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Evolution of the Southern Kenya Rift from Miocene to present with a focus on the Magadi area

Alexandria L. Guth
Michigan Technological University

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Evolution of the Southern Kenya Rift from Miocene to Present with a Focus on the Magadi Area

By

Alexandria L. Guth

A THESIS

submitted in partial fulfillment of the requirements

for the degree of

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Keywords: Geology, Geochronology, Remote Sensing, Mapping, Lake Magadi, Soda Lakes, Chert, Kenya Rift

This thesis, "Evolution of the Southern Kenya Rift from Miocene to Present with a

Focus on the Magadi Area" is hereby approved in partial fulfillment of the

requirements for the degree of MASTER OF SCIENCE in the field of GEOLOGY

Department of Geological and Mining Engineering and Sciences

Thesis Advisor: James R. Wood

Department Chair: Wayne D. Pennington

Committee Members: William I. Rose, Ph.D.
William J. Gregg, Ph.D.
Susan T. Bagley, Ph.D.

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Alexandria L. Guth
August 09, 2007

Abstract

The Kenya (a.k.a., Gregory) Rift is a geologically active area located within the eastern branch of the larger East African Rift System (EARS). The study area is located in the southern Kenya Rift between 1° South and the Kenya-Tanzania border (covering approximately 1.5 square degrees, semi-centered on Lake Magadi) and is predominantly filled with extrusive igneous rocks (mostly basalts, phonolites and trachytes) of Miocene age or younger. Sediments are thin, less than 1.5Ma, and are confined to small grabens. The EARS can serve both as an analogue for ancient continental rifting and as a modern laboratory to observe the geologic processes responsible for rifting.

This study demonstrates that vintage (as in older, quality maps published by the Kenya Geological Survey, that may be outdated based on newer findings) quarter-degree maps can be successfully combined with recently published data, and used to interpret satellite (mainly Landsat 7) images to produce versatile, updated digital maps. The study area has been remapped using this procedure and although it covers a large area, the mapping retains a quadrangle level of detail. Additionally, all geologic mapping elements (formations, faults, etc.) have been correlated across older map boundaries so that geologic units don't end artificially at degree boundaries within the study area. These elements have also been saved as individual digital files to facilitate future analysis. A series of maps showing the evolution of the southern Kenya rift from the Miocene to the present was created by combining the updated geologic map with age dates for geologic formations and fault displacements. Over 200 age dates covering the entire length of the Kenya Rift have been compiled for this study, and 6 paleo-maps were constructed to

demonstrate the evolution of the area, starting with the eruption of the Kishalduga and Lisudwa melanephelinites onto the metamorphic basement around 15Ma. These eruptions occurred before the initial rift faulting and were followed by a massive eruption of phonolites between 13-10 Ma that covered most of the Kenya dome. This was followed by a period of relative quiescence, until the initial faulting defined the western boundary of the rift around 7Ma. The resulting graben was asymmetrical until corresponding faults to the east developed around 3Ma. The rift valley was flooded by basalts and trachytes between 3Ma and 700ka, after which the volcanic activity slowed to a near halt. Since 700ka most of the deposition has been comprised of sediments, mainly from lakes occupying the various basins in the area.

The main results of this study are, in addition to a detailed interpretation of the rift development, a new geologic map that correlates dozens of formations across old map boundaries and a compilation of over 300 age dates. Specific products include paleo-maps, tables of fault timing and displacement, and volume estimates of volcanic formations. The study concludes with a generalization of the present environment at Magadi including discussions of lagoon chemistry, mantle gases in relation to the trona deposit, and biology of the hot springs.

Several biologic samples were collected during the 2006 field season in an attempt to characterize the organisms that are commonly seen in the present Lake Magadi environment. Samples were selected to represent the different, distinctive forms that are found in the hotsprings. Each sample had it own distinctive growth habit, and analysis showed that each was formed by a different cyanobacterial. Actual algae was rare in the collected samples, and represented by a few scattered diatoms.

Acknowledgements

Table of Contents

List of Figures

List of Tables

List of Files

File Name	File Type	File Size	Description
Ages	XLS	160 KB	Compilation of Age Dates
Comp	XLS	72 KB	Chemical Compositions
KenyaMap	PDF	178 MB	Map of Southern Rift
KenyaShp	ZIP	3.7 MB	All .shp and associated files
Magadi	PDF	47 MB	Magadi Field Guide

Note: Clicking on the above links will open the files described

List of abbreviations and acronyms

ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer

DEM: Digital elevation model

DCW: Digital chart of the world

DO: dissolved oxygen

EARS: East African Rift System

ETM+: Enhanced Thematic Mapper Plus, sensor on Landsat 7 that detects visible, infrared and thermal data, in addition to a higher resolution panchromatic band that can be used to sharpen the other images collected by the sensor

GPS: Global Positioning System

ka: kilo-annum, one thousand years

KGS: Kenya Geological Survey

KRISP: Kenya Rift International Seismic Project

Ma: Mega-annum, one million years

Moho: Mohorovicic Discontinuity, the boundary between the crust and mantle

MrSid: Multiresolution Seamless Image Database, a file type commonly used for very large image files used in GIS. Files from NASA's GeoCover page are of this type.

m.y.a.: million years ago

NASA: National Aeronautics and Space Administration

NIR: near infra-red

SEM: Scanning electron microscope

SRTM: Shuttle Radar Topography Mission

Introduction

Purpose

The East African Rift System (EARS, Figure 1, Appendix A) has been the subject of a number scientific studies in a variety of fields; geology, paleontology, biology and anthropology, among others. Human history is intimately linked with the rift, and recent papers (Potts et al., 2004; McBrearthy and Jablonski, 2005; White et al., 2006; Wynn et al., 2006; etc…) have been published regarding new finds from the human family tree in the rift system. These different studies all rely in one way or another on the unique geological setting of the rift valley. However, except for some small-scale detailed maps for scattered locations, most of the geological maps for the Kenya Rift are vintage 1950-1960's Kenya Geological Survey (KGS) reconnaissance maps. The term 'vintage' is used here and throughout this thesis to refer to the fact that these maps were produced several decades ago, and, though they are of high quality, they are, in many instances, outdated based on newer data and mapping efforts.

Modern satellite imagery now provides large volumes of versatile and geographically accurate data world-wide that can be adapted for a variety of uses including geologic mapping. It is an indispensable tool for mapping remote and/or hostile (environmentally and/or politically) areas that would require many man-hours at great expense to map in the field. In addition, satellites like Landsat 7 and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) collect data from the infrared and thermal bands, in addition to the visible wavelengths, which can aide in the mapping of geologic units. The older, mostly grayscale, aerial photography that many of the early

maps were based on lacked this added dimension. Accurate, detailed, cohesive and adaptable geologic maps are essential to many studies but are not, generally, available for many parts of the EARS.

The primary aims of this study are to:

- Remap the geology of the southern Kenya Rift in a digital format using satellite images and modern software
- Compile published age dates and combine with the digital map to create a time series of images that show the evolution of the rift
- Extract volumetric data from the digital mapping effort and combine with the age dates to analyze volume versus time

Many of the previous geologic maps were mainly reconnaissance in nature, some are based on incorrect base maps and do not align correctly with georeferenced satellite images or adjacent maps, and unit detail and naming can change abruptly at map boundaries (Fig. 2). The newly produced maps are seamless over several square degrees and can be applied to a variety of scientific problems relating to the EARS, such as the origin of the salt deposits at Lake Magadi and the volcanic evolution of the area. Also, the digital format will facilitate the distribution of these maps and digital files would be easily adaptable to suit various needs.

A description of the study area is provided below and is followed by a review of the literature regarding the Southern Kenya Rift and Magadi areas, with a focus on those studies that dealt with the evolution and mapping of this area. The methods used for mapping, constructing rift evolution time series images and determining volume estimates follow the literature review. Results and discussion of the mapping, evolution

and volume estimations are then presented and are followed by Part II, which contains ancillary information as described in the two paragraphs below. The main conclusions and recommendations for future work may be found following the ancillary data. In addition to the standard list of references, a library of pertinent works will also be included as there are many papers devoted to the Kenya Rift and EARS, and while all were read during the course of this study, not all were cited. Accumulating all of these papers took considerable time, and some were found by chance or referenced only rarely by others. This library is provided for completeness and to acknowledge the many researchers who have studied this area before.

While the main focus of this thesis will be mapping the evolution of the Southern Kenya Rift, other unique problems of the Magadi area will be briefly discussed such as water analyses, volcanic gas estimates in relation to the source of carbonate in the spring waters and the biology of Lake Magadi. This will be done to characterize the present lake system in an effort to define the current state of rift evolution in this area. The present environment is a product of the geological evolution of the Southern Kenya Rift, and is interesting in its own right. Discussion and results regarding these studies can be found in Part II of this thesis.

Additionally, an electronic field guide was developed from the 2005 and 2006 field excursions to Lake Magadi in order to present images, descriptions and geographic coordinates for points of interest (both general and geologic) in a readily accessible form. The reasoning behind this effort was that such a guide could help new investigators better visually interpret their surroundings and hopefully expedite research and interest in this area. This field guide is included in Appendix I on the CD included with this thesis.

Regional Setting

Lake Magadi is a sodium-carbonate alkaline lake (with minor NaCl and NaF) occupying 89 sq. km in a closed basin within the East African Rift near the Kenya-Tanzania border (Fig. 3). Of that lake area, 77.7 square kilometers is trona ($Na_3(CO_3)(HCO_3)\cdot2(H_2O)$) most of the year rather than open water, which is generally constrained to the shallow lagoons fed by hot springs located at the base of fault scarps. This trona deposit is the reason why there is a town here. The Magadi Soda Company is located on a small peninsula on the eastern shore of the lake, and produces soda ash by washing and calcining trona. The soda has many manufacturing uses and is a major part of Kenya's mineral exports with over 337,000 metric tons of Magadi soda ash being exported in 2004 (Yager, 2004).

A digital elevation model (DEM) created from the version 2 Shuttle Radar Topography Mission (SRTM) data shows Lake Magadi sitting at an elevation of 605 m, and Little Magadi to the north at 613 m (published elevations for Magadi range from 580m (Behr-Röhricht, 2000) to 650m (Eugster 1969)). Magadi is flooded seasonally by rainwater, and a thin layer (1-3 m) of water covers the trona surface during part of the year. This water evaporates during the dry season and exposes the trona surface, with the only open water being found around the springs and in the lagoons (Fig. 4). These springs vary in temperature, from around 40°C to above 80°C, mineral concentration, size, and output, with some springs being only seeps and others being relatively vigorous. Lake Magadi is supplied with water from these springs and by monsoonal rains (there are two rainy seasons, the 'long rains' from March to May, and the 'short rains' from November to December); no perennial rivers or streams flow into this basin. It is about 110 km from

Nairobi, and once there, the road network is mostly a series of 4-wheel drive tracks. The terrain is broken by numerous faults, easily seen in Figure 4, and the scarps and poor roads combined with the hot climate makes for difficult field work.

Sediments are confined to the grabens produced by the faulting of the volcanic units that comprise most of the rift fill. Around Magadi the flat graben floors are the deposits of old lakes and the horsts are trachytes that range in age from 1.4 to 0.7 Ma. The largest displacements occurred along the bounding faults of the rift (Fig. 5) which create a significant elevation difference between the rift shoulders and floor. Nairobi, which sits on the rift shoulder, has an elevation about 1060m higher than Magadi which is in the rift.

Literature Review

With geological interest in the area dating back to the late 1800's, there are numerous papers and reports regarding the Lake Magadi area. A review of some of the earliest investigations of the Lake Magadi region is covered by Baker (1958), with some of the early work described briefly here per Baker's report. The first extensive report on the geology was published by Parkinson in 1913 and described the faults, lake sediments and the silicification in lake beds and along fault lines. He also proposed that the salts in the hot springs were derived from the leaching of alkaline lavas. J.A. Stevens wrote a report for the Magadi Soda company in 1932 (unpublished, but much of the data are reported in Baker 1958) regarding the chemical composition of the hot spring waters surrounding Magadi.

Baker's "Geology of the Magadi Area", published for the KGS (1958), details the

geology between 1.5-2°S and 36-36.5°E, and includes information on the geologic units

of the area and hot springs, along with chemical analyses of spring waters and some

sketch maps. A large format map accompanied this report and is the only large scale map

known to cover this entire quadrangle. However, the map is currently out of print from

the KGS. By the time Baker published his report "Geology of the Area South of Magadi

(1963), it was determined that the base map used for the Magadi area was in error and

thus the map cannot be registered to correctly overlie the recent satellite data. In addition,

the map is over 50 years old and the geology of the area has been further defined by other

investigators over the years. Quantitative age dates for the geologic units are also lacking

in this report, and it was not until the 1970's that age dates based on modern

geochronological studies began to appear. After these two reports Baker continued to be a

major publisher on the geology of this area until his death in 1986.

In addition to age dates, a number of papers from the 1970's added further

definition to Baker's original map by recognizing new units or by renaming or

regrouping older units, with key mapping resources shown in Figure 6. Williams (1967)

renamed the bulk of the Ol Keju Nero basalts described by Matheson in the Kajiado KGS

report (1966) as the Singaraini basalts. A number of age dates from volcanic units were

compiled and published in 1971 (Baker et al.) along with discussions about both the

plateau volcanics, and the deposits of central volcanoes. Fairhead et al. (1972) also

presented a number of K-Ar age dates, however, the age dates presented for the Kirikiti

and Singaraini flows cannot be reconciled with newer age dates, which in turn affects

Fairhead et al.'s presented timing for the faults and overall geochronology. One age date

presented in their paper for an obsidian flow within the Oloronga lake beds has been instrumental in setting the upper age limit of this sedimentary unit and has not been contested by any of the more recent studies of the area. The Singaraini basalts were themselves subdivided in a 1976 paper by Baker and Mitchell into the Singaraini, Ol Tepesi and the Ol Keju Nero basalts based on differing ages in the northern and southern exposures. Baker and Mitchell (1976) was also a key paper in that they mapped the Kordjya basalts as a distinct unit (previously mapped as Plateau Trachytes by Baker, 1958) and divided the Orthophyre Trachyte (Baker 1958) into the Ol Tepesi basalts and benmoreites. This same paper however, only mentions examining the eastern occurrences, but the western exposure of Orthophyre Trachyte is also mapped according to the new unit name. This is despite being outside of the area being considered in detail for the paper and not being represented in their sampling and age dating. This paper by Baker and Mitchell (1976) is mainly focused on the geology and ages of units centered in the Olorgesailie-Kedong region to the northeast of Magadi, and contains a nicely detailed map from approximately 1°7'30" – 1°37'30" S and semi-centered on the 36.5° E longitudinal line (Fig 6). This detailed map covers the four-corner intersection of the old KGS report maps and is very useful for correlating across the boundaries of the older maps. Baker and Mitchell also introduce in this paper the idea of a massive flood caused by the sudden draining of a lake to the north. Termed the Kedong Flood, the authors list a variety of evidence to support the mass movement of sediment-laden water. Deposits relating to this flood can be seen to the northeast of Olorgesailie in the Ol Tepesi Basin. These deposits are mapped on the detailed map they present, and are prominent, easily recognizable features on the satellite imagery.

Crossley (1979) conducted mapping of the western boundary of the Southern Kenya Rift and also presented new age dates for the area. This paper revealed that the western exposure of 'orthophyre trachyte' from Baker's 1958 report, (later renamed by Baker and Mitchell (1976) as the Ol Tepesi Basalts) was really two different units; the Ewaso Ngiro Trachyte and N. Kordjya Trachyte. Crossley also extended the mapped area of the Oloronga lake bed deposits to the northwest, and mapped a new lake deposit; the Orkaramatian beds.

While mainly concerned with the paleomagnetics of the area, Patel and Raja (1979) also published several small geologic maps in their paper, and, while lacking details seen in Crossley's (1979) map and the new units presented by Baker and Mitchell (1976), their work is of particular interest as their map shows several small outcrops of Kordjya basalts along the Kordjya escarpment and to the northwest of Little Magadi.

The region to the north (Kedong-Naivasha-Kinangop region) was covered in a 1988 paper by Baker et al. This, Baker's last paper, has some small maps covering the central and southern Kenya Rift which show major and minor fault patterns, and the simplified geology northeast of Magadi, in addition to a number of age dates.

Although there has been a number of mapping efforts for the South Kenya Rift since Baker's original KGS map (1958), these smaller maps have not been previously synthesized into a whole, comprehensive map.

Finally, with regards to geologic mapping, in researching the biology of the lake, one map cropped up in several papers (Wilson et al. 2000; Wilson et al. 2004) that was adapted from Maina et al. (1996). This map shows Lake Magadi and the main roads, and while it is not concerned with the geology of the area, it has an inaccurate lake outline,

uses different names for the lagoons surrounding the lake than found in the geological papers, and maps trona as being where there are only lake silts and chert. By having different names for the lagoons, comparing water analyses between these papers and those written by geological researchers can be confusing, and this author believes that this underscores the need for an easily accessible, accurate, map which can be flexible enough for suiting the needs of different scientific fields.

In addition to works focused on general geologic mapping and geochronology, certain units have received more attention than others. In particular, the cherts that are common in the Magadi area have been studied by a variety of authors, and their origin has been under debate for nearly 50 years. They were originally named the 'Chert Series' by Baker (1958) and placed between the Oloronga and High Magadi Beds in age. It was then determined that they were older than the Oloronga beds based on exposures to the south of Magadi (Baker, 1963). Hans Eugster became the foremost researcher on the Magadi cherts and wrote a number of papers over several decades regarding their formation. One of his earliest papers discusses the link between pH and chert deposition in the paper, "Silica in Alkaline Brines" (Jones et al., 1967). Silica enrichment in the waters of Magadi is believed to be due to evaporative enrichment and, due to the high pH of the brines, the silica can remain in solution. Eugster (1967) proposed that magadiite ($NaSi_7O_{13}(OH)_3 \cdot 4(H_2O)$), a soft, white layer that Baker (1958) had noticed in the High Magadi Bed exposures, was a chemical precipitate from the alkaline brines, and that kenyaite ($Na_2Si_{22}O_{41}(OH)_8 \cdot 6(H_2O)$), was formed by the leaching of sodium from the magadiite by percolating water. It was believed that with further leaching of sodium, chert could be formed. In a 1968 paper Eugster and Jones discuss gels found near the hot

springs that feed the northeastern lagoon. These gels seemed to have been derived from the *in situ* decomposition of the trachyte lava debris, and the gels were probably reformed annually leading to a probably significant accumulation of silica gels in the lake. Eugster claimed that that the Chert Series originated from areas similar to those where the gels are found in the present, unlike the magadiite which was thought to be a lake-wide deposit. The Chert Series was noted to be aligned along faults, showed evidence of soft sediment deformation and seemed to show evidence of algal mat growth, all of which seemed to point to a soft, gelatinous, precursor. It was speculated that sodium leaching of the gels would convert them to the normal porcellaneaous chert seen in the field.

In 1969, Eugster tried to show that the Chert Series was stratigraphically equivalent to the magadiite beds in the High Magadi sediments based on digging trenches near the chert ridges and seeing that they seemed to be laterally contiguous with magadiite. He believed that the cherts were formed inorganically by the leaching of sodium from magadiite as discussed above. Having a putty-like precursor made it easy to explain the numerous soft-sediment type deformation seen in the chert, and in this paper he proposes that magadiite is the soft chert predecessor rather than the gels he discussed in 1968. Using aerial photography Eugster (1969) stated that the prominent chert ridges of the area formed closed polygons which were explained as being desiccation polygons. He proposed that the magadiite formed in a stratified lake where brines and freshwater came into contact and formed a chemocline where the pH would be lower but there would be an ample supply of silica. Magadiite could then precipitate at this boundary layer. After this paper, Eugster no longer refers to the Chert Series and instead places those rocks within the High Magadi Beds.

Schubel and Simonson (1990) continued the line of reasoning started by Eugster that the bulk of the cherts were formed inorganically from magadiite and conducted a more in-depth study on the cherts around Magadi. Behr and Röhricht (2000) however, believed that inorganic cherts formed from magadiite were actually rare in this area, and that they comprised less than 10% of the Magadi area cherts. They concluded that most of the cherts are older than the High Magadi Beds, and thus were older than the magadiite layers, and were formed from bioherms growing on silica gels (similar to those mentioned by Eugster and Jones in 1968) and thus contained numerous biologic remains. Seismotectonic activity then caused the collapse, liquefaction and extrusion of the plastic siliceous material resulting in the soft sediment type deformation. Instead of inorganic, putty-like magadiite, a mush of silica, calcite, and cyanobacterial remains was formed which remained deformable for long periods. Tectonic activity led to cracks in overlying bedded cherts, and the cyanobacterial mash could then rise to form diapirs and dikes. This is similar to Eugster and Jones' 1968 theory regarding the gels seen at the northeastern lagoon and how they, rather than the magadiite, were the precursors for the Chert Series. Age dating indicates two generations of chert with about 90% of the chert in the Magadi Area being part of what Behr and Röhricht refer to as the Green Beds. This formation was placed between the Oloronga and High Magadi beds in age, which is where Baker had originally placed his Chert Series. It is the cherts in the High Magadi Beds, which overlie the Green Beds, that contain the magadiite and kenyaite horizons. Behr and Röhricht also present in this paper images of some of the biologic remains found in the chert and two very detailed maps showing the aerial distribution of the Green Bed chert exposures. However, it was noticed that one of the scale bars used for

these detailed maps is inaccurate and is inconsistent with the scale provided on the

location map in the same image. The inaccurate scale bar makes the mapped area appear

about three times larger than it really is.

Behr (2002) continued the study of cherts in the Magadi area and found that the

chert ridges follow a 90° grid pattern, which can be correlated with faults, and no

desiccation features as postulated by Eugster were found. Behr presents a nice

stratigraphic record of the sedimentary units of the Magadi Basin and shows the names

used by Baker and Eugster, fossil distribution, and lake level development. He also goes

into more detail about the biologic remains found in the cherts and includes a number of

thin section and Scanning Electron Microscope (SEM) images of the remains found.

Geologic Introduction

It is generally believed that the incursion or one of more plumes occurred before the initiation of rifting (Burke and Wilson, 1976; Thiessen et al., 1978; Latin et al., 1993; Hofmann et al., 1997; Davies, 1998; Ebinger and Sleep, 1998; George et al., 1998; Nyblade and Langston, 2002; Nyblade, 2003; Weeraratne et al, 2003; Nyblade et al., 2004; Rogers, 2004). The exact number, timing, and migration of plumes is under debate. The oldest volcanism occurred in the Turkana region around 35-30 Ma (George et al., 1998; Macdonald, 2003; McDougall and Watkins, 2006) and initiation of magmatism has been noted by a number of authors to decrease in age to the south (Khan et al., 1999; Nyblade and Brazier 2002; Macdonald et al., 2003; Chorowicz, 2005 etc.). The East African Rift System as a whole, propagated to the south at a rate of 2.5-5 cm/yr and avoided cratons. Instead, the rift system propagated along the old mobile belts from the Neoproterozoic Pan-African events (Chorowicz, 2005).

Downwarping in the Kenya Dome occurred where the rift would eventually develop and large amounts of volcanics (basalts, phonolites and melanephelinites) were erupted into this proto-rift during the Miocene (Crossley, 1979; Williams and Truckle, 1980; Smith, 1994; Macdonald, 2003). From the Miocene to present, volcanic flows and ashes dominate the Southern Kenya Rift in terms of both duration of activity and volume of deposits. Sedimentary units are generally limited in area and confined to grabens within the rift valley. While deeper sedimentary basins exist to the north of the study area and in the western rift branch, in the Southern Kenya Rift such basins are recent and lack significant sedimentary fill.

An obvious feature of the rift is the large number of fault scarps that cut the landscape and form sediment-trapping grabens. Very few of the faults are actually exposed, but two normal faults were measured by Baker (1958, 1963) and found to have dips around 60°. The tilted fault blocks that are common in this area are suggested to indicate the presence of curved faults that get shallower with depth; combining this with the observed vertical displacements (which is a minimum estimate of total displacement) on the faults, a minimum horizontal extension was estimated at 15km by Baker et al. (1977a) and revised to 20km by Baker et al. (1988). These estimates were made assuming that all the faults dip at 60° and gives an estimated extension rate of 3mm per year, however, it is noted by these authors that extension rates were probably variable over time due to periods of discrete faulting.

In regards to the calculations presented by Baker et al. (1977a, 1988), it was noted by Crossley (1980) that fractures in the rift floor were nearly vertical and dips on the Sambu fault vary from 65° to 45°, making the assumption that all faults dip at 60° overly simplistic. Additionally, the assumption that the boundary faults become listric with depth seems to be contradicted by the results of Ibs-von Seht et al. (2001), where plotted earthquake foci seem to indicate that the western boundary faults of the Magadi area dip at 65° to at least 25km depth.

Recent stretching factor (β-factor) estimates for the southern Kenya Rift, which are based on the thickness ratio of crystalline crust outside the rift to the thickness inside the rift, yield values always less than 1.4 for this area (Khan et al., 1999). Despite the various difficulties in pinpointing the exact amount of extension for the area, it is

14

generally reported (Khan et al., 1999; Macdonald, 2003; Prodehl et al. 1997, etc…) that

the extension is between 5 and 10 km for the Southern Kenya Rift (which would be

equivalent to a β-factor of 1.1 to 1.2). A full 10km of extension over 7 million years

would lead to an average of 1.4 mm/yr extension. For comparison, present extension in

the Main Ethiopian Rift (MER) has been measured to be 4mm/yr based on GPS

measurements (reported in Keranen et al., 2004), however, it is unknown if similar GPS

measurements have been made for the Kenyan Rift.

Also, the studies by Keranen et al. (2004) have shown that extension in MER can

be attributed to a combination of fault movements and injection of magma into the crust,

which has also been discussed by authors for the Kenya Rift. In fact, it was recently

reported that 60km of fracturing in the Afar region was caused by the lateral flow of

magma from chambers below local volcanoes into dikes 2-9km below the surface

(Sigmundsson, 2006). This created fissures up to 8m wide in the rift floor and it is

postulated that this method of extension can happen well before lithospheric thinning

progresses to the point of allowing normal faulting. For the section of the MER studied

by Keranen et al., (2004) a maximum of 6 km extension could be accounted for by dike

injection while fault displacements accommodate more than twice that.

Recent seismic surveys have been conducted for sections of the EARS and have

allowed for the visualization of the rift structure. Of these studies, the KRISP (Kenya Rift

International Seismic Project) surveys have provided large volumes of data, and.

Importantly for this study, had shot points at Magadi (Green et al., 1991; Ibs-von Seht et

al., 2001; Khan et al., 1999; Prodehl et al., 1997; Simiyu and Keller 1998, 2001). These

studies show that the severe crustal thinning that had been earlier assumed to exist under

Magadi was not present, and in fact crustal thinning at Magadi is less than the thinning seen at Lake Baringo. Only a minor upwarping of the mantle was seen (Prodehl et al., 1997), however, it was later argued however, that lack of observed thinning could be explained by underplating of the crust by magmatic materials related to rifting (Simiyu and Keller, 2001).

Methods

Geologic Mapping

Baker's 1958 Magadi map (but not the report that is meant to go along with it) is out of print and difficult to obtain. In the "Geology of the Area South of Magadi" report, Baker (1963) reported that the base map used for the Magadi Area had been in error. This can easily be seen when the map is georeferenced using the stated corner coordinates from the map and overlaid on a satellite image (Figures 7 & 8). These errors would be difficult to correct, as the offset is not a simple shift in one direction, but rather a complex warping.

Landsat 7 satellite images (false color images using bands 7, 4 and 2) were used as the new base map (obtained as compressed MrSid files from NASA's GeoCover webpage) and geologic boundaries were traced from the satellite images using previously published maps (Baker 1958; Baker and Mitchell, 1976; Baker et al., 1988; Behr, 2002; Crossley, 1979; Crossley and Knight, 1981; Joubert, 1957; Matheson, 1958; Patel and Raja, 1979; Randel and Johnson, 1991; Saggerson, 1991; see Figure 6) as geologic keys. Where possible, nomenclature and shown geologic boundaries from the originally published maps were used, but there were occurrences where the satellite imagery and the published maps were in disagreement (such instances are noted in the Results section of this report). The smaller scale, more recent maps (not published by the KGS) included new units and added detail which were incorporated into the newly produced map presented with this thesis. For this study, six quadrangle maps covering the lower part of the Kenya Rift, from 1° South to the Tanzania border, were remapped in detail in this

manner. It should be noted that using satellite images to aide in the mapping and analysis

of the Southern Kenya Rift is not novel. Mboya (1986), Gaciri (1992) and Atmaoui and

Hollnack (2003) all used satellite images to map lineaments and help analyze the

structure of the region. Newer techniques using the synthetic-aperture radar method

(satellites such as RADARSAT-1 and the European Space Agency's Envisat) allow for

the calculation of cm-scale changes in elevation that is useful in tracking deformation

caused by movement of magma and has been applied to areas north of the current study

area (Poland, 2006; Sigmundsson, 2006).

   As noted previously, the formation names and detail can change when crossing a

map boundary. An effort was made to preserve the most detail when crossing a boundary.

To facilitate this, a unit correlation table was constructed showing the units and their

equivalents in each of the KGS maps (Appendix B). A similar chart was constructed by

Baker (1965) but age dates and newer studies have helped improve the correlation efforts.

Units that are considered correlative (based on either description, correlation made by

previous papers, or by matching unit boundaries across maps) are placed in the same row

and units that are similar but do not have exact equivalents are placed under the

correlating units and are alone in the row. Some formations present in older maps have

since been subdivided based on newer age dates or petrological studies. In such cases, the

old name is in the table for completeness, with the newer name, which takes precedence,

highlighted.

   ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)

imagery was also used to augment the mapping of some units around Magadi. ASTER

images have the advantage of being obtainable as time series data and have increased

spatial resolution for the visual and near infrared (NIR) bands compared to the Landsat 7

data. ASTER visible and NIR bands are collected at 15m spatial resolution, while the

similar Landsat 7 bands are collected at 30m and then sharpened to 15m using the

panchromatic band; however, this sharpening process cannot produce an image as clear

as one simply taken at 15m resolution. Also, ASTER images contain information from 14

spectral bands, and some of the thermal bands proved useful for mapping cherts of the

Green Bed series. Areas known to be the Green Beds (Chert Series) could be seen to

standout in the thermal bands (8.125-11.65 µm) and this was enhanced by performing a

Principal Components transformation on the thermal bands (Figure 9). It is unknown why

these beds stand out in the thermal images, and time did not allow for an in-depth

investigation of this phenomena.

The bulk of the digital mapping was done in Global Mapper by using the geologic

maps and satellite imagery as discussed above. Each formation was traced on the satellite

data and then saved individually as vector shapefiles (an ESRI file format that saves

attribute tables and projection information along with each file). It was attempted to map

each formation out in its entirety rather than stopping at artificial boundaries (political

boundaries or certain lat/long coordinates), which is one reason mapping was continued

across the Kenya-Tanzania border into the Lake Natron region. Once the shapefiles had

been created for each geologic formation, the map was then assembled in ESRI's

ArcMap due to its enhanced layout, legend and symbol tools.

In addition to act of mapping the geology, some changes had to be made when

constructing a printable map. Many of the abbreviations used on the old KGS maps

utilized numbers to indicate the order of formations during a certain time period. Since

six maps were combined for this study, and each KGS map had its own abbreviation system, it was decided to devise a new scheme that could be expanded as needed to accommodate new maps into the process. The general system produced abbreviations such as Pkp, where 'P' stood for Pliocene, 'k' was from the formation name (in this case for Kapiti), and 'p' indicates the unit is a phonolite. Epoch time divisions are based on those published by the International Commission on Stratigraphy (ICS) and the lower time boundaries are as follows: Miocene, 5.33 Ma; Pliocene, 1.806 Ma; Pleistocene, 11.5 ka.

There are also standard colors suggested by the ICS and the United States Geological Survey for geologic map making, however these could not be used satisfactorily due to the limited age range of the exposed rocks in the study area. Due to this, a color scheme was developed such that color families were related to the petrology/origin of the formations rather than the age. Ashes and tuffs are colored based on petrology, when known, in accordance with the proposed scheme. However, in some cases the composition of the ash is not given, in which case the ash formations are grouped based on texture (in that they are ashes) and represented by browns on the presented map.

Constructing cross sections through areas where previous cross-sections are absent or outdated requires a good understanding of how the area evolved. In order to visualize the succession of events and construct a cross section through the map area, a series of block diagrams were constructed to diagrammatically represent the major events west of Lake Magadi. These can be seen in Figure 10 and were constructed mainly using the ages and events outlined in Crossley 1979 while attempting to understand how his

cross sections fit with his order of events. While Crossley presents a cross section of the area and describes the events that occurred to create the present situation, it was difficult to conceptualize without a visual aide. Figure 10 represents the events described by Crossley (1979) and demonstrates quite succinctly that a very complex situation can result from a series of simple steps. This exercise led further to the construction of similar maps for the entire study area to represent the geologic evolution from the Miocene to the present, as discussed below.

Part B:

Several products were derived from the initial mapping efforts, and are described here. They have been separated from the mapping methods to emphasize the fact that they were dependant upon the initial mapping and cross section processes as described above.

Time Series

To construct a visual time series of events, the first step was to compile age dates from the literature for as many formations as possible. This list of age dates can be seen in Appendix C. Since an age can be associated with almost every mapped formation, the shapefiles produced for digital mapping to represent the different formations can be grouped by age and then displayed to represent the activity during different stages of the rift evolution.

Volume and Petrographic Analysis

Having digital shapefiles also allows for quick determinations of the exposed surface area and, when combined with thicknesses estimates from the literature, can provide minimum volume estimates (areas and thickness used for volume calculations can be seen in Appendix D). Volumes obtained in this manner are considered to be minimum estimates because the exposed area does not account for the subsurface extent of the formations. Each formation probably had an area significantly larger than the mapped area, but after deposition the formations were eroded, faulted and/or partially buried by subsequent eruptions.

In some instances, a larger volume can be obtained to approximate original volume by estimating the total extent of the flow. This was already done, in part, for the volcanic units of the Nairobi region, by Saggerson (1991) who provided a map of probable maximum extents for some of the formations. For units that had patchy surface extents, larger volume estimates were obtained by assuming the original flow must at least had a perimeter that contained all visible outcrops. Some maximum extents were based on verbal descriptions in the literature, for example, Crossley (1979) mentions that the Kordjya basalts can be traced as far east as the western margin of the Magadi trough.

For the pre-rift units such as the Plateau Phonolites (which include the Kapiti, Kandizi, Nairobi, Mau, Kericho and Rumuruti (among other) flows, of which the Kapiti, Kandizi and Nairobi outcrop in the study area) it was assumed that they covered the entire area between their eastern and westernmost outcrops, which includes the area currently occupied by the rift. Smith (1994) also provides a map with the probable extent of the Plateau Phonolites which agrees with this assumption. Since they occurred before

the initial faulting and extension, the area currently occupied by the rift zone was contracted by 20%, based on estimated β-factors (or stated extension in km) mentioned by Khan et al., (1999) Macdonald, (2003) Prodehl et al. (1997) and others, for volume calculations.

In all cases a simplistic calculation was done assuming the flow was a sheet of even thickness and central volcano volumes were calculated as if they were cones. The calculated volumes, both those using mapped area and estimated extent, along with a cumulative volume, were then plotted versus time. These are also presented along the time series images with the time period corresponding with the image highlighted to facilitate discussion.

In addition to accumulation of age and volume information for various flows, chemical analyses were also gathered from a variety of sources (Baker, 1958; Baker, 1975; Baker et al., 1977b; Crossley and Knight, 1981; Gittins and Jago, 1998; Macdonald, 2001; Le Roex et al. 2001; Otando, 2004; in addition to a number of analyses compiled by GEOROC) and plotted on silica versus total alkali plots. The full list of chemical analyses can be found in Appendix E. Individual plots for eruptions during discrete time periods are shown and discussed with their corresponding time series images in Results.

Results and Discussion

Geologic Maps

A small version of the map produced for this study is presented here as Figure 11. The full size electronic copy of the produced geologic map from 1° South to the Kenya-Tanzania border, along with associated cross-sections, can be found in Appendix F. The associated shapefiles for all the geologic formations may be found on the accompanying CD in Appendix II.

As mapping was done from the Landsat images, and not simply by tracing the boundaries from the old maps, numerous small differences exist between the new digital map and the sources used to interpret the satellite data. Such minor changes will not be detailed here, but there were some significant changes and unit reassignments from Baker's 1958 map that were not made by previously published reports. These changes were made in the following areas:

- The northern border of the Oloronga Beds west of Magadi was mapped by Baker as being cut off at a near 90° angle where Quaternary sediments were shown to cut across the lake beds. Such a boundary is not seen in the satellite images; however, there is a fairly distinct boundary on the western edge of the Oloronga beds which continues until it meets the Magadi Trachytes, which can be seen in Figure 12. The Oloronga beds are easily discernable from the Quaternary sediments in the satellite images. Using the same visual clues, the Oloronga beds also seem to occur in a basin to

the northwest of Magadi, which again is not shown by older geologic

maps. This choice in mapping seems validated however, by the recent

hominid research in Lainyamok, the basin northwest of Lake Magadi,

where the sediments have been identified as belonging to the Oloronga

beds (Shipman et al., 1983; Potts et al., 1988; Potts and Deino,1995).

