IDENTIFICATION OF AN EXTRA-TERRESTRIAL IMPACT CRATER (ETIC): A CASE STUDY OF SILALI CRATER, KENYA

BY

KIPKIROR LOICE JEPKEMBOI

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DECLARATION

DECLARATION BY THE STUDENT

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LOICE JEPKEMBOI KIPKIROR **Date**

SES/D. Phil/ 003/08

DECLARATION BY THE SUPERVISORS

This thesis was submitted for examination with our approval as University Supervisors.

__________________________________ __________________________

Prof. E.K. Ucakuwun **Date**

School of Environmental Studies

Department of Environmental Earth sciences

University of Eldoret

Kenya

__________________________________ __________________________

Dr. Fatuma Daudi **Date**

School of Environmental Studies

Department of Environmental Monitoring, Planning and Management

University of Eldoret

Kenya

DEDICATION

This thesis is dedicated to my sons: Kevin Kipruto Mutai, Victor Kibet Mutai, Titus Kipkoech Mutai and Jesse Yano Mutai.

I am thankful for their love, patience, encouragement and for sharing with me moments of cheerfulness and difficulty, before and during the period of study. God bless you boys.

To a special girl, a daughter whom God brought my way; Jackline Chebosis. God bless you child.

To my parents; Joseph and Christine Simaton Bellioni. They rooted my academic life. God bless them.

To Sammy, my friend and late husband, the Lord rest his soul in eternal peace. His foresightedness in life and aspirations for the family have continued to inspire me.

ABSTRACT

For years, extra-terrestrial impact cratering was esoteric. However, impacts have become very important currently, mainly because they have been identified as the likely immediate cause of dinosaur extinction. Impact cratering by extra-terrestrial bodies including asteroids comets and meteorites is an important geologic process, not only for the minerals that it forms, but also because of the knowledge that it is dangerous to mankind and life on earth. There is also the fact that extra-terrestrial impact crater building is a continuous process that may be going on even this very minute, somewhere in the universe. Consequently, the earth, just like other members of the solar system, is targeted by extra-terrestrial falling objects. The purpose of this study was to assess the effects of impact cratering on Kenya's environment, with focus on Silali basin. Silali basin is a depression that is found to the north of Lake Baringo; around Kapedo town. It is suspected to be an Extra –Terrestrial Impact Crater (ETIC). The objectives of the study were to: Map and characterize the Silali basin/crater and provide evidence on the nature of its formation. Secondly, to document the effect that the impact cratering of Silali had on the environment in the area. To attain these objectives, remote sensing was utilized to map the Silali basin. Satellite images were used to identify the nature of the crater and characterize it, since most large terrestrial impact craters are not identifiable from the surface of the earth. The images provided critical information that was used to map out the morphological aspects of the crater, some of which have long been buried by forces of denudation, together with tectonic and anthropogenic forces. Analysis of satellite images and ground pictures was supplemented by other research methods, including interviews, analysis of secondary data, observation and sampling of various rocks. Information gathered has been presented in the form of analyzed satellite images, ground pictures, tables, Digital Elevation Models, cross sections, an aerial photograph, maps and discussions. This study has characterized the Silali basin as a possible ETIC and explained the nature of its formation. In addition, it has documented the effects of Silali's impact cratering on the environment in the area to include formation of physical features and rock formations. The crater's potential economic and social significance has also been cited and include tourism, paragliding, quarrying of breccias and geothermal power harvesting.

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DEFINITION OF TERMS

Allochthonous – Material that is formed or introduced from somewhere other than the place it is presently found in. In impact cratering, this may refer to fragmented rock (and other ejecta) thrown out of the crater during its formation, which either falls back to partly fill the crater or blankets its outer flanks after the impact.

Asteroid – A small rocky body that orbits the Sun. Most asteroids reside between Mars and Jupiter, but some have orbits that cross the earth's path and could collide with it. Asteroids are also known as *planetoids* because they look like small planets.

Breccia –A coarse grained rock composed of angular broken rock fragments held together by mineral cement or a fine grained matrix.

Plate 1: Tertiary breccia at Resting Springs Pass, Mojave Desert, California (Adapted from www.lpi.usra.edu).

Plate 2: Upper Triassic breccia from York County Pennsylvania (Adapted from www.lpi.usra.edu)

Central Peak – The exposed core of uplifted rocks in complex impact craters. Central peak material typically shows evidence of intense fracturing, faulting and shock metamorphism.

Chondrule - Chondrules are round grains found in chondrites. They form as molten or partially molten droplets in space before being accreted (gravitationally pulled) to their parent or host asteroids. Chondrites are some of the oldest solid materials that build our solar system and they contain varied fractions of chondrules with some of them having none at all (http://en.wikipedia.org/wiki/chondrule). Chondrules can range from a few micrometers to over one centimeter in diameter and most of them are composed of silicate minerals of olivine and pyroxenes, surrounded by a feldspar material that may either be glassy or crystalline.

Comet – One of the primitive icy bodies originating in the outer reaches of the solar system. Comets move in elliptical orbits around the sun. Near the sun, the icy material vaporizes and streams off the comet forming a tail.

Crater:

A crater is a circular depression or basin on the Earth's surface.

Craters that result from the impact of an asteroid, a comet or a meteorite on the earth's surface are called *Extra-terrestrial Impact Craters* (ETIC$_S$). ETICs look like *volcanic craters* but *Volcanic Craters* are produced by volcanic activity and most of them are found at the top of conical volcanic mountains or on the flanks of volcanoes. Volcanic craters that are devoid of an edifice are called **maars.** They form when magma rises through water saturated rocks and causes a phreatic eruption. More specifically, a **maar** (from Latin word *mare*, which means sea) is a broad, low-relief volcanic crater that is caused by phreatomagnetic eruption that is caused by ground water coming into contact with hot lava or magma. Characteristically, a maar is filled with water, which transforms it into a shallow crater lake. Maars, then, are shallow flat floored craters that scientists believe to have formed above diatremes, as a result of violent expansion of magmatic gas or steam. A deep erosion of a maar would expose a diatreme; a breccia filled volcanic pipe that was formed by a gaseous explosion.

Cratons – The relatively stable portions of continents composed of shield areas and platform sediments. Cratons are bounded by tectonically active regions, characterized by uplift, faulting and volcanic activity.

Cretaceaous – This is a geological term denoting an age of Earth history, beginning around 145 million years ago and ending at 65 million years ago, with the formation of the Chicxulub impact structure in Mexico.

Cretaceous Tertiary (K-T) Boundary – A major stratigraphic boundary in history, marking the end of Mesozoic era, best known as the age of dinosaurs. The boundary is defined by a global extinction event caused by the abrupt demise of the majority of life on earth. It has been dated to 65 million years ago – coeval with the age of the 200 kilometers wide Chicxulub Impact Structure.

Crystalline – Rock types made up of crystals/fragments such as metamorphic rocks that re-crystallize at high temperature or pressure environments, or igneous rock that formed from the cooling of a melt (Plate 3).

Plate 3: A crystal of quartz (Adapted from www.lpi.usra.edu).

Diaplectic glass / Impact glass – A natural glass formed by shock metamorphism or transformation of several minerals without melting. It is similar to volcanic glass but it is associated with siderophile elements, suggesting a meteoritic contamination. Impact glasses are found in allogenic breccia deposits within and around impact craters. They are also found in spherules in distal ejecta or within melt rocks that may be smooth or rough (semi melted).

Ejecta - Materials such as glass and fragmented rock thrown out of a crater at impact, leading to its formation. Distal ejecta are impact ejecta found at distances greater than 5 crater radii from the rim of the source crater while proximal ejecta are impact ejecta which is found closer than 5 crater radii from the crater rim. The latter constitutes 90% of all materials thrown out of the crater during the impact event.

High Pressure Mineral Phases – Mineral forms that are stable only at extremely high pressure, typical of the earth's deep interior, but not its surface. High pressures are generated instantaneously during terrestrial impact and this leads to the formation of minerals such as stishovite, which is formed from quartz, just as diamond is formed from graphite when it is subjected to high pressure.

Hummocky – Uneven or lumpy terrain.

Impact melt rock – Rocks melted during impact, including small particles dispersed in various impact deposits and ejecta and larger pools and sheets of melt that coalesce in low areas within the crater. Impact melts are extremely uniform in composition, but highly variable in texture. They are, predominantly, composed of target rocks, but may contain a small amount of the impactor.

Meteorite – This is a natural object originating from outer space, which survives impact with the earth's surface or the surface of any other heavenly body. It can be any size. It may also be a remnant of a meteor, a comet or an asteroid. Meteorites which are recovered after being observed as they transited the atmosphere or impacted the earth are called **falls.** All other meteorites, which are discovered without prior knowledge, are called **finds**.

Meteorites have traditionally been divided into three categories; **stony meteorites**, **iron meteorites** and **stony-iron meteorites**. Stony meteorites are mainly composed of silicate minerals, while iron meteorites are composed of metallic iron and nickel. Stony-iron meteorites, on the other hand, contain large amounts of iron and rocky material.

Stony meteorites may be classified as **chondrites** and **achondrites**. Stony chondrites have small rounded particles (chondrules) which are composed mainly of silicate minerals that appear to have been melted, while free floating in space. Chondrites are typically old, for instance, about 4.55 billion years old and are considered to be the building blocks of the solar system (which is said to have formed 4.6 billion years ago). Achondrites are stony meteorites that lack chondrules.

Nanodiamonds–These are diamonds that are produced by impact events. Their scale is about 4-5 nanometers and they are found in meteorites. Nanodiamonds can also be produced by nuclear explosions (https://en.m.wikipedia.org.wiki/Nanodiamond). One nanometer is one billionth of a meter (10^{-9}m) or 0.000000001m^2 in terms of spatial coverage.

Paleozoic – A geological term denoting the time in earth history between about 570 – 245 million years ago.

Peak ring – A central uplift characterized by a ring of peaks rather than a single peak. Peak rings are typical of large terrestrial impact craters (complex impact craters), say of above 4km in diameter.

Precambrian – A geological term denoting the time in earth history prior to 570 million years ago.

Planar features in quartz and feldspar grains/Planar deformation features.
These are microscopic features in grains of quartz or felspar consisting of very narrow planes of glassy material arranged in parallel sets that have distinct orientations with respect to the grain's crystal structure. They may be the factors forming the hexoctahedaral structure in meteoritic remnants. Notably, planar deformation features (PDFs) are produced by extreme shock compression on the scale of meteoritic impacts. They are not found in volcanic environments. Their presence is therefore the primary criterion for recognizing that an impact event has taken place in an area (http://www.Ipi.usra.edu/publications/slidesets/craters/glossary.shtml).

Shield – An extensive region where ancient Precambrian crystalline rocks are exposed at the earth's surface.

Shock metamorphism – The production of irreversible chemical and /or physical changes in rocks by a shock wave generated by impact or detonation of high explosive or nuclear devices.

Suevite – A breccia composed of angular fragments of different rock types as well as glass inclusions. Glass can make up more than half the rock. The minerals in the rock fragments within suevites (also called suevite breccias) commonly display shock metamorphic effects. Suevite was named after a rock found at Ries Crater in Southern Germany.

Synthetic Aperture Radar (SAR) is a radar that uses a relatively small antenna to produce a broad beam and makes use of Doppler effect/shift or change in frequency of the radar signal moving across the target to synthesize (with extensive computer processing) the azimuth resolutions of a very narrow beam.

Siderophile – these are 'iron loving' elements such as iridium, osmium, platinum and palladium, which are quite common in undifferentiated meteorites and in chemically segregated asteroids and planets. Relatively, these elements are extremely rare on the earth's surface but found in impact areas and in meteorites.

Shatter Cones – striated conical impact fracture surfaces produced by meteorite impact on fine grained brittle rocks, such as limestone.

Plate 4: Shatter cones in the Santa Fe impact structure near Santa Fe, New Mexico (Adapted from www.lpi.usra.edu).

Stishovite – A dense, high pressure phase of quartz that has so far been identified in nature only in a shock metamorphosed quartz bearing rocks within meteorite impact craters. The quartz in a stishovite may form tetragonal crystals, such as those of a wulfenite mineral as shown by Plate 5 below:

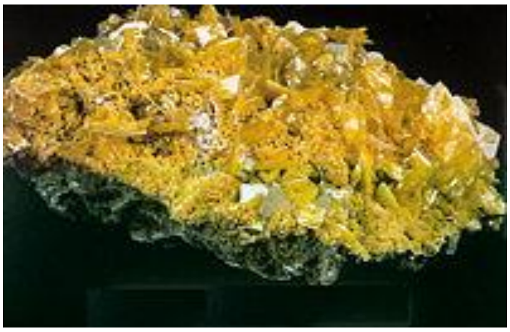

Plate 5: An example of tetragonal crystals in a wulfenite mineral (Adapted from www.lpi.usra.edu).

Target rocks – The surface rocks that an asteroid or a comet impactor smashes into in an extra-terrestrial impact event.

Tektite – Natural, silica-rich homogeneous glasses produced by complete melting of target rocks and may be dispersed as droplets during terrestrial impact events. They range in color from black to dark brown to gray or green and most are spherical in shape. Some tektites can form very far from their source ETIC, for example, Bosumturi crater in Ghana is linked to the Ivory Coast tektites.

Note: Most of the above definitions were adapted from www.lpi.usra.edu Website.

LIST OF ACRONYMS

AP	-	Aerial Photography
a.s.l	-	above sea level
ALRMP	-	Arid Lands Resource Management Programme
DEM	-	Digital Elevation Model
EIA	-	Environmental Impact Assessment
ETIC	-	Extra-terrestrial Impact Crater
GBR	-	Green Blue Red
GDC	-	Geothermal Development Company
GP	-	Ground Photography
GPa	-	Geophysical altimeter
IR	-	Infra Red
MT	-	Magnetotelluric
NEOs	-	Near Earth Objects
PDFs	-	Planar Deformation Features
PHAs	-	Potentially Hazardous Asteroids
RCMRD	-	Regional Center for Mapping of Resources for Development
RGB	-	Red Blue Green
SI	-	Satellite Image
TEM	-	Transient Electrical Magnetic
USGS	-	United States Geological Survey
TNT	-	Trinitrotoluene
UTC	-	Universal Time Coordinated
UV	-	Ultra Violet

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CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Extra-terrestrial impact craters, on the earth's surface, are formed by the impact of an asteroid, comet or a meteor on the earth's surface. The mechanisms associated with impact cratering are diverse but generally, when a sizable solid body strikes the ground at high speed, shock waves propagate into the target rocks. At collision speeds of tens of kilometers per second, the initial pressure on the material engulfed by the expanding shockwaves is millions of times the earth's normal atmospheric pressure, which is 101,300 Newtons per square meter. This can squeeze dense rocks into 1/3 of their normal volume. Stress can then overwhelm target rocks to an extent that they initially begin to flow almost like a fluid. A decompression wave follows the advancing front wave into the compressed rock, allowing the material to move sideways. As more and more of the target rock becomes engulfed in the shock wave, which expands more or less radially from the point of impact, the flow of the target material behind the shock front, is diverted out along the wall of a rapidly expanding cavity created by the decompression wave. The compacted body, now vaporized or melted, moves outward with the divergent flow and lines the cavity, forming a conical sheet. Rocky material continues to flow outward until stresses in the shockwave drop below the strength of the target rocks. In large impact craters, the rock walls slump inwards, soon after excavation of the initial or transient cavity.

Generally, the extra-terrestrial impact process can be divided into two phases; **contact/ compression stage** and **excavation stage.** Contact or the compression stage begins the instance the leading edge (downwards) of the projectile makes contact with the earth's surface. If the target area consists of solid rock, the projectile is stopped and its kinetic energy is transferred to the target rocks by shock waves generated at the interface between the projectile and the target rocks (Melosh, 1989). The projectile itself becomes compressed and the shock waves from the interface or contact area begin to spread toward the rear of the projectile. When the shock waves reach the rear of the projectile, they are reflected forward as a tensional wave or **refraction**.

It is this refraction wave that instantaneously melts the projectile or vaporizes it (O'Keefe and Ahrens, 1972). Shock waves are transmitted outwards from the impact point, in a radial manner (Melosh, 1989).

Excavation stage or the transient crater stage follows the contact/compression stage. It involves the opening up of target rocks to create an impact crater. It may also be said to be an interaction between the expanding shock waves and the original ground surface (Grieve and Pesonen, 1996). The shock waves, expanding outwards from the impact point, fracture and shatter the area rock before pushing it outwards, to produce a rounded excavation. In the upper levels, target material moves upward and outward while in the lower levels, target material moves downward and inward. These movements produce a bowl-shaped depression, which is an ETIC. For this reason, ETICs are generally circular and their outer walls are rough with an overflow of distal ejecta. The immediate inner walls are steep, especially on the upper parts, due to slumping of materials and later denudation. The lower inner walls are gently sloping upwards (conically) due to melt material lining up the inner walls and the slumped or eroded materials that cover the melt. Denudation forces, unfortunately, do more than simply remodeling an ETIC because, in conjunction with other forces, such as tectonic and volcanic forces, they can either completely disfigure an ETIC or bury it.

In some instances, as the slumping material converges inwards, a central peak or hill is produced, that rises above the general floor of the crater as in the case of Tenoumer crater, Mauritania (French *et al*., 1970). A few large craters exhibit a ring shaped inward ridge or more complex central structures. In fact it is said that evidence of uplifted rocks at the center of an ETIC and subsidence or inward flow from the sides, are important clues for recognizing deeply eroded impact structures on earth (Beatty *et al.*, 1999).

Occasionally, the heavenly body is vaporized by the impact so that it burns up completely and metamorphoses the country rock (kinetic metamorphism or both kinetic and thermal metamorphism) to form different rock types and minerals. Still at other times, the impactor may be broken up into small fragments which may be collected within the impact crater or scattered around it.

On the earth’s surface, many of the extra-terrestrial impact craters have been flattened and or filled by erosion, deposition, volcanic resurfacing and tectonic activity. Consequently, only about 200 ETICs have been recognized and documented worldwide, the majority being in the geologically stable cratons of North America, Europe and Australia. Incidentally these are the areas where most exploration, involving ETICs, has taken place. High level remote sensing (Satellite Imagery) has made it possible for these features to be identified.

The Barringer Crater in Arizona, which is a meteor crater, was the first ETIC to be identified in 1920s by workers who discovered fragments (e.g. allochthonous) of the meteorite within the crater. Several other relatively smaller craters were also found to contain meteoritic (meteorite impactor) fragments. For many years, these remnants were the only accepted evidence of meteoritic impact on earth but over time, scientists have come to accept that Meteoritic Impact Craters can exist even without fragments. This is because fragments of some of the meteors that hit the earth's surface may not have survived the impact of the collision and may have been completely pulverized. The very high temperatures generated by an impact can vaporize the meteorite all together or can completely melt and mix it with melted target rocks. Sometimes, non-terrestrial relative abundance of siderophile elements can be detected in the impact melt rock within large craters, giving a signature of the meteorite impactor.

