tole, 1984, Opiyo and Nyambok, 1984) and can now be related to conceptual facts of thrust-geometry (Daly, 1986).

The main fold-style in the region is of upright inclined synforms and antiforms. Southwest of the YSZ, stereographic projections of foliation planes and lineations indicate that the regional structure has a predominant northeast to north-northeast trend and plunge (Saggerson, 1963). Along the YSZ stretching lineations and fold axes trend and plunge northwest to north-northwest (Fig. 8b). Northeast of the YSZ, a broad belt of north-trending migmatites show a pronounced inversion in dip (Saggerson, 1957, 1963) which coincides with the culmination of the Kitui anticlinorium (Fig. 6a). East of the Mutito fault, in the Ithanga Hills and Ishiara areas, regional S1 fabric has a northwest to north-northwest trend - only locally a superimposed S2 fabric (shear zone) has re-oriented regional structural trends (Mathu and Tole, 1984;Opiyo and Nyambok, 1984).

This pronounced change in the structural trend (northeast to northwest) must have had greater implication than previously interpreted (re-orientation of regional structures). It seems more reasonable instead to conceive the change in orientation as inherited. The fold-geometry along laterally climbing thrusts is estimated to be parallel to tectonic transport direction (Daly, 1986). The north-trending structures of the Kitui anticlinorium may be taken as an example of possible lateral ramp, reactivated by late Proterozoic shearing (Mathu, 1992). It is proposed that westward thrusting was laterally guided along the YSZ and controlled by the Tanzania craton which acted as corner-shape obstacle during thrust tectonics. The continuity across the Kenya Rift is not obvious because the intervening section is covered by the Cenozoic volcanics.

## CENOZOIC RIFTING

No signs of Cenozoic faulting and lava outpouring along the YSZ were observed or interpreted (Vidaly, 1985). This may serve as proof that the phonolitic lava, which stands higher than the Precambrian basement rocks, flowed (along) an ancient fault-valley acting thereafter as protective cover to weathering. Excluding reactivation along the YSZ, Cenozoic rifting was restricted to the Kenya Rift.

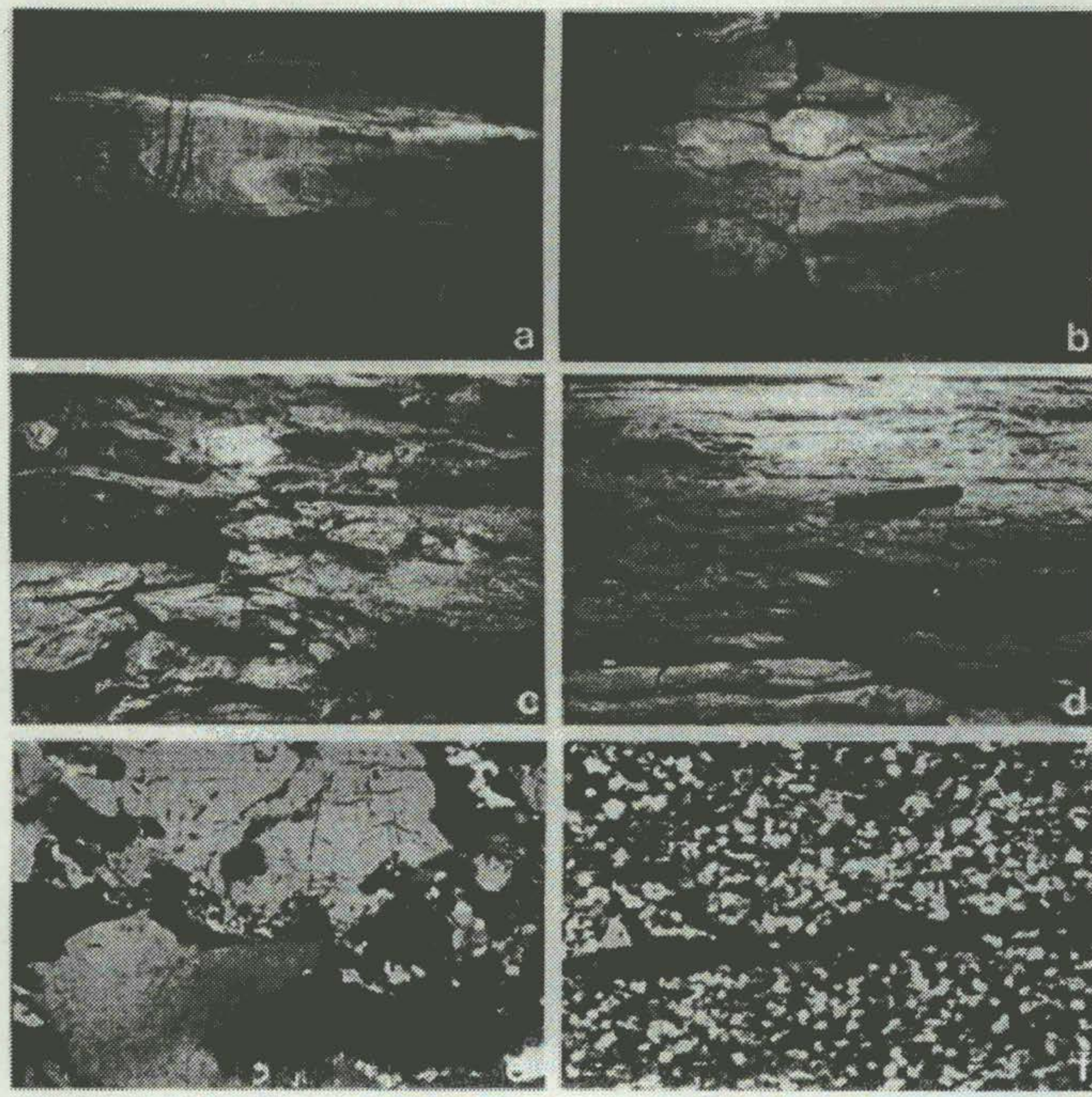

Fig. 9 - Photographs taken across the YSZ. (a) Clean surface of an amphibolite showing folded threadlike filaments and/or nebulous bands of felsic composition (S-type closure) and thin disrupted pegmatites parallel to strike. The scale in Figs. a,b,c,d is shown by the felt-pen, and the cap points towards the direction of shear movement). (b) A 'nutlike' pegmatitic nodule embedded in strongly deformed amphibolites still showing plumose relics of pegmatitic nature and attesting shear deformation. (c) Disrupted boudins of pegmatitic veins within amphibolitic gneisses. (d) Mylonites showing relics of strongly composed and parallelized pegmatitic fragments. Thin sections of muscovite-biotite gneiss (e) and the equivalent but mylonitized rock (f)- the scale is approximately 5 mm across the length.

The Elgeyo scarp is the north-trending western border fault along the Kenya Rift (Fig. 2). The scarp plane is interpreted to curve downwards (Vidal, 1985) and it shows a clear asymmetry which is deduced from sedimentary basin-infilling and late volcanism along the Elgeyo scarp. The asymetry is interpreted to be caused by the hanging-wall rollover anticline on a listric fault which increases up-section. This type of flexural slip-folding is associated with extentional tectonics (Wemicke and Burchfield, 1982; Higgs et al. 1991). The Elgeyo scarp parallels the fault zone marked by the ophiolites, and is in line with the Cenozoic Mau transverse fault (Fig. 2) while the northwest continuation of the YSZ correlates with the Cenozoic Sattima fault.

The observed shifting in the East African Rift System from normal transform faults (rift-segmentation) was interpreted by McConnel (1972), Villeneuve (1978), Chorowicz (1992) to follow inherited structures. Ebinger (1989) contends this view because rift-border and transfer faults have a poor correlation with pre-rift structures, and proposes that along axis-segmentation is controlled by local changes in stress orientation during discrete episodes of rifting and volcanism. The contention that pre-existing weaknesses in the East African Rift are unrelated to rifting need some explanation.

In the Mozambique Orogenic belt of Central Kenya the prominent S1 fabric is taken to have developed during burial metamorphism (Sabachian event) prior to thrusting (Samburuan and Kipsingian events) and folding (Baragoian, Barsaloian, Loldaikan events) of differently oriented shears (Key et al. 1989). Therefore, in the controversy (poor correlation between pre-existing weaknesses and rifting) based upon the 'facts' that border fault segments rarely occur at lithological contacts or at boundary between tectonic units (Ebinger, 1989), the compelling argument against reactivation of pre-existing weaknesses is only demonstrated if shear zones (the boundaries between tectonic units) are major thrusts.

We propose that the listric fault bounding the Egeyo scarp was a late Proterozoic frontal ramp reactivated by shearing which, ultimately, controlled the Cenozoic rifting and kinking of the northern Kenya Rift (Gregory Rift). The non-reactivation of the suture-marked by ophiolite to the west into rift-geometry is probably related to crustal attenuation of the East African Rift above the plane of detachment (decollement zone).

## CONCLUSION

The Yatta Shear Zone originated as subvertical wall of a laterally climbing major thrust zone during Pan-African collision. Reactivation during post-collisional history was progressively transferred to the Mutito fault. Northwest of the Kenya rift, the shear zones associated with ophiolites mark major frontal ramps. If the continiuity of the Elgeyo scarp across the Kenya Rift is eventually proved, the relationship between compressive structures (lateral and frontal ramps) of the Mozambique Orogenic belt and extensional structures (border and transfer faults) of the Kenya Rift are non-controversial facts which may explain the curving in the northern Kenya Rift.

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# LITHOSTRATIGRAPHIC SETTING OF MINERALISATION IN THE MIGORI SEGMENT OF THE NYANZA GREENSTONE BELT, KENYA

D. W. Ichang'i
Department of Geology, University of Nairobi, P.O.Box 30197, Nairobi.

**ABSTRACT**

*The Migori segment forms about a third of the portion of the Nyanza greenstone belt to the south of the Winam Rift and is located just north of the Kenya-Tanzania border. The segment is part of the greenstone terrane in the northern part of the Archaean Tanzanian Craton. The 80 km southwestern margin of the segment with the Migori Granite parallels the northwest to southeast strike of the marine volcano-sedimentary greenstones of the Migori Gold Belt which forms its southwestern portion. The Macalder Zn-Cu-Au-Ag massive sulphide deposit and numerous small gold occurrences are restricted to the greenstones of the Gold Belt. These rocks consist of tholeiitic and calc-alkaline volcanics, sills and dykes, as well as greywacke turbidites. The northeastern boundary of the Gold Belt is delineated by a thick section of less deformed, massive subaerial high-K calc-alkaline porphyritic dacite flows. The rocks of the segment have been placed into eleven formations through paleovolcanic facies mapping, five at the northwestern Macalder end, four at the southeastern Lolgorien end and two in the intervening Migori region. Central, proximal and distal facies with considerable intrafacies variation are recognizable within the formations. The coincidence of central and proximal volcanic facies in the formations at both Macalder and Lolgorien delineate two centres of volcanism with interfingering distal tuffs and sediments in the Migori region. The formations have been placed within the Macalder and Lolgorien Subgroups, each subgroup representing a paleovolcano and the two subgroups together in turn form the Migori Group. The Macalder massive sulphide orebody and other volcanogenic sulphide showings are clustered in the marine central and proximal facies of the Macalder and Lolgorien volcanic centres which is the typical setting for volcanogenic massive sulphides. This type of setting is also well represented in the rest of the Nyanza greenstone belt and has the most economic potential for massive sulphide mineralisation. Gold mineralisation occurs in oblique and semiconformable quartz veins within strike-slip faults traversing all rock types, and also in banded iron formations (BIF), stratabound horizons in tuffs, and in alluvial-eluvial deposits. These are the most common and widespread types of gold mineralisation in other Archean cratons and considerable economic potential for gold therefore exists in the Migori segment and in similar settings elsewhere in the rest of the Nyanza greenstone belt.*

## GEOLOGY OF THE MIGORI SEGMENT

The Migori segment represents about a third of the southern terrane of the Archaean Nyanza (2.8-2.5 Ga) greenstone belt (Ichang'i, 1990; Ichang'i and MacLean; 1991) south of the Kavirondo (Winam) Rift (Shackleton, 1951), an arm of the East African Rift System (Fig. 1). The segment includes the Migori Gold Belt (Shackleton, 1946) adjacent and immediately to the north of the Migori Granite which marks the southwestern margin to the segment (Fig. 2). The 80 km southwestern margin of the Migori segment with the Migori Granite parallels the northwesterly strike of the greenstones of the Gold Belt which have suffered thermal metamorphism along the remarkably linear contact with the granite. The Gold Belt is underlain by marine volcano-sedimentary greenstones consisting of tholeiitic and calc-alkaline volcanics, sills and dykes, as well greywacke turbidites (Ichang'i and MacLean, 1991). The northeastern limit of the Gold belt is marked by a thick section of less deformed, massive, subaerial, porphyritic high-K calc-alkaline dacite flows. The northeastern margin of these high-K calc-alkaline dacites marks the limit of the Migori segment (Ichang'i and MacLean, 1991). Geological mapping along transects perpendicular to strike by Ichang'i (1990) has facilitated the development of a geological framework which facilitated the tentative characterization of the lithostratigraphy following recommendations of the International Subcommission on Stratigraphic Classification (ISSC) (1976) and the North American Commission on Stratigraphic Nomenclature (NACSN) (1983) amongst others (Table 1; Figs. 2, 3). The lithologies have been placed into the Myunya, Osiri, Mine, Kwach and Oyani Formations of the

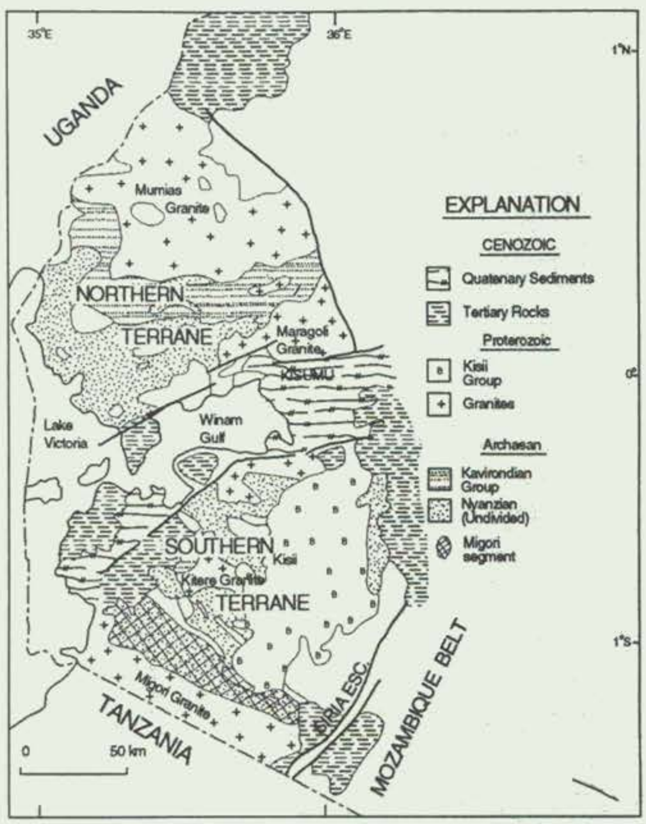


Fig 1 The Nyanza greenstone belt in western Kenya (Ichang'i and MacLean, 1991). The Migori segment is represented by the crosshatched region.

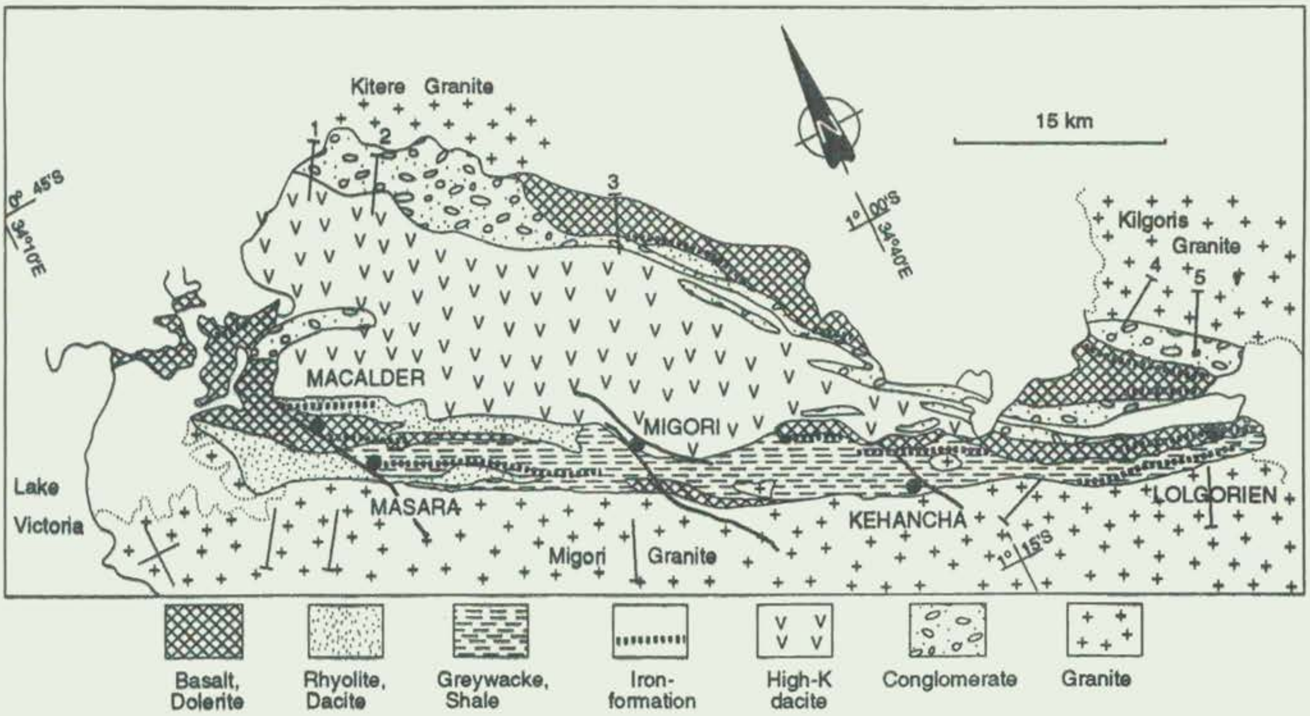


Fig. 2. Geology of the Migori segment and five of the mapping transects The main mining centres at Macalder, Masara, Kehancha, and Lolgorien are located within the Migori Gold Belt (Shackleton, 1946) south of the high-K dacites of the Oyani Formation.

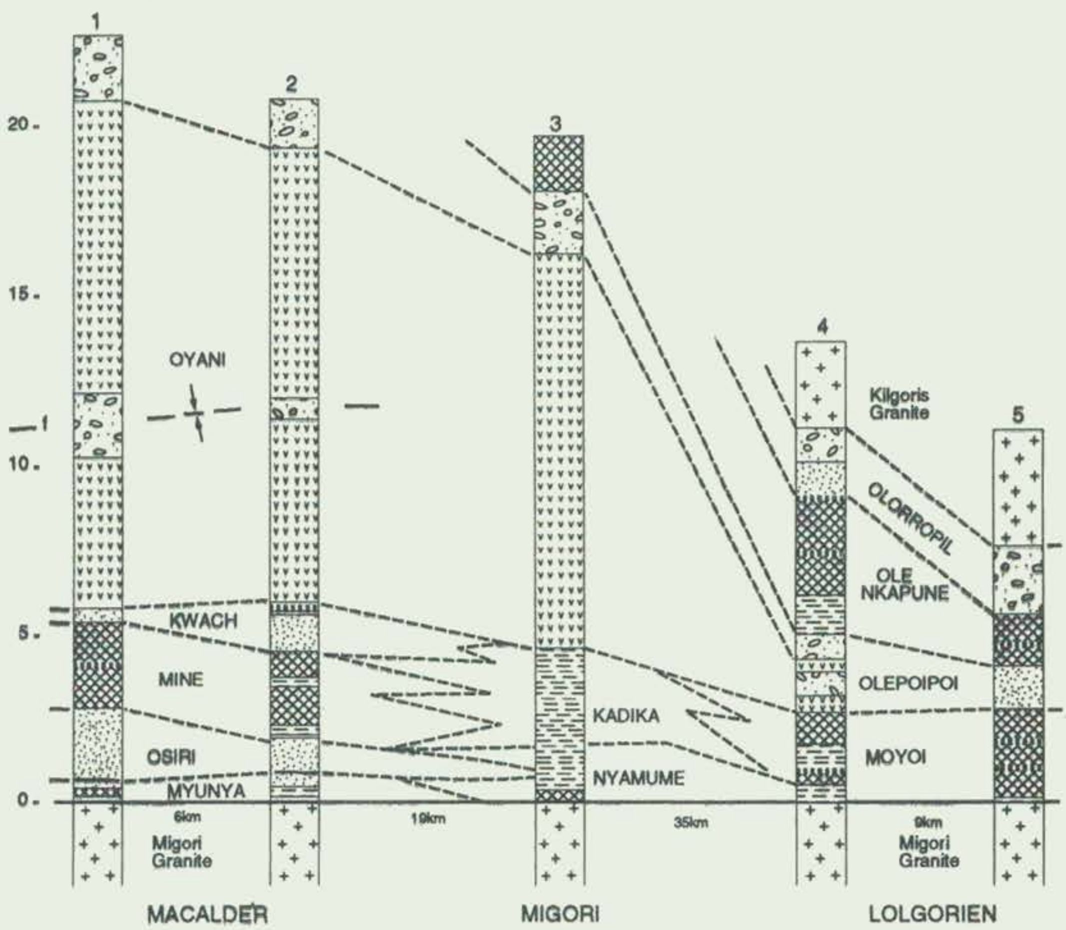


Fig 3. Simplified stratigraphic sections across the mapping transects 1-5 shown in Fig. 2 (Ichang i and MacLean, 1991). Possible folding of faulting in the Oyani Formation is indicated by f=fault and arrows=fold; distances between sections indicated; symbols as in Fig. 2.

**Table 1.** Formations, Subgroups and Group of the Migori segment illustrated in Figs. 2 and 3 and their lithologic characteristics. The Nyamume and Kadika Formations form the lower portion of the intervening region between Macalder and Lolgorien (Ichang'i and MacLean, 1991).

| THE MIGORI GROUP | | |
|---|---|---|
| MACALDER SUBGROUP | | LOLGORIEN SUBGROUP |
| | GRANITES | |
| 5. OYANI FORMATION Compositionally uniform high-K dacite lava, minor agglomerates and tuff with lenses of conglomerate. | | 4. OLORROPIL FORMATION Porphyritic rhyolite, conglomerate, greywacke. |
| 4. KWACH FORMATION Porphyritic dacite and rhyolite lava, lithic and crystal tuff, minor rhyolite breccia, greywacke. | KADIKA FORMATION Conglomerate and greywacke. | 3. OLE NKAPUNE FORMATION Basalt, minor graded greywacke, minor dacite, banded iron formation. |
| 3. MINE FORMATION Older dolerite ($D_1$) sills, massive and pillow basalts including the Kolal basalt northwest of Macalder, rhyolite porphyry, lava and tuff, greywacke, and banded iron formation. | | 2. OLE POIPOI FORMATION High-K dacite, conglomerate, and minor greywacke. |
| 2. OSIRI FORMATION Porphyritic dacite tuff, agglomerate and lava. | NYAMUME FORMATION Shale, greywacke, and tuff. | 1. MOYOI FORMATION Pillowed and massive basalts, graded greywacke, fine grained volcanic derived sediments, porphyritic dacite, banded iron formation. |
| 1. MYUNYA FORMATION Porphyritic dacite tuff and (lesser) lava, older dolerite ($D_1$) sills, minor mafic tuff. | | |

Macalder Subgroup at the northwestern Macalder end, the Moyoi, Ole Poipoi, Ole Nkapune and Olorropil Formations of the Lolgorien Subgroup at the southeastern Lolgorien end, and the Nyamume and Kadika Formations in the intervening Migori regions with these two subgroups in turn forming the Migori Group (Ichang'i, 1990; Ichang'i and MacLean, 1991; Ichang'i, 1992).

The Migori segment has a history of mining since the early 1930's through the middle 1960's. The main mining operations were at Macalder, Masara, Kehancha and Lolgorien (Fig. 2). With the exception of the Macalder mine these were gold mining centres. During these years gold production in Kenya was essentially all from the Archaean region of the country and amounted to about 34,000 kg (Du Bois and Walsh, 1970). More than one-half (~19,000 kg) came from the Migori Gold Belt. The only copper production in the country came from the Macalder mine between 1951 and 1966. There is at present local small-scale gold production in the belt mainly from alluvial and eluvial deposits.

The major mineralisation known to date, massive sulphide and gold, is restricted to the Gold Belt portion of the Migori segment (Shackleton, 1946; Kenyon, 1954; McCall, 1958; Sanders, 1964; Onuonga, 1983; Ogola, 1987; Kuehn et al., 1990). The geological setting of the mineralisation is assessed in light of the lithostratigraphy and lithochemical framework established for the belt. This assists in appraising the potential for mineralized environments and new deposits, and also in the delineation of target areas for exploration within the Migori segment.

## PALEOVOLCANIC SETTING OF VOLCANOGENIC MASSIVE SULPHIDES

The Macalder volcanogenic massive sulphide deposit (Onuonga and Moore, 1982; and Onuonga, 1983) was the only producer of copper in Kenya and also within the Tanzanian Craton. The only other massive sulphide deposit mined in the East African region was the Kilembe Cu-Co deposit ~19 million tons) in Uganda which occurred in the Proterozoic Ruwenzori mobile belt (Warden, 1985). The Macalder deposit was operated from 1941 to 1949 as an open pit mine for gold and silver in gossans overlying the massive sulphides. Copper ore was exploited in an underground operation from 1951 to 1966 with gold and silver as byproducts. It has been closed since 1966. The deposit contained about 2 million tons of ore (Sanders, 1964); a composite ore sample from the third level averaged 5.1 Zn, 3.8% Cu, 0.9% Pb, 0 3% Co, 5 g/tonne Au and 95 g/tonne Ag (Shackleton, 1946), but only copper, gold and were recovered. This deposit and associated banded iron formations which occur at the contact of basalts and overlying greywacke, turbidites and rhyolites, generally face and dip steeply to the northeast along with the rest of the Mine Formation.

The identification of individual paleovolcanoes by volcanic facies mapping has been shown by Roobol and Hackett (1987) to be an important first step in assessing the ore potential of greenstone belts, and also in the selection of target areas for mineral exploration. The concept of paleovolcanic facies mapping for mineral exploration as applied by Roobol and Hackett (1987) in the Arabian Shield involves mapping sequences of rocks which comprise volcanic facies rather than individual lithologies. They stress that only the dominant lithology is mapped and minor components are ignored. Recognition of different facies is dependent on preservation of original textures and each paleovolcanic facies generally consists of a large continuous area, and boundaries between facies are intercalated. The three broad facies or zones recognized from the mapping are central, proximal and distal, with considerable intrafacies variation between different volcanic centres depending on the rock types present in each (Easton and Johns, 1986; Roobol and Hackett, 1987; c.f. Williams and McBirney, 1979, p. 310-313).

In the Migori segment the Macalder and Lolgorien centres of volcanism have been established and the lithologies in each divided into formations consisting of related rock units (Ichang'i and MacLean, 1991). In transects across the Macalder volcanic centre, central facies volcanics are recognized in the Myunya, Osiri, Mine and Kwach Formations, and lateral changes to proximal and distal facies were mapped to the northwest and southeast. Following Roobol and Hackett's (1987) criteria, the Macalder deposit occurs in the central volcanic facies of the Mine Formation; other sulphide showings around Macalder are in central and proximal facies. The Macalder orebody has been interpreted by Ichang'i and MacLean (1991) as a distal deposit emplaced in a small basin down-slope from a mineralizing seafloor hydrothermal vent. The volcanic environment in the Migori segment including the Macalder and Lolgorien volcanic centres, are schematically illustrated in Fig. 4. As volcanogenic massive sulphides deposits tend to occur in clusters associated

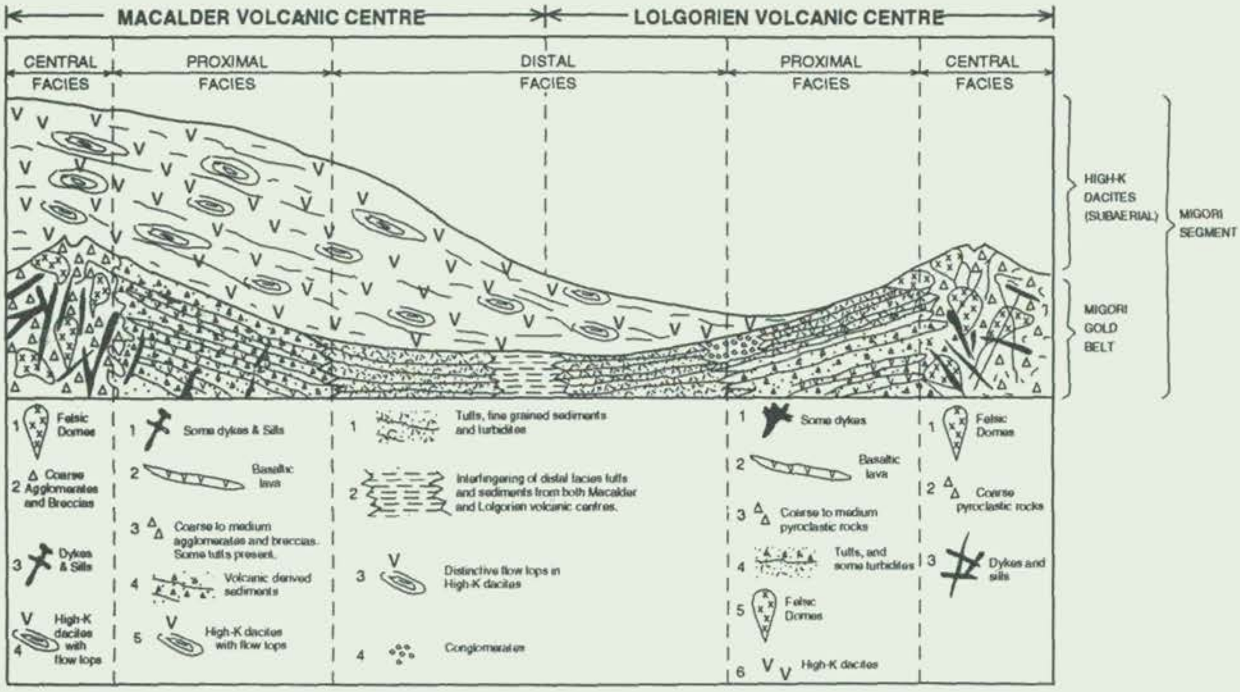


Fig 4. A schematic model of the volcanic environment in the Migori segment showing the Macalder and Lolgorien volcanic centres.

with rhyolites at volcanic centres (Sangster, 1980; Franklin and Thorpe, 1982), there is a potential for other occurrences in the belt.

Massive sulphide mining districts in greenstone belts of the same age have other identifiable characteristics. In the mineral-rich Abitibi greenstone belt (~2.7 Ga) of the Canadian Shield, volcanogenic deposits occur in a spectrum of submarine deposited volcanic rocks. These comprise differentiated tholeiites (e.g. Matagami, MacGeehan and MacLean, 1980), mixed tholeiitic and calc-alkaline volcanics (e.g. Noranda, Gélinas et al., 1982), and less often calc-alkaline volcanic rocks alone (Lesher et al., 1986). The volcanogenic sulphide occurrences in the Migori segment are, on a regional scale, in a volcanic centre, are hosted by mixed tholeiitic and calc-alkaline volcanics erupted in a marine environment, and are in central and proximal volcanic facies. The showings with most potential are associated with accumulations of rhyolites within central facies dominated by basalts and dolerites. Some of the marginal zones of thick domal rhyolite units in the segment contain gossans which have been mapped as banded iron formations.