- The area covering the lower third of Little Magadi was originally mapped

  by Baker as trona, whereas only small sections of the southern end show

  the distinctive trona response in the circa 2000 Landsat image. Comparing

  ASTER images from January, March and September 2003 and December

  2005 showed that the extent of the trona in the southern corner of Little

  Magadi changes significantly between years and even a little between

  seasons (Fig. 13). The large amount of exposed trona in December 2005 in

  Little Magadi was most likely due to the drought that occurred during that

  year, while 2003 was considered to be a more normal year for

  precipitation (Earth Observatory, Kenya Red Cross). In addition to yearly

  variations, the amount of exposed trona in Lake Magadi is seasonal and it

  is assumed that during the rainy seasons the trona spectral response is

  masked by overlaying water (Fig. 14). For mapping, the minimum extent

  seen at Little Magadi was used, as this seems like the average extent

  during normal years, and the maximum extent of the exposed trona was

  used for Lake Magadi, as it more accurately reflects the area occupied by

  the trona deposit, distinctly defines the lagoon areas, and the lake basin

  exhibits this exposure every year during the dry season. It should be kept

in mind however, that the appearance of these two water bodies will vary

during the seasons and between years.

A variety of vector data can be obtained online from Digital Chart of the World

(DCW) including country borders, roads, rivers and population points. While these can

be useful for identifying roads that might be otherwise hard to follow on sections of

satellite images, there are a number disadvantages with these data: digitizing was done

from maps at 1:1,000,000 scale so the resolution is not as fine as can be traced from the

satellite data and features have a stated positional accuracy of 2km. This can be distinctly

seen in Figure 15 which shows the DCW road file, a GPS track and the road as seen in

the Landsat image. The GPS track is thought to be the most accurate, however, since only

a small percentage of roads were driven and thus had a GPS track, and since geology was

mapped using the Landsat imagery, it was determined that all roads would be mapped

from the Landsat as well.

Rift Evolution and Time Series Images

Events prior to 10Ma

Figure 16. In the highlands west of Lake Magadi there are several

melanephelinitic units which exist as the old volcanic center Lisudwa, located between

the Kirikiti and Sambu faults, and the Kishalduga Formation which is farther to the north

above the Naitiami Fault. The Kishalduga rocks gave ages between 12-15.2 Ma, and all

of these melanephalinitic rocks were erupted onto the metamorphic basement from

fissures or volcanic centers within the downwarped area where the rift later developed

(Crossley 1979). These are the oldest known rift-related volcanics in the southern Kenya
Rift.

One of the other early volcanic events is likely the Simbara basalts, which only
outcrop in stream valleys north of Nairobi; this is assuming Smith (1994) was correct in
his conclusion that these basalts are correlative with the Samburu basalts which have an
age range of 14.2-23 Ma (Chapman and Brook, 1978; and Baker et al., 1971). This is
despite a published age for the Simbara basalts in Baker et al. (1971) of 5.5 Ma, which
Smith argues is really for a sample of the Sirrima Basalts, which are included within the
Thomson's Falls Phonolites (that do not exist within this paper's study area). The
Samburu basalts have an assumed fissure origin due to their sheet-like morphology and
association with dike swarms and intrusive plugs (Smith, 1994).

The largest volcanic series to erupt in association with the doming and eventual
rifting also occurred during this time and are termed the Plateau, or Flood, Phonolites.
These eruptions give ages between 10-16.4 Ma (Logatchev et al., 1972; Chapman and
Brook, 1978; Smith, 1994; Behrensmeyer, 2002) with the majority being erupted between
13 and 11 Ma (MacDonald, 2003). These phonolites represent the largest eruptive event
within the central and southern Kenya Rift area (note that these were all erupted before
the rift initiated) and represent over 40,000 km^3 of extruded material. Within the study
area however, which only represents the southernmost limit of this activity (Macdonald,
2003; Smith, 1994), the volume is estimated to be closer to 4,000 km^3. These phonolites
show sheet-like morphologies, but a definitive source for these flows has not been
identified (Smith 1994). Based of the flow extent presented by Smith (1994) it is
reasonable to assume that these phonolites exist within the present rift valley but are

buried by other flows. The only units that outcrop within the present study area that are considered part of the Plateau Phonolites are the Kapiti, Kandizi and Nairobi Phonolites, which are all preserved on the eastern rift shoulder near Nairobi.

10 to 6 Ma

Figure 17. After the early to mid-Miocene events, the volcanic activity, at least that we have evidence of, was relatively quiet until around 7 Ma when there was another period of volcanism following the initial rift faulting that defined the western boundary. In the southern Kenya rift, the first major fault displacement was on the Naitiami fault with a movement of at least 250 m, which was subsequently followed by 200 m displacements on the Sonjo and Northern Sambu faults (Crossley, 1979). The Lengitoto Trachyte and Endosapia Formation were erupted into this early rift from 5.0 to 6.9 m.y.a. Based on preserved morphology of the Lengitoto flow, it appears that these flows are elongated in a north-south direction either due to eruption from similarly oriented fissures and/or confinement by the fault scarp. The flows that erupted outside, or before, the rift seem to have a more puddle-like morphology as they were not confined and probably erupted onto gentle or flat topology.

Age dates for rocks associated with the Ol Esayeti complex indicate that this volcanic center may have started erupting around 6.7 m.y.a. (Baker et al. 1971).

6Ma to 3Ma

Figure 18. There was a second period of faulting on the Naitiami, northern Sambu, Sonjo, Lengitoto and Kirikiti faults, after which the rift was at least 450 m deep (Crossley 1979). There are two formations that exist on the present eastern shoulder that

28

were correlated with the Olorgesailie complex based on petrologic similarities to lavas found on the volcano (Matheson, 1966). These phonolites and nephelinitic-phonolites suggest that Olorgesailie may have started erupting around 5.8 m.y.a. (Baker et al., 1971). Additional rocks from Ol Esayeti indicate periods of eruption from 5.85 and 5.64 Ma (Baker et al. 1971) and around 3.6Ma (Baker and Mitchell, 1976). Assuming all of these age dates are accurate, then this volcanic center had around 3 million years of activity.

The Nairbobi trachytes can be seen on the eastern shoulder of the rift, probably originated from north of the study area, and are dated between 3.17-3.45 Ma (Baker et al., 1971). Within the rift up to 550m of the Kirikiti basalts were erupted, (Baker et al., 1977a), probably from fissures, between 2.5 and 3.1 Ma (Crossley, 1979).

3Ma to 2Ma

Figure 19. The first faulting to define the eastern side of the rift occurred sometime around 3Ma (Baker et al. 1977a). A trachyte from Olorgesailie was dated at 2.7Ma (Baker et al. 1971) and another Olorgesailie volcanic gave an age of 2.2 Ma (Fairhead et al., 1972). Given that the oldest flow associated with this vent is dated to 5.8Ma, this eruptive center was also active for over 3 million years like Ol Esayeti. The Singaraini basalts were the first volcanics to erupt into the newly down dropped eastern section of the rift and the lowest exposed flow examined by Baker and Mitchell (1976) was dated to 2.33 Ma. These basalts also exhibit flow elongation similar to the Lengitoto trachytes and Kirikiti basalts, and based on this similar morphology, the Singaraini basalts were probably also erupted from fissures. They were as much as 550m thick and confined by the newly formed eastern boundary fault (Baker et al. 1977a). Also around 2.3 m.y.a. (Crossley and Knight, 1981), the Mosiro trachytes were erupted in the north

section of the study area, were around 300m thick, and probably covered at least half of the northern rift floor (Baker et al., 1977a)..

To the west, the Kordjya basalts (2.17 Ma, Baker and Mitchell, 1976) and Ewaso Ngiro trachytes (2.1 Ma, Crossley, 1979) started erupting onto the rift floor. Ol Doinyo Sambu, a volcanic center to the west of Lake Natron in northern Tanzania and centered on the Sambu fault, erupted further basalts that overlapped onto the Kirikiti basalts around 2 m.y.a (Crossley and Knight, 1981). In addition to the continued activity of Olorgesailie, ages of 2.62 and 2.0 Ma (Fairhead et al., 1972) for Lenderut and Shombole respectively, indicate that these two volcanoes were also initiated during this time.

2Ma to 1.5 Ma

Figure 20. The Limuru trachytes were at least 300m thick and flooded the northern section of the study area starting around 1.96 m.y.a. (Baker and Mitchell, 1976) and locally overflowed the eastern fault scarp and spread onto the rift shoulder (Baker et al. 1977a). Combined with the Mosiro trachytes these two trachyte flows probably covered the entire rift floor in the northern study area (Baker et al., 1977a). The Ol Tepesi Benmoreites and Ol Keju Nero Basalts were both erupted around 1.65 Ma (Baker and Mitchell 1976) in the eastern rift floor near Olorgesailie.

To the south near Lake Natron, the Humbu sedimentary formation has been dated between 1.35 and 2Ma (Mora et al. 2003; Thouveny and Taieb, 1986) and represents the oldest dated lacustrine unit in the study area. This formation is in the Lake Natron basin and suggests that a paleolake existed during this time, although, would have been confined to the north by the larger sizes of Sambu and Shombole (Dominguez-Rodrigo et

al., 2001). Also, unlike the present Lake Natron, the Humbu Formation represents a

freshwater deposit (Thouveny and Taieb, 1986).

1.5Ma to 100ka

Figure 21. The Ol Tepesi basalts were erupted between 1.6 and 1.4 Ma in the

Olorgesailie area (Baker 1988). One of the most prominent volcanic formations in the

present rift landscape, the Magadi Trachytes, flooded the center of the rift between Suswa

in the north and Gelai in northern Tanzania (note that Suswa did not exist at this time) to

a depth of at least 190m starting 1.4 million years ago. These flows thicken towards the

center of the rift (Baker et al. 1977a) and were probably erupted from fissures rather than

any of the large central volcanoes in the area (Fairhead et al., 1972; Crossley, 1979). This

was the last major eruption in the study area, and the youngest flow, which is located in

the Lake Magadi area, has been dated to 780ka (Fairhead et al., 1972). This young flow

intercalates with the Oloronga beds, so a large paleolake occupying the present location

of Lake Magadi, must have existed at this time. It should also be noted that Bye et al.,

(1987) remark that this obsidian in the Oloronga beds is nearly identical to the obsidians

of Ol Doinyo Nyokie. Based on this chemical similarity it is possible this obsidian flow

may be from Ol Doinyo Nyokie, or rather, that Ol Doinyo Nyokie is a manifestation of

the Magadi Trachyte eruptions and thus an obsidian from the main Magadi trachyte

eruption would chemically resemble the obsidians from Nyokie. Other young flows from

the Magadi trachytes have been dated between 0.9 and 0.7 (Baker et al., 1971) which

coincides with an age of 0.66 Ma for Nyokie (Fairhead et al., 1972).

Another large lake existed near Olorgesailie between 1 and 0.5 m.y.a. (reported in

Behrensmeyer et al., 2002b) and deposited a large amount of diatomite. Hominid artifacts

are also associated with these lake deposits and include numerous handaxes and a partial

hominid skull (Potts et al., 2004). There was a flurry of minor volcanic events around

600ka, with Ol Doinyo Nyokie, Ol Doinyo Alasho (both small trachytic centers in the

rift), and the Mosiro basalts all erupting at this time. The Mau ashes, which currently

blanket the rift shoulder to the west of Suswa, were also erupted during this time. A

number of closely spaced grid-faults broke up the rift floor by 400ka (Baker et al.,

1977a). The Suswa volcanic center started building around 240ka and eruptions

continued until 100ka (Baker et al., 1988). There is evidence of some eruptive activity

from Suswa being less than 100 years old, as there are some flows in the crater floor that

are unvegitated, and thus must be relatively fresh (GVP website).

Details regarding the sedimentary units may be found below in the Magadi-area

Sediments section.

Fault Summary

The faulting history is an important aspect of the evolution of the rift and a

summary of the reported fault movements can be seen in Table 1 below and has been

plotted as displacement in meters versus time in Figure 22. In the plot, displacement on

western faults are represented by the blue bars, eastern faults by the red bars, and

displacements in the rift floor are represented by yellow bars. For Figure 22 the

movements are binned in half million year increments, so what may be listed as several

events in Table 1 below, may be represented by only one bar in Figure 22.

Understanding the timing of the faults is important as they define the rift

boundaries, confine volcanic flows, create sedimentary basins, and complicate the

stratigraphy and correlation efforts for the rift related geology. By narrowing the age

range in which the fault displacements took place in different areas, the evolution of the

rift can been looked at as a series of simple steps that create a complicated final picture as

in Figure 10.

Table 1: Major fault movements in the southern Kenya Rift

West Fault	Rift Floor	Eastern Fault	Age of movement (Ma)	Displacement (m)	Source
Kirikiti				20	
Kirikiti-Lengitoto-Sambu			0.6	700	Crossley 1979
	Grid faults		0.9-0.4	45	Baker et al. 1977a
	West of Emerit		1.42-1.2		Baker and Mitchell 1976
		Kedong and Kiriri	1.65-1.91		Baker and Mitchell 1976
		Esayeti-Kedong	2-1.7		Baker et al. 1977a
		Turoka-Ngong	3	500	Baker et al. 1977a
Kirikiti-Enkorika			5-3	820	Baker et al. 1977a
Sonjo-Sambu			Before 6.9 Ma	200	Crossley 1979
Naitiami			Before 6.9 Ma	250	Crossley 1979

One of the more interesting aspects of the fault timing is that the rift did not start

as simply a narrower version of the present rift geometry. There were at least 3 million

years between the displacements that formed the western rift boundary and those that

defined the eastern boundary. So for 3Ma, all evidence indicates that the rift existed as a

half-graben. Simiyu and Keller (2001) claim that the southern and central Kenya Rift (in

their paper taken to be south 1° North) is dominated by asymmetric grabens that have

western master faults (the western sides of the basins are deeper than the eastern sides).

The development of rift segments farther to the north of the present study area may have

a similar evolutionary course as seen here, where the western faults move first and accommodate most of the displacement. It may be possible that the time gap between the faulting of the western and eastern boundaries of the rift may be related to the crustal thickness on the two sides of the rift, as seismic experiments indicate that the crust to the east of Lake Magadi is significantly thicker than the crust to the west (35 vs. 40km, Prodhel et al., 1994; Khan et al., 1999). The nature of the faults on the opposing sides is also different. The major western boundary faults all experienced at least two periods of reactivation (Crossley, 1979) while some of the large boundary faults on the east only moved once. There is at least 1400m displacement on the western Sambu and Kirikiti faults, meaning that the basement rocks cannot be any higher than sea level. However, metamorphic rocks are much higher to the east, as the Singaraini Basalts are thought to have been erupted directly onto the metamorphic rocks and may be as thin as 60m near their eastern boundary (Baker, 1963). In fact, Baker (1963) mapped an outcrop of metamorphic rock at 1150-1200m elevation within the rift floor (Lebor, plane-table survey station) that is surrounded by exposures of Singaraini Basalt.

Baker et al. (1977a) provide discussion on how stress fields affect whether magma intrusion or faulting occurs. They note that fields of stability for intrusion and faulting are generally separate and there is "no condition under which magma can ascend and normal faulting can occur simultaneously" which explains the general observation that episodes of faulting and eruption alternate. This is discussed again in the Volume Estimates section below.

While the study area seams seismically and volcanically quiet at the present, a study done by Ibs-von Seht et al., (2001) recorded an average of 10 micro-earthquakes a

day over a period of 8 months. All originated from depths greater than 10km, with a significant amount of activity occurring down to 22km. An earthquake swarm was also recorded by this team between May and June 1998 where over 300 events were recorded per day and mapped epicenters traced a linear feature that is in the same strike direction as the grid faults. One of the events associated with the swarm produced and a surface crack to the northeast of Magadi that was several kilometers long and had vertical and horizontal displacements up to 30cm. In addition to seismic activity along the grid faults, some micro-quakes could also be associated with the Nguruman escarpment faults.

Volume estimates

A plot of erupted volcanic volume versus time can be seen in Figure 23 (the same plot can be seen in the paleomap images, Figures 16-21, with the data for the different time spans highlighted). Three different plots were made, one using areas measured directly from the digital geologic map (i.e., the exposed surface area), one using estimated areas of probable extent and the third showing cumulative volume. The Plateau Phonolites dominate in volume and were left out of the cumulative volume measure. It is interesting to note that it was not until recently that volcanic volume exceeded that extruded during the massive pre-rift phonolite eruptions. Additionally, no other flow of nearly that magnitude occurred in this area. In comparison, the other events were small and localized and it took around 10 million years before these small events surpassed the Plateau Phonolites in volume.

To facilitate analysis of the contribution of different volcanic rock types towards the overall erupted volume, Figure 24 was created. It is essentially the same as Figure 23, in that the bars represent volume versus time, except that the bars have been subdivided

to show the contributions of the different petrologic groups. As can be clearly seen from this figure, after the initial eruption of the Plateau Phonolites, phonolitic eruptions were an insignificant portion of the material erupted over the next 13 million years. It also demonstrates quite well the shifts in erupted material over time (with a seeming trend here of phonolites giving way to basalts, which then get surpassed by trachytes).

A number of authors have provided volume estimates for different units, total volume for sections of the rift, and even estimates of the required source material to create all the flows. A comparison of values given by different authors can be seen in Table 2 below. It should be noted that these different papers look at areas of differing sizes for their calculations. Baker et al. (1988) use the area from the equator to 200km south (to just south of Olorgesailie), Baker and Mitchell (1976) examine the area from 1° South to approximately 2.25° South for their volume estimations, and the volumes reported Macdonald (2003) are for the entire Kenya Rift.

The main area of study in this report is from 1° South to the Kenya-Tanzania border and thus corresponds most closely with the area considered by Baker and Mitchell (1976). However, units that were easily identifiable that extended out of the defined study area for this study were mapped in their entirety, and an effort was made to get a total estimate of the plateau phonolites despite their existence well outside of the study area in order to be comparable to estimates presented by Macdonald 2003.

It can be seen that there is a large discrepancy between the volume estimates obtained by Baker and Mitchell (1976) and this author for the Limuru trachytes. Based on Baker et al. (1988), it appears that the Mosiro trachytes, Gesumeti trachytes, and the lavas

of Saggerson's (1971) Middle-trachyte division (the Kabete, Karura and Tigoni

trachytes) were all correlated with the Limuru trachytes.

Table 2: estimated volumes in km^3, for various units and total volcanics from different authors including data from this study. Note that the Totals may not equal the sum of the boxes above, as a number of basalt and trachyte flows were not directly comparable to calculations done by previous authors, but are tallied into the totals to represent activity in the study area.

	Baker et al. 1988 (max estimate)	Baker and Mitchell 1976	Reported in Macdonald 2003	Guth 2007 (max estimate)
Limuru Trachyte	1230	1230		560
Plateau Trachyte	540	540		475
Kordjya, Ol Tepesi & Ol Keju Nero Basalts		340		220
Singaraini Basalt		330		685
Plateau Phonolites			25,000 – 50,000	40,000
Total basalt	700	670		2360
Total trachyte	6500	1770		1860
Total basalts + trachytes	7200	2440		4220

Adding those units to the volume calculation for the Limuru trachytes would

bring the total volume to 1060 km^3 which is closer to the estimate provided by Baker and

Mitchell (1976). These authors provide a breakdown of the values used in their volume

calculations, and while their approximate outcrop area of 1,200 km^2 is close to the

mapped area of about 930 km^2 (for the Limuru trachytes alone) in this study, they

estimated the total extent to be 4,100 km^2. Baker and Mitchell claim that their estimated

volume is based on the assumption that the flood lavas spread across the entire width of

the inner graben of the rift valley. Taking the other units Baker and Mitchell (1976) correlated with the Limuru trachytes for their volume calculations into account, the maximum total extent obtained here is about 3800 km^2, which is in close agreement with the value they used.

It can also be seen that the volume estimates made by Baker and Mitchell (1976) for the Ol Tepesi, Kordjya and Ol Keju Nero basalts combined is larger than the total of the values obtained in this study. However, by examining their geologic map for the southern Kenya Rift, it can be seen that units later identified by Crossley (1979) as the Ewaso Ngiro and North Kordjya trachyte, and by Crossley and Knight (1981) as the Mosiro trachytes, are all included as part of the volume calculation made by Baker and Mitchell for the combined basalts.

In addition to estimating volumes of outcropped or erupted volcanics, several authors have attempted to estimate the amount of parental magma needed to produce the volumes seen at the surface. Baker and Mitchell (1976) state that 19 parts of basaltic parental magma are needed to make one part trachyte flood lava via fractionation. So, 34,000 km^3 of basaltic magma would be needed to account for the 1800 km^3 of trachyte they estimated exists in the Southern Kenya Rift. A positive gravity anomaly and high P-wave velocities along the axis of the rift seemed to agree with a body of basaltic rocks under the rift. Baker et al. (1977b) suggested that the parental magma would likely exist as a body 15 km wide, 20 km deep and 100 km long under the axis of the rift, and that eruptions from this magma body would result in gravity faulting of the reservoir's roof. Baker et al. (1988) suggest that an order of magnitude more basaltic parental magma is needed assuming fractionation, and, knowing that, the source would equate to a body

70km wide, 86 km deep and 200 km long. Please see the discussion in the Volcanic gas estimates section for a further discussion of this supposed axial magma body.

According to Baker et al. (1977b) geophysical and geochemical evidence support the idea that magma intrusion into the crust accompanied rift formation, but, as noted above in the Fault Summary section, it was shown that, based on stress calculations, that magma ascension and normal faulting cannot occur simultaneously. Figure 25 shows the volume calculations and fault displacements on the same plot. However, the alternation of volcanism and periods of faulting mentioned by Baker et al., (1977a) cannot be seen as it is suspected that the bin size of 0.5Ma used to create the plot is too large to resolve a pattern.

Magadi-area Sediments

Sedimentary units comprise only a minor part of the rift fill, both in terms of age, with the oldest lacustrine units of the area dating back to 1.35 Ma in the Natron basin, (Thouveny and Taieb, 1986; Mora et al., 2003) and 780 ka in the Magadi basin, and volume. The Kenya rift is dominated by an extensive series of volcanics, with the oldest being around 15 Ma, that are related to the doming, and eventual rifting event that lead to the modern landscape. The sedimentary units are comparatively thin and recent, are mainly confined to grabens, and overlie these volcanic rocks. Due to grid faulting and sometimes patchy preservation, determining the chronology of these sediments is difficult and the chronological order of some of these units has been shuffled several times since Baker's original attempt in 1958.

Sedimentary formations around Lake Magadi include the Evaporite Series, High Magadi Beds, Green Beds, and Oloronga Beds, listed from youngest to oldest. The ages for each of these units, and how they were determined, can be seen in Table 3 on page 43.

The oldest lake deposits that occur in the Magadi basin are the Oloronga beds. These contain tuffs, carbonates and cherts and overlie the Magadi Trachytes (Baker, 1958). There is an area to the northeast of Lake Magadi where a trachyte flow was noted to overlie some Oloronga deposits (Eugster, 1980) and the contact between the flow and the lake beds was chilled to produce a 1m layer of glass which was dated by Fairhead et al. (1972). The obtained date of 780ka serves as a key date for placing the end of the Magadi Trachyte activity and the initiation of lake sedimentation in the basin. A young date on these lake beds of 300ka is presented by Behr and Röhricht (2000) from U/Th dating of a Hippopotamus tooth. These lake beds feature two carbonate boxwork layers (Potts et al. 1988) which Baker (1958) described as "honeycomb rock". While the lake deposits around Olorgesailie to the northeast have been known for years for the hominid artifacts found there, hominid artifacts have too been found in the Oloronga beds (Shipman et al., 1983; Potts et al., 1988; Potts and Deino, 1995) within the locality known as Lainyamok that is northwest of Lake Magadi (Figure 12, denoted by the star). At this site hominid teeth, a femur and Acheulian tools have been found along with a number of animal remains. Potts et al. (1988) provide a fairly detailed description of the Oloronga Beds associated with the Lainyamok site, including a stratigraphic section, and lists of the fauna found at this locality are provided by Potts et al. (1988) and Shipman et al. (1983).

The Green Beds are confined to the Magadi trough and the cherts they contain have been the subject of numerous studies (Eugster, 1967, 1969, 1980; Schubel and Simonson, 1990; Behr and Röhricht 2000; Behr, 2002). This formation was originally named the "Chert Series" by Baker (1958) but was then abandoned as a formal formation by Eugster (1969, 1980), who divided the cherts between the High Magadi and Oloronga beds. Recent papers (Behr and Röhricht, 2000; Behr, 2002) have again established the Chert Series as its own formation based on age dates intermediate to the Oloronga and High Magadi beds, and have renamed them as the Green Beds due to the greenish color of the silts and tuffs in this formation (Behr and Röhricht, 2000). This definition and naming has been retained in this report.

The most recent high lake level is represented by layers of brown silts and clays which belong to the High Magadi beds. Baker (1958) suggests that these deposits probably covered the entire basin, most of which have since been removed by erosion. These beds also include reworked sediments from the underlying Oloronga beds, and thus distinguishing between the two can be difficult. The High Magadi beds also contain the magadiite layers studied extensively by Eugster (1967, 1969, 1980), several layers containing tilapia remains (which are significantly larger than the stunted fish that live in today's lake) and, as noted by Baker (1958), some instances of hollow kunkar tubes which most likely formed around stems and branches of plants. Similar tubes were noticed during the 2006 field season on the track west of the North-West Lagoons. The High Magadi beds also host later stone age artifacts at a site termed Olkena located on the, mainly trachyte, peninsula that divides Lake Magadi (Barthelme et al., 2003). Blades, scrapers, micro-drills, grindstones, eggshell beads and burnt land-snail shells were found

associated with a sand and gravel unit located between the Oloronga and High Magadi

beds. The layer containing the artifacts was interpreted by Barthelme et al. (2003) as

being from a fluvial environment during a cooler, drier period with lower lake levels

(compared to Lakes Oloronga and High Magadi). Also found by these authors was a

burial cairn in the same area made of lava blocks, but unfortunately an age date could not

be obtained to link it with the artifacts.

The Evaporite Series is currently being deposited, and is represented by a large

trona deposit (hydrated sodium bicarbonate carbonate, $Na_3HCO_3CO_3 \cdot 2H_2O$) that

occupies the center of the Lake Magadi basin. This deposit is up to 40m thick and has

been mined by the Magadi Soda Company since 1911 (Magadi Soda website). Present

practice is to mine one area of the deposit for a number of years and then to move the

mining area. The previously mined area will recrystallize due to the continued input of

solutes from the hot springs, and over time, the pit created by mineral extraction can be

observed to close (Figure 26). This area is then again mineable, and is of even higher

quality then before due having more consistent crystal size and lack of interbedded muds

found in the original deposits.

Outside of the Magadi area, there are two notable sedimentary deposits located in

the present study area. In the Legemunge basin there are deposits associated with the

previous Lake Olorgesailie (Gregory 1921, attributed these beds to a 'Lake Kamasia';

Reported in Owen and Renault, 2000) that existed to the north of the extinct Olorgesailie

volcano. These lake beds are dated between approximately 1 – 0.5 Ma (reported in

Behrensmeyer et al., 2002) and contain numerous Acheulian aged hominid handaxes, and

a large deposit of diatomite.

Table 3: Sedimentary and Volcanic formations of the Lake Magadi basin and their ages

Unit	What was dated	Dating method	Age	Source
Evaporite Series	Tilapia	14C	4650 +/- 400	1
	Oncoids		5000	2^
	Trona		7100	3^
	Trona		9120	2
	Trona		10,010	2^
High Magadi Bed	Na-silicate	U/Th	6000 +/- 3000	4
			9310	2^
	Ostrich eggshell	^{14}C*	9940 +/- 60	5
	Ostrich eggshell	^{14}C*	10,300 +/- 100	5
	Total Organic Matter (TOM)	^{14}C AMS	10,800 +/- 120	6
	TOM	^{14}C AMS	12,090 +/- 120	6
			14,515	2
	TOM + authigeneous zeolites	U/Th	23,700 +/- 6000	6^
Green Beds	TOM + authigeneous zeolites	U/Th	40,000 +/- 6500	6^
	Lower chert	U/Th	98,500 +/- 20,000	4
Oloronga Beds	Hippopotamus tooth	U/Th	300,000	3^
	Lainyamok Khaki layer 1, An-feldspar	40Ar/39Ar isochron	330,000 +/- 6000	7
	Lainyamok Khaki layer 2, An-feldspar	40Ar/39Ar isochron	392,000 +/- 4000	7
Nyokie	Obsidian	K/Ar	0.66 +/- 0.04	8
Magadi Trachyte	Obsidian	K/Ar	0.78 +/- 0.04	8
	anorthoclase	K/Ar	0.92 +/- 0.01	7
Kordjya Basalt		K/Ar	1.66 +/- 0.05	9
		K/Ar	1.76 +/- 0.06	9
		K/Ar	2.17 +/- 0.10	9
Singaraini Basalt		K/Ar	2.31 +/- 0.10	9
		K/Ar	2.33 +/- 0.09	9
Kirikiti Basalt		K/Ar	2.5 +/- 0.2	10
		K/Ar	2.68 +/- 0.16	9
		K/Ar	2.7 +/- 0.2	10
		K/Ar	3.1 +/- 0.2	9

* uncalibrated, ^ reported in
1- Hillaire-Marcel et al., 1986, 2- Behr, 2002, 3- Behr and Rohricht, 2000, 4- Goetz and Hillaire-Marcel, 1992, 5- Barthelme et al., 2003, 6- Williamson et al., 1993, 7- Potts and Deino, 1995, 8- Fairhead et al., 1972, 9- Baker and Mitchell, 1976, 10- Crossley, 1979

In addition to the handaxes, which have been known for decades, a partial skull (possibly a small *Homo erectus* that lived between 0.97 and 0.90 Ma) was recently reported by Potts et al. (2004) and found in association with the handaxes. Due to the hominid artifacts and remains, these lake deposits have been the subject of a number of papers (Potts et al., 2004; Behrensmeyer et al., 2002; Owen and Renaut, 1981, etc…) and excavations continue at present.

In the Ol Tepesi Basin to the east of Legemunge, a very distinctive deposit from what Baker and Mitchell (1976) refer to as the Kedong Flood can be seen. This flood is thought to have resulted from the catastrophic release of water from the Kedong Basin near Suswa about 100ka and has been dated based on the lava flows that show scouring versus those that do not. This unit is very distinctive in the satellite images, but not as obvious when driving across the plain.

One additional unit of interest was noted in Prodehl et al. (1997) although it was insufficiently described to identify. While attempting to drill for a seismic shot point close to Lake Magadi, the team kept running into a very soft layer at shallow depths (depth was not quantified) so the drilling was relocated to 30m above the lake on one of the trachyte horsts. Drilling was accomplished through 30 meters of (presumably) trachyte before that soft layer was again encountered. No inter-volcanic sediments are described for the area, however, it may be possible that the drilling site was on one of the young lava flows that over-rode the old lake deposits like to the NE of Magadi (as dated by Fairhead et al., 1972 and as described by Eugster, 1980). It is interesting that the initial drilling attempts were at current lake level, they gained 30m in elevation and hit the same

soft layer 30m down which seems to indicate the trachyte flowed over a lake flat similar

to what exists today. However, that still begs the question of what the soft layer was.

Part II: A Characterization of the Lake Magadi Area

Lagoon Water analysis

The brines surrounding Lake Magadi have been of interest to scientists for a number of decades. Stevens did a number of water analyses for the spring brines (reported in Baker 1958) and calculated the input of calcium carbonate to the lake basin from the brines. Eugster's "Chemistry and origin of the brines of Lake Magadi" (1970) delves into the aqueous chemistry of the lake brines and rivers. In an earlier 1968 paper, Eugster and Jones note that the chemistry of the hotsprings had not changed in the 34 years since Stevens' report, and Stevens had reported that the springs had not changed in the 20 years prior to his paper. It should be mentioned however, that in a more recent report done to evaluate the geothermal potential at Magadi (McNitt et al., 1989), an unpublished work by K. Crane is said to have concluded that temperature and flow rates of the springs show both cyclic and progressive trends. These changes are linked to earthquake activity and the suspected opening or closing of upflow channels. Crane (1981) mentions that despite the claims by Eugster (1970) and Baker (1958), Stevens relayed through personal communication to her that there were indeed dramatic changes in temperature and flow rates of the springs. This paper by Crane makes mention of several interesting phenomena that are not known to be described elsewhere: an unusual feature termed the "bottomless pit" that existed before 1933, the fact that the Bird Rock Lagoon springs were much more active before 1948, and that in 1958 mud volcanoes and boiling geysers were noted near the south end of the lake. These events are linked by Crane to seismic activity in the area, rather than volcanic events. While Crane focused on

correlations of seismic events over 5 on the Mercalli scale, as it was noted before, Ibs-von Seht et al. (2001) recorded a number of micro-earthquakes over the span of 8 months which indicates a near constant seismicity of the region. With this constant background activity, it could be possible that the springs may show gradual changes due to constant micro-quake activity, but such small changes would require careful monitoring of the springs over a long period along in addition to monitoring of micro-quakes.

Based on the isotopic evidence, Eugster (1970) concluded that the bulk of the thermal waters are meteoric in origin and resulting salinity is a function of basin size, depth of circulation and the total inflow. Lake Magadi has a large evaporation area and probably a deep and slow circulation. Helium isotope analyses on the brines done by H. Craig (reported in McNitt et al., 1989) suggests that hot, mantle derived, gases are rising from depth and mixing with the waters supplying Little Magadi springs (those springs are supposed to have the deepest source). Craig suggests that the Little Magadi springs contain 46-47% mantle derived helium, while the sample from the southern end of Magadi had approximately 25-26% mantle helium. Also, the temperature of the Little Magadi brines at the surface springs is about twice that of the brines at the south end of Magadi (over 80°C versus around 40°C). There are not enough samples to draw significant conclusions, but it may be interesting to test if there is a general correlation between temperature of spring water and mantle derived helium (i.e. hotter springs would be expected to have a more direct connection with the heat source/ magma body and thus more mantle derived Helium, while cooler springs might be expected to undergo more dilution and thus have lower values of mantle derived Helium). Additional stable isotope analyses also indicate a difference between the spring sources at the southern end of

Magadi and those at Little Magadi. This isotopic evidence indicates either different brine origins or different mixing histories for the brines.

A variety of authors have conducted and presented water analyses for Lake Magadi. With the findings reported in McNitt et al. (1989) and by Crane (1981), it seems plausible that the spring chemistry may not be as stable as originally thought considering the temperature and flow rates have been seen to change. A brief comparison of the chemical composition of the spring waters based on analyses done by Stevens (1927 Unpublished, reported in Baker 1958) , Eugster (1970) and Wilson et al. (2004) can be found below in Table 4. While these authors analyzed for a number of chemical species, a short subset showing the $[Na^+]$ and $[Cl^-]$ was selected to allow for quick comparison.

As can be seen in Table 4 some springs yield pretty consistent measurements over the past 70-odd years such as the Fish Springs, South Western, and North West Lagoons. The others seem to vary quite a bit, but this may be due to various errors rather than actual changes in the springs. For example, Wilson et al. (2004) use a different naming scheme when referring to the springs/lagoons than do the geology papers, so exact correlation with individual springs is difficult. Also, it appears that the waters measured by Wilson et al. (2004) are those where tilapia were found living, and thus would not be sampled directly at a spring outflow, and in cases like Graham's Lagoon, Wilson noted that the water in the lagoon was layered due to water entering from two chemically distinct springs. One was hot and alkaline (45.3°C, 4500 mmol/L Na+, 1283 mmol/L Cl-), while the other was cooler and fresher (37°C, 102 mmol/L Na+, 20 mmol/L Cl-). Thus the waters that the fish were living in were a mixture of these, and based on the

temperatures and salinities, the hotter of the two springs had not been reported by the

other authors.

Table 4: Comparison of [Na$^+$] and [Cl$^-$] in Spring Waters at Lake Magadi Kenya. Values are expressed in mmol/L. Stevens (1932) did not provide totals for the sodium and chlorine ions, so values presented here are summations from measured species containing these ions.

Author/ Researcher	Year	Spring												
		Fish Springs		Grahams'[1]		Bird Rock[2]		South West		Western[3]		North West[4]		Little Magadi	
		Na$^+$	Cl$^-$	Na	Cl	Na$^+$	Cl$^-$	Na$^+$	Cl$^-$	Na$^+$	Cl$^-$	Na$^+$	Cl$^-$	Na$^+$	Cl$^-$
Wilson	2004	335	113	978	693	326	203	454	190	183	46	390	156	372	192
Jones	1977	330	102	171	44	685	222	583	183	436	138	356	112	2390	807
Stevens	1932	335	103	570	180	521	267	566	180	283	83	400	126	511	158

*Note: The spring names used are those commonly used by geologists and are the names shown in one of Baker's sketch maps (1958). However, the names used by Wilson et al. (2004) differ in some cases and correlations made are noted here:
1: Sports Club Lagoon
2: South East Lagoon
3: Wilson Lagoon
4: Western Lagoon

Direct spring and lagoon comparison is further made difficult by the number of

small seeps and springs in an area, the drastic change in salinity and temperature that can

occur in a short distance and the fact that the lagoons (such as Graham's) can have

distinct and well developed density layers in water depths of only 4cm (Wilson et al.

2004 provide an interesting anecdote on how they discovered that this was the case).

Trying to compare spring and lagoon composition over time would require careful and

consistent measurements preferably by one investigatory team, or a group of researches

that agree to define and sample the waters in the same manner.

Volcanic gas estimates

As noted above in the Water analysis section, the helium ratios seen in the hotsprings around Lake Magadi indicate some input of mantle-derived gases. Based on the average gas compositions outgassed by magmas (Symonds et al., 1994), magma-derived carbon would also be expected in the spring waters.