In the 1960s, scientific studies found shock metamorphism to be another physical evidence of impact structures or ETICs. Shock metamorphism produces metamorphic effects which are unique and can only be associated with an ETIC. According to the Solar Views website (www.solarviews.com.) no earthly mechanism, including volcanism, can produce such high pressure that can compact and produce the kind of shatter cones, multiple sets of microscopic planar features in quartz and feldspar grains, diapletic glass and high pressure mineral phases, such as Stishovite, that extra-terrestrial impact metamorphism can produce. These shock features, or some of them, are known to be associated with ETICs.

In other extra-terrestrial impact events, the heavenly bodies may be coming into the earth with a lot of speed. This causes them to drill the earth's crust and disappear into it, leaving behind hollows that are modified by denudation forces to form round-shaped craters, which may remain dry or be filled with water. This water that fills up an ETIC may be from rain water or from the ground, if a heavenly body manages to break through the water table of an area, while drilling into the earth. An example of an ETIC lake is Lake Bosumturi in Ghana.

Besides forming craters, extra-terrestrial impacts must be noted for their other environmental effects such as their association with earthquakes, volcanic activity, formation of new landscapes and land deformation following fracturing, tsunami waves, dust displacement, cessation of photosynthesis, collapse of food chains, and acid rains, among social impacts such as death and displacement of people.

In yet another occasion, the impactor may remain on the earth's surface in the form of a rock that is rich in iron, silica and gold amid a host of other minerals (meteorite/meteoritic rock). Meteorites on the earth's surface are usually believed to have originated from other heavenly bodies or from elsewhere in space. The heavenly body/ extra-terrestrial object/ projectile object, if it is large enough, may survive transit through the earth's atmosphere more or less intact and strike the ground or the ocean without burning up or fragmenting much. The threshold size for survival depends on the material strength and density of the body and its velocity at the time of the impact (Beatty *et al.*, 1999).

Smaller objects are sheared dramatically; by aerodynamic drag; leading to production of hot fragments that can cause fire on impact, for example the Tunguska fireball over western Siberia (30th June 1908). Nobody knows, for sure, what the object was but according to cosmic particles of resin in some surviving trees, it is believed that the object was an asteroid (Beatty *et al.*, 1999).

An example of a meteorite in Kenya is Kiptabar hill in Cherangani forest, near Kapcherop Town, in Marakwet, Elgeyo Marakwet County. This is a rock that has not been much mentioned in scientific discussions but one that is unique because;

i) It is square in shape while the rest of the hills in the area are somewhat conical.
ii) It is isolated and not linked to any other hill, the way the other hills are part of the continuous landscape. Kiptabar looks like it was placed where it is, like a stone on a table.
iii) It is rocky, except for the parts that weathering has affected over the years, allowing vegetation to grow on it.
iv) It is dark in color, probably because it burned up as it was hurtled through space. Laboratory tests of samples from the Kiptabar hill (rock) were done to give the exact mineral composition of the rock that makes up the hill. The results are presented in Chapter Four of this thesis, together with the probable meteorite type that Kiptabar is.
v) Mythology of the Marakwet community holds that the rock fell from the sky. The story tells of people who were dancing in the area where the rock fell and a bird that warned them to move away because a rock was going to fall on them. Sensibly, they dismissed the warning with claims that a bird cannot talk. So the rock fell on them, covering them alive. The people believe that the cries of these

people can still be heard echoing from the rock. These ‘voices’ were investigated by the study and they turned out to be echoes from the rock face, when people talk. There is also a probability that the rock is hollow from the inside, a likely reason why it did not drill the ground and disappear.

vi) When broken up, Kiptabar rock appears rough with its particles looking like stishovite- quartz particles that assume tetragonal shapes due to impact high pressure metamorphism.

The current study did not delve into the mapping out of meteorites in Kenya-; however, a picture of Kiptabar hill is included in the data. This will be an illustration of the possible presence of extra-terrestrial matter on the Kenyan land surface, like the one shown by Plate 1.1.

Plate 1.1: A Picture showing Kiptabar hill (Source: Author, 2013).

The most recent known extra-terrestrial object to fall on Africa and close to Kenya, besides Kenya’s own Kimwiri meteorite fall, is Asteroid 2008 TC3 that fell over northern Sudan on the 7th of October 2008. It fell in the morning and was recorded by an infrasound array in Kenya and according to one Dr. Peter Brown of the University of Western Ontario; the asteroid was to hit the earth at 0243 UTC with energy in the range of 1.1 to 2.1 kilotons of TNT. Most of the 3m space rock should have been vaporized in the atmosphere with only small pieces reaching the ground as meteorites. The fireball fell on a remote area with a few or possibly no onlookers capable of recording the event. So far, the only report of a visual sighting came from Jacob Kuiper, General Aviation Meteorologist at the National Weather Service in Netherlands, who said that he informed an official of Air France, at Amsterdam Airport, about the possibility of their crews and passengers within the vicinity, having a chance of seeing the fireball half an hour before Asteroid 2008 TC3 hit the earth's surface. The prediction became a success because the airliner, which was roughly about 750 nautical miles south, confirmed seeing a flash shortly before the time of impact, which took place at 0246 UTC.

Because of the distance of observation, it was not a very large phenomenon. Projected as an infrared Satellite image of Meteosat 7 of 0300 UTC, the asteroid/meteor, impact area was confirmed to be Northern Sudan (http://spaceweather.com/archive2008).

Notably, asteroid 2008 TC3 was discovered on 6th October 2005 by astronomers using the Mt. Lemmon telescope in Arizona as part of the NASA – funded Catalina sky survey for Near Earth Objects. Asteroids, the size of Asteroid 2008 TC3, hit the earth 5 to 10 times a year but this is the first time one was discovered before it hit (http://spaceweather.com/archive2008).

If such an object had fallen on a highly populated area or on a developed area, it may have caused such furor that all and sundry would have known about it by now. This affirms the fact that extra-terrestrial impact cratering is an ongoing process that is mostly unexpected and has the potential of causing disasters on the earth's surface.

Table 1, which was downloaded from a space weather website (http://spaceweather.com/archive,2008) on 29th September 2009, shows that there are quite a number of loose heavenly bodies that are a potential threat to life on earth. These are mainly comets, asteroids and meteors. The known group comprises of PHAs (potentially hazardous asteroids). These are space rocks, larger than approximately 100 m, in diameter, that can come close to the earth and can collide with it or hit a part of it. Some of the PHAs, though, have diameters of less than 100 m.

On October 7th 2008, there were 988 PHAs in space but none was on a collision course with the earth, as shown below.

Table 1.1: Potentially hazardous asteroids (PHAs) of various sizes sighted on different dates in 2008 (https://en.m.wikipedia.org/wiki/potentially_hazardous_object).

Asteroid	Date Seen	Miss Distance	Magnitude	Size
2008 QS 11	October 2	11 LD	14	470 m
2008 SH 148	October 4	5.8 LD	19	26 m
2005 GN 59	October 6	20 LD	15	1.4 km
2008 TC3	October 7	Impact	-13	3 m
2008 TZ	October 10	5.3 LD	18	37 m
1999 VP 11	October 16	72 LD	17	860 m
2001 UY 4	October 18	74 LD	17	1.1 km
2000 EX 106	October 23	69 LD	18	1.1 km
2005 VN	October 29	4.1 LD	15	116 m
4179 Toutatis	November 9	20 LD	14	3.8 km

Note:
LD is "Lunar Distance". 1 LD = 384, 401 km, the distance between the earth and the moon.
Magnitude is the visual magnitude of the asteroid on the date of closest approach.

Out of the 988 PHAs, it is only Asteroid 2008 TC3 that impacted the earth and because of its small size, its impact was local and much of it may have vaporized in space, as stated earlier. A catastrophe may have followed in the wake of one of the other larger PHAs hitting the earth, for example, were it to have been 2001 UY4, 2000 EX 106 or 4179 Toutatis.

Recently, on Saturday, 16th of July, 2011, the people of Thika, Kangundo and Yatta were gripped by fear, following the explosion of an object in the skies over the area. A black stone from outer space, weighing 5kg and 6 cm in diameter, was recovered from a farm. It is said that the stone fell on the farm at 1.017 hours and was accompanied by a thunderous sound and a tremor, after it had impacted on the land. In addition, the object blasted a small crater on the maize field, where it fell and displaced some dust that was visible from a distance.
These are characteristics of a falling or fallen extra-terrestrial body, on a small scale. Included below is a satellite image, from Google maps, showing the area that the object fell on (Plate 1.2). Plate 1.3 is a photograph showing the Kimwiri meteorite as it is today, while Plate 1.4 shows the appearance of the meteorite the day it fell. Plate 1.5 shows the crater that was created

by the meteoritic impact, hence the important need for the continued studies on ETICs, their associated events and features.

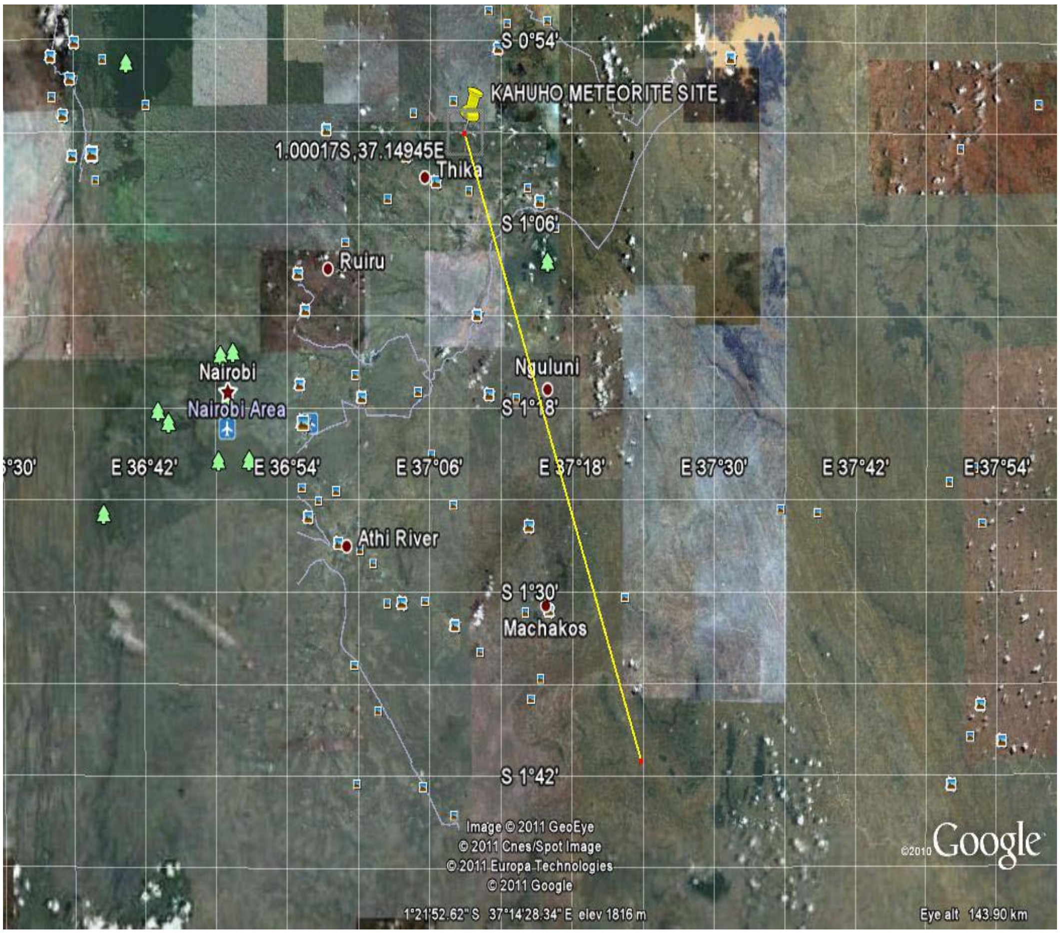


Plate 1.2: A GeoEye satellite image showing the location of the Kimwiri meteorite fall and the direction of flight from South East (courtesy of the Department of Mines and Geology-Kenya).

The yellow line shows the path followed by the Kimwiri meteorite. The rock followed a SE-NW direction, before landing on the maize field around Thika, a place that lies approximately on longitude $37^0$10' E and latitude $1^0$01' S. It fell at a place called Kahuho, on Kimwiri farm.

Plate 1.3: A picture of the Kimwiri meteorite, taken where it sits at the commissioner's office, Department of Mines and Geology –Kenya (Source: Author, 2013).

From Plate 1.3, the meteorite is about 6cm wide. It is dark in color, probably because it burned up as it fell. The freshly broken portions display a speckled appearance, like a granite rock.

The size of the meteorite is also shown by the photograph that was taken by Mr. Masibo, the commissioner, Department of Mines and Geology - Kenya, the day it fell (Plate 1.4).

Plate 1.4: A picture showing the Kimwiri meteorite, taken the day it landed. (Photograph courtesy of the Department of Mines and Geology -Kenya).

The meteorite is brown on Plate 1.4, probably because of dust or lighting variations and the camera used to take the picture. The rock appears to have been bigger, say about 11cm in diameter. This may be attributed to thermal expansion and when the rock cooled, it may have shrunk to the present room temperature diameter of 6 cm.

Plate 1.5: A picture showing the crater created by the Kimwiri meteorite (courtesy of the Department of Mines and Geology -Kenya).

One can clearly see the circular nature of the crater and the displaced soil around the crater. There is also evidence of soil that had slipped back into the crater, making the crater walls gentler, from the inside, just like it happens in all ETICs.

Another recent impact event on Kenyan soil is the Kuresoi- Nakuru County, fireball event that took place around 7:30pm local time, on Thursday, 27th February 2014. This entailed a space object that cruised through the Kenyan space, sighted by many and landed on Kipara village-Kuresoi (approximately, 0^{o}3'S, 35^{o}5'E) burning down a mud-walled-grass-thatched house.

On Friday, 7th March 2014, when samples were collected from the impact site, the fire was still raging and the government had not issued a statement about the event, that caused property losses to a widow and left a girl injured. This goes to prove how impact events can occur without warning and how people and governments are caught unprepared.

It appears that the event involved an object that burnt up into tiny fragments. It did not blast a crater on the floor of the house but caused a fire, elicited a loud bang and a tremor when it hit the house, all of which are characteristics of an impact event.

Notably, the rock fragments were so small that a magnet was used to collect them. They are believed to be pieces of the heavenly body that hit Kuresoi and are, thus, suspect meteoritic fragments.

Plate 1.6: A picture of an impact burned house at Kipara- Kuresoi, Nakuru County, taken on Friday, 7th March 2014 (Source: Author, 2014).

Plate 1.6 shows the eastern section of the house that was burnt down by the flaming heavenly body that hit it. The object is reported to have hit the house from the East. The red mud is brick burnt earth that comprises of the floor and the walls of the house. Unfortunately, the picture was taken after the floor had been dug up by mineral prospectors.
The vegetation near the house remained but showed signs of heat effect. The ground was still burning up downwards.

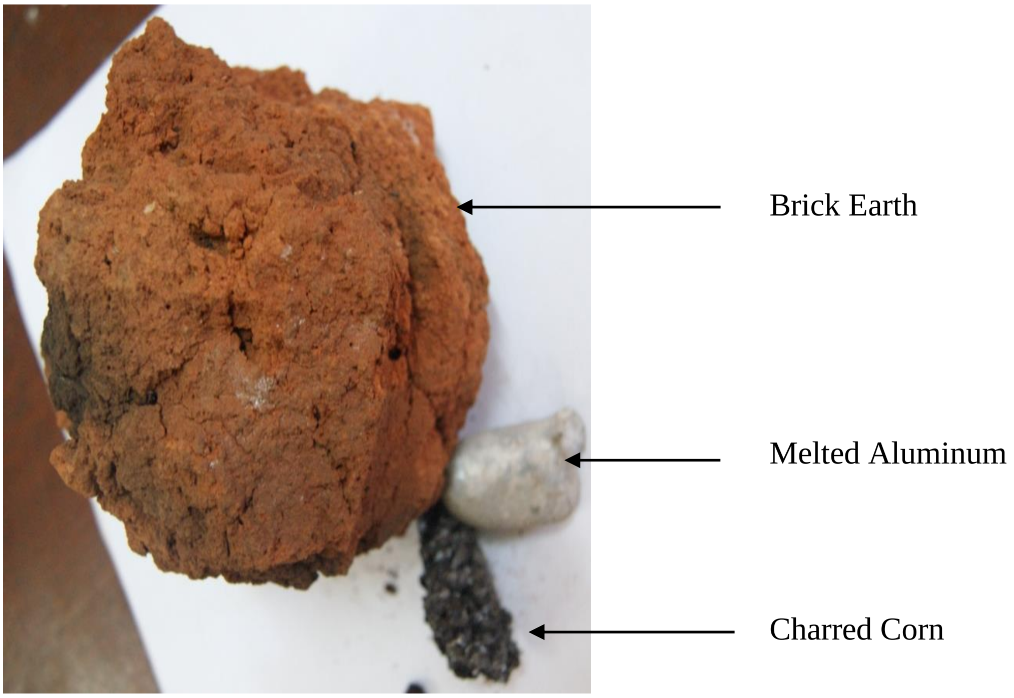


Plate 1.7: A picture of samples collected from the Kuresoi impact site (Source: Author, 2014).

The samples on Plate 1.7 include the brick burnt earth, a piece of melted aluminum and a piece of charred corn. The house that burned down is said to be the family's kitchen. It therefore had some aluminum utensils and food stuff. Everything that was in the house was gutted by the intensive fire that ensued after the impact. The high temperatures of the fire must have melted down any metal objects in the house. Food stuff like the corn, potatoes and vegetables were completely destroyed. Three children are reported to have escaped the fire, with the help of the injured girl.

As stated earlier, the heavenly body appears to have exploded and left behind tiny rock particles that are rich in iron. A magnet was used to pick the rock particles from the crumbled soil and some of the iron dust appears to have wrapped itself around the red earth, as shown by Plate 1.8.

Plate 1.8: A sample of magnetic rock fragments collected from Kuresoi impact site (Source: Author, 2014).