## GEOLOGICAL SETTING OF GOLD MINERALISATION

Gold has been mined from central, proximal and distal facies volcanics in both the Macalder and Lolgorien volcanic centres, and a large number of these deposits were mined strictly for gold. The gold deposits fall into three categories depending on their relationship to the enclosing rocks. They occur in (a) quartz veins, (b) stratabound horizons, and (c) eluvial/alluvial deposits Gold mineralisation in the belt also includes the Macalder and other massive sulphide deposits (Shackleton, 1946) which were originally worked for eluvial gold in the gossans.

### Auriferous Epigenetic Quartz Veins

The more common of the two types of gold-bearing quartz veins in the belt are normally aligned sub-parallel to the strike of the host rocks in an *en echelon* fashion with a right-handed overlap (Shackleton, 1946). These veins are largely massive quartz with traces of sulphides and carbonates. They mainly occur close to the contact of the greenstone with the Migori Granite, and dip towards the granite. This type of vein deposit was mined across the Gold Belt with the larger deposits at Masara, Kehancha, and Lolgorien. The less common type consisting of large quartz veins with lengths of up to 8 km traverse obliquely across the segment. They are widely spaced (10's of km) with an *en echelon* left-handed overlap, and have so far been known to contain only sporadic amounts of gold. The quartz veins are emplaced along large strike faults oblique to the strike of the greenstones. Some of the showings in the belt are, as a result of the present work, now known to occur along these faults. Gold showings on this type of structure are located northwest and southeast of Macalder. Both the sub-parallel and oblique quartz veins were emplaced in this conjugate set of shear zones.

### Strata bound Gold Mineralisation

Two types of stratabound gold mineralisation are found in the belt. The first consists of gold in banded iron formations and was referred to as "auriferous pyritic impregnations" by Shackleton (1946). The gold has been worked from gossanous zones in sulphide-bearing iron formation where it has been liberated and concentrated. Iron formations are well represented in the area east of Macalder and north of Masara, in the Mine and Kwach Formations, and at Lolgorien in the Moyoi and Ole Nkapune Formations (Figs. 2, 3). Although no major mining operations were carried out on the gold mineralisation in the iron formations, it is presently being worked on a small scale at Lolgorien.

A second type of stratabound gold mineralisation is in conformable cherty horizons in distal facies felsic tuffs of the Osiri Formation; it accounts for a major part of the production in the Masara area (Fig. 2). Although the gold bearing cherty layers are narrow (a few cm), they are rich in gold, and where a number of them are closely spaced they have been mined. To date these have only been recognized in the Masara area, but there are other similar distal facies tuffs in the Migori segment that warrant examination.

The gossan formed over the massive sulphides at the Macalder mine constitutes the largest alluvial gold deposit in western Kenya. According to Sanders (1964), ~1,050 kg of gold and ~1,200 kg of silver were produced at the mine from ~200,000 tonnes of gossan ore during the open pit operations. Other alluvial deposits were formed on quartz veins and the sulphide-bearing banded iron formation described above. These are currently being exploited on a small scale.

The alluvial deposits formed along the Migori River where it crosses the Osiri Formation south of Macalder. These are presently of local economic importance. The Osiri Formation contains numerous gold-bearing quartz veins and showings, some of which were large enough to be mined on a small scale. These are the most likely source of the alluvial gold.

## COMPARISONS WITH MINERALISATION ELSEWHERE IN THE TANZANIAN CRATON

The types of mineralisation in the Migori Gold Belt are typical of those found in other greenstone rocks in the Tanzania Craton (Huddleston, 1951; 1954; Ichang'i, 1983; Van Straaten, 1984; Garbert, 1990; Kuehn et al., 1990; Borg et al.1990). Gold deposits are widespread, especially in Tanzania which was the main gold producing country in East Africa. Gold production between 1935 and 1980 from the Lake Victoria Goldfields of northern Tanzania was approximately 50,000 kg, mostly from the Geita, Buhemba and Kiabakari mines (Harris, 1961; Van Straaten, 1984). The Geita mine in banded iron formation was the largest in East Africa. Between 1939 and 1966 it produced ~29,000 kg of gold from about 5 million tonnes of ore.

## COMPARISONS WITH TYPES OF MINERALISATION IN OTHER ARCHAEAN CRATONS

The types of ore deposits most commonly found in Archaean cratons are gold, volcanogenic massive sulphides and magmatic nickel deposits. Except for the large deposits in ancient conglomerate of the Witwatersrand type almost all of them are in greenstone belts. Gold deposits of the varieties described for the Migori segment are the most common and widespread types of economic mineralisation in other Archean cratons. Gold is the most important type of deposit in the Kaapvaal and Zimbabwe Cratons of southern Africa (Anhaeusser, 1976a,b) and the Yilgarn Craton in western Australia (Hallberg and Glikson, 1981), and forms major deposits in the Canadian Cratons (Card et al., 1989). Major deposits occur throughout the greenstone successions and are hosted by both calc-alkaline and tholeiitic volcanics as well as associated sedimentary rocks. Banded iron formations are important hosts to gold mineralisation (Harris, 1961; Fripp, 1976; Phillips et al., 1984; Groves et al., 1987). One of the most conspicuous targets for gold in the Migori segment are the banded iron formations which are known to contain some gold, especially in the Lolgorien area.

Massive sulphides and magmatic Ni-ores are not as equally represented in the cratons (Franklin et al., 1981). There are large magmatic nickel sulphide deposits, but a lack of major volcanogenic massive sulphides, in the Yilgarn Craton. Nickel sulphide occurrences are present in both the Kaapvaal and Zimbambwe cratons but are mined only in the latter (Anhaeusser 1976a; Williams, 1979; Anhaeusser and Wilson, 1981). Conversely, Archaean Cratons of the Canadian Shield are well known for their large massive sulphide deposits, but magmatic sulphides are not well represented (Naldrett and Gasparrini, 1971). These magmatic sulphide deposits, which are sources of platinum-group metals as well as nickel, are essentially restricted to komatiites in the greenstone belts. Since komatiites have not been recognized in the Tanzanian Craton, the related mineralisation is not to be expected. On the other hand, massive sulphide deposits occur with tholeiitic or a mixture of tholeiitic and calc-alkaline bimodal (basalt-rhyolite) sequences in major volcanic centres in Archean cratons, for example those of the Canadian Shield. This type of bimodal suite (containing the Macalder massive sulphide orebody) is well represented in the Nyanza greenstone belt and massive sulphide mineralisation is to be expected.

## CONCLUSIONS

The lithostratigraphic framework developed for the Migori segment has facilitated the recognition of the coincidence of central and proximal volcanic facies in the formations at both Macalder and Lolgorien, these delineating two centres of volcanism with interfingering distal facies tuffs and turbiditic sediments. Characterization of the lithostratigraphy and volcanic facies has therefore provided an adaptable and predictive geological tool for assessing the mineral potential of the segment. The Macalder massive sulphide and other volcanogenic sulphide showings as well as stratabound gold occurrences are clustered in the central and proximal volcanic facies of the Macalder and Lolgorien volcanic centres. These settings have most potential for these types of ore deposits. Structural controls on the other hand are responsible for the localization of epigenetic gold-bearing quartz veins in oblique and parallel strike-slip faults cutting through all rock types in the segment.

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# PETROGENETIC MODELLING OF SOME VOLCANICS FROM THE MASENO AREA OF THE ARCHAEAN GREENSTONE TERRANE IN WESTERN KENYA.

N. Opiyo-Akech
Department of Geology, University of Nairobi, P.O.Box 30197, Nairobi, Kenya.

**ABSTRACT**

*The volcanic rocks around Maseno consist of a diverse range compositions from basalts and basaltic andesites, through andesites, dacites to rhyolites, which have been metamorphosed to greenschist facies.*

*The problem has been to identify the processes of differentiation through which these rocks may be related. It is noted that the composition of igneous rocks are as a result of complex chemical and physical processes, starting from the generation of magma by partial melting of pre-existing rocks, followed by fractionation. In the case of volcanics, this includes the history of transformation of this magma as it rises upwards to the surface. The transformation also includes its reactions and re-equilibration en route with rocks through which it is traversing. It is on reaching the surface that crystallization begins and rocks that have differentiated and re-equilibrated with the wall rocks are formed. In the Maseno area it has been determined from discriminant diagrams that the volcanic sequences belong to two distinct magmatic groups, the basaltic to basaltic andesites sequence, which are tholeiitic and the andesitic to rhyolitic sequence, which are calc-alkaline.*

*Each rock sequence is modelled separately, based on differences, observed geochemically on the discriminant plots of major and trace elements. Thus the petrogenesis of these volcanics has been carried out assuming differentiation from contrasting magma sources. The patterns produced on trace elements and REE models with the mineral assemblages obtained from least squares modelling on major elements, indicates that it is possible to derive the more fractionated varieties of these volcanics from the more primitive assemblages within the specific groups by fractionation.*

## INTRODUCTION

The Archaean greenstone rocks of the Nyanzian system are found in two portions of the studied area. The main occurrence is to the west of Maseno township, where a whole sequence of the volcanics from basalt, through andesites, dacites to rhyolites is observed (Fig. 1). A minor sequence of andesites to rhyolites is observed around Kakamega. However, the sub-division into basalts, andesites and rhyolites is rather arbitrary as each sub-division includes rocks of varying compositions, grouped together as one unit.

Geochemical discriminant plots of the Maseno volcanics suggests that the rocks can be sub-divided into units closely related in their petrogenesis. From the studies of geochemistry, it has been possible to model the petrogenesis of the volcanics following differentiation patterns from contrasting magma sources. The basalts have been modelled separately from the andesitic to rhyolitic groups, because of their chemical differences as observed on the discriminant diagrams.

## GEOCHEMISTRY

Geochemical discriminant plots major and trace elements suggests that the rocks can be subdivided into smaller units that are related in their petrogenesis, and are distinctly different from the other groups.

The chemical patterns of these volcanics from the Maseno area show progressive elemental variations between basic and acid end members. For the major elements, the basalts show a distinctive difference from the andesitic to rhyolitic groups. It has been established (Opiyo-Akech, 1988) that these rocks belong to two distinct magmatic groups. The basalts are tholeiitic, while the andesitic to rhyolitic groups are calc-alkaline (Fig. 2).

The andesites fall into two groups as observed from trace element patterns (Opiyo-Akech, 1988, 1992). The andesites to the west of Maseno township, are andesites type I and type II, while those to the west of Kakamega are andesites type II as described by Davis and Condie (1976). The andesite type I is a low-K andesite, and is differentiated from type II by its higher concentration of LIL elements and low total iron and titanium.

## PETROGENESIS

Of prime importance in the studies of petrogenetic paths are the source regions of the rocks. In considering the source of the Maseno basalts the Mg-Fe diagrams developed by Langmuir and Hanson (1980) and Rajamani et al., (1985). This assumes that melts that are parental to basic magmas are produced by partial melting of mantle peridotites (Tarzey, 1987), or sources that are secondary to the pyrolite source. Shown on this diagram (Fig. 3) are liquid lines of decent for fractional crystallisation of olivine (after Rajamani et al., 1985). At the early stages of olivine fractionation forsteritic compositions fractionate first, depleting Mg in the melt, but having little effect on the absolute abundances of Fe. With increased fractionation more fayalitic olivines begin to fractionate, thus both Mg and Fe will be depleted from the melt, hence the curve outlined by the samples shows depletion of both Mg and Fe at later stages of olivine fractionation. On this plot the Maseno basalts, have lower Mg

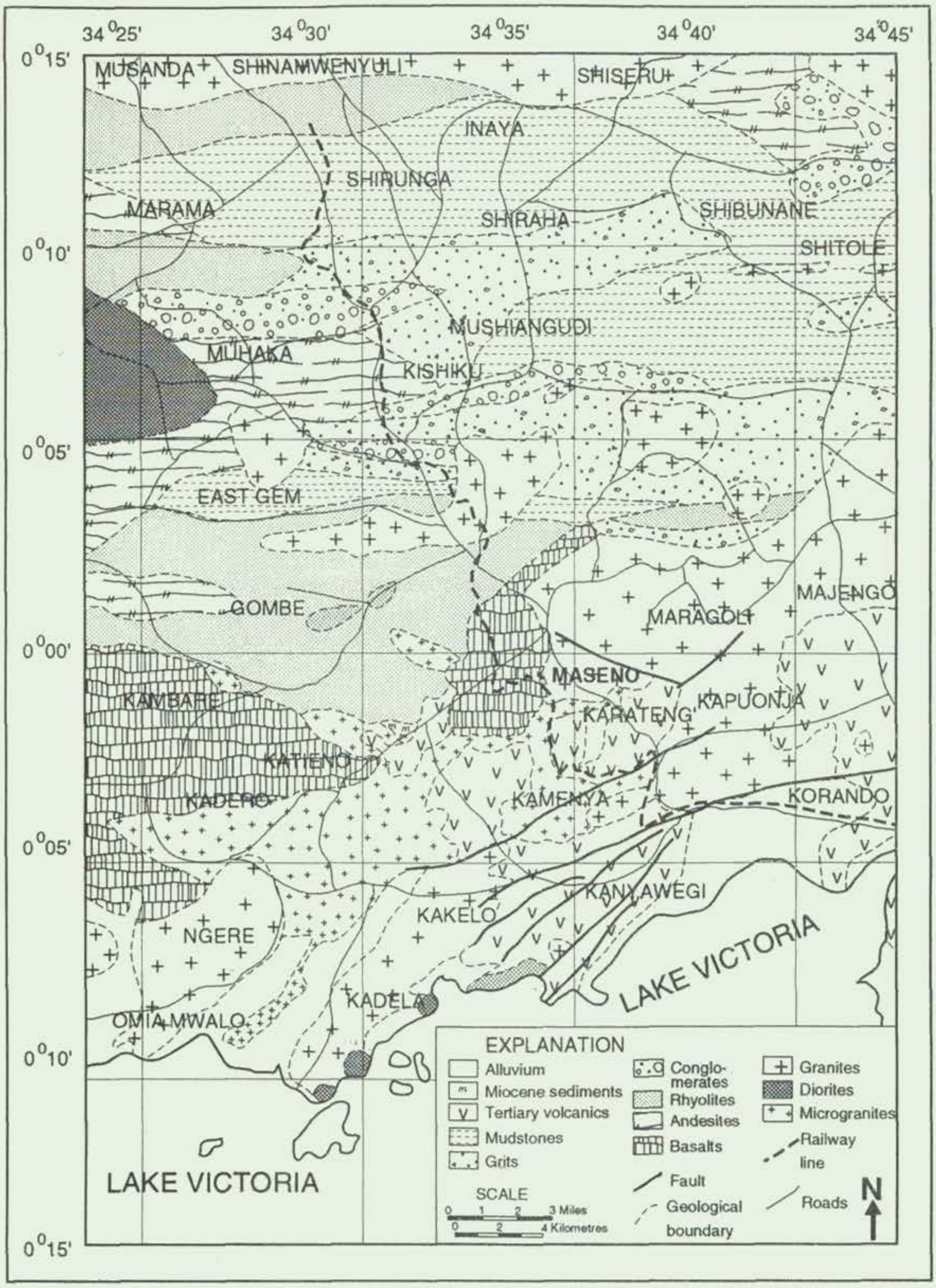


Figure 1. Location and Geology of the study ara.

and higher Fe abundances than would be expected from an olivine fractionation pattern. This suggests that the source had higher Fe/Mg ratio than pyrolite. The variations in Fe abundances are attributed to variations in the FeO/MgO ratios of the source regions. However, in a fractionating sequence, coprecipitation of plagioclase or pyroxene will allow a greater enrichment of Fe (Langmuir and Hanson, 1980), resulting in a pattern somewhat similar to what is observed for the basalts around Maseno.

The problem has been to identify the processes of differentiation by which these rocks are related. From studies of trace elements behaviour (Allegre, 1978, Minster et al., 1978), it is assumed that trace elements can be used to establish which

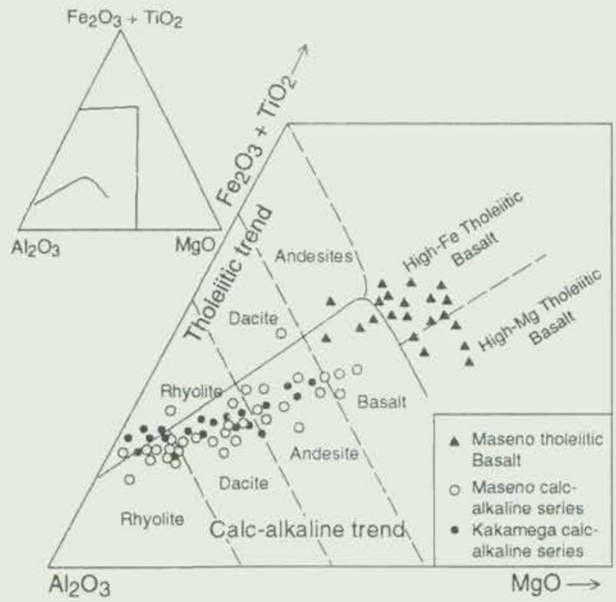


Figure 2. The Jensen (1976) plot of the Maseno volcanics.

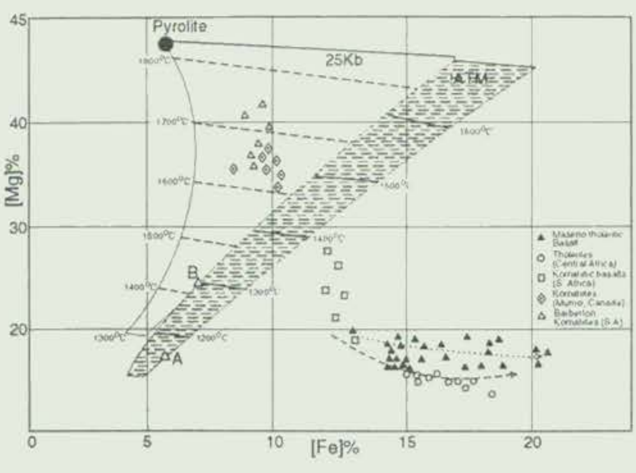


Figure 3. [Mg]-[Fe] diagram (after Rajamani et al., 1978) showing melt fields at 1ATM and 25Kbars.

processes are responsible for the final trends observed in a rock sequence. The graphical method of Allegre and Minster (1978) points to the possibility of distinquishing the two major processes, partial melting and fractional crystallization. This method is based on the behaviour of the more incompatible (magmatophile) elements (M elements - Ta, Th, La, Ce) relative to the less incompatible (hypermagmatophile) elements (H elements - Zr, Hf, and heavy REEs).

In a system where the ratio of the concentrations
CHl/CMl = CHo,l/CMo,l is a constant;

Where CHl = concentration of the (H-element) in the liquid.
CMl = concentration of the (M-element) in the liquid.

Then, on the CHl/CMl vs CMl diagram, the points representing equilibrium partial melting would plot along a straight line of slope DMo/CMo,s and fractional crystallization would be represented by points plotting along a horizontal line (Allegre et al., 1978). It is therefore possible to distinquish the trend where fractional crystallization is the main petrogenetic factor from those where partial melting is the main factor. From these plots (Fig. 4), the chemical variations in rocks from the study area may be explained by partial melting, fractionation, and possibly magma mixing acting upon a parent magma. On this plot the basalts are noted to be predominantly related in their differentiation along a partial melting trend with possibly a small degree of fractionation. The andesitic to rhyolitic group shows a predominantly fractional crystallization trend. The rocks from Kakamega district are noted to have a different fractionation trend from the rocks west of Maseno, as is seen in figure 4

Fractional crystallization is considered to be primarily responsible for the range in compositional variations within the calc-alkaline groups. Models involving both partial melting and fractional crystallisation are carried out. The rhyolitic rocks can be derived from the andesitic rocks by fractional crystallization, but these two groups, namely the andesitic and rhyolitic groups

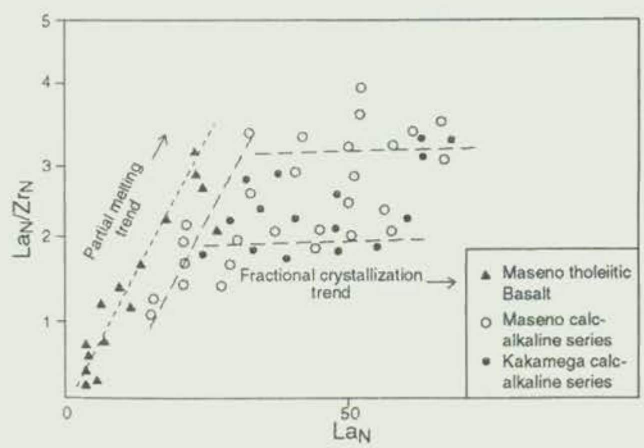


Figure 4. Plots giving an indication of the dominant differentiation process.

cannot be directly related to the basalts by fractionation.

## MODELLING

On the basis of similarities in the trace element patterns, REE patterns, the trends in major elements and field associations, there are indications that these rocks essentially evolved by the same petrogenetic processes, but possibly from different magma sources. The rocks that are closely associated and display a progressive development from the most primitive basaltic material to the most evolved rhyolites are modelled as a group, while those showing variations are modelled as separate groups..

From the observations fractionation is assumed to be the major influencing determinant in their differentiation. When modelling the choice of samples to be modelled are restricted to rocks within groupings displaying similarities displayed by their geochemistry. The most primitive member of each group is assumed to representative of the parental magma from which all the differentiates are derived.

**Major elements modelling based on the Least Squares Method.**

The model employed for the major elements uses the least squares method as developed by Bryan et al., (1969) and modified by Le Bas., (1985). The model gives an indication of the possibility of deriving a particular rock from a more primitive one by assessing the residues (squared residuals, $R^2$). This is done by fractionating the possible crystal phases from the system. This works out the percentages of the various mineral phases fractionated and gives the squares of the residuals. Low $R^2$ indicates a good fit and an indications of the possibility of obtaining a more evolved rock from a more primitive source rock.

In modelling, a stepwise approach on samples from the same sequence is taken. The modelling starts with the least evolved samples and a progressive stepwise analysis is followed until the compositions of the most fractionated member is obtained. The phases fractionating are also changed to reflect the important fractionating phases in the assemblages. Tables 1, 2, and 3 reflect the results of models obtained from modelling within the groups. In modelling these rocks, the $R^2$ values obtained for these rocks within the various groups are consistent and reasonable. Within the basaltic group it was possible to arrive at the compositions of the more evolved basalts by modelling between rocks with small differences and repeating the process progressively upwards to rocks of andesitic basalt compositions. Similarly in the andesitic to rhyolitic group, it possible to achieve reasonable fractionation models. But within the more acid rocks the $R^2$(Squared residual) values obtained using realistic mineral assemblages are higher than in the basic rocks. The higher $R^2$ is attributed in part to weathering and mobility of the alkalies which are important components of these highly silicic rocks.

The results obtained from the least squares method are satisfactory and to test their reliability, the fractionating mineral assemblages obtained are used when modelling fractionation using the REEs.

Table 1. Fractination from the most primitive basalt within the basalt group to a more evolved basalt.

| Anal: | Parent NR/14 | Calc-parent | ol | cpx | plag | mt | ilm | Daughter NR/12 | Residues (R) |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 49.42 | 49.44 | 39.20 | 51.83 | 67.39 | 0.93 | 0.31 | 51.15 | -0.0239 |
| $TiO_2$ | 1.23 | 1.23 | 0.00 | 0.49 | 0.00 | 2.74 | 51.98 | 1.09 | -0.0013 |
| $Al_2O_3$ | 15.37 | 15.35 | 0.12 | 3.07 | 18.97 | 0.69 | 0.00 | 13.79 | 0.0237 |
| $Fe_2O_3$ | 13.27 | 15.27 | 19.20 | 8.40 | 1.30 | 89.10 | 41.60 | 13.20 | 0.0002 |
| MnO | 0.19 | 0.24 | 0.31 | 0.17 | 0.14 | 0.39 | 0.94 | 0.22 | -0.0532 |
| MgO | 6.94 | 6.92 | 39.98 | 16.00 | 0.38 | 0.11 | 3.23 | 7.09 | 0.0226 |
| CaO | 10.63 | 10.59 | 0.00 | 19.21 | 0.40 | 0.00 | 0.06 | 9.91 | 0.0408 |
| $Na_2O$ | 2.20 | 2.09 | 0.32 | 0.27 | 10.67 | 0.04 | 0.41 | 3.08 | 0.1100 |
| $K_2O$ | 0.44 | 0.39 | 0.00 | 0.02 | 0.11 | 0.04 | 0.00 | 0.29 | 0.0000 |
| Mix | | | 8.44 | 19.80 | 22.02 | 2.09 | 0.39 | | |
| Squared residual (R2) = 0.0196 | | | | | | | | | |

Table 2. Further fractination within the basalt group to a more evolved basalt.

| Anal: | Parent NR/12 | Calc-parent | ol | cpx | opx | plag | mt | ilm | Daughter NR/29 | Residues (R) |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 51.15 | 51.15 | 39.20 | 51.83 | 53.17 | 67.39 | 0.9[illegible] | 0.31 | 53.26 | -0.0008 |
| $TiO_2$ | 1.09 | 1.09 | 0.00 | 0.49 | 0.22 | 0.00 | 2.7[illegible] | 51.98 | 1.07 | -0.0012 |
| $Al_2O_3$ | 13.79 | 13.78 | 0.12 | 3.07 | 0.45 | 18.97 | 0.69 | 0.00 | 14.85 | 0.0086 |
| $Fe_2O_3$ | 13.20 | 13.20 | 19.20 | 8.40 | 18.30 | 1.30 | 89.10 | 41.60 | 14.80 | -0.0003 |
| MnO | 0.22 | 0.13 | 0.31 | 0.17 | 0.48 | 0.14 | 0.39 | 0.94 | 0.26 | 0.0860 |
| MgO | 7.09 | 7.09 | 39.98 | 16.00 | 23.81 | 0.38 | 0.11 | 3.23 | 6.84 | 0.0003 |
| CaO | 9.91 | 9.91 | 0.00 | 19.21 | 2.67 | 0.40 | 0.00 | 0.06 | 5.04 | 0.0002 |
| $Na_2O$ | 3.08 | 3.09 | 0.32 | 0.27 | 0.47 | 10.67 | 0.04 | 0.41 | 1.73 | -0.0100 |
| $K_2O$ | 0.29 | 0.42 | 0.00 | 0.02 | 0.00 | 0.11 | 0.04 | 0.00 | 0.65 | -0.1343 |
| Mix | | | 14.21 | 40.09 | 39.23 | 19.40 | 5.49 | 0.35 | | |
| Squared residual (R2) = 0.0256 | | | | | | | | | | |

Table 3. Fractination from a basalt group to a basaltic andesite.

| Anal: | Parent NR/29 | Calc-parent | cpx | opx | plag | horn | mt | ilm | Daughter NR/37 | Residues (R) |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 53.26 | 53.26 | 51.83 | 53.17 | 67.39 | 48.40 | 0.93 | 0.31 | 54.87 | -0.0037 |
| $TiO_2$ | 1.07 | 1.07 | 0.49 | 0.22 | 0.00 | 1.08 | 2.74 | 51.98 | 0.86 | -0.0008 |
| $Al_2O_3$ | 14.85 | 14.81 | 3.07 | 0.45 | 18.97 | 7.27 | 0.69 | 0.00 | 15.50 | 0.0364 |
| $Fe_2O_3$ | 14.80 | 14.80 | 8.40 | 18.30 | 1.30 | 11.40 | 89.10 | 41.60 | 9.87 | -0.0003 |
| MnO | 0.26 | 0.21 | 0.17 | 0.48 | 0.14 | 0.10 | 0.39 | 0.94 | 0.15 | 0.0478 |
| MgO | 6.84 | 6.83 | 16.00 | 23.81 | 0.38 | 5.86 | 0.11 | 3.23 | 5.68 | 0.0078 |
| CaO | 5.04 | 5.04 | 19.21 | 2.67 | 0.40 | 1.25 | 0.00 | 0.06 | 8.64 | -0.9917 |
| $Na_2O$ | 1.73 | 1.77 | 0.27 | 0.47 | 10.67 | 1.90 | 0.04 | 0.41 | 2.34 | -0.0387 |
| $K_2O$ | 0.65 | 0.98 | 0.02 | 0.00 | 0.11 | 0.17 | 0.04 | 0.00 | 0.92 | -0.3296 |
| Mix | | | 24.50 | 18.12 | 8.23 | 6.94 | 2.54 | 0.17 | | |
| Squared residual (R2) = 0.1138 | | | | | | | | | | |

Table 1. Fractination within the andesitic to dacitic group.

| Anal: | Parent NR/41 | Calc-parent | cpx | opx | plag | horn | bio | Kspar | ilm | Daughter NR/43 | Residues (R) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 62.42 | 62.42 | 51.83 | 53.17 | 67.39 | 48.40 | 38.22 | 64.70 | 0.31 | 64.94 | 0.0004 |
| $TiO_2$ | 1.23 | 0.56 | 0.49 | 0.22 | 0.00 | 1.08 | 2.96 | 0.00 | 51.98 | 0.48 | -0.0012 |
| $Al_2O_3$ | 15.37 | 16.31 | 3.07 | 0.45 | 18.97 | 7.27 | 14.71 | 18.56 | 0.00 | 15.74 | -0.0014 |
| $Fe_2O_3$ | 13.27 | 5.48 | 8.40 | 18.30 | 1.30 | 11.40 | 17.20 | 0.20 | 41.60 | 5.41 | 0.0003 |
| MnO | 0.17 | 0.13 | 0.17 | 0.48 | 0.14 | 0.10 | 0.52 | 0.00 | 0.94 | 0.08 | 0.0578 |
| MgO | 6.94 | 3.55 | 16.00 | 23.81 | 0.38 | 5.86 | 13.45 | 0.00 | 3.23 | 2.59 | -0.0020 |
| CaO | 10.63 | 5.41 | 19.21 | 2.67 | 0.40 | 1.25 | 1.46 | 0.00 | 0.06 | 4.00 | 0.0006 |
| $Na_2O$ | 2.20 | 4.66 | 0.27 | 0.47 | 10.67 | 1.90 | 0.50 | 2.46 | 0.41 | 4.59 | 0.0000 |
| $K_2O$ | 0.44 | 1.88 | 0.02 | 0.00 | 0.11 | 0.17 | 7.90 | 12.72 | 0.00 | 2.29 | 0.0006 |
| Mix | | | 2.33 | 1.09 | 3.52 | 15.03 | 32.73 | 11.09 | 0.10 | | |
| Squared residual (R2) = 0.0034 | | | | | | | | | | | |

## Trace elements vector modelling.

In fractional crystallization of a magma, the variations of a trace element as a magma evolves is dependent on the mineral phases crystallizing. The concentration in these minerals, which is the sum total of the concentration in each individual mineral phase is influenced by the distribution co-efficients (Dvalues) in each phase.

Co-variant plots of minerals known to be highly compatible in certain phases are used to test for the possibility of certain phases fractionating from the melt. Zr which is incompatible in the major phases expected to be fractionated from the melt is used as the fractionation index. Theoretical element vectors are calculated to investigate the effect of minerals in which these elements have high Dvalues (values from Henderson, 1982). The vectors show the expected trends on a melt composition crystallizing single mineral phases, assuming Rayleigh fractionation. The vectors are annotated according to the proportions of the melt remaining. In the calculation an arbitrary starting composition is assumed, with the plotted vector direction and magnitude on the diagrams only indicating the expected trends, from a theoretical starting composition. On these diagrams the vectors are independent of the starting composition.