The axial gravity high used by Baker et al. (1977b, 1988) to support the existence of a parental magma body under the rift has been given further consideration with the recent seismic projects, such as the KRISP (Kenya Rift International Seismic Project) studies (Prodehl et al., 1997; Simiyu and Keller, 1998, 2001; Khan et al., 1999) in the southern Kenya Rift which have allowed for imaging of the subsurface. The axial gravity high has been noted since 1972 (Darracott et al.) and has been modeled since then by a variety of authors (Baker et al., 1977b, 1988; Swain, reported in Macdonald 2003) as resulting from a massive dike injection zone, which is expected to occupy 22-26% (9-10 km) of the rift width and go down 22km to possibly contain 135,000 km^3 of basaltic material (Swain, reported in Macdonald 2003). This seems to be in close agreement with the volume estimation made by Baker et al. (1988) but has dimensions closer to that estimated by Baker and Mitchell (1976). However, Simiyu and Keller (1998) argue that there is no evidence from the KRISP studies to support the presence of crustal-scale dikes and that most of the gravity and seismic data can be explained by the presence of an intrarift horst. At Magadi, this horst divides the rift valley into 2 basins, with the western basin being 3.5 km deep and the eastern one being only 2.0 km deep. Simuyu and Keller do not argue against the presence of dykes in the crust, and indeed they should exist

given the magnitude of the volcanism present, only that they are not the major cause of the gravity anomalies as previously thought.

Regardless of the cause of the gravity anomaly, it is generally accepted that there are intrusive bodies of some magnitude within the crust. In addition to dikes and intrusive bodies within the crust, underplating of large volumes of magmatic material near the Moho between Lakes Baringo and Magadi is expected, and would explain why the expected crustal thinning is not readily seen on seismic studies as mentioned in Prodehl et al., 1997 (Simiyu and Keller, 2001). A seismic tomography study of the Magadi area presented by Green et al. (1991) supports the presence of gabbroic intrusions between 10-35 km depth. For comparison, the Moho is expected to be around 35km depth in the Magadi region (Prodehl et al., 1997). Keranen et al. (2004) performed a similar seismic tomography study in the Main Ethiopian Rift as part of the EAGLE project (Maguire et al., 2003) and also imaged high velocity bodies along the rift axis at 10 km depth that were interpreted as gabbroic intrusions. It is thought that these large mafic bodies under the rift axis may be the precursors to forming seafloor spreading ridges. Importantly for volcanic gas estimates, Keranen et al. (2004) conclude that the crust overlying the magma bodies can be at maximum 30% dikes.

Gerlach (1989) estimated that the initial CO_2 composition of basalts in the Afar region (before any degassing at depth) was 0.12 wt % and that degassing could occur at depths less than 11 km. Approximately 85% of that CO_2 could be degassed at depth. Using these figures and an estimated basalt source 2.7 km wide (derived from estimating that the width of 9km presented in Macdonald, 2003, contained at maximum 30% dikes as claimed by Keranen et al., 2004), 10 km deep and running the length of the Magadi

basin (35.5 km), a potential maximum source of carbon can be (very roughly) estimated. This amount of magma under Magadi has the potential to release approximately 6×10^{13} moles of carbon through degassing (calculations can be seen in Appendix G). The general idea is that these magmas degass at depth, and these gases rise through fissures and interact with the ground waters. Bailey and Macdonald (1987) comment on the high CO_2 flux through the Kenya rift and mention that carbon dioxide leaks from the entire length of the rift. Additionally, unlike normal volcanoes where H_2O is the dominant gas species, Bailey and Macdonald (1987) also note that at volcanoes like Nyiragongo and Ol Doinyo Lengai, which are both situated in the rift, CO_2 is the dominant gas. An influx of CO_2 will acidify waters through the formation of carbonic acid which will then leach minerals from the surrounding rocks as the waters ascend. The alkali volcanics that are common in the Southern Kenya Rift are higher in sodium, and the leaching of these volcanics by acidified waters may explain the alkaline waters of many of the rift lakes.

It is also of interest to estimate the amount of carbon currently locked away in the trona deposits of Magadi. With an area of 77.7 km^2 and an estimated average trona thickness of 25m , there are about 3.7×10^{13} moles of carbon stored in a deposit of this size. While these are all rough estimates, it seems likely that the magma under Magadi could produce more than enough CO_2 to account for all the trona in the basin.

Based on the helium gas analyses done by H. Craig (reported in McNitt et al., 1989), it seems likely that the hottest brines, which also have the largest amount of mantle-derived helium, are from waters with a more direct connection to the magmatic heat source at depth than the cooler springs with less mantle-derived helium. These

cooler springs would probably experience more mixing with meteoric waters that would simultaneously decrease the temperature and alter the helium ratio.

While there is some debate about the size, shape and placement of magmatic intrusions in the crust (Baker et al., 1977b, 1988; Fairhead and Girdler, 1972; Green et al., 1991; Ibs-von Seht et al., 2001; Keranen et al., 2004; Simiyu and Keller 1998, 2001; etc…) no author totally discounts their presence as the amount of surface volcanism requires that there be magmatic alterations of the crust; it is simply the scale that is under debate. For simplicity, the measurements given in Macdonald (2003) were used in the calculations and modified to account for the estimation made by Keranen et al. (2004) that the crust above the main magmatic bodies (which are situated at, or below, the limit for degassing to occur) can contain, at most, 30% dikes.

Lake Magadi Biology

Lake Magadi has also become a site for recent numerous studies on extremophile/alkaphile bacteria living in the lake. Dubinin et al. (1995) collected and cultured microbes from Magadi, and found that a number of alkaliphilic cyanobacteria, mainly from the genus *Spirulina,* lived in the lake waters. A list of the bacteria and diatoms that have been noted to exist in Lake Magadi in both modern and ancient times, can be seen in Appendix H. A similar listing was created by Baumgarte (2003) and, being a Doctoral dissertation, provides a comprehensive look at the microbes of soda lakes, with examples from Lake Magadi being discussed explicitly, in her introductory chapters.

Dubinin et al. (1995) present a finding of particular interest that some unicellular forms of cyanobacteria undergo significant morphological changes under different environmental conditions. Changes that were induced by changing environment included

alterations to cell size, color and morphology, among other cell characteristics, and made some species easily mistakable with others. This could provide additional difficulty for identifying microfossils in the cherts and sediments around Magadi, as lake level, salinity and pH have fluctuated throughout the history of the lake (Barker et al., 1990; Icole et al, 1990; Roberts et al., 1993; Trauth et al., 2005; Williamson et al., 1993). Jones and Grant (1999) discuss some of the different bacterial species and their roles in the carbon, sulfur and nitrogen cycles. They note that there is a distinctive difference in the microbial communities between Magadi and more dilute lakes like Nakuru to the north. Behr and Röhricht (2000) identified a number of coccoid cyanobacteria preserved in the Green Bed cherts; *Pleurocapsa, Gloeocapsa polydermatica, Entophysalis granulose* and *Synechococcus,* which are all mat-forming organisms, and *Chroococcus minor*. Also found were the mat-forming *Microcoleus* (a filamentous cyanobacteria), *Phormidium* and *Schizothrix*. These mat organisms were the most abundant seen in the samples; however, *Micrococcus* and *Micromonospora* bacteria and *Hyphomicrobium* were also identified. Diatoms were rare (only one genus, *Navicula*, was recognized) and a number of coccoid and rod-shaped cells were seen but could not be identified. Behr (2002) continues the discussion of the biologic remains found in the chert, and, in addition to the micro-organisms mentioned in his previous paper, *Microcystis*, a free-floating unicellular genus, is also identified.

In addition to the study of the lake's microbial communities, there have also been a number of biologic studies on the tilapia fish that live in the extreme Magadi environment. Gikunju et al. (1992) examined the fluoride concentrations in the tilapia. Franklin et al. (1994) investigated the oxygen consumption of Tilapia from Magadi, and

found tilapia living in pools over 42°C. It was noted that oxygen consumption by the fish

increased at higher temperatures and a gulping behavior observed indicated that the fish

use aerial respiration to supplement their O_2 needs. Wilson et al. (2000) found that the

tilapia in Magadi are separated into three habitats that are divided by the trona deposits,

with genetic studies showing an extended period of separation between the Fish Springs

and Southeast Lagoon populations. Wilson et al. (2000) also found that Fish Springs

tilapia have an airbladder to do supplementary respiration, they excrete urea instead of

ammonia due to the high pH of the water, and these fish also have the highest recorded

routine metabolic rate for a cold-blooded bony fish. Anatomical differences between the

gills of the Fish Springs and Southeast populations were also observed. At the time of this

thesis however, the third tilapia population in the Southwest lagoon had not been studied.

Walsh et al. (2001) conducted a study focused on the urea production of Magadi tilapia

and found that their urea excretion rates were similar to that of mammals. Most fish can

get rid of ammonia directly, but a high pH environment like Magadi would prevent the

direct expulsion of ammonia. Urea is normally produced by mammals as a way of getting

rid of ammonia, as it is a much less toxic waste product. The Magadi tilapia have

adapted to this harsh environment by producing urea instead of ammonia, and the fish

collected for this study continuously excreted urea (rather than in discrete pulses), with

most of the nitrogen exchange occurring by the gills.

A 2004 paper by Wilson et al. goes into further depth with the genetic analysis of

the Lake Magadi tilapia, provides a good overview of earlier studies, and also presents a

brief analysis of the spring waters as seen above in the discussion about the Lagoon

waters. It should be noted however, that the spring names used in Wilson's paper differ

from the names commonly used in the geologic reports. Correlations between the lagoon names used in Wilson's paper and those seen in the geologic reports can be seen in the Table 4 notes above.

Seven biologic samples were collected during the 2006 field season in order to generally categorize the growths around the hotsprings. During the 2005 field season, it was noted that there were several distinctive types of growth (different shades of green, swaths of magenta etc.) surrounding the hotsprings. The original intent was to pick one hotspring and map the changes in fauna away from the vent as temperature and water depth changed. However, the distinct changes of color seen in 2005 were not observed in 2006, and it was decided that the relative positions of the mats probably shift throughout the year. Notably, the vibrant red/magenta colored mats seen in 2005 seemed to be mostly gone, or covered by green growth during the 2006 field visit. When the hotsprings were visited in 2005, it was wet enough that it was nearly impossible to drive across the mudflat to get to the springs, but by the time the springs were visited in 2006, it was dry enough to drive. It is possible that as the area dries out the populations shift or change in dominance.

Instead of the intended sampling plan, samples were taken of the different representative growths seen around the hotsprings in an attempt to generally categorize the organisms that live there. A water sample was taken at each collection site in addition to the biologic sample. Water temperature at each site was measured, and pH, Na+ and K+ were measured for all but 1 sample within 6 hours of collection. The biologic samples were preserved with a 2% solution of formaldehyde formed by mixing formalin with the requisite amount of spring water at the sample collection site. While glutaraldehyde

would have been the preferred preservative, with the difficulty of international travel with

chemicals, it was determined that obtaining formalin in Nairobi would be most efficient.

Samples were examined under wet mount with a Zeiss Axioplan2 microscope and

digital micrographs were acquired using a MTI 3CCD camera with Scion ImagePC

software (release Beta1a for Windows95). The digital files were calibrated by taking

images of a calibrated slide at different magnifications and determining the number of

pixels between the scale bars. Because the camera is at a fixed distance (assuming that

stage height is not altered between images of the same magnification), it was determined

that the length represented by a pixel should not change at a given magnification setting.

It was also determined that the length represented by a pixel should change linearly with

the change in magnification. To test both of these assumptions, up to three images of the

calibrated slide were taken at a given magnification with refocusing between each, and

the number of pixels between the scale bars were measured and compared. Pixel counting

was done with the "Calliper Rule" in the GraphicConverter image program to eliminate

human error in manually counting pixels. Image taken by the camera attached to the

microscope system are rotated with respect to the view through the microscope, so care

was taken that the pixel measurements were taken perpendicularly to the imaged scale

bars. Measurements were repeated multiple times per image to test precision. Once a

measurement was obtained for the 100x image, predicted pixel calibrations were made

assuming a linear relationship between pixel size and magnification to compare with the

measured results.

It can be seen in Table 5 below that the predicted number of pixels per scaled

distance changed linearly as expected, and since measurements were stable between

images taken at separate times, it seems justifiable to use this method for calibrating the

digital images.

Table 5: Pixel calibration measurements for digital microscope images taken with a MTI
3CCD camera on a Zeiss Axioplan2 microscope.

Magnification	# of measurements	Rounded Average # pixels/ 0.01mm	Predicted # pixels/0.01 mm	Error between predicted and measured (! m)
100x	6	9	-	-
160x	6	14	14.4	0.29
400x	6	35	36	0.29
640x	6	56	57.6	0.29
1000x	3	87	90	0.34
1600x	3	141	144	0.21

Scale bars were added to the digital images of the biologic samples in GraphicConverter,

again using the caliper rule tool to ensure that the added bars were the correct number of

pixels long.

Characterization of Lake Magadi Biology

Samples were identified by visual comparison, with the goal to achieve

identification of at least genus-level. Results are shown in Table 6 and images of the

collected samples and their proposed identifications can be found in Appendix A (Figures

27-33).

The hypothesis that the biologic growths around the hotspring could be

characterized and identified based on visible properties such as color, texture and habit,

seems to be validated by the results. All the samples represented distinctive forms seen in

the springs, and indeed, each sample seems to be dominated by a different organism

(rather than seeing the same organism forming two very different growths or samples

being well mixed biologically). When attempting to identify the samples, organisms

represented in Appendix H were given preference as they are already known to occur in Lake Magadi. However, given the number of papers in recent years detailing the discovery/isolation of new bacteria from the lake (Florenzano et al.., 1985; Zhilina et al. 1996; Kevbrin et al., 1998; Grant et al., 1999; Zhilina, et al.,1998; Zhilina, et al., 2001a; Zhilina et al., 2001b; Boltyanskaya et al., 2004; Bhatnagar and Bhatnagar, 2005), it seems very plausible that certain genera or species may have been overlooked or discounted during the identification process if they had not been mentioned in the available literature.

In addition to the water parameters given in Table 6 below, a few dissolved oxygen (DO) measurements were taken during the 2005 field season. While the DO measurements cannot be correlated directly to the exact locations where the 2006 samples were collected, it still may be instructive to discuss them. The measurements were taken in the field from the same general springs as where samples A1-A5 were collected. Measurements were made with an Extech Instruments Heavy Duty Dissolved Oxygen Meter, model 407510. Measurements ranged from 0.5 to 0.9 mg/L DO, however, the stated accuracy of the oxygen meter is +/- 0.4 mg/L, so it cannot be stated if there really is a difference in DO between the springs in this area. These measurements have not been corrected for elevation or salt content, however, temperature is the main determining factor for how much oxygen can be held in solution. This range of DO represents between 10-18% saturation based on an elevation of 600m, temperature of 45-48°C and 8 ppt of salts (obtained from the average sum of total Na+ and K+ as measured for biologic samples A1-A5). These waters are oxygen poor, which may, in addition to the high temperatures, explain the lack of tilapia near the hotspring vents. While no quantitative

measurements were taken, the DO meter gave a spike in readings when the probe tip

brushed against gas bubbles trapped by some of the bacterial mats in the springs. As the

microbes collected were identified, for the most part, as photosynthetic cyanobacteria, it

is expected that oxygen would be produced during the day and possibly trapped in the

microbial mats.

Table 6: Basic water conditions for the different cyanobacteria samples in addition to in-field sample description and proposed identification. Refer to Figures 27-33 for images of each of the samples and their proposed identifications.

ID #	Water Temp °C	pH	Na+ ppm	K+ ppm	Sample Description	Proposed Identification
A1	41.5	10.2	7900	98	Grew along low linear ridges in standing water. Green-brown in color.	*Oscillatoria*
A2	42.8	10.2	7500	86	Yellow-green, floating on the surface near the springs. Trapped large bubbles in a slimy film.	*Synechocystis*
A3	41.8	10.3	7500	86	Red mat, right at the mouth of a small seep. Almost completely covered by a dark green growth.	*Calothrix**
A4	43.4	10.3	7500	82	Purple in color, encrusting a small rock, mostly covered by green growth.	*Synechococcus** and *Spirulina subsalsa*
A5	44.4	10.2	7900	90	Dark green gritty pillars right near hot spring. Only growth in area and was spotted in other bare locations near hotsprings with a fine gravel substrate.	*Chromatiacaea vinosum* and *Phormidium*
A6	34.6	10.4	8250	100	Red-brown mat-forming variety found near very weak springs. Did not seem to have any competition.	*Myxosarcina*
A7	NA	NA	NA	NA	Floating green variety in the fresher pools near the salt concentration ponds.	*Spirulina*

*Note, while these identifications seem to be a good match with what was imaged under the microscope, it is possible that intended sample was not obtained. For example, what was thought to be a sample of a red mat-forming organism was identified as Calothrix, which is a cyanobacterial, and the actual red, mat-forming organism may not have been identified.

One interesting observation is that Sample A6 started in the field as a dark red/brown color, but after collection, preservation, and storage at room temperature for a few months, the sample had altered to green in color with translucent edges. While the exact cause of the color change is unknown, it may be possible that accessory light harvesting pigments might have degraded. Identifying sample A6 also proved troublesome as none of the microbes mentioned in the literature matched the characteristics of this mat-forming organism seen commonly around the shore of the lagoons. The ovoid cells in Sample A5 were difficult to identify as there were several unrelated genera that looked similar. A7 was collected from a fresher pool located near the salt ponds and appears to be composed of Spirulina, which is an important food source for the flamingoes in the area (Ndetei and Muhandiki, 2005; Koenig, 2006). While water testing was not performed on the A7 sample during the same time frame as Samples A1-A6, it seems logical that the sampled water was fresher and cooler than the samples taken directly from the springs sampled for A1-A6. This is based on the abundance of birds in the A7 pool, the relative deep nature of the pool (the springs sampled for A1-A6 were quite shallow, where as at A7 the bottom could not be seen), in addition to the larger size of the tilapia at this location. Maina et al., (1996) studied tilapia found in Lake Magadi, and found that even though the fish in Fish Springs Lagoon (where sample A7 was collected) were genetically the same as fish found in a water holding tank (the fish would travel through the water intake pipes), the fish in the holding tank were over twice as large due in part to cooler water temperatures making for a less harsh environment.

Of the identified samples, *Synechococcus* and *Phormidium* (a.k.a., *Schizothrix*) were noted by Behr and Röhricht (2000) to be present in the 98,000 year old Magadi cherts. These two organisms are still living at the modern springs and are also part of the geologic history of the area. Additionally, *Synechococcus* was described as being a major precipitator of carbonates by Thompson and Ferris (1990) in addition to having the ability to alkalinize their surroundings through photosynthetic metabolism. This increase in alkalinity occurs due to the use of HCO_3^- by *Synechococcus* as a primary carbon source. Also, due to the increase in pH, Magnesite ($MgCO_3$) was also noted by Thompson and Ferris (1990) to be associated with dense colonies of *Synechococcus* in experiments. During a period of 72 hours, these cyanobacteria were observed to increase the pH of their surroundings from 7.97 to 8.57. A variety of other interactions can occur between biological agents and their environment, however, it is not within the scope of this research to list all the potentials. Of particular interest, Janusz (2004) showed that bacteria (specifically Natrialba magadii, from Lake Magadi) can influence the morphology of zeolites as they use the minerals for cations and water exchange during dry periods and Heinen and Oehler (1979) discuss the roles microbes can play in general, in the silica-cycle. Not only do microorganisms get preserved in the geologic record, they also alter their environment and can help deposit minerals. While the exact role of these biologic communities with respect to the geologic history of the Magadi basin is unknown, they probably did affect the stability and deposition of certain minerals through time.

Conclusions

While many topics were covered during the course of this study, there were three main products derived from this research:

1. A geologic model detailing the evolution of the Southern Kenya Rift produced through utilization of actual field work performed by previous authors/researchers which was then synthesized to form a more complete picture of events in this area.

2. Demonstration that combining vintage geologic maps with satellite imagery is a successful tactic to produce updated geologic maps that are more detailed and versatile that the originals.

3. A reworking of the volcanic and sedimentary stratigraphy using numerous age dates to produce a cohesive account of the volcanism and sedimentation in this area over the past 15 million years.

Evolution of the Southern Kenya Rift:

One of the continuing questions concerning rift valleys is the nature and timing of their evolution and formation; when and how do they form? A key step in understanding this is to look at the timing of rift-related volcanism in a spatial context. While this work does not cover the entire East African Rift, nor even the entire Kenya Rift, it does however take beginning steps in that direction by showing that the lower third of the Kenya Rift experienced three discrete periods of volcanism over the past 15 million years. The first eruptive phase occurred pre-rifting with the oldest units in the area being

the 15Ma melanephelinites of the Kishalduga and Lisudwa formations. These two

formations however, were of fairly limited extent, and of the volcanism during this first

eruptive phase prior to 10Ma, the Plateau Phonolites that were erupted over much of the

Kenya Dome between 13-10Ma dominated volumetrically. Following this initial activity,

the area was volcanically quiet until, what could be considered the second phase, took

place after the initial rift faulting. This initial faulting only defined the western boundary

of the rift and occurred around 7Ma. The oldest of the second phase volcanics were the

Lengitoto trachytes which were erupted into the early half rift graben. Since this flow was

confined by the escarpment on one side, and probably also erupted from fissures of

similar orientation, this formation exhibits an elongated morphology based on present

outcrop area. This is in contrast to the earlier flows that were probably erupted onto flat

or gently sloping terrains, and seemed to form lobate shapes as demonstrated by the

Nairobi Phonolites.

The third phase occurred after the formation of a complete rift graben when the

eastern side finally faulted some 3 million years after the initial movements that defined

the western boundary. It is tentatively speculated that the reason for the extended period

between the events that defined the west and eastern boundaries of the rift may be related

to the difference in crustal thickness on the different sides, with the eastern side having

the thicker crust. During the most recent 3.5 Ma, the amount of rift-related volcanism

volumetrically surpassed that of the earlier Plateau Phonolites. However, the Plateau

Phonolites are thought to have erupted most of their bulk in less than 1 million years

(Fitch et al., 1978) whereas the recent volcanism was erupted in relatively small, discrete

eruptions. Volcanic activity in the study area has been quiet since around 600 thousand

years ago, except for the building of Suswa to in the north which started around 240 thousand years ago. Since then most of the geologic activity has been related to the expansion and contraction of lake levels in the rift and the deposition of sedimentary formations.

Digital mapping

This study also showed that vintage geologic reports and maps can be combined with modern satellite images to create digital maps that are often more detailed and accurate than the original maps. Quadrangle maps can be improved by using 15 meter Landsat images as base-maps, which are easily available, free, and allow mapping of detail on a level similar to, or better, than the original 1:125,000 scale maps. Additional improvements can be made when more recently published articles, with smaller-scale or sketch maps that make updates to geological boundaries, are assimilated into the mapping process. There are also benefits inherent to digital data such as the ability to easily manipulate boundaries, use the same digital files for multiple purposes (such as showing time sequences or adjusting formation colors, layers or labeling to create maps for varied uses) and to easily share/distribute data and produced maps.

Time series maps were made possible through the collection of over 300 published age dates covering the entire Kenya Rift. A concerted effort to gather age dates for this part of the rift has not been made since 1971 when Baker et al. published "Sequence and geochronology of the Kenya rift volcanoes". Many new, and better defined, age dates have been published since then, and they lead to an enhanced view of the timing of rift volcanism and sedimentation. Also important to the mapping process

was the correlation of geologic units across map boundaries as many units have been

added, renamed and/or subdivided since the original maps were produced.

An extensive library of age dates, in addition to the digital map data that spans old

map boundaries seamlessly, can lead to a number of interesting applications. Examining

volume of erupted volcanic material or fault displacements versus time are two such

applications that can provide an instructive look into the evolution of the rift. Such

exercises would be even more useful when combined with data covering larger stretches

of the EARS.

These techniques are probably widely applicable to other areas and were made

successful in the Southern Kenya Rift due to the extensive library of previous works that

could be drawn upon, relatively young formations that enhanced the definition between

formations, and the sparse vegetation and dry seasons that allowed for clear satellite

views. The wide application of these methods is enhanced by the free satellite data

available online. While the resolution is not fine enough to map small areas in detail, it is

quite sufficient for mapping quarter degree areas. For areas lacking the substantial

number of previous works like those available for the Kenya Rift, it may be possible to

make a tentative map using similar techniques prior to starting field work.

Stratigraphy

In order to combine the various geologic maps that covered the study area into a

single, cohesive, map, a correlation table had to be made. Unit names and boarders did

not always line up so decisions had to be made as to what map had the borders and unit

designations preferred for mapping. In general, the newest maps (those found in journal

articles) were preferred and used to update the older Kenya Geologic Survey (KGS) maps

(it should be kept in mind that while the publishing dates for some of the KGS reports are listed as 1991, the actual maps were created decades earlier and do not reflect updates made by publications from the 1970's-1980's). The compiled age dates, many of which were produced after the initial mapping efforts, were combined with the correlation table to construct a comprehensive stratigraphy for the entire study area. Formation symbology, for use in map construction, has been totally reworked for the mapping project to account for the better constrained formation ages, better knowledge of the stratigraphy/geologic history, and the fact that the newly produced map represents an area previously covered by 6 quarter degree maps.

The stratigraphy of the Magadi area has been changed a number of times since Baker's Kenya Geologic Survey report on the area (1958). Most of the uncertainty has been associated with the sediments that have patchy preservation and limited aerial extent. Additionally, a lot of early work done to define the sequence of formations was completed prior to the collection of age dates from sediments of the rift valley. The preferred sedimentary stratigraphy for the Magadi area is that presented in Behr and Rohricht (2000), which also demonstrates that the original sedimentary order presented by Baker (1958) over 40 years earlier was on target, with the minor change of the renaming of the Chert Series to the Green Beds.

Age dates are clearly a valuable tool in straightening out the geochronology of this area, which otherwise can be hopelessly complicated. It was for this reason that age dates covering the entire Kenya Rift were compiled. While many of the formations do not appear in the study area covered by this thesis, starting a compilation may help continue similar studies up the Kenya Rift.

Biology

There is obviously a complex and dynamic microbial population at the springs of Lake Magadi. This study has demonstrated that the microbiology of the hotsprings at Magadi can be distinguished in the field by visual clues such as growth shape, texture, color and location. Only seven biologic samples were analyzed for this study, but each sample was unique both macro- and microscopically. One commonality was that the bulk of all samples were identified as cyanobacteria. The only actual algae seen during this investigation were a few scattered diatoms that were not important constituents of the growths sampled. With new bacteria being isolated from Lake Magadi on a fairly regular basis, it is safe to say that there is a lot more to discover about the microbiology of the lake, especially with regards to bio-geologic interactions. The analysis provided here regarding the biology of the Lake Magadi hotsprings is in no way exhaustive, but could provide a useful springboard for future research regarding the unique microbial populations of this lake.

Future Work

Lake Magadi and its surrounding area still present a number of opportunities for future work. While Magadi has been a shot point for the large scale KRISP studies, there has yet to be a detailed seismic study of the lake basin and surrounding area. Having a detailed view of the bottom of the Magadi trough would allow for a more complete analysis of core data from the lake. It would also be instructive to perform seismic studies near the chert dykes in the South East Lagoon at Magadi. If there really are chert

dykes/diapirs as Behr and Röhricht (2000) believe, then that should be easily visualized using seismic techniques, which could, in addition, possibly identify their source horizon.

There are also opportunities for isotopic studies in the area. Alleman et al. (2005) examined the silicon isotope fractionation in Lake Tanganyika, which is in the western branch of the EARS. They found that biologic activity preferentially uses ^{28}Si and thus enriches the surrounding waters in ^{29}Si and ^{30}Si. It would be interesting to examine the cherts around Lake Magadi, especially to compare the magadiite with the Green Bed cherts, to see if there is any isotopic evidence to support the idea of biologic mediation for the Green Beds and/or inorganic formation of the magadiite and associated cherts.

Also of interest is some of the work regarding desert varnish dating. One study (Harrington and Whitney, 1987) suggests that by comparing the average thicknesses of the varnish an age can be estimated. In the Magadi area, the Green Bed cherts that are prominently exposed as dikes seem to have a dark varnish or coating on them, and it may be instructive to see if they give consistent thickness/ages across the outcrops. If consistent varnish thicknesses are obtained, it may be possible to estimate when the chert was exposed or when the siliceous material hardened, which could give further insight into the formation of this unit. In addition to the possible desert varnish studies, Brueckner (1979) mentioned that it may be possible to date cherts using Rb-Sr isotopes. While it seems fairly secure at this point that there are several generations of chert at Magadi, it could be useful to try dating the chert directly. There are also other opportunities for age dating which would be beneficial in filling gaps in the current knowledge. There are a number of formations whose ages are only constrained by one age date which may have been performed several decades ago.

Continued mapping along with plotting volume and faulting versus time for larger sections of the rift could lead to analysis or recognition of patterns in rift development. For example, it is reported in Keranen et al. (2004) that the Ethiopian Rift also experienced a hiatus in volcanism of about 3Ma and it would be interesting to see if this hiatus corresponds with breaks in volcanism in the Kenya Rift.

Crane (1981) mentions that the hot springs at Lake Magadi are large enough to monitor by satellite, and thus it might be possible to monitor changes in heat flow over time and through the southern Kenya Rift. If it was considered possible in 1981, advances in the spatial resolution of thermal imaging satellites in the time since then would be an added benefit of attempting such a study.

Additionally, there exists core data for a large number of exploratory holes drilled by the Magadi Soda Company, in addition to cores drilled and examined by a number of authors over the past 50 years (Baker 1958, Surdam and Eugster 1976, Barker et al., 1990; Damnati et al., 1992; Roberts et al., 1993; Williamson et al., 1993; Damnati and Taieb, 1995). These core data could be combined to provide detailed sediment mapping across the Lake Magadi basin for a detailed treatment of environment change and basin dynamics.

Obviously the microorganisms at Magadi could receive a more thorough treatment, especially in terms of seasonal growth cycles and roles in the formation of geologic units. Identification attempts could also be improved by using more advanced imaging techniques to better highlight cell structures in addition to molecular studies of the populations present at the Magadi springs.