The principal criteria for determining if a geological feature is an impact structure formed by the hypervelocity impact of a meteorite or comet are outlined below. These are classified as either megascopic (overview – bird's eye/satellite scale) or macroscopic (visible to the naked eye) or microscopic (those that require observation under a microscope).

i) Presence of shatter cones that are on site (macroscopic evidence).

ii) Presence of multiple planner deformation features (PDFs) in minerals within the site lithologies (microscopic evidence).

iii) Presence of high pressure mineral polymorphs within in situ lithologies (microscopic evidence and requiring proof via X-ray diffraction).

iv) The morphometry of the crater: -On other heavenly bodies such as the Moon and Mars, the shape of an impact crater is relied upon to determine its presence and type (simple or complex). This is a megascopic characteristic that can be seen, unaided, by the human eye, though requiring remote sensing and aerial photography for detailed mapping. On the earth, recognizing impact structures, solely by their morphology, is hampered by denudation and tectonic forces which deform the craters. The situation is worsened by certain terrestrial features having a circular shape and appearing like impact craters, for instance volcanic craters, such as Maars, salt diapirs, some glacial features, like cirques and kettle lakes and solution aided craters. This disqualifies the circular form, alone, as a sufficient claim for a structure to be accorded the status of an impact crater. Buried craters that are revealed by geophysical techniques, also require a drill core to reveal macro and microscopic evidence to prove an impact origin.

v) Presence of an impact melt sheet and breccias: - These are generated by hypervelocity impact and are macroscopic. Impact melt has a crustal composition derived from the fusion of target rocks and meteoritic/ impactor's components. The rock may also have some suevite, especially around the center of the crater. Impact melt can be determined by sampling, followed by microscopic observation and geochemical analysis.

vi) Pseudotachylites and breccias: - Pseudotachylite is a rock type generated by faulting at either microscopic or macroscopic scales. Unfortunately, pseudotachylites are also associated with tectonic faulting and are not therefore, exclusively impact generated. However, association of pseudotachylites with the above factors can make them one of the evidence of ETICs.

vii) Presence of unshocked or preserved fragments of the impactor around or within a crater.

As for the reasons why heavenly bodies fall onto the earth, three hypotheses have been advanced by scientists (www.csienceclarified.com/Ge-He/Gravity-and-Gravitation.html), as follows:

i) The sun has a faint undiscovered companion star that revolves on a highly eccentric orbit with a period of 26 million years. When this star passes close to the sun, it draws a stream of materials from the sun and sets them in motion around the sun. Some of these materials cool down to form new planets and some are attracted by the forces of gravity of other heavenly bodies, causing impacts, as these materials slam into these heavenly bodies.

ii) There is a fairly massive undiscovered planet that orbits beyond Pluto and periodically disturbs an unseen disk of comets in the neighborhood. These comets, once disturbed, are scattered and some fall onto heavenly bodies, including the earth.

iii) The up and down oscillations of the sun through the massive central plane of the Milky Way, may cause gravity differences between heavenly bodies of the galaxy. Consequently, some of the heavenly bodies may become unstable and vulnerable to the earth's gravitational pull, which attracts them, leading to extra-terrestrial impacts on the earth (Allen, 2014).

Extra-terrestrial impact Craters are divided into three categories according to their morphology, namely:

i) Simple Craters
ii) Complex Craters
iii) Basins

Simple craters are relatively small with a smooth bowl shape. In larger craters, though, gravity causes initially steep crater walls to collapse downward and inward, forming a complex structure with a central peak or peak ring and a shallower depth (Figure 1.1). The diameter at which craters become complex depends on the surface gravity and the planet. The greater the gravity, the smaller the diameter that will produce a complex crater. On the earth, the transition diameter of a complex crater is 2 to 4 km, depending on the target rock properties (www.solarviews.com). On the moon, where gravity is low, the transition diameter is 15-50 kilometers.

The peak ring or the central peak of a complex crater is formed as the initial (transient) deep crater floor rebounds from the compressional shock of impact. Slumping of the rim further modifies and enlarges the final crater. Complex structures on crystalline target rocks will also contain sheets of impact melt rock, atop the shocked and fragmented rocks of the crater floor. On the earth's surface, weathering and erosion of the target rocks, as mentioned earlier, quickly alter the surface appearance of the structure, though in some cases, the resistant rocks will stand out as concentric rings/peak rings within the crater. On the surface of the moon, complex craters are said to be intact till they are destroyed by subsequent impact events (www.solarviews.com).

A basin, on the other hand, is an ETIC whose diameter is large and with the increasing diameter, a ring of peaks appear within it, transiting the complex crater into a basin. A single interior ring can qualify an ETIC into a basin (Therriault *et al.*, 2002).

It must be noted that ETICs can also form in marine environments and the morphology of a marine ETIC is quite distinct. Marine impact structures are characterized by a broad shallow brim, extensive sedimentary infilling and prominent fault blocks on the floor (Tsikalas *et al.*, 1999).

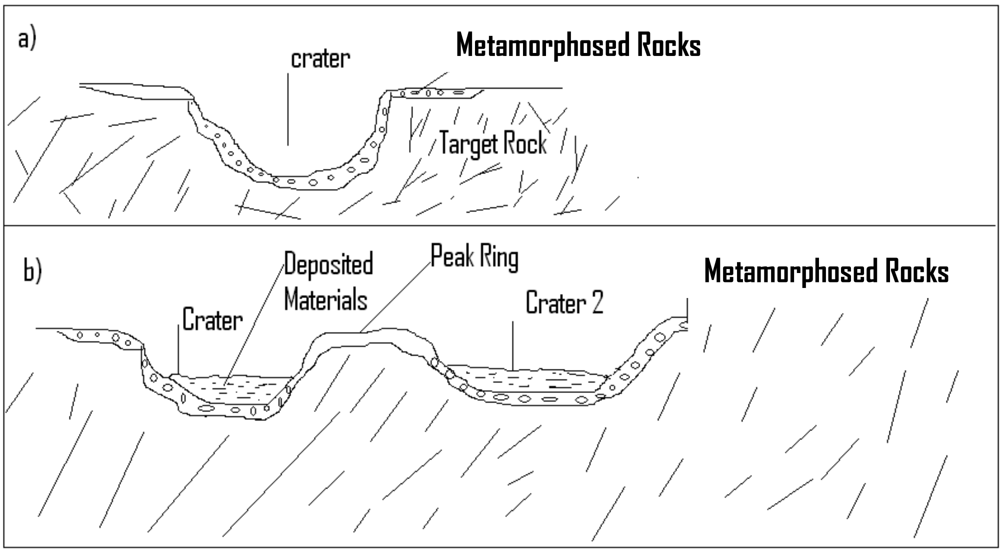


Figure 1.1: Diagram showing a simple crater (a) and a complex crater (b) with associated features (Source: Author, 2013).

1.2 Statement of the Problem

Extra-terrestrial impacts are major environmental events that can cause catastrophes of mega scales. Again, extra-terrestrial impacts and their effects have not been researched much in Kenya yet extra-terrestrial impacts have occurred and can occur again in Kenya, just like in other parts of Africa and the world. In addition, Silali crater, also known as Silali basin in this study, is a major geological feature in the northern part of Kenya yet its formation is not very clear from existing literature. Some scholars believe that the existing crater is sitting on an older crater (Dunkley *et al*., 1993), while others believe that were Silali basin's features indicative of a bonding within an early caldera, some mechanism of topographic inversion would be required (Williams *et al*., 1984).

Indeed, extra-terrestrial impacts take place without warning, especially for the less developed countries, where scientific space study is underdeveloped. Asteroids, comets, and meteors can hit anywhere on the earth's surface and cause unfathomable pain and loss. It should be clearly known that nature has no human author nor instructor. It does as it chooses most of the time and that includes bombarding the earth with rocks from outer space, be they small or big.

People, thus, need to know that extra-terrestrial impacting is a continuous process, that is never totally predetermined at any one time.
The environmental effects of extra-terrestrial impacts include; environmental hazards and disasters such as loss of flora and fauna, formation of craters, volcanicity, formation of meteorites, displacement of rocks and dust, death of people and animals, injuries, destruction of property and climate change among other environmental challenges and changes.

Extra-terrestrial impacts can cause death to people in various ways that include; people being buried by meteorites, people being blasted away during crater formation, people being burnt alive by fire breakouts that accompany an impact event, people dying when space vessels are crashed by falling heavenly bodies, people dying following sudden volcanic eruptions or tsunami wave rages that are instigated by an extra-terrestrial impact, people dying of suffocation from dust and poisonous gases that are released by an extra-terrestrial impact and people dying of fear and shock after experiencing an impact event and its various effects. Animals can also die in a similar manner.
Extra-terrestrial impacts can displace large quantities of dust into the atmosphere, causing glaciations and cold temperatures that can kill species. Sulfur can also be released into the atmosphere by an impact, through volcanicity. This may lead to acid rains, which can kill vegetation and animals in turn.

On the physical environment, an extra-terrestrial event can lead to deformation of landscapes, earthquakes, massive dust deposits, destruction of human structures and climate change among other negative effects.

In spite of the negative side of extra-terrestrial impact cratering, it must be acknowledged that there is a measure of good associated with it and the meteorites they can form, such as formation of minerals, beautiful sceneries and formation of ornamental rocks.

The study sought to establish the ETIC characteristics of Silali basin, its formation and explain the environmental changes that accompanied the basin’s formation, besides highlighting the importance of the basin to the people of Silali and Kenya. Silali basin is an environmental resource that is already benefitting the community around it but not economically.

Being a pioneer study on the identification of ETICs in Kenya, the study may form a basis for further research on ETICs in the country, besides enhancing knowledge on Extra-terrestrial impact cratering in Kenya and its environmental significance. It is also hoped that the study will enhance the economic utilization of the Silali basin.

1.3 Objectives of the Study

This study is aimed at ascertaining the origin of the Silali basin, describing the basin's outstanding features that reflect on its possible extra-terrestrial impact formation and to propose its classification or type.

The specific objectives of the study are to:

i) Map and characterize the Silali basin/crater and provide evidence on the nature of its formation.

ii) Document the effect that the impact cratering of Silali had on the environment in the area.

1.4 Research Questions

1. What is the morphology that characterizes Silali Basin?
2. What environmental/geological evidence is available in and around the basin to suggest an impact origin?
3. How did Silali crater form?
4. In what ways did Silali basin's formation affect the physical environment of the surrounding area?

1.5 Hypotheses of the Study

i) Silali basin is an extra-terrestrial impact crater.

ii) Silali basin is a dried up maar.

1.6 Limitations to the S**tudy**

The study area is highly inaccessible by road and it is also insecure because of frequent cattle rustling. This led to the collection of limited rock and soil samples from the study area. GDC (Geothermal Development Company) has a small road cleared to some place near the basin, to

the south, but the road can only be used by a strong four wheel drive vehicle. The basin, thus, had to be accessed on foot for a distance of five kilometers from the point where a vehicle can reach and even then, one has to take a walking stick for support and to scare off wild animals or to push away the 'wait a bit' thorns from one's way.
The basin's floor is 300 m below the rim of the basin's wall and the wall is extremely steep. The locals ascend and descend the basin's steep walls without difficulty. Strangers, like the researcher, found the walk to the basin's floor quite a challenge. The high temperatures in the area and within the basin made the descent even more difficult. Dehydration, shortage of breath and exhaustion threatened researchers who decided to climb down into the basin's floor and out of it later.

No fatalities occurred and none have been reported in the area but future researchers should be aware of these challenges. Anyone with a heart or breathing problem should not attempt to climb down the Silali basin on foot.

Silali basin is difficult to access from the west, east and the north. It is much tougher from the north where the terrain is very unfriendly and insecurity is at its highest point all the time. It is from the south, for now, that the basin can be reached; first using a car then by walking.

There is value in learning about Silali's past morphology from a black and white Radar satellite image, which was rather expensive to be purchased for this research. At the RCMRD, in 2015, one scene of TerraSAR-X radar imagery was costing £ 1,475. One scene is 30 km by 50 km square kilometers or 150 km^2. As of June 6th 2016, one British pound was equivalent to 146.12 Kenyan shillings (https://www.google.com). Consequently, about 6 scenes would be required to cover only the basin, let alone the surrounding areas, which are also important. The 6 scenes would cost £8,850 ($1,475 x 850 km^2/150 km^2, rounded off) or 1,293,162 Kenyan shillings (8,850 x 146.12).
Radar images provide data about the earth's surface, even up to 3-4 meters beneath the earth's crust. They are, thus, very helpful when it comes to the investigation of the older morphology of buried features of the earth, including old basins like the Silali basin. In fact, Space Imaging Radar's C/X band or Synthetic Aperture Radar SIR – C/X – SAR that flew on the space shuttle Endeavour in April and October 1994 enabled the discovery of many ETICs, including the Aorounga Craters in Northern Chad. According to www.solarviews.com website, the Aorounga craters (Aorounga South and Aorounga Central) were the first impact craters to be

discovered in SIR – C data and they show the power of SIR – C instrument in unearthing buried craters, such as the Chad craters that had been buried by wind-blown sand. Buried ETICs are particularly difficult to see while standing on the ground. Luckily, the crater at hand, Silali basin, is quite visible from the earth's surface, but it was difficult to see its past morphology because of lack of a Radar satellite image.

1.7 Rationale of the Study

The study of extra-terrestrial impact craters and the process of extra-terrestrial impact cratering are pertinent because of the danger that extra-terrestrial impact cratering poses to life on earth and to the future of the planet. It is clearly notable that extra-terrestrial objects can fall on any place on the earth's surface and can cause utter destruction and death.

A study of a satellite image of Kenya's Kerio Valley and its environs revealed a nearly circular basin within Silali area of East Pokot/Turkana East Districts. A further examination of the circular feature showed that Silali area is indeed within a huge geologic basin that is nearly very circular. The postulation that Silali area is lying on an extra-terrestrial impact crater began and it is the basis of this study. It is also an indication that there may be other extra-terrestrial impact craters in Kenya.

An additional reason why this study becomes inevitable is the fact that very little information is available with regard to ETICs in Kenya and the rest of Africa, yet extra-terrestrial impacts on the earth's surface have lots of environmental and social repercussions. Furthermore, impact cratering is a continuous process that may not be determined well in advance because of lack of the appropriate technology in Kenya and most of the other African countries. Thus, Kenyans should be made aware of ETICs and their potential blessings and hazards. For example; ETICs may be associated with valuable minerals and in some cases, they are tourist attraction sites that are useful for income generation (Winchester, 2006). On the other hand, impact cratering can cause catastrophes that are of different magnitudes, depending on the size of the falling heavenly object or projectile body (meteoroid, comet or asteroid), distance between the source of the heavenly body and the earth, together with the speed of the projectile body. If the heavenly object is from a distant source, is huge and moves at a very high velocity, its impact will be very destructive if it fails to burn out prior to reaching the earth's surface. This has far reaching effects that may include massive fire breakouts, climate change and extinction of flora and fauna species, locally or globally. Incidentally, impacts may not be so eventful, depending on where they fall, in particular on low populated areas and whether there is any ensuing visible displacement of soil. Extra-terrestrial objects that drill the earth, on impact, largely, cause earthquakes as they displace target rocks. The earthquakes, themselves, have many other negative effects on both living organisms and the environment.

It is important to note that; impacting of the earth's surface by extra-terrestrial objects is an on-going process over which no one has control and can happen anywhere; anytime. Kenyan landscape is equally vulnerable to these impacts of varying magnitudes as anywhere else worldwide.

Extra-terrestrial impact craters may be present in Kenya but their existence is not known and their social and economic values cannot be fully ascertained. These natural structures have immense socio-economic values. For instance, Silali basin as an ETIC may be of appreciable value with regard to:

i) Significantly contributing to tourism in the country, at both local and international level. In itself, apart from being a source of revenue, tourism will stimulate infrastructural development in the concerned area; encourage urbanization, besides fostering national and international unity.
ii) Providing additional insight into Kenya's geomorphological history, through describing Silali basin as an ETIC and bringing in a number of ETIC related features and rocks that are associated with the Silali basin. These include the breccias presented in Chapter Four of this study, the Chemolingot rock and the shatter cones in Chemolingot and on Silali.
iii) Mining and mineral exploitation. Extra-terrestrial Impact Craters, of which Silali basin may be one, are associated with metamorphism and certain minerals, such as impact glass, gold, siderophile elements including platinum, iridium, osmium and palladium. These are rare on the earth's surface, as stated earlier, but abundant in meteoritic impact sites.

With regard to the above, it is evident that research on ETICs in Kenya has not been realized, hence their importance as outlined above, remains to be exploited, a scenario that may be explained by the theory of the 'Tragedy of the Anti-commons'(Heller and Eisenberg, 1998).

1.8 Significance of the Study

This study brings to light the fact that Kenya, like the rest of the earth, is in the inherent potential danger of being hit by heavenly bodies. In addition, it provides, to a large extent, evidence implicating Silali basin to be a possible ETIC and the possibility of the presence of other ETICs in Kenya.

The study is important because of the following reasons:

i) It enhances existing knowledge about Silali basin as an area of geological and environmental interest. First, the formation of the basin appears very complex and even from existing texts, there are questions about it. According to Dunkley and a team of other researchers, for instance, the 'break off walls' (stepped walls) of Silali basin mark the traces of an earlier caldera (Dunkley *et al*., 1993). The team suggested that the 'break off' wall features are not contemporaneous because they relate to different volcanic compositions. According to Williams and another team of researchers, were these features indicative of a bonding within an early caldera, then some mechanism of topographic inversion is required (Williams *et al*., 1984). The study at hand suggests an extra-terrestrial impact as the mechanism that can bring about a topographic inversion, which can make the current Silali crater a bonding within an older caldera (refer to the formation of Silali basin in Chapter Two).

ii) The knowledge gathered as evidence of Silali basin's origin may shed light on the understanding of extra-terrestrial bodies and their effects on the topography of the earth. Consequently, people will be able to visualize various extra-terrestrial phenomena. For example, they will be able to form links between the occurrence of various landscapes and meteoritic impacts. Thus, they will be well informed to be able to revisit and critically evaluate the country's preparedness for such an event. Indeed, heavenly debris are still falling onto the earth's surface and no one knows when or where another one will fall, similar to the one of Saturday 16th July 2011 or the many others in the past.

If Silali basin is an ETIC, then just as it was created millions of years ago by an extra-terrestrial impact, the basin and the Kenyan landscape as a whole, stands to be hit again and this has many environmental implications. The Kimwiri meteorite is evidence enough that this is possible. The study thus enhances disaster preparedness, more so preparedness against space disasters, among Kenyans and anyone reading this thesis.

iii) The study has also given a different approach to the formation of one of the greatest land marks in Kenya's northern rift; the Silali basin. Before this thesis, Silali basin was a volcanic crater formed by various volcanic processes and subsidence. The study has brought it out as a possible ETIC and explained how it was formed by an extra-terrestrial impact.

iv) It is believed that the study has stretched Kenya's geological data to include ETICs, such as Silali basin and ETIC related features, for example shatter cones, possible tektites, impact ejecta and meteorites.

v) It is also believed that this study will enhance the knowledge of all who read its findings, on extra-terrestrial impact cratering and all its possible effects. Besides creating awareness of such an event, it is hoped that environmental and social preparedness is cultivated so that, the shock of witnessing an impact event will not kill anyone who will have survived the impact itself.

vi) Finally, the study has demonstrated how a potential ETIC can be investigated using remote sensing and other research methods.