To test for the role of olivine in the fractionation, a plot of Ni against Zr (Fig. 5a) is used. Ni is taken up in olivine (Dol>10), with the result that in a system where olivine is strongly fractionating, the Ni will be depleted in the residual magma. The concentration of olivines in the most previously removed from them. The consequent depletion of nickel in these rocks does not follow a strict olivine trend as per the calculated vectors. This indicates that clinopyroxene is also controlling the fractionation trend of nickel. Nickel behaviour in the basalts however, differs from that in the andesites and the rhyolites.

Cr trends are used (Fig. 5b) as an indication of clinopyroxene fractionation. The trends for the plotted points indicates that clinopyroxene is an important fractionating phase in the andesites. In the basalts the trend is not as distinctive as in the andesites and rhyolites. The Cr in the basalts also show a separate grouping from the andesites and rhyolites.

Vectors calculated for Sr are used to investigate the effect of plagioclase in the system (Fig. 5c). The strontium values increase with fractionation in the basalts. This indicates that plagioclase may not have been the major phase fractionating the Sr in these basalts. The trend in the andesites is indicative of plagioclase fractionation, the plots follow a plagioclase fractionation trend.

The vectors from the Nb plot (Fig. 5d) indicate that the phases plagioclase, clinopyroxene and magnetite are equally important in the fractionation of these rocks. The basalts however, are of a separate group, with higher Nb/Zr ratios than the andesites and rhyolites.

Vanadium and titanium (Fig. 5e,f) are used to test as to whether Fe-Ti oxides were important fractionating phases in these

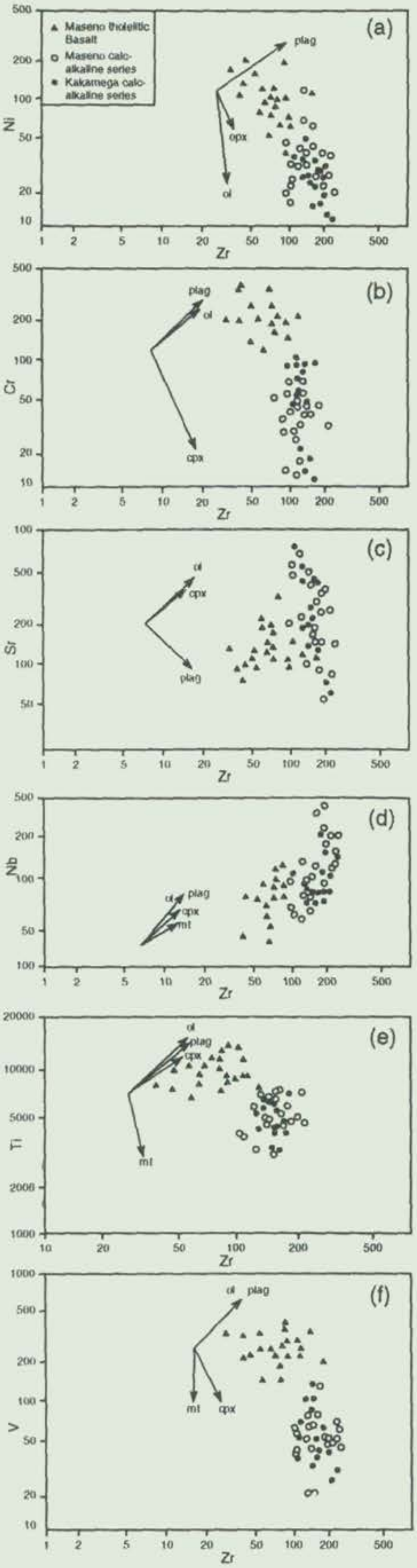


Figure 5. Trace elements covariation plots for various elements against Zr.

rocks. From the vectors calculated for V, and Ti, titanomagnetite is seen not to be the sole contributor to the Ti and V. There is a wide scatter within the separate groups, with Ti/Zr and V/Zr ratios being distinctively higher in the basalts, while there is a gap between these and the andesites and rhyolites.

**Rare Earth Element fractionation.**

For practical purposes the percentage mineral assemblages used are those calculated from the major element models. These do not neccessarily give the best fit, but form a good working basis for modelling and comparison with the model calculations for the major elements.

The patterns produced from these models with the mineral assemblage values obtained from major elements modelling indicates that it is possible to derive the more fractionated varieties of rocks from the more primitive assemblages within the same units by fractionation. Fairly good fits are generated using mineral proportions taken from the the least squares fit for the major elements.

For the basaltic group, the fit for modelled patterns and the analysed patterns indicates that it is possible do derive rocks of similar composition to NR/12 from a parent rock of similar composition to NR/14, by fractionating an assemblage made up of 16 wt% olivine, 41.8 wt% plagioclase, 37.5 wt% clinopyroxene, and 3.96 wt% magnetite, and 0.74 wt% ilmenite with only a small deviation on the NREEs (Fig.6a). As shown on figure 6b, itis possible to derive the more evolved andesitic basalts of sample NR/29 by fractionation of an assemblage of 11.9 wt% olivine, 34.1 wt% I clinopyroxene, 32.8 wt% orthopyroxene, 16.2 wt% plagioclase, and 4.6 wt% magnetite from sample NR/12. Several models using value from the major elements fractionation model reveal patterns that are close to what would be expected from fractional crystallization. From the least squares calculations and these models, it is noted that olivine plays a very minor role in the fractionation of these basaltic rocks.

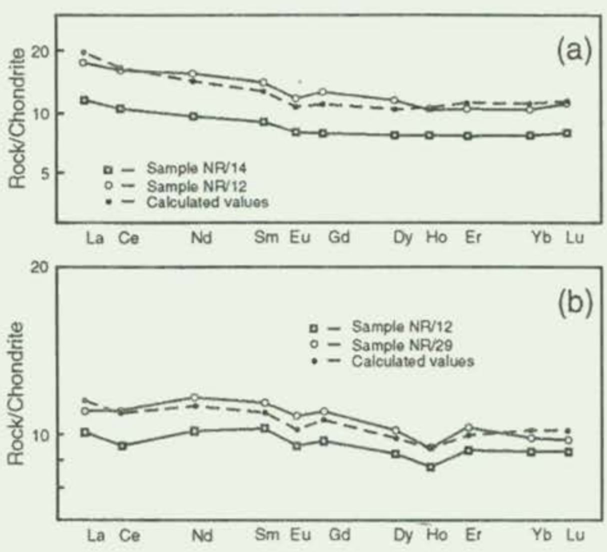


Figure 6. REE fractionation within the basaltic group.

Similarly when modelling the andesitic to dacitic group, it is noted that within the groups, it is possible to model from the more primitive andesites to the more evolved dacites by fractionation. On figure 7a, sample NR/29 is modelled from sample NR/37 by crystallization of an assemblage of 37.6 wt% clinopyroxene, 40.8 wt% plagioclase, 7.81% orthopyroxene, 5.5 wt% amphiboles and 6.2 wt% magnetite. From Kakamega district sample NR/49 is modelled by 17.9 wt% clinopyroxene, 36.4 wt% plagioclase, 2.5 wt% orthopyroxene, 29.45% hornblende and 2.9 wt% magnetite from NR/51 (Fig. 7b).

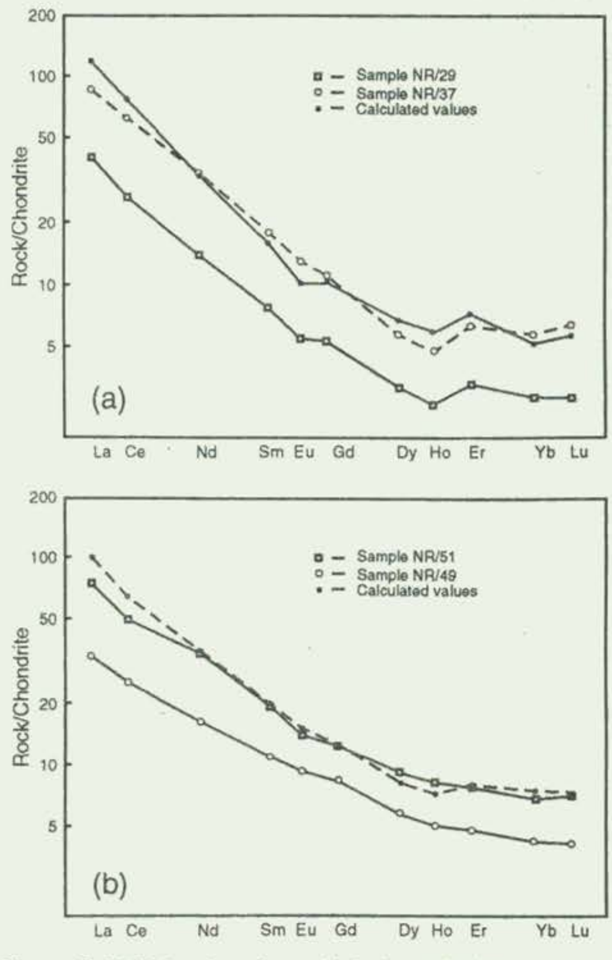


Figure 7. REE fractionation within the andesitic group.

## SUMMARY AND CONCLUSIONS

The patterns produced from these models with mineral assemblage values obtained from major elements modelling, indicates that it is possible to derive the more fractionated varieties of rocks from more primitive assemblages within the same units by fractionation. It is however, not possible to produce the REE patterns of the andesitic group by either partial melting or crystal fractionation of the basalt. The most primitive basalts are regarded as representing material closest in composition to the parent magma.

The enrichment of the LREE relative to the HREE (Fig. 7) in the andesitic group indicates that these andesites cannot be produced by direct batch melting of mantle material. The patterns would require a source where garnte remains in the residue after partial melting and melt segrsgation.

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## HYDROGEOLOGY AND HYDROCHEMISTRY OF THE GROUNDWATER RESOURCES OF THE FLOOR OF THE RIFT VALLEY, NAKURU NORTH, KENYA

Isaac O. Nyambok*[1], Pravin S. Bhogal*[2] and Sebastian Bwire-Odhiambo*[3]

*[1]Department of Geology, University of Nairobi P.O. Box 30197, Nairobi.
*[2]Department of Physics, University of Nairobi P.O. Box 30197, Nairobi.
*[3]Geothermal Project, Kenya Power and Lighting Co. Ltd., P.O. Box 30177, Nairobi.

**ABSTRACT**

*The Rift Valley has a varied water availability depending on the different geographical positions. In general, the floor of the Rift Valley has very limited surface water resources and yet the availability of water is crucial for farming; the development of industry and the geothermal resources in the area. Consequently, an integrated study was undertaken to determine the groundwater potential in the Nakuru North area. The study revealed that there is a vast amount of groundwater on the floor of the Rift Valley, but its abstraction potential is influenced by the swamps of faults and fractures found on the floor. Three aquifer types have been identified in the area. However, the main water yielding aquifers are controlled by secondary permeability zones such as fractures, fissures and faults since most of the volcanic rocks occurring in the area are rather impervious. Another important zone is the interface between rock formations of significantly different ages called "old land surfaces" of paleosols. The existing structures thus control the flow of the subsurface water, with the main ground-water aquifers occurring within the volcanic rocks.*

*Chemical concentrations of the various elements in the groundwater of the area are unexpectedly low. However, the fluoride content in the western part of the study area is very high. Otherwise the rest of the area has acceptable dissolved mineral concentrations. The only cause for concern is the high ammonia content, although the treatment for this is rather simple.*

*The tested yields in the different aquifers vary considerably, but can be summarised as follows:*

*(a) Lake sediments - 4.1 to 23.6 cubic meters per hour with an average of 13 cubic meters per hour.*
*(b) Tuffs - averaging 9.0 cubic meters per hour*
*(c) Fractured lavas and lava flow interfaces - 3.6 to 27.3 cubic meters per hour.*

### INTRODUCTION

#### Purpose of Study

The Subukia Water Supply Project encompasses an area of approximately 600 km$^2$ in the northern part of Nakuru District in the Rift Valley Province of Kenya. In the efforts to develop the water supply for the population in the Subukia area, we were commissioned to carry out preliminary feasibility studies of the groundwater conditions in the Subukia Water Supply Project area. This report presents our findings on the groundwater conditions. It is the result of four months of field work followed by detailed laboratory and office analysis of all the data relevant to the study.

The feasibility study of the groundwater conditions comprised of among others, hydrogeological geological, and hydrogeochemical investigations, with the aim of evaluating the groundwater potential in the Project area; and investigating possibilities of groundwater development and establishment of basic data for groundwater management.

Geological and hydrogeological investigations have resulted in a good understanding of the morphological, geological and hydrogeological factors which govern the movement, recharge, subsurface flow and discharge of groundwater in the project area.

#### Location

The area is centered around 35km. to the northeast of Nakuru Town in the Rift Valley Province of Kenya (Fig.1). It lies approximately between latitudes 0° 08' S and 0° 15' N and longitudes 36° 5' E and 36° 17' E. The Project covers an area of approximately 600km$^2$ of the northern part of Nakuru District. The neighbouring districts are Baringo to the northwest, Laikipia to the northeast and Nyandarua to the east. The general southern boundary of the Project area runs approximately 2km. to the north and parallel to the Chania/Olobanit River.

#### Topography

The Project area lies approximately between 1500m and 2450m above sea level. Fig. 2 shows the general topography along a profile A-A', shown in Fig. 3, across the middle part of the Project area. The topographic profile shows that the Project area is divided in the middle by a north-south trending Subukia ridge. To the west of this ridge the Project area is generally low lying and dry. It is traversed by several rivers which drain into Olobanita Swamp and Lake Solai which is also swampy. Most of the rivers are normally dry except for a few months after the rainy season. The middle Subukia ridge forms the highlands with intermittent valleys typical of a horst and graben structure generally found in the central part of the Kenya Rift Valley.

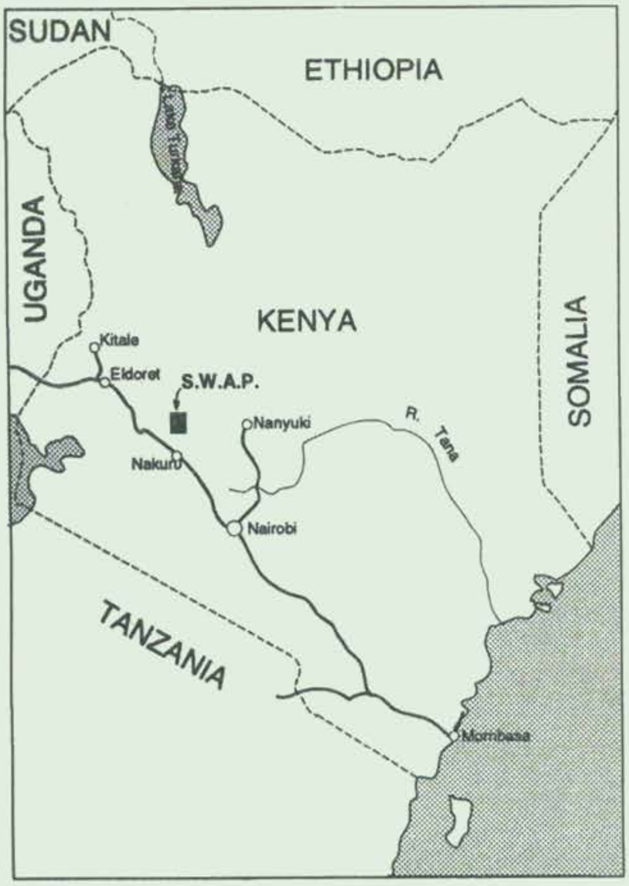


Figure 1. Location map - S.W.A.P.

To the east of the middle ridge is Subukia Valley. The northward flowing Waseges river forms the only major drainage away from this rich agricultural valley. The valley is bordered to the east by the Marmanet escarpment which also forms the eastern boundary to the Project area. This escarpment rises to an altitude of 2450m at the Project area boundary and to higher altitudes to the east beyond the Project area boundary.

The extreme northern part of the Project area is semi-arid and has poor vegetation. The terrain is rugged and difficult to traverse and thus making communication poor. It is through this area that the Waseges river flows towards Lake Bogoria.

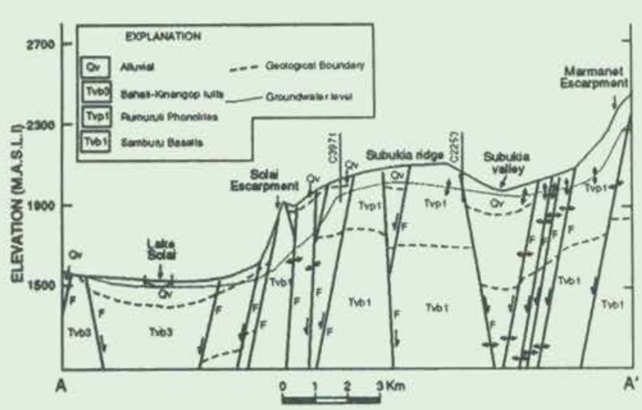


Figure 2. Cros§ section along A-A' of figure 3, showing elevation, geology and groundwater level.

## GEOLOGY

### General Geology

The Project area had been originally mapped at scale of 1:125,000 (McCall, 1967). In this area, all the rocks exposed are of Miocene or younger age. The oldest rock formation is the olivine basalts which often occur together with picrites. These rocks are presumed to occur widely in the area, but are exposed only in the central Subukia ridge, on the western edge of the Marmanet escarpment and on the eastern side of Lake Bogoria. The rocks are grouped as the Samburu Basalts. Although the thickness of Samburu Basalts is not well known it is estimated to be approximately between 300 and 400 metres. Found among this basaltic formation are minor intercalations of pumice and tuff. A small outcrop of diatomaceous lake beds is found at the northern end of the Subukia ridge which is a part of the oldest Miocene formation.

Overlying the Samburu Basalts are phonolites. The phonolites are predominantly porphyritic. This formation is referred to as the Rumuruti Phonolites. They are found in almost a half of the area and are exposed on the Subukia ridge, Marmanet escarpment and Sattima escarpment. The Rumuruti Phonolites, which thin out towards the edges, average about 300 to 400 metres in thickness.

After the Rumuruti phonolites come Pliocene phonolites and surbodinate trachytes which overlie the Rumuruti Phonolites unconformably. The difference between these phonolites and the Rumuruti Phonolites apart from the stratigraphic position, is that the Dispei-Lake Bogoria Phonolites are finer grained and do not contain abundant phenocrysts like the Rumuruti Phonolites. The difference in their textures have a slight effect on their porosity and permeability. On the other hand the trachytes are well crystallised, some of which are coarsely porphyritic. This formation of phonolites and trachytes averages about 250 metres in thickness.

The next in succession within the Pliocene period and overlying the phonolites and trachytes are the tuffs and ignimbrites. These are exposed in a few scattered places, but extensively overlie the Rumuruti Phonolites, the extent of which is obscured by the overlying superficial alluvial deposits. They extend mostly from Lake Solai latitude southwards. The tuffs and ignimbrites overlie the Rumuruti Phonolites and trachytes conformably.

These are grouped under the name of Bahati and Kinangop Tuffs. The main rock types within this formation are cream to yellow pumice tuffs, thin welded tuffs, massive welded tuff flows with coarse fragmental, laminar textures and trachytic lavas of fragmental type. In most of the area under investigation the Bahati-Kinangop Tuffs average about 70 metres in thickness. These tuffs and ignimbrites are considered to have somewhat higher porosity and better permeability than the preceding older formations of basalts, phonolites and trachytes.

After the tuffs and ignimbrites come the stratified deltaic deposits of gravel tuffs and diatomaceous silts. This succession has no significant relevance to this particular investigation and will therefore require no further discussion here. However the succession which bears direct relevance to the groundwater conditions and recharge is the superficial alluvial deposits. These mostly overlie the Bahati-Kinangop Tuffs, but directly overlie other formations in some places as well. The superficial deposits vary considerably in composition, ranging from lacustrine, pluvial to alluvial deposits. Some of the superficial deposits result from in situ weathering of the country rock, thus forming residual deposits. These superficial deposits are commonly friable, unconsolidated material. They are highly permeable and average about 60 to 70 metres in thickness at th section of maximum sediment deposition.

**Structures**

The area has a complex structural pattern of faulting with varying orientations (Fig. 2). The faults mostly trend in a north-south direction. Accompanying the intense faulting, are numerous fissured and fractured zones, which are often water bearing. The faults are normal and have hades of varying directions, but mostly tend to face west or east. Most of the hades are very steep, almost vertical, but few are as low as 60 degrees. The common hade inclination is about 80 degrees. The angle of inclination of these hades are important and have to be taken into consideration when citing boreholes. In addition the inclination direction of the hades (i.e. east or west) will influence the recharge flow direction, particularly when the faults cut across less permeable formations like those of the phonolites, trachytes and basalts.

Apart from the faulting and fracturing, there is another structural feature which has direct relevance to the occurrence of groundwater and that is unconformity, representing old land surface. Where there is unconformity it means there was a significant time lapse before the next geological succession was formed and during the time lapse there would be alteration and weathering of the already formed rocks. Thus in the interface of two geological formations where the unconformity occurs, and the top portion of the lower formation which has been weathered, the groundwater can flow or be stored, thus forming an aquifer. Three unconformities have been identified within the stratigraphy of the area. The first unconformity is found between the Samburu Basalts and Rumuruti Phonolites, the next between Rumuruti Phonolites and Dispei-Lake Bogoria Phonolites and the last between Bahati-Kinangop Tuffs and superficial deposits. This last unconformity has the maximum influence on the flow of groundwater especially in unconfined terrain.

**Groundwater Recharge Areas**

In discussing the recharge areas, attention is mainly focussed on geological features which would facilities groundwater replenishment. This may not necessarily tally with the actual recharge areas but rather recharge potential in the area, since actual recharge is dependent on other factors such as rainfall, vegetation, etc. Consequently actual groundwater recharge will be dealt with in the following section.

However an attempt is made here to amplify and delineate suitable geological recharge areas. The level of certainty of the delineated recharge areas is considered high. Most of such areas are best exemplified by places covered by superficial alluvial deposits, particularly in confined faulted and fractured depressions like Sidai Farm and Munanda Farm areas. The deposits which cover most of the flat areas and graben appear relatively absorptive. They transmit precipitation and runoff to the underlying fault, fracture and fissure systems of less permeable ignimbrites, phonolites and trachytes.

In some cases, recharge is also facilitated by runoff or streams traversing exposed fault planes. The exposed fault planes break the water flow, thus allowing for percolation along the faults. Apparently the most important recharge areas are grabens, faulted and fractured zones.

## HYDROGEOLOGY

**Groundwater Occurrence and Major Aquifer Types**

The geology and structure of the area under study have been discussed in the preceding section. There are about fifty six drilled boreholes in the area and three major springs. Table 1 gives data for some of these boreholes and springs.

In most cases groundwater occurs under confined semi-artesian conditions whereby the water level usually rises above the level at which it is struck. Most water bearing aquifers in this area, as in most of the Rift Valley zone, would be considered as semi-aquicludes like in many parts of the world where sedimentary aquifers occur. A typical high capacity borehole in the area yields hardly more than 15 cubic metres per hour. In comparison, a good irrigation well drawing water from a permeable coarse grained sedimentary aquifer would yield between 200 and 500 cubic metres per hour.

As discussed in the previous section, most of the area is covered by volcanic lavas and tuffs except for the northern part of the area and around Lake Solai where lake sediments are found and is highly fractured. Investigations of the borehole records reveal that all types of rocks are water bearing but with variable water yielding capacities in any one formation. Most of the boreholes draw water from more than one aquifer with the tested yield generally higher from the deeper aquifers.

There are a lot of limitations as to the reliability of the borehole lithologic logs as obtained from the Drilling Contractors' logs. Quite often they report only the relative hardness and colour of the cuttings obtained. Only in few cases have the cuttings been studied under a microscope by a qualified geologist. One has therefore to examine the reported rock formations in the borehole data kept by the Ministry of Water Development and correlate it with the geology. The pump testing techniques and water flow measurement methods used by various contractors are not consistent either.

After careful study of the existing borehole data, three major aquifers were delineated and are shown in Fig. 4 and Table 3. These are:-

(i) Lake sediments
(ii) Tuffs
(iii) Fractured lavas and lava flow interfaces (old land surfaces).

Table 1. Some borehole data for the Subukia water supply.

| BOREHOLE NO. | DATE COMPLETED | ELEVATION masl | DRILLED DEPTH m. | WATER STRUCK m | WATER REST LEVEL | | | | TESTED YIELD $m^3/hr$ | SPECIFIC CAPACITY lps/m | TRANSMISSIVITY $m^2/day$ | AQUIFER TYPE | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | ON COMPLETION | NEW | DATE | ELEVATION | | | | | |
| C2390-D | 3.9.56 | 1759.8 | 134.1 | 61.0 | 43.3 | 33.1 | 15.2.73 | 1726.7 | 2.57 | 0.08 | 18.2 | Lake sediments | Borehole working<br>Good quality water<br>Water temp = 25°C |
| C2605 | 27.11.56 | 1777.7 | 114.3 | 67.1 | 59.7 | - | - | 1718.0 | 13.65 | ? | - | Lake sediments | Pump removed from borehole and blocked by stones |
| C2940 | 11.11.59 | 1584.8 | 112.8 | 62.5 | 57.3 | 57.0 | 13.5.71 | 1527.8 | 9.10 | 0.56 | - | Fractured lavas and weathered lava interfaces | Borehole working<br>water slightly coloured<br>Water temp = 27°C |
| C2311 | 24.2.54 | 1599.6 | 97.8 | 79.2 | 54.9 | 43.8 | 13.5.71 | 1555.8 | 6.62 | - | - | Lake sediments | Borehole drilled but no equipped. Covered with a tin cover<br>Water temp = 25°C |
| C3018 | 10.7.59 | 1583.7 | 98.3 | 46.8 | 44.2 | - | - | 1539.5 | 23.6 | ?? | - | Lake sediments | Borehole working<br>water looks rusty |
| C2309 | 6.12.84 | 1934.6 | 149.4 | 106.7 | 86.9 | - | - | 1847.7 | 8.19 | 0.06 | - | Fractured phonolites | Borehole working<br>Good quality water |
| C3037 | 7.7.68 | 2266 | 179.8 | 63.4<br>111.9<br>122.5<br>173.7 | 89.3<br>103.9<br>105.2 | - | - | 2094.8 | 1.37<br>8.53<br>6.83 | ? | - | Volcanic sand | Owner engaged contractor to clean the well but found caved in. |
| C867-D | 19.5.49 | 2297.2 | 146.3 | 28.0<br>55.2<br>104.2<br>126.5 | 25.9 | 28.9 | 15.3.73 | 2268.3 | 9.6 | 0.1 | 11 | Vesicular trachyites | Borehole working<br>Good quality water |
| C1674 | 13.2.52 | 1920 | 92.7 | 50.3 | 42.1 | - | - | 1877.9 | 13.10 | - | - | Fractured lava | Water sample looks muddy |
| C3954 | 22.11.73 | 1920 | 99.4 | 49.0 | 48.65 | 49.6 | 6.3.81 | 1870.4 | 27.3 | 4.5 | 162 | Fractured lava | Water sample looks muddy and dried up after short time of pumping |
| C343 | 31.5.45 | 2260 | 83.5 | 80.8 | 57.9 | 59.9 | 5.6.71 | 2200.0 | 11.36 | - | - | Fractured lava | Borehole working<br>Good quality water |
| C4817 | 11.3.80 | 2220 | 174.0 | 35.3 | 34.2 | - | - | 2075.0 | 19.6 | 0.9 | - | Tuffs | Borehole working<br>No water level taken<br>Water is lukewarm |
| C736 | 24.7.48 | 2302.0 | 111.3 | 23.8<br>33.5<br>59.1<br>99.4<br>107.6 | 9.8<br>9.8<br>9.8<br>9.8<br>9.8 | 56.8 | 8.6.71 | 2245.2 | 0.23<br>0.91<br>9.10<br>20.5<br>24.6 | ? | ? | Fractured lava | Borehole working<br>Good quality water<br>slightly acidic |
| DWI | ? | 1938.6 | 27.0 | ? | 11.3 | 11.4 | 4.3.81 | 1927.2 | ? | - | - | ? | Hand dug well.<br>Measured depth at 27m<br>No pump |
| C1747 | 18.4.52 | 2020 | 140.2 | 26.2<br>132.6 | 29.9 | 23.8 | 4.3.81 | 1996.2 | 5.45 | - | - | Tuffs | Borehole equipped with electric submissible pump.<br>Not working. |
| C3432 | 7.4.67 | 1540 | 106.7 | 16.7<br>42.7<br>35.3<br>106.7 | 15.2 | 10.3 | 13.5.71 | 1529.7 | 1.37 | - | - | Lake sediments & fissured trachyite | Borehole not working, but submissible pump still in |
| C2272 | 24.9.54 | 1549.2 | 57.6 | 33.3 | 16.8 | 13.0 | 13.5.71 | 1536.2 | 18.0 | 0.29 | 39.6 | Fissured trachyite | Pump broken down |
| C828 | 17.2.49 | 1587.8 | 76.2 | 39.6 | 33.2 | - | - | 1534.6 | 4.09 | - | - | Lake sediments | Borehole blocked by disused pump |
| C298 | 1.4.44 | 1514.4 | 60.0 | ? | 4.0 | - | - | 1510.4 | 13.6 | - | - | Lake sediments | Borehole blocked but pump functions |
| C3610 | ? | 1529.6 | 61.0 | 50.3 | 15.5 | - | - | 1514.1 | 9.1 | - | - | Lake sediments | Borehole equipped with submissible pump.<br>Not working. |
| C2939 | 7.8.59 | 1864.3 | 189.9 | 54.9<br>68.6<br>88.4 | Falling to 81.7 | 95.8 | 11.5.71 | 1768.5 | 12.27 | - | - | Weathered lava | Borehole equipped with pump.<br>Clean cold water |
| C2271 | 16.9.54 | 1533.0 | 106.7 | 54.90 | 15.2 | - | - | 1517.8 | 22.7(?) | - | - | Lake sediments | Borehole not equipped and blocked by rubbish |

### Lake Sediments

These are recognizable from most of the boreholes around Lake Solai and north-eastwards towards White Rock. Their tested yields vary from 4.1 to 23.6 cubic metres per hour, averaging about 13 cubic metres per hour. The lake sediments here are mainly graded tuffs with diatomaceous intercalations.

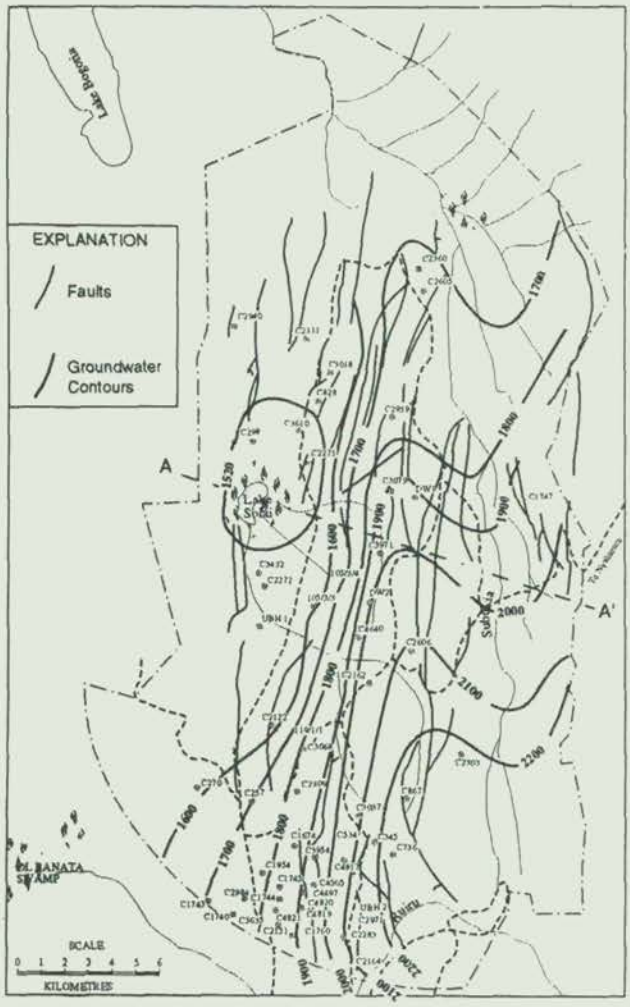


Figure 3. Groundwater contours and faults.