A. Guth, MS Thesis, 2007

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Appendix A: Figures
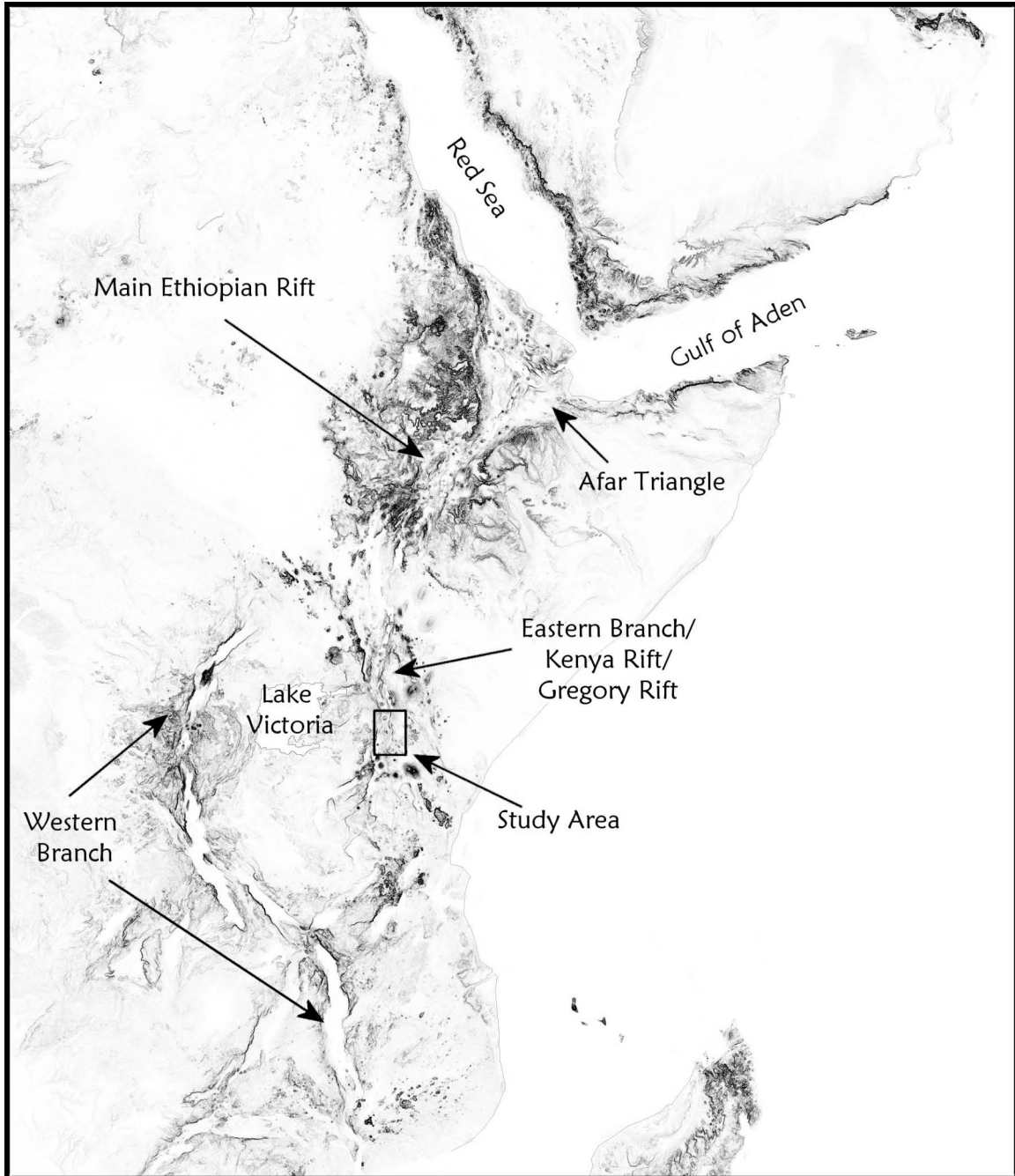
Figure 1: Shaded Digital Elevation Model (DEM) of Eastern Africa showing the rift system. To the north, the typical three-arm rift is apparent with two of the arms already having been flooded to form the Red Sea and the Gulf of Aden and with the third arm going to the south as the Main Ethiopian Rift. This branch splits around the Lake Victoria region to form the Eastern and Western branches, with the study area being a part of the Eastern Branch.
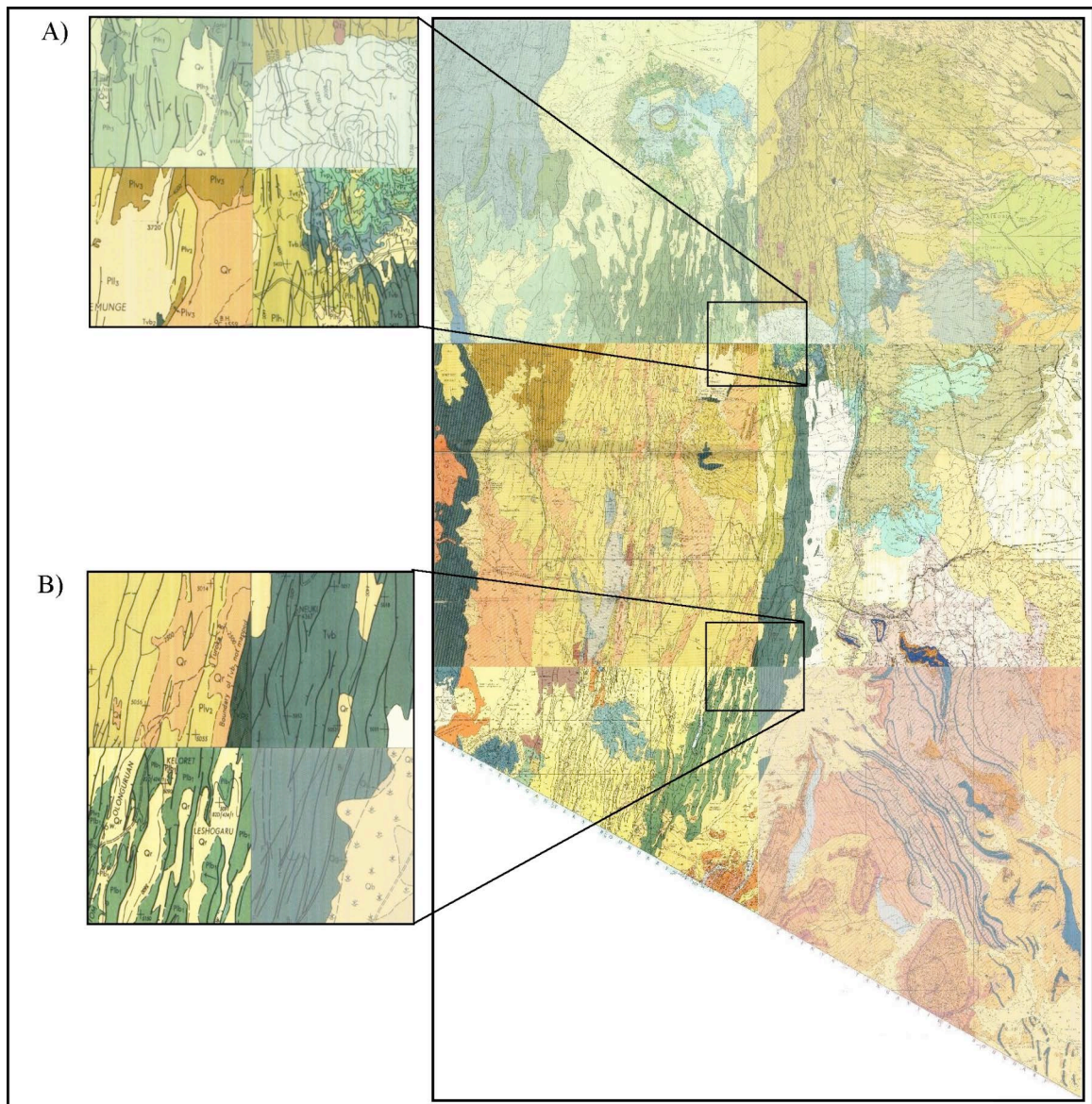
Figure 2: Assemblage of Kenya Geological Survey (1958-1991) maps on the right covering the study area. Note the changes in detail and color across map boundaries. Enlargements are shown to highlight such changes. A) shows the intersection of the northern four maps (clockwise from upper left: Suswa, Nairobi, Magadi and Kajiado maps) B) is the intersection of the southern four (clockwise from upper left: Magadi, Kajiado, South Magadi and Namanga maps).
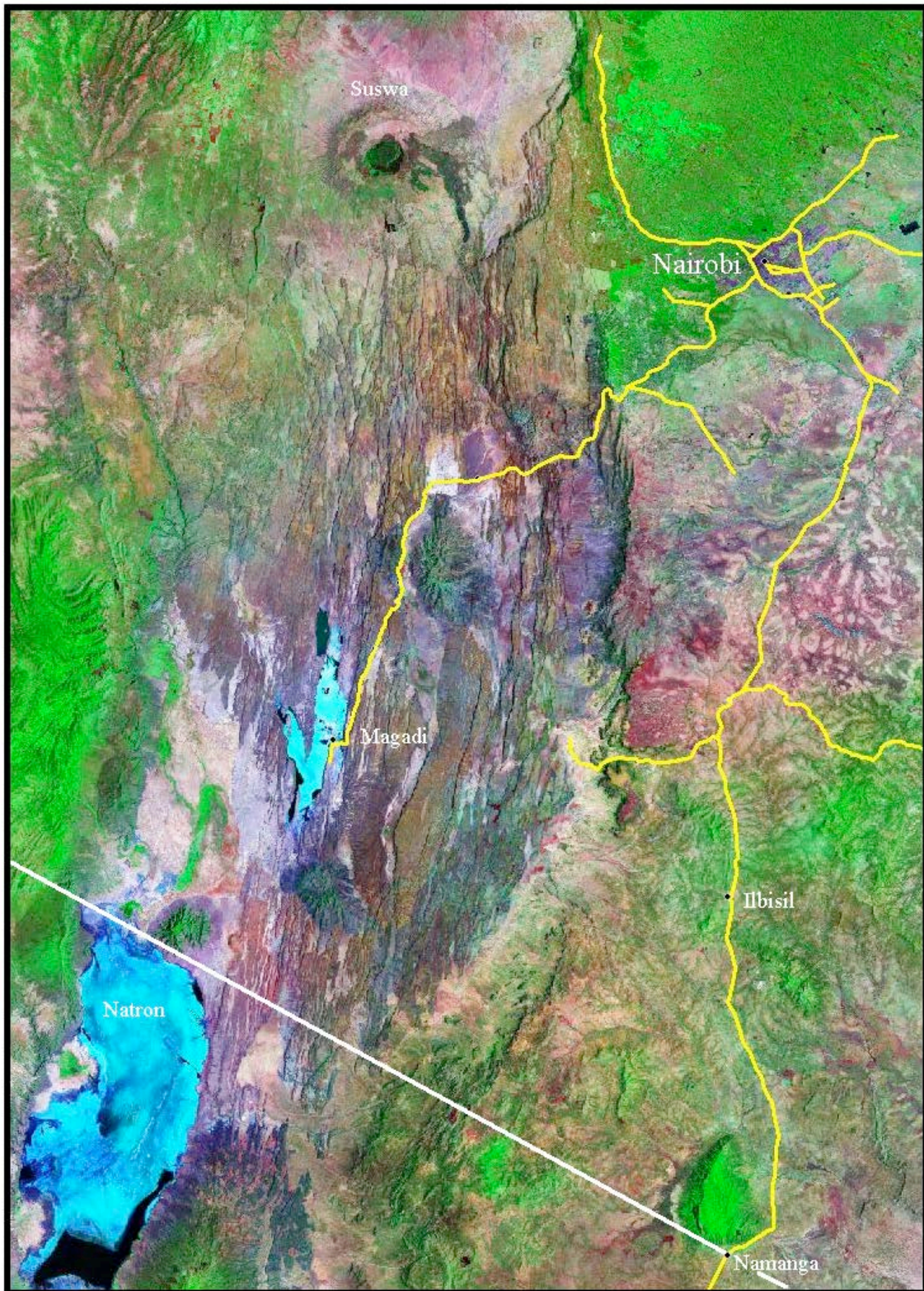
Figure 3: A false-color Landsat image of the study area obtained from the NASA GeoCover web site showing roads (yellow), the Kenya-Tanzania border (white) and selected towns and features.
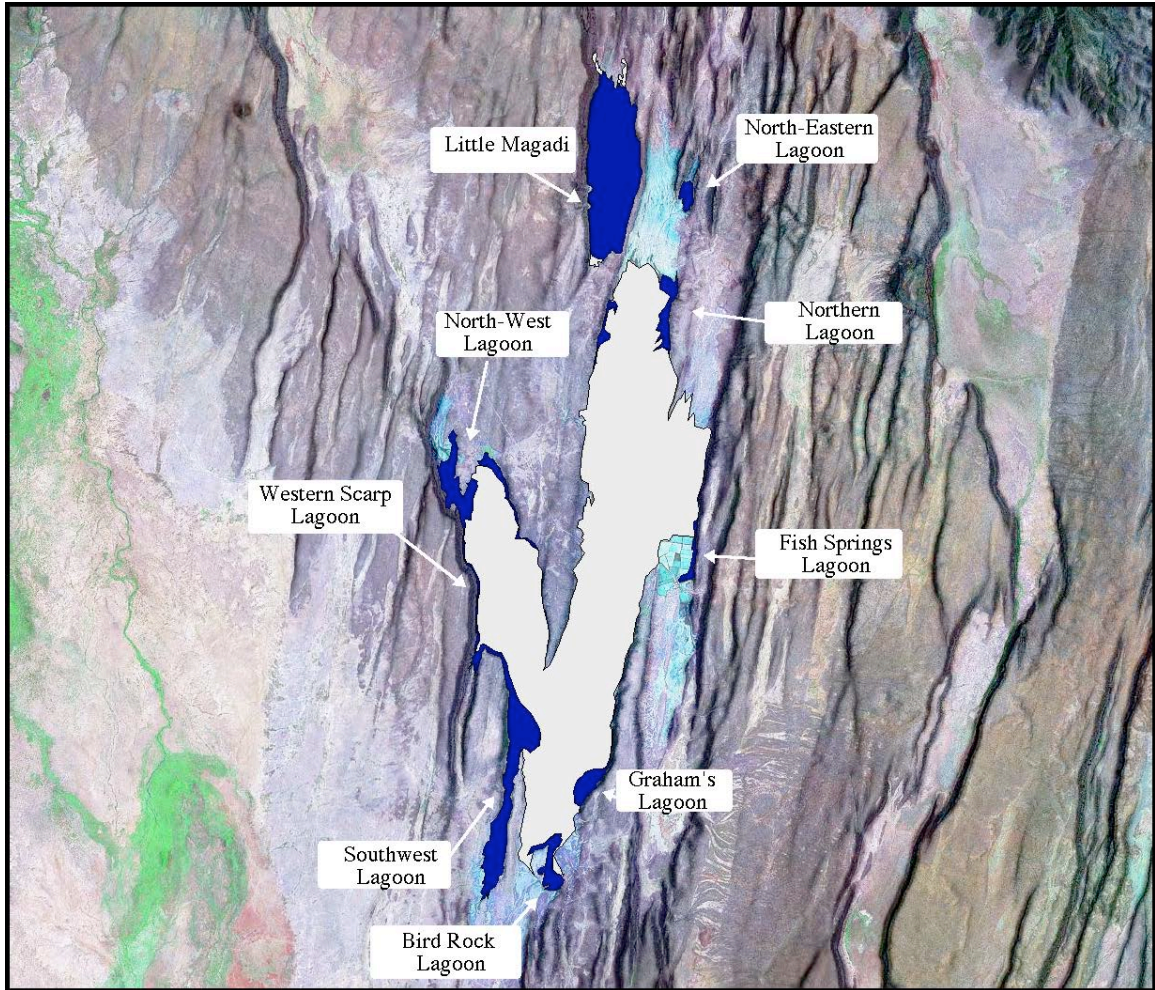
Figure 4: False color Landsat image draped over a DEM to emphasize the fault scarps and their relation to the lagoons (labeled after Baker 1958) surrounding Lake Magadi.
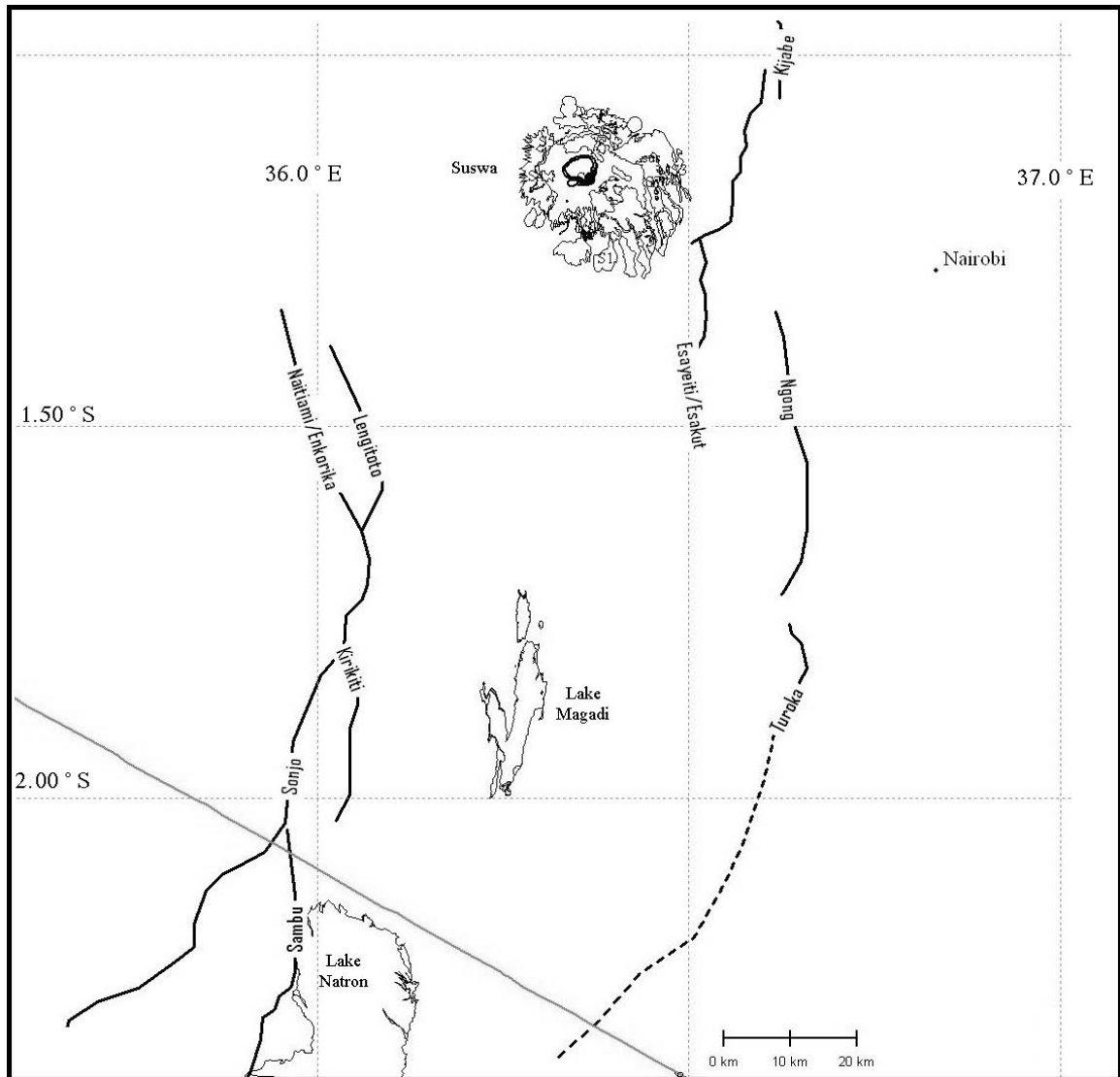
Figure 5: Map of the Southern Kenya Rift showing the major, named, rift bounding faults. Also shown are the outlines of Suswa, a shield volcano in the northern part of the study area, and Lakes Magadi and Natron. The grey line running diagonally through the image between the two lakes is the Kenya-Tanzania border. Nairobi is also shown for reference.
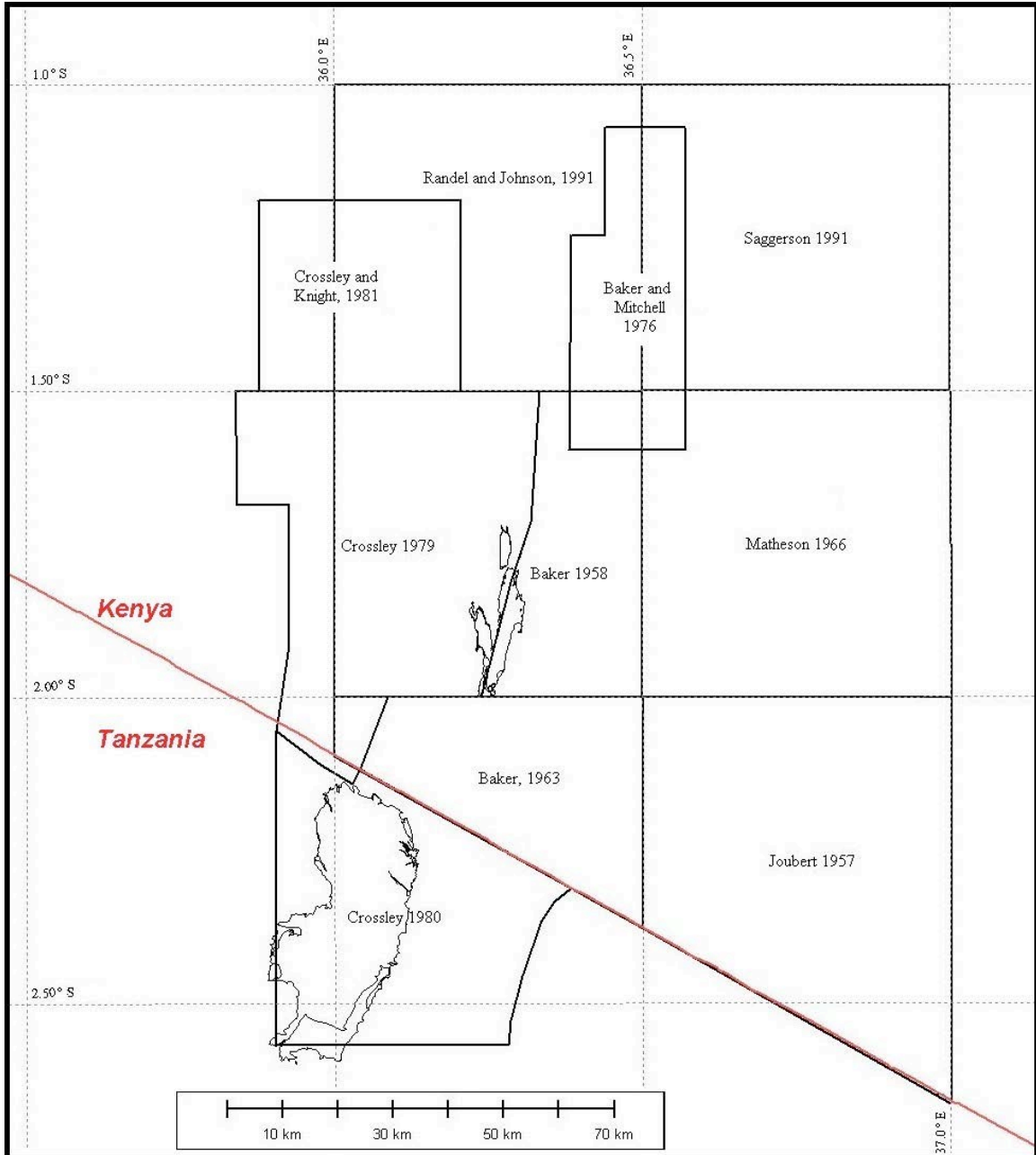
Figure 6: Plan view diagram showing location and source of geologic maps used as keys to interpreting the satellite images. Note that the larger (roughly quarter degree) maps were done by the Kenya Geologic Survey and the smaller maps which overlap them were from papers published later and provide much of the new detail seen in the maps produced for this study. Also note that while the publication year for Randel and Johnson and Saggerson is 1991, the mapping was done in the 1960's, therefore the overlapping maps from 1976 and 1981 reflect more recent geologic information.
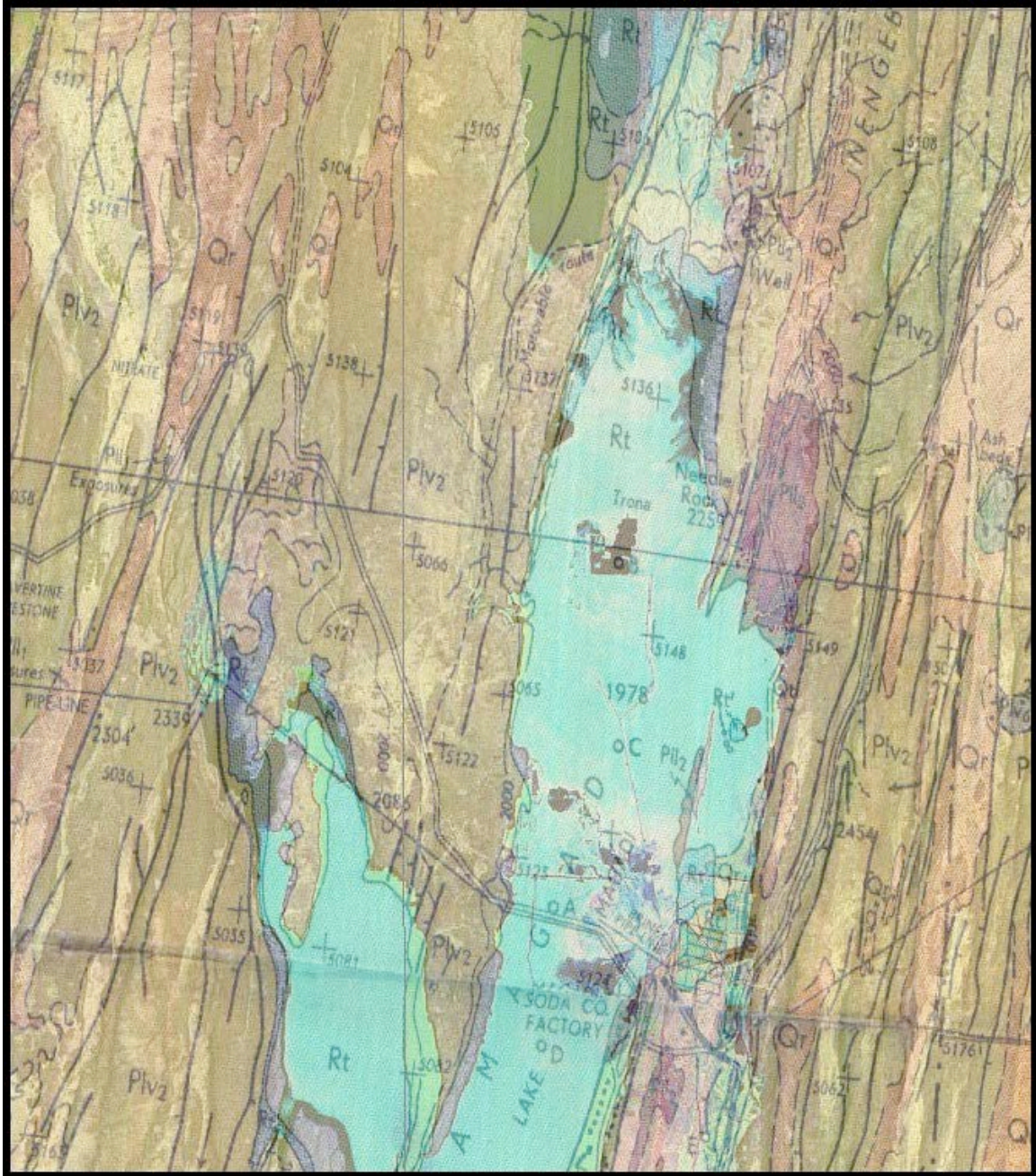
Figure 7: Geologic map of Magadi Area (Baker 1958) overlaid onto a Landsat image. The geologic map has been georeferenced using the stated corner coordinates. This unedited mosaic shows a distinct offset between the coordinates of the geologic map and the Landsat image.

Figure 8: Mosaic of central portion of Lake Magadi using geologic map (Baker 1958), which has been simplified to a line drawing, and Landsat image (bands 1,2,3). Coordinate offset between the geologic map (black lines) and the Landsat image is clearly evident. Offsets range from 590-800 m and displacement azimuths vary between 70-122°.
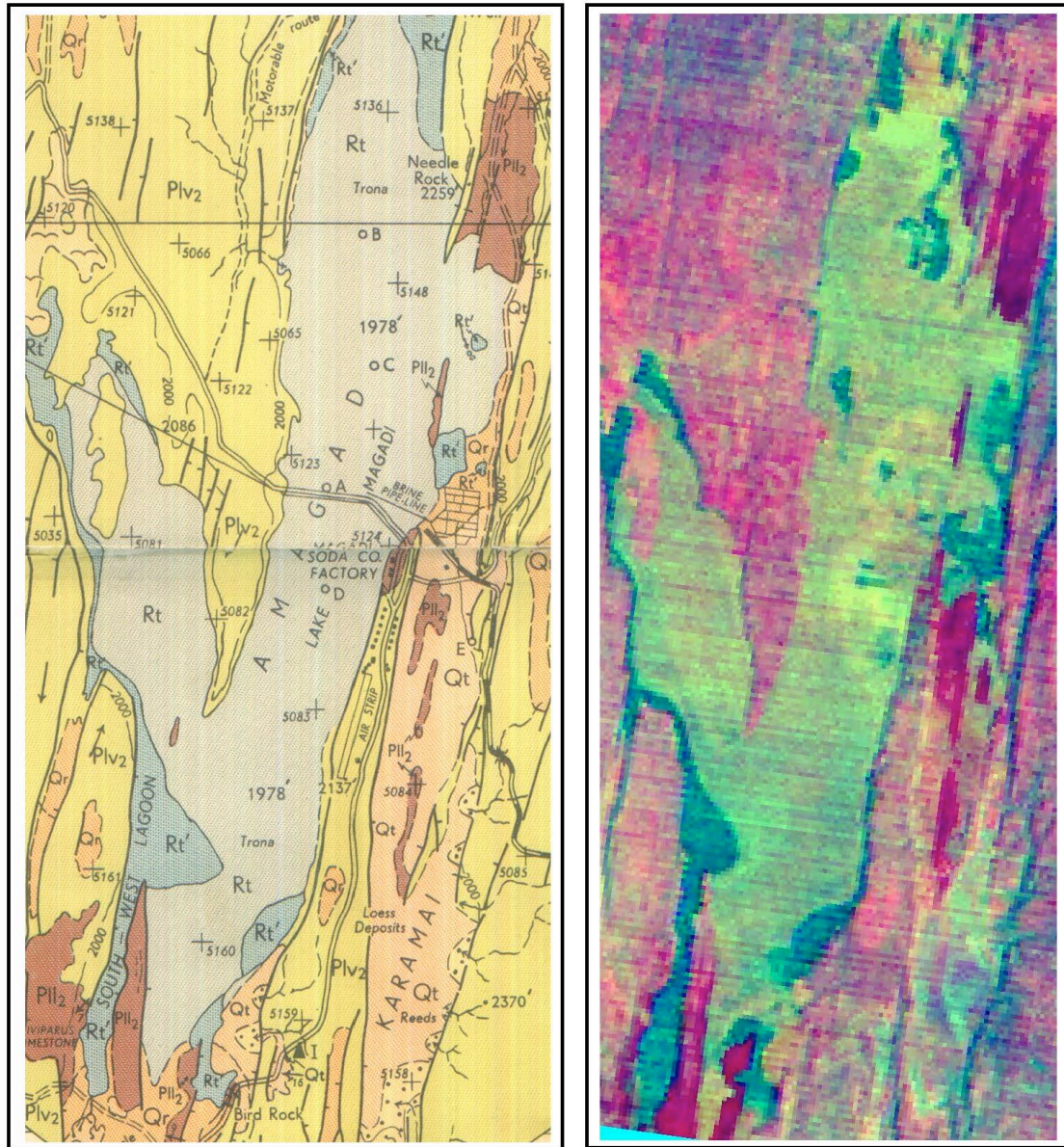
Figure 9: Geologic map (from Baker 1958, left) and Principal Components (PC) image (right) of the Lake Magadi area. The PC image was created from a 2005 ASTER satellite image using the thermal bands. The Chert Series (Green Beds) are shown in red on the geologic map and matching areas can be seen as dark magenta in the PC image.
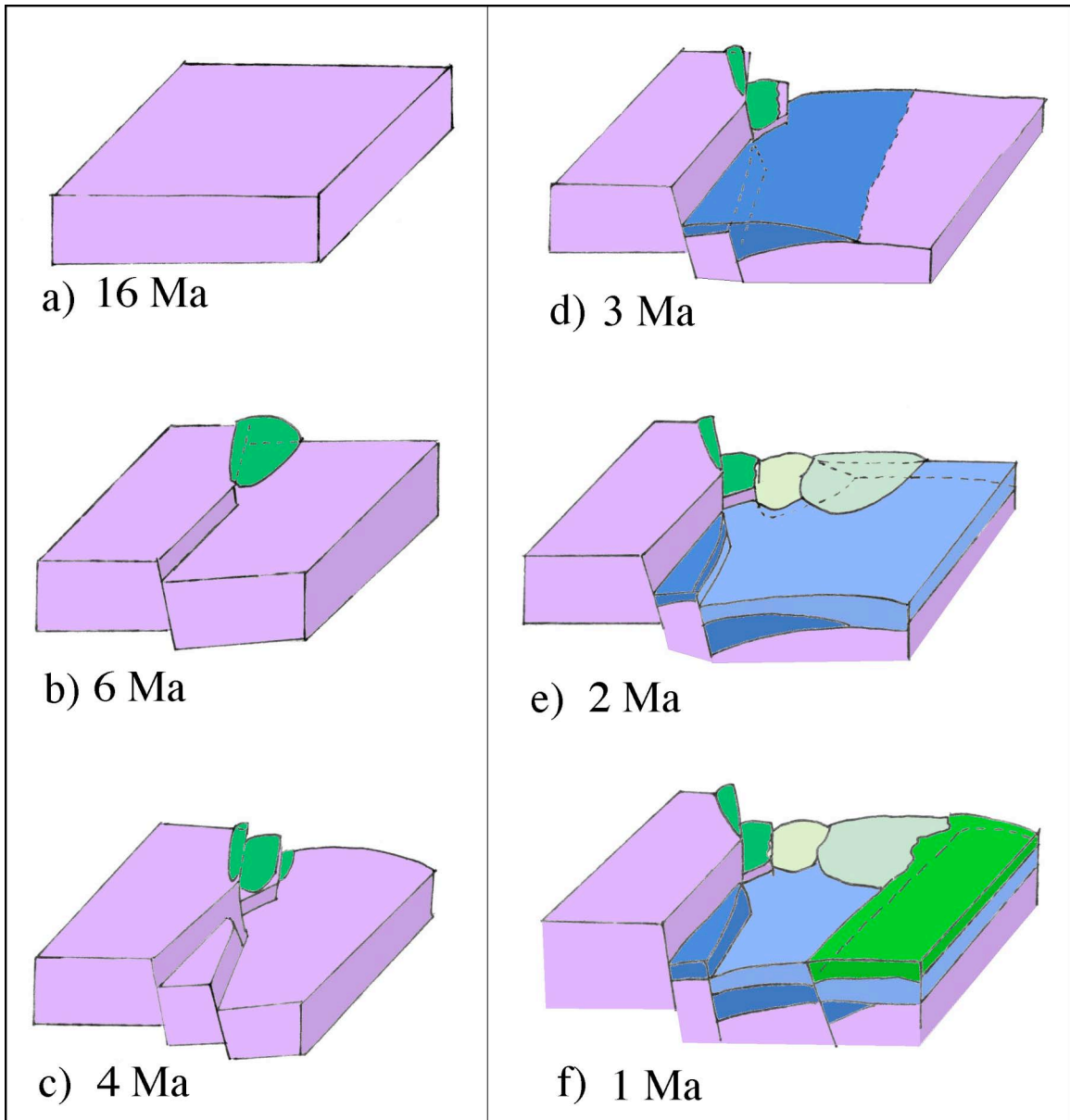
Figure 10: Diagram illustrating the evolution of the northwest section of the Magadi map area, based on events outlined in Crossley, 1979. Images from top to bottom, left to right, show the progression from 16 Ma to 1 Ma. The final image shows a complex relationship between a variety of volcanic formations, but this can be arrived at through a series of relatively simple steps. For example, a fault cuts basement rocks and lava is erupted into the graben and overtops the escarpment (b). Renewed faulting breaks up the volcanic flow (c) with the down dropped part buried by more recent volcanism (d). These simple processes lead to the situation where one unit is seen at various elevations and is only covered by younger flows in certain locations.

Geology of the Southern Kenya Rift
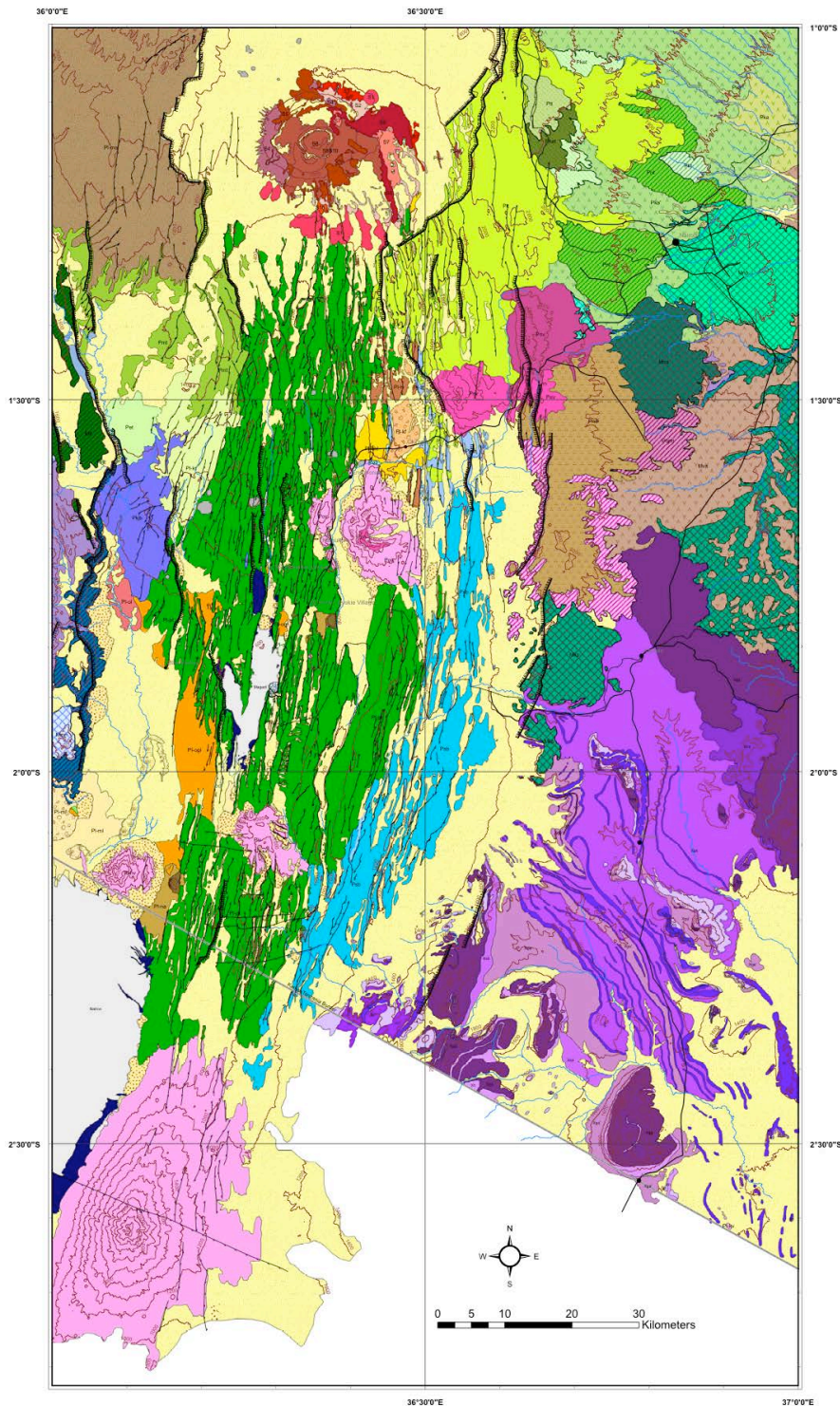
Figure 11: Completed geologic map of the Southern Kenya Rift. This map extends from 1.5° S to the Tanzania border with the exception of a small area (southwest corner of map) that extends into Tanzania. Map covers the following KGS map areas: Suswa, Nairobi, Magadi, Kajiado, South Magadi and Namanga.
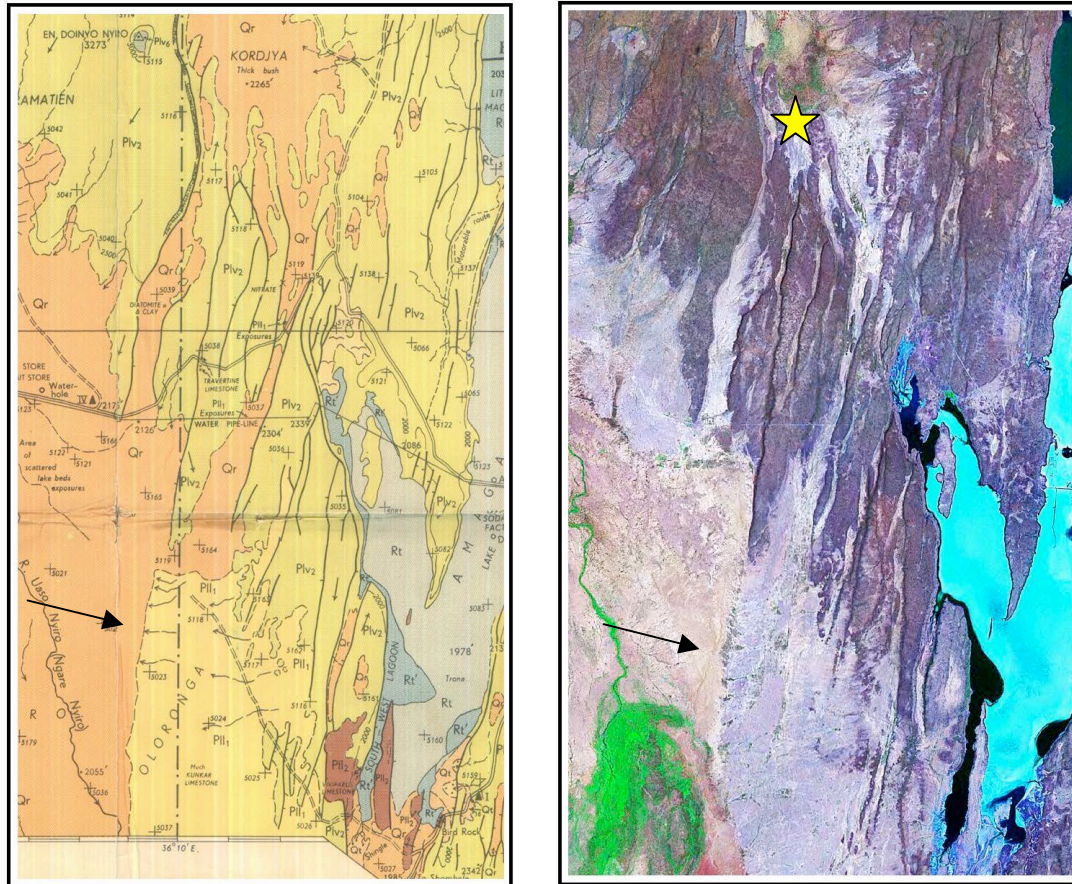
Figure 12: Comparison between Baker's 1958 Geological map (left) and Landsat image (right). The Oloronga lake beds are shown in yellow near the bottom of the geologic map (see arrow). In the Landsat image the Oloronga beds are easily distinguished from the Quaternary sediments by their light purple color (see arrow). For the geologic map produced in this study, the boundaries seen in the Landsat image were given preference over the 1958 map, which is confirmed by mapping done by Crossley (1979), and reports by Potts et al. (1988) and Shipman et al. (1983) that place the Lainyamok hominid site (represented by the star) within the Oloronga Beds.