1.9 **Area of Study**

The study reported in this thesis covers the Silali basin, also known as Silale, which is found in East Pokot/Turkana East, within the mid Graben of the Great Rift Valley, 50 km north of L.Baringo and near Kapedo Town. It is located on Latitude 1^{0}10' N and Longitude 36^{0}12' E. The basin or crater is named *Kotong*, by the Pokot community living around it, which means a depression. The Turkana people call it Silali while the Pokot call it Silale. The basin covers an area of about 850km^2 and has a NNE diameter of about 5 km and an ESE diameter of 8 km. It can be estimated that the impactor's size, could be 0.25-0.4 km in diameter or 42.5km^2 in area, on the basis of the rule that an impactor's size is 1/20 the crater's size (Beatty *et al.*, 1999), stated elsewhere in this thesis. Consequently, the Silali impact event may have been a great event.

Figure 1.2 and Plate 1.9 are maps of Kenya showing the location of Silali basin. Geographically, the area is in southern Turkana but administratively, it is at the border of Turkana East and East Pokot districts. Factually, the area is a social hot spot because it is a cattle rustling area. Separately, it is an area whose ownership is disputed between the Pokot and the Turkana communities, hence frequent fights over pasture. In addition, the Silali area is very rich culturally, being endowed with special archeological sites, some of which have been mentioned as part of the discussion of the thesis.

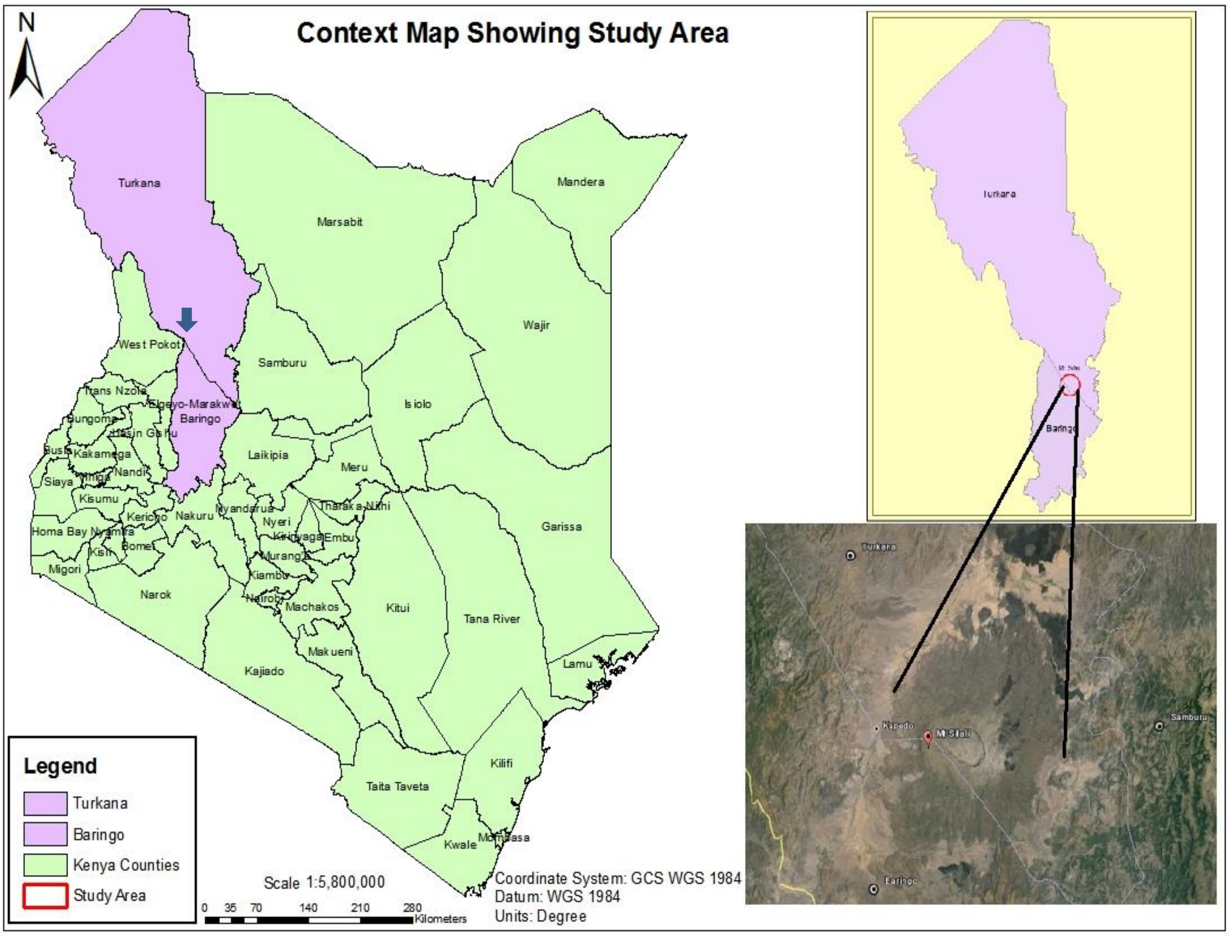


Figure 1.2: A map of Kenya, drawn to scale, showing the study area, pointed by a blue arrow and circled in red (Courtesy of RCMRD).

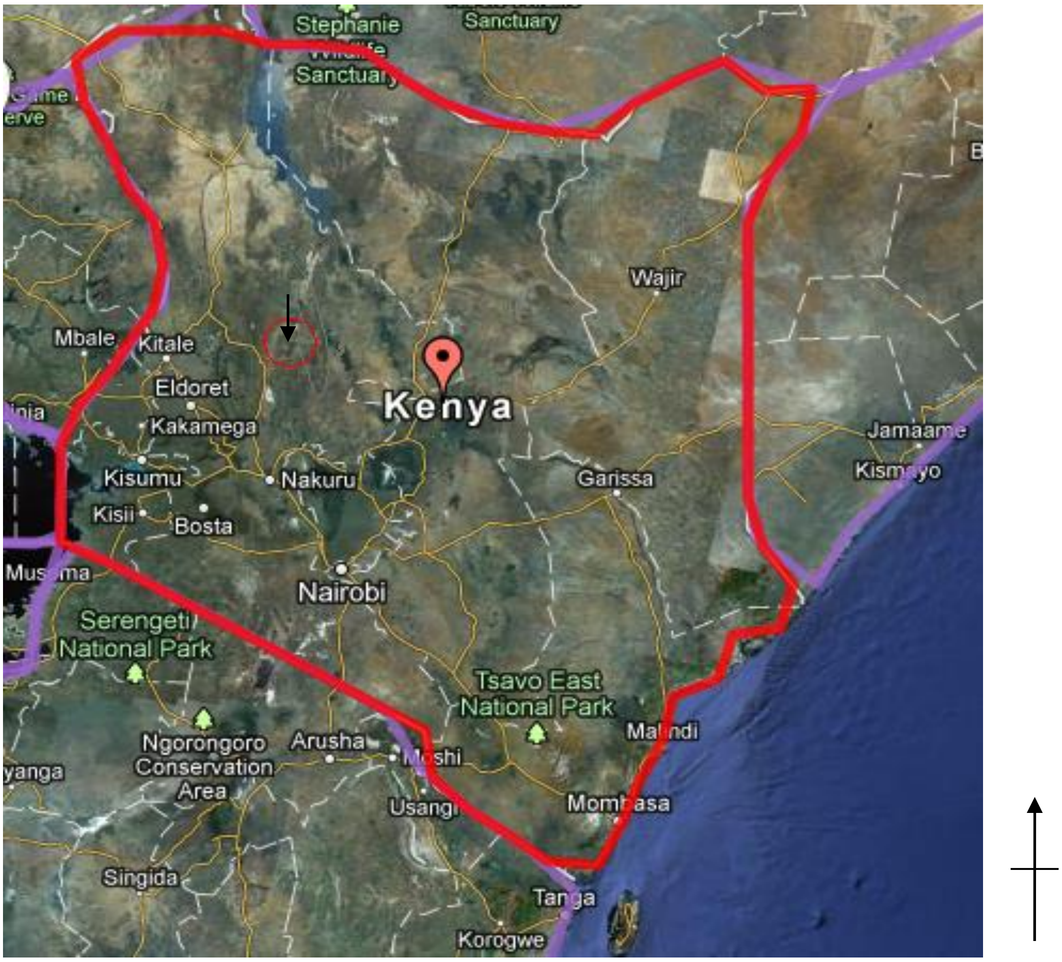


Plate 1.9: A map of Kenya (not to scale) showing the study area; circled by a red line and pointed by a black arrow. Map adapted from Google Earth maps.

LEGEND

	Kenyan boundary
	Fresh water
---	Provincial boundaries
	Road network
	Salty water
	International Borders

From Figure 1.2 and Plate 1.9, Silali basin, circled in red, is to the south of L. Turkana, to the northeast of Eldoret Town, to the north of Nakuru Town and 50 km north of L. Baringo, near the small semi-rural town of Kapedo. It is in a very remote area that can only be accessed by heavy four wheel vehicles or a helicopter.

CHAPTER TWO

LITERATURE REVIEW

2.1 Studies on ETICs

From the status of 'minor curiosity' 50 years ago, impact cratering has now been elevated to one of the most important geologic processes that affect the earth's surface. About 200 impact craters are known on earth (Plate 2.1, Appendix II).

Plate 2.1, is a map of the world showing the distribution of some of the recognized ETICs globally.

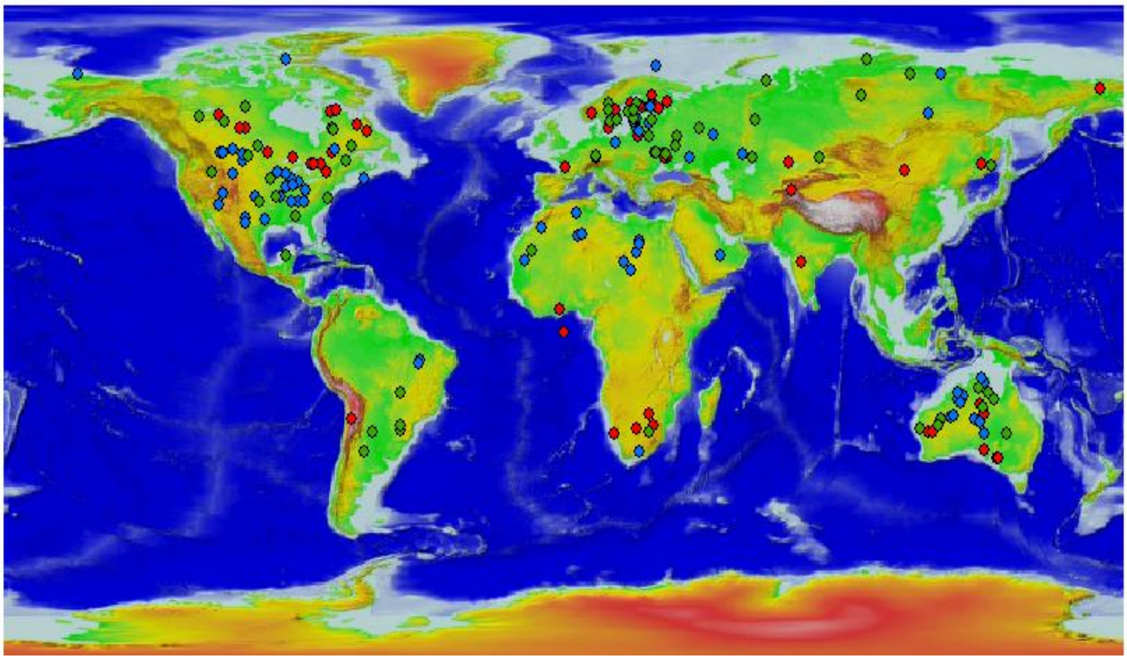


Plate 2.1: Global distribution of some of the recognized terrestrial impact structures superimposed on a digital elevation map (DEM) of the Earth. The red dots represent structures formed entirely in crystalline target rocks; blue dots represent structures formed entirely in sedimentary target rocks; and green dots represent mixed crystalline–sedimentary targets. Data was adapted from the Earth Impact Database (www.google.com).

Impact cratering is not unique to the earth. It occurs on other bodies of the solar system such as the natural satellites (moons) and the planets. The earth's moon, for example, has conspicuous craters which are generally circular depressions, ranging in size from less than one inch to more than 1,200 km in diameter. Many of the larger ones are visible at full moon, viewed through a pair of binoculars. The most visible lunar impact structure is Tycho, which is located on the moon's southern hemisphere. This crater has the classic hallmarks of an impact crater, namely; concentric nest of slumped walls inside the rim, central (uplift) peak, rough irregular crater floor and ejecta in hummocky deposits. The craters on the moon are almost quite intact because craters on heavenly bodies are safe from erosion and tectonic deformation that plaque impact craters on the earth's surface. Consequently, on the earth's surface, truly circular structures are rare but mapping of parts of the continents since the early 19th Century has led to discoveries of many ETICs that are nearly circular. Some of these will be discussed in this chapter and other sections of this thesis.

Less than 100 years ago, near circular craters were products of volcanic processes. This is because, some volcanic craters, such as maars, have a circular shape. As discussed earlier, maars are formed when lava encounters near surface water, which flashes into steam, causing overhead rocks to be pushed out explosively, leaving a depression that is somewhat backfilled by volcanic fragments and land sediments washed into it by surface runoff. Despite this similarity, impact craters differ from volcanic craters in various attributes as depicted in the Table 2.1.

Table 2.1: Some pertinent differences between volcanic and impact craters (http://rst.gsfc.nasa.gov/sect18)

	Volcanic craters	Impact craters
1.	Except for maars, they occur at the top of built up mountain-like edifices (volcanic cones)	They occur anywhere, even on plains and flat lands
2.	They have steep interior walls that sometimes become gentler due to slumping	They have gentle, slumped interior walls
3.	The layered units are at low angles (are sub-horizontal)	Layered units are overturned or rippled away.
4.	The crater rim is slightly raised	The crater rim is low
5.	Do not have distinct ejecta beyond the rim, only lava flow	Have distinct ejecta (fragments with broad size range, from small to massive blocks) beyond the rim
6.	Occur solely due to volcanic activity in the earth's crust and on the earth's surface.	They occur due to extra- terrestrial impact and can induce volcanism, leading to presence of volcanic rocks in or around it.

There are also circular craters on the earth's surface that are not impact related in their origin, besides the maars. These are craters that are produced by other geologic processes, other than volcanicity. They include sinkholes and depressions caused by the solution of sodium chloride (natural salt) in salt domes that reach the surface after diapiric piercing of sedimentary rocks by plastically flowing salt. This plastic flowing salt can invade rocks, causing them to collapse. This phenomenon occurred in Melville Island, near Baffin Island in the Canadian Arctic, leaving a crater on the earth's surface (Spencer *et al*., 2008).

Until the space programme in the 1960's, debate over the nature of lunar craters raged as a controversy for more than a century. But with close exploration of the moon and other planets, like Mercury, opinion has shifted in favor of impact as a dominant process creating the myriads of circular depressions spread widely over the surfaces of heavenly bodies.

Impact, as a lunar and terrestrial process, was first suggested by European geoscientists in the early 1900's. The proposal that the Meteor crater in Arizona had a meteorite impact origin opened the possibility of extra-terrestrial impact as the cause of other similar circular features. Gulbert (1898) conceived the idea and supported it by finding iron meteorites around the crater (http://rst.gsfc.nasa.gov/sect18). Though there were skeptics, all skepticism changed in 1960 with the study of cratering mechanisms at meteor craters and several nuclear explosions of craters by Shoemaker (Shoemaker *et al*., 1994), who came up with discoveries of shock metamorphism on target rocks in impact craters, alongside its various effects.

The earth today, despite much recycling of the oceanic and continental crust, retains signs of huge impacts that have taken place over many years, including smaller ones. Some of the craters that have been identified on the earth's surface will be discussed in this chapter. Nevertheless, more craters remain to be discovered. Satellite imagery remains the most effective means for conducting systematic research on ETICs, with the support of other research methods, as it has been done in this study.
Various satellite images were studied and analyzed to provide information pertaining to the mapping of the Silali basin. They also aided in identifying the possible mechanisms that led to the formation of the basin. The satellite images included Landsat, SPOT, GeoEye and ASTER images-among other remote sensing data that provided critical information about the basin.

Landsat images are acquired from Landsat earth observing satellites which are jointly managed by NASA and the US Geological Survey, since 1972. Landsat satellites also acquire images from space and currently, starting on 11th February 2013, they are a part of Landsat Data Continuity Mission (Landsat 8). These satellites provide up-to-date images through Landsat 7, which was launched on 15th April, 1999. The images are both in true and false color, depending on the procedure used to process (compositing) the multispectral band data. A false color image/ false color composite, is an image that depicts an object in colors that are different from those of a photograph, the latter being a true color image. A false color image sacrifices natural color rendition in order to ease the detection of features that are not readily discernible otherwise. Typically, some or all the energy used is from electromagnetic (EM) radiation, outside the visual spectrum, including infrared (IR), ultraviolet (UV) or X- ray. The choice of spectral bands to be composited is governed by the physical properties of the object being investigated. Three spectral bands are commonly combined to produce a false color image. However, two bands can also be used to produce a false color image. It is also possible to combine many bands into three visual red-green-blue (RGB) bands; the ability of the human eye to discern 3 channels is a major limiting factor. A true color image, on the other hand, shows an area in actual colors for example vegetation appears green as it is in the visible spectrum. The RGB channels from the camera are mapped to the corresponding RGB channels of the image, yielding a RGB-RGB mapping. For a false color image, this relationship is altered. The simplest false color encoding results when a RGB image in the visible spectrum is mapped differently for example green-blue-red against red-green-blue (GBR-RGB). A traditional false color image of the earth would have a NRG-RGB mapping, where N is Near IR and the blue spectral band remaining unused. This yields a false color image where vegetation appears reddish, almost corresponding to the false color images presented in this thesis. Unfortunately, the red tone may be representative of the soils of an area and not vegetation. To establish the truth, ground truthing is always recommended and it was done in this study.

SPOT (Systeme Pour l'observation or system for earth observation) is a high resolution optical imaging earth observation satellite system, operating from space, at an altitude of 832 km. It is a French satellite that was initiated and launched by the French Space Agency. It is manned by SPOT from France. Many SPOT images or combinations of SPOT and other satellite images, have been presented in this thesis.