### Tuffs

It is pretty difficult to recognize pure volcanic tuffs from stratified water-reworked tuffs. However, in general, boreholes north-east of Upper-Solai and to the east of the Solai escarpment covering Subukia ridge and Subukia Valley produce water from tuffs. These are the least water yielding formations in the area under study, averaging 9.0 cubic metres per hour.

### Fractured Lavas and Lava Flow Interfaces

Most of the lavas in the area are Samburu Basalts, Rumuruti Phonolites and Bogoria (Hannington) Phonolites and Trachytes. These are generally fine grained and would not be expected to yield any water. However, from the study of the available borehole data, these have the highest water producing boreholes. The tested yield ranges from 3.6 to 27.3 cubic metres per hour. The low minimum figure may be due to poor testing method employed by the drilling contractors.

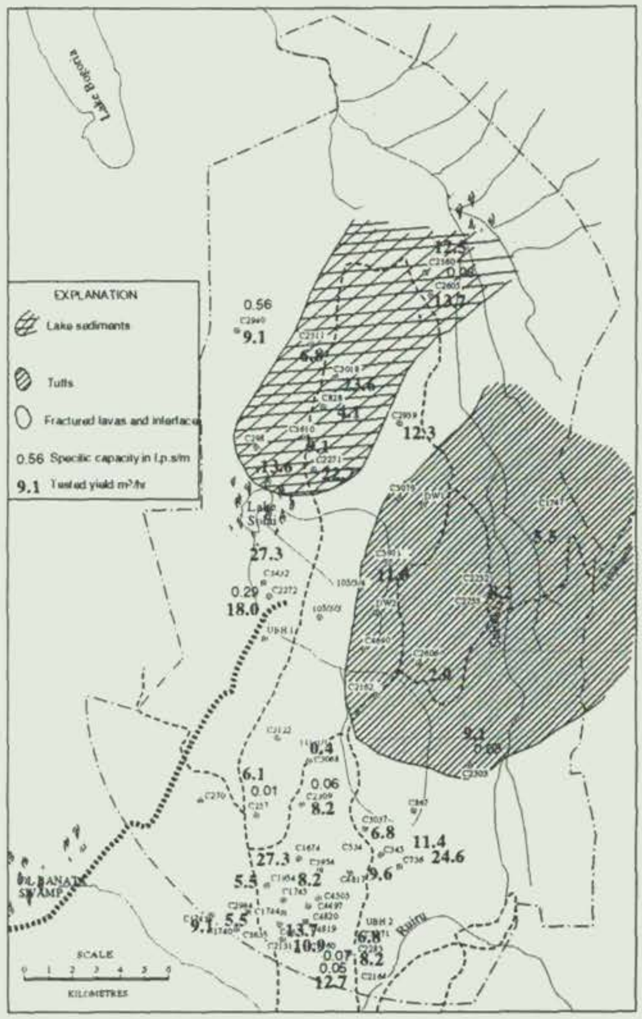


Figure 4. Types of aquifers; tested yields and specific capacity.

Lavas only yield water from secondary permeability zones such as fractures. Fractures have the tendency to interconnect and intersect water bearing aquifers or faults and thus yield substantial amounts of water when struck. Other sources of permeability in these rocks are the interfaces between lava flows of different ages called "old land surfaces" in the Kenyan geological literature. They occur when after one period of volcanic eruption, the volcanic activities subside and the usually frothy lava tops weather to various sizes of clayey and sandy materials. These interfaces usually remain open or semi-open after younger lava flow activity and thus act as water bearing aquifers. All springs in the area occur in these formations.

### Depth to First Aquifer

Figure 5 shows a contour map of depth to the first struck water aquifers in the area. It shows a large area where water is struck below 50 metres running southwards and west of the Solai escarpment from Lake Solai and north-eastwards from Lake Solai across the Solai escarpment, Subukia ridge and valley and on towards Iguameti ridge. Areas with depth to first water aquifer deeper than 90 metres occur on the southwestern corner, on the Subukia ridge northeast of Solai Police Station and on the eastern slopes of Subukia ridge.

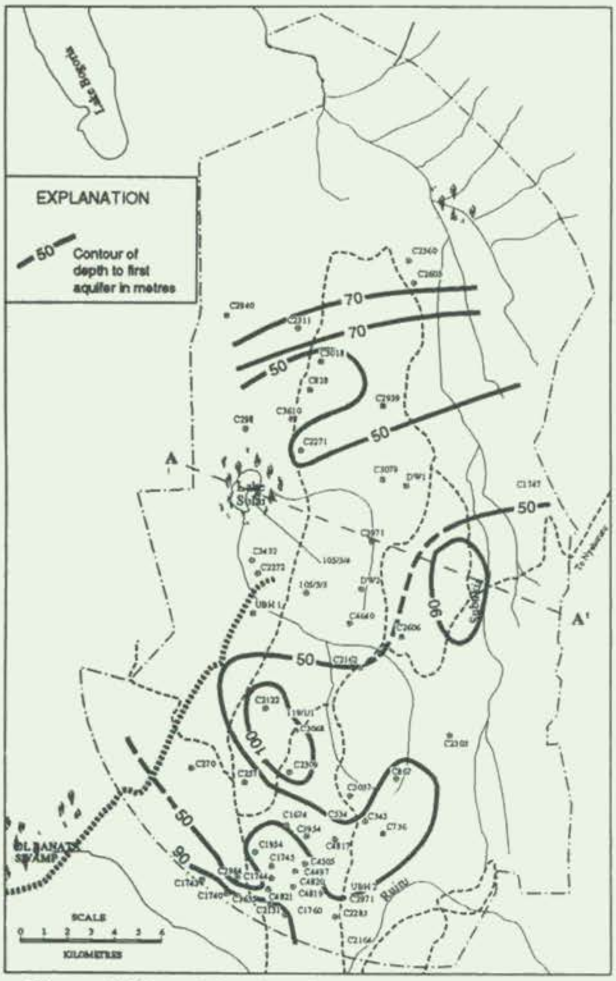


Figure 5. Map of depth to first water aquifer.

**Groundwater Movement, Recharge and Discharge Areas**

Figure 3 shows the groundwater contours (piezometric surfaces) and fault locations in the Project area, while Fig. 2 shows a cross-section of the groundwater level along profile AA' in Figs. 3 and 5. As described under section 1.3 the topography of the area is dominated by high ground to the east, the central Solai escarpment and Subukia ridge and lowlands north and south of Lake Solai. There is also a general topographic drop northwards. The central part and the eastern flank are the major faulted areas. Rainfall is highest in the Subukia-Bahati forests and generally lower in the rest of the Project area. Recharge is therefore highest in the Subukia-Bahati part of the area and in the Subukia valley region.

From the groundwater contours and rainfall intensity mentioned above, the Bahati area recharge zone forms a groundwater ridge which would enable groundwater percolation into deeper reservoirs and intercept fissures and faults. The groundwater movement in this area would thus have a higher downward vector before it intercepts horizontally striking aquifers. This would be in conformity with the deep water aquifers around this area as shown in Fig. 3. Owing to intense faulting in this region, north-eastward groundwater movement within the faults under gravity would also be expected. There is, therefore, a north-eastward vector along the faults and a north-westward vector perpendicular to the piezometric surfaces forming a resultant NNW to northward groundwater movement. This would explain the general occurrence of the springs and the north to NNW flow directions of the rivers towards and through Lake Solai from the Solai escarpment.

The area around Sidai Farm (C4640) forms another groundwater ridge. This ridge is postulated to yield water in three directions. One north-northeastwards along the faults, another north-westwards perpendicular to the groundwater contour lines towards Lake Solai and the other north-eastwards towards Lake Bogoria along the Waseges catchment. The last one joins the northward flow parallel to river Subukia from the Bahati forest recharge zone. This one forms a northerly groundwater stream. Lake Solai forms a marshy perched water table basin with an almost enclosed groundwater basin as shown by the 1520 m.a.s.l. groundwater contour. This lake therefore acts as a groundwater discharge basin. Another discharge area is Lake Bogoria both from the groundwater moving parallel to the Waseges river and north westwards from the Solai escarpment, northeast of Lake Solai.

Fig. 2 profile indicates that the groundwater contour follows the topographic trend rather than stepped due to faults as would be expected. Though there is some downward water movement along the faults in the central and northern part of the area, it seems as though many of the faults act as north-eastward conduits for groundwater rather than vertical step-conduits. This would indicate that the faults are filled with fine grained rather impervious clays that conduct water more along the fault strike rather than along the fault dip.

**Aquifer Characteristics**

The various aquifer characteristic parameters discussed hereunder include tested yields, specific capacity, transmissivity, drawdowns and a line or two on storage coefficient. Tested yield capacities of the boreholes from the different aquifers were discussed under section 4.1 above. Fig 4 shows also specific capacity values of a few boreholes where these data are available in addition to showing tested yield values and aquifer type regions. Table 1 gives specific capacity and tested yield values. These two parameters can be used to calculate drawdown values using the following formula:

$S = \frac{Q}{Sc}$, Meters where
S = drawdown, meters
Q = Tested yield in $m^3/hr$
Sc = Specific capacity in $m^3/hr/m$.

Using the specific capacity units given in the table (l.p.s/m), the formula becomes

$$S = 0.278 \frac{Q}{Sc}, \text{ in meters}$$

As will be seen from the formula, specific capacity is directly proportional to the tested yield and a look at the specific capacity values in Table 1 and figure 4 shows that these values are generally very low. It also shows that wells drawing water from tuffs have the lowest values while those in the southern and western parts of the area have the highest value. These are drilled in fractured lavas and lava flow interfaces. The values range from 0.01 to 4.5 l.p.s./m. The reason why there are fewer specific capacity values than the tested yields is because most contractors report the tested yield, but do not put the maximum drawdowns during pumping tests. Without drawdowns, specific capacity cannot be computed.

Another important parameter in the assessment of aquifer capacity to yield water is the coefficient of transmissivity (transmissibility) or simply transmissivity. This is defined as the rate of groundwater flow through unit length wide of a vertical section of an aquifer whose height is the thickness of the aquifer when the hydraulic gradient is 1.00. It will be seen from Table 1 that these values are given in square meters per day. The actual units are cubic meters per day (volumetric flow rate) per meter (width) thus cancelling out to be $m^2$/day. This is also a measure of the aquifer permeability and can be calculated from proper pumping test data.

Five wells in the project area have had complete pumping tests so as to enable computation of transmissivity values. The calculated values also show as much variability as the tested yield and specific capacity. They range from around 10 to over 160 $m^2$/day. These values are low compared to sedimentary formation aquifers. For better understanding and to enable possible construction of theoretical curves relating transmissivity to specific capacity and storage coefficient in the area, proper pumping tests with observation wells are required.

Storage coefficient is another aquifer characteristic parameter useful to know. Unfortunately, it is the most difficult parameter to compute unless pumping tests are carried out in one well with one or more observation wells to monitor the rate of change of the cone of depression. It is defined as the volume of water released from or taken into storage per unit surface area of an aquifer per unit change in head. It is therefore a dimensionless unit. For water table aquifers, it is the same specific yield (the quantity of water a unit volume of material releases when drained by gravity) and ranges between 0.01 and 0.35. Artesian aquifers have storage coefficient ranges from 0.00001 to 0.001. As stated above, all the pumping tests carried out in the area have no observation wells near the pumped well so no storage coefficient values could be calculated.

## HYDROGEOCHEMISTRY AND GROUNDWATER TEMPERATURES

Figure 6 shows areas of low and high concentrations of fluoride (F) and chloride sulphate ($C1/SO_4$) ratios in the area while Table 2 gives the chemical characteristics of the groundwater. It is evident from the map that most of the area east of Lake Solai southwards to east Lake Solai area has low fluoride content quite often below the recommended maximum of 1.5 ppm. A similar trend is seen in the $C1/SO_4$ ratio values. The only anomalous well is DWI which is an open hand-dug well in which the water is stagnant and the high mineral content is due to evaporation. High $C1/SO_4$ ration usually shows that the water is old or has stayed in the ground for a long time allowing chloride to be leached from the rocks into the water since chloride goes into solution faster than sulphate. Their absolute values, however, are below maximum allowed levels in all the waters.

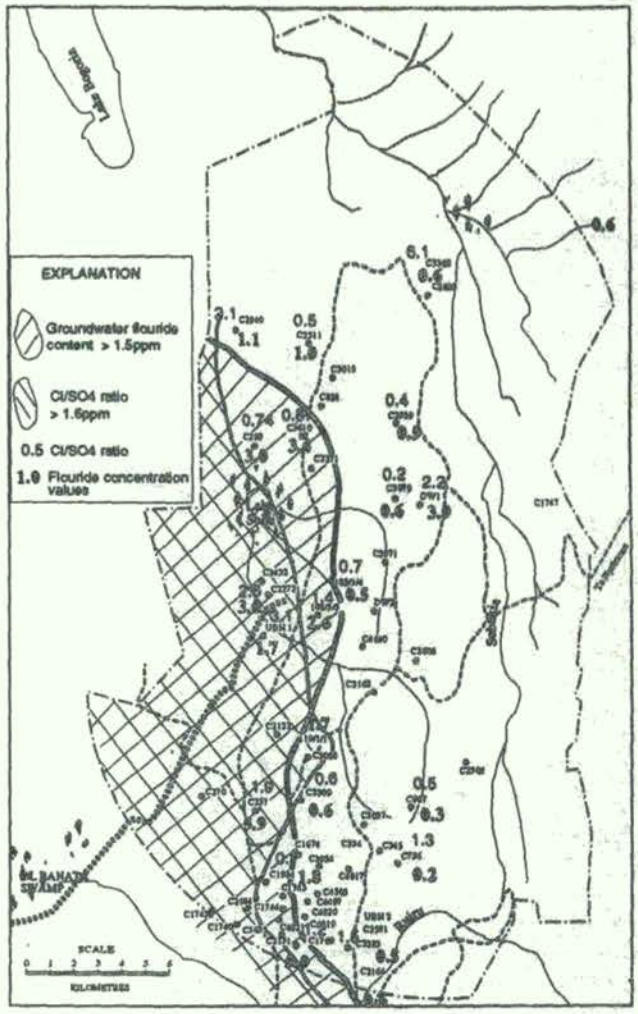


Figure 6. Map showing groundwater flouride content and $Cl/SO_4$ ratio

Looking at the chemical concentrations of the various elements in the Subukia Water Supply Project area as shown in Table 2 the waters are unusually low mineralized for normal groundwater and apart from the high fluoride content on the western part of the area, the rest of the area has chemically acceptable mineral concentrations. The only cause for concern is the high ammonia content. This is due to organic pollution which could cause stomach upsets when drunk. Treatment for this is, however, more simple than de-mineralization. Most of these ground waters can be treated by simple chlorination methods.

Groundwater temperatures are shown in Fig. 7. It will be seen from this drawing that most of the groundwaters in the area have temperatures below 25°C. Exceptions are the areas north-west of Lake Solai, the Solai escarpment area and the southern area around Milmet Estates. These areas generally coincide with areas where the first struck water aquifers are deeper than 50 meters and with areas of high intensity of faulting (Cf. Fig 3).

Table 2. Chemistry of groundwater ofsome boreholes for the Subukia water supply project

| BOREHOLE NO. | C3610 | C2939 | C3073 | C2272 | C3971 | UBHI | C270 | C257 | C2309 | C867 | C2984 | C3535 | C4821 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DATE | May'71 | May'71 | June'71 | May'71 | March'81 | June'71 | March'81 | May'71 | March'81 | June'71 | May'72 | May'71 | March'81 |
| TEMP. (°C) | - | 24 | 25 | 25 | - | 22 | - | - | 26 | 23 | 24 | 27 | |
| CONDUCTIVITY (micro-mhos/cm³). | 740 | 315 | 278 | 217 | 415 | 420 | 309 | 350 | 370 | 85 | - | 360 | 390 |
| COLOUR. | Clear | Clear | Clear | Clear | Clear | Clear | Clear | Clear | Clear | Clear | Clear | Clear | Brownish |
| pH | 6.8 | 6.75 | 6.95 | 6.8 | 6.6 | 7.25 | 6.2 | 6.9 | 7.9 | 6.15 | 6.6 | 7.0 | 6.2 |
| TOTAL HARDNESS (ppm) | - | - | - | - | 4.0 | - | - | - | 3.2 | - | - | - | |
| FREE CARBON-DIOXIDE (ppm) | 51 | 69 | 32 | 50 | 28 | 24 | 18 | 38 | 0.6 | 50 | 70 | 29 | 26 |
| ALKALINITY AS CARBONATE ($HCO_3$) (ppm) | - | - | - | - | - | - | - | - | - | - | - | - | - |
| ALKALINITY AS CARBONATE ($CO_3$) (ppm) | 300 | 225 | 176 | 161 | 240 | 240 | 110 | 167 | 234 | 40.5 | 158 | 195 | 144 |
| AMMONIA ($NH_3$) (ppm) | - | - | - | - | 0.24 | - | 0.07 | - | 0.34 | - | - | - | 0.06 |
| POTASSIUM (ppm) | 17.2 | 11.3 | 9.8 | 13 | 5.7 | 12 | 7.3 | 7 | 8.3 | 6.8 | 6.5 | 10 | 10.8 |
| SODIUM (ppm) | 130 | 21.7 | 22.2 | 53 | 22.4 | 61.6 | 38 | 80 | 30.3 | 12.0 | 67 | 88 | 43.2 |
| CALCIUM (ppm) | 21.4 | 32.2 | 24.6 | 12.2 | - | 24.1 | - | 6.6 | 20.5 | 2.75 | 3.4 | 4.5 | - |
| MAGNESIUM (ppm) | 4.3 | 16.1 | 7.1 | 6.2 | - | 8.5 | - | 0.97 | 7.0 | 0.98 | 1.8 | 1.1 | - |
| CHLORIDE (ppm) | 22.0 | 1.94 | 0.8 | 10.2 | 15 | 13.9 | 16 | 13.6 | 10 | 1.6 | 5.9 | 9.7 | 12 |
| FLOURIDE (ppm) | 3.35 | 0.43 | 0.58 | 3.0 | 0.4 | 1.7 | 0.8 | 3.05 | 0.4 | 0.33 | 4.0 | 4.8 | 0.9 |
| SULPHATE (ppm) | 79 | 13 | 10 | 10.8 | - | 12.7 | - | 19.5 | 11.7 | 8.5 | 10 | 52 | - |
| SILICA (ppm) | 80 | 95 | 47 | 58 | 60 | 55 | 67.5 | 81 | 85 | 40 | 41 | 59 | 83 |
| TOTAL DISSOLVED SOLIDS (TDS) | - | - | - | - | 310 | - | 236 | - | 210 | - | - | - | 248 |
| COMMENTS | High flouride content | Good quality water | Good quality water | Chemically Good water apart from high flouride content | Soft but slightly polluted by organic matter | Chemically Good water | Soft water apart from high flouride content | Mildly soft but slightly polluted by organic matter | Good soft water | Slightly high flouride content | High flouride content | High flouride content | Good quality water containa minimal organic matter |

## GROUNDWATER ABSTRACTION

Only about 46% of all the boreholes drilled in the area were functioning during the investigation. These are also pumped for a few hours only in a day and the installed pumps have capacities below the tested and recommended abstraction yields. Assuming an average pumping time of four hours a day and taking the abstraction rates to be the tested yield values, the total groundwater abstraction is hardly more than 1000 m³/day. This is less than the estimated yield of 1200 m³/day from the warm spring numbered 105/3/4 on the map. The occurrence of this spring has been discussed under section 2.2-5 above. At the time of the investigation, the only water being used from it was through a 3" diameter gravity feed line to the community around. The water is of good quality, and the reported organic pollution is perhaps due to the algal growth in the pool where the water was sampled from. This spring can supply the community west of Solai ridge from Solai Police Station to Lower Solai Community centre through gravity feed lines since it is higher in elevation that the proposed supply area. There would, therefore, be no need for drilling of boreholes in this area.

Boreholes drilled on the Sidai Farm and Jumatatu Farm around C2309 would serve the Subukia area. Kabazi to Bahati area has also got good quality water and potential tò supply these centres. Milmet Estates area should be exploited with proper monitoring programme of the groundwater level drop due to overpumping because of the high density of boreholes in this area.

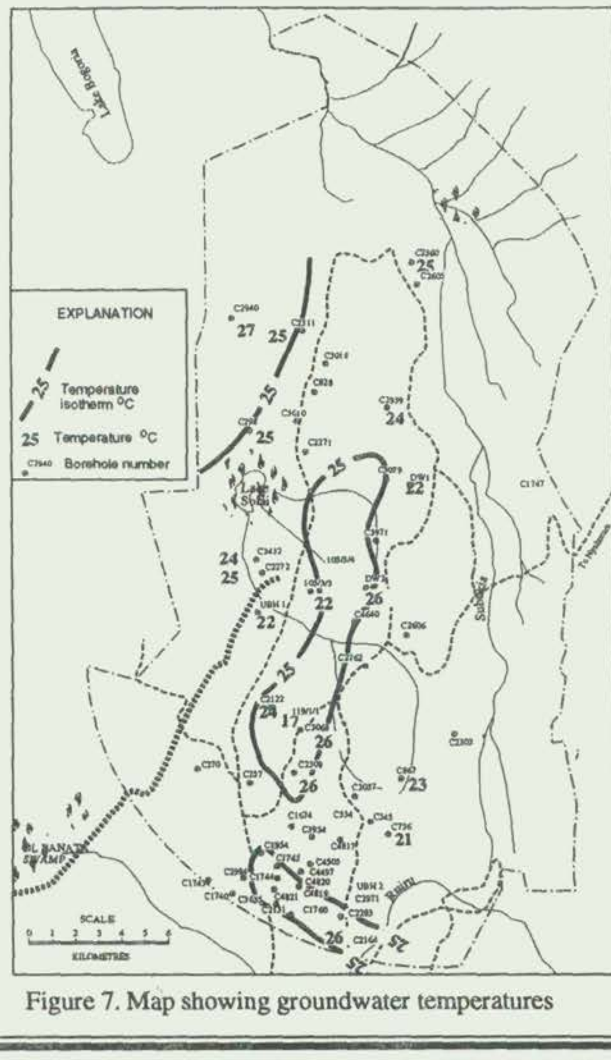


Figure 7. Map showing groundwater temperatures

**SUMMARY**

An integrated investigation, using geological, and hydrogeological approached, has been carried out to determine the groundwater potential in Subukia Water Supply Project area. These approaches have revealed that there is a vast amount of groundwater in the Subukia Project area. The areas of higher groundwater potential are found to be Subukia ridge and down-faulted Solai areas. Three aquifer types have been identified in the area. However the main water yielding aquifers are controlled by secondary permeability zones such as fractures, fissures and faults since most of the volcanic rocks occurring in the area are rather impervious. Another important zone is the interface between rock formations of significantly different ages, called "old land surface". The existing structures therefore control the flow of groundwater and thus the main groundwater aquifers occur within the volcanic lavas.


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Ministry of Water Development record Section.

# ENVIRONMENTAL DEGRADATION DUE TO GROUNDWATER ABSTRACTION IN MALINDI

C. O. Owuor
Mombasa Polytechnic, P.O. Box 90420, Mombasa

**ABSTRACT**

*This paper discusses the adverse effects that will result if no steps are taken towards limiting groundwater abstraction in the Malindi aquifer. The proliferation of wells and their unmetered abstractions have resulted in lowering of groundwater levels. This phenomenon, if unchecked, will finally lead to sea water intrusion and consolidation settlement of the aquiferal material, hence a reduction of storage capacity of the aquifer. Collected data indicates the ratio of the number of wells compared to boreholes is 4:1. Despite this, the Ministry of Water Development lacks an organized database on wells with information comparable to borehole data.*

*CAP 372 of the Laws of Kenya, which deals with protection and conservation of groundwater, has also been discussed. Suggestions have been made to help in the management of groundwater in Malindi aquifer.*

## INTRODUCTION

Malindi town, 120 km north of Mombasa town on the Kenyan coast, has an annual rainfall of approximately 1000mm and, like most of the country, falls in a bimodal trend from April to June and October to December. According to the Resource Development Proposals of TARDA, July 1983, the population of Malindi town based on the 1979 census with an assumed growth rate (AGR) of 8% from 1979 to 2000 is tabulated below:

| AGR | 1979 | 1983 | 1990 | 2000 |
|---|---|---|---|---|
| 8% | 23,275 | 31,665 | 54,269 | 17,163 |

The water demand for Malindi in 1983 was 9,930 m3/day and projected to 15,670 m3/day in 1990. The study area lies on the coastal plain and comprise Pleistocene deposits which are characterised by Wind-blown Sands, Coquinas, Fossil Coral Limestone and Breccias, Lagoonal Sands and Clays, and Red Magarini Sands, in that order of succession. These overlie Tertiary deposits of the Marafa beds.

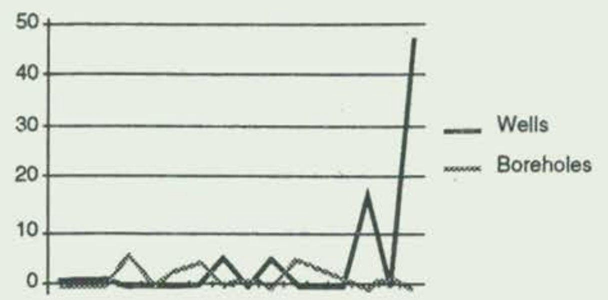


Figure 1. Growth trend of wells and boreholes in Malindi

Table 1. (Pump type and number in use)

| PUMP TYPE (NUMBER) | | |
|---|---|---|
| Davey(14) | Grundfos (1 1) | Calpeda (6) |
| Jacuzzi (5) | Caprari (4) | Saer (4 0 |
| Edrollo (3) | Windpump (3) | Grunding (2) |
| Guastella (2) | Other.s (8) | |

## BACKGROUND

The meteoric rise in the number of wells (Fig.1) and their uncontrolled abstraction is due to the rapid population increase, the unreliable Sabaki pipeline supply, and the lack of a national groundwater management policy. Records available indicate that 74% of boreholes are of good water quality and no monitoring has taken place in 88% (Table 1). A survey carried out in 1990 by the author found 79 wells, as compared to 24 boreholes already documented. These wells represent a major groundwater source and, coupled with the installed water pumps are a significant investment whose performance should draw more attention than is at present. Given that Malindi is an important tourist destination earning Kenya much-needed foreign currency, and creating many jobs in tourism and related industries, it is important that its groundwater resources be used in a sustainable manner. About 86 % of wells are used for domestic use, 17% for minor irrigation and less than 1% for swimming pools. The total abstraction is about 12,000 m3/day, approximately 76.6 % of the projected total demand in 1990.

In 1958 T.T. Bestow noted the cessation of flow of the Mere springs around Malindi and recommended the reduction in abstraction of the Ganda boreholes, namely C848, C2241, C2881. In 1987 the present author, following complaints of low yields in the Ganda boreholes, noted that the rest water level had dropped by 1 Om as compared to its level at the completion time of the borehole (water rest level fell from 28m in 1949 to 38m below the surface in 1987). Considering that the Ganda well field has the most productive boreholes in Malindi (thought to be the former Sabaki River course due to rounded pebbles found during drilling), the yields of other wells in Malindi would be more affected by a lowering of the groundwater table. No attempt has been made to limit the abstraction of water in this aquifer and the mandatory distance between wells, as stipulated in the Water Act. Despite warnings made as early as 1958 (T.T. Bestow), no serious effort has been made to redress this deteriorating situation.

Tabulated below was the prevailing situation of borehole C 848 in 1987, of Ganda wellfield in Malindi contrasted with the year of drilling (1949):

| Total Depth (m) | Water Struck Level (m) | Water Rest Level (m) | Yield m3/h | Year |
|---|---|---|---|---|
| 46 | 30 | 28 | 38.16 | 1949 |
| 41 | 30 | 38 | 9.00 | 1987 |

From the above, it can be seen that the water level has dropped by 10 metres due to the high abstraction rate. Bestow had recommended that the abstraction in the Ganda wellfield (Ganda wellfield comprised of 3 production wells) be limited to 136 m3/day until the Mere springs recommenced to flow. This warning went largely unheeded because of the dire need of water. Prior to the reported yield of 9 m3/h in 1987, the borehole alone had an extraction of 170 m3/day greater than the recommended 136 m3/day.

Since groundwater is not metered, many well owners find it cheaper to use groundwater compared to tap water which costs more. The total number of cubic metres from the wells would represent an income of over KShs. 36,000 per day if the abstraction was metered (12,000m3/day @ KShs. 3 per m3), compared to a total of KShs. 17,800 received from licensing (cost of licencing is currently KShs. 200 per well). This therefore necessitates a pricing policy that would take into consideration the costs of construction and equipping wells. The money collected from groundwater licensing or pricing could be useful in monitoring and management of groundwater resources.

CAP 372 of the Laws of Kenya are very explicit on the protection and conservation of groundwater. Part Vl, subsection 28, allows the Water Apportionment Board to prescribe measuring and controlling devices that can be used to safegaurd the use of groundwater. Part IX on "Abstraction of Groundwater and Permits", empowers the board to give penalties for the failure to carry out its orders. These legislations are difficult to implement because of the lack of: control measures to determine the optimum abstractions of groundwater, a complete groundwater database, and monitoring data.

## EFFECTS OF EXCESSIVE GROUNDWATER ABSTRACTION

Sustained yield has been defined as "the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at that rate is harmful to the aquifer itself, or the quality of water; or is no longer economically feasible." The uncontrolled abstraction of groundwater above sustained yield from a confined aquifer can result in:

- plastic deformation of the aquifer
- sea water intrusion due to severance of the seawater/ freshwater interface
- high cost due to increased height of pumping
- reduction of storage capacity of the aquifer

Plastic deformation can occur due to the lowering of the head of groundwater, as a load consisting of the overburden is always supported by grain-framework of the aquifer and the pressure of water held in its interstitial pores. Elastic deformation defines the movement of the aquifer; this results in no loss of void space, while consolidation results in a decrease in the volume of voids. The magnitude of consolidation is dependent upon the 'compressibility' of the aquifer, while the rate of consolidation depends on both compressibility and permeability. Sea water intrusion resulting from breakage of seawater/freshwater interface formed by density separation of water over time takes up to 30 years! to separate.