A) Baker 1958

B) December 2005

C) September 2003

D) January 2003

Figure 13: Comparison of exposed trona in the southern end of Little Magadi. Image on the right is a December 2005 ASTER image with the yellow box showing the area of interest as seen during different years on the left. A: Baker's 1958 Geologic Map B: December 2005, a known dry year. Note the large exposure of trona (bright white), which is probably exposed due to lower water levels. C, D: 2003 was a more normal year in terms of precipitation and the exposed trona is significantly less than in B. This clearly shows that the amount of trona exposed is the result of a dynamic system and will vary year to year.
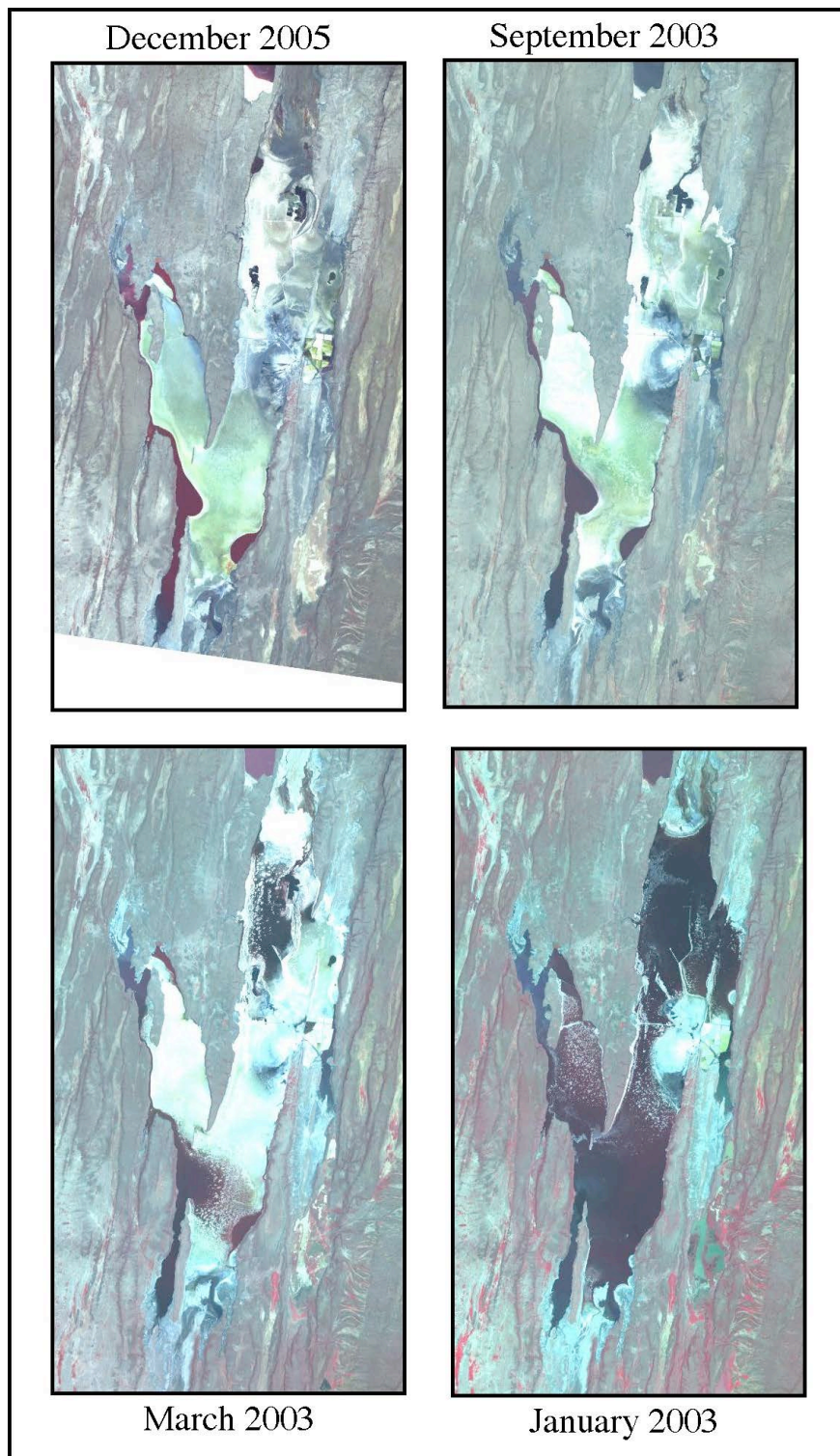
Figure 14: Lake Magadi through the seasons, with the upper left image from 2005. The light blue/white color is trona while black areas are water. During the rainy season 1-3m of water submerges the trona surface which is then exposed again as the water evaporates.
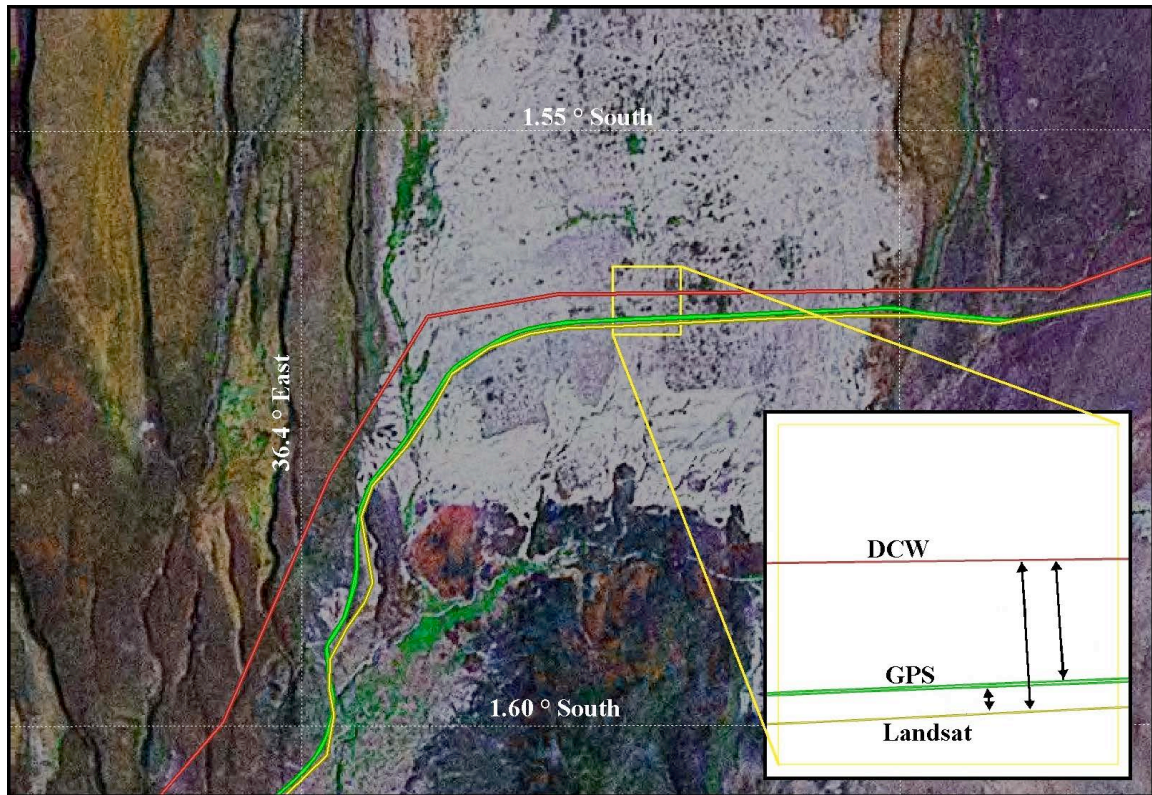
Figure 15: Landsat image of the northern Olorgesailie area showing three different road traces that are meant to represent the same road. The red line is from Digital Chart of the World (DCW), the green line is GPS data collected during the 2006 field season, and the yellow line represents the road as seen on the Landsat data. The offsets were measured at four locations within the zoomed area, perpendicularly to the three traces, and the averages are as follows:

DCW-Landsat: **287 m**
DCW-GPS: **235 m**
GPS-Landsat: **54 m**

Figures 16-21
Paleo-Geology Maps for 10Ma – 100ka

Figure 16: 10 Ma Paleomap. The first volcanism in this area was likely the Kishalduga and Lisudwa melanephelinites (light blue) which were erupted as early as 15.2 Ma near what would become the western rift boundary. By 10 Ma the area of the Southern Kenya rift was flooded by Plateau Phonolites (green), of which only the southern-most limit enters the study area. Graphs on the right show composition of volcanics (upper right) and volume (lower right). Composition plot shows total alkali versus silica with the units erupted before 10Ma shown in color. The volume plot shows volume based on measured area (taken from the geologic map shown in Figure 10), volume based on estimated area (area of total estimated extent, or area shown in paleomap) and cumulative volume. The cumulative volume excludes the Plateau Phonolites shown on this paleomap as the 3 different shades of green.

Figure 17: 6 Ma paleomap. The initial fault movements to define the western rift boundary occurred before 7Ma. These movements downthrew much of the Kishalduga formation and the Lengitoto trachytes were erupted into the newly formed half graben. Some rocks from the Ol Esayeti complex to the east have also been dated to this time period suggesting that it may have begun building during this time.

Figure 18: 3 Ma paleomap. More than 3 million years after the initial movements that defined the western rift boundary, corresponding movements occur to the east. There are additional fault movements along the western boundary during this time as well. Phonolites and Phonolitic-nephelinites seen on the east rift should are thought to be related to Olorgesailie, so the volcano was likely building at this time. The Ngong hills are also thought to have developed in this period. The Kirikiti basalts erupted against the western boundary faults and extend to the present location of Sambu in the South. The Nairobi trachytes in the north were probably erupted within the rift and overflowed onto the rift shoulders.

Figure 19: 2 Ma paleomap. A number of volcanoes developed between 3 and 2 Ma including Sambu, Shombole, Lenderut, and Gelai in addition to further eruptions from Olorgesailie. Some small trachyte eruptions occurred on the eastern shoulder as well as the eruption of the Kerichwa Tuffs. Within the rift the Singaraini basalts were erupted along the eastern side and the Kordjya basalts were erupted in the area northwest of present-day Lake Magadi. The Mosiro and Ewaso Ngiro trachytes were also erupted onto the rift floor at this time.

Figure 20: 1.5 Ma paleomap. Between the eruption of the Mosiro trachytes around 2.3 Ma and the Limuru trachytes at 1.9 Ma, much of the northern study area was likely covered by trachyte flows. The Limuru trachytes also overflowed the eastern fault scarps and flowed onto the rift shoulders. There were some smaller, more localized eruptions of Pantellerites and Benmoreites during this period. The oldest lake beds in the study area are in the Lake Natron basin and are about 1.5 Ma indicating the presence of a paleolake at this time.

Figure 21: 100 ka paleomap. The center of the rift floor was flooded by the Magadi (a.k.a. Plateau) trachytes which were probably erupted from fissures. The oldest flows in this eruptive series are 1.4 Ma with activity continuing until around 780ka. A number of small cones (both trachytic and basaltic) were formed around 600ka and the Mau ashes in the northwest were erupted around the same time. The rift floor was broken by a number of small faults that have been dated to around 400ka. Suswa, a shield volcano in the north of the study area, began erupting around 240ka. There was likely a large lake occupying the Magadi and Natron basins at this time, and a massive flood caused by the catastrophic draining of a lake in the Suswa area is thought to have occurred at this time.
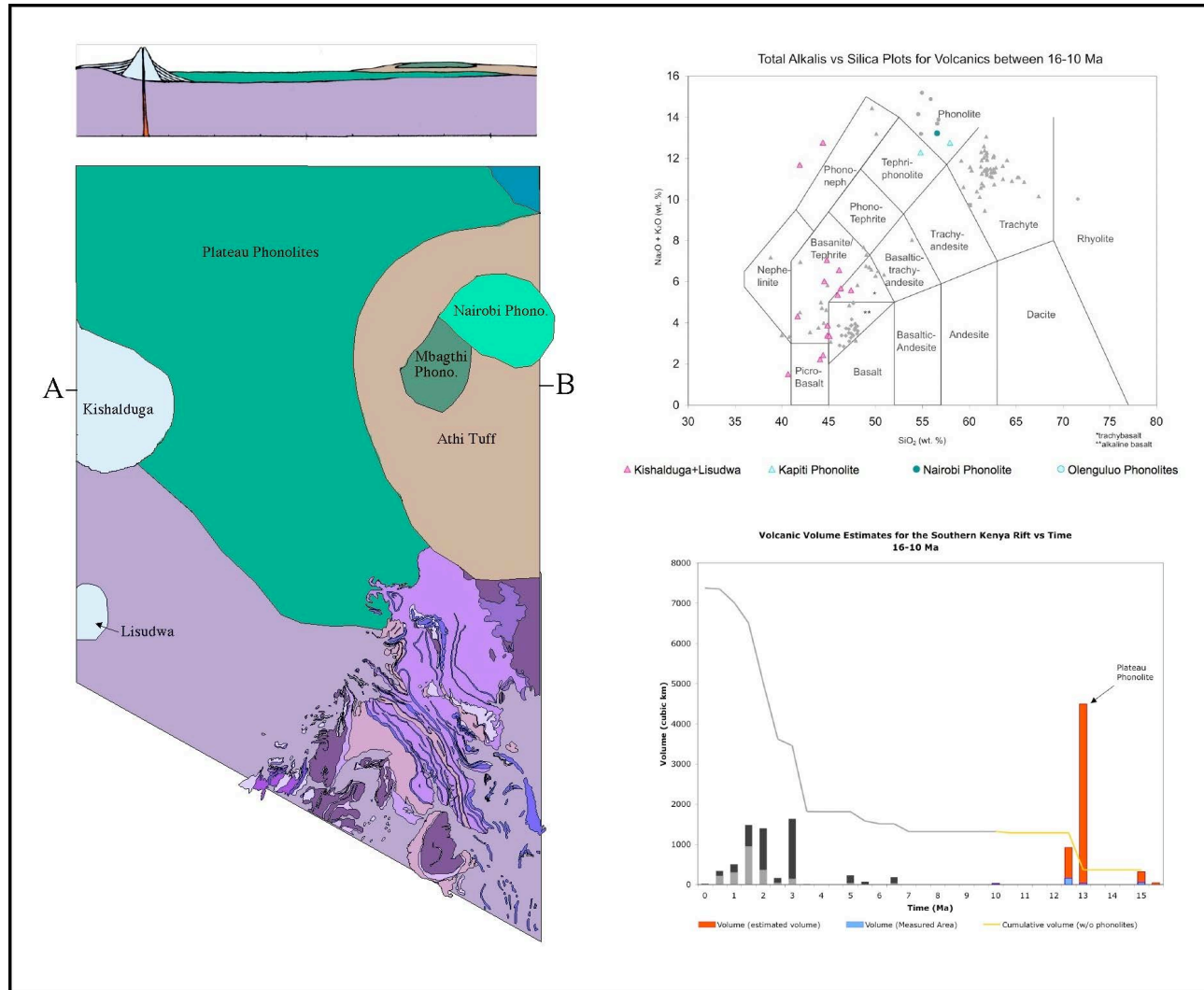
Figure 16: 10 Million Years Ago

A-18
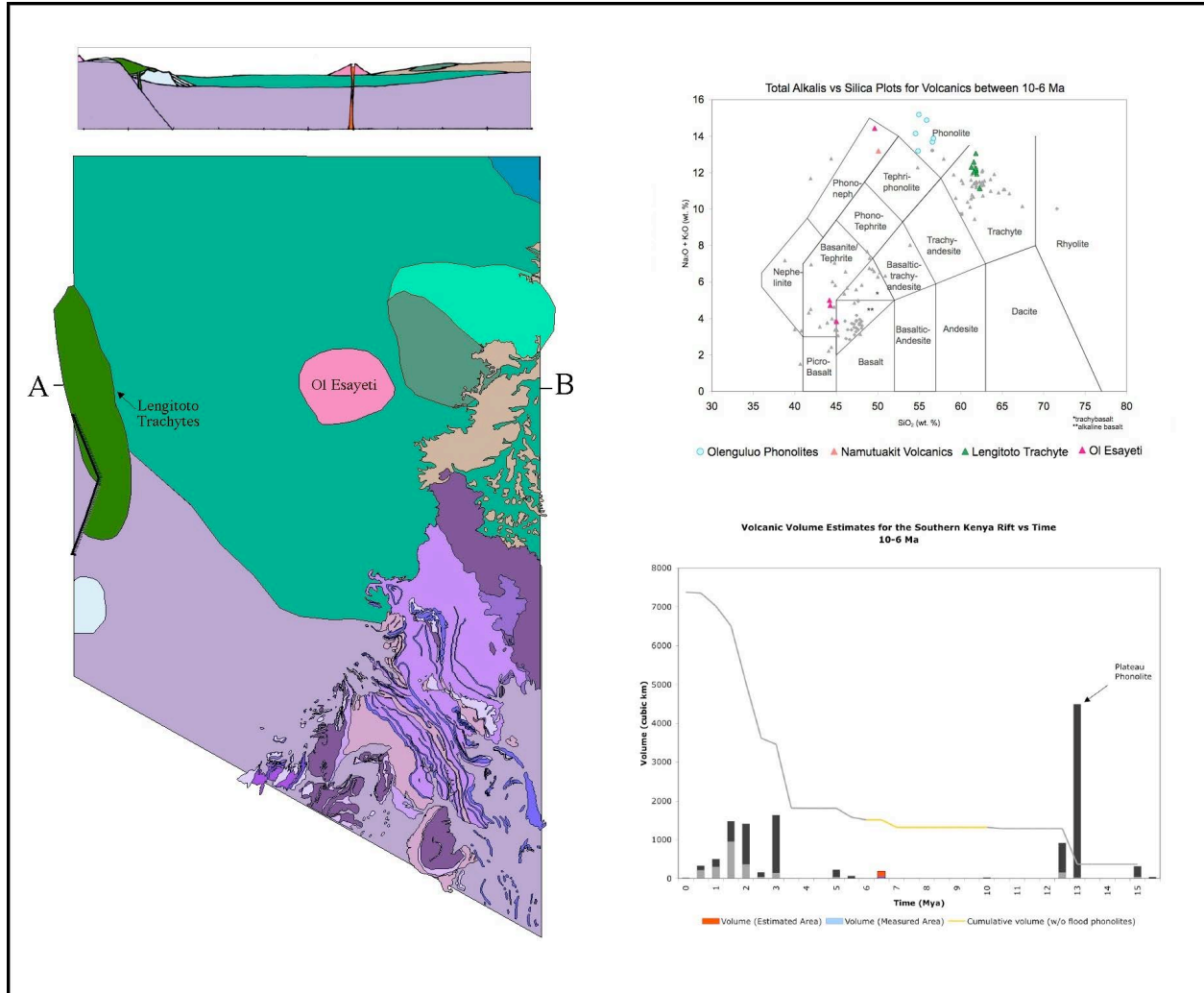
Figure 17: 6 Million Years Ago
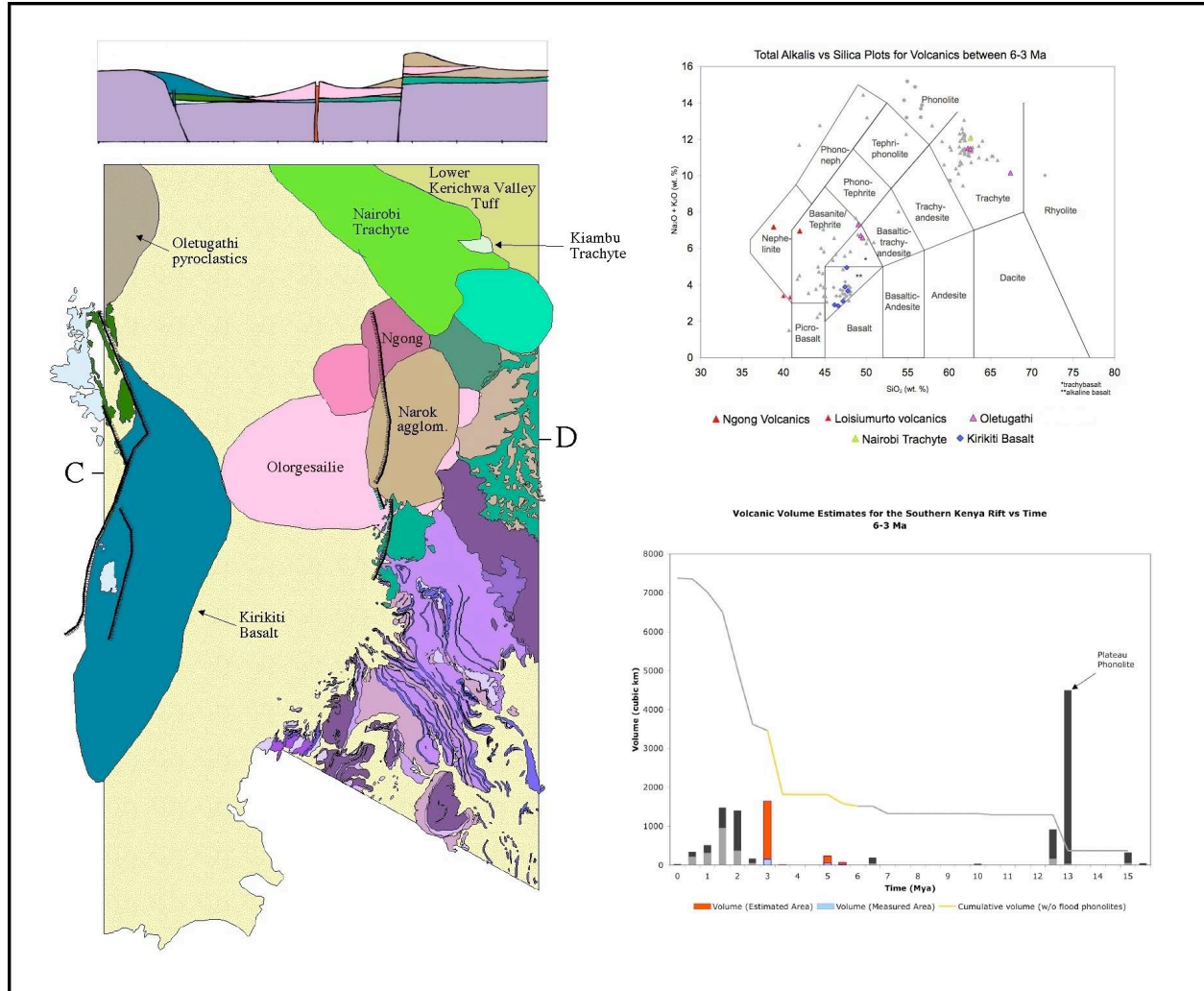
Figure 18: 3 Million Years Ago
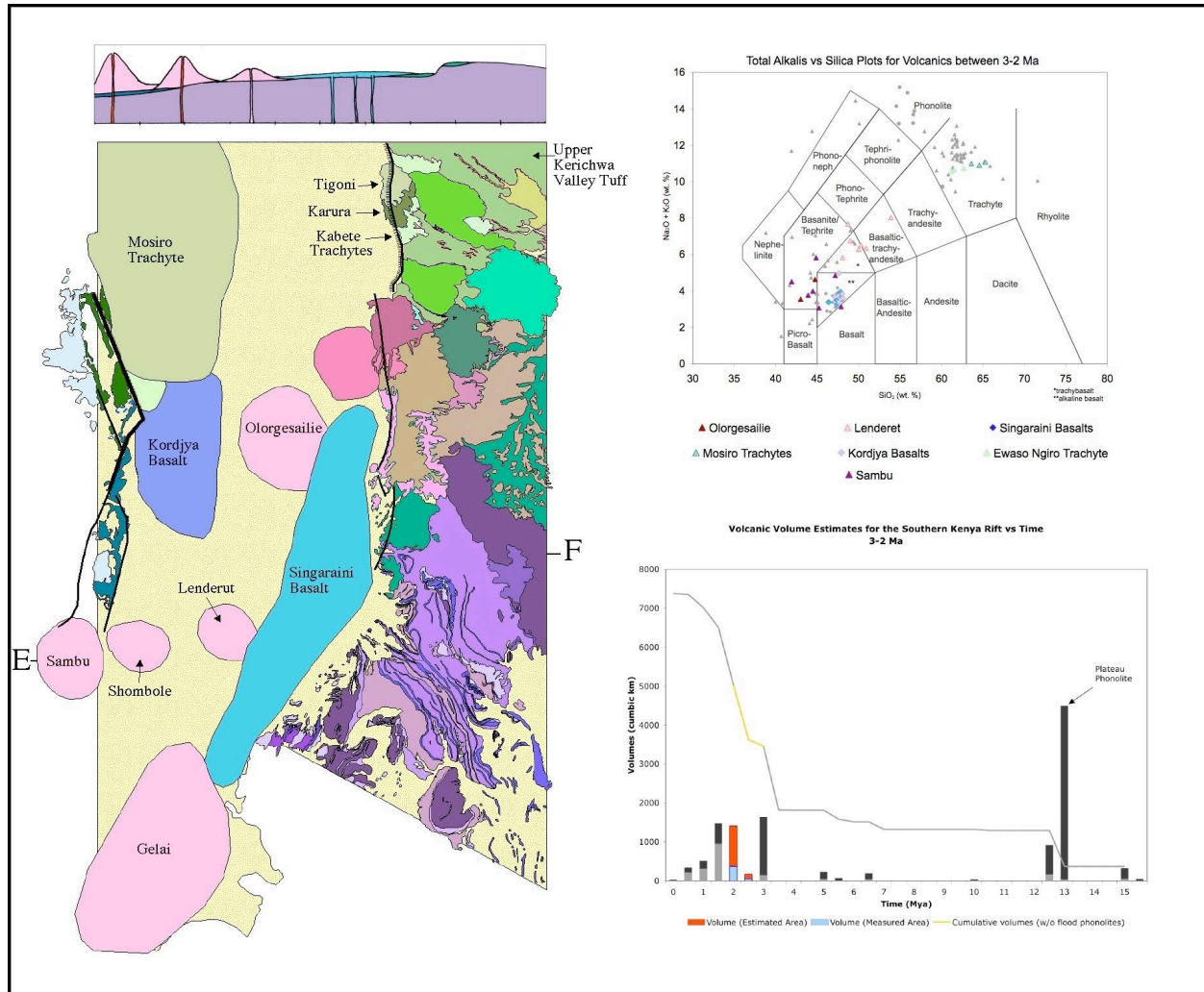
Figure 19: 2 Million Years Ago
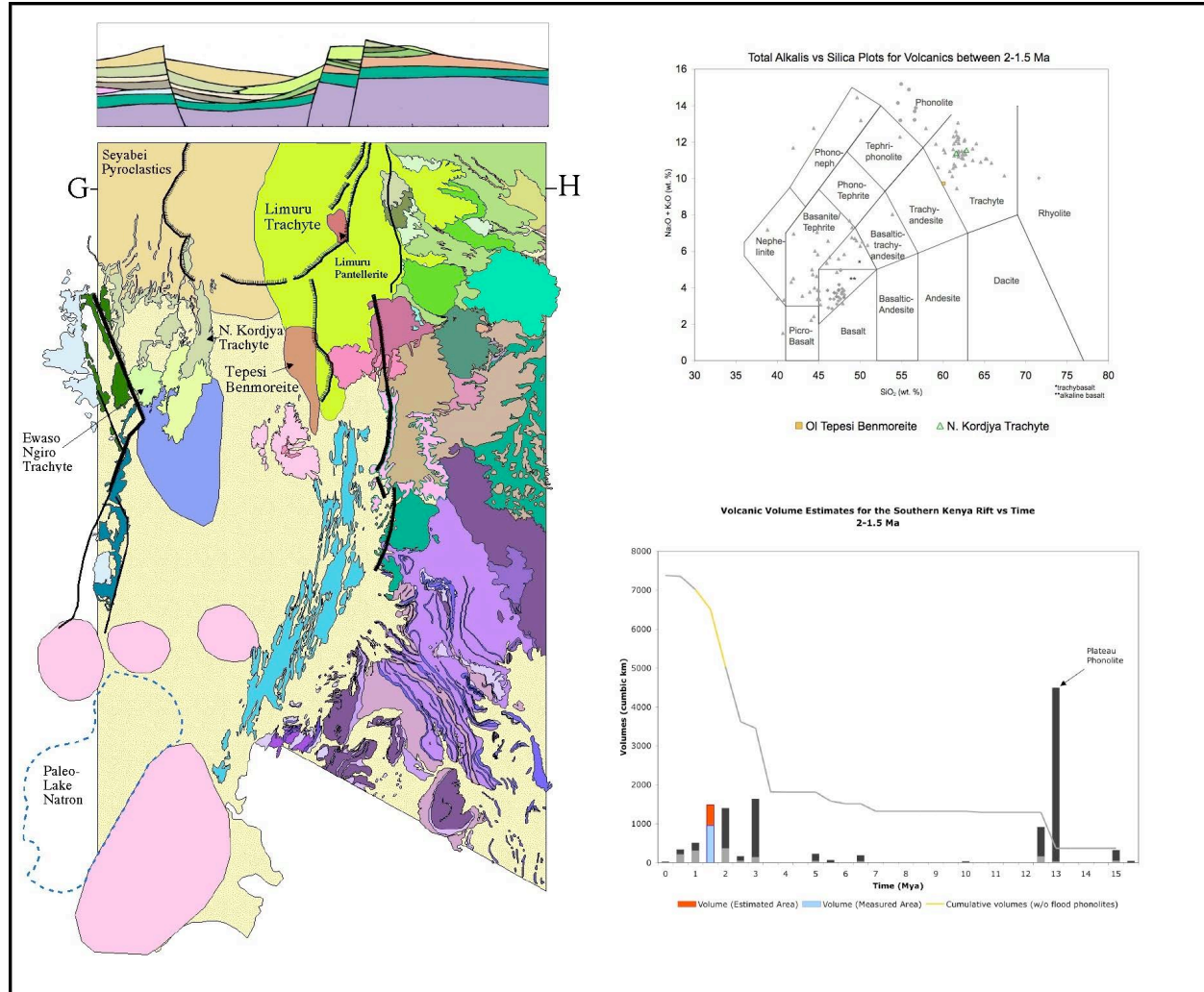
Figure 20: 1.5 Million Years Ago
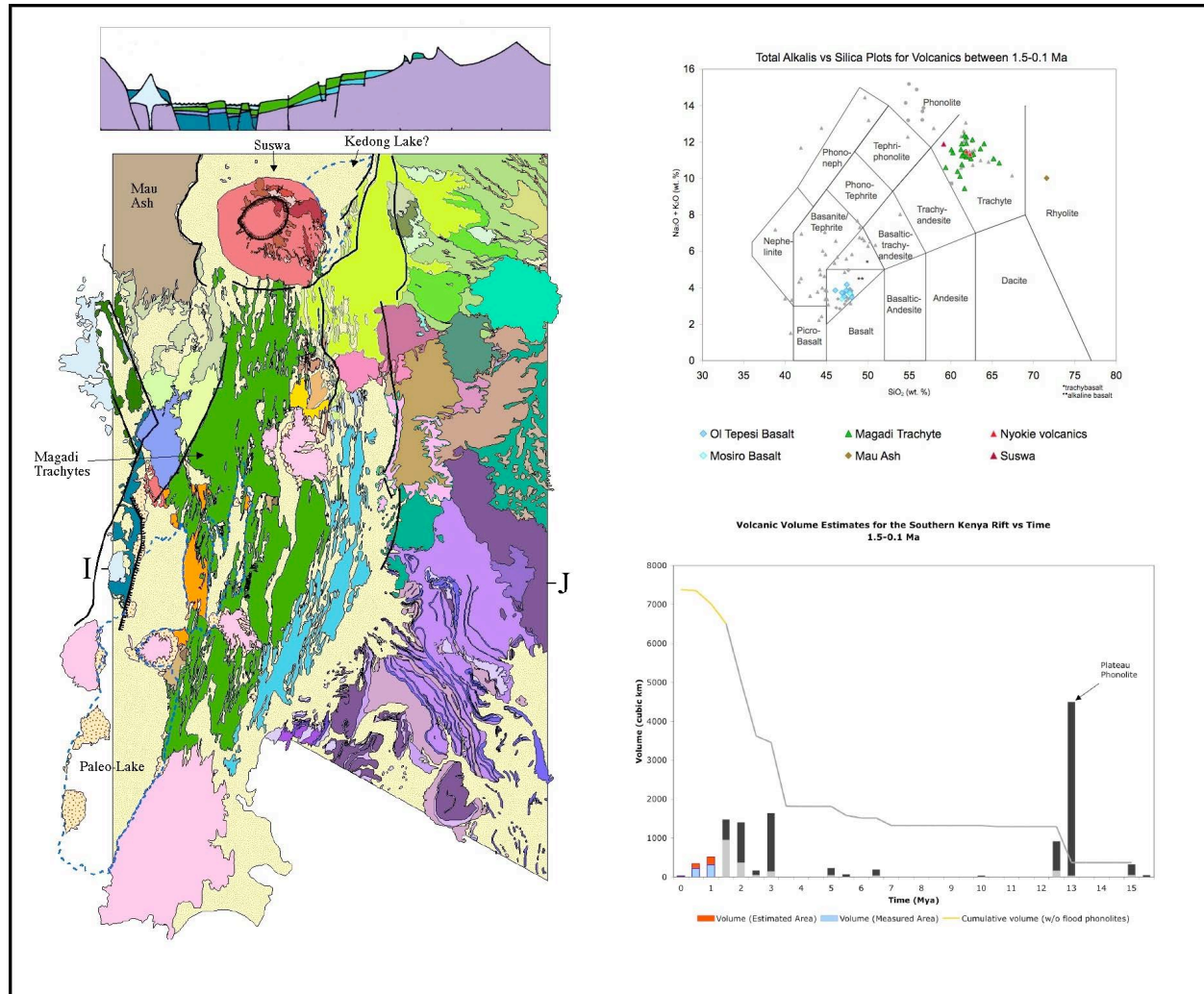
Figure 21: 100 Thousand Years Ago

Estimated Fault Displacement in the Southern Kenya Rift vs Time
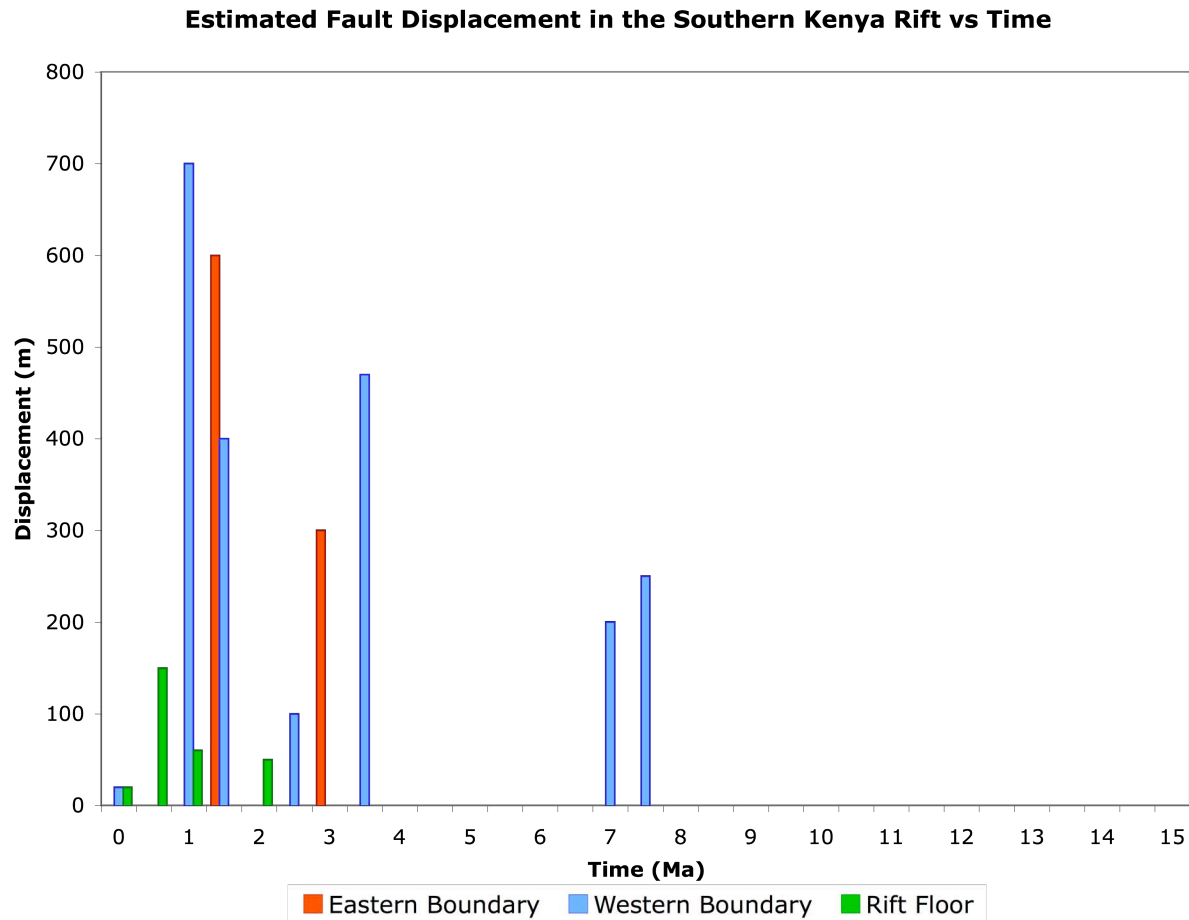
Figure 22: Graph showing estimated fault displacement over time. Blue bars represent vertical displacements in meters along the faults that define the western boundary of the rift. Red bars are the same except for eastern boundary faults and green bars represent fault displacements in the rift floor. See Table 1 in text for references for displacement estimates.

Volcanic volumes of the Southern Kenya Rift vs Time
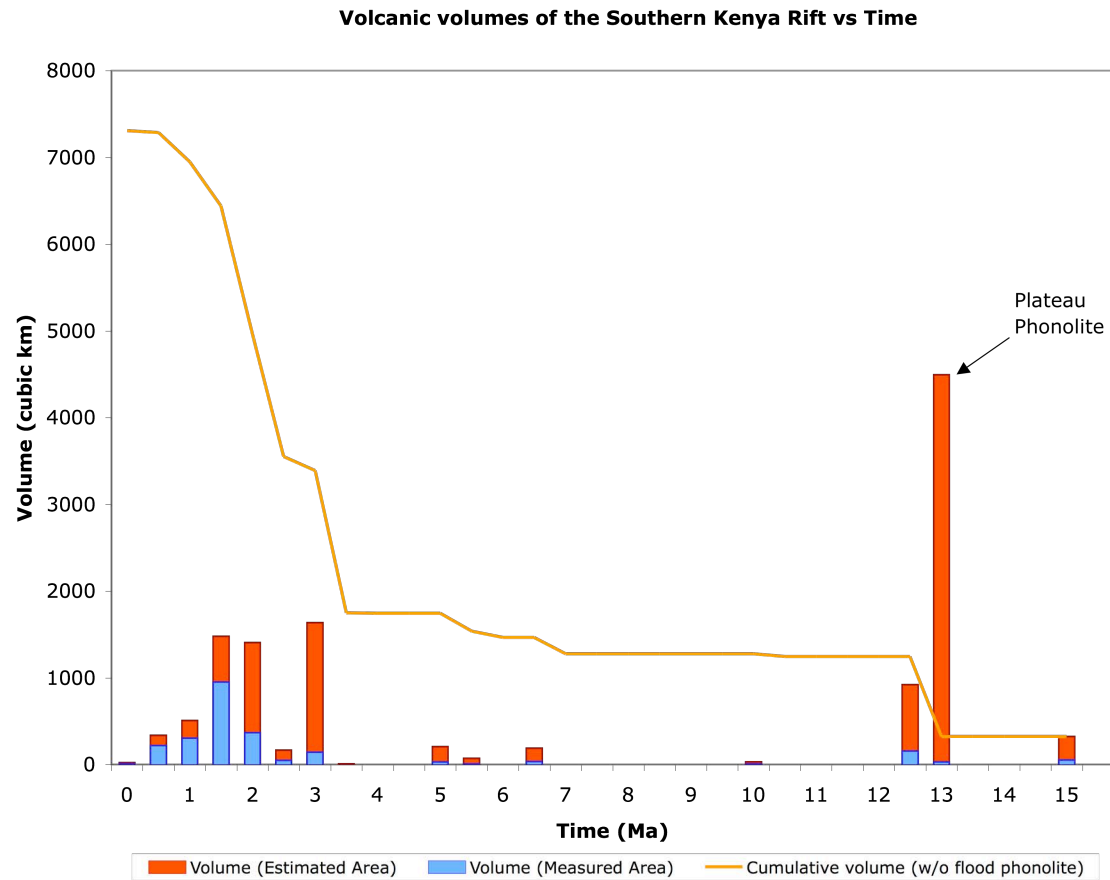
Figure 23: Volume versus time plot for the Southern Kenya Rift volcanics. The blue bars represent the volume calculated from exposed (mapped) surface area. The red bars show volume based on estimated probable extent and the Orange line represents the cumulative volume based on estimated volumes without input from the Plateau Phonolites.