GeoEye imagery, like SPOT, is high resolution imagery. The designers of GeoEye satellite technology define it as ‘the state of the earth imagery’ because the geospatial data that GeoEye satellite captures is of high resolution and is currently the most accurate. GeoEye comprises of a constellation of earth imaging satellites and an information network of ground stations; that are capable of all imagery processing capabilities, all of which yield broad spectrum imagery products. The satellites in the GeoEye constellation include GeoEye 1 and IKONOS. IKONOS is the world’s first sub-meter high resolution satellite that combines panchromatic (black and white) images with one meter resolution and multispectral imagery with four meters resolution. Thus, the GeoEye is a sub-meter high resolution satellite and is commercial. Some of the images presented in this study are GeoEye images of the study area, acquired from the internet and acknowledged accordingly.

ASTER is one of the five state-of-the-art instrument sensor systems on-board Terra, the latter being a satellite that was launched in December 1999. It was built by a consortium of the Japanese government, industry, and research groups. ASTER monitors cloud cover, glaciers, land temperature, land use, natural disasters, sea, ice, snow and vegetation patterns at a spatial resolution of 90 to 15 m. The multispectral images obtained from this sensor have 14 different colors, which allow scientists to interpret wavelengths that are not visible to the human eye, such as near infrared (NIR), short wave infrared and thermal infrared (www.msnbc.com). ASTER is the only high spatial resolution instrument on Terra that is important for change detection, calibration and/or validation of land surface studies. ASTER data is expected to contribute to a wide array of global change-related application areas, including vegetation and ecosystem dynamics, hazard monitoring, geology and soils, land surface climatology, hydrology, land cover change and the generation of digital elevation models (DEMs). Satellite Imaging Corporation (SIC) is an official distributor for ASTER Imagery through United States Geological Survey (USGS). Other key features of ASTER include: Multispectral thermal infrared data of high spatial resolution and highest spatial resolution of surface spectral reflectance, temperature, and emissivity data within the Terra instrument suite. One ASTER image of the Silali basin is also presented in this thesis with acknowledgement of its source.

LIDAR (Light Interferometry Detection and Ranging) is a technology for measuring distance by illuminating a target with a laser and analyzing the reflected light. It produces black and white images that are good for detecting land surface features, because they enhance the contrast between valleys, depressions and raised areas. LIDAR images are acquired at low level altitude, by a sensor that is attached to a light remote controlled aircraft that flies over the area of interest. A LIDAR image of Silali basin has been presented in this study (Plate 2.2), to show the faults, ridges, cones, depressions and the general terrain of the Silali basin and its environs.

2.2 Some Important ETICs Found Outside Africa (www.solarviews.com)

i) Barringer Meteor Crater, Arizona, USA.

It is located on latitude 35^{0}02'N and longitude 111^{0}01'W. It has a diameter of 1.186 km and is 49,000 years old. It has overturned rocks and hummocky deposits.

ii) Chicxulub, Yucatan Peninsula, Mexico

It is found on latitude 20^{0}20'N and longitude 89^{0}30'W. It has a diameter of 170 km and is 64.98 million years old. It was named after a village located near its center. It is buried under hundreds of meters of sediments, which hid it from view. It is believed to be an asteroid crater which scientists associate with glaciation and extinctions of dinosaurs.

iii) Wolfe Creek Australia

This crater is located at latitude 19^{0}10'S and longitude 127^{0}47'E. It has a diameter of 800 m and is about 300,000 years old. It is a relatively well preserved crater that is partly buried under wind-blown sand. It is situated in a flat desert plain, North-Central Australia. Its crater rim rises to about 25 m above the surrounding plains and the crater floor is about 50 m below the rim. Oxidized remnants of iron, meteoritic material and some impact glass are found in and around the crater.

iv) Mistastin Lake, New Foundland and Labrador, Canada

It is found on latitude 55^{0}53'N and longitude 63^{0}18'W. It has a diameter of 28 km and is about 38-40 million years old. The crater has been heavily eroded by glaciers, which have removed most of the impact melt sheet and breccias, exposing the crater floor, which is evident in the form of a lake occupying it at a diameter of about 10 km. Horse Shoe Island, in the center of the lake, is part of the central uplift and contains shocked Precambrian crystalline target rocks. Away from the crater, one encounters meteorite features in the form of quartz, feldspar and diapletic glasses.

v) Manicouagan, Quebec Canada

It is found at latitude 51^{0}23'N and on longitude 68^{0}42'W. It has a diameter of about 100 km and is about 212 million years old. It is one of the largest impact craters still preserved on the surface of the earth. A lake fills a ring where impact-brecciated rock has been eroded by glaciation. The lake surrounds the more erosion resistant melt sheet transformed by impact into metamorphic and igneous rock types.

vi) Clear Water Lakes, Quebec, Canada

There are two of these;

a) Clear water lake West, which is at latitude 56^{0}13'N and longitude 74^{0}30'W and has a diameter of 32 km and;

b) Clear water lake East, which is located on latitude 56^{o}05'N and longitude 74^{0}07' W, with a diameter of 22 km.

These twin circular lakes were formed simultaneously by the impacts of an asteroid pair which slammed into the area about 290 million years ago. They are located within the low terrain of the Canadian Shield, East of the Hudson Bay. They have central peak rings and their waters are extremely clear, hence their name.

vii) Deep Bay, Saskatchewan, Canada

It is located at latitude 56^{0}24'N and longitude 102^{0}59'W. It has a diameter of 13 km and is aged about 50 – 150 million years old. It is a circular lake which is unusual in the region where glacial gouging is common. Its central part is totally submerged but it may be a complex impact crater with multiple peak rings. Samples obtained from drilling into the central structure revealed shocked and fractured metamorphic rocks, flanked by deposits of allochthonous, mixed with breccias.

viii) Gosse's Bluff, Northern Territory, Australia

This crater is at latitude 23^{0}50'S and longitude 132^{0}19'E. It has a diameter of 24 km and is about 142 million years old. It is believed to be the product of an asteroid or comet impact on Northern Australia's Missionary Plains. The crater is highly eroded, especially at its center, creating a ring of hills. It is thus, a complex crater.

ix) Kara-Kul, Tajikistan

It is on latitude $38^0 75$'N and longitude $73^0 24$'E. It has a diameter of 45 km and is about 10 million years old. It bears a lake and is at an altitude of 3900 m above sea level, in the Pamir Mountain Range, near Afghan border. It has impact shock features such as breccias.

2.3 Some of the Known ETICs in Africa (www.solarviews.com)

i) Aorounga, Chad, Africa

It is located at latitude $19^0 06$'N and longitude $19^0 15$'E. It has a diameter of 12.6 km and is about 345 million years old. The impact of an asteroid or comet many years ago left scars on the landscape that are still visible in the area, especially viewed from space. The original crater was buried by sediments, which were then partially eroded to reveal the current ring-like appearance. Aorounga is believed to be a product of multiple impacts within the Sahara in northern Chad.

ii) Roter Kamm, South West Africa/Namibia

It is found at latitude $27^0 46$'S and longitude $16^0 18$'E. It has a diameter of 2.5 km and is about 5 million years old. It is situated in the Namib Desert and is rich in impact melt breccias.

iii) Bosomturi, Ghana

This crater is located on latitude $06^0 32$'N and longitude $01^0 25$'W. It is 10.5 km in diameter and is about 2 million years old. It is filled by a lake and is believed to be the source of Ivory Coast's tektites and micro tektites in nearby ocean sediments.

iv) The Qattara Depression

This is a depression whose origin is still a geological puzzle. A common origin by wind deflation is the most accepted explanation. Other explanations include formation by solution, mass wasting, stream excavation or Karst scenery activity. Being a great feature in the Sahara, Qattara Depression is a closed inland basin bounded from the North and West by steep escarpments with an average elevation of 200 m above sea level. Within it, cones, towers, mushroom blocks, and plateau like hills, ranging in height up to 5630 m, are common. Sinkholes and caves are also common, besides fresh water springs and near surface salty water in some areas. It also has Sand Dunes. Strikingly, the Qattara

Depression, to the West, is an area of enigmatic silica-glass – ultra pure glass, 98% silica, which is believed by some scientists to be the product of meteoritic impact while others believe that they are the products of a dried up lake. The silica field is located at latitude $25^0$17'N and longitude $25^0$33' E, between two dune ridges of an average height of about 200 m. Some chunks of the glasses are between 5-26 kg in weight and are half buried, like icebergs in the reddish sand. Pure as they are, the glasses still have bubbles, white wisps and black inky swirls and are rich in iridium, an evidence of extra-terrestrial impact by a meteorite or comet. The problem is, the depression has no iron in the glass area and there is no sign of a giant crater in Qattara, except for two areas where the glass is found in an oval-shaped depression and another area where there is a circular depression, which has no glass. The question being asked today is whether there was a 'Soft' projectile impact on the Qattara area. The blast of hot air may have melted the sand beneath. Such a craterless event is believed to have occurred in 1908 during the Tunguska event in Siberia. The Qattara Depression is believed to have a huge underground fossil water reservoir, of unknown volumes of water that joins Egypt, Libya, Sudan, and Chad. The area also has the finest alabaster material the world has ever known (http://who.unesco.org/en/tentativelists). In addition, it has underground karst scenery features that include the largest karst scenery caves in Egypt; however such caves are extremely rare in arid environments.

v) Some of the Least known Craters in Africa

There are some craters in Africa that are least known. Table 2.2, adapted from http://www.unb.ca/passc/impactDatabase/Africa.html, in 2012, shows these craters. Symbols have been used to represent some of the information but a key has been provided to aid in interpreting the symbols.

It must be noted that by now, some of these craters would have graduated from the least known to most known or verified impact craters. An example here is the Tenoumer Crater.

Tenoumer Crater is found in Mauritania on latitude $22^0$55' N and longitude $10^0$24' W. It is about 1.9 km in diameter and located in Western Sahara desert. The crater is very circular in shape with a rim that rises 110 m above the crater floor. Its floor is covered by about 200-300 m thick layer of sediments. Due to the presence of igneous rocks outside the crater, a volcanic origin was preferred till PDFs were discovered in the crater. Deformed biotite and feldspar rocks were also found in Tenoumer crater alongside lechatelierite, a glass that is made up of fused silica. Lechatelierite is a tektite that can also be found in shatter cones. It has hollow tube shaped particles.

Table 2.2 : Table showing ETICs that are little known in Africa (www.solarviews.com)

Crater Name	Location	Latitude	Longitude	Diameter (Kilometers)	Age (Ma)	Exposed	Drilled	Target Rock	Google map links	Bolide type
Amguid	Algeria	26º 5' N	4º 23'E	0.45	< 0.1	Y	N	S	GO	-
Aouelloul	Mauritania	20º15'N	12º 41'W	0.39	3.0 ± 0.3	Y	N	S	GO	IRON
Bp structure	Libya	25º19'N	24º20'E	2.00	< 120	Y	N	S	GO	-
Gweni –	Chad	17º25'N	25º45'E	14.00	< 345	Y	N	S	GO	-
Fada	S.Africa	32º 43'S	24º 26'E	0.64	0.250±0.050	Y	Y	S	GO	-
Kalkkop	Botswana	22º29'S	27º 35'E	3.5	<180	Y	Y	C	GO	-
Kgagodi	S.Africa	26º 28'S	23º 32'E	70.00	145± 0.8	N	Y	C	GO	CHONDRITE
Morokweng	Libya	27º35'N	24º 24'E	18.00	< 120	Y	N	S	GO	-
Oasis	Algeria	22º55'N	7º 33'W	3.50	< 70	Y	N	S	GO	-
Quarkziz	Algeria	25º40'S	4º 2'E	1.75	<3	N	Y	S	GO	-
Talemzane	Mauritania		10º 24'W	1.90	<70	Y	N	M	GO	-
Tenoumer	S.Africa	27º 0'S	5º 7'E	6.00	< 70	Y	N	S	GO	-
Tin Bider										
Tswaing	S.Africa		28º 09'E	1.13	-	Y	Y	M	GO	CHONDRITE

KEY:
Ma- Millions of years
C- Crystalline target
M- Mixed Target
S- Sedimentary target
Y- Yes
N- No

2.4 Recently Discovered ETICs and Unconfirmed ETICs in Africa (**www.solarviews.com**)

Since research on ETICs has been on going, the following ETICs were recently discovered in Africa and they are listed as ‘unconfirmed’ because they are not yet included in the Earth Impact Database, owing to the stringent requirements regarding evidence of impact and peer reviewed publications.

i) Kebira Crater, Egypt

This is a crater found in the western desert of Egypt, close to Libya, on latitude 24^0 40’ N and longitude $24^0$58’ E. It is 31 km wide and its name is derived from an Arab word *Kebira*, which means large. It is about 220 m deep and has a circular lake whose central uplift is submerged. Drillings carried out in the 1960s revealed fractured metamorphic rocks and deposits of allocthonous and mixed breccias in the lake.

ii) Temimichat Crater, Mauritania

This is a crater that is not well preserved because large portions of it have been eroded, dissected and masked by Aeolian deposits. Its rim is formed of gneiss while its erodible parts are formed of gabbro dikes. The crater floor is buried under aeolian sediments. It is located on latitude $24^0$15’ N and $9^0$39’ E.

iii) Wembo-Nyama ring structure, Congo

It is located on latitude $3^0$37’ S and $24^0$31’ E. It is believed to be a giant impact crater. Deforestation in the Congo basin has revealed what may become the biggest impact crater in central Africa. The ring feature is 36-46 km wide and it is circular in shape. The Unia River flows around the ring, emphasizing its ring shape. The rim of the feature is about 550 m high. Unfortunately, not much ground work has been undertaken in the Wembo –Nyama structure.

It is worthwhile noting that, of all the almost 200 ETICs distributed in the world, only a handful has been located on the large continent of Africa, when compared to other parts of the world. More craters are found in the stable cratons of the earth and even with the cratonic areas, more craters are found in the populated or well researched regions of Western Europe, North America and Australia.

Notably, Africa, South America and Eastern Europe have few ETICs displayed because of little research that has been carried out in these areas (Thackrey *et al*., 1976). It should also be mentioned that the distribution of ETICs today is not a primary distribution or the original distribution. This is because of the contribution of three main geological processes in deleting ETICs. These geological processes are; Plate tectonics, Erosion and Burial/ Sedimentation. Plate tectonics have a greater negative effect on crater preservation and may be said to be the leading agents of ETIC's deletion and deformation (Thackery *et al*., 1976).

2.5 **Literature on ETICs**

Most information about ETICs is found in the Internet. A number of websites post information about ETICs and the websites include the ones quoted in the text and reference section of this study. Besides these, there are individual people who have carried out studies on ETICs. Beatty *et al*. (1999) outline a witness account of extra-terrestrial impacting that took place in 1994. They explain that in July 1994, the inhabitants of the earth witnessed a serendipitous experiment in planetary scale impacts, as fragments of a comet slammed into the upper atmosphere of Jupiter. The series of collisions created huge dark stains on the planet, which remained recognizable for months thereafter. At the end of the 'impact week', there was a newfound appreciation that such impacts have happened on earth in the past and can happen again, at any time, with devastating effects on civilization. They also say that crater hunters can identify ETICs, primarily, by their structure and evidence of shock metamorphism in rocks. The craters themselves are ephemeral, for instance, they tend to fill in or corrode away very quickly. If erosion has not encroached too deeply, some of the breccia may be preserved. The authors also concur with what has been stated earlier that impact cratering creates an enhanced amount of trace elements such as the noble metals (iridium, platinum and gold) in an impact area. These elements are relatively abundant in meteorites but greatly depleted in the earth's crust.

Beatty *et al*. (1999) also noted that it is possible to estimate the size of an impactor from the diameter of the crater. For example, the size of an impactor is taken to be 1/20 the given crater's size or diameter, leading to a ratio of 1:20.

This rule has been used to estimate the size of the impactor that caused the Silali basin to be about 1/20 x 5 or 8, which is 0.25 -0.4 km in diameter or 42.5 km^2 in area (1/20 x 850 km^2). This suggests a huge impact event.

Pillington and Grieve (1992), noted that 20% of ETICs are buried beneath post- impact sediments and geophysics is thus a major tool in recognizing them. According to them, the most conspicuous geophysical signature of an ETIC is its circular gravity low. For simple bowl-shaped craters, the gravity models indicate that the anomaly is due to the presence of an interior allochthonous breccia lens. In complex craters, modeling indicates that the main contribution to the gravity anomaly is from fractured target rocks in the floor of the crater. The scholars also indicated that the size of the gravity signature usually increases with increasing crater diameter. Magnetic signatures for craters, though, are varied. The dominant effect is a magnetic low. The confirmation of an impact origin, however, is based on geologic evidence. Geophysical data for Silali basin, was acquired from geophysical studies that were carried out in the study area by Lichoro (2013). The results are recorded in Chapter Four of the thesis.

McCall (1963), from a brief examination of aerial photographs, noted that there is a caldera at Kilome hill- Eldalat. He considered it to be the surface depression of a deep seated cauldron subsidence of the Glencoe type. Of particular interest is syenite boulders found scattered over the hillside, outside the caldera. The unusual cruciform formation of the caldera produced by four sector grabens is compared with that of the nearby Menengai caldera and with the peak structure of many lunar craters (McCall, 1963).The Kilome caldera of McCall is not clear whether it is volcanic or impact in origin. The exact location of the caldera is not also known and it may even be the Silali basin, which is found to the North East of the Menengai crater.

According to a Kenya's government report written on the geology of Maralal area, the Silali basin is referred to as Silali crater on Silali volcano. It is described as a major topographic feature of the 'Median Graben' which is the middle section of the Gregorian Rift Valley (G.o.K, 1987). Silali is further described as a large volcanic shield with relatively gentle profiles, walls that are sharply delineated and a bottom that features volcanic cones.

The crater, according to McCall (1968), formed in the late Pleistocene period (12-1 million years ago) and has fumaroles on its western flanks. Recent research though, puts Silali basin's formation at 62-65 million years ago, which is about the same time that Chicxulub crater formed in Mexico (64.98 million years), Telemzane in Algeria (less than 70 million years ago) and Tswaing in South Africa (less than 70 million years ago).

According to McCall and Hornung (1972), the whole of the Silali volcano has an enveloping of an alluvial apron. According to these researchers, there is a lot of volcanic rock, of various kinds, around the Silali basin but the trachyte cones (Black Hills) to the east of the basin's wall are made of almost pure black glass (McCall and Hornung, 1972). The volcanic rocks found in the basin include trachyte and basalt. Alluvium and lake deposits cover a large part of the basin's floor. There are also traces of calcrete, which comprises of a hardened deposit of calcium carbonate, containing gravel, sand, clay and silt (hardpan) on the basin's floor. The crater walls comprise of foliated mafic monzonites, syenites and granodiorites (McCall and Hornung, 1972). This is in agreement with McCall's (1963) finding of syenite boulders scattered over the Eldalat crater, which may have been the Silali basin before 1968, when books by the same author feature it as Silali. Basalts, trachytes and alluvium rocks are also found around the basin.