## SOLUTIONS

To remedy the situation, the following are recommended:-

- Issuance of groundwater permits to be reviewed with a view to limiting abstraction, and mandatory metering of all abstractions.
- Introduction of a pricing policy to discourage wasteful use of groundwater.
- Artificial replenishment of groundwater (artificial recharge is a water conserving measure, which often results in improved water quality). The source of recharge may be storm run-off, river water, industrial waste-water, and treated sewage water. Recharge may be accompanied by various surface spreading methods through vertical shafts, horizontal collector wells, pits and trenches.
- Creation of a database, inclusive of wells that comprise over 60% of groundwater sources. This database could use the unique licence serial number as primary key in the database definition. Other fields could be the same as those in the current groundwater borehole database. The inclusion of all groundwater sources in a database would greatly enhance the management of groundwater.
- Declaration of conservation areas to protect further groundwater abstraction.
- Strict compliance with the Water Act, CAP 378 part VI subsection 28, that allows the Water Apportionment Board to prescribe measuring and controlling devices that can be used in safe-gaurding the usage of groundwater; and Part IX of the same Act, which empowers the Board to give penalties when its orders are contravened.
- Periodic and consistent monitoring of groundwater level fluctuations (wells/boreholes) and their qualities.
- Curb unfair and illegal discriminative licensing prctices for boreholes and wells. Creation of a transparent policy where all persons are treated equally.
- Mandatory distance rule be related to the yield of the aquifer, since the cone of depression is dependent on permeability.
- Dissemination of information to users through appropriate media channels.

- Review existing legislation with respect to defining the qualifications of the Technical Representative in the Water Resources Authority, and Water Apportionment Board. This should include the nomination of a competent professional technical person who must be ratified by the appropriate professional body, who will in turn advise the Minister of the sector.
- Initiate seminars to explain policies in the groundwater sector, disseminate new ideas, define and deliberate on problems related to groundwater.

The above measures, if implimented, would result in the recovery of the aquifer. In order to redress the harzards caused by excessive groundwater abstractions, water balance studies must be carried out and abstraction limits set.

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# GROUND SUBSIDENCE APPRAISAL IN THE NAKURU AREA

J. Kagasi
Mines and Geological Department, P.O.Box 30009, Nairobi.

## ABSTACT

*A sludy oJground subsidence in the Nakuru area has been conducted, whose aims were ~o delineate and map out areas prone to this phenomena.*

*This paper attemps to unveil possible causes and highlights remedial measures to be undertaken from already accomplished work done in the past by'of officers of the Mines and Geological Department. This report is further designed to provide background data for use by town and land use planners.*

*Field traverses and aerial photo-study carried out revealed numerous N-S to NNW striking fissures/cracks and other linear lfeatures. Zones identified with these linearfeatures are known to be prone to ground subsidence phenomena.*

*The possible model of the dynamics of subsurface erosion has been deduced to be along the vertical fissures/cracks and the horizontal discontinuities.*

## INTRODUCTION

Ground subsidence have periodically occurred in the Nakuru Municipality and its environs. Areas which have been affected by this phenomena include those to the west and south west of the town in the Shabab, Ronda, Kaptembwa estates, Industrial area and much of the Baruti farm outside the municipal boundaries. The form of ground subsidence which has affected these areas is attributed to several causes. Recent studies in the area using both geological and geophysical methods have been carried out in the area by geologists from the Department of Mines and Geology in 1985, 1988 and 1989 whose results have been used to compile this paper. Reference has also been made to previous work carried out in the area by earlier researchers.

Geological mapping and photo-interpretation techniques have been used to delineate the numerous lineaments in the area along which subsurface cavities resulting from subterrancan denudation has occurred. Geophysical surveys carried out over areas of known subsidence has been done using four techniques ie magnetics, seismics, gravity and VLF-EM (Very Low Frequency Electromagnetics).

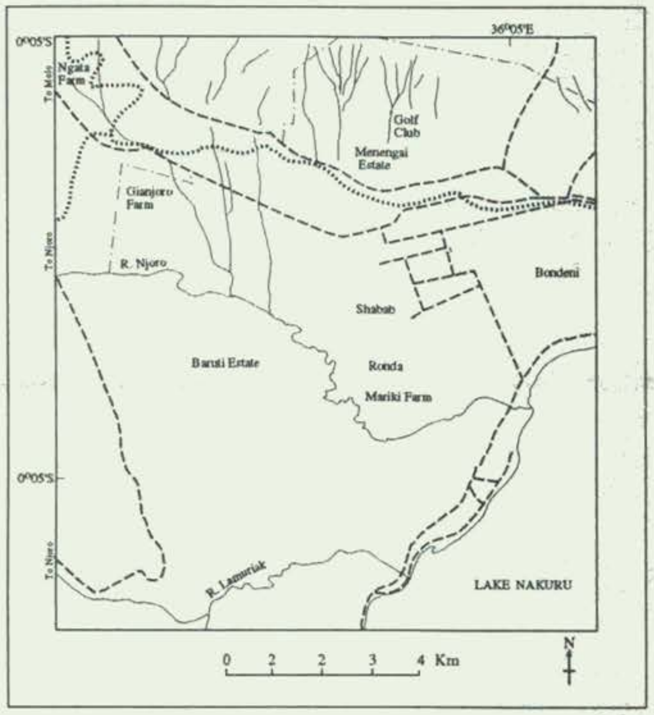


Figure 1. Location map of the Study area.

### Location

The study area is situated 156 km North west of Nairobi, a highly populated major town and administrative headquarters for the Rift Valley Province. It is a major communication centre linking Western Kenya, North Rift, South Rift to the capital of Kenya, Nairobi (Fig. l).

### Physiography

The study area lies within the Rift Valley floor on the general northern slope of the central dome. The area lies at an altitude of between 1760m to 2000m above sea level. Slopes of the Menengai crater occupy the northern part of the area which reaches the highest point at 2100m Lake Nakuru lies in the southeast within a graben between the Mau escarpment to the far west. Part of the Western boundary of the lake is bounded by N-S trending fault cliffs which is part of the faulted effects that has formed the Ronda hill.

Drainage in the area is characterised by very poor surface run-off due to the highly porous nature of the volcaniclastic highly pumiceous and poorly sorted rocks covering the older consolidated lava flows. The few rivers running down from the Mau escarpments ie Lamuriak, Njoro loose much of their water through porous and fissured zones. Those originating from the Menengai disappear to become subsurface on the upper slopes of the crater. Lake Nakuru which is a shallow pan is recharged from mainly rainfall and from the little surface drainage that can reach the Lake during the wet season.There,however exist a number of spings which drain into the lake.

On the whole the drainage system in this area is controlled by faults. This is manifested by the sudden changes in the direction of water coarse which respond to the general orientation of the rift valley faulting.

## GEOLOGICAL SETTING

The area lies on the northern slopes of the central rift dome within what has been described as the Nakuru trough (Baker 1970) (Fig 2). The trough is bordered by the Naivasha trough in the south; the two separated by the Ebuuru shield and to the north is the Bogoria trough. Rocks exposed in the area represent varied series of lava flows and sheets to superficial sediments and volcanic soils. Lava sheets have their origin from the fissures associated with the rift valley faulting and those associated with the eruption of the central volcano (Menengai). Pumiceous tuffs and sediments owe their origin to the dust and vitric ash which emanated from the explosive episode of the Menengai caldera. Some of the sediments were deposited in a lake environment during periods of the "proto" the larger lake Nakuru.

Rift faulting has affected all the rock formations as reflected from the presence of linear faults/fractures where fissures have developed as seen from the sudden change in the direction of water courses. The area is, however, bounded by major regional faults (Fig. 2). The man faults in the south forms a complex fault zone, comprised of numerous minor faults whose orientation is N-S to NNW and extend into the present study area. These faults are obscured by very thick accumulation of vulcaniclastic sediments in the present study area and is compounded further by the Menengai Caldera volcanics in the north. The Bahati faults have a NNW structural orientation, located to the east and shows parallelism with some of the faults in the Nakuru area.

## PREVIOUS GEOLOGICAL WORK

Summaries of geological work previously done in the area in order to understand the origin of the fissures in this area are given. Pulfrey (1951) made geological investigations in the area which were aimed at the siting of grain storage silos and if they would be safely constructed. He advised the consulting engineers to dig down through the unconsolidated deposits to one of the old lava flows which he thought would hold the intended construction and remain structurally sound.

Pulfrey (1951), commented that the fissures in the area were caused by underground streams flowing along lines of weakness marked by many faults and fractures. He discussed the problems of earthquake hazards and concluded that this more central section of the rift was less prone to earthquakes than the rift margins.

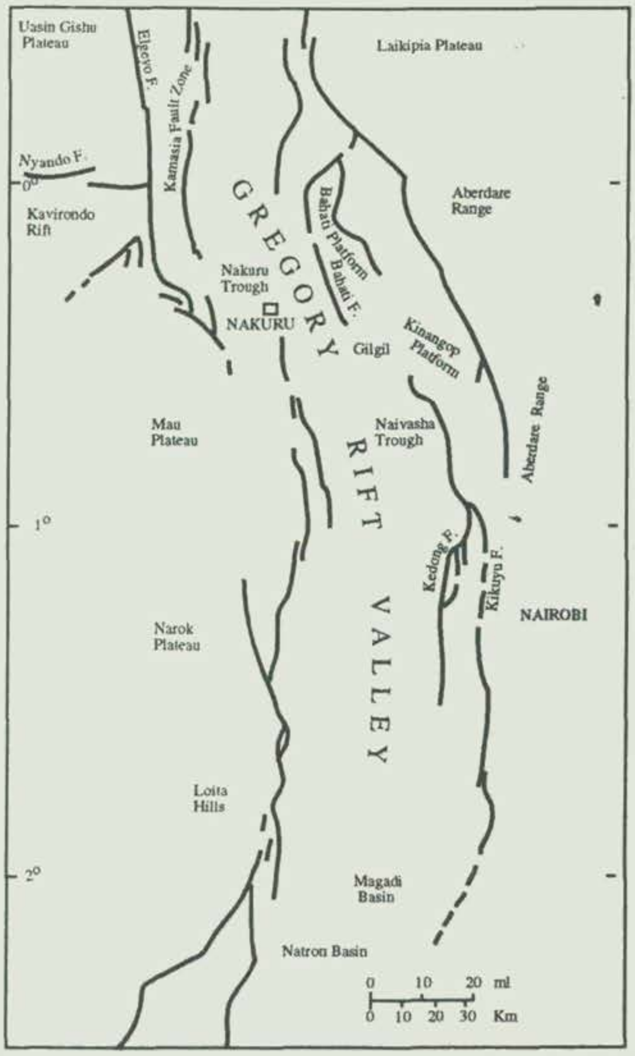


Figure 2. Main elements of the Gregory Rift Valley ( After Baker, 1970)

McCall (1957) published a report on the geology and groundwater conditions in the Nakuru area. In his report are many considerable interests which are important in determining causes of ground subsidence in the Nakuru area and noted the following:-

(i) The study area and many adjacent areas in the floor have very poor surface water run off due to the very porous nature of the thick pumiceous deposits which cover extensive tracks of the older rocks.

(ii) Lake Nakuru is a very shallow body of water usually less than 2m deep. The Lake floor is an impervious salt impregnated clay beneath which coarse porous sediments contain groundwater under very low hydrostatic pressure of about 1.3m head of water.

(iii) Boreholes in the lakeshore plain show perched aquifers which are hydrologically connected and that the whole underground water system is open and connected in three dimensions under the lakeshore plain.

(iv) The rivers Njoro, Lamuriak, Makalia and Enderit which drain down from the Mau escarpment into Lake Nakuru loose much of their water through fissures into the groundwater systems before reaching the lake.

Officers of the Mines and Geological Department have made numerous investigations in this area since 1976.

Pandit and Dow (1976) reported on the earth collapse which took place near the Timber Company (Timsales) just north of the Nakuru-Eldoret Road. The visible signs of subsidence that remained at that time was a large cavity 400m south of the main road.

They described a N-S trending zone of subsidence marked by discontinuous depressions some of which are 2m deep.

During periods of heavy rainfall, collapse into these depressions was reported to be common and the surrounding soils were washed into them making them larger. They were eventually temporarily filled with soil by local residents.

They considered that this particular line of subsidence continued south from the Menengai estate as far as the old Rehemtulla estate (Ronda). They, however, attributed this subsidence to a collapse into an underground lava tube, here incorrectly making a conclusion with little field evidence.

In 1985, the Provincial Mining Engineer accompanied a Provincial Evaluation and Monitoring team led by the Rift Valley Provincial Commissioner to some of the areas of subsidence on the Njoro-Nakuru road and in the Baruti farm area. In the former area, repair work of the road was going on and in the latter(Baruti farm) an old fissure zone marked by big Acacia trees which must have exploited the ground water in the fissures for a considerable length of time.A further four sites were visited ie, Lalwet, Chebwagan, Ronda Hill and Bangladesh villages. A four Kilometer long N-S fissure with subsidence were marked by cracks in the base of an old aligned depressions. Other sites visited and which showed similar characteristics included those to the north of the GK Prison and at the Union Carbide's factory. During the visit facts recorded showed similar linear zones up to 10m wide which had collapsed with loose soil and sub-soil being washed into a narrow fissure 12m wide and greater than 10m deep. Subsequent to this visit, the department embarked and carried out a geological and geophysical survey over areas of known subsidence.

The reports by geologists which were confirmed by measurements of natural sections and by study of logs from boreholes, showed the very thick nature of the poorly sorted and unconsolidated volcaniclastics which measured up to over 100m in places. The geophysical techniques particulary magnetics gave clues to the presence of underground voids.

## SUMMARY OF GEOLOGY.

A summary of the geology of the study area is presented from work previously done by McCall (1967 and from actual fieldwork carried out during our numerous investigations.

The geology of the area is comprised of mainly Tertiary through Quaternary to Recent volcanic rocks, sediments and volcanic soils. The eruption and deposition of various rock types was accompanied by different episodes of faulting and tilting. Rocks and sediments that comprise the geology of the area include a varied series of the following:

(4) Unconsolidated pumiceous ash and sand including glassy "bombs". They range between 6 and 50 metres in thickness with a maximum of 100m recorded from one borehole. These deposits are thickest to the west of Nakuru towards Rongai.

(3) Old Lake sediments including the white or buff, very fine grained diatomite interbedded with pumice, sand and gravel as well as the finely laminated silts and clays.

(2) Welded pyroclastic, fairly compact and found around the Menengai crater. These are used as building stone and aggregate.

(1) Lava flows and sheets (mainly phonolitic and trachytic) which form the base rock in the area (Quarried for road metal).

The extent of the lava and pyroclastic (welded tuffs) in the study area are not very well known with accuracy. Some of the lava sheets are exposed west of Lake Nakuru and those forming the Ronda hill are composed of phonolitic trachyte and older lacustrine sediments (McCall, 1967). Stratified pumiceous tuffs interlayered with diatomite separate the Ronda lava flows from the underlying basalt of the Mbaruk suite which are exposed west of Lake Nakuru. The sediments exposed to the west and NW of Lake Nakuru have been referred to as Larmudiac beds. These sediment are cut by a series of late faults and fractures which are envisaged to be zones where the present fissures and cracks might be developing. Evidence for this can be seen in the Grey sand quarry adjacent the area north of Njoro river where actual flow movement of material is evident.

From structural evidence it is apparent that the thick Recent sediments West of Nakuru town have covered old fractures. The long cracks and or fissures in the Baruti farm area and those in areas within the municipality where subsidence has occurred is a pointer to a close association to the already existing faults which were associated with the major rift faulting.

## SUBSIDENCE

Reports of fissures opening up in the Nakuru area has been a subject of concern. Such reports have been made during certain periods in the mid 1960, 1972, 1978, 1981, 1982, 1985 and 1988. None of these incidence coincided with any known local earthquakes in the area but have proceeded heavy rainfall periods. Results from previous geological work and evidence recorded during recent geological investigations in the area has enabled us to establish a factual background to these natural hazards.

The recent geological investigations was done by actual field evaluation of the problem and use of photo-interpretation as a tool to reveal features which were not readily seen on the ground. It was noted that fissures occur in the area along or above faults or fractures. These can be seen to be aligned approximately N-S or just east of north. From aerial photo study, these linear zones often appear branched or interlinked and generally spaced about 100-500m apart (Fig. 3). However, closer spacings are also known.

Their depth as deduced from geological study is not possible to measure but these cracks are long and narrow when they first appear. The opening of these fissures is due to the collapse of relatively thick unconsolidated deposits including soil and sub-soil accompanied by slumping and flushing of material down deep, near vertical fissures. The effect of this on the land surface is the introduction of surface sink holes and funnel shaped depressions which are usually linked and aligned. In certain cases these are often marked by large trees (Acacia) perhaps to give an indication of their age. In most cases the ground surface shows no vertical displacement as has been shown by continuity of root systems of trees across cracks.

Examination of the fissure walls (in the more solid volcanic units) shows the effects of erosion by sediment laden running water. No signs of structures resulting from tectonic movements ie slikenslides, brecciation etc are evident. At one location a solid rock covering an open fissure was recorded, and such tunnels may be common particularly in the Baruti area where good examples of this was seen.

The surface effects of collapse appear to be most pronounced (deepest and widest) in areas with thin to moderately thick surface layers of unconsolidated material ie up to 10 metres. When the unconsolidated material is very thick there maybe no surface sign that considerable subsurface erosion is in progress until a major collapse occurs. This later situation may cause even more serious dangers to unsuspecting land developers who maybe unaware of this situation.

From the foregoing, available evidence suggests that the fissure zones are controlled by faults and fractures which are initially of tectonic origin, the recent sites where ground subsidence eventually occur have however, resulted from subterranean drainage which has developed and extended during the last approximately ten thousand years. The major control on the fissure opening being erosion along planes of weakness by flowing groundwater charged with abrasive particles.

The beginning of subsurface water system coincides with the highest known margin of the "Proto" Lake Nakuru whose shorelines were at about 1940m contour. It is hence speculated that fissures were originally opened by underground water flowing along fault controlled planes of weakness when the lake started to receed. It is presumed that this process post dated the eruption of Menengai and since then the widening of fissures has been an on going process to the present day. The height of ground subsidence occurrences coincide with periods of heavy rainfall.

## ASSESSMENT OF GEOLOGICAL HAZARDS CAUSED BY GROUND SUBSIDENCE

Assessment of the geological hazards caused by ground subsidence in the Nakuru area entails not only locating the various places of weakness ie faults and/or fractures, but also being able to locate zones of underground water convergence. Sites which are likely to have maximum water flow will experience underground erosion and hence experience the largest ground subsidence. A number of areas in the study area have been affected by this phenomena and are assessed individually (Fig. 3).

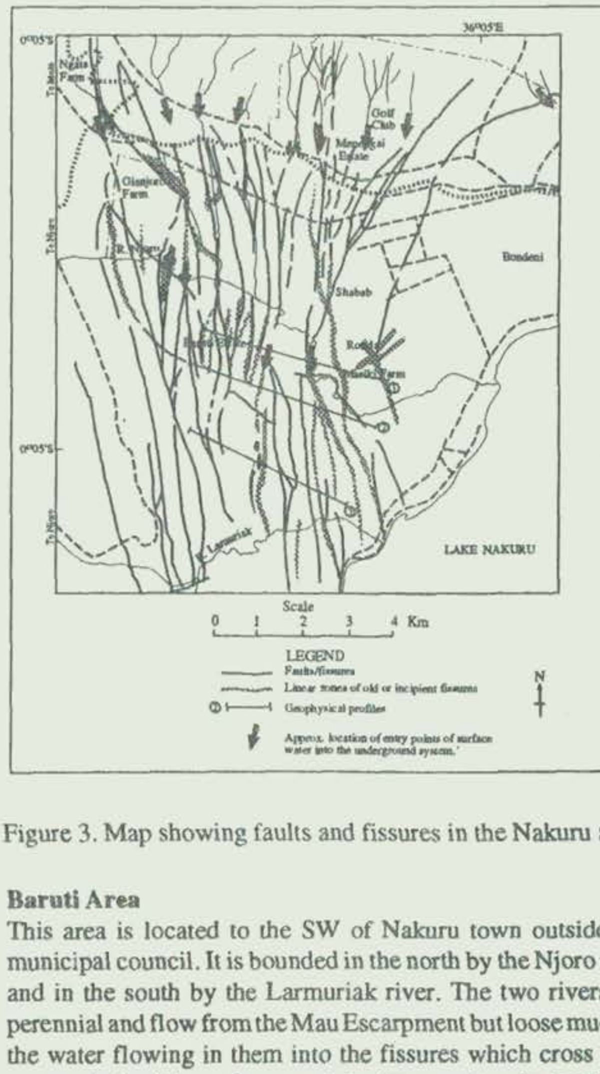


Figure 3. Map showing faults and fissures in the Nakuru area.

### Baruti Area

This area is located to the SW of Nakuru town outside the municipal council. It is bounded in the north by the Njoro river and in the south by the Larmuriak river. The two rivers are perennial and flow from the Mau Escarpment but loose much of the water flowing in them into the fissures which cross their courses to feed the underground drainage system. In the Baruti area, the weakest zones and zones of highest potential risk are around the junctions of one or more faults/fissures. Some of the fissures are open ie they are presently active and those inactive have ceased activity due to collapse thus they have become zones of subsidence awaiting renewed underground erosion. Fissures in this area open anytime, they give no warning but are usually possible during the heavy rainfall. There hence remains possibilities that other zones may exist which have not as yet been identified by geophysical and photo-geological methods. The present open fissures are expected to be widenned by erosion which will result into lose of productive top soil and land.

**Nakuru West**
In this area Nakuru-Eldoret and the Nakuru-Njoro roads have suffered from this phenomena in the past. Near the Njoro junction two wide gullies across which the main Eldoret road and the railway runs close to each other are possibly old collapse zones that are now overgrown by vegetation. They are presently inactive but this may not be permanent. The two lie above major fracture/fissures system which controls the courses of major streams passing under the large bends of the railway track. To date the railway line has so far been unaffected by subsidence.

**Nakuru Municipality**
Within the built up area of the Nakuru town, identification of fault/fissure zones is difficult by use of the normal geophysical techniques. From the well known areas of subsidence in the western part of the town, there is evidence to suggest that the fissure system extends across much of the central part of town following a north easterly trending set of fractures. These are linked to the faults which are most clearly seen to the east and northeast of the Menengai crater. Evidence for a system of fissures under the central part of Nakuru includes the existence of ground depressions within the town, the disappearance of surface water down into the fissure system as seen at the Provincial Police Headquarters, cracks and settlement building walls at the "Japanese" flats. Reports of vibrations being a result of the presence of underground cavities.

With all the above evidence, some areas with possible fissuring have been marked on the map. The exact location require confirmation, but the continuity of these suspected fissures with lines at drainage from Menengai slopes is considered to be strong supporting evidence for their existence. The greatest potential ground subsidence hazards exist within a broad zone between 300 to 500m wide on the western margin of town running south from the GK Prison on the slopes of Menengai through Timsales and the Total Petrol Station roundabout as far south and affecting shabab, Ronda and kaptembwa estates. In this zone surface drainage from the Menengai slopes above the GK Prison and the Golf course disappears to the underground systems.

To this end therefore an examination of the natural drainage of the town is required with particular emphasis on the interface between surface run off from the hill slopes and the underground drainage system.

**Contamination of Groundwater**

It is from work already done that its clear that the bulk of the groundwater flows in Nakuru area follows in linear fissure zones which link gently dipping perched water tables in an open system which extends under Lake Nakuru. This type of system is hence prone to widespread contamination. This therefore means that industrial and town effluents and sewage must be kept away from this groundwater systems if any of the boreholes are to be used for town water supplies. Farming operations should ensure that animal wastes and excess fertilizers do not similarly enter the same and tipping of rubbish into sink holes and depressions should be stopped.

## RECOMMENDATIONS

Problems associated with ground subsidence in the Nakuru area are natural and are there to stay. There will be very little that can be done to safeguard what has already been constructed in areas prone to this phenomena. Precautions should, however, be undertaken to avoid disaster just in case of a recurrence.

Several suggestions and opinions have been made although not exhaustive but can be used to alleviate and bring about awareness.

(i) Normal soil conservation methods should be undertaken in areas which have already suffered this phenomena by leaving natural vegetation bordering the fissure zone grow uninterfered with.

Cultivation in such areas to the edge of the fissures should be avoided so that development of mature and broad stable depressions are encouraged.

(ii) In this area the widening of fissures by erosion has already adversely affected communication. The sheer physical size and underground extent rules out trying to block these fissures by tipping in aggregate. However, small girder bridges wide enough to span the zones of subsidence may probably be more effective.

At the moment local people should avoid siting houses in such depressions if they do proper foundations and proper materials to withstand such dangers is suggested.

(iii) Nakuru is a fast growing urban centre, and problems associated with housing have become more apparent. There is in addition limited land on which to build so that if some of these areas have to be built on, it ishere recommended that no storeyed houses should be built in areas prone ground subsidence.

(iv) Considerable thought should be given to the siting of sewerage, waste and water pipes as well as culverts in order to prevent excess water going into the fissures.

In the long term an examination of the natural drainage of the town is required with particular attention on the interface between surface run off from the hill slopes and the underground drainage system. If some of this surface runoff can be re-directed without opening new fissures, the present zones of collapse may stabilize. On larger scale, channelling of water flow from the Menengai slopes above the town should be investigated further.

## CONCLUSIONS

Nakuru and the surrounding area is at risk from a number of naturally occuring geological hazards which are very difficult to predict and difficult to control. From work done in the area its been noted that subterranean drainage system is very efficient so that this situation aids very rapid drying after heavy rainfall. This characteristic also promotes rapid splushing of underground water through already fissured areas thereby promoting subterrenean erosion culminating in collapse in these fissure zones which risk lives and damage property. The fissure system is constantly enlarging with time pausing and probably may create more widespread problems.

In the study area, the main danger zone begin from the GK prison and runs south to the Ronda estate to include sections of Shabab and Kaptembwa. More serious zones of subsidence have been observed in the Baruti farm estate. There have been no reports of occurrences in the town centre, but vibrations of buildings on passing tracks still indicate the potential voids that may pose some dangers to be expected in the future. Cases of sink holes have been reported in the town centre ie at the Police Headquarters. Perhaps one of the greatest threat come from contamination of groundwater resources by eMuents from the rapidly growing urban population coupled with industrialisation.

From the foregoing, it is hence quite evident that the western part of the town which is prone to dense faulting/fracturing and eventually affected by subsidence is much less favourable to further development as compared to the eastern part of the town underlain by solid volcanic rock. There will definately be other controlling factors to steer development of an area but conclusions in this paper are drawn from purely geological considerations.

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# STRATIGRAPHY, DEPOSITIONAL HISTORY AND ENVIRONMENTS OF DEPOSITION OF CRETACEOUS THROUGH TERTIARY STRATA IN THE LAMU BASIN, SOUTH EAST KENYA AND IMPLICATIONSON HYDROCARBON EXPLORATION.

Kivuti Nyagah
National Oil Corporation of Kenya

## ABSTRACT

*The Lamu Basin, which is characterized by an extensional tectonic style, is the failed arm of a tri-radial rift system and possesses tectonic and stratigraphic elements in the post-rift series that are analogous to those of the West Coast of Africa. Development of the southern part of the basin as a passive margin, is closely related to considerations of the pre-drift position of Madagascar and formation of the Indian Ocean basin during Mesozoic times.*

*Cretaceous and Tertiary strata in the basin comprise an eastward thickening succession of sediments on which eustatic sea-level fluctuations and a sequence of unconformities related to pulses of transgressive and regressive depositional trends, are superimposed. Recognition of these trends has provided the basis for classification of the strata into Megasequences representing distinct provinces with regard to time stratigraphy, sedimentation, tectonics, depositional environments and hydrocarbon potential. Megasequence II includes strata of the Cretaceous and Early Paleocene, deposited in tide-influenced shelf and marine settings. These are, in ascending order: the Ewaso Sands, the Freretown Limestone, the Hagarso Limestone, the Walu Shale and the Kofia Sands. Megasequence III includes strata of the Eocene through Oligocene, which were deposited in fluvial, deltaic, and restricted-shelf settings. These are, in ascending order: the Pate Limestone, the Kipini Sands, the Linderina Limestone, the Dodori Limestone and the Barren Beds Formation. Meqasequence IV includes strata of the Miocene through Pliocene, which were deposited in restricted-shelf, middle to outer shelf and fluvial settings. These are, in ascending order: the Baratumu Limestone Formation, the Lamu Reefs and the Marafa Beds. Understanding the depositional history and environments of deposition of these rocks has been crucial for predicting areas with the potential for hydrocarbon accumulations.*

## INTRODUCTION

The Lamu Basin of southeast Kenya is located east of the 39th meridian and also includes the continental shelf and slope areas of the Indian Ocean (Fig. 1). It is the largest basinal area of Kenya, encompassing 132,770 sq km. The sedimentary prism in the onshore depocentre has a thickness ranging from 3250 m in the northern boundary to 10,000 m in the coastal area. These sediments consist of Permo-Carboniferous through Tertiary continental rift basin sandstones, fluvio-deltaic sandstones, marine shales and carbonates. The offshore depocentre has a sedimentary column which is 12,000 m to 13,000 m thick.

The Cretaceous and Tertiary sedimentation history of the Lamu Basin can be divided into three megasequences each bound by regional hiatal surfaces recording interruptions in basin depositional history. These megasequences are in turn divided into five regressive and four transgressive cycles.

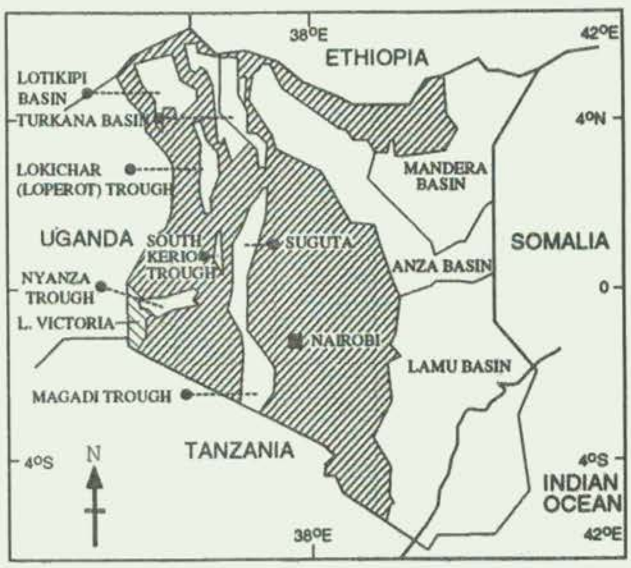


Figure 1. Map showing the locations of the basins in Kenya.

## METHODS OF INVESTIGATION

Studies of geological and geophysical well data from 14 wells drilled in the Lamu Basin (Fig. 2), augmented by descriptions of exposed strata in southeast Kenya provided the initial basis for reconstructing the depositional history of the Lamu Basin. The subsurface lithological characteristics of descriptive units were assessed from well cuttings available for most of the wells and cores available from 6 wells. Additional well and outcrop information from the other Kenyan basins, including neighbouring Somalia and the DSDP well 241 were integrated to determine the spatial distribution of descriptive strata. These units were correlated throughout the subsurface and cross-sections constructed to display their post-depositional structure. Descriptions of the distribution and composition of fossils from past geological work provided important information on the ages and environmental conditions of the enclosing stratigraphic units. Sedimentary facies were interpreted from log characteristics, descriptions of cores, and outcrops and the relative positions of facies.

## STRATIGRAPHY

### Cretaceous Stratigraphy

Mesozoic rocks of Early Cretaceous age in the Lamu Basin are represented in outcrop by the Freretown Limestone and the Walu Shale. The Ewaso Sands occur predominantly in the Neocomian interval of the Walmerer-1 well and comprise a deltaic succession of alternating fine to coarse grained orthoquartzites, siltstones, shales and subordinate calcareous sandstones, measuring 1450 m in thickness. The basinal equivalent of the unit are shales which have however not been penetrated by any of the wells drilled in the coastal and offshore areas.