A-25

Volume contribution of different petrologic groups vs Time
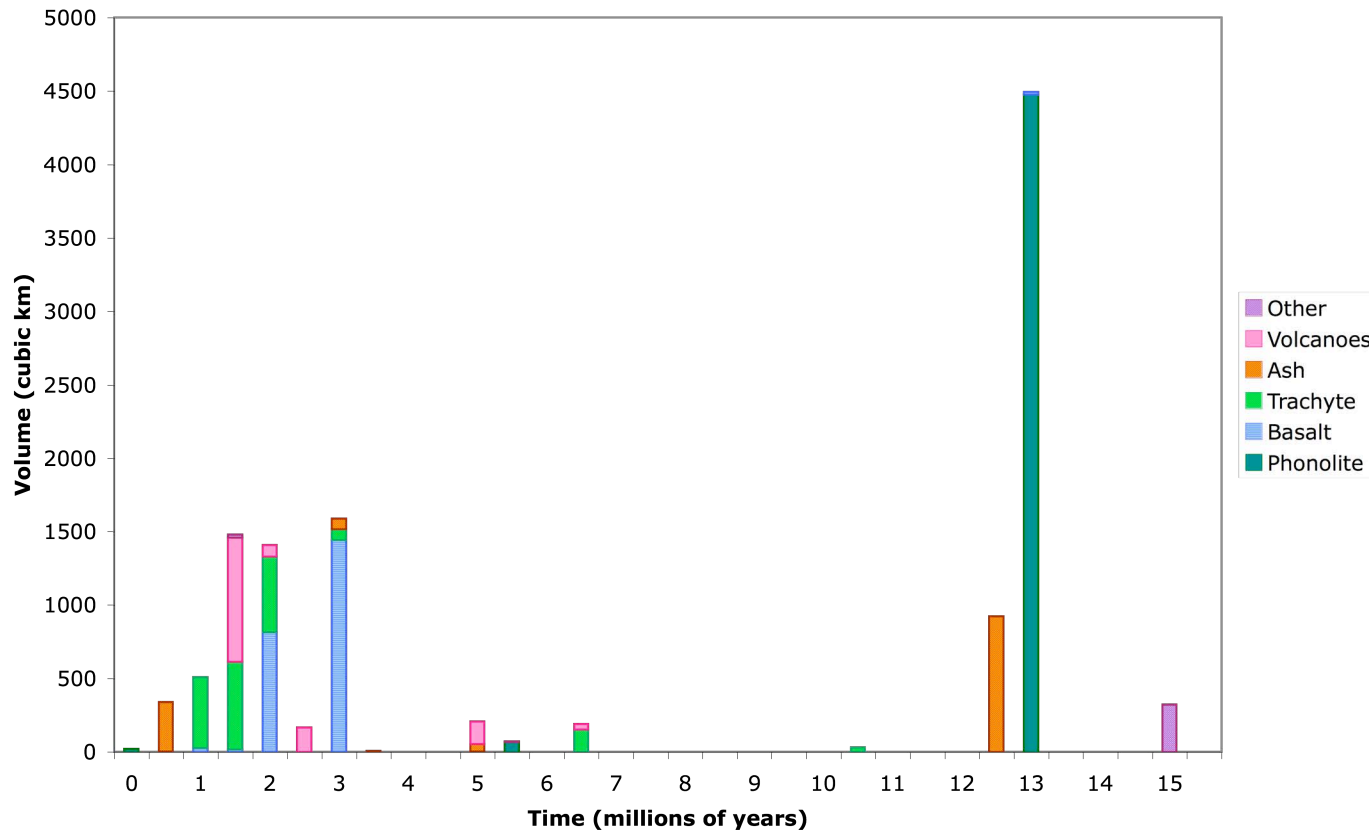
Figure 24: This plot is the estimated volume versus time as in Figure 23, except that the bars have been subdivided to show the contribution of the different types of volcanic rocks. It is clearly shown that volume of the different major volcanic rock types has not been constant over time.

Estimated Fault Displacement and Eruption Volume vs Time for the Southern Kenya Rift
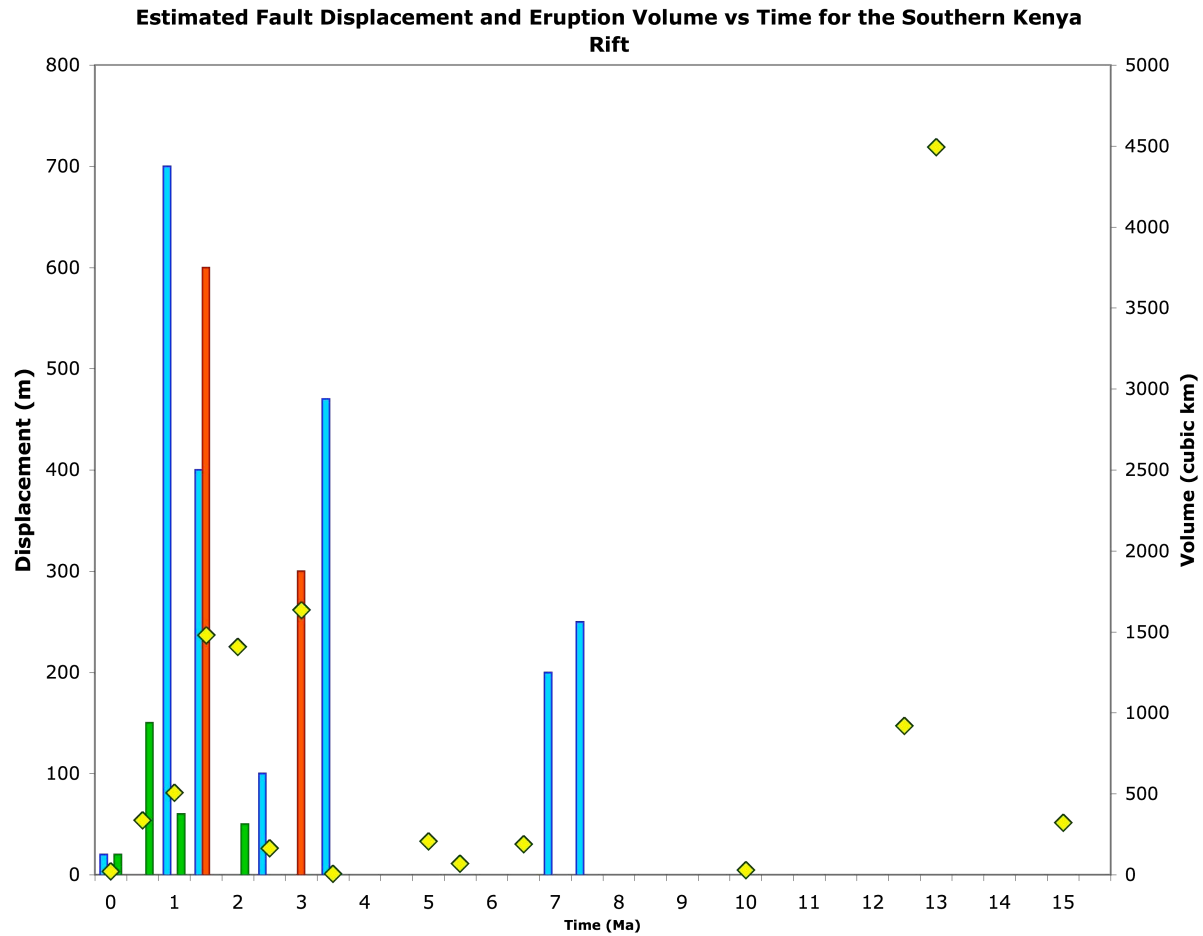
Figure 25: Graph of fault displacement and erupted volcanic volume versus time. Yellow diamonds represent erupted volume in cubic kilometers and bars represent fault displacement in meters. Bars indicate fault displacement in meters on the western boundary faults (blue), eastern boundary faults (red), and in the rift floor (green).
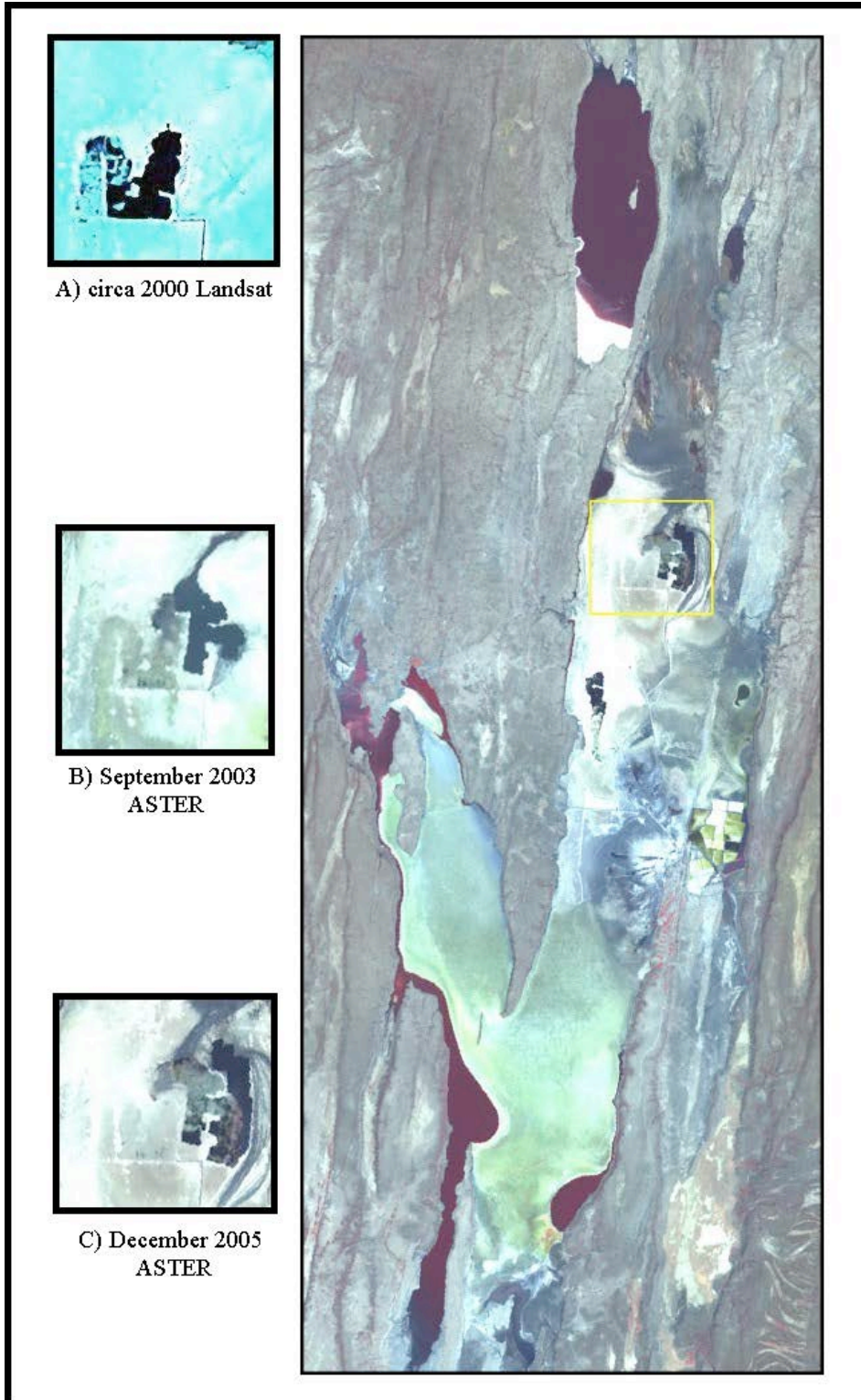
Figure 26: ASTER image of Lake Magadi (December 2005) on the right with the area of focus shown by the yellow box. Images on the left show the active mining area in 2000 (A) which was relocated sometime between 2000 and 2003, and afterwards, the previous excavation site can be seen to close up with trona.

A. Guth, MS Thesis, 2007

Left- A) In the field: Sample A1 grew along linear ridges about 1-inch high that were covered by shallow water and were located away from the spring vents. The ridges are probably fractures through which waters well up and supply nutrients to the biologic communities growing on them.

Right- B) 1000x magnification: This image shows one of the infrequent diatoms (not identified) in addition to segmented filaments that comprise the bulk of the sample. At low magnification the bulk of the sample appears as a hairy green mass, probably composed of *Oscillatoria* (see below).
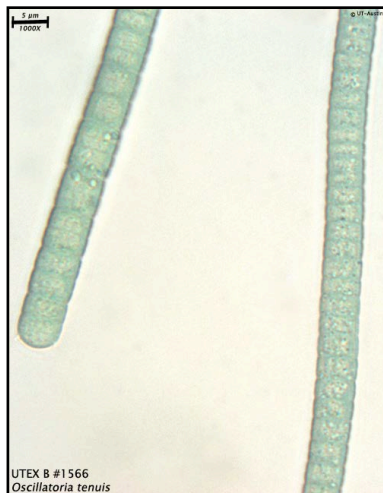
Left-C) *Oscillatoria* image from the UTEX image bank. According to CyanoDB, all species of *Oscillatoria* grow as mats in shallow water, which describes the growth habit and environment seen at the collection site.

Figure 27: Images of biologic sample A1 in the field (A) 1000 x magnification (B) with suggested identification (C)

A. Guth, MS Thesis, 2007

Left- A) In the field: Sample A2 grew as mucilaginous, bubble-trapping films that floated on the water's surface.

Right- B) 640x magnification showing one of the infrequent diatoms seen in this sample, while the small green spherical cells compose the bulk of the A2 sample. It is suspected that these small green cells are *Synechocystis* (see C below).
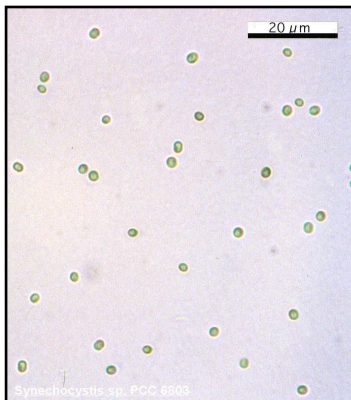
Left-C) *Synechocystis* image from the Spanish National Research Council's (CSIC) Institute of Vegetal Biochemistry and Photosynthesis.

Figure 28: Images of biologic sample A2 in the field (A), 640 x magnification (B), with suggested identification (C)

Left- A) In the field: This red growth (circled) was found at the mouth of a small spring, and was almost completely covered by green growth. The red was much more prominent during the 2005 field season which was earlier in the year and wetter than when this sample was collected in 2006

Right- B) 1000x magnification: This sample was composed mostly of fine filaments and small green spheres similar to those in sample A2 which are believed to be "contamination" from the overlying green growth. The filaments are segmented (black bars align with segments) with segments ranging between 6-9 microns long. These threads are believed to be *Calothrix,* a common mat forming bacteria (see C).

Left-C) 1000x *Calothrix* image from the UTEX image bank. A3 specimens shown above also resemble Phormidium or Schizothrix.

Figure 29: Images of sample A3 A) in the field B) at 1000 x magnification C) Suggested identification
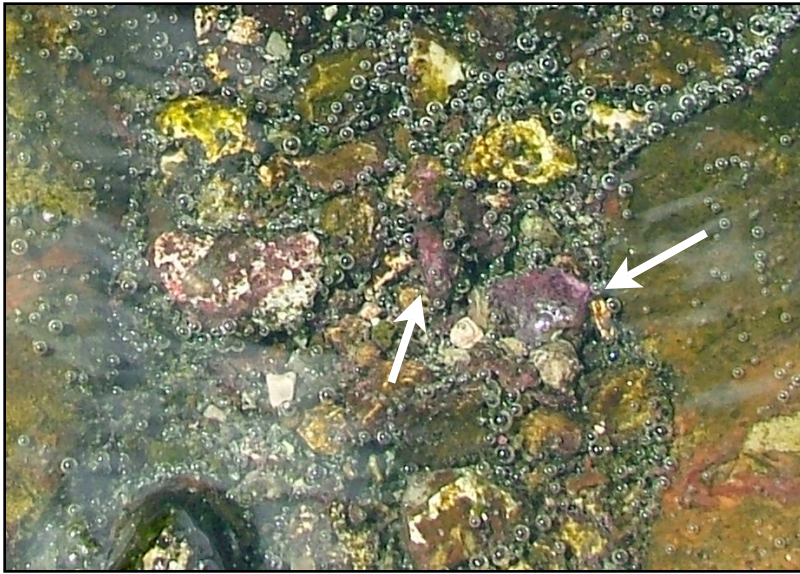
Left- A) In the field: Purple growth that encrusted pebbles as indicated by the arrows.

Right- B) 1600x magnification showing red, ovoid cells. Sample A4 is a mix of red and green cells as seen in C below. Red cells may be *Synechococcus* which may have a pink color according to CyanoDB.

0.01 mm

0.01 mm
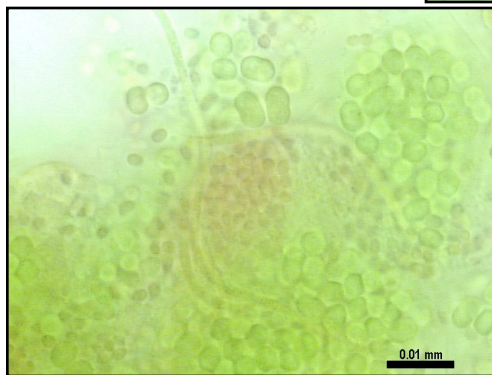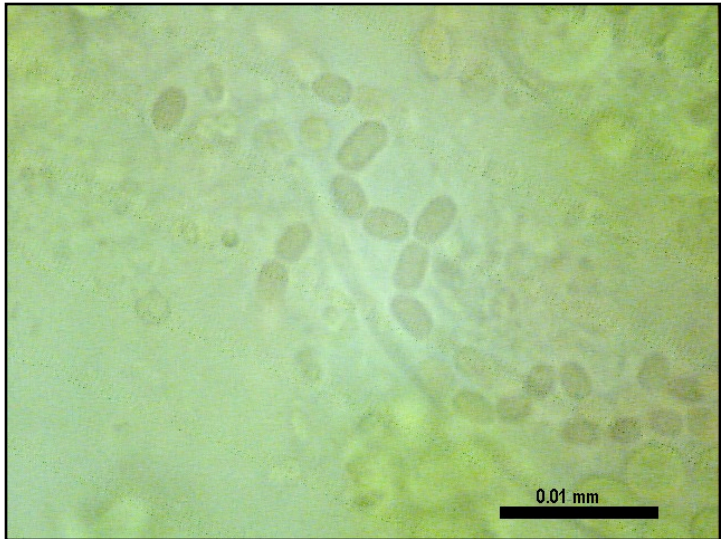
Left-C) 1000x magnification of A4 showing mixture of red and green cells.

S. subsalsa
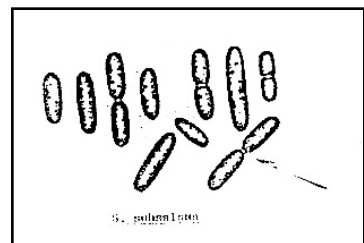
Above- D) image of *Synechococcus* from CyanoDB.

Figure 30a: Images of sample A4 A) in the field. B) at 1600 x magnification. C) 1000x magnification D) Suggested identification

Right- D)1600x magnification showing another common specimen that appears in sample A4. Though not seen here, they often appear in groups, and it is believed that this may be *Spirulina subsalsa* as shown in E below.
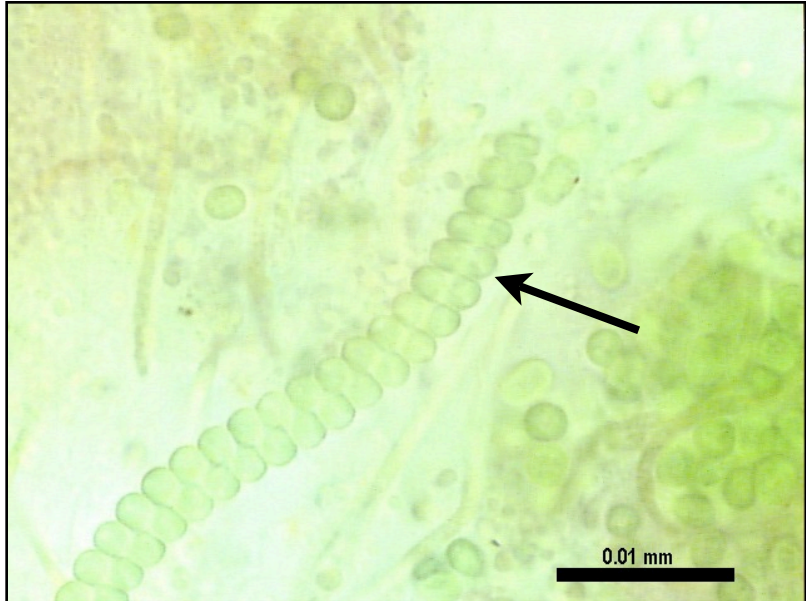
Right- E) Image of *Spirulina subsalsa* from the NIES (National Institute for Environmental Studies) Microbial Culture Collection.

Figure 30b: D) additional common specimen in A4 E) suggested identification for D

Left- A) In the field:

Sample A5 formed columnar mats (the image to the left is a top-down image, circular patches are the tops of the mats that are attached to the substrate and then rise above the floor) in areas of elevated temperature. Growths had a gritty texture, probably due to the entrainment of substrate. The inclusion of mineral grains in the sample made for difficult slide mounting as the incompressible grains would prevent the cover-slip from laying flat.

Right- B) 1000x magnification:
A large bulk of the sample seemed to be detrital and the red/orange tint seen on the left of image B may be due to iron-bearing minerals. Also shown here are fine translucent filaments and an oblong cell which may be one of several species including the purple sulfur bacterium shown in C below.
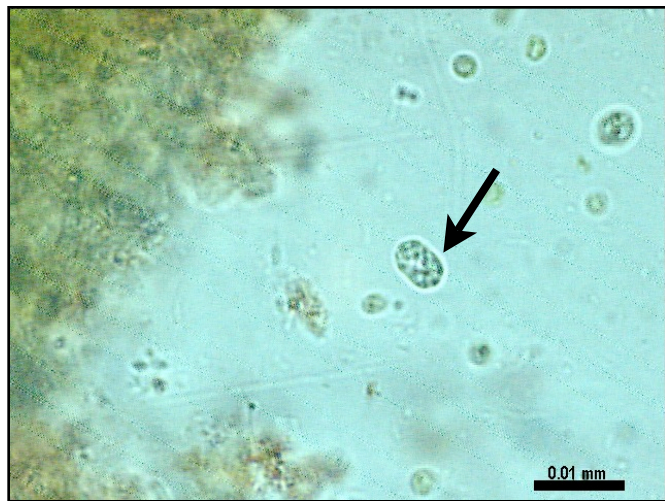
Left-C) *Chromatiacaea vinosum* image is from R. Burnette's Purple Sulfur Bacteria page. Unfortunately the scale bar has not been provided in full by the source. Also similar are a drawing from Komárek (1992) on CyanoDB of a *Synechococcus* species and *Gloeocapsa* as seen on the UTEX image bank.

Figure 31a: Images of sample A5 A) in the field. B) at 1000 x magnification C) Suggested identification

Right- D) 1600x magnification: Segmented translucent filaments often seen in orange-tinted clumps. Image at right was selected to show the filament structure. These filaments comprise the bulk of the biologic sample, and are suspected to be *Phormidium* as in E below.
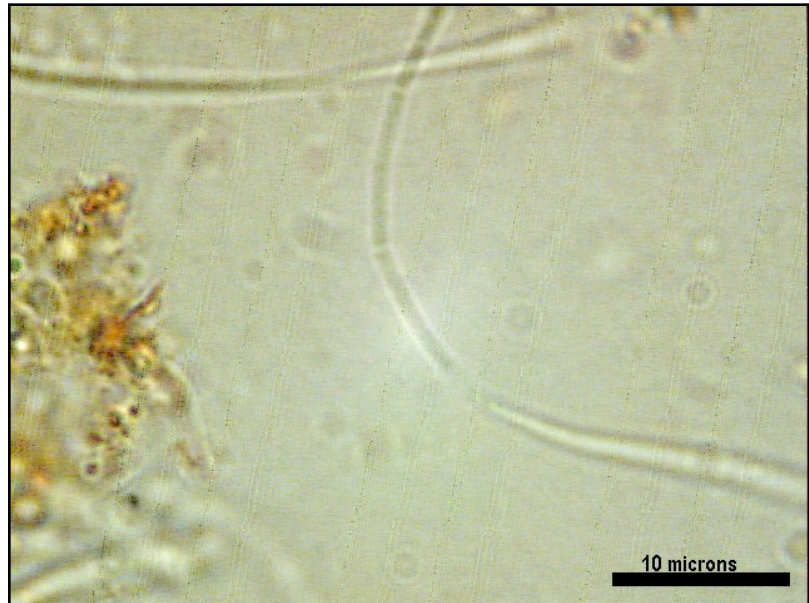
Left- E) 1000x magnification of *Phormidium foveolarum* (a.k.a. *Schizothrix calcicola*) from the UTEX Image Bank.

Figure 31b: D) 1600x magnification of filaments composing bulk of sample E) Suggested identification for D

Left- A) Sample A6 is a mat-forming growth that is seen at very weak springs with virtually no competition. The environment where these growths are found is probably harsh as they were never totally submerged and the rapid evaporation deposits salts around the growths as seen in the lower right.

Right- B) 1000x magnification. While the image above is obviously red-brown, this color is not seen in the preserved sample to the right. It is believed that the non-green pigments may have deteriorated between collection and examination.
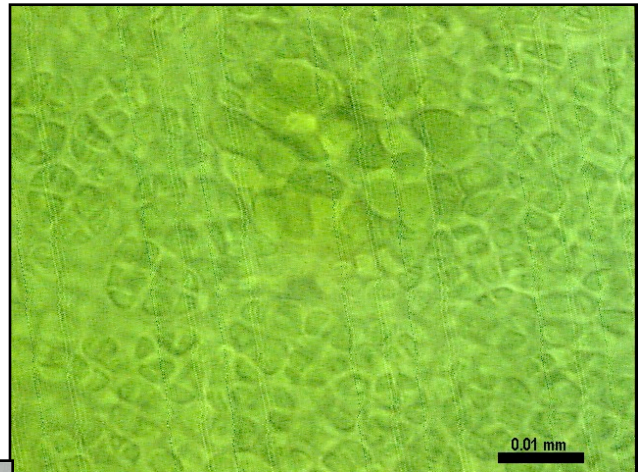
Left-C) *Myxosarcina* image from (http:// galerie.sinicearasy.cz/). Note the similar pattern of cells between B and C. The difference in color is, as stated above, probably due to the break down of pigments during storage.

Figure 32: Images of sample A6 in A) the field. B) at 1000 x magnification with C) Suggested identification

Left- A) In the field:
In one of the fresher pools near the salt concentration ponds this sample floated as a green scum on the water's surface. The same cyanobacteria that comprises the material floating on the surface is probably also responsible for the overall green color of the water.

Right-B) 640x magnification: This image shows two loose spirals that have been identified as *Spirulina* (see C below). Also pictured are an unidentified ovoid cell between the two spirals, and possibly a coiled mass of *Anabaenopsis* in the upper left (see D).

Above-C) 400x image of *Spirulina platensis* from the UTEX image bank.

Above- D) 640x magnification: Possible *Anabaenopsis*. Image is only a partial due to an incomplete image capture. However, it appears that there are two heterocysts together (arrows) which distinguish this genus from *Cyanospira*.

Figure 33: Sample A7 A) in the field, B) at 640x magnification, C) suggested identification D) supplemental image of sample.

Appendix B: Formation Correlation Chart

The first two columns show geologic formations present in the map created for this study. Other columns represent the six original KGS maps that cover the study area. Each map is represented by 2 columns, one for formation name, and the other for formation symbology. Reading across the columns one can see what the formations present in the newly created map have been correlated with in the older maps. Formations that correlate directly between maps are found in the same rows, and similar formations that may not have a direct correlation are placed in the rows immediately below the formation they most are closely identified with.

Correlation is often based on what boundaries match across maps, or in some cases, what a formation had previously been mapped as. In cases where a formation was unrecognized or misidentified, the older, less favored identification is highlighted in grey. A number of formations that are present in the newly created map are not found in the older KGS maps, and instead have been mapped from sources found in more recent journal articles.

Guth - South Kenya	Joubert - Namanga	Baker- South Magadi	Matheson- Kajiado Column4	Baker- Magadi	Randel-Suswa	Saggerson-Nairobi
Alkaline Lagoons Alluvial Fans		Alkaline Lagoons Rt Pebble Beds Qp		Alkaline Lagoon Rt' Boulder Beds	Talus Rt	
Quaternerary Sed Qr	Red Brown Sandy soil Qr Black cotton soil Qb Grey sandy soil Qg Recent Terrestrial Deposits Rt Calcareous surface deposits Qc	Soils Qr	Loessic soil Qr black cotton soil Qb red volcanic soil Qv Grey sandy soil Qg	Loessic soil Qr	Volcanic soils Qv	Seds, loess, lake deposits, diatomite Qt2 Terrestrial Deposits w/ artifacts Qt1
Trona Beds				Trona beds Rt		
High Magadi Beds Pl-ml High Magadi-pebble Pl-ml'		High Magadi-clays Qt2 High Magadi- pebble Qt1		High Magadi Beds Qt		
Green Beds Plc		Chert Series Pll1		Chert Series Pll2		
Kedong Flood Pl-kf				Loessic soil Qr	Seds Pl	Kedong Valley Seds Qvf
Suswa Volcanics S1-S10					Suswa Volcanics Plp1-6, Plt2-3,	
Orkaramatian Beds Pl-ol				Loessic soil Qr		
ash vents Pl-va				ash vents Plv6	Basalt cinder cones Plb	
Mau Ashes Pl-ma					Mau Ashes Plt1	
Mosiro basalts Pl-mb					Kirikiti basalts Tvb1	
Nyokie ash Pl-na Nyokie obsidian Pl-nv		Pumic tuffs Plv5 trachytes Plv4		Nyegi pumice ash plv5 Nyegi obsidian plv4		
Oloronga Beds Pl-ogl		Oloronga Beds Pll2		Loessic soil Qr Oloronga Beds Pll1		
Olorgesailie Lake Beds Pl-okl			Olorgesailie lake beds Pll	Olorgesailie Beds Pll3		
	Amboseli lake beds Pl					
Kilimanjaro basalts Pl-kv	Kilimanjaro basalts Plv					
Gesumeti trachyte Pl-gt					Alkali Trachyte Plh2	
Plateau Trachyte Pl-pt		Plateau trachyte Plv2	Plateau Trachyte Plh1	Alkali trachytes plv2	Alkali Trachyte Plh2 *Note, this unit has been re-identified as several different units, but part still correlates with what is known elsewhere as Plateau trachytes	

Guth - South Kenya	Joubert - Namanga	Baker- South Magadi	Matheson- Kajiado Column4	Baker- Magadi	Randel-Suswa	Saggerson-Nairobi
Tepesi Basalt Pl-tb			Ol Keju Ngiro Basalt Tvb / Alkali Trachyte Plh1		Alkali Trachyte Plh2 / Orthophyre trachyte Plh3	
Limuru Pantellerite Pl-lv						Limuru Trachyte Plh1
Tepesi Benmoreite Pl-tv			Orthophyre trachyte Plh2		Orthophyre trachyte Plh3	
N. Kordjya trachyte Pl-kt			Orthophyre trachyte Plh2	Orthophyre-trachyte plv3	Alkali Trachyte Plh2 / trachyte Plh3	
Leshuta trachyte Pl-lt						
Ol Keju Nero Pob				Ol Keju Nero tvb2		
Gelai Pgv						
					Longonot trachyte Plh5	Longonot trachyte Plh2 / Kinari Tuffs Plt1 / Mt Margaret Plt2 / Rhyolite, comendites, pantellerites, trachyrhyolites Plr
Sambu Psv						
Limuru Trachyte Plt			Orthophyre trachyte Plh2			Limuru Trachyte Plh1
Ewaso Ngiro Trachyte Pet				Orthophyre-trachyte plv3	Orthophyre-trachyte Plh3	
Kordjya Basalt Pkb		Plateau trachyte Plv2				
Tigoni Trachytes Ptt / Karura Trachytes Pkat / Kabete Trachytes/Ruiru Dam trachytes Pket						Tigoni Trachytes Tvt7 / Karura Trachytes Tvt6 / Kabete Trachytes/Ruiru Dam trachytes Tvt5
Upper Kercherwa Valley Tuff Pka'						mid-Upper Kerichwa Valley Tuffs Tvtf2
Lower Kerichwa Valley Tuffs Pka						Lower Kerichwa Valley Tuffs Tvtf1
Shombole volcanics Pshv		Shombole volcanics Tvn				
Mosiro Trachyte Pmt					trachyte Plh3	
Singaraini Basalts Psb	Miocene Basalts B1	Olivene basalts Plb1	Ol Keju Ngiro Basalt Tvb	Ol Keju Nero tvb2		
Olorgesailie volcanics Pov / Olorgesailie Nephelinite Pon			Olorgesailie volcanics Tvt2	Olorgesailie trachytes Tvt / Olorgesailie Nephelinite Tvn		
Lenderut volcanics Plv		Lenderut volcanics Tva				
Kirikiti Basalt Pvb1		Kirikiti basalts Tvb		Kirikiti basalt Tvb1	Kirikiti basalts Tvb1	
						Ololua Trachytes Tvt3
Nairobi Trachytes Pnt						Nairobi Trachytes Tvt2

Guth - South Kenya		Joubert - Namanga		Baker- South Magadi		Matheson- Kajiado	Column4	Baker- Magadi		Randel-Suswa		Saggerson-Nairobi	
Ol Doinyo Narok Agglomerate	Pna					Ol Doinyo Narok agglomerate/ Kerichwa Valley Tuff	Tvf2					Ol Doinyo Narok Agglomerate	Tvf
						Ol Doinyo Narok agglomerate Phonolite	Tvp3						
Ngong Volcanics	Pnv											Ngong Volcanics	Tvu, Tva1-3
Kiambu Trachyte	Pkt											Kiambu Trachyte	Tvt1
Olorgesailie biotite phonolite	Pop					Olorgesailie biotite phonolite	Tvp2						
phonolitic nephelinite	Popn					phonolitic nephelinite	Tvpn						
Ol Esayeti	Pev					Ol Esayeiti lower trachyte	Tvt3					Esayeti Trachytes	Tvt4
						Ol Esayeiti upper trachyte	Tvt4						
						Ol Esayeiti phonolite	Tvp4					Ol Esayeiti Phonolite	Tvp5
												Esayeti Phonolites	Tvp6
												Esayeti Phonolites	Tvp4
						Ol Esayeiti oligoclase tephrite	Tva					Ol Esayeiti Oligoclase Tephrites	Tva4
						Ol Esayeti agglomerate	Tvf3					Ol Esayeiti Volcanics	Tv
Lengitoto Trachyte	Mt							Lengitoto trachyte	plv1	Lengitoto Trachyte	Plh1		
										Kirikiti Basalt	Tvb1		
Nairobi Phonolite	Mnp											Nairobi Phonolite	Tvp3
Kandizi Phonolites	Mknp											Kandizi Phonolites	Tvp2
Mbagathi trachyte	Mmt					Mbagathi trachyte	Tvt1					Mbagathi Phonolitic trachytes	Tvtp
												Simbara basalt	Tvb
Upper Athi tuffs	Mva					Upper Athi tuffs	Tvf1					Athi Tuffs & lake beds w/ chert	T
Kapiti Phonolites	Mkp	Kapiti Phonolites	Tvp			Kapiti phonolite	Tvp1					Kapiti phonolite	Tvp1
Kishalduga + Lisudwa Melanephelinites	Mmn			Kirikiti Basalt	Tvb								

Guth - South Kenya	Joubert - Namanga	Baker- South Magadi	Matheson- Kajiado Column4	Baker- Magadi	Randel-Suswa	Saggerson-Nairobi
Archean X		Undifferentiated X		Archean X		Archean X
Quartzites Xq	Quartzites Xq Muscovite quartzo-feldspathic granulites Xqm	Quartzites Xq	Quartzites Xq			
Crystalline limestones Xl	Crystalline limestones Xl	Limestone Xl	Crystalline Limestone Xl			
Biotite Gneiss Xs	Biotite Gneiss Xs" Banded Gneiss Xs'	Biotite gneiss Xs"	Biotite Gneisses Xs"			
Quartzo-feldspathic gneiss Xgg Muscovite gneiss Xsm Kyanite-biotite Xa		Muscovite gneiss Xsm Kyanite-biotite Xa	Quartzo-feldspathic gneiss Xgg			
Undifferntiated, peltic-host Xga Undifferntiated, semi-peltic host Xga'	Undifferntiated, peltic-host Xga Undifferntiated, semi-peltic host Xga'		Undiff gneisses Xga			
Augen Gneiss Xna	Augen Gneiss Xna		Augen gneisses Xna			
Hornblend pyroxene gneiss Xsd	Hornblend pyroxene gneiss Xsd Hornblend schist Xsh					
Hornblend gneiss Xh	Hornblend gneiss Xh Hornblend-biotite gneiss Xh'					
	Granite intrusive G1					
	Basic Intrusives Xu					
	Meta-dolerites Xd					

Appendix C: Age Dates for the Kenya Rift

This is a chart showing the accumulated age dates from all sources and for all parts of the Kenya Rift. Formations are sorted by age, with the youngest at the top and the oldest at the bottom of the chart. Notes should be read carefully as there are some instances were an age date was called into question by a later author.