McCall and Hornung (1972) provided an explanation for Silali's present day shape. They state that, the craters around the main basin are volcanic and that Silali basin is a composite volcanic dome that was built by clustered vents. The first eruption deposited trachyte. This was followed by an effusion of trachyte phyroclasts before the return of a quiet effusion. Later, according to the researchers, the volcano suffered some sagging (Holocene sagging) in which a fine grid of normal faults developed, following an extensive emission of thin basaltic lava flows from the many small vents. The erupted basalts obscured the trachytes of the main phase but further trachyte eruption occurred, just before the subsidence. The Silali basin, for the researchers, appears to have been formed by volcanicity and subsidence. There is neither mention of an impact nor multiple impacts.

Interestingly, the scholars agree that ‘high and low magma reservoirs exist beneath the Silali (Silale) basin, with the basalts tapping a deeper chamber and the trachytes emanating from high standing (near surface) cupola reservoirs’ (McCall and Hornung, 1972).

Subsidence does not completely explain the circular shape of the basin, especially if it is a product of fissure eruption (small vents) and not a vent type eruption. Fissures mainly build up volcanic shields and elongated domes, which in most cases do not have craters, let alone the 5-8kmwide crater- like formation of the Silali basin. The question that arises here is how the fissures that are responsible for the building of the Silali basin occurred in a concentric formation culminating into the formation of a near circular depression. Additionally, how these developed lithologically into a ring-like formation. The map below (Figure 2.1) of Silali area provides evidence of fractures all around the basin that appear concentric in formation.

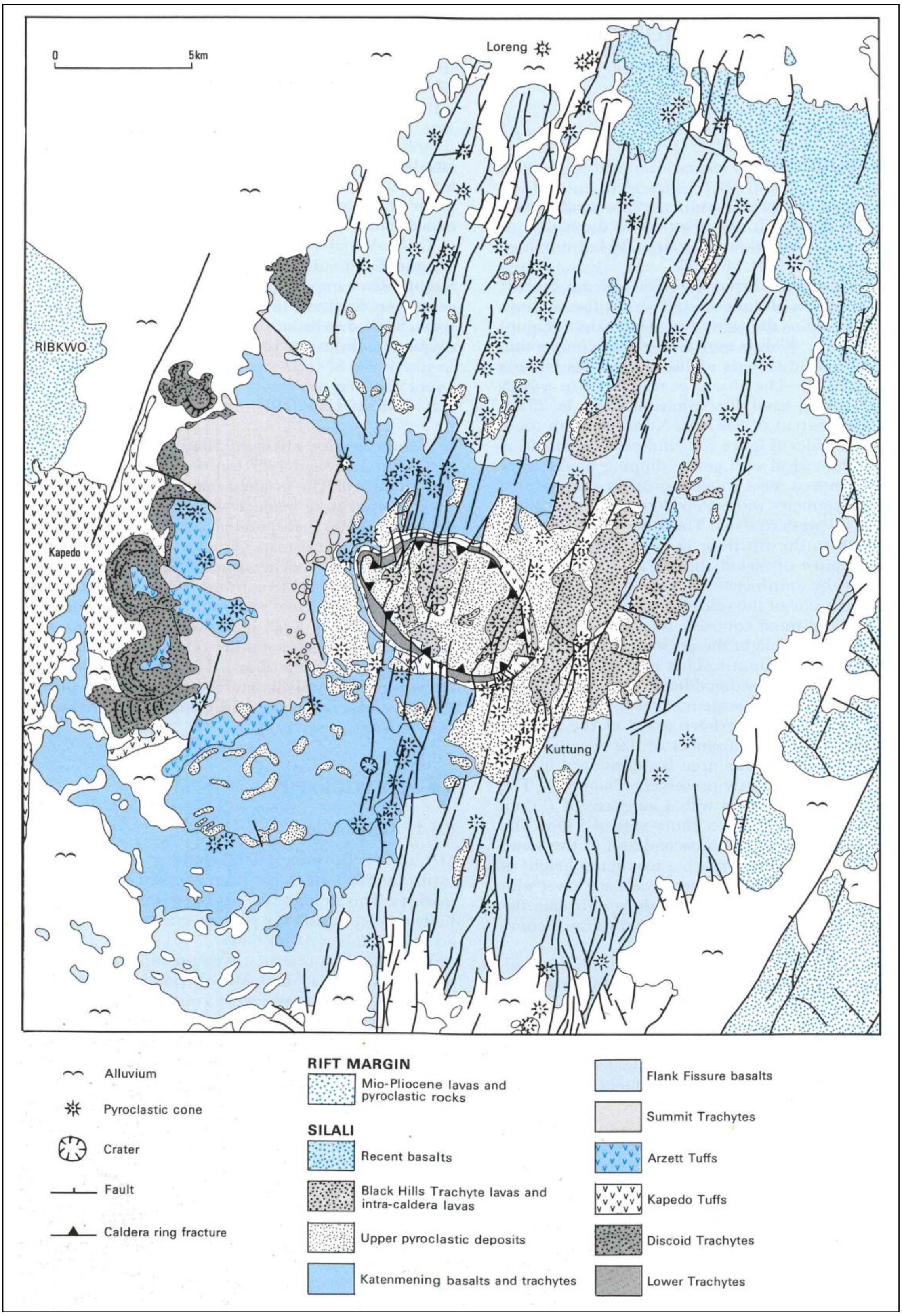


Figure 2.1: Simplified geological map of Silali basin, showing the basin's ring like structure and the fault lines cutting across the basin (adapted from Dunkley *et al.*, 1993). The dust blanket over Silali basin's wall is also visible on the map. Noting that the material making up the basin's wall is not uniform.

In some cases, caldera subsidence can cause ring structures similar to those found in Silali basin, due to doming effects. However, the same feature can also form as a result of an extra-terrestrial impact. When a heavenly body falls on an area, it causes the area rock to fracture in a concentric manner. The fractures are caused by hypervelocity shock waves, which usually radiate outwards from the impact point at speeds of 10km/s or more (Therriault *et al.*, 2002). Further outward pressure can produce distinctive shock deformation effects (shattering and fracturing) in large volumes of unmelted target rock (Melosh, 1989). Figure 2.2 illustrates how an extra-terrestrial impact results in concentric fracturing of rocks.

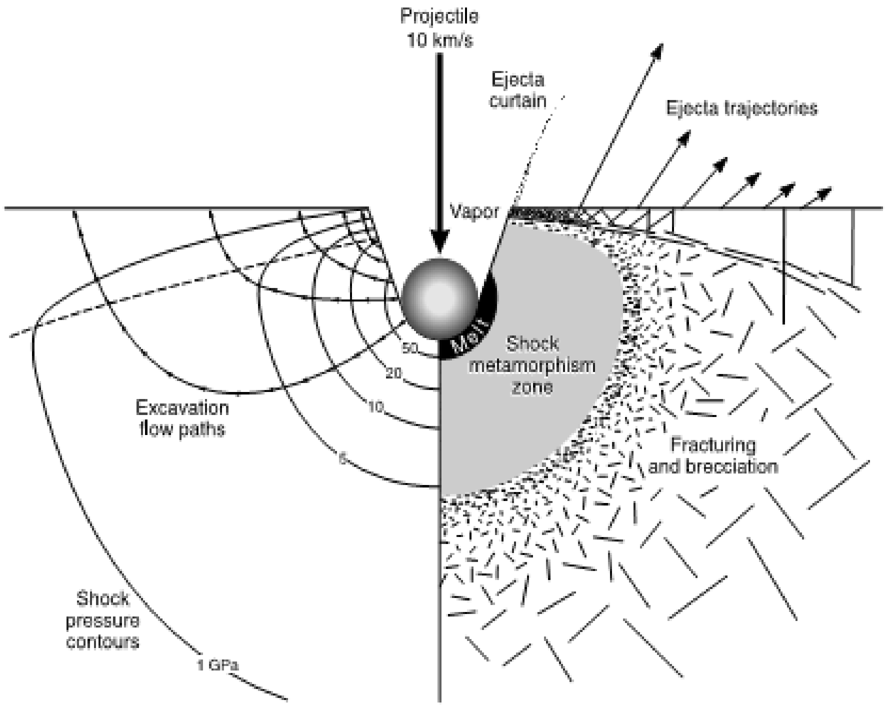


Figure 2.2: A cross section of an ETIC showing the effects of shockwaves on target rocks (shattering and fracturing). The figure was adopted from <u>www.lpi.usra.edu/publications</u>.

2.6 Silali Basin's Formation

According to Dunkley *et al.* (1993), Silali volcano was formed around 225ka and the caldera (crater or basin) collapsed around 66-62ka. As stated before, Silali basin is a basin within a larger basin (the outer basin) with smaller basins within it. In addition, there seems to have been impacts at different times in the area, the oldest being the one that formed the huge 'outer basin' and probably triggered the formation of a section of the Great Rift Valley, example the mid graben and the many spectacular geological features within and around it. The 'outer basin' is surrounded by the rugged Arzett hills to the northwest of Kapedo Town, towards Tiati. This is the basin in which the Suguta gorge, Suguta River and hot water falls, cross bedding slumps, sink holes, the shatter cones of Chemolingot and several breccias occur. Different volcanic rocks, prehistoric caves, some of the mentioned smaller craters, several swamps, hot springs, fumaroles and alluvial deposits are also found in this basin.

Previous studies by some scholars who carried out research in Silali basin came up with a proposition that there existed an earlier caldera before the present 'volcanic caldera'. According to Dunkley *et al.* (1993) the 'break off walls' (stepped walls) of Silali basin, mark the traces of an earlier caldera. The researchers suggested that the 'break off' wall features are not contemporaneous because they relate to different volcanic compositions. According to Williams *et al.* (1984), were these features indicative of a bonding within an early caldera, then some mechanism of topographic inversion is required (Williams *et al*,.1984).

Silali basin appears to have formed much earlier than the Great Rift Valley (66-62ka against 25-22ka), though the shield upon which it was formed may have formed way earlier, probably soon after the outer basin had formed, about 400-220ka, according to Smith *et al.* (1995).

Silali basin appears to have formed in three stages that include; a volcanic shield stage, an extra-terrestrial impact stage and a subsidence stage. Two of these stages are discussed below.

i) Volcanic Shield Stage

It is evident that there existed a volcanic shield that had built over many years by deposition of magma that emanated from a fissure. The shield seems to have been stretching in a north-south direction. According to Smith *et al.* (1995), Silali's volcano started forming 400-220ka. This included the formation of a low relief lava shield. Volcanic eruptions in Silali occurred during different times and some of the later ones, according to the authors, resulted in an inward collapse of the shield summit, owing to the lateral drainage of magma from beneath the volcanic shield. These are the eruptions that led to the formation of the caldera around 66-62ka (Smith *et al*., 1995 and Dunkley *et al*., 1993).

The existence of a volcanic shield in Silali before the ETIC formed is favored by the following incidences:

- The fact that Silali basin's wall is made up of volcanic materials placed in layers;
- The non-contemporaneous nature of the wall materials in terms of age and physical characteristics; and
- The 'break off' or stepped walls of Silali basin, which may be layers of different volcanic materials, bearing different strengths against denudation.

It is worthwhile to note that there is no massive lava deposition on the outer walls of Silali basin. Instead, the basin's outer walls are covered by a mixture of broken up rock materials (rough dust).

ii) Subsidence Stage

To be able to understand Silali's formation by subsidence, following a probable impact event, formation of calderas by subsidence should be looked into as discussed by other scholars.

According to Traver (2007), there are many theories that have been brought forward to explain caldera subsidence. These include:

a) The crater elevation theory

The crater elevation theory suggests the existence of massive lavas that accumulate on gentle slopes and are later arched to form high cones. The arching might produce wide tension fissures on the flanks of the cones and summit calderas. The theory was discarded after a few years.

b) The explosion theory

The theory states that large calderas are similar in origin to small craters, the difference being in size. Consequently, calderas form from decapitation of former cones and the deeper the explosion focus, the greater the volume of lithic debris from the sub volcanic basements. This theory was abandoned due to scarcity of such lithic debris in areas of caldera collapses.

c) The gas-coring theory

Eischer (1929) believed that if a large cylinder was drilled by an explosion, in sliding will occur forming a depression that can be many kilometers wide. In fact it has often been observed that slumping of the wall, both during and after volcanic eruptions, enlarges craters.

d) Sandberg’s ‘mantle pipe’ theory

This theory held that calderas and craters are formed in the same way. The argument rested in the assumption that the original conduits of volcanic cones are of caldera proportions and that as activity continues to diminish in intensity, the conduits decrease in size and calderas are slowly filled in.

e) Internal solution theory

According to this theory, volcanoes might enclose a large chamber of liquid lava which might grow larger as a consequence of melting of the chamber walls. As the magma remains inside the chamber, it would crystallize to form a resistant core that can be revealed by erosion. However, if lateral vents drained some of the magma from the chamber, the top solid shell might collapse to produce a caldera.

f) Wing Easton’s cell theory

The theory suggested that volcanic conduits tap magma from the magma chamber. After the first eruption, magma levels fall and gas pressure accumulates in the overlying space, till magma is again forced out. The process is repeated and a high cone is formed at the expense of a diminishing magma chamber. When the magma level falls below a certain threshold, the volcanic cone conduit is plugged by solid lava. The gas in the magma chamber is forced to escape through scattered fissures in the roof. The fissures widen and release magma that flows down the cone slopes. Finally, the upper part of the cone will be too heavy for the small magma chamber, hence collapses to form a caldera.

g) Collapse theories involving withdrawal of magmatic support

The theory stated that caldera collapse occurs due to the removal of magmatic support, occasioned mainly; by withdrawal of magma to the surface and injection of deep seated dykes. The removal of magma from a volcanic chamber leads to crustal subsidence and production of calderas.

These theories, except for the 'internal solution theory' which entails a volcano, suggest the existence of an active volcanic vent which does not exist in Silali basin.

As a volcanic shield, caldera formation by subsidence involving a volcanic pipe is not plausible. This is because subsidence would not be a quiet event and an explosion would most likely occur, pouring out magma onto Silali walls. One would then expect Silali to exhibit magma outpourings from its ring structure onto its flanks. This is not the case. Again, the collapse would not produce a perfectly ring structure unless there was an outline of a ring structure in existence.

Caldera subsidence occurs in various ways, such as through plate / piston subsidence, trap door subsidence, chaotic subsidence and downsag subsidence, among others. Plate or piston subsidence involves the subsidence of a coherent block of rock into a magma chamber that evacuates magma along a ring fault. The caldera floor may be variably faulted but the faults are less active than the ring faults (Traver, 2007). Trap door subsidence on the other hand, is subsidence that involves multiple collapse centers. It is a piecemeal subsidence. As for chaotic subsidence, wholesale disruption and brecciation of caldera floor rocks is involved. This generates low density materials which cause a caldera to register a low gravity signature. Finally, downsag subsidence occurs when ring faults either do not form or do not penetrate the ground surface so that summit material subsides by bending downwards.

Silali's subsidence may be said to be a plate or piston type of subsidence because the rock layers forming the basin's walls show continuous uniformity in material type and height. This is supported by observations made by Dunkley and team, that; the caldera

has a regular outline and vertical walls suggesting that it was formed by a piston like collapse (Dunkley *et al*., 1993). Unlike in the case of volcanic calderas, Silali's ring fracture was less active compared to the floor fractures, in magma emission. It is thus the crater floor fractures that evacuated most of the magma that may have been beneath the volcanic shield on which Silali basin was built. The lava flow to the northeast of Silali basin can be evidence of such an event. This is because it appears that the magma jetted off the base of the basin's wall. Notably the floor fractures of the basin extend outwards from the basin and not otherwise. The subsidence can also be termed chaotic because of the presence of brecciated rock on Silali's floor and walls, as discussed in Chapter Four.
A more apt subsidence theory for Silali basin is any theory that involves withdrawal of magmatic support hence collapse. All the theories mentioned above, entail the existence of a volcanic cone and presumably, a vent/ pipe/conduit. Silali's formation, as a volcanic shield or an ETIC, lacks these two and according to McCall and Hornung (1972), Silali volcano was built by clustered vents (not a central single vent or a volcanic pipe). An extra-terrestrial impact, consequently, provides a viable explanation on how Silali developed a crater, via impact and consequent subsidence.

Silali's subsidence can be said to be the factor behind the basin's stepped or 'break off' walls, because as subsidence occurred, the more resistant rocks of the basin's wall remained standing while the softer parts collapsed more and later got washed away by denudation. Denudation removed the softer rocks that made up the initial walls of the volcanic shield, forming scalloped areas, while resistant rocks, such as the young volcanic rocks making up the top most layer of Silali basin's wall, remained intact, forming the wall's protruding parts. There is a lot of evidence along the basin's wall, supporting subsidence and especially block/piston/plate subsidence. These include;

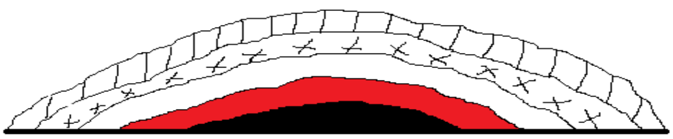
- The layers that make up Silali basin's wall are almost uniform and continuous around the basin and at the same height from the basin's floor (about 300m for the top most layer).
- The walls appear to have collapsed inwards, towards the basin. There is an appearance of 'turning inwards' on Silali basin's inner walls, which is different from the 'turning outwards' appearance of the basin's outer walls. Slumping has

modified the appearance of the basins inner walls, giving the walls a concave appearance.

Subsidence was possible for Silali basin because, after a probable extra-terrestrial impact, fractures formed around the basin, encouraged by pre-existing rock weaknesses, some of which built the Silali volcanic shield (400-200ka). The impact must have also widened the existing rock cracks, triggering the exit of magma from within the shield's magma chamber onto the areas around the basin. This should have formed some amount of emptiness beneath the impact basin, bringing about a collapse that left high stepped walls. There is evidence (in the form of brecciated and metamorphosed rocks on the crater walls) that hot gases and liquids hissed out of the crater chamber through the many fractures surrounding the crater. From the pictures and satellite images of the basin, presented in Chapter Four, one can clearly see volcanic cones around the basin. These were built by magma that outpoured from the impact area, forming part of the evidence of subsidence in Silali. The volcanic cones sitting on the basin's walls would be as old as the Silali volcanic shield.

The following simplified schematic diagrams can explain the formation of Silali basin, especially the volcanic shield and impact stages.