Strata of Middle Cretaceous age are represented by the Freretown Limestone dated Aptian in age. The Freretown Limestone which occurs in outcrop over a limited area is in contact with bluish grey nodular shales containing ammonites, and are best exposed at the Bamburi quarry west of the Freretown Limestone outcrop area. These shales are known as the Walu Shales and are dated as Albian to Cenomanian (Walters and Linton, 1973). In the Walu-2 well, the succession of Aptian age related to deposition of the Ewaso Sands (Fig. 2), in an intertidal setting, comprises 110 m of very fine grained sandstones and siltstones with worm burrows and highly fractured zones. The same strata comprises 324 m of calcareous shales and siltstones in the Hagarso-1 well and 251 m of siltstones and sandstones in the Walmerer-1 well. The shales of Albian age occurring in the Walu-2 well comprise 1174 m of pale gray to dark green, glauconitic, pyritic and ammonitic shales, exhibiting slumping, nodular and conglomeritic structures. The shales are in lateral contact with the Hagarso Limestone which is interbedded with shale in the Hagarso-1 well where the thickness is 1134 m and in the Walmerer-1 well in which a total thickness of 627 m is attained (Fig. 2). A complete Cenomanian succession comprising dark gray shales with prolific marine planktonic fauna is present in the Walu-2 and Hagarso-1 wells where thicknesses are 450 m and 225 m respectively. Thus, the shales of Albian through Cenomanian age that occur in the subsurface are equivalent to those that occur in outcrop. In the Walmerer-1 well the sequence of strata of Middle Eocene through Oligocene rests unconformably on strata of Albian age.

The Turonian in the Hagarso-1 well comprises 250 m of slightly carbonaceous shales associated with thin sandstones. These sandstones constitute the Kofia Sands and continue into an eroded 300 m of Coniacian strata below the Cretaceous-Tertiary unconformity. The Upper Turonian and Coniacian are absent in the Walu-2 well due to erosion. Turonian strata has been recognized offshore in the DSDP 241 well. The interval comprises 300 m of interbedded, silty clays and claystones forming incomplete Bouma sequences of turbidite divisions. The Santonian-Campanian interval is continuous with this phase and is characterized by nearly complete Bouma sequences. The Campanian-Maastrichtian interval is characterized by shale deposition with minor sandstones and limestones in the Kipini-1, Simba-1 and Kofia-1 wells. The sandstones show an upward vertical increase in grain size in the Maastrichtian section of these wells and are a continuation of the Kofia Sands.

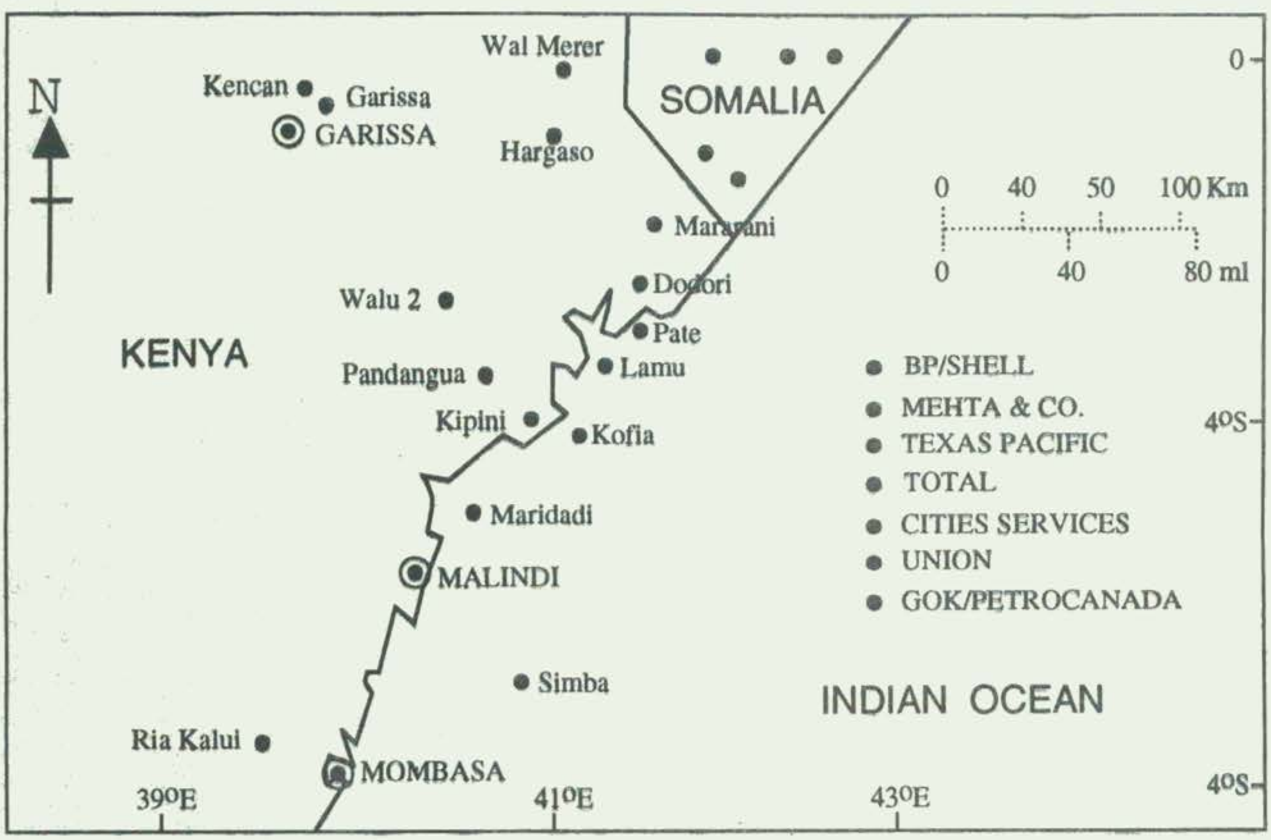


Figure 2. Map showing the location of wells drilled by the different Companies.

**Tertiary Stratigraphy**

The Tertiary sequence is widely distributed in the Lamu basin and rests unconformably on the Late Cretaceous erosion surface. Paleocene rocks in the south-eastern coastal and offshore region are known from the Dodori-1, Simba-1 and Kofia-1 wells. Elsewhere and further inland, Middle Eocene rocks rest unconformably on eroded strata of Late Cretaceous age. The Dodori-1 well contains the most complete succession of Paleocene strata, comprising light grey to yellowish grey micaceous sandstones, carbonaceous siltstones, shales and minor limestones. An algal limestone forming the uppermost member of the Hagarso Limestone is present in the Early Paleocene interval. The Paleocene succession in the offshore is generally identical in lithofacies and distribution to the underlying Upper Cretaceous and onshore Paleocene interval. The strata thin seaward from a maximum of 775 m in the Dodori-1 well to 463 m in Kofia-1 and 425 m in Simba-1. In the DSDP 241 well, the interval is represented by only 40 m of silty clays and claystones, carried below the carbonate compensation depth by dilute suspension turbidity currents.

The Lower Eocene succession seen in the Dodori-1 and Pate-1 wells comprises a transgressive limestone unit that onlaps on to the Paleocene terrigenous clastics. In the Dodori-1 well (Fig. 2), the succession comprises two distinct carbonate facies. A lower algal stromatolite overlain by alternating cycles of medium gray nummulitic limestones and greenish gray shales, that span the entire interval of the Lower Eocene. The shales are vested with features that indicate terrestrial and marine derivation and deposition between periods of carbonate build-up. Overlying the oolitic limestone is a dolomitized limestone with shale interbeds. The shales preserve a low salinity restricted marine fauna which includes ostracods and miliolids. Equivalent offshore strata is also highly fossiliferous and contains a more open-marine planktonic species. The sequence is however attenuated in the offshore area. The deposition of carbonate strata therefore continued into the Early Middle Eocene, a time of episodic tectonic movements and concomitant sea level fluctuations. The oolitic limestone represents the final imprint of this deposition and the sea level oscillations that began during the Early Eocene. This limestones constitutes the Pate Limestone (Fig. 2). Another relatively brief rise in sea level is recorded in the deposition of a richly fossiliferous limestone unit referable to the Linderina Limestone which contains the Middle Eocene species Linderina brugesi (Patrut, 1977). The progradation of delta-front clastic sediments of the Kipini Sands over the Linderina-bearing limestone reflects renewed emergence in the west and northwest sections of the depocentre, and basin subsidence. These clastics which were deposited during periods of carbonate build-up are in turn overlain by nummulitic limestones, olive-brown shales and mudstones that constitute the Dodori Limestone, which was formed during Late Eocene times. The entire Middle to Upper Eocene sequence thins significantly in an oceanward direction. The termination of Eocene deposition is placed above the last occurrence of non-reworked forms of Nummulites hormoensis and Nummulites fabiani. The boundary is an unconformity separating the sequence of limestones and clastics of Early Eocene to Early Late Oligocene age from the shelf carbonate facies of the Neogene Period. The Middle Eocene through La'e Oligocene strata observed in the wells further onshore constitute the Barren Beds Formation. These occur as distinct packages of cyclic fining-upward fluvial assemblages, typical of point-bar deposits, as seen in the Walu-2 well (Fig. 2). The series thins considerably in the southeast part of the basin where it expands into a broad fan. Strata of the Late Oligocene are eroded indicating another cycle of tectonic movements at the end of Late Oligocene.

Rocks of Early Miocene age and their lateral equivalents are exposed at various locations east of the coastal Mesozoic outcrops. Two distinct rock types are distinguished in most of the coastal wells. These are referred to as the Baratumu Limestone Formation and the Lamu Reefs. A typical exposure of the Baratumu Limestone Formation comprises a rhythmic shoaling sequence of carbonate strata interbedded with thin mudstones. This depositional realm persisted throughout Late Miocene time and was interrupted by a brief period of erosion during the Early Pliocene. Strata of the Late Pliocene sequence comprise a thin basal marine facies unit and an upper regressive unit comprising strata of the Marafa Bed. These occur in outcrop as poorly consolidated, calcite cemented quartz sandstones depicting mega-scale cross-bedding.

## DEPOSITIONAL HISTORY AND ENVIRONMENTS OF DEPOSITION

The general structure of the Lamu Basin is typical of passive margin development consisting of a seaward-thickening sedimentary wedge characterized by listric faulting and salt tectonics. A model depicting the general scheme of evolution and summarizing the salient tectono-sedimentary features is presented (Fig. 3). The phase relevant to the Cretaceous through Tertiary Period is the post-rift stage characterized by passive development. Preceding continental break-up, north-south, northeast to southwest and northwest to southwest lineaments developed on the basement platform creating the structural fabric upon which the earliest rifts were superimposed, and progradational sediments accumulated. After the movement of Madagascar along the Davies Fracture, in Early to Middle Jurassic time the paleo-Tethyan sea invaded the Trans-Erythrean trough depositing carbonates in the Ogaden, Mandera, Anza and Lamu Basins.

The orthoquartzitic sandstones that constitute the lower member of the Ewaso Sands represent the progradational deposits of a tidally influenced delta formed in a supratidal setting. This depositional phase was contemporaneous with uplift of strata belonging to the Meqasequence I group and the Precambrian Basement, in areas west and northwest of the depositional center. Equivalent and distant movements occurred as far north as Somalia, with rejuvenated movements of the Arabo-Somali massif (Kamen Kaye et al, 1979) and Bur Acaba uplift. In the Aptian, a gradual encroachment of the sea, south of the Walu-2 well culminated in a complex of intertidal and subtidal facies represented by the Freretown Limestone and upper member of the Ewaso Sands. A marine influence, related to a world-wide eustatic event, the fragmentation of the India-Madagascar-Antarctica block and movement of India along the Owen Fracture, in Albian to Cenomanian times, resulted in deposition of the Walu Shale and Hagarso Limestone. The fracturing of

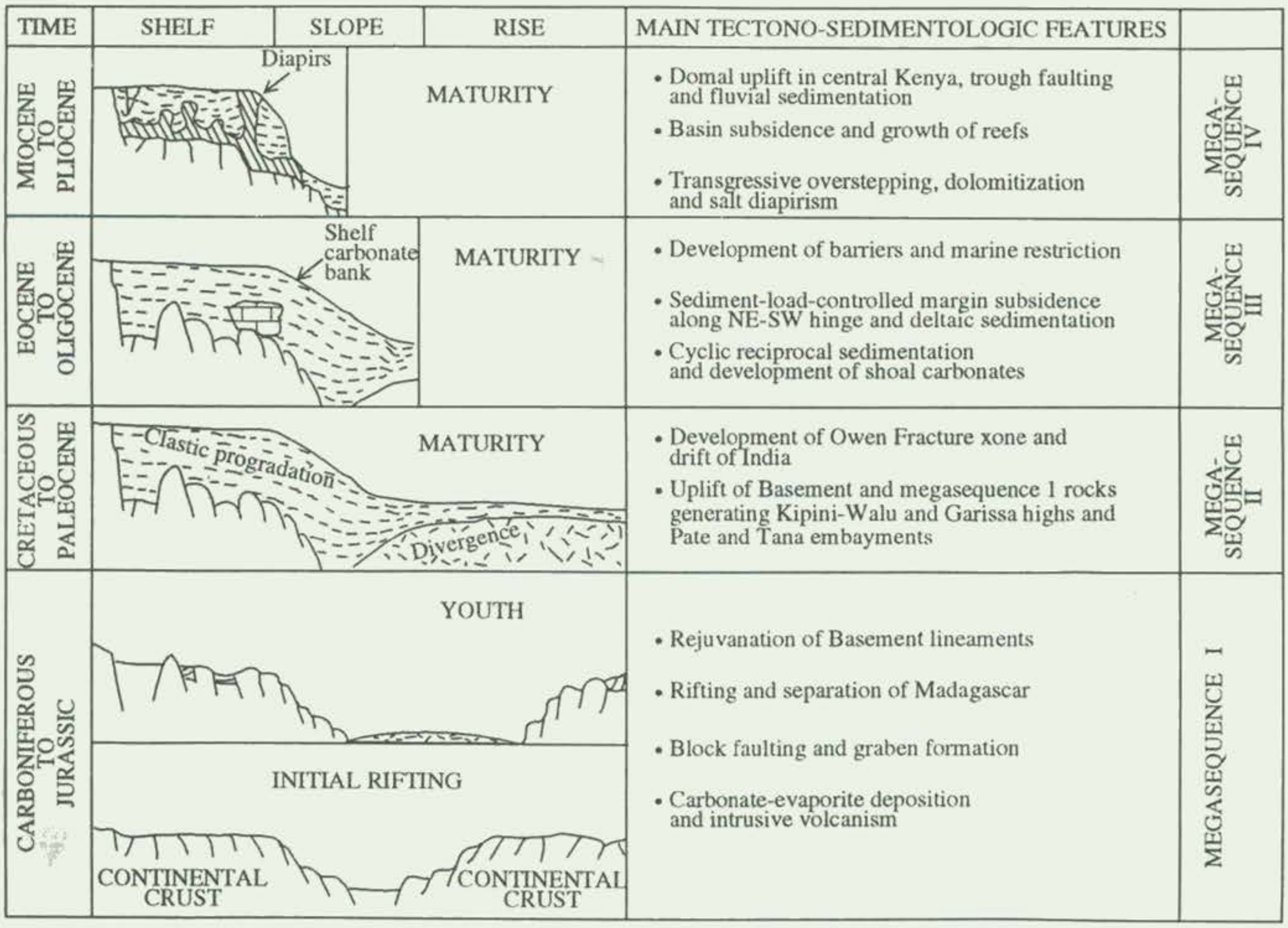


Figure 3. A Schematic diagram depicting Tectono-sedimentary features in the Lamu basin.

Aptian strata, associated hydrothermal activity and sediment slumping may be allied to this phase of tectonic instability.

Uplift of the basement to form a ridge extending from the offshore depocentre parallel to the Davies Fracture into the onshore area along the Walu-Kipini and Garissa axis induced erosion and deltaic deposition in Turonian through Early Paleocene time when the Kofia Sands were deposited. Further erosion of the Upper Cretaceous successions in Megasequence II was most severe along the trend of this uplifts resulting in the deposition of the Kipini Sands. The Tana and Pate areas evolved as separate synclinal depressions separated by the Kipini-Walu ridge and received substantial accumulations of the erosional detritus. Growth faults, clay and salt diapirs and listric faults, known from similar deltaic settings elsewhere, were probably generated during the development of this regressive deltaic-offlap sequence, due to the disequilibrium created by the rapid deposition of sand wedges on undercompacted shales (Dailly, 1976).

A destructional process following Cretaceous-Paleocene deltaic deposition or development of a northeast trending basement ridge may account for the restricted marine environment that prevailed at the onset of the Paleogene depositional phase. Wave action and longshore currents, produced by tides similar to those operative on the present day coast, may have re-distributed sediments from the delta front in a shore parallel fashion to create such conditions. This may have coincided with the time of oceanic divergence, when upwelling waters carried nutrients to shelf settings, thus supporting biogenic production of pelagic sediments. Hence the Pate Limestone largely developed as an upward shoaling carbonate sequence, interrupted by minor influxes of terrigenous material to form localized cycles of carbonate-clastic couplets. The stromatolite interval is a typical intertidal deposit, formed on a restricted inner shelf while the oolitic and ostracodal limestone horizons characterize restricted conditions within a shelf edge to middle shelf and back-reef lagoonal setting. Conversely, the Linderina Limestone and Dodori Limestones are outer-shelf facies of open marine circulation, that formed as well defined carbonate marker beds under fully marine conditions. The Barren Beds Formation constitute "red beds" deposited in a fluvial oxidizing environment and include distributary channel deposits that give rise to composite, multi-storey lateral-accretion deposits in the Walu-2 well, and large-scale cross-bed sets in the Garissa-1 well. Progradation of the Paleogene clastic sediments established a new configuration on the continental shelf and created substantial flexural loading and subsidence along a fixed landward north-easterly hinge. The sea level motions during Eocene time were simultaneous with the mantle-wide convection motions, affecting the Afar region and the early stages of formation of the Red Sea graben (Girdler and Styles, 1974). The attendant volumetric changes in the capacity of the Indian Ocean (Pitman, 1978) may have had significant impact until the Late Eocene. Movements in the western and north-eastern regions resulted in erosion of Upper Paleocene and Lower Eocene strata, the clastics of which were arrested in near-shelf settings to allow the deposition of carbonates on shelf areas, and hemipelagic or no deposition in the deeper subsiding and starved offshore basin. The Late Oligocene regression may be related to the extensive glaciation that took place in Antarctica (Shackleton and Kennet, 1975) and the corresponding drop in sea level.

The sedimentary facies and general environmental settings that prevailed during the Paleogene were repeated in the Neogene Period. The Baratumu Limestone Formation, constitutes an upward-shoaling inner-shelf facies deposited during periods of subsidence and sea-level fluctuations. The nature of the component facies, the rhythmic arrangement, and impoverished fauna reflect restricted and oscillatory environmental conditions in subtidal and intertidal depositional settings. These conditions were accompanied by reefal build-ups in middle to outer shelf areas, forming the Lamu Reefs. Increased river gradients associated with the Late Miocene and Pliocene phases of uplift and the rapid rates in sea level fall, coincided with the deposition of clastics in fluviatile conditions to form the Marafa Beds. The emergent structural elements had a genetic affiliation to the developing Rift Valley in central Kenya, which began to evolve at the end of Middle Miocene time, asserting a strong northward and south-eastward drainage pattern. This regressive depositional period and fall in sea level is commensurate in time frame with the increased capacity of the Indian Ocean basin, following the collision of India against Eurasia. The northward prolongation of the Carlsberg Rift system, connecting the Red Sea with the Indian Ocean, may be linked with the brief sea level-rise in the Late Miocene. The abrupt regressive episode which occurred in Late Pliocene coincided with the final and most pronounced deformation associated with the Rift Valley tectonic paroxysm. The salt deposited offshore may have undergone significant diapiric movement, following these last phases of shoreward clastic progradation.

## IMPLICATIONS FOR HYDROCARBON ACCUMULATION

Early exploratory drilling in the Lamu Basin focused primarily on marine Jurassic and Cretaceous rocks and large block-faulted structures on intrabasinal high and platform areas. Only in latter stages did the drilling activity move into the Tertiary depocentres where the most encouraging wet gas shows in the basin were encountered. Recent time-temperature index determinations for coastal wells indicates that the oil window is generally located at depths greater than 3000 m, due to the low geothermal gradient associated with the great sediment thickness in this part of the Lamu basin (Maende, et al., pers. commun, 1992). The occurrence of the oil window in most of these wells did not coincide with strata possessing well developed porosities. In the Pate-1 well, which barely reached gas saturated porous sands of the Kipini Sands at terminal depth, the oil window was seen to be deeper than previously determined. The porosity in these sands was the first to be encountered within the oil window.

The underlying assessment of the hydrocarbon potential of the basin hinges on the established time-stratigraphic framework, interpretations of the depositional conditions of the different facies, and regional paleogeographic reconstruction. Potential prospects are in deeper parts of the basin where the occurrence of good reservoir facies in association with suitable entrapment structures coincides with the zone of peak oil generation. A summary of the different prospective facies is presented in Table 1.

Table 1.Prospective facies in the Lamu Basin, south-east Kenya.

| MEGA-SEQUENCE | STRATIGRAPHIC UNIT | AGE | DEPOSITIONAL SETTING | TRAPPING CONFIGURATIONS |
|---|---|---|---|---|
| II | Ewaso Sands | Early Cretaceous | Deltaic | Distributary mouth bar and channel sands draped over basement horsts or rolled over into listric growth faults or antithetic fault blocks. |
| | Kofia Sands | Late Cretaceous to Early Paleocene | Deltaic | Distributary channel sands truncated by unconformity surface. |
| III | Kipini Formation | Early Paleocene to Late Oligocene | Deltaic | Updip pinchouts of distributary channel sands on Basement ridges. Multiple traps associated with salt piercement structures. Updip pinchouts of turbidite sands |
| | Barren Beds Formation | Middle Eocene to Late Oligocene | Fluvial | Fluvial channel, point bar and crevasse splay sands onlapping unconformity surface or pinching out on Basement ridge. Fault related traps |
| | Pate Limestone | Early Eocene | Inner to outer Shelf | Back-reef oolitic and shoal facies on underlying Basement horsts or pinching out Basement ridge |
| | Linderina Limestone | Middle Eocene | | |
| | Dodori Limestone | Late Eocene | | Reefal build-ups |
| | Baratumu Limestone Formation | Early to Late Moicene | Inner Shelf | Multiple traps associated with salt piercement structures |
| | Lamu Reefs | | Middle to outer Shelf | |

### Prospects for Strata of Megasequence II

Structural-stratigraphic traps, associated with the Early Cretaceous Ewaso Sands and the Late Cretaceous to Early Paleocene deltaic Kofia Sands should be present within this sequence. These include distributary mouth bar and channel sands draped over deep buried basement horsts or rolled over into down-to-the basin listric growth faults or antithetic fault blocks, distributary channel sands truncated by the Cretaceous-Tertiary unconformity surface and distributary channel sands pinching out on the Walu-Kipini High. The immediate offshore area may also have several trapping possibilities that include up-dip pinchouts of turbidite sands and multiple traps associated with salt piercement structures. These facies should be sealed and fed by pro-delta shales.

### Prospects for Strata of Magasequence III

The Eocene to Oligocene deltaic clastics and shelf carbonate facies underlying the present coastal area constitute good prospects. The play comprises the transgressive-regressive cycle wedges corresponding to an intertonguing relationship between deltaic deposits of the Kipini Sands and the Pate, Linderina and Dodori Limestones. The sequence has prospects that are geologically similar to those of the Kofia sands combining structural and stratigraphic entrapment configurations. Thick porous sands of the Kipini Sands which are present just above the oil window in the Kipini-1 well should occur within the oil window on the flanks of the Walu-Kipini High. Other possibilities include fluvial channel, point bar and crevasse splay sands of the Barren Beds Formation onlapping the Late Oligocene unconformity or pinching out on the Garissa High, back-reef oolitic and shoal carbonate facies of the Pate, Linderina and Dodori Limestones underlying basement horsts or pinching out on the Walu-Kipini basement ridge. Shelf edge patch reefs commonly associated with these shelf facies could also be targets in the shallow offshore area of the Pate embayment. The pattern of alternating periods of subsidence and sedimentation should have brought about source and reservoir facies into spatial and temporal coincidence.

**Prospects for Strata of Magasequence IV**

Reservoir facies comprising bioclastic and reefal limestones associated with the deposition of the Baratumu Limestone Formation and the Lamu Reefs provides prospects in the immediate offshore area. The facies change laterally from the offshore starved basin argillaceous deposits to reefal build-ups on the shelf-edge and updip into cycles of alternating bioclastic limestones, calcarenites and calcilutites of the subtidal and intertidal setting. Bioclastic debris transported by gravitational processes downslope to bathyal settings and associated with traps generated from salt diapirsm should provide additional prospects. The Tertiary episodes of subsidence, cyclic-reciprocal-sedimentation, halokinesis and faulting are important from the standpoint of hydrocarbon formation and migration. The starved ocean basin conditions following basin subsidence would have been critical in limiting compaction and thermal conductivity and hence development of favourable and shallow thermal regimes.

## CONCLUSIONS

The geological evolution of Cretaceous through Tertiary succession in the Lamu basin can be divided into three major depositional phases, encapsulating a total of five regressive and four transgressive cycles and punctuated by three main unconformities. Megasequence II includes strata of the Cretaceous and Early Paleocene, deposited in tide-influenced shelf and marine environments and bound by the Cretaceous-Tertiary unconformity. Megasequence III includes strata of the Eocene through Oligocene comprising shoal carbonate facies that built-up on restricted shelf settings and clastic sediments that fed through fluvial depositional systems into deltaic environments. Megasequence IV includes strata of the Miocene through Pliocene, onlapping the Late Oligocene unconformity surface. The megasequence comprises facies of the inner shelf to shelf-edge environmental setting bound by an end-Miocene unconformity, and overlain by a fluvial facies. The areas corresponding to depocentres of sand-rich deltaic deposition and favourable thermal regimes, namely the Pate and Tana embayments, may be the key to future exploration success in the Lamu basin of southeast Kenya.

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# BOREHOLE SITE INVESTIGATIONS IN FRACTURED HARD ROCK AQUIFERS IN GACHOKA DIVISION, EMBU DISTRICT, KENYA

J.Anyumba°, P.Van Dongen* and J.Nzomo°

Department of Geology, University of Nairobi P.o Box 30197, Nairobi.
* Groundwater Survey (K) Ltd, P.o Box 25025, Nairobi.

**ABSTRACT.**

*The paper describes a systematic approach that has been applied sucessfully in the selection of suitable sites for borehole drilling in a quest to provide adequate water supply to a rural population in Gachoka Division. The study area lies in Embu District in Kenya and measures about 1.500 km². Geologically this area is underlain by the Precambrian Basement system mainly consisting of quartzo–feldsparthic gneiss, granulites, amphibolites and meta–dolerites.Locally the Basement is overlain by Tertiary lavas, comprising phonolites, agglomerates and tuffs.*

*A systematic approach for the exploration of groundwater was followed to enable selection of optimum drill sites and also to minimize the incidence of dry wells and the total drilled meterage in the area. This approach consisted of the following multi–steps:–*

- *i. Rigorous hydrogeological reconnaissance of the whole area, mapping different groundwater potential areas on the basis of aerial photo interpretation, available data and geological data acquired in the field were used in compiling the geological map.*
- *ii. Detailed structural mapping based on aerial photo interpretation for selection of suitable lineaments;*
- *iii.Geophysical field surveys involving Electrical magnetic (EM), Very Low frequency (VLF), and Vertical Electric Sounding (VES);*
- *iv.Interpretation of the data acquired in the field and laboratory studies leading to selection of drill sites, indications on potential yield and depth of acquifers.*

*Hydrogeological interpretations based on preliminary EM and VLF regional exploration followed by VES for localized exploration, correlated very well with well–logs. Subsequent drilling has confirmed that the approach was a success, with more than 78% of the drilled boreholes being productive.*

## INTRODUCTION

Water is one of the most vital natural resources on earth since without it there would hardly be any life. An available and reliable water supply is a pre–requisite to socio–economic development of a community. This calls therefore for a systematic harnessing and management of the resource so as to meet increasing water demand for either agricultural and/or industrial development, especially in the developing world today. Whereas water availability and quality are some of the major factors that determine spatial distribution of ecosystem on earth, it is noted that, in Kenya, over 80% of the territory is covered by arid and/ or semi arid lands, leaving less than 20% as potential agricultural land (Tippetts et al, 1980).

Population in the country was estimated at 24 million in 1989 with a growth rate at 3.4%. It is expected that by the year 2000 the population would be about 32–35 million. This implies that the majority of the Kenyan population will need to find settlement areas in the marginal lands, which include arid and semi arid lands, despite migration and rapid urbanization of Kenyan towns (4.5% in Mombasa and Nairobi, 4% in Kisumu,Thika Nakuru and Eldoret), Tippetts et al (1980). However, in rural areas of Kenya where arid and semi arid types of climates prevail, piped water is very scarce and the main source of supply is from either limited surface water resources, roof catchments and/or few groundwater supplies. Thus, retarded socio–economic development is commonly experienced. Therefore, for the future development of the country, the Kenyan government is uniting efforts with non governmental organizations to ensure that reliable and sufficient water reaches rural areas, in particular the arid and/or semi arid areas.

In this context, Foster Parent Plan International (a non governmental organisation) commissioned both Groundwater Survey Kenya Ltd to undertake a regional assessment of the quality and quantity of water resources and well drilling in the Gachoka division.

This paper describes the hydrogeological assessment of an area covering 1500km², comprising the elevated volcanic regions around Embu and Karaba, and the gently undulating areas of the Precambrian Basement system. The most prominent geomorphological features in the area are the Kanjiro and Kiambere hills of meta- dolorites (Precambrian intrusives) cropping out at Twoinoni, Rongoi and Nduni. The less elevated parts are mostly covered by black cotton or red sandy soils.

Rainfall is closely related to elevation, with 1100– 1200 mm/yr in the higher western areas, decreasing to 650mm/yr in the lower eastearn part (Braun 1977, Fairburn 1963). Consequently, vegetation in the area is very much related to the rainfall, morphology and geology of the area. In this respect it is observed that the whole area is fairly vegetated, varying from sub-tropical humid woodlands and bushes in the west to dry scrubland in the east.

Drainage systems in the study area are highly dependent on structural controls, but poorly developed in areas of subdued relief. Geological boundaries generally coincide with the river valleys. Hydrographically there are perennial rivers such as the Tana, Thiba and Rupingazi, while the remaining streams are ephemeral.