The final column is a "Quality Assessment" with values ranging between from 1 and 3, where values of 1 indicate an age date of dubious quality that should probably be reevaluated, and 3 indicates a newly obtained, well corroborated date. This is especially the case if the specific unit dated is considered pivotal (such as, a lava flow used to constrain the age of sediments or other flows) or the suspect date is the only one available for the entire formation. The Quality Assessment is gauged based on a variety of factors including age of the analysis, number of other dates that either corroborate or conflict with the date, dating method (K-Ar, Ar-Ar, whole rock, single crystal etc…) and assessed quality of other dates published along with the date in question. This is mainly to call attention to units or formations that should be re-dated to ensure an accurate image of the evolution of the rift. A number of age dates presented here are well outside the study area for this thesis, and due to unfamiliarity, quality assessments were not attempted for all age dates, in which case the field will be blank.

Age Date Compilation for the Kenya Rift

Unit Name	Event	Age Min	Age Max	Age Units	Uncertainty	Method	Author	Year	Notes	Quality Assessment
Ol Doinyo Lengai		18		annum			Gittins and Jago	1998	1988 June-Nov eruption	3
Ol Doinyo Lengai ash		23		annum			Dawson, Pinkerton et al.	1990	1983, small ash eruptions and small volume lava	3
Ol Doinyo Lengai ash		40		annum			Dawson, Pinkerton et al.	1990	1966 violent ash eruption	3
Ol Doinyo Lengai		46		annum			Dawson, Pinkerton et al.	1990	1960 eruption	3
Suswa		100		annum			GVP	2006	? Youngest flow is devoid of soil or vegetative cover	
Longonot trachyte		200		annum			reported in Lagat	2003	(Clarke et al. 1990) Most recent activity erupted onto the N and SW flanks of the cone	
Ololbutot comendite		250		annum			reported in Lagat	2003	(Clarke et al. 1990) Youngest lava from the Upper Olkaria Formation, 14C dated carbonized wood for age	
Eastern Eburru pantellerites		400		annum			reported in Lagat	2003	(Clarke et al. 1990) youngest rocks of the Eburru volcano	
	high lake level	4.65		ka			hillaire-marcel et al.	1986	C14 date from tilapia at 605m, SE Magadi	
Oncoids		5		ka			reported in Behr	2002	Tichy/Seegers	
Na-silicates		6.3		ka			Goetz & Hillaire-marcel	1992	isochron age	
massive lahars, Meru crater collapse		7.8		ka			Wilkinson et al	1986		
	lake recessions	9.1		ka			hillaire-marcel et al.	1986	strong volcanic activity, ashes killed tilapia	
Little Magadi Trona		9.12		ka			Behr	2002		
High Magadi Beds		9.31		ka			reported in Behr	2002	tilapia, Tichy/Seegers	
	Magadi joined with Natron	10.2		ka			Roberts et al.	1993		
3rd Gen. Stromatolites		10.3	11.4	ka		C14	hillaire-marcel et al.	1986	corrected C14 age	
	block lifting	10.3	11.8	ka			hillaire-marcel et al.	1986	displaced stromatloites found on Nguruman escarpment, ~20m lift	
	Magadi intermediate	10.7		ka			Roberts et al.	1993	deep enough to be stratified	
	Magadi lake level minimum	10.8		ka			Roberts et al.	1993		
	Magadi separated from Natron	10.9		ka			Roberts et al.	1993		
	Magadi joined with Natron	11.1	12	ka			Roberts et al.	1993	lave level rise 58m+ from current	
Travertine pipe		12		ka		Th/U	hillaire-marcel et al.	1986	corrected Th/U age	
High Magadi chert/magadiite		15		ka			Behr	2002		
High Magadi, Erionite silts		23.7		ka			reported in Williamson et al	1993	Goetz 1990, * Note: C14 dates were also aquired for this section of core but there was evidence for contamination by bacteria, so the U/Th dates are preferred (Taieb et al., 1991)	
Green beds		40		ka			reported in Williamson et al	1993	Goetz 1990, * Note: C14 dates were also aquired for this section of core but there was evidence for contamination by bacteria, so the U/Th dates are preferred (Taieb et al., 1991)	
Meru main cone built		60	160	ka			Wilkinson et al	1986		
Chert		96		ka			Goetz &hillaire-marcel	1992	isochron age	
Suswa		100		ka	+/- 0.01	K-Ar	Baker et al.	1988	post-caldera, pre-Kedong flood, E flank	3
Suswa		100		ka	+/- 0.01	K-Ar	Baker et al.	1988	post-caldera, post-Kedong flood, NE flank	3
2nd Gen Stromatolites		129	170	ka			hillaire-marcel et al.	1986	Magadi Area	
Meru alkaline lavas		160	350	ka			Wilkinson et al	1986	alkaline lavas from W, NW and N of Meru	
Kilimanjaro, Kibo Caldera		210		ka			Wilkinson et al	1986	end of cone building period	
Suswa		240		ka	+/- 0.01	K-Ar	Baker et al.	1988	Primitive shield eruption on rift floor	3
Lake Baringo trachyte		260		ka			reported in Chapman and Brook	1978	Miller, whole rock analysis	
1st Gen Stromatolites		290	304	ka			hillaire-marcel et al.	1986	Natron area	

Unit Name	Event	Age Min	Age Max	Age Units	Uncertainty	Method	Author	Year	Notes	Quality Assessment
Oloronga		300		ka			Behr	2002		
Hannington phonolites		300		ka			Chapman and Brook	1978	Baringo basin	
Lainyamok Khaki 1		330		ka			Potts & Deino	1995	isochron analysis	3
Kilimanjaro, Rhombporphyry series		365		ka			reported in Baker et al	1971	Evernden and Curtis 1965	
Barajai trachytes		370	410	ka	+/- 0.02, +/- 0.03	K-Ar	Baker et al.	1988	S. of Suswa, prev. correlated w/ Magadi Trachyte, possibly related to earliest Suswa activity	
Lainyamok Khaki 2		392		ka			Potts & Deino	1995	isochron analysis	3
Longonot		0.4		Ma			Lagat	2003		
Kilimanjaro, lower olivene basalts		0.42		Ma			reported in Baker et al	1971	Curtis (per. Comm, 1968)	
Kilimanjaro, Lavaturm series		0.463		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	
Olorgesailie M12-M14		0.493	0.601	Ma			reported in Behrensmeyer & Potts et al.	2002		3
Loyamarok phonolite		0.5		Ma			reported in Chapman and Brook	1978	Miller, whole rock analysis	
Kilimanjaro, Mawenzi		0.514		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	
Ol Doinyo Nyokie		0.57	0.66	Ma	+/- 0.05 +/- 0.04	K-Ar	Fairhead et al.	1972	dated obsidian, Reversed polarity	2
Olorgesailie M10-14		0.6	0.7	Ma			Bye et al	1987		3
Oloronga		0.6		Ma			reported in Behr	2002	Kaufman et al	
Mosiro basalt		0.6		Ma			reported in Crossley	1979	Knight, 1976 thesis	
Olorgesailie M10-M12		0.601	0.662	Ma			reported in Behrensmeyer & Potts et al.	2002		3
Lengorale trachyte		0.63	0.64	Ma			reported in Baker et al	1971	SW of Magadi, Fitch and Miller unpub.	
Ol Doinyo Nyokie		0.65	0.75	Ma			Baker	1976	using Fairhead et al., 1972 date	2
Kapthurin Frm		0.67		Ma			reported in Chapman and Brook	1978	Miller, whole rock analysis	
Marsabit, youngest flows		0.68	0.76	Ma			Key	1987	Marsabit area	
Olorgesailie M1-9		0.7	0.93	Ma			Bye et al	1987		3
Olorgesailie M10		0.71	0.74	Ma		K-Ar	Bye et al	1987	K/Ar from pumice	3
Plateau trachytes		0.72	0.91	Ma			reported in Baker et al	1971	W. of Magadi, Fitch and Miller unpub.	2
Silbo Tuff		0.72		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, Ar-Ar date	
Silbo Tuff		0.74		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, K-Ar date	
Olorgesailie M7-M9		0.746	0.78	Ma			reported in Behrensmeyer & Potts et al.	2002		3
Lava flow in Oloronga Lake Beds		0.78		Ma	+/- 0.04	K-Ar	Fairhead et al.	1972	Key date used to date initiation of Oloronga beds. Noted by Bye et al., 1987 to be nearly identical to Nyokie obsidian	
Oloronga		0.8		Ma			reported in Behr	2002	Fairhead et al	1
*Singaraini basalts		0.82	0.92	Ma	+/- 0.08 +/- 0.07	K-Ar	Fairhead et al.	1972	*Too young for Singaraini Basalts, Of the samples Fairhead et al. examine, these have the most Atmos. Argon contamination. Sample location 5 miles East of Singaraini station, so abnormal dates may be due to alteration/contamination	1
Plateau trachytes		0.84		Ma	+/- 0.03	K-Ar	Fairhead et al.	1972	Reverse polarity	2
Kilimanjaro, lower olivene basalts		0.85	1.1	Ma			reported in Baker et al	1971	Curtis (per. Comm, 1968)	
Plateau trachytes		0.86	0.89	Ma	+/- 0.03	K-Ar	Fairhead et al.	1972	Normal polarity	2
Magadi Trachyte		0.89	0.92	Ma			Potts & Deino	1995	from floor and walls of Lainyamok graben	3
Gesumeti trachyte		0.9	1.25	Ma	NA	NA	Baker and Mitchell	1976	not specifically dated, but have reversed magnetic polarities, overlie the Limuru trachytes, and are older than the Plateau trachytes of the Kedong Gorge. Note that these age estimates are quite different than the ages presented in Baker et al. 1988 of 1.95-2.1 Ma	2

Age Date Compilation for the Kenya Rift

Unit Name	Event	Age Min	Age Max	Age Units	Uncertainty	Method	Author	Year	Notes	Quality Assessment
Hannington phonolites		0.9	1.1	Ma			Chapman and Brook	1978	Baringo basin	
Plateau trachytes		0.93		Ma	+/- 0.06	K-Ar	Baker and Mitchell	1976	top flow in scarp, NW of Olorgesailie N.P.	3
Olorgesailie M1-M5		0.974	0.992	Ma			reported in Behrensmeyer & Potts et al.	2002		3
Plateau trachytes		0.98	1.23	Ma	+/- 0.04, +/- 0.02	K-Ar	Baker et al.	1988		3
*Kirikiti Basalts		1		Ma	+/- 0.01	K-Ar	Fairhead et al.	1972	*Too young for Kirikiti Basalts	1
Marsabit, main shield		1.13		Ma			Key	1987	Marsabit area	
Plateau trachytes		1.17		Ma	+/- 0.04	K-Ar	Baker and Mitchell	1976	bottom flow in scarp, NW of Olorgesailie N.P.	3
	WNW-ESE faulting	1.18	1.23	Ma			reported in Wilkinson et al	1986		
*Kirikiti Basalts		1.27	1.31	Ma	+/- 0.08 +/- 0.09	K-Ar	Fairhead et al.	1972	*Too young for Kirikiti Basalts	1
*Singaraini basalts		1.31	1.44	Ma	+/- 0.06 +/- 0.05	K-Ar	Fairhead et al.	1972	*Too young for Singaraini Basalts, noted by Fairhead to have Normal Polarity, so rocks may have Argon imbalance. Sample location South of Ol Esakut, and may be sampled of Ol Tepesi Basalts instead	1
Intra-Moinik basalt		1.33	1.38	Ma	+/- 0.05, +/- 0.09		Thouveny and Taieb	1986	At base of the Moinik Formation, Natron area	
Humbu Formation		1.35	2	Ma			reported in Mora et al.	2003	Natron, 40 m thick, mostly alluvial	
Moinik Formation		1.35	1.15	Ma			reported in Mora et al.	2003	Natron, 30-40m thick, lacustrine	3
Plateau trachytes		1.36	1.42	Ma			reported in Baker et al	1971	Magadi Area, Fitch and Miller unpub.	2
Chari Tuff		1.38		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, Ar-Ar date	
Chari Tuff		1.39		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, K-Ar date	
Ol Tepesi basalt		1.4	1.6	Ma			Baker et al.	1988		3
Magadi Trachyte		1.4		Ma			Crossley	1979		3
Ol Tepesi basalt		1.42		Ma	+/- 0.06	K-Ar	Baker and Mitchell	1976	Reverse polarity	3
Chemeron Frm		1.5	4	Ma			Chapman and Brook	1978	Baringo basin - 200m sed unit, age range from bracketting lavas	
Kapsalop phonolite		1.5	2.1	Ma			Chapman and Brook	1978	Baringo basin	
Ndau mugearite		1.5		Ma			reported in Chapman and Brook	1978	Everndam and Curtis, whole rock analysis	
Meru area volcanics		1.5	2	Ma			Wilkinson et al	1986	alkali volcanics 100s meters thick	
Limuru trachytes		1.55	1.59	Ma			reported in Baker et al	1971	Fitch and Miller unpub.	2
Wa Mbugu basalt		1.55	2.27	Ma	+/- 0.03, +/- 0.06		Thouveny and Taieb	1986	Intercalated with the Humbu basaltic tuff, normally magnetized, Natron area	
Hannington phonolites		1.6		Ma			Chapman and Brook	1978	Baringo basin	
Ol Keju Nero Basalts		1.64	1.79	Ma	NA	NA	Baker and Mitchell	1976	not dated, between 2 dated units, Normal polarity	
Ol Tepesi benmoreite		1.65		Ma	+/- 0.06	K-Ar	Baker and Mitchell	1976	Reverse polarity	3
Kordjya basalts		1.66		Ma	+/- 0.05	K-Ar	Baker and Mitchell	1976	top flow in scarp W side of Kordjya depression	3
Limuru trachytes		1.66	1.68	Ma	+/- 0.02	K-Ar	Baker et al.	1988	Ages may be too young due to potential argon loss. Dated pantelleritic obsidians were hydrated and had lost Na and Fe, so argon loss is suspected.	1
Marsabit, basal unit		1.7		Ma			Key	1987	Marsabit area	
Limuru trachytes		1.72		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	2
Plateau trachytes		1.74		Ma			reported in Baker et al	1971	Nairobi-Magadi road, Everndam and Curtis 1965	2
Kordjya basalts		1.76		Ma	+/- 0.06	K-Ar	Baker and Mitchell	1976	2nd flow in scarp	3
Sambu lavas		1.77	1.9	Ma			reported in Mora et al.	2003	Isaac and Curtis 1974	2
Marsabit, main shield		1.78		Ma			Key	1987	Marsabit area	

Age Date Compilation for the Kenya Rift

Unit Name	Event	Age Min	Age Max	Age Units	Uncertainty	Method	Author	Year	Notes	Quality Assessment
Ol Tepesi benmoreite*		1.81		Ma	+/- 0.05	K-Ar	Baker and Mitchell	1976	This age is considered high, possibly due to too much argon- magnetic results agree more with the age of 1.65Ma	2
Limuru trachytes		1.84		Ma	+/- 0.06	K-Ar	Baker and Mitchell	1976		3
Malbe Tuff		1.85		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, Ar-Ar date	
Malbe Tuff		1.86		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, K-Ar date	
KBS Tuff		1.88		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, K-Ar and Ar-Ar date	
Ainapno mugearites		1.9		Ma			Chapman and Brook	1978	Baringo basin	
Mosiro trachyte		1.9	2.3	Ma			reported in Cossley and Knight	1981	Knight, 1976 thesis	
Limuru trachytes		1.91		Ma	+/- 0.06	K-Ar	Baker and Mitchell	1976	Reverse polarity	3
Kulal Shield, Basal Unit		1.91		Ma			Key	1987	Marsabit area	
Limuru trachytes		1.94		Ma	+/- 0.06	K-Ar	Baker and Mitchell	1976		3
Limuru trachytes		1.94	2.64	Ma			Baker et al.	1988		3
Gesumeti trachyte		1.95	2.1	Ma	+/- 0.02, +/- 0.04	K-Ar	Baker et al.	1988	*note: previously correlated with Plateau trachytes, but age dates and Zr/Nb ratios are similar to Limuru trachytes. Considered by Baker at al. to be localized fissure eruptions of Limuru trachyte magma	
Limuru trachytes		1.96		Ma	+/- 0.04	K-Ar	Baker and Mitchell	1976		3
Shombole		1.96	2	Ma	+/- 0.07 +/- 0.05	K-Ar	Fairhead et al.	1972	Reverse polarity	2
	N-S faulting	1.97	2.37	Ma			Wilkinson et al	1986	synchronous w/ Tarosero faulting (2.1 Ma)	
Kaperyon Frm*		2	7	Ma			Chapman and Brook	1978	Baringo basin - 130m sed unit, *noted, that the original 1971 mapping of this unit by Chapman included 3 units of different ages, Mpesida beds (7Ma), Lukeino Frm (6.5 Ma) and Chemeron Frm (2-4 Ma)	
Songoiwa mugearite		2		Ma			reported in Chapman and Brook	1978	Everndam and Curtis, whole rock analysis	
Peninj group basalt base		2		Ma			reported in Mora et al.	2003	Thouveny and Taieb 1987, 10 m thick	3
Hajaro basalt		2		Ma		K-Ar	Thouveny and Taieb	1986	Curtis (Isaac 1967), is reversely magnetized, Natron area	2
Sambu lavas		2.02		Ma			reported in Baker et al	1971	Curtis (Isaac 1967)	2
Asie Shield, Upper Unit		2.04	2.07	Ma			Key	1987	Marsabit area	
Gombe Group		2.07		Ma			Wilkinson	1988	Allia Bay area, N. Kenya, K/Ar dating, whole rock	
Ewaso Ngiro trachyte		2.1		Ma			Crossley	1979		3
Kordjya basalts		2.17		Ma	+/- 0.10	K-Ar	Baker and Mitchell	1976	11th flow in scarp	3
Olorgesailie		2.2	2.7	Ma			Baker et al. (a)	1977		
Olorgesailie		2.21		Ma	+/- 0.06	K-Ar	Fairhead et al.	1972	Sampled Olorgesailie	2
Gombe Group		2.25		Ma			Wilkinson	1988	Allia Bay area, N. Kenya, K/Ar dating, whole rock	
Singaraini basalts		2.31		Ma	+/- 0.10	K-Ar	Baker and Mitchell	1976	flow top in scarp at Singaraini trig. Station	3
Singaraini basalts		2.33		Ma	+/- 0.09	K-Ar	Baker and Mitchell	1976	lowest flow in scarp at Singaraini trig station	3
Koobi Fora beds		2.37	2.64	Ma			reported in Baker et al	1971	Lake Rudolf. Fitch and Miller 1970	
Olorgesailie		2.4		Ma	+/- 0.07	K-Ar	Fairhead et al.	1972	Normal polarity, Sample from Shanamu	2
Lenderut volcano		2.5	2.7	Ma			Baker and Mitchell	1976	referenced Baker 1963	2
Emsos mugearite		2.5		Ma			Chapman and Brook	1978	Baringo basin - Laikipia escarpment	
Kirikiti basalts		2.5	2.7	Ma			Crossley	1979		3
Kanapoi basalt		2.5	2.9	Ma			reported in Baker et al	1971	Geochron lab (Patterson, 1966;Patterson and Howells 1967)	
Koobi Fora beds		2.5	3.45	Ma			reported in Baker et al	1971	Lake Rudolf, Fitch and Miller 1970	
Ngong Basanite		2.53	2.58	Ma			Saggerson	1991	rock collected by Curtiss, Evernden and Miller. Whole rock K/Ar dated	2
Lenderut		2.53		Ma	+/- 0.08	K-Ar	Fairhead et al.	1972	Normal polarity	2

Unit Name	Event	Age Min	Age Max	Age Units	Uncertainty	Method	Author	Year	Notes	Quality Assessment
Olorgesailie		2.6	2.62	Ma	+/- 0.06 +/- 0.08	K-Ar	Fairhead et al.	1972	Normal polarity, samples from both Shanamu and Olorgesailie	2
Lenderut		2.62		Ma	+/- 0.07	K-Ar	Fairhead et al.	1972	Normal polarity	2
Basalt flow younger than Kingangop tuff		2.63		Ma	+/- 0.04	K-Ar	Baker et al.	1988	6.1 km ESE of Naivasha township, gives minimum age for tuff formation	3
Mt Kenya nepheline syenite plug		2.64		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	
Kirikiti basalts		2.68		Ma	+/- 0.16	K-Ar	Baker and Mitchell	1976	5th flow in scarp	
Narosura pyro.		2.7		Ma			Crossley	1979		
Asie Shield, Basal Unit		2.7		Ma			Key	1987	Marsabit area	
Olorgesailie trachyte		2.7		Ma			reported in Baker et al	1971	Evernden and Curtis 1965, Anorthoclase K-Ar dated	2
Kanapoi basalt		2.71		Ma			reported in Baker et al	1971	Gilbert (Patterson et. Al 1971)	
Kirikiti basalts		2.93		Ma	+/- 0.20	K-Ar	Baker and Mitchell	1976	top flow in scarp	3
Ninikaa Tuff		3.01		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, Ar-Ar date	
Ninikaa Tuff		3.06		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, K-Ar date	
Kirikiti basalts		3.1		Ma	+/- 0.2	K-Ar	Baker and Mitchell	1976	9th flow in scarp	3
Mt Kenya volcanics		3.1		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	
Gombe Group		3.1		Ma			Wilkinson	1988	Allia Bay area, N. Kenya, K/Ar dating, whole rock	
Nairobi trachyte		3.17	3.45	Ma			reported in Baker et al	1971	Fitch and Miller unpub., Whole rock K-Ar dated	2
Bulal basalt		3.2		Ma			Ebinger et al.	2000	SW Ethiopia	
Toroto Tuff		3.31		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, Ar-Ar date	
Toroto Tuff		3.33		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, K-Ar date	
trachyte in Kinangop tuffs		3.34		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	
Harr basalt		3.4		Ma			Ebinger et al.	2000	SW Ethiopia	
Isolated Basalt Plateau		3.44		Ma			Key	1987	Marsabit area	
Ribkwo volcano - Ribon trachyte		3.5	3.9	Ma			Chapman and Brook	1978		
Sambu lavas (Kirikiti basalts?)		3.5		Ma			reported in Mora et al.	2003	Isaac and Curtis 1975, possibly Kirikiti basalts underlaying the Sambu basalts? (Alex Guth)	1
Ol Esayeti		3.6	6.7	Ma			Baker and Mitchell	1976		2
Tirr Tirr volcanics		3.6	3.9	Ma			reported in Baker et al	1971	F.M. Consultants for GSK unpub	
Bulal lavas		3.61		Ma			Key and Watkins	1988	Sabarei Area, N. Kenya	
Ol Esayeiti		3.61		Ma	+/- 0.10	K-Ar	Fairhead et al.	1972	Reverse polarity	2
Kingangop tuff		3.65	3.68	Ma	+/- 0.07, +/- 0.08	K-Ar	Baker et al.	1988	Obsidian fiamma from ash	3
Sill in Lothagam group		3.71		Ma			reported in Baker et al	1971	Gilbert (Patterson et. Al 1971)	
Kaparaina basalt		3.96	4.67	Ma			reported in Chapman and Brook	1978	Dagley et al. 1976, Baringo Basin, Ndau River exposure, near base of most complete continuous sequence of this unit	
Mursi basalt		4		Ma			Ebinger et al.	2000	SW Ethiopia	
Moiti Tuff		4.1		Ma			reported in Key and Watkins	1988	McDougall 1985, Koobi For a region, K-Ar date	
Eldama Ravine Tuff		4.2	4.4	Ma			Chapman and Brook	1978	Baringo basin - Kamasia E. foothills, South of 0.5°North	
Kinodo phonolites		4.2		Ma			Chapman and Brook	1978	Baringo basin - Laikipia escarpment, stratigraphically above Tasokwan trachyte, but several ages from one sample were determined to be 11.5-12 Ma	
Loisiumurto volcanics		4.2		Ma			Crossley	1979		
Ribkwo volcano		4.5	5.5	Ma			reported in Chapman and Brook	1978	Baringo basin - low angle trachyte volcano	
Ribkwo volcano - Ribon trachyte		4.7	5.1	Ma			Chapman and Brook	1978		
Marti Illaut basalt		4.7		Ma			Charsley	1987	Laisamis area, Northern Kenya	
Isolated Basalt Plateau		4.7		Ma			Key	1987	S. End of Marti Engweta Plateau, Marsabit area	

Unit Name	Event	Age Min	Age Max	Age Units	Uncertainty	Method	Author	Year	Notes	Quality Assessment
Kerichwa valley tuff / Nairobi Stone		4.84	5.67	Ma			reported in Baker et al	1971	Langata, Nairobi, Fitch and Miller unpub, Sanidine and Anorthoclase K-Ar dated	2
Lengitoto trachytes		5	5.5	Ma			reported in Crossley	1979	L.A.J. Williams, per. Comm. 1975'	2
Kirikiti basalts*		5.03	5.07	Ma			reported in Baker et al	1971	Fitch and Miller unpub., *note from crossley-may be from unit older than kirikiti	1
Kaparaina basalt		5.1	5.6	Ma			Chapman and Brook	1978	Baringo basin - Kamasia E. foothills, North of 0.5°North	
Kirikiti basalts*		5.13		Ma			reported in Baker et al	1971	Fitch and Miller unpub. *note from crossley-may be from unit older than kirikiti	1
Nairobi phonolite		5.2		Ma			reported in Baker et al	1971	Evernden and Curtis 1965, from Beacon ranch quarry, Anorthoclase K-Ar dated	1
Tasokwan trachyte		5.5		Ma			Chapman and Brook	1978	Baringo basin - Laikipia escarpment, possibly equivalent to Kabarnet trachyte	
Upper Tinderet volcanics		5.5	5.8	Ma			reported in Baker et al	1971	F.M. Consultants for GSK unpub	
"Simbara series"/ Sirrima Basalt (see Note)		5.5		Ma			reported in Baker et al	1971	F.M. Consultants for GSK unpub, *Note, according to Smith 1994, this sample was probably from the Sirrima Basalts which are contemporaneous with Thomson's Falls Phonolites. The Simbara series is most likely over 12 Ma	1
Ol Esayeiti		5.64	5.85	Ma			reported in Baker et al	1971	Fitch and Miller unpub. Tephrite, feldspar K-Ar dated	2
Olorgesailie neph.		5.8		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	2
Lengitoto trachytes		5.8		Ma			reported in Crossley	1979	Knight, 1976 thesis	
Olorgesailie phonolite		5.83		Ma			Saggerson	1991	rock collected by Curtiss, Evernden and Miller. Nepheline K/Ar dated	2
Thomson's Falls phonolites		6.2	6.7	Ma			reported in Baker et al	1971	F.M. Consultants for GSK unpub	
Kabarnet trachytes		6.4	7	Ma			Chapman and Brook	1978	Baringo basin- Kamasia Range	
Kapkut volcano		6.4	6.8	Ma			Chapman and Brook	1978	Baringo basin - Kamasia E. foothills, South of 0.5°North	
Kaparaina basalt		6.4	7	Ma			Chapman and Brook	1978	Baringo basin - Kamasia E. foothills, South of 0.5°North	
Kaparaina basalt		6.7	7.1	Ma			Chapman and Brook	1978	Baringo basin - Kamasia E. foothills, South of 0.5°North,	
Ol Esayeiti		6.7		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	2
Lengitoto trachytes		6.9		Ma			Crossley	1979		3
Ewalel Phonolite		7	7.6	Ma			Chapman and Brook	1978	Baringo basin- Kamasia Range	
Kabarnet trachytes		7.1	7.3	Ma			reported in Baker et al	1971	F.M. Consultants for GSK unpub	
Kapkut volcano		7.4	7.8	Ma			Chapman and Brook	1978	Baringo basin - Kamasia E. foothills, South of 0.5°North	
Olomorooj Phonolite		7.4		Ma			Crossley and Knight	1981	between 1°50' and 1°30' S	
Tasokwan trachyte		7.6		Ma			Chapman and Brook	1978	Baringo basin - Laikipia escarpment, possibly equivalent to Kabarnet trachyte	
Pliocene basalts		8.31		Ma			reported in Baker et al	1971	S. Turkana, Gilbert (Patterson et. Al 1971)	
Ewalel Phonolite		8.5	9.1	Ma			Chapman and Brook	1978	Baringo basin- Kamasia Range	
Tinderet Volcanics		8.9	9.4	Ma			reported in Baker et al	1971	F.M. Consultants for GSK unpub	
Nairobi phonolite		9.74	10.22	Ma			Saggerson	1991	rock collected by Curtiss, Evernden and Miller. Feldspar K/Ar dated	2
Tinderet Volcanics		9.9		Ma			reported in Baker et al	1971	Curtis (Bishop et al. 1969)	
Rumuruti phonolite		10	11.9	Ma			Chapman and Brook	1978	Baringo basin - Laikipia escarpment	
Upper Rumuruti phonolites		11		Ma			reported in Baker et al	1971	Geochron lab. For Patterson, unpub	
Microfoyaite Intrusion		11.6		Ma			Wilkinson	1988	Allia Bay area, N. Kenya, K/Ar dating, whole rock	
Tiim Phonolites		11.7	13.5	Ma			reported in Behrensmeyer et al.	2002	upper units- equivalent to the Uasin Gishu Phonolite	
Kericho phonolites		11.8		Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Nakwele Formation		11.91		Ma			Key and Watkins	1988	Sabarei Area, N. Kenya	
Kishalduga Frm		12		Ma			Crossley	1979		2
Upper Uaso Gishu phonolites		12		Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Lower Rumuruti phonolites		12		Ma			reported in Baker et al	1971	Geochron lab. For Patterson, unpub	

Unit Name	Event	Age Min	Age Max	Age Units	Uncertainty	Method	Author	Year	Notes	Quality Assessment
Simbara Basalts		12		Ma			Smith	1994	12Ma is a miniumum age estimate. Smith claims that the age published in Baker et al. 1971 was for a different unit entirely	1
Tatesa Hills		12.1		Ma			Key and Watkins	1988	Basalt, Sabarei Area, N. Kenya	
Kericho phonolites		12.1	13.4	Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Kericho phonolites		12.3	12.4	Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Lower Kisumu phonolites		12.3		Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Mimo phonolites		12.4		Ma			Ebinger et al.	2000	SW Ethiopia	
Kericho phonolites		12.5	12.6	Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Lodwar volcanics		12.5	14.9	Ma			reported in Baker et al	1971	Grasty(Reilly et al. 1966)	
Getra-Kele tephrite		12.7		Ma			Ebinger et al.	2000	SW Ethiopia	
Kapiti phonolite		12.9	13.1	Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	2
Gurro rhyolite		13		Ma			McDougall and Watkins	2006	Asille Group, NE of Turkana	
Kisumu phonolites		13.1		Ma			reported in Baker et al	1971	Curtis (Bishop et al. 1969)	
"Upper" Tiim Phonolites		13.12		Ma			Behrensmeyer and Deino et al.	2002	Baringo Area, Muruyur Type section, Ar/Ar date	
Uasin Gishu phonolite		13.2	13.8	Ma			Chapman and Brook	1978	Baringo basin- elgeyo escarpment	
Yatta phonolite		13.2		Ma			reported in Baker et al	1971	Fairburn, 1963	2
Tiim Phonolites		13.24		Ma			reported in Behrensmeyer et al.	2002	a corrected date from Deino 1990	
Tiim Phonolites		13.3	15.3	Ma			reported in Behrensmeyer et al.	2002	lower units- equivalent to the Uasin Gishu Phonolite	
Muruyur Beds (top)		13.37		Ma			Behrensmeyer and Deino et al.	2002	Baringo Area, Muruyur Type section, Ar/Ar date	
Chew Bahir basalt		13.4		Ma			Ebinger et al.	2000	SW Ethiopia	
Kapiti phonolite		13.4		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	2
Lower Uasin Gishu phonolites		13.5	13.6	Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Kumbi rhyolite		14		Ma			Ebinger et al.	2000	SW Ethiopia	
Upper Turkana basalts		14		Ma			reported in Baker et al	1971	Geochron lab. For Patterson, unpub	
fossiliferous tuffs, s. of Tinderet		14		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	
fossiliferous tuffs, s. of Tinderet		14	14.7	Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Weyto phonolite		14.1		Ma			Ebinger et al.	2000	SW Ethiopia	
Samburu basalts		14.2		Ma			Chapman and Brook	1978	Baringo basin - Laikipia escarpment	
Jibisa Porphyritic microsyenite		14.4		Ma			Key and Watkins	1988	Sabarei Area, N. Kenya	
Chof phonolites		14.5	15.5	Ma			Chapman and Brook	1978	Baringo basin- elgeyo escarpment	
Kumbi rhyolite		14.5		Ma			Ebinger et al.	2000	SW Ethiopia	
Kumbi rhyolite		14.6		Ma			Ebinger et al.	2000	SW Ethiopia	
Kiahera series		14.6	15.9	Ma			reported in Baker et al	1971	Evernden and Curtis 1965, (Everndam et al 1964)	
Sidekh Phonolites		14.8		Ma			reported in Behrensmeyer et al.	2002	corrected date of upper flow from Chapman and Brook 1978, "Saimo phonolite" in Martin 1969	
Kumbi rhyolitic tuff		14.9		Ma			Ebinger et al.	2000	SW Ethiopia	
Elgeyo basalts		15.1	15.6	Ma			reported in Baker et al	1971	F.M. Consultants for GSK unpub	
Upper Elgon volcanics		15.1	15.5	Ma			reported in Baker et al	1971	F.M. Consultants for GSK unpub	
Kishalduga Frm		15.2		Ma			Crossley	1979		2
BPRP #122 Tuff		15.35	15.45	Ma			Behrensmeyer and Deino et al.	2002	"Baringo Paleontological Research Project" Tuff	
Biryokwonin Tuff		15.55		Ma			Behrensmeyer and Deino et al.	2002	Baringo Area, BPRP #89, Ar-Ar date	
Biryokwonin Tuff		15.58		Ma			Behrensmeyer and Deino et al.	2002	Baringo Area, BPRP #122, Ar-Ar date	
Biryokwonin Tuff		15.62		Ma			Behrensmeyer and Deino et al.	2002	Baringo Area, BPRP #89, Ar-Ar date	
Muruyur Beds (base)		15.63		Ma			Behrensmeyer and Deino et al.	2002	Baringo Area, Muruyur Type section, Ar/Ar date	
"Lower" Tiim Phonolites		15.8		Ma			Behrensmeyer and Deino et al.	2002	Baringo Area, BPRP #89, Ar-Ar date	
Asille Group		15.8	34.3	Ma			McDougall and Watkins	2006	earliest magmatism of rift, tilted 6° SSW	
Gum Dura Upper Rhyolites		15.8		Ma			McDougall and Watkins	2006	Asille Group, NE of Turkana	
Turkana basalts		15.8		Ma			reported in Baker et al	1971	Geochron lab. For Patterson, unpub	
"Lower" Tiim Phonolites		15.84		Ma			Behrensmeyer and Deino et al.	2002	Baringo Area, BPRP #122, Ar-Ar date	
BPRP #89 bonebed Tuff		15.96		Ma			Behrensmeyer and Deino et al.	2002	"Baringo Paleontological Research Project" Tuff	

Age Date Compilation for the Kenya Rift

Unit Name	Event	Age Min	Age Max	Age Units	Uncertainty	Method	Author	Year	Notes	Quality Assessment
"Lower" Tiim Phonolites		15.98		Ma			Behrensmeyer and Deino et al.	2002	Baringo Area, Muruyur Type section, Ar/Ar date	
Irile alkali basalts		16	20.6	Ma			McDougall and Watkins	2006	Asille Group, NE of Turkana	
Sabarei volcanics		16.2		Ma			Key and Watkins	1988	Ankaramitic basalt, Whole Rock, Sabarei Area, N. Kenya	
Lunene lava		16.3	16.8	Ma			reported in Baker et al	1971	Miller (Van Couvering and Miller, 1969)	
Buluk Rhyolites		16.4		Ma			McDougall and Watkins	2006	Asille Group, NE of Turkana	
Sidekh Phonolites		16.4		Ma			reported in Behrensmeyer et al.	2002	corrected date of lower flow from Chapman and Brook 1978, "Saimo phonolite" in Martin 1969	
Lunene lava		16.5	16.6	Ma			reported in Baker et al	1971	Miller (Van Couvering and Miller, 1969)	
Weyto phonolite		16.7		Ma			Ebinger et al.	2000	SW Ethiopia	
Turkana basalts		16.7		Ma			reported in Baker et al	1971	Geochron lab. For Patterson, unpub	
Turkana basalts		16.8		Ma			reported in Baker et al	1971	Patterson et al. 1970	
Jarigole Phonolites		16.9		Ma			Wilkinson	1988	Allia Bay area, N. Kenya, K/Ar dating, whole rock	
Basal Elgon volcanics		17.2	19.8	Ma			reported in Baker et al	1971	Armstrong (Bishop et al. 1969)	
lower Elgon volcanics		17.4		Ma			reported in Baker et al	1971	Armstrong (Walker et al. 1969)	
Turkana basalts		17.5		Ma			reported in Baker et al	1971	Geochron lab. For Patterson, unpub	
Samburu basalts		18.5	23	Ma			reported in Baker et al	1971	F.M. Consultants for GSK unpub	
Getra-Kele basalt		18.8		Ma			Ebinger et al.	2000	SW Ethiopia	
Rangwa complex		19	19.3	Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Teltele basalt		19.3		Ma			Ebinger et al.	2000	SW Ethiopia	
Rusinga agglomerate group		19.5	19.6	Ma			reported in Baker et al	1971	Miller (Van Couvering and Miller, 1969)	
Koru beds (SW of tinderet)		19.5	19.6	Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Koru beds (w. of Tinderet)		19.7	19.9	Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Teltele basalt		20.2		Ma			Ebinger et al.	2000	SW Ethiopia	
Samburu basalts		20.7		Ma			Chapman and Brook	1978	Baringo basin - Laikipia escarpment	
Olo rhyolite		20.7		Ma			Ebinger et al.	2000	SW Ethiopia	
Jibisa sodic granite		20.7		Ma			Key and Watkins	1988	Sabarei Area, N. Kenya	
Turkana basalts		20.7	23	Ma			reported in Baker et al	1971	Grasty(Reilly et al. 1966)	
Kiahera series		21.7		Ma			reported in Baker et al	1971	Evernden and Curtis 1965	
Basal Elgon volcanics		21.9	22	Ma			reported in Baker et al	1971	Miller (Walker et al. 1969)	
Upper series, Karungu Lake		22.5		Ma			reported in Baker et al	1971	Miller (Bishop et al. 1969)	
Teltele basalt		23		Ma			Ebinger et al.	2000	SW Ethiopia	
Jarigole Phonolites		23.2		Ma			Wilkinson	1988	Allia Bay area, N. Kenya, K/Ar dating, whole rock	
Upper Turkana basalts		23.3	23.5	Ma			reported in Baker et al	1971	Grasty(Reilly et al. 1966)	
Langaria Formation Rhyolites		26.8		Ma			McDougall and Watkins	2006	Asille Group, NE of Turkana	
Nabwal transitional basalts		27.6	34.8	Ma			McDougall and Watkins	2006	Asille Group, NE of Turkana	
Turkana basalts		31.5	32.2	Ma			reported in Baker et al	1971	Grasty(Reilly et al. 1966)	
Balesa Koromto Basalts		35.2		Ma			Wilkinson	1988	Allia Bay area, N. Kenya, K/Ar dating, whole rock	
Gamo-Amaro basalt		35.6		Ma			Ebinger et al.	2000	SW Ethiopia	
Gamo-Amaro basalt		36.9		Ma			Ebinger et al.	2000	SW Ethiopia	
Gamo-Amaro basalt		38.3		Ma			Ebinger et al.	2000	SW Ethiopia	
Gamo-Amaro basalt		39.9		Ma			Ebinger et al.	2000	SW Ethiopia	
Hamer basalt		95	151	Ma			Ebinger et al.	2000	*min age estimated from Ar-Ar step heating of whole rock, SW Ethiopia	
Aluma basalt		97		Ma			Ebinger et al.	2000	SW Ethiopia, dike in metamorphic basement	
Phlogopite crystals		480	530	Ma			Saggerson	1991	indictaes last metamorphic event to affect basement	
basement gneiss		510	522	Ma			McDougall and Watkins	2006	K-Ar biotite cooling, Pan-African	

Appendix D: Volume Estimate Calculations

Description of the chart columns:

Unite Name- Name of the geologic formation or unit

Measured Area- Surface area calculated from the digital files produce for mapping (i.e. the exposed surface area of the unit at present)

Estimated Area- Probable original area of formation

Thickness- The formation thickness

Volume- Calculated from Measured Area and Thickness

Max Volume- Calculated from Estimated Area and Thickness

Thickness Source- Key to references used to obtain formation thickness

Estimated Area Source- In some cases probable formation extent has been verbally or visually described by authors. Unless specified otherwise, estimated areas were from conservative assumptions, such as the original flow must have at least had a perimeter that includes all outcrops.