(i)



(ii)

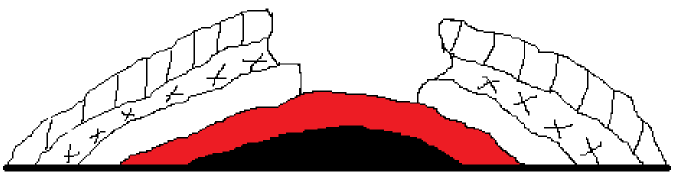


Figure 2.3: Schematic diagrams showing the formation of the Silali basin. (i) Represents the pre-impact volcanic shield. The shield is made up of different layers of volcanic rock. (ii) Represents the post impact volcanic shield (Source: Author, 2015).

As explained earlier, an extra-terrestrial impact could have created a crater at the center or near center area of the volcanic shield, opening up the volcanic shield to agents of erosion and weathering. These land remodeling processes caused the softer rocks of the basin's wall to be washed away, forming indented sections. The more resistant rocks, however, remained standing hence forming the protruding areas of Silali wall. Consequently, the basin's wall developed a stepped appearance while the basin's floor accumulated about 300 m thick sediments.

The LIDAR image below (Plate 2.2) shows fractures that are found within and around Silali basin. Some of the fractures may have existed beneath the Silali volcanic shield while others may have formed during the formation of the basin by a possible extra-terrestrial impact.

It is not possible to explicitly demonstrate the dynamics that led to the formation of Silali basin because direct evidence has long been covered up by sediments or distorted and changed by neotectonics. Some of Silali's distal ejecta and melt rock, for instance, may have been buried by lava and sediments.

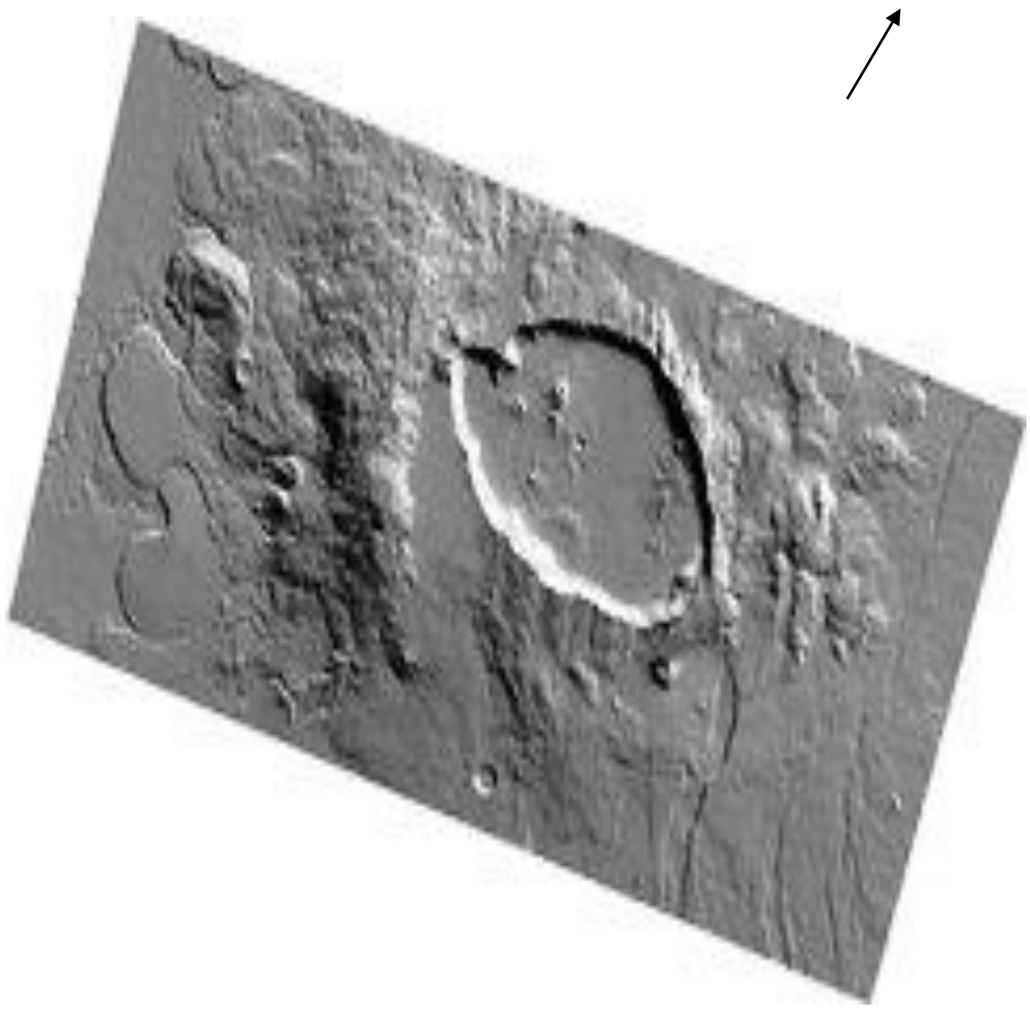


Plate 2.2: A LIDAR image showing the crater and the fault lines within and around it. (Source: GDC library).

The LIDAR image displays many aspects of the basin, besides the shape and the fault lines. It shows some of the volcanic cones and craters inside and outside the basin.

2.7 Theoretical Framework

Two theories have been used to support this study. The first one is the Extra-terrestrial Impact Hypothesis and the other is the Tragedy of the Anti-commons.

2.7.1 Extra-terrestrial Impact Hypothesis/ Younger Dryas Hypothesis

This has also been referred to as the Clovis Comet Hypothesis. It hypothesizes that a large airburst hit the earth or an object or objects from outer space impacted on the earth, about 12,900 years ago and initiated the Younger Dryas cold period. The theory further explains that, the air burst or impact of the earth by a swarm of carbonaceous chondrites or comet fragments, set areas of North America continent on fire. This led to the extinction of most of the megafauna in the region and the demise of North American Clovis culture (Llano culture). Llano culture is a prehistoric Paleo-Indian culture which entailed hunting of megafauna. The Younger Dryas period is believed to have lasted for about 1200 years before the climate warmed up again, following the last glacial period.

The swarm of chondrites or comet fragments is hypothesized to have exploded above or possibly on the Laurentide ice sheet, in the region of the great lakes, though no impact crater has yet been identified. The air burst would have been similar to the Tunguska event of 1908. It was proposed that animal and human life in North America, which was not directly killed by the blast or the resulting coast to coast wildfires, would have likely starved on the scorched surface of the continent. The evidence of this hypothesis is a carbon rich layer of soil that has been found at some 50 Clovis dated sites across North America. The layer contains Nanodiamonds, metallic micro spherules, carbon spherules, magnetic spherules, iridium, charcoal, soot and fullerenes (carbon molecules in the form of hollow spheres, ellipsoidal tubes or cage structures). All these evidence point to an extra-terrestrial impact event.

Recently, a 16 member team of international researchers identified a nearly 13,000 year old layer of thin dark sediment containing an exotic assemblage of materials including nanodiamonds, impact spherules and other components at Lake Cuitzeo in central Mexico (Firestone *et al.*, 2007). According to the researchers, these are elements that result from a cosmic body impacting on the earth. After a baton of tests, the researchers conclusively identified a family of nanodiamonds called *ionsdaleite,* which are associated with cosmic impact. The researchers also found spherules which had collided with other spherules at high velocities, probably during the impact and concluded that, a comet or an asteroid or most likely a large fragmented body that would have been hundreds of meters wide, entered the earth's atmosphere at a shallow angle. The heat of the impact burned biomass, melted surface rocks and caused major environmental disruption, hence mega fauna extinction, human and cultural change.

The sediment layer identified by the researchers was of the same age as that previously reported at numerous locations throughout North America, Europe, Greenland and Western Europe (Firestone *et al*., 2007).

According to the team, there are only two known continent wide layers of nanodiamonds, impact spherules and aciniform soot. These are in the 65 million year old cretaceous-paleogene boundary layer (K-T Boundary) that coincided with major extinctions of many large American animals, including the dinosaurs and ammonites and the 12,900 years old Younger Dryas boundary. The Younger Dryas boundary event that occurred 12,900 years ago, while being associated with extinction of animals, is closely associated with the extinction of many more North American large animals including the mammoths, mastodons, saber tooth cats and dire wolves (Firestone *et al*., 2007).

The timing of the 12,900 years ago impact event coincided with many extra ordinary biotic and environmental changes in North America, Europe and probably all around the world. It is on the basis of this background that this study examines the origin of the Silali basin and brings out a likelihood of it being the product of an extra- terrestrial impact. Evidence of Silali's past climate could have been attained from the pre-historic drawings and cave dwellings that are found to the south east of the basin, were it not for inaccessibility.

2.7.2 The Tragedy of the Anti-commons

The present case of Silali basin's existence and underutilization or non-utilization of the basin as an ETIC and consequently an environmental resource, can be explained by the 'Tragedy of the Anti-commons' theory.

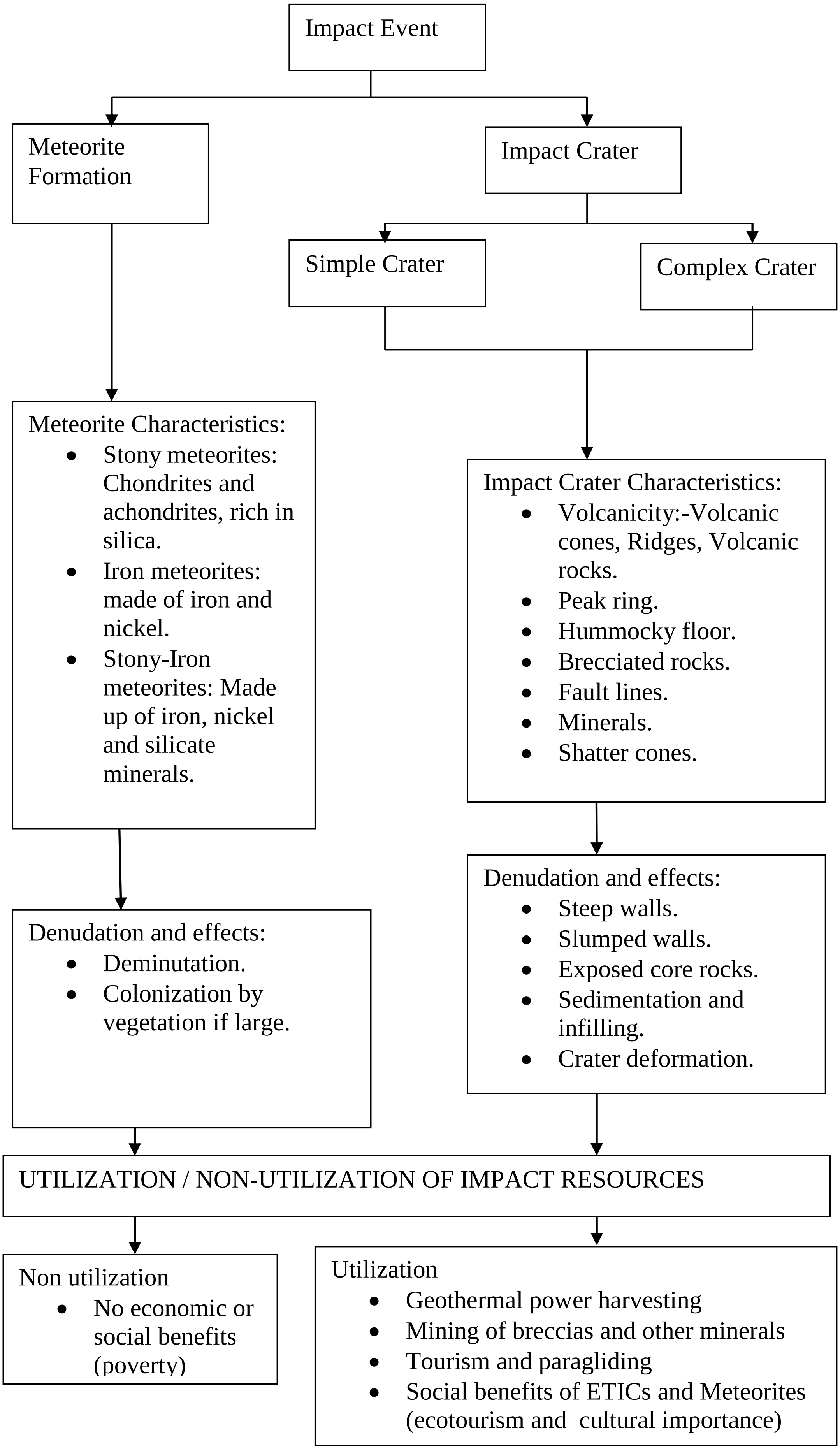
The 'Tragedy of the Anti-commons' is a theory that describes a situation whereby rational individuals, acting separately, collectively waste a given common resource by underutilizing it. It is the opposite of the 'Tragedy of the Commons' theory that was advanced by Garret Hardins (1968), which describes a situation whereby, individuals, acting separately, collectively over-utilize a certain common resource. A common resource in this case, is that which is owned by all and no one at the same time (communal resource).

The term 'Tragedy of the Anti-commons' was originally coined in a 1998 Harvard Law review article by Michael Heller. In a 1998 article in 'Science', Heller, alongside Rebecca Eisenberg, pointed to biomedicine as one of the key areas where competing patent rights could actually prevent useful and affordable products from reaching the market place. This is because, too many property rights can lead to too little innovation (www.sciencemag.org, 1st May 1998).

The freely existing resources in Kenya include in this case, the unknown ETICs, which Silali could be one. These common resources are untapped for their economic worth.

Kenyans may be acting individually in their 'non-utilization' of these resources but overall, the loss that accrues from their not using the resources is borne by all. For example national poverty may partially proliferate due to lack of interest in untapped tourist resources, including the ETICs. Some countries have discovered the tourism potential of ETICs. In the USA, a meteor crater located 69 km East of Flagsruff, near Winslow in northern Arizona desert (the Barringer crater) is a popular tourist attraction in the region. There is $15 entrance fee to see the crater, for adults (Winchester, 2006). The crater is owned privately by the Barringer family (http://en.wikipedia.org/wiki/meteor-crater).

2.8 Conceptual Framework



CHAPTER THREE

METHODS

To succinctly explain the origin of the Silali crater, the study has partially depended on observation and various pertinent sources of scientific information, which include: remote sensing, past geographical and geological studies, interviewing, field observation, photography and laboratory analysis.

For the study, the researcher employed Mixed Methods Design of research where qualitative (observation and interviews) together with quantitative (remote sensing, sampling and laboratory testing) research approaches were used to collect data. The nature of data that was needed was specific for the characterization of Silali basin and seeking evidence on the nature of its formation. Consequently, morphological data (shape of the crater, peak ring, slumping, ejecta spread and wall terraces), geological data (ETIC related geology), geomorphological data (ETIC related landforms) and sociological data (myths and importance of the basin to the locals) was sought.

The data sources that were available to the study included remote sensing, the internet and the local community. Remote sensing provided morphological data, geomorphological data and geological data and can be said to be the major research tool and research data source in the study. The internet provided literature on the study area and on extra-terrestrial impact cratering. The local people, on the other hand, supplied information on the origin of Silali basin (according to mythology), importance of the basin to the local community and the interaction of the basin's features.

Silali basin was sampled purposively as a study area. This is because of the uniqueness of the basin, the literature gap on the basin's formation and the researcher's interest in ETICs and the process that creates them. Rocks and soil were sampled randomly while interviewees were sampled by chance ('by chance' sampling), noting that at the time of the study, there were major security conflicts between the Turkana and the Pokot communities inhabiting the area of study. These caused the locals to hibernate and treat visitors suspiciously. The researcher, thus, interviewed any local that was chanced upon.

Data collection materials included a camera (working with a checklist), polythene papers, a small hammer, pens, labelling papers, tapes, ruler and a notebook. Data collection tools consisted of a checklist, laboratory testing, visual interpretation of satellite images, an aerial photo, analysis of pictures and analysis of geophysical data besides terrain analysis through the use of a GIS software (Global Mapper) and drawing of cross sections.

Data analysis involved the use of a GIS software to draw a DEM, drawing of cross sections using a computer and free hand drawing, visual analysis of remote sensing and geophysical data, interpretation of laboratory testing results and analysis of existing literature. Finally, the research findings have constituted this thesis and have yielded some publications. The research findings will also be presented in research conferences.

In the thesis, research findings have been presented in the form of satellite images, an aerial photograph, pictures, charts, tables and discussions.

Generally, several research methods and tools were used to acquire data for the study. These include the use of:

3.1 Remote Sensing

Although remotely sensed images cannot adequately replace the usual sources of information concerning the environment, they can provide valuable supplements to the field data, by revealing broad scale patterns that are not easily recognizable on the surface.

As stated earlier, many ETICs are not recognizable from the earth's surface perspective because they are megascopic. In addition, a large proportion of them are quite old and have been deformed by physical processes such as erosion, denudation and plate tectonics. Geological processes can interfere with evidence on the formation of ETICs and their related features, making them hard to recognize on the earth's surface.
For the current work, remote sensing products which include satellite images, an aerial photograph and pictures, were variously used to:

i) Explain how impact craters are located and recognized on the earth's surface, using morphological characteristics.

ii) Reveal details about the Silali basin, for instance its size, shape and associated features.

iii) Identify the general topography of the area where Silali crater is found and the alignment of rock formations in the area and

iv) Provide images and pictures of the basin, its related features and the surroundings.

Natural and false color satellite images (Landsat, SPOT, GeoEye and ASTER images) were important and useful in this study because of their high resolution and clarity in the appearance of the features on the earth's surface.

Hand camera ground pictures of features around and within the Silali basin were also acquired. First, these were a means of data collection but were used to record and present whatever information was collected. A substantial number of ground pictures form a crucial part of this study, as sources of evidence regarding the formation of the Silali basin and the basin's ETIC characteristics.

An aerial photograph was used to confirm features found in some of the satellite images. It provided an important means of data comparison.

3.2 Interviews

Qualitative research interview was used to obtain the understanding of the people, living in the proximity, about Silali basin's existence and any folklore that has been passed on through generations with regard to its formation. The area residents clearly described the existence and operation of some of the geographical features found within and around the Silali basin, such as the operation of the hot water falls, the existence of warm grounds (fumaroles) in the basin and the life of the Pokot families that live within the crater.

Exploratory interviews were also tactfully conducted in the area of study to seek the local people's understanding about the basin's importance, noting that the area is a social hot spot.

The questions that were used for the interviews were compiled (see sample in Appendix I) while others were asked directly, as follow up to previous ones, when it was deemed appropriate by the researcher. As stated earlier, the interviewees were sampled through a 'by chance' kind of sampling; wherever they were found, whenever they were found, which was actually by chance because of the insecurity that prevailed in the area.