Across the study area, it is observed that run-off accounts for a significant proportion of effective precipitation, but the majority of precipitation is lost through evapotranspiration. Deep inflitration to aquifers is highly dependent upon developed fractured systems and a reasonable porosity on the soil cover

## CATCHMENT BASINS

The area is divided into five sub–basins on the basis of drainage systems. All tributary basins are subordinate to the Tana river system which borders the southern and the eastern part of the area.Tributaries generally flow to the east with a fairly dense drainage pattern of dendritic type (Fig.1). Streams are generally ephemeral and structurally controlled with faults being the major controlling factors in the area.About 80% of the area is underlain by the Basement.The catchment area can be summarized as in the table below.

| Name/Location* | area ($km^2$) | Description |
|---|---|---|
| Thiba/Rupingazi | 592 | The most extensive catchement; perennial; drives flow from Mt. Kenya; passes through volcanics. |
| Thura | 151 | The system is subordinate to River Thura (rises from Mt. Kenya to NE); a small catchment. |
| Ena | 4 | Tributary system subordinate to River Ena, to the NE, arising from Mt. Kenya; a small catchment. |
| M1 and M2 | 633 | Poorly developed streams (ephemeral ditches) draining into River Tana; has severe recharge limitations due to clayey soil cover SW of the study area; M2 has the better recharge conditions. |

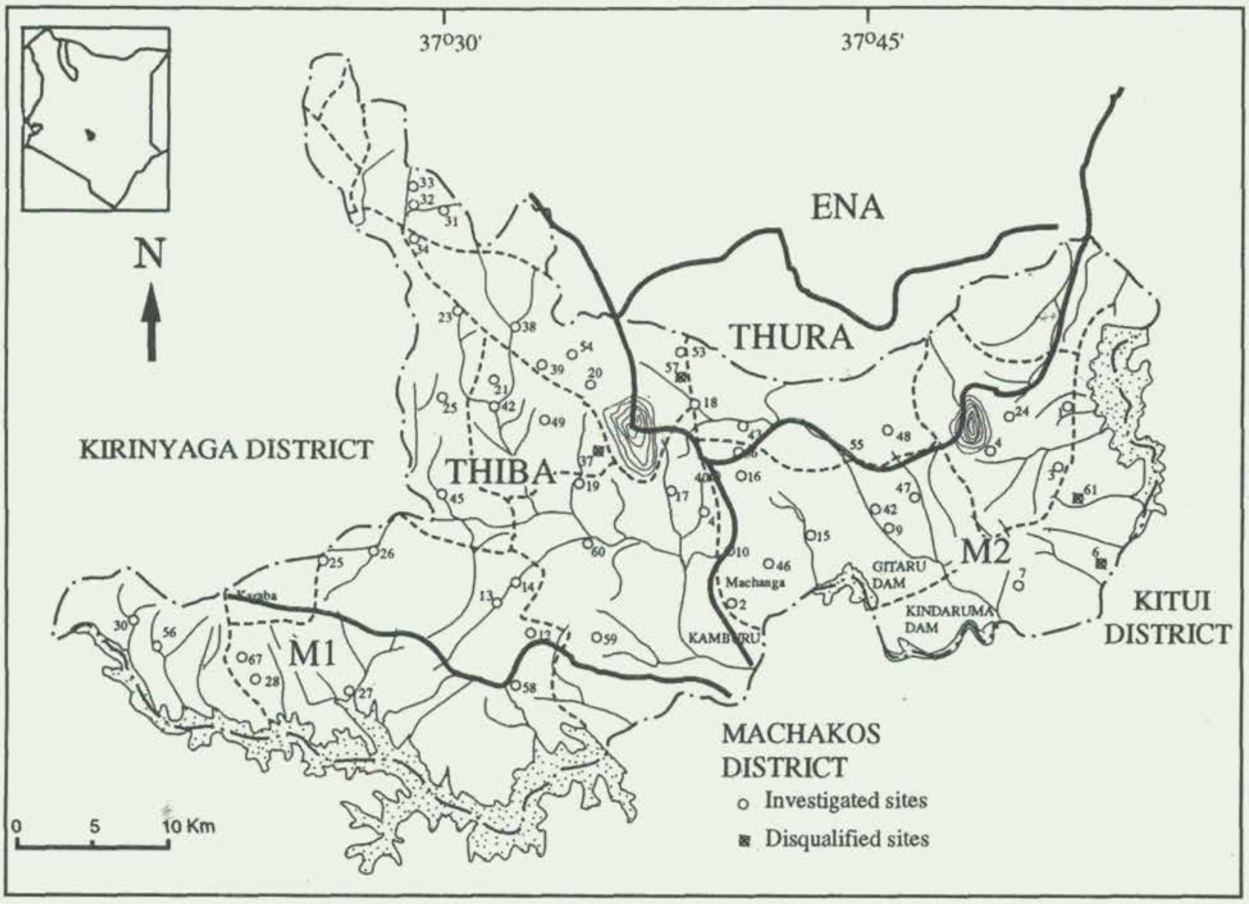


Figure 1. Map of Gachoga Division showing the hydrological catchment boundaries.

## GEOLOGY

The rock units in the study area fall into four groups: Precambrian rocks of the Basement system, the Embu series, the Tertiary volcanics and the superficial deposits of Pleistocene and Recent age.

**The Mozambique belt.**
The area is underlain by the Precambrian Mozambique belt rocks, which are locally overlain by Tertiary and Quaternary volcanic products. The Precambrian rocks consist mainly of a variety of gneisses, granulites, amphibolites and meta-dolorites. The occurrence and distribution of these rocks is largely related to tectonics of the area. During the Precambrian period, a regional folding and metamorphism of sediment occurred, resulting in recrystallization and further granitization. It is observed that extensive amounts of faulting may have occurred which fractured some rocks. At the sametime, intrusions of meta-dolorites invaded the area along fracture strikes Fairburn 1966, Bear 1952).

**Embu Series.**
The Embu Series are considered to be younger than the Precambrian System of rocks. They include the non-granitized rocks, mainly calcareous, pelitic and psephitic types. They occur south of Siakago, an area which is considered to have suffered varying degree of contact metamorphism and where the rocks are fine grained granoblastic types (hornfels). It is also noted that in some of these rocks, there exists some horizon beds which contain alternating thin micaceous and quartzo-feldaphic layers.

**The Tertiary Volcanic rocks.**
The period between Archaen and Tertiary was one of uplift and erosion and is devoid of any signs of sedimentation or vulcanicity.During the Tertiary period, the first eruptions occurred from Mount Kenya and included phonolites, basalts, agglomerates, and tuffs.Faulting, although burried under lava flows, is slight and characterised by NW-SE directions.

**Quaternary deposits.**
These are superficial deposits which comprise of red soils and black cotton soils on undifferentiated basement, and olivine basalt.The bulk of the cotton soils are confined to the south - western section of the study area, where soils have developed irrespective of the nature of the underlying rock, on the interfluves and effectively cover the underlying rock.Small patches are also observed in localized marshy areas.Loosely consolidated conglomerates, gravels and sands are exposed in many stream channels.Their distribution is dependent on the drainage distribution but, at some locations,scattered patches are observed, including localities on the River Tana South-east of Kindaruma and alluvial fans of the southern tributaries of Thau (Bear 1952).

Using remote sensing methods,it was noted that the faults, foliations, lineations,and unconformities between the Basement and the volcanic series exist in the area. An analysis yielded a total of 370 lineaments of lengths varying between 2 - 15 Km. A rose- diagram analysis indicated one clear maximum oriented NE-SW and three sub-maxima directions which include N-S (N170°-180°), NW-SE (N 110°-130°). The faults and fractures display nearly straight outcrops on the map of the study area and they dip predominantly to the west. Major and distinctive features are found in Gachoka, Kiritiri and Kiambere locations, but tectonic features in the southwestern part are obscured by superficial soil cover.The structure has significant control over the drainage pattern in the area.

## GROUNDWATER DISTRIBUTION AND ZONES OF OCCURRENCE

Evaluation of groundwater potential is based on climatic data analysis and the geology and geo-tectonicity of the area.It is observed that groundwater occur in terrains of the following characteristics:

i) Weathered and/or fractured zones in the volcanic rock formations,

ii) Weathered and/or fractured zones in the Basement rock formation,

iii) Levees of main drainage channels,

iv) Contact zones (old land surfaces).

Using the mentioned characteristics in the area, eight groundwater potential zones have been recognized (Fig. 2), ie I, IIa, IIb, IIc, IId, IIIa, IIIb, and IV.

**ZONE I and IIa - High groundwater potential.**
The zone lies on the irregularly banded migmatitic gneisses of the Basement System and the volcanic formations at higher elevation.Fracture interconnectivity is extensively developed.With relatively high annual precipitation , recharge conditions are excellent and this reflects the type of climate, nature and characteristics of the drainage system observed. In addition to contact zones that have a series of springs of relatively good yields and quality,high yields with a mean of 2.2 $m^3/h$ is abstracted from boreholes sited on fault and fractured areas.

**ZONES IIc,IId, IIIa and IIIb. - Medium groundwater potential.**
These zones occur on granitoid and magmatic gneiss rock formations. Although the area is highly fractured with a fairly well developed drainage system, recharge is moderate and evaporation is relatively high, increasing from west to east. There are springs and waterholes emerging from the contact between the volcanic and Basement formations. Average yields abstracted from boreholes sited are within $0.9 m^3/h$.

**ZONES IIb and IV - Low groundwater potential.**
These zones are distibuted within the Basement System, the gneisses of the semi- calcareous formation, which are overlain by black cotton soils. Due to low rainfall, high evapotranspiration, poor fracture interconnectivity and limited percolation through clayey soils, these zones have the lowest groundwater potential. Mean yields from sited boreholes are estimated to be $0.3 m^3/h$.

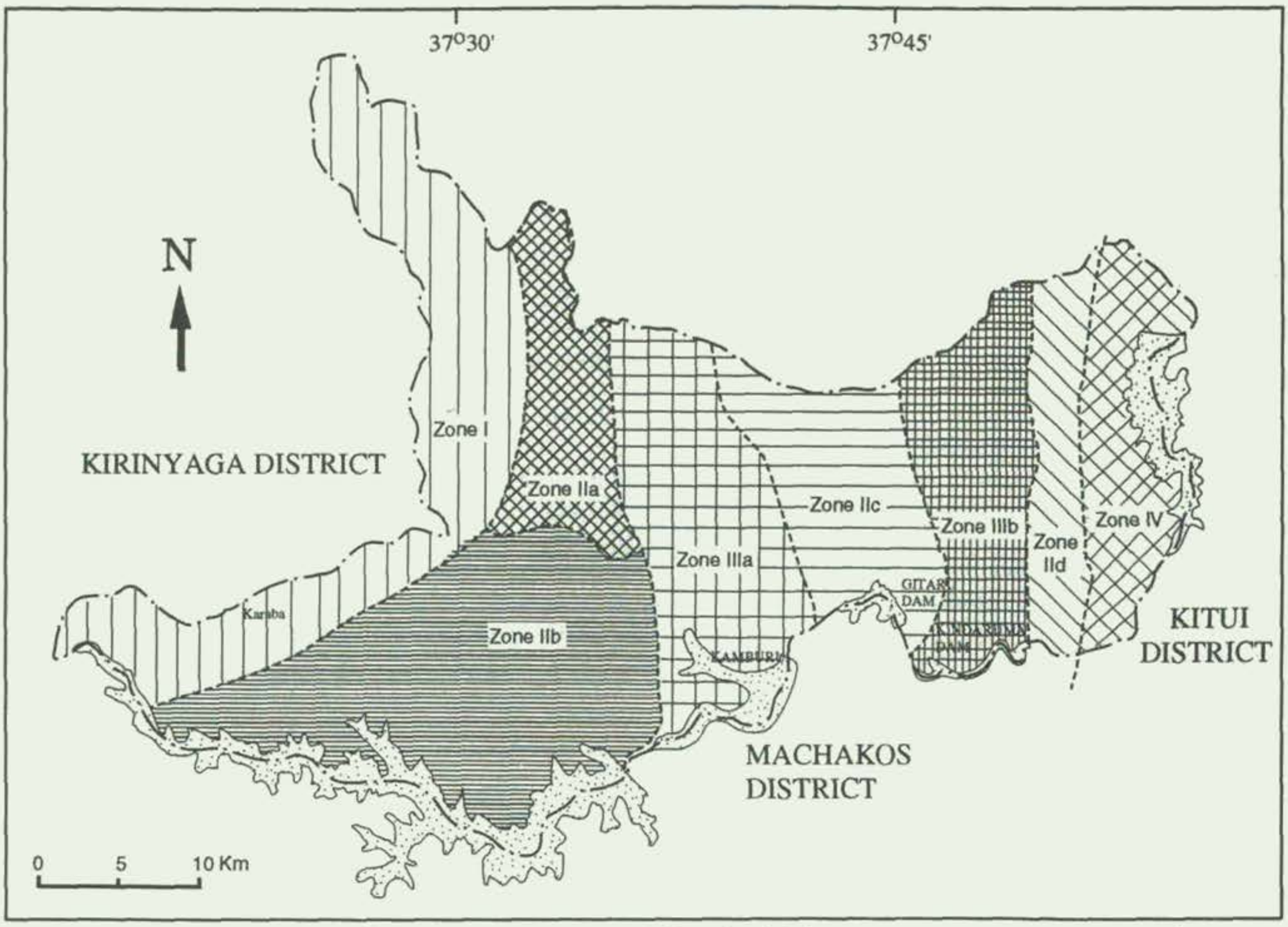


Figure 2. Water availability map of Gachoka division.

## SITE INVESTIGATION

The main objective of a successful borehole site investigation is to determine the optimum drilling site and reasonable depth of drilling which would yield sufficient water of good quality. For the purpose of this project the minimum requirement were: yields not less than 0.5 $m^3/h$ and electrical conductivity not exceeding 1500 uS/cm. On the basis of the geology of the study area, investigations were carried out in order to identify appropriate sites on faulted, weathered and/or fractured zones in both the Basement and volcanic rocks formation and in alluvial deposits. The groundwater exploration programme consisted of a logical systematic multi– approach steps as follows:

1. Rigorous hydrogeological reconnaissance of the whole area, mapping different groundwater potential areas on the basis of aerial photo interpretation, study of the available data and geological data were used for general study and compilation of geological map.

2. Detailed structural mapping based on aerial photo interpretation for selection of suitable lineaments. By considering morphology, lineaments and drainage systems, catchment areas were defined and hydrographic basins determined.

3. Geophysical field surveys involving Electrical Magnetic (EM), Very low Frequency (VLF), Vertical Electric soundings (VES) and Electrical resistivity profiling. EM and VLF were executed in the reconnaissance stage, principally to evaluate the pattern and form of the underlying geology. The data was evaluated qualitatively to identify structural anomalies (fault zones, dykes, fractures, burried channels, lithological contacts) and thicknesses of the weathered zones. This was followed by electrical profiling and VES investigations. The VES method was used mainly to identify the thickness of the weathered formation above the fresh rock and indirectly identify potential water bearing zones. EM profiling was performed using a "Geonics EM 34–3", whilst VLF was carried out with an "ABEM WADI (VLF)" instrument. For VES and electrical profiling, and "ABEM SAS 3000B Terrameter" (with Schlumberger array) was used. During electrical resistivity profiling, a fixed electrode separation of 20m was maintained (logitudinal traverse). The interpretation depicted a background subsurface resistivity with anomalies in certain localities. The defined anomaly location was thereafter targetted for detailed investigations.

4. Interpretation of the data acquired in the field and desk studies leading to selection of drill sites, indication of potential yields and depth of aquifers.

Consequently, a total of 60 sites were investigated, of which 55 were geophysically surveyed. The other 5 were logistically and geologically disqualified. Of the 55 sites geologically surveyed, only 50 were recommended for drilling. The number of documented measurements amounted to:

–22 EM profiles (approximately to a total of 5 km).
–76 vertical electrical soundings.
–localized VLF soundings.

## RESULTS AND INTERPRETATIONS

Geophysical site investigations of Gachoka Division have been documented with VES graphs, resistivity data, EM and VLF profiles and hydrogeological cross–sections showing interpretations for all 60 sites investigated.

VES profiles. These have been interpreted using 3–4 model layers; with the first layer having about 1 metre thickness with a very variable resistivity in the order of 20 – 1000 ohm.m. This depends on the type of soil (sandy, gravel, clayey) and moisture content at the time of investigation of the specific site. The other layers have typical resistivity (Fig. 3).

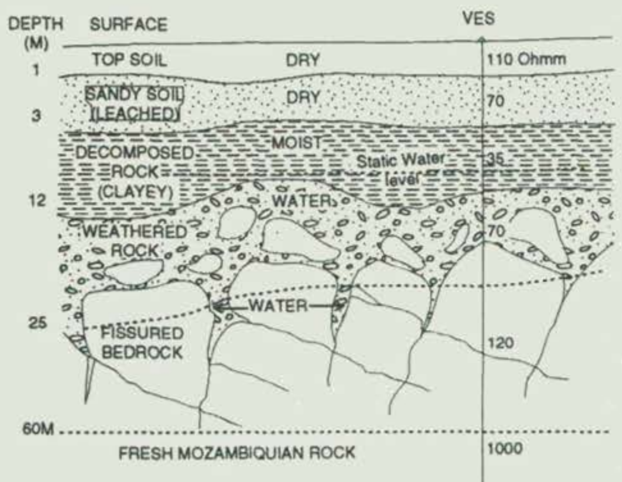


Figure 3. Typical example of VES interpretation on crystalline Basement rock in the Gachoka Division.

It is observed that in most cases there is a thin layer of top soil which overlies a sandy zone that consists of weathering debris. Below this zone lies completely decomposed rock, containing a large amount of clay minerals, depending on the composition of the parent rock. Despite the decomposition one can observe remnants of primary structures. The zone underlying the decomposed zone is the weathered bedrock zone. In this zone, primary structures are still maintained. This zone overlies relatively fresh fissured bedrock.

Below the zones described above, lies the fresh crystalline Basement rock which has remained unaltered since its formation. It is observed that the upper part of the profile are usually dry, although they may yield some little and unreliable water from perched aquifers. The decomposed zone and the weathered zone are typically moist, but yield very little water. These zones are not reliable due to low permeability. The fissured zones contains fresh cracks with moderate to high permeability. However, for high yielding wells, it is necessary to locate a major fault zone with intense fracturing at a greater depth. EM profiles. VLF and EM, together with VES methods, have been applied in Gachoka Division (Embu District) for location of hydrogeologically favourable drill sites with remarkable success. In general, VLF and EM were of limited use in detailed investigations, being more helpful in regional surveys. EM was, however applied where necessary. The EM profiles of the surveys executed in the area may be categorized into two groups as follows:

**Distinct sharp reduction in conductivity profile**

Profiles that belong to this category show low amounts of noise with respect to maximum anomaly response. This is a good indicator of faults or deep fractured zone. (The jagged appearance in some instances is due to superimposed anomalies). This is exemplified by anomaly 48–1 at site 48, location Mboche.(Fig. 4).

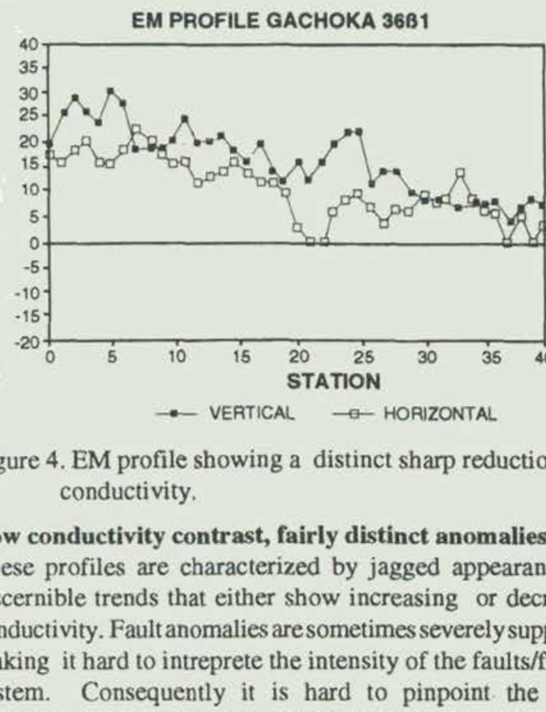


Figure 4. EM profile showing a distinct sharp reduction in conductivity.

**Low conductivity contrast, fairly distinct anomalies**

These profiles are characterized by jagged appearance and discernible trends that either show increasing or decreasing conductivity. Fault anomalies are sometimes severely suppressed making it hard to intreprete the intensity of the faults/fracture system. Consequently it is hard to pinpoint the causal inhomogeneity. The case is exemplified by profile 36–1 (Fig. 5).

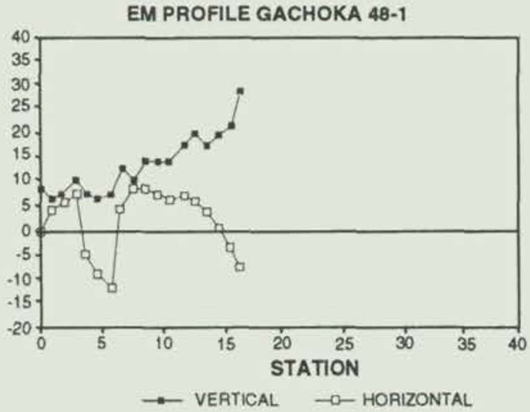


Figure 5. EM profile showing low conductivity contrast, but fairly distinct anomalies

## CONCLUSIONS

A geological and hydrogeological assessment of Gachoka Division, Embu, has been carried out using geophysical investigations. The area can be subdivided into 8 potential groundwater zones (ie varying degree of high, moderate and low potential for groundwater yield). Remote sensing techniques aided the identification of lineaments and any other lateral anomalies on the surface. With detailed geophysical exploration techniques, locations of lateral variations were defined, thickness of the formations were evaluated and possible occurrence of groundwater was determined. Comparing the above methods with the drilling results from boreholes, it is observed that a 78% success rate was achieved using this multi-step approach for groundwater site investigation in fractured hard rock formation.

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# PROPOSAL FOR THE FORMATION OF A WORKING GROUP TO REVISE THE STRATIGRAPHIC NOMENCLATURE APPLIED TO THE ARCHAEAN TERRANE Of WESTERN KENYA

D.W. Ichang'i
Department of Geology, University of Nairobi,P.O.Box 30197, Nairobi.

## ABSTRACT

*There is a growing consensus that the stratigraphic nomenclature that has been applied to the Archaean terrane of the Tanzanian Craton for the last half century should now be critically reviewed and revised. The same point can be made about existing stratigraphic divisions in the Proterozoic and Phanerozoic strata of East Africa. Judging by the experience of the last fifty years, stratigraphic nomenclature, though often surrounded by controversy, has controlled our perception of the Archaean geological environment in this region. The chronostratigraphic terms "System" and "Series" have been erroneously applied to describe and discuss the lithostratigraphy of the granite-gneiss and granite-greenstone regions of the Tanzanian Craton. The terms "Dodoman System", "Nyanzian System", "Kavirondian System", and " Samia Series" have therefore been used invariably in such discussions. This is not in keeping with current practice as recommended, for example, by the International Stratigraphic Guide of the International Subcommission on Stratigraphic Classification (ISSC), and the North American Stratigraphic Code of the North American Commission on Stratigraphic Nomenclature (NACSN) amongst others. Lithostratigraphic classification and nomenclature should now as a first step be adopted in remapping the Archaean terrane of western Kenya because stratigraphic boundaries should be defined by actual observations "in the rock". Under this approach, closely related lithologies are placed within members, formations, subgroups, groups and supergroups which are given local geographic names to specifically characterize local geology It is the opinion of this writer that all the Archaean volcano-sedimentary rocks in western Kenya and perhaps in adjacent parts of northern Tanzania and southeastern Uganda should be placed within a single Nyanzian Supergroup with lower rank stratigraphic divisions being subject to local geology. Other opinions on the aspects raised above no doubt exist and coordination in the application and development of the stratigraphic nomenclature in western Kenya and in the rest of the Tanzanian Craton is now required. It has therefore become necessary to form a multidisciplinary working group to revise the stratigraphic nomenclature in western Kenya with the principal aim of developing a geologically sound, useful and versatile framework in the light of recent advances in geological sciences.*

## INTRODUCTION

The stratigraphy, and paleovolcanic facies development of the greenstone belts of the Archean Tanzanian Craton (Fig. 1) are only poorly understood as a result of which their mineral potential has not been fully appreciated. The strati~raphic nomenclature applied during the last half century and mostly now in use broadly divides the greenstones in the craton into Nyanzian and the younger Kavirondian Systems (Stockley, 1943). This conflicts with modern usage and application of stratigraphic classification and nomenclature. There is, therefore, a growing consensus that with the resurgence of research and remapping within the craton, the strati~raphic classification and nomenclature should now be critically and systematically reviewed and revised to remove inconsistencies (Gabert, 1990; Ichang'i and MacLean, 1991). The purpose of this paper is to review the stratigraphic nomenclature as it has been applied within the Tanzanian Craton in general and in the portion of the craton occurring in western Kenya in particular. Secondly, the lithostratigraphic framework proposed by Ichang'i (1990, 1992) and Ichang'i and MacLean (1991) for the stratigraphic division of the Archaean terrane of western Kenya is briefly presented with a proposal that a multidisciplinary working group on stratigraphy in Kenya be now formed for the purpose of coordinating the application and development of stratigraphic classification and nomenclature in the Archean terrane of western Kenya.

## THE TANZANIAN CRATON

The ~ 950 by 450 km Tanzanian Craton extends from northern Tanzania to southeastern Uganda and is surrounded by Proterozoic mobile belts of various ages (Fig. 1). These are the Usangaran, Ubendian and Ruwenzori Belts (2100-1770 Ma), Kibaran or Karagwe-Ankolean Belt (1370-1310 Ma), and the Mozambique Belt (1000-450 Ma; all ages compiled from Cahen et al., 1984). During early mapping the craton emerged as consisting of contrasting northern and southern regions (Clifford, 1970). From the earliest works the regions were recognized as belonging to an ancient part of the Precambrian crust, with Scott-Elliot and Gregory (1895), for example, referring to an Archaean Series in the northern region. The early workers used a variety of divisions to map and correlate the rock successions in both regions. These evolved into the "Systems and Series" classification adapted for the craton by Stockley (1943) and later workers (Table l; Ichang'i 1990). The northern region was mapped as different but distinct segments. The Samia Hills and Kakamega regions, for example, were recognized very early to consist of distinctive sedimentary sequences underlain by volcanic rocks (Scott-Elliot and Gregory, 1895; Gregory, 1896., Odman, 1929; Pulfrey, 1936a,b). Stockley (1943) proposed the terms Nyanzian System and Kavirondian System for the greenstone volcano-sedimentary sequences of Tanzania,. Nyanzian System of Stockley (1943) replaced what was then known as the Upper Division of the Basement Complex (Table 1). The highly metamorphosed rocks of the Mozambique Belt (Proterozoic age) were mistakenly classified as the Lower Division of the Basement Complex but this was corrected later

(Holmes, 1951; Sanders, 1965). The predominantly sedimentary lithologies overlying the Nyanzian System were placed by Stockley (1943) into the Kavirondian System Rocks in the northern region assigned to the Nyanzian System are mafic to felsic volcanics, with subordinate sedimentary rocks including small banded iron formations. Dominantly sedimentary sequences of greywackes, argillites and conglomerate that unconformably overlie the Nyanzian rocks were grouped into the Kavirondian System.

The southern region of the craton in central Tanzania is a granite-gneiss terrane with narrow enclaves of amphibolite facies greenstones. It was named the Dodoman System by Quennell et al. (1956) following Stockley s (1943) nomenclatures. The Dodoman System rocks are similar to those of the Nyanzian but are more highly metamorphosed and deformed (Harpum, 1954; Quennell et al. 1956, Cahen and Snelling, 1966; Hepworth, 1972; Wendt et al., 1972). A number of isotopic age determinations were made on granites and Nyanzian greenstones from the 1950s onward. A variety of methods were used and the dates range from about 2.4 to 2.7 Ga. The dates show that the rocks belong to the late Archaean (Cahen and Snelling, 1966; Dodson et al., 1975; Bell and Dodson, 1981; Yanagi and Suwa, 1981; Cahen et al., 1984).

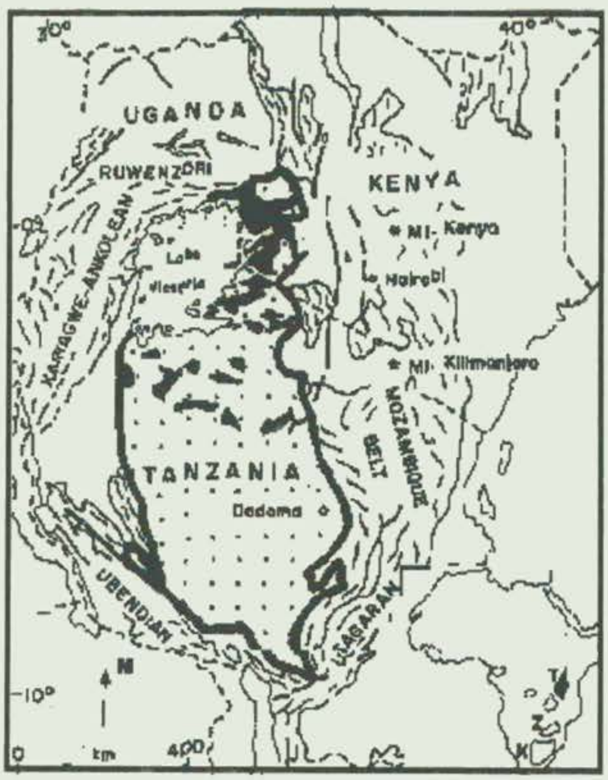



Fig. 1. The Tanzanian Craton, its greenstone belts (in black), and surrounding mobile belts (Ichang'i and MacLean, 1991). Cratons are shown in the inset after Clifford (197O) with T, Z, K, representing the Tanzanian, Zimbabwe and Kaapvaal Cratons respectively.

## THE NYANZA GREENSTONE BELT IN WESTERN KENYA

The Nyanza greenstone belt in western Kenya (Ichang'i, 1990; Ichang'i and MacLean, 1991) is divided into northern and southern geographic terranes by the Kavirondo (Winam) Rift (Shackleton, 1951) (Fig. 2).

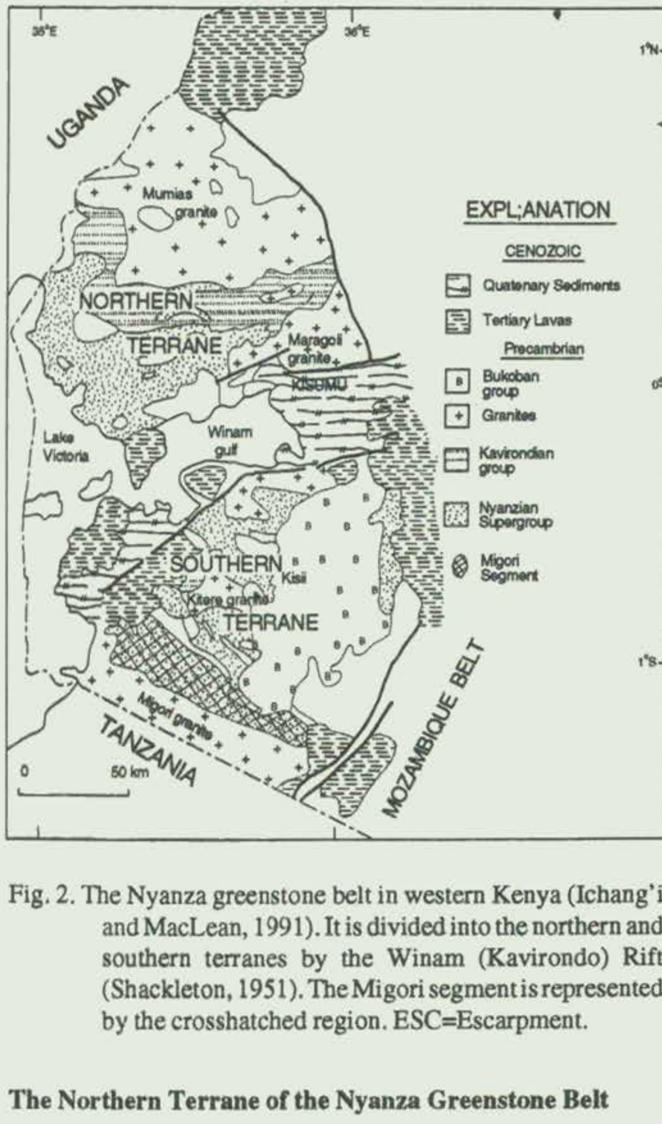



Fig. 2. The Nyanza greenstone belt in western Kenya (Ichang'i and MacLean, 1991). It is divided into the northern and southern terranes by the Winam (Kavirondo) Rift (Shackleton, 1951). The Migori segment is represented by the crosshatched region. ESC=Escarpment.