Sources

1 1976 Baker and Mitchell,
2 2004 Otando, S.W.
3 1958 Baker x-section
4 1958 Baker report
5 1963 Baker S. Magadi x-section
6 1991 Randel KGA report,
    *Geology of Suswa map x-section
7 1991 Saggerson Geology of Nairobi map
    *est from x-section
8 1979 Crossley
9 1988 Baker, Mitchell and Williams
10 1993 Skilling
    *minimum extimate from a drawing,
    **thickness of 45m used for max
    volume based on 50% being a 75m unit
    in old caldera,

    ***back calculated from given volume
11 estamated from DEM, probably a bare min.,
    *-average height of 10 cinder cones,
    volume of volcanic centers esimated as a
    cone
12 1981 Crossley and Knight
13 1991 Saggerson Geology KGS report
14 estimated extent based on current outcrops
and landsat extrapolation,
    *combo plp4+5
15 1966 Matheson, KGS
16 1966 Baker, Nyokie
17 2001 Mora et al.
18 2002 Behrensmeyer et al.
19 1994 Smith

Volume Estimate Calculations

Unit Name	Measured Area (sq Km)	Estimated Area (sq km)	Thickness (km)	Volume (cu km)	Max Volume (cu km)	Thickness Source	Est. Area Source
Suswa10	5.84		0.017	0.10		10***	
Suswa8-plp6 (Ol Doinyo Onyoke)	95.70		0.03	4.77		6*	
Suswa6-plp4 (Entarakua)	46.43	157	0.015	0.70	7.07	10**	14*
Suswa7-plp5 (Entarakua)	19.15		0.015	0.29		10	
Suswa4-plt3 (Esinoni)	31.31		0.025	0.78		10	
Suswa5-plp3, Oloolwa	44.90	180	0.003	0.13	0.54	10*	14
Suswa Olgumi frm		95	0.014	NA	1.33	10	14
Suswa3-plt2	12.52		0.002	0.03		6	
Suswa1+2 (plp, plp2)	79.63	640	0.03	2.39	6.40	10	14*
cinder cones	11.90		0.52	2.06		11*	
Lengorale	0.54		0.03	0.02		8	
Mau ash	708.00	1105	0.304	215.23	335.92	6*	
Mosiro basalt	11.45		0.011	0.13		8	
minor centers (e.g. Nyokie)	6.92		0.2	0.46		11	
minor ash	34.28		0.012	0.41		16	
Gesumeti trachyte	1.90	21.3	0.22	0.42	4.69	1	
Plateau trachyte	1996.46	3172	0.15	299.47	475.80	1	14
Tepesi Basalt	45.00	181	0.15	6.75	27.15	1	
Limuru pantellerite	1.77	31	0.01	0.02	0.31	11	
N. Kordjya trachyte	160.00	267	0.14	22.40	37.38	8	
Kordjya Basalt	171.23	1281.23	0.15	25.68	192.18	8	

Volume Estimate Calculations

Unit Name	Measured Area (sq Km)	Estimated Area (sq km)	Thickness (km)	Volume (cu km)	Max Volume (cu km)	Thickness Source	Est. Area Source
Leshuta trachyte	0.38		0.01	0.00		8	
Tepesi benmoreite	29.52	134	0.15	4.43	20.10	1	
Gelai	971.43	1312	1.93	624.95	844.05	11	
Limuru trachyte	931.17	1874	0.3	279.35	562.20	1	
Sambu	124.54	261	0.18	22.42	15.66	8	14
Ol Keju Nero	1.66		0.085	0.14		1	
Ewaso Ngiro trachyte	47.80	100	0.26	12.43	26.00	8	
Kabete trachyte	59.80		0.03	1.79		13	
Karura trachyte	36.10		0.035	1.26		7*	
Shombole	45.01	247	0.933	14.00	76.82	11	14
Tigoni trachyte	43.90		0.061	2.68		13	
Mosiro trachyte	260.41	1796	0.27	70.31	484.92	6*	14
Singaraini basalt	524.53	1500	0.457	239.71	685.50	5	
Lenderet	60.49	290	0.3985	8.03	38.52	11	
Olorgesailie	150.44	472	0.8022	40.23	126.21	11	
Kirikiti basalt	101.10	2624	0.55	55.61	1443.20	8	14
Upper Kerichwa Tuff	609.45	1725	0.04	24.38	69.00	13	
Nairobi trachyte	241.60	1238	0.061	14.74	75.52	13, 2	13
Sambu	124.54		0.4	49.82		17	
Lower Kerichwa Tuff	24.03	1133	0.006	0.14	6.80	13	
Narok agglomerate	70.31	824	0.061	4.29	50.26	13	
Ngong hills	156.59	310	0.5	26.10	155.00	11	13
Kiambu trachyte	20.60	55.9	0.046	0.95	2.57	13	13
Nairobi phonolite	329.00	573	0.04	13.16	22.92	13	13
Olorgesailie neph	6.05		0.15	0.91		3	
Olorgesailie neph-phono	60.83	230	0.06	3.65	13.80	15	14

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Unit Name	Measured Area (sq Km)	Estimated Area (sq km)	Thickness (km)	Volume (cu km)	Max Volume (cu km)	Thickness Source	Est. Area Source
Olorgesailie phono	157.90	789	0.038	6.00	29.98	15	14
Esayeti	112.72	316	0.363	13.64	38.24	11	
Lengitoto trachyte	96.45	688	0.22	21.22	151.36	8	14
Kandizi phonolite	9.97	103	0.015	0.15	1.54	11	13
Mbagathi trachyte	178.00	504	0.061	10.86	30.74	13	13
Athi Tuff	515.60	3022	0.305	157.26	921.71	7	
Simbara basalts	NA	440	0.035	NA	15.40	7*	13
Kapiti phonolite	509.00	2182	0.06	30.54	130.92	15	13
Melanephelinitic (Kishalduga)	159.12	1148	0.26	41.37	298.48	8	8
Melanephelinitic (Lisudwa)	22.70	159	0.47	10.67	24.91	8	8
Plateau Phonolite		60748.4	0.7		42523.88	18-est	19

Appendix E: Silica and Alkali Contents of South Kenya Rift Volcanics

These data were used to make the composition charts seen alongside the paleomaps presented in this study. Some data were obtained for formations near the area mapped for this thesis and were included even though they are not represented by outcrops in the study area. If a formation was not located within the study area (In study area = n), then a note was made in the "relation to study area" column to denote where the formation can be found in relation to the study area.

Formations are first sorted by whether they appear within the study area or not, and are then sorted by age.

Sources can be seen below and also at the bottom of the table.

Sources:
1 Baker 1958
2 Baker 1975
3 Baker et al 1977
4 Crossley and Knight 1981
5 reported in GeoRoc, Bellieni et al. 1986 (8088)
6 reported in GeoRoc, Paslick et al. 1996 (7817)
7 reported in Gittins and Jago, 1998
8 reported in GeoRoc, Rogers et al. 2000, (7729)
9 reported in GeoRoc, Macdonald et al. 2001, (8029)
10 Le Roex et al. 2001
11 reported in Otando 2004

A. Guth, MS Thesis, 2007   Composition of Rift Volcanics

Unit name	Na2O	K2O	SiO2	Total alkalis	source	sample #	age (max)	In study area	Relation to study area
N. slope Suswa phonolite	7.23	4.66	59.14	11.89	11		0.24	y	
compound dike 2.6 km NW of Nyokie summit	6.26	5.08	62.34	11.34	2		0.60	y	
Nyokie ignimbrite	6.29	5.20	61.93	11.49	2		0.60	y	
Mosiro basalt	0.78	2.91	47.82	3.69	4	48	0.60	y	
Mosiro basalt	0.94	2.44	46.81	3.38	4	49	0.60	y	
Mau Ash	4.49	5.53	71.59	10.02	4	40	0.60	y	
Magadi trachyte	5.32	4.14	61.67	9.46	10	KR015	1.40	y	
Magadi trachyte	5.76	5.02	61.35	10.78	10	KR040	1.40	y	
Magadi trachyte	5.31	4.82	61.12	10.13	10	KR042	1.40	y	
Magadi Trachytes	5.25	6.66	61.32	11.91	4	55	1.40	y	
Magadi Trachytes	5.21	6.73	61.89	11.94	4	56	1.40	y	
Magadi Trachytes	5.57	6.72	61.89	12.29	4	57	1.40	y	
Magadi Trachytes	5.51	6.87	61.65	12.38	4	58	1.40	y	
Magadi Trachytes	6.96	5.18	62.61	12.14	4	59	1.40	y	
Magadi Trachytes	6.46	5.14	61.23	11.60	4	60	1.40	y	
Magadi Trachytes	6.47	5.02	61.82	11.49	4	61	1.40	y	
Magadi Trachytes	5.98	5.61	60.09	11.59	4	62	1.40	y	
Magadi Trachytes	6.39	4.92	62.55	11.31	4	63	1.40	y	
Magadi Trachytes	6.02	5.08	62.43	11.10	4	64	1.40	y	
Magadi Trachytes	5.99	5.21	61.87	11.20	4	65	1.40	y	
Magadi Trachytes	5.86	5.57	61.89	11.43	4	66	1.40	y	
Magadi Trachytes	6.03	5.06	65.15	11.09	4	67	1.40	y	
Magadi Trachytes	5.86	5	65.85	10.86	4	68	1.40	y	
Magadi Trachytes	6.92	4.5	60.25	11.42	4	69	1.40	y	
Magadi Trachytes	6.44	4.99	61.63	11.43	4	70	1.40	y	
Magadi Trachytes	6.33	5.59	64.02	11.92	4	71	1.40	y	
Magadi Trachytes	5.95	5.47	61.77	11.42	4	72	1.40	y	
Magadi Trachytes	6.2	5.05	61.34	11.25	4	73	1.40	y	
Plateau (Magadi) Trachyte	6.11	5.23	62.76	11.34	3		1.40	y	
Plateau (Magadi) Trachyte	5.78	4.62	60.82	10.40	1		1.40	y	

A. Guth, MS Thesis, 2007 — Composition of Rift Volcanics

Unit name	Na2O	K2O	SiO2	Total alkalis	source	sample #	age (max)	In study area	Relation to study area
Magadi Trachyte (magadi hospital)	5.60	5.01	59.38	10.61	11		1.40	y	
Magadi Trachyte (NW and NE of Olorgesailie)	6.07	5.22	61.87	11.30	2		1.40	y	
Plateau (Magadi) trachyte (under east side of Nyokie)	6.63	5.01	63.57	11.64	2		1.40	y	
Ol Tepesi basalt	2.69	0.78	48.04	3.47	3		1.42	y	
Ol Tepesi basalt	3.12	0.61	46.86	3.73	10	KR003	1.42	y	
Ol Tepesi basalt	3.18	0.57	47.79	3.75	10	KR004	1.42	y	
Ol Tepesi basalt	3.03	0.83	46.05	3.86	10	KR007	1.42	y	
Ol Tepesi Ferrobasalts	3.00	1.18	47.44	4.18	3		1.42	y	
Ol Tepesi volcanics, alkaline basalt	2.83	0.684	47.13	3.51	8		1.42	y	
Ol Tepesi volcanics, alkaline basalt	2.82	1.038	47.38	3.86	8		1.42	y	
N. Kordjya trachyte	5.34	6.22	62.85	11.56	4	53	1.70	y	
N. Kordjya trachyte	5.26	6.14	61.59	11.40	4	54	1.70	y	
Ol Tepesi Benmoreites	5.48	4.25	60.09	9.73	3		1.81	y	
Ewaso Ngiro Trachyte	4.66	6.01	61.51	10.67	4	50	2.10	y	
Ewaso Ngiro Trachyte	4.88	5.86	62.65	10.74	4	51	2.10	y	
Ewaso Ngiro Trachyte	4.78	5.8	61.23	10.58	4	52	2.10	y	
Kordjya Basalt	2.73	0.66	47.63	3.39	9		2.20	y	
Kordjya Basalt (CENTER WEST OF LISUDWA	1.71	1.01	41.37	2.72	9		2.20	y	
Kordjya basalts	0.68	2.93	48.1	3.61	4	44	2.20	y	
Kordjya basalts	1.41	3.58	47.62	4.99	4	45	2.20	y	
Kordjya basalts	0.95	2.89	48.03	3.84	4	46	2.20	y	
Kordjya basalts	0.69	3.01	47.14	3.70	4	47	2.20	y	
Seyabi Grey Tuff Bed	5.71	5.78	61.53	11.49	4	39	2.20	y	
Mosiro trachytes	5.82	5.26	65.28	11.08	4	41	2.30	y	
Mosiro trachytes	5.72	5.19	64.56	10.91	4	42	2.30	y	
Mosiro trachytes	5.72	5.28	63.6	11.00	4	43	2.30	y	
Singaraini basalt	2.97	0.52	47.38	3.49	10	KR020	2.30	y	
Singaraini basalt	2.89	0.50	46.36	3.39	10	KR022	2.30	y	
Singaraini basalt	3.27	0.68	47.81	3.95	10	KR024	2.30	y	
Singaraini basalt	2.53	0.75	47.36	3.28	9		2.30	y	

A. Guth, MS Thesis, 2007   Composition of Rift Volcanics

Unit name	Na2O	K2O	SiO2	Total alkalis	source	sample #	age (max)	In study area	Relation to study area
Brown Tuff Unit, Olengoirenito valley	5.22	4.9	56.09	10.12	4	38	2.70	y	
Lenderet Benmoreite	5.24	2.79	53.89	8.03	10	KR016	2.70	y	
Lenderet Mugearite	5.36	2.32	48.72	7.68	10	KR009	2.70	y	
Lenderet Mugearite	4.34	1.95	49.99	6.29	10	KR010	2.70	y	
Lenderet Mugearite	4.49	2.04	50.26	6.53	10	KR011	2.70	y	
Lenderet Mugearite	4.24	2.10	50.89	6.34	10	KR017	2.70	y	
Lenderut Hawaiite	4.08	1.76	48.05	5.84	10	KR008	2.70	y	
Lenderut Hawaiite	4.79	1.97	48.98	6.76	10	KR018	2.70	y	
Olorgesailie	2.91	1.722	44.74	4.63	8		2.70	y	
Olorgesailie	2.36	1.19	43.01	3.55	9		2.70	y	
Kirikiti basalt	2.40	0.50	46.16	2.90	10	KR028	3.10	y	
Kirikiti basalt	3.47	1.48	47.62	4.95	10	KR030	3.10	y	
Kirikiti basalt	2.57	0.54	47.18	3.11	10	KR033	3.10	y	
Kirikiti basalt	2.38	0.47	46.59	2.85	10	KR034	3.10	y	
Kirikiti basalt	3.05	0.61	47.76	3.66	10	KR035	3.10	y	
Kirikiti basalt	3.06	0.83	47.42	3.89	10	KR038	3.10	y	
Nairobi trachyte	6.42	5.64	62.56	12.06	11		3.45	y	
Sambu alkaline basalt	2.33	0.74	45.21	3.07	9		3.50	y	
Sambu alkaline basalt	3.55	1.31	47.18	4.86	9		3.50	y	
Sambu alkaline basalt	2.29	0.85	47.88	3.14	9		3.50	y	
Sambu basanite	2.73	1.27	44.47	4.00	9		3.50	y	
Sambu basanite	2.47	1.3	43.9	3.77	9		3.50	y	
Sambu basanite	3.62	0.9	41.92	4.52	9		3.50	y	
Sambu basanite	4.05	1.78	44.87	5.83	9		3.50	y	
Oletugathi Hawaiite	4.31	2.4	49.34	6.71	4	32	4.00	y	
Oletugathi Hawaiite	4.15	2.44	49.55	6.59	4	33	4.00	y	
Oletugathi Hawaiite	4.82	2.5	49.01	7.32	4	34	4.00	y	
Oletugathi series, Ewaso Ngiro series tuff	6.62	4.89	62.26	11.51	4	37	4.00	y	
Oletugathi series, L. Entapot unit tuff	5.37	4.79	67.42	10.16	4	35	4.00	y	
Oletugathi series, U. Entapot unit tuff	6.59	4.9	62.59	11.49	4	36	4.00	y	
Loisiumurto volcanics	2.5	0.83	40.79	3.33	4	14	4.20	y	
Loisiumurto volcanics	2.65	0.76	39.97	3.41	4	15	4.20	y	

Composition of Rift Volcanics

Unit name	Na2O	K2O	SiO2	Total alkalis	source	sample #	age (max)	In study area	Relation to study area
Ngong Volcanic series, nephelinite	4.95	2.02	41.95	6.97	9		5.00	y	
Nairobi Phonolite	7.53	5.69	56.56	13.22	11		5.20	y	
Olivene-limburgite near Lisudwa	1.79	0.99	41.57	2.78	4	16	5.80	y	
Ol Esakut Phonolite (Esayeti complex)	9.00	5.45	49.62	14.45	11		6.70	y	
Ol Esayeiti Basanite	3.59	1.14	44.26	4.73	10	KR001	6.70	y	
Ol Esayeiti Basanite	4.18	0.82	44.17	5.00	10	KR002	6.70	y	
Ol Esayeiti, basanite	2.72	1.12	45.02	3.84	9		6.70	y	
Lengitoto trachyte	6.93	5.21	61.85	12.14	4	24	6.90	y	
Lengitoto trachyte	6.85	5.09	61.93	11.94	4	25	6.90	y	
Lengitoto trachyte	6.85	5.46	61.27	12.31	4	26	6.90	y	
Lengitoto trachyte	7.63	5.43	61.82	13.06	4	27	6.90	y	
Lengitoto trachyte	6.92	5.32	61.79	12.24	4	28	6.90	y	
Lengitoto trachyte	7.21	5.38	61.56	12.59	4	29	6.90	y	
Lengitoto trachyte	6.97	5.08	61.56	12.05	4	30	6.90	y	
Lengitoto trachyte	5.92	5.22	62.27	11.14	4	31	6.90	y	
Namutuakit volcanics	7.78	5.42	50.07	13.20	4	17	6.90	y	
Olenguluo phonolites Group I	7.83	6.32	54.56	14.15	4	18	7.40	y	
Olenguluo phonolites Group I	8.25	6.94	54.96	15.19	4	19	7.40	y	
Olenguluo phonolites Group I	7.92	5.27	54.85	13.19	4	20	7.40	y	
Olenguluo phonolites Group II	9.27	5.61	55.89	14.88	4	21	7.40	y	
Olenguluo phonolites Group II	7.9	5.79	56.58	13.69	4	22	7.40	y	
Olenguluo phonolites Group II	8.23	5.65	56.72	13.88	4	23	7.40	y	
Lower Simbara Basalt, alkaline basalt	2.64	0.706	47.56	3.35	8		12.00	y	
Lower Simbara Basalt, alkaline basalt	2.31	1.09	45.01	3.40	9		12.00	y	
Lower Simbara Basalt, nephelinite	3.35	1.35	41.93	4.70	9		12.00	y	
Athi plains (Kapiti?) phonolite	7.63	5.13	57.94	12.76	11		13.10	y	
Kapiti phonolite	6.88	5.41	54.81	12.29	11		13.10	y	
Kishalduga	4.16	2.41	46.11	6.57	4	1	15.20	y	
Kishalduga	2.68	3.01	46.29	5.69	4	2	15.20	y	
Kishalduga	3.53	1.83	45.96	5.36	4	3	15.20	y	
Kishalduga	3.54	2.05	47.39	5.59	4	4	15.20	y	

Composition of Rift Volcanics

Unit name	Na2O	K2O	SiO2	Total alkalis	source	sample #	age (max)	In study area	Relation to study area
Kishalduga	2.71	1.17	44.85	3.88	4	5	15.20	y	
Kishalduga	4.25	1.78	44.53	6.03	4	6	15.20	y	
Kishalduga	0.88	0.63	40.65	1.51	4	7	15.20	y	
Kishalduga	2.79	1.53	41.67	4.32	4	8	15.20	y	
Kishalduga	7.69	4	41.89	11.69	4	9	15.20	y	
Kishalduga	7.29	5.48	44.38	12.77	4	10	15.20	y	
Lisudwa	2.23	1.13	45.07	3.36	4	11	15.20	y	
Lisudwa	1.75	0.68	44.39	2.43	4	12	15.20	y	
Lisudwa	4.4	2.65	44.78	7.05	4	13	15.20	y	
Lisudwa Volcanics, alkaline basalt	2.21	1.172	44.84	3.38	8		15.20	y	
Lisudwa Volcanics, nephelinite	1.57	0.66	44.08	2.23	9		15.20	y	
alkali basalt, rogati river, Kikuyu	2.63	0.94	43.50	3.57	11			y	
Nephelinite (w. of Ngong)	5.00	2.19	38.80	7.19	11			y	
Lengai natrocarbonatite	31.79	8.51	0.19	40.30	7		0.00	n	South
Mosonik basanite	4.19	1.7	41.93	5.89	6		2*	n	South
Mosonik foidite	8.43	2.7	43.7	11.13	6		2*	n	South
Mosonik foidite	12.17	6.16	43.53	18.33	6		2*	n	South
Ngorongoro, basanite	3.29	0.96	44.94	4.25	6		8*	n	South
Ngorongoro, trachyte	6.24	4.57	64.97	10.81	6		8*	n	South
Pre-rift Second Cycle, alkaline basalt	2.46	0.38	46.35	2.84	5		8.00	n	North
Pre-rift Second Cycle Volcanics, alkaline basa	3.23	1	48.3	4.23	5		8.00	n	North
Pre-rift Second Cycle Volcanics, alkaline basa	3.17	0.87	48.15	4.04	5		8.00	n	North
Pre-rift Second Cycle Volcanics, alkaline basa	3.2	1.2	46.94	4.40	5		8.00	n	North
Pre-rift Second Cycle Volcanics, alkaline basa	3.27	1.25	47.27	4.52	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	2.4	0.47	51.5	2.87	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	2.29	0.33	51.82	2.62	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	2.55	0.5	52.16	3.05	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	2.41	0.34	51.54	2.75	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	2.39	0.37	52.26	2.76	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.04	0.82	49.68	3.86	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	2.98	1	50.27	3.98	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.08	0.91	51.36	3.99	5		8.00	n	North

Composition of Rift Volcanics

Unit name	Na2O	K2O	SiO2	Total alkalis	source	sample #	age (max)	In study area	Relation to study area
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.05	1.05	51.56	4.10	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.24	0.95	49.93	4.19	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	2.93	1.11	51.55	4.04	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	2.91	1.2	50.81	4.11	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.05	1.11	50.69	4.16	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.13	1.12	50.5	4.25	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.04	1.23	50.79	4.27	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.23	0.86	50.48	4.09	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.07	1.12	50.46	4.19	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.08	1.12	50.31	4.20	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.01	1.25	51.46	4.26	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.06	0.97	49.96	4.03	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.06	1.05	49.85	4.11	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.07	0.93	50.49	4.00	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	2.91	1.11	50.49	4.02	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.23	0.87	50.53	4.10	5		8.00	n	North
Pre-rift Second Cycle Volcanics, tholeiitic bas	3.18	1.35	50.23	4.53	5		8.00	n	North
Pre-rift Second Cycle Volcanics, transitional	2.68	0.54	48.62	3.22	5		8.00	n	North
Pre-rift First Cycle Volcanics, alkaline basalt	2.85	0.7	46.19	3.55	5		12.00	n	North
Pre-rift First Cycle Volcanics, alkaline basalt	3.34	1.14	46.08	4.48	5		12.00	n	North
Pre-rift First Cycle Volcanics, alkaline basalt	3.02	1.08	45.07	4.10	5		12.00	n	North
Pre-rift First Cycle Volcanics, alkaline basalt	3.33	1.15	45.99	4.48	5		12.00	n	North
Pre-rift First Cycle Volcanics, alkaline basalt	2.9	0.54	47.79	3.44	5		12.00	n	North
Pre-rift First Cycle Volcanics, alkaline basalt	2.67	0.82	47.81	3.49	5		12.00	n	North
Pre-rift First Cycle Volcanics, basanite	3.61	1.14	45.03	4.75	5		12.00	n	North
Pre-rift First Cycle Volcanics, basanite	3.14	1.14	44.53	4.28	5		12.00	n	North
Pre-rift First Cycle Volcanics, basanite	3.36	1.15	45.15	4.51	5		12.00	n	North
Pre-rift First Cycle Volcanics, basanite	3.07	1.19	45.02	4.26	5		12.00	n	North
Pre-rift First Cycle Volcanics, tholeiitic basalt	2.59	0.49	50.02	3.08	5		12.00	n	North
Pre-rift First Cycle, tholeiitic basalt	2.35	0.36	50.4	2.71	5		12.00	n	North
Pre-rift First Cycle, tholeiitic basalt	2.61	0.38	50.88	2.99	5		12.00	n	North
Pre-rift First Cycle, tholeiitic basalt	2.59	0.35	51.22	2.94	5		12.00	n	North

Composition of Rift Volcanics

Unit name	Na2O	K2O	SiO2	Total alkalis	source	sample #	age (max)	In study area	Relation to study area
Pre-rift First Cycle, tholeiitic basalt	2.56	0.41	49.91	2.97	5		12.00	n	North
Pre-rift First Cycle, transitional basalt	2.82	0.5	48.77	3.32	5		12.00	n	North
Pre-rift First Cycle, transitional basalt	2.73	0.77	49.74	3.50	5		12.00	n	North
Pre-rift First Cycle, transitional basalt	2.72	0.52	48.15	3.24	5		12.00	n	North
Basanite (Aberdare range)	2.74	1.42	45.65	4.16	11			n	North
Nyeri Hill phonolite	7.54	4.85	57.05	12.39	11			n	North
olivine basalt, Kijabe hill	4.17	1.67	46.74	5.84	11			n	North

* age estimated

1 Baker 1958
2 Baker 1975
3 Baker et al 1977
4 Crossley and Knight 1981
5 reported in GeoRoc, Bellieni et al. 1986 (8088)
6 reported in GeoRoc, Paslick et al. 1996 (7817)
7 reported in Gittins and Jago, 1998
8 reported in GeoRoc, Rogers et al. 2000, (7729)
9 reported in GeoRoc, Macdonald et al. 2001, (8029)
10 Le Roex et al. 2001
11 reported in Otando 2004

Appendix F: Geologic Map for the Southern Kenya Rift

The electronic map file produced for this study is available on the accompanying CD.

 File name: KenyaMap.pdf

 File size (digital): 178 MB

 Map size: 31 inches (78.74 cm) wide x 36 inches (91.44 cm) long

A printed version of the map is also available in the back pocket of this thesis.

Appendix G: Volcanic Gas Estimates

Presented here are some rough estimates of the amount of carbon that could be derived from a magma body degassing under then rift valley floor. Several authors have made estimates as to the size of the magma body, the initial amount of CO_2 and the amount that can potentially be degassed at depth. Using these estimates the goal was to see if such a magma body degassing could account for the carbon locked up as carbonate in the Lake Magadi trona deposit.

Length of Magadi Basin (km)
35.5

Dyke zone width (km)
2.7

Macdonald 2003
30% max dikes from Keranen et. Al, 2004

Dyke zone depth (km)
10

based on Gerlach, that degassing happens at depths less than 11km. 10 km is used in the calculation as magma is not present at the surface

Volume magma under Magadi Basin (cubic km)
958.5

Density of basalt melt (kg/km3)
2.7E+12

Density of basalt (kg/m3)
2700

Basalt density from (http://www.nsm.buffalo.edu/courses/gly431/431studyI_01.html)

CO_2 content of magma (wt %)
0.1

CO_2 content of magma (decimal wt %)
0.001

Magma under Magadi (kg)
2.59E+15

Potential Mass CO_2 under Magadi (kg)
2.59E+12

Moles of CO_2
5.88E+13

Moles Carbon
5.88E+13

Trona Area (m2)	Average Trona Thickness (m)	Trona Volume (m3)	Trona Mass (kg)
77700000	25	1942500000	4.14E+12

Moles Trona
1.83E+13

Moles Carbon in Trona
3.66E+13

Potential Magma derived Moles Carbon - Moles Carbon locked in Trona
2.22E+13

Appendix H: Microbiology of Lake Magadi

Description of the chart columns:

Type: Higher-order classification

Genus-Species: Genus and species classification (Note comments below)

Age (ka): Some of the names provided here are for microbes found in the geologic

record that got preserved in sediments around the lake. Age is included to help

discriminate between modern and ancient species.

Author and Year: Source that listed the species as living in Magadi.

Notes:

*CyanoDB claims *Cyanospira* is synonomous with *Anabaena*
*But, Iteman et al. (2002) shows high similarity in rDNA between *Anabaenopsis* and *Cyanospira* and they might be combined into a single genus
** published as "*Tindallia magadii*", but name was corrected to magadiensis in 1999 by Int. J. Syst. Bacteriol., vol 49, pg 1-3
+published as *Natronoincola*, ""
***originally *Natronobacterium*
++ originally *Natrobacterium*

Classifications obtained from "Catalogue of Life" <http://www.catalogueoflife.org/> June 22, 2007, when not given specifically by the reference otherwise listed.

	Phylum	Genus-Species	Age	Author	Year
Eukarya	Bacillariophyta (Diatoms)	*Anomoeoneis*	18-17 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Anomoeoneis*	12.5-10 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Anomoeoneis sphaerophora*	recent	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Aulacoseira*	17-12.5 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Cyclotella*	17-12.5 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Cyclotella*	780-300 ka	Behr and Rohricht	2000
	Bacillariophyta (Diatoms)	*Epithemia*	17-12.5 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Fragilaria*	17-12.5 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Hantzschia*	18-17 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Navicula*	18-17 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Navicula*	17-12.5 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Navicula*	12.5-10 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Navicula*	98 ka	Behr and Rohricht	2000
	Bacillariophyta (Diatoms)	*Navicula gawaniensis*	recent	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Nitzschia*	18-17 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Nitzschia*	12.5-10 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Rhopalodia*	18-17 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Rhopalodia*	17-12.5 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Stephanodiscus*	17-12.5 ka	Barker et al.	1990
	Bacillariophyta (Diatoms)	*Thalassiosira*	17-12.5 ka	Barker et al.	1990
	Chlorophyta (green algae)	*Chlorella minutissima*	recent	reported in Baumgarte	2003
Bacteria	Actinobacteria	*Micrococcus*	98 ka	Behr and Rohricht	2000
	Actinobacteria	*Micromonospora*	98 ka	Behr and Rohricht	2000
	Cyanobacteria	*Aphanothece*	recent	Dubinin et al.	1995
	Cyanobacteria	*Chamaesiphon*	recent	Dubinin et al.	1995
	Cyanobacteria	*Chroococcus*	98 ka	Behr and Rohricht	2000
	Cyanobacteria	*Cyanospira* capsulatus*	recent	Florenzano et al.	1985
	Cyanobacteria	*Cyanospira* ripkae*	recent	Florenzano et al.	1985
	Cyanobacteria	*Entophysalis*	98 ka	Behr and Rohricht	2000
	Cyanobacteria	*Gloecocapsa*	98 ka	Behr and Rohricht	2000
	Cyanobacteria	*Microcoleus*	98 ka	Behr and Rohricht	2000
	Cyanobacteria	*Oscillatoria*	recent	Dubinin et al.	1995
	Cyanobacteria	*Phormidium*	recent	Dubinin et al.	1995
	Cyanobacteria	*Phormidium*	98 ka	Behr and Rohricht	2000
	Cyanobacteria	*Pleurocapsa*	98 ka	Behr and Rohricht	2000
	Cyanobacteria	*Rhabdoderma*	recent	Dubinin et al.	1995
	Cyanobacteria	*Schizothrix*	98 ka	Behr and Rohricht	2000
	Cyanobacteria	*Spirulina*	recent	Dubinin et al.	1995
	Cyanobacteria	*Spirulina platensis (see note)*	recent	Reported in Florenzano et al.	1985
	Cyanobacteria	*Synechococcus*	recent	Dubinin et al.	1995
	Cyanobacteria	*Synechococcus*	98 ka	Behr and Rohricht	2000
	Cyanobacteria	*Synechocystis*	recent	Dubinin et al.	1995
	Firmicutes: Bacilli	*Amphibacillus fermentum*	recent	Zhilina et al. (b)	2001
	Firmicutes: Bacilli	*Amphibacillus tropicus*	recent	Zhilina et al. (b)	2001
	Firmicutes: Clostridia	*Natronincola+ histidinovorans*	recent	Zhilina et al.	1998
	Firmicutes: Clostridia	*Tindallia magadiensis***	recent	Kevbrin et al.	1998
	Proteobacteria	*Ectothiorhodospira*	recent	Zhilina et al.	1998
	Proteobacteria	*Halomonas campisalis*	recent	Boltyanskaya et al.	2004
	Proteobacteria	*Halomonas magadii*	recent	reported in Bhatnagar and Bhatnagar	2005
	Proteobacteria	*Halorhodospira*	recent	reported in Grant et al.	1999
	Proteobacteria	*Hyphomicrobium*	98 ka	Behr and Rohricht	2000
	Spirochaetes	*Spirochaeta africana*	recent	Zhilina et al.	1996
	Spirochaetes	*Spirochaeta alkalica*	recent	Zhilina et al.	1996
Archaea	Halobacteroidaceae	*Halonatronum saccharophilum*	recent	Zhilina et al. (a)	2001
	Halobacteroidaceae	*Natronomonas****	recent	reported in Grant et al.	1999
	Halobacteroidaceae	*Natronococcus*	recent	reported in Grant et al.	1999
	Halobacteroidaceae	*Natrialba++ magadii*	recent	reported in Grant et al.	1999

Note: noted in East African
alkaline lakes in general