3.3 Observation

The researcher visited the Silali area, to observe the nature of the basin, its environs and associated features. The observation that was done in this study was mostly non-participatory. It involved taking into consideration the observations made by field guides on the observable features of the basin. In addition, rock and soil samples were collected for chemical analysis. Pictures of the rock samples, rock formations in the study area and associated features were taken.

3.4 Sampling

In this study, probability sampling was done. This is because it gave each area of the field a chance (greater than zero) to be sampled, or to be selected as a site for collecting a sample. Probability sampling, in itself, can apply systematic and stratified sampling but for bias to be avoided, simple random sampling (SRS) was done. This ensured that no area was missed out on the basis of a certain criteria, as it is in systematic and stratified sampling. SRS was also applied in the 'by chance' sampling of interviewees. Samples that were collected from the field included:-

- Rocks that were collected within and around the basin.
- Soil samples.
- Other specimens that were of interest, such as the broken up obsidian rock particles.

Samples were also collected from the area outside the basin (the outer basin) as well as the Silali basin or crater itself. A rock sample was collected from the Kiptabar hill. Kiptabar hill is a suspect meteorite whose scope does not fit into the study at hand.

3.5 Laboratory Testing

Laboratory testing was essentially carried out to establish the chemical composition of rock samples collected from within and around the basin, with the aim of finding out whether the rocks from the area of study bore mineral elements and mineral formations that are associated with ETICs. The mineral elements of interest included; Silicon Oxide (SiO_2), Aluminum Oxide (Al_2O_3), Sulphur Oxide (SO_3) and Iron Oxide (Fe_2O_3) - among others. The mineral formations that were of interest included; high pressure mineral polymorphs, PDFs, silica and siderophile elements. The chemical composition of the rock (homogenous rock) that makes up Kiptabar hill was also assessed.

Laboratory tests were not carried out to determine Silali basin's age because this had previously been reported to be about 62-62ka (Smith *et al*., 1995 and Dunkley *et al*., 1993). Ages of most of the ETICs on the earth's surface are known thus, it is necessary to also document the age of Silali basin, because there is a coincidence between the ages of Hypervelocity Impacts (HVIs) crater formation and major events on the earth's surface. Impact cratering is closely associated with instantaneous drastic environmental change.
(http://jgs.geoscienceworld.org/cgi/content/abstract/164/5/923/).

Identification of the chemical components of the rocks around or within the basin, together with the chemical composition of the Kiptabar hill, is important since this will provide useful information on the mineral potential of the basin and the hill, for economic purposes.

3.6 Use of Geophysical data

Geophysical data was used to determine the gravity signature of the Silali basin and to ascertain whether the basin is actually an ETIC. ETICs are expected to register low gravity readings because of the factors stated earlier, for instance brecciation and target rock fracturing and shattering (Pillington and Grieve 1992).

Besides the Basin's gravity signature, the magnetic signature, seismic signature and the electric signature of Silali basin were also investigated, because they are all part of the geophysics of the crater.

Due to the fact that geophysical data is very expensive to acquire, secondary data sources were relied on. Consequently, Silali basin's geophysical data was deduced from a geophysical study of the area that was carried out by Lichoro (2013). The results are presented in Chapter Four of this thesis.

3.7 Terrain Analysis

Terrain analysis of the area of study was done through the drawing of topographic sections of the area and the drawing of a Digital Elevation Model (DEM) of the basin. The topographical sections of Silali basin were drawn using a computer and by free hand. However, the sections (cross-sections) were all drawn from the topographical maps of the area; the map of Kapedo (77/3) and the map of Nakali (77/4) - maps of Kenya. Figure 4.1 shows a topographical section of the Silali basin and the 'outer basin' that was drawn with the aid of a computer. Hand drawn topographical sections/cross sections of Silali area are found in the appendix section of this thesis (Appendix III).

Global mapper GIS software was used to create a DEM of the Silali basin (Plate 4.18).

3.8 Ethical Considerations

Kombo and Tromp (2006) argue that researchers whose subjects are people or animals must consider the conduct of their research and give attention to the ethical issues associated with carrying out their research. Ethical issues such as confidentiality, responsibility, informed consent, honesty and openness in dealing with other researchers and research subjects, physical and psychological protection and explanation of the purpose of the study and 'de-briefing' subjects afterwards should therefore be considered. The rights of informants or participants in this study were protected by all means. The principle of voluntary participation was encouraged and participants were by no way coerced into participating in the study. Participants in the study first consented to participation after being fully informed about the procedures to be taken in the study. Those participating in the study were not put into a situation where they would be at risk of harm as a result of participating. Harm can be defined as physical, psychological and emotional stressful situation. The researcher guaranteed the informants confidentiality. Anonymity of the participants was maintained by asking them not to disclose their names in whatever part of the research that they participated in. They were also assured that the information provided would not be made available to anyone who was not directly involved in the study. These are the ethical considerations that were applied when interviews were conducted; bearing in mind that Silali basin is an area prone to frequent cattle rustling between the Pokot and the Turkana communities that 'own' it and who named it Silale and Silali, respectively .

CHAPTER FOUR

RESULTS AND DISCUSSION

Chapter Four presents the study findings in accordance to the research objectives. Evidence on the nature of Silali basin's formation is outlined in this chapter, besides the basin's morphology and related features. The effect of Silali's impact cratering in the physical and human environment of the area is also discussed in the chapter.

4.1 Silali's ETIC Characteristics

Silali basin may qualify to be an ETIC because of the following ETIC characteristics or evidence:-

4.1.1 Morphological Evidence/ Characteristics

The basic shape of an impact structure is a circular or near circular depression with an upraised rim, though other crater details may vary with the crater's diameter. With an increased diameter, impact structures become shallower and develop complex rims and floors (Therriault *et al*., 2002). The Silali crater has a near circular shape as shown by the various satellite images presented in this thesis. The topographical maps in the appendix of this thesis, together with the DEM and the LIDAR image of the study area, also show the near circular lithological structure of the Silali basin. Like stated earlier, Silali's near circular shape is a product of remodeling of the original crater shape by various geological processes. These processes, as mentioned earlier, include subsidence, plate tectonic movements, erosion and sedimentation. Further, the Silali crater can be classified as a complex crater, because of its hummocky floor, or a basin, because its diameter is above 4 km (it is 5-8 km). Silali's floor is hummocky/ lumpy, as shown by the satellite images presented in this thesis. The crater floor contains small craters, volcanic cones and ridges besides slumped rock materials. Silali basin does not display a clear peak ring but there is an outline of a peak ring as shown by Plate 4.24. The original peak ring may have been distorted by the basin's collapse, faulting, erosion and volcanicity. Faulting and volcanicity are not uncommon to impact cratering. These processes though, have not only re-shaped the basin but have made its origin quite complex.

A Spot image of the area that can be viewed from Google maps, shows the Silali basin to be circular as it is in the Landsat images. However, in the Spot image (for example Plate 4.7), the basin's walls appear to be very steep and five mini craters are clearly visible within the main crater. Also evident are cones that look like volcanoes, within the basin. Ground truthing has placed the number of the mini craters at 5 and 2 cones with summit craters on them. There is a possibility that the cratering that led to the formation of the Silali basin may have triggered a spate of volcanicity within the main crater and around it. There is also another possibility that the area may have been hit more than once by extra-terrestrial bodies, as it happened to Arounga crater in Chad. Multiple impact cratering, in Silali, is suggested by the presence of minor craters within the basin and around it, together with the fact that the Silali basin appears to be a basin formation within another basin (Plates 4.4, 4.5, and 4.6). The outer basin covers the area around the crater walls and it is as near circular as the Silali basin itself, going all around Silali. It is covered by alluvial material and volcanic flows in many places. It is the basin that bears the Suguta River and on the satellite images, it appears as the dark and bright circular area around the Silali basin. Unfortunately, multiple impact cratering of the Silali basin is not a target of this study. The image below (Plate 4.1) shows one of the mini craters within the Silali basin.

Plate 4.1: A SPOT satellite image showing one of the smaller craters (mini craters) found within the Silali basin, adapted from Google Earth maps.

The mini craters, as stated, are about five in total and are circular, just like the one shown by Plate 4.1. The wall of the small crater shown is rocky and steep. The floor is flat and hummocky.

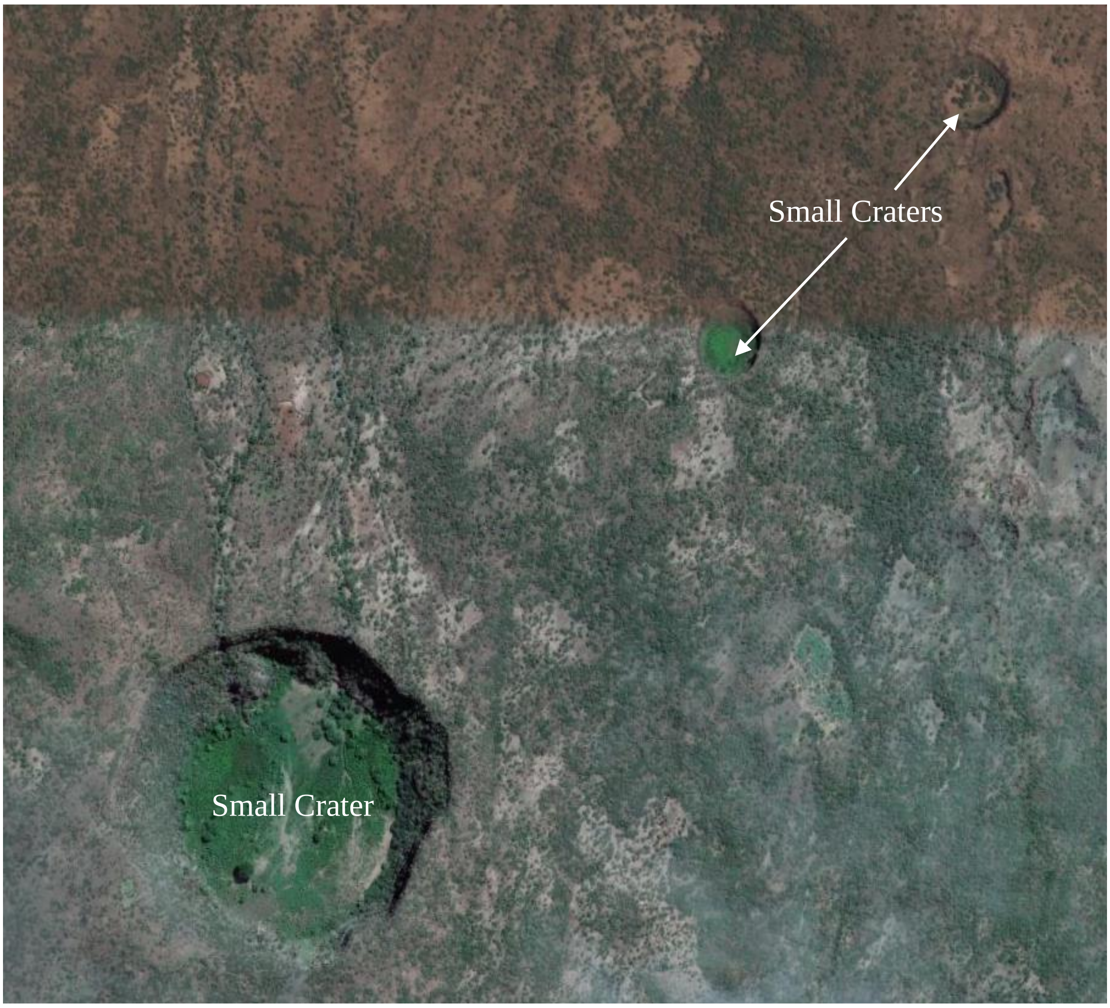


Plate 4.2: A GeoEye / SPOT satellite (natural color) image showing some of the small craters found outside the Silali basin (www.Google.com).

The three craters shown on Plate 4.2 are found to the southwest of Silali basin. Like the ones inside the main crater, these three have very steep walls. Their floors are also flat and two craters appear to have swamps, as evidenced by the lush green floor vegetation. There are also small seasonal streams running into the two craters, an indication that rain water collects in the craters. The image also shows numerous shallow circular craters around the three prominent craters and all may have formed through an impact event. The walls of the larger crater appear to be very steep. This may be attributed to works of erosion and slumping.

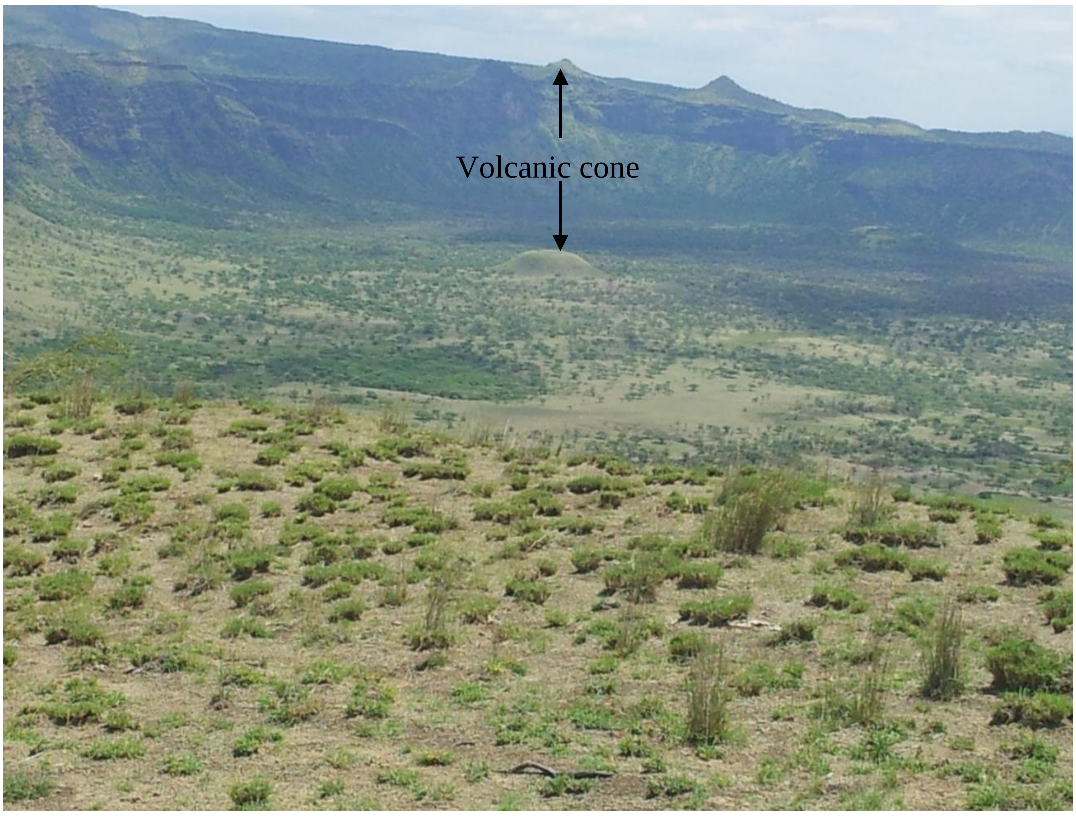


Plate 4.3: A picture showing one of the cones found on the Silali basin's floor (Source: Author, 2015).

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The cone on Plate 4.3 is volcanic and it is the most prominent cone within the basin. As mentioned elsewhere, there are cones right on the wall of the basin and outside it. These cones may have been part of the Silali volcanic shield; the shield upon which the Silali basin formed.

Looking at a satellite image of Kenya, Silali area appears to have many craters besides the Silali basin itself. The majority of the craters are smaller than Silali basin in size and are found outside the Silali basin, on the outer basin's floor, with a few inside Silali basin itself. Some of these basins are occupied by vegetation while others are extremely rocky. Incidentally, all the small craters, in and around the Silali basin/depression, are circular. This supports the suggestion being propagated by this study that the Silali basin, the ‘outer basin’ and the craters within and around it may all be products of impact cratering.

The following satellite images (Plates 4.4 - 4.5) show the shape of the Silali basin and some of the associated topography and physical features, a few of which are discussed more in this chapter.

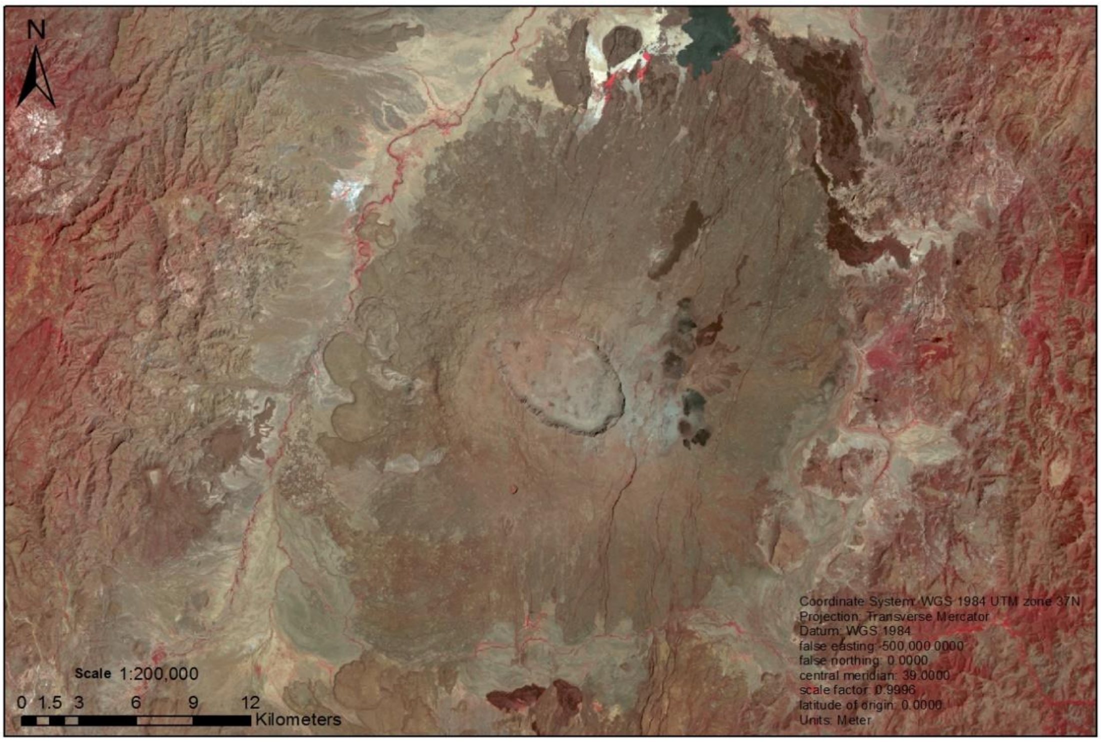


Plate 4.4: A false color image of Landsat 8, bands 5 (Red), 4 (Green) and 2 (Blue