### The Northern Terrane of the Nyanza Greenstone Belt

Odman (1929) recognized the Archean age of what he called the Kavirondo Supracrustal Series (or simply his Kavirondo Series) consisting of lavas, sediments and granites (Table 1). He recorded the general lack of regional metamorphism and the uniformity of strike and concluded that the series was isoclinally folded. Odman (1929) put the mafic lavas as the oldest rocks in his Kavirondo Series, and the felsic lavas and pyroclastics, which he called "the quartz-porphyritic or dacitic groups", as the younger. He also noted lateral changes within the volcanic units, and concluded that the abundant tuffs and agglomerates in the series indicated a waning of volcanism. The upper half of Odman's (1929) Kavirondo Series comprised a very thick sequence of alternating arenaceous and argillaceous sediments, which he thought might be related to the Samia Hills Series at the Kenya-Uganda border by facies changes.

Table 1. Development of the stratigraphic nomenclature for Archean volcano-sedimentary rocks in the northern part of the Tanzanian Craton.

| Odman (1929) | | Pulfrey (1936a) | | Hitchen (1936,1937), Pulfrey (1938) | | Stockley (1943) | |
|---|---|---|---|---|---|---|---|
| ARCHAEAN | Granites | PRECAMBRIAN | Granites | PRECAMBRIAN | Granites | PRE-KARROO | Granites |
| | Upper Half of Kavirondian Series Sedimentary rocks | | Kavirondian Series Sedimentary rocks | | Kavirondian Series Sedimentary rocks | | Kavirondian System Sedimentary rock |
| | — | | — | | Granites | | Granites |
| | (Others) Samia Hills Facies and Kavirondo Series Volcanic rocks | | Samia Hills Series and Volcanic rocks | | Pre-Kavirondo Volcanic Series | | Nyanzian system: Volcanic rocks and banded iron formations |
| | Gneisses and Schists [Stratigraphic position not defined] | | Basement Complex | ARCHAEAN | Basement Complex | | Basement System |

Note ------- represents unconformities

Large sections of the northern terrane were later mapped by Hitchen (1936, 1937), Pulfrey (1936a,b, 1938, 1945, 1946), Saggerson (1952) and Huddleston (1954). This work outlined in considerable detail the volcanic, sedimentary and intrusive rocks, and made a basis for comparison and interpretation of stratigraphy in adjoining areas. Pulfrey (1938), for instance, argued for the presence of a number of volcanic centres in the terrane based on successions of agglomerates and mafic to felsic lavas and compared them to a modern volcanic island "archipelago".

During the early part of this mapping Odman's (1929) Kavirondo Series was subdivided into a Pre-Kavirondo Volcanic Series, and a Kavirondo Series which comprised the overlying sediments (Table 1). Stockley s (1943) Nyanzian System and Kavirondian System were adopted by Pulfrey (1945) for his Pre-Kavirondo Volcanic Series and Kavirondo Series, respectively. This nomenclature was used by later workers in this part of the craton, and persists to the present. The detailed mapping showed that the Kavirondian sedimentary rocks underlie a large section of this terrane. The general structural synthesis was that the Nyanzian volcanics were more strongly deformed than the Kavirondian sediments. This was interpreted as two periods of coaxial deformation, one post-Nyanzian and the other post-Kavirondian.

The intensity of mapping during this period was due to the mineral potential of the area, mainly gold and silver deposits. The general area of the Northern Terrane was known as the Kakamega Goldfield. Massive sulphides also occur in Kavirondian sedimentary rocks near Kakamega (Ichang'i 1983). Huddleston (1954) reported diamonds in alluvial gold workings, and a number of kimberlite pipes have been discovered in the terrane (Ito et al., 1981a,b; Barongo, 1983).

### The Southern Terrane of the Nyanza Greenstone belt

The Southern Terrane of the Nyanza Greenstone belt lies between the Winam Rift and the Migori Granite (Figs. 2, 3). The Proterozoic Kisii volcanics overlie the greenstones in the eastern third of the terrane. The Migori segment forms the southern part of this terrane, and comprises the Migori Group and adjoining granitic rocks (Fig 3). The segment includes what Shackleton (1946) called the Migori Gold Belt, which became the South Nyanza Goldfield with the larger mines at Macalder, Masara, Kehancha and Lolgorien in the Migori Gold Belt (Fig. 3), and others at Kitere and Kibigori to the north of the Migori segment.

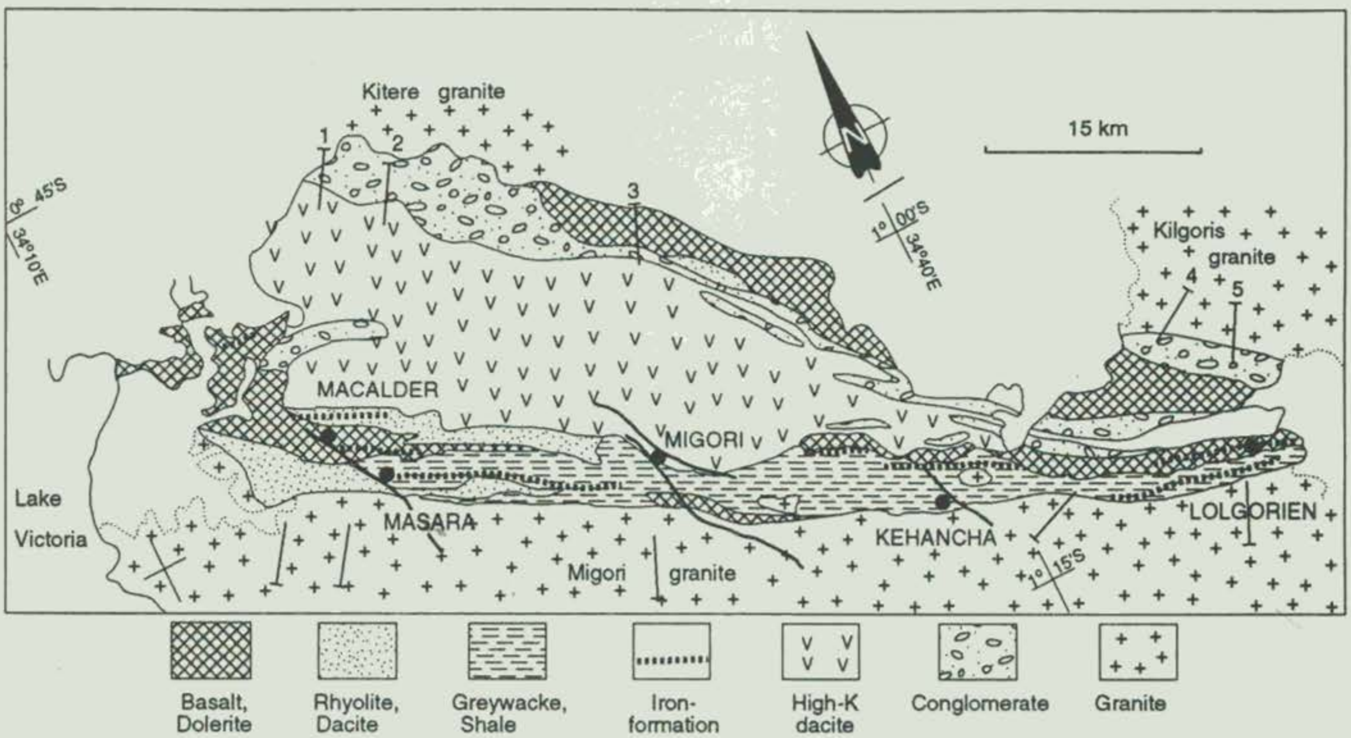
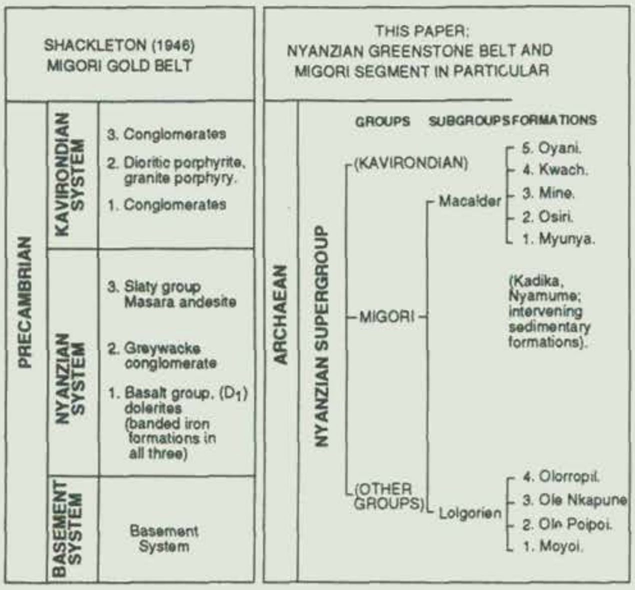



Fig. 3. Geology of the Migori segment. The main mining centres at Macalder, Masara. Kehanca, and Lolgorien are located within the Migori Gold Belt (Shackleton, 1946) south of the high-K dacites of the Oyani Formation.

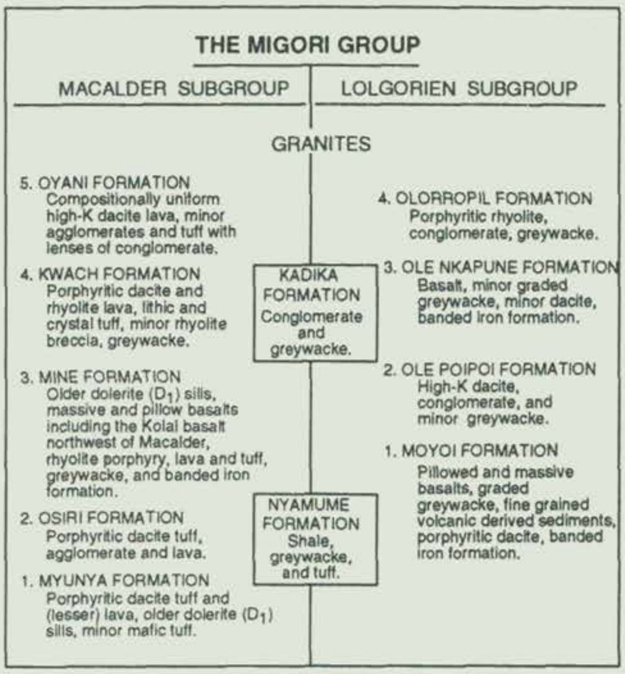
Table 2. Lithostratigraphic division and nomenclature for the Archean rocks of the Migori segment. The divisions of Shackleton (1946) for the Migori Gold Belt are also shown.




The earliest published geological work in the Southern Terrane was by Osward (1914) who made a traverse from Karungu to Kisii and recognized the area to consist of ancient rocks including volcanics and granitic gneisses. He recognized tuffs in what is referred to by Shackleton (1946) as "dioritic porphyrite" and by Ichang'i (1990), and Ichang'i and MacLean (1991) as the Oyani Formation (Tables 2, 3). Murray-Hughes (1933) published the first geological report in the terrane on the Lolgorien region showing an area "Favourable for prospecting". According to Huddleston (1951) geologists working for Kenya Consolidated Goldfields Ltd. from 1934-1937 used the rock classification "Greenstone Series" for mafic to felsic lavas, tuffs and agglomerates, which were overlain by the Kavirondo Series comprising dolerite, granites, diorite porphyrite and associated conglomerates. These were, in turn, overlain by the Proterozoic(Bukoban) Kisii Series consisting of flat to gently dipping basalts, quartzites and andesites. During the late 1930's and 1940's a large part of the Southern Terrane was mapped as districts by Shackleton (1946), Schoeman (1949), Huddleston (1951), McCall (1958) and Binge (1962). They all used Stockley s (1943) stratigraphic nomenclature.

Shackleton (1946) made the first comprehensive set of geological maps for the southwestern portion of the segment and coined the term "Migori Gold Belt". He divided the oldest lithologies into the basic volcanic, greywacke, and slaty and andesitic groups (Table 2), and recognized older ($D_1$) and younger ($D_2$) suites of dolerites. He placed all these rocks in the Nyanzian System, and unconformably overlying conglomeratic rocks and the large mass of "dioritic porphyrite" north of the Migori River in the Kavirondian System. McCall (1958) who mapped the Gwasi area to the north also interpreted the porphyrite to be intrusive, but placed it in the Nyanzian System. Shackleton (1946) and earlier investigators (Tables 1, 2) divided the granitic rocks into pre-Kavirondian and post-Kavirondian suites. The Migori Granite, the largest in the region is foliated along the contact with the greenstones (Shackleton. 1946).

Table 3. Formations, Subgroups and Group of the Migori segment and their lithologic characteristics. The Nyamume and Kadika Formations form the lower portion of the intervening region between Macalder and Lolgorien (Ichang'i and MacLean, 1991).




Shackleton (1946) distinguished two periods of deformation, a post-Nyanzian phase and a post-Kavirondian phase, which he combined into a Kavirondian orogenesis. His reasons for placing them into the same orogenesis were that both phases occurred in the same region and produced structures with similar orientations. A major phase of post-Nyanzian shearing and deformation was produced along the full length of the contact of the greenstone with Migori granite which he interpreted as a syntectonic intrusion. The sheared and foliated zone was up to ~1.5 km wide with the greenstones consistently dipping towards the granite. The greenstones have been thermally metamorphosed to lower amphibolite hornfels. He concluded that the Nyanzian rocks formed a major anticlinal structure.

The post-Kavirondian phase of the orogenesis was typified by broad folds and strike faults. Shackleton (1946) placed the "dioritic porphyrite" and associated polymict conglomerates in a synclinal structure lying unconformably on the Nyanzian volcanics. He observed shearing but no true cleavage in the Kavirondian rocks, and found the strikes of the folds, faults and cleavage to be parallel to the post-Nyanzian structures. He considered a suite of granites emplaced at the end or declining state of the post-Kavirondian phase of the orogenesis to be essentially post-tectonic (Shackleton, 1946).

Schoeman (1949) mapped the Sotik District on the eastern side of this terrane, and Binge (1962) mapped the Kericho District north of Sotik but most of it is covered by Tertiary rift volcanics. As with other workers in western Kenya, they referred to the Mozambique Mobile Belt rocks as the Basement System.

Huddleston (1951) mapped the Kisii District which is just north of the Migori Gold Belt, mapped prior to this by Shackleton (1946). The lithologies contained pillow basalts, banded iron formations, intermediate-felsic volcanics, argillaceous feldspathic sandstones, and a thick series of "andesites" which Shackleton (1946) had called "dioritic porphyrite" (Table 2). There were apparently differences of opinion among the field geologists concerning whether these "andesites" were shallow intrusives or eruptive. Huddleston (1951) concluded that they were eruptive and equated them with the Kuria Volcanic Series of Stockley (1943) across the border in Tanzania. He placed all these volcanic dominated greenstone rocks into the Nyanzian System, and the overlying sedimentary rocks into the Kavirondian System.

Sanders (1964) remapped part of the Gold Belt around the Macalder mine, including underground mapping. He showed that the Macalder orebodies were in a northeast dipping volcano-sedimentary sequence which was tightly to isoclinally folded. Minor folds in the banded iron formation associated with the ore had a consistent easterly plunge. The major fractures observed underground were reverse and wrench faults, the former being the most common and concentrated in the axial planes of some of the folds. Sanders (1964) concluded that the main structure at the Macalder mine was a "thrust anticline" dipping steeply to the northeast. Structures in the rest of the southern terrane are of a similar nature (Huddleston, 1951; Schoeman, 1949; Binge, 1962).

As with the northern terrane, the most important economic mineral deposits in the southern terrane have been those worked for gold. The most important area in this respect was within the Migori segment. Almost all the prospecting and mining activity in the segment was carried out in the Migori Gold Belt (Shackleton, 1946; Kenyon, 1954; McCall, 1958; Sanders, 1964; Onuonga, 1983; Ogola, 1987; Kuehn et al., 1990), adjacent to and to the north of the Migori Granite. The mineral deposits were gold bearing quartz veins and iron formations, and a massive sulphide deposit.

## REVIEW AND REVISION OF THE STRATIGRAPHIC NOMENCLATURE

Judging by the experience of the last fifty years, the stratigraphic nomenclature proposed by Stockley (1943) and adopted by later workers, though often surrounded by controversy, has controlled our perception of the Archaean geologic environment in this region. The usage of the chronostratigraphic terms "System" and "Series" to discuss and describe the lithostratigraphy of the granite-greenstone and granite-gneiss regions of the Tanzanian Craton is in conflict with modern practice as recommended, for example, by the guide to stratigraphic terminology and nomenclature by van Eysinga (1970), the International Stratigraphic Guide of the International Subcommission on Stratigraphic Classification (ISSC) (1976) the north American Stratigraphic Code of the North American Commission on Stratigraphic Nomenclature (NACSN) (1983), and the rules and recommendations for naming Geological Units in Norway by the Norwegian Committee on Stratigraphy (NCS) (1989). Inspite of this, the terms "Dodoman System", "Nyanzian System", "Kavirondian System", and "Samia Hills Series" or simply "Samia Series" continue to appear in discussions characterizing the geology of the Tanzanian Craton and specifically western Kenya. The chronostratigraphic terms as applied in this region imply wide ranging to global time stratigraphic correlations that may not be in agreement with the rock record. There is now need to review and revise the stratigraphic nomenclature to remove the inconsistencies. In the current research and remapping exercises in western Kenya, application of lithostratigraphic classification and nomenclature are best suited in the division of the stratigraphy as definition of the stratigraphic boundaries will be done by actual observation in the rock strata. Under this approach, closely related lithologies are classified in ascending order of rank into members, formations, subgroups, groups and supergroups which are given local geographic names to characterize the geology of specific regions.

Using this approach. Ichang'i (1990), Ichang'i and MacLean (1991) and Ichang'i (1992) tentatively divided the stratigraphy of the Migori segment of the Nyanza greenstone belt (Fig. 3) into eleven formations, two subgroups and one group (Tables 2, 3). At the Macalder end the succession was divided into the Myunya, Osiri, Mine, Kwach and Oyani Formations of the Macalder Subgroup while at the Lolgorien end the succession was divided into the Moyoi, Ole Poipoi, Ole Nkapune and Olorropil Formations of the Lolgorien Subgroup. Rocks in the intervening distal region between Macalder and Lolgorien were placed into the Kadika and Nyamume Formations. Following the approach of Easton and Johns (1986) and Roobol and Hackett (1987), the two subgroups on the basis of volcanic facies mapping delineated volcanic centres with central, proximal and distal volcanic facies as recognized by Williams and McBirney (1979, p.310-313). The two subgroups were placed into the Migori Group. It has been proposed by Ichang'i (1990), Ichang'i and MacLean (1991) that this group together with others to be defined elsewhere in the Nyanza greenstone belt be placed within the proposed Nyanzian Supergroup. It is therefore the opinion of this writer that all the Archaean volcano-sedimentary rocks of western Kenya and perhaps in adjacent parts of northern Tanzania and southeastern Uganda should be placed within the Nyanzian Supergroup. A recent practice is to call the Nyanzian System and Kavirondian System the Nyanzian Group and Kavirondian Groups respectively (e.g. Onuonga, 1983; Barongo 1989). There is more than one group as defined by van Eysinga (1970), ISSC (1976), NACSN (1983) and the NCS (1989) of volcanic dominated greenstone rocks in the Nyanza greenstone belt and the same is probably true for the sedimentary successions in the belt. The substitutions of the names does not reflect this and is therefore simplistic.

The lithostratigraphic division of the volcano-sedimentary succession in western Kenya should be done in such a manner as to be geologically sound, versatile, useful for correlative purposes and amenable to revision from time to time. It is known, for example, that several types of lithostratigraphic associations with distinctive metallogenic associations occur within the various Archaean cratons around the globe (e.g Anhaeusser et al. 1969; Anhaeusser, 1976; MacGeehan and MacLean, 1980; Condie, 1981; Franklin and Thorpe, 1982; Lesher et al. 1986., Thurston and Chivers, 1990). Characterization of the lithostratigraphy in the western Kenya region therefore has potential economic benefits as it could characterize lithostratigraphic associations and lead to the identification of the possible metallogenic associations and suitable ore horizons.

It should also be noted that although Archaean successions irrespective of age have many similar characteristics, the distinctive differences noted above have led to various approaches in the subdivision of the earliest time period in the history of the earth. Lumbers and Card (1991) have reported on the approved Proterozoic and recommended Archaean time scales given by the International Union of Geological Sciences (IUGS) Subcommission on Precambrian Stratigraphy. This subcommission has recommended the chronometric subdivision of the Archaean Eon into four divisions of Era status with boundaries at 3.6, 3.2, 2.8 and 2.5 Ga (Table 4). The four divisions are the Eoarchaean, Palaeoarchaean, Mesoarchaean and Neoarchaean. According to the subcommission, the boundaries were selected to delimit major cycles of sedimentation, volcanism and orogeny.

Table 4. Approved Proterozoic and recommended Archean chronometric subdivisions (Lumbers and Card, 1991).

| EON | ERA | PERIOD |
|---|---|---|
| | (Base of Cambrian) | |
| PROTEROZOIC | NEOPROTEROZOIC | Neoproterozoic III |
| | | 650Ma |
| | | CRYOGENIAN |
| | | 850Ma |
| | | TONIAN |
| | 1000Ma | |
| | MESOPROTEROZOIC | STENIAN |
| | | 1200Ma |
| | | ECTASIAN |
| | | 1400Ma |
| | | CALYMMIAN |
| | 1600Ma | |
| | PALEOPROTEROZOIC | STATHERIAN |
| | | 1800Ma |
| | | OROSIRIAN |
| | | 2050Ma |
| | | RHYACIAN |
| | | 2300Ma |
| | | SIDERIAN |
| | 2500Ma | |
| ARCHAEAN | NEOARCHAEAN | No further subdivision into periods |
| | 2800Ma | |
| | MESOARCHAEAN | |
| | 3200Ma | |
| | PALEOARCHAEAN | |
| | 3600Ma | |
| | EOARCHAEAN | |

Nisbet (1982; 1987, p. 9-11; 1991) on the other hand has convincingly argued that under the rules of stratigraphic nomenclature, a stratigraphic boundary should be defined "in the rock" (ISSC, 1976, p. 82). He therefore has well grounded objections about dividing the stratigraphic column by selecting arbitrary age numbers dependent on, for example, the accuracy of our isotopic clocks which are in turn dependent on how accurately the isotopic decay constants are measured and therefore the technology involved. Nisbet (1991) argued that care should be taken to distinguish the history of the earth, which is classifiable, from time which is the calibrating devise and is therefore not classifiable. Nisbet (1991) recognizes four eons of Earth history (Table 5) distinguished on the basis of the history of life, which he observes is the truly distinctive feature of the planet. These are the Hadean. Archaean, Proterozoic and Phanerozoic. Nisbet (1991) places the boundary between the Hadean and Archean at the origin of life.

Table 5. Schematic representation of the four eons recognized by Nisbet, (1991).

| EON | | Boundaries |
|---|---|---|
| PHANEROZOIC | ↑ Multicellular animal and plant life ↓ | |
| | | Boundary "in the rock" when life became manifest |
| PROTEROZOIC | | |
| | | Boundary transitional and best placed "in the rock", e.g the cooling age of the Great dyke of Zimbabwe |
| ARCHAEAN | | |
| | | Boundary best placed at the origin of life i.e. at the moment of first self replication on Earth |
| HADEAN | Probiotic ↓ To beginning of Earth's history ↓ | |

The boundary between the Archaean and Proterozoic is transitional in nature and Nisbet (1991) argues it is best placed "in the rock", for example, at the cooling age of the Great Dyke of Zimbabwe. Lastly, the boundary between the Proterozoic and Phanerozoic is also best set "in the rock" at the point when life became manifest on the planet. The lithostratigraphic division of the Archaean successions in western Kenya by various workers should be carried out taking these and other points of view into consideration, following standard practice and the rules stratigraphic classification and nomenclature. This approach has been increasingly followed in greenstone belts within other Archaean cratons, especially in Southern Africa (Anhaeusser, 1973; Wilson et al., 1978; Nisbet, 1987, p. 89), the Canadian Shield (Jensen, 1985; Blackburn et al., 1985; Padgham, 1985), and Western Australia (Hallberg and Glikson, 1981; Hickman, 1984) and has facilitated intercratonic and intracratonic correlation.

## PROPOSAL FOR THE FORMATION OF WORKING GROUP ON STRATIGRAPHY

In light of the above discussion, a multidisciplinary working group on stratigraphy consisting of workers actively engaged in geological research and mapping in the region is best suited to adequately address the question of reviewing and revising the lithostratigraphic classification and nomenclature in western Kenya. The principal aims of the working group would be to ensure that there is a coordinated approach in the development of the classification and nomenclature, and secondly that correct procedures are followed in formalizing the divisions agreed upon. This writer therefore proposes to the geological community in Kenya that such a group be now formed to address the inadequacies and inconsistencies discussed above in the division of the lithostratigraphy of the Archaean rocks in western Kenya and also in the rest of the Tanzanian Craton in general.

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## RESOLUTIONS OF THE GEOLOGICAL SOCIETY OF KENYA (GSK)'93 CONFERENCE

We, the professionals and conference participants of GSK '93 conference held at the University of Nairobi, Chiromo Campus on 10-llth February, 1993 after careful deliberations do hereby resolve as follows:

1. In recognition of the urgent developmental needs of Kenya, we, the professionals urge that appropriate legislation be put in place in order to regulate the exploitation of industrial minerals.

2. Noting the importance of the environment in sustainable development, and the damages inherent in planning without considering the geological environment, the conference recommends that future urban planning, water abstraction and development take careful consideration to the geological environment.

3. That appropriate seminars/workshops be held for small-scale miners and prospectors regarding the usefulness of sound geological application in their trade.

4. That in recognition of the importance of scientific knowledge to development of a country. We strongly urge for strengthening of national databases of all geological resources of remote sensing, geophysical and other relevant nature, especially for urban planning, the improvement of health and food production, and for geotechnical purposes. We also strongly recommend that laws governing the classification of scientific data under secret and confidential cover be reviewed to allow for free access to such data.

5. In redirecting our efforts for discovery of new sources of the physical resources, namely mineral resources, geothermal energy, we urge for evaluation of these resources and of our marine resources especially within our 200 mile Exclusive Economic Zone (EEZ).

6. To reduce duplication of our efforts, we urge for positive action in the improvement of communication, exchange of information and establishment of data linkages between our national institutions as well as at the international levels. This conference resolved to form a working group on Stratigraphic Classification to review, revise, and standardise the stratigraphic and geological nomenclature applied to the Archaean terrane of western Kenya.

7. In recognition of the need to further develop the geological sciences at the national level and also to make the geologists legally responsible for their actions, we stress the urgent need and urge for the enactment of the Bill of Registration for Geologists without any further delay.

## CLOSING SPEECH BY THE PERMANENT SECRETARY MINISTRY OF ENERGY - MR. GAYLORD AVEDI

Ladies and Gentlemen,

It is my pleasure on behalf of the Ministry of Energy and on my own behalf to say a few words on closing this important Conference on the Geology of Kenya.

I also note with great pleasure that you have planned a post-conference field trip to YATTA PLATEAU - one of the most interesting geological phenomenon in the country. In fact one of the papers presented here did indicate that Yatta Plateau is an ophiolite. As you all know ophiolites represented remnants of an oceanic crust - this then would imply that the area around Thika was once part of deep ocean floor. This is not to say that the trip to the Karroo and Jurassic formations of the coast is less interesting. It is in Karroo and Jurassic that we hope to discover petroleum. It is also a known fact that Karroo formations have hiqh potential for mineral resources like gold as indicated in one of the papers presented. The formation has also potential for minerals like lead, zinc, coal and uranium to name only a few.

Geological exploration is one of the most essential~ inputs towards attainment of a country's development goals. Hence, the provision of adequate and secure supplies of mineral resources in their various forms are vital for development. This therefore calls for the formulation of appropriate and relevant exploration strategies.

Kenya has not been very successful in this regard to a extent that we have been invariably referred to as an agricultural country. We know that many industrialised countries have achieved high level of development through utilisation of their mineral resources. Kenya should be no exception, and therefore I am happy to note that this Conference with the Theme "Geology for Sustainable Development" is highliting techniques and methods for exploration and development of mineral resources.

As you are all aware, my Ministry is involved in the exploration of Geothermal, Petroleum and other energy minerals like coal and uranium. The biggest task in this business of exploration is to locate these mineral resources.

Kenya is well endowed with geothermal resources and the development at Olkaria East where a 45 MW Power Station is in operation is generally believed to be only a small fraction of the total potential.

Since the creation of my Ministry, the Government has continued to promote the development of geothermal energy by mobilising domestic resources and assistance from both bilateral and multilateral aid donors. Towards the end of 1970 a major Geothermal Exploration programme was started by the Kenya Government with some financial support from the United Nations Development Programme (UNDP). This programme which came to an end in 1976 covered Olkaria, Eburru and Lake Bogoria Areas. Of the three areas Olkaria was chosen for development. In 1981 the first 15 MW Geothermal Plant in Africa was commissioned followed by 15 MW each in 1982 and 1985.

Further production drilling is being undertaken at Olkaria North East and as soon as financial resources available, construction of another 64 MW geothermal power plant will start.

From 1980, further geothermal surface exploration has been going on at Eburru and as a result, six exploratory wells were sited and completed in 1990. The results are promissing and more work is to be done in this area. There is however, an area of two square kilometres which is assumed to have geothermal potential of 12 - 24 MW for 25 years which by Kenya ' s standards is big enough for appraisal and subsequent development.

The Geothermal surface exploration along the nothern part of Kenya has been going on from 1988, in particular, it aims to study the geothermal potential of the young volcanic complexes and other hot spring systems along the eastern and western shores of Lake Turkana.

The study has already been completed and the reports will be published before the end of this year.

Kenya currently spends nearly 31% of her foreign exchange earnings on crude oil importation. A discovery of petroleum will result in a significant saving in import costs. Also income will be generated by the selling of the excess oil abroad.

It is therefore of crucial importance to determine if petroleum exists in the subsurface rocks of Kenya, as any indigenous oil production would have an immediate effect on the amount of crude oil that has to be imported.

At the present moment, only one consortium consisting of two oil companies, namely Shell and Amoco hold an exploration licence for petroleum.

Geologically, approximately 260,000 square kilometres or about one third of Kenya's surface area is considered potentially favourable for hydrocarbon exploration. To-date, only 30 oil wells have been drilled, most of them in the period between 1954-1978 and 1985-1993. Current statistics world-wide, indicate that 80% to 90% of all wells drilled, even in areas of proven oil potential, do not find oil. It follows that exploration effort in Kenya to-date, has been small and, of course, the greater the effort made, the bigger the chances of a discovery. This is evidenced in our neighbouring countries whose intensive exploration efforts have led to the discovery of a large gas field in Tanzania and in Sudan where oil in commercial qualities has been found.

I still believe that oil companies should be encouraged to explore for oil in Kenya. It is reflected in the few exploration wells drilled, only one well per about 8,665 square kilometres.

It is a challenge to you Kenyan Geoscientists to actively promote Kenya as a country where oil can be discovered. A conference of this nature can be a starting point.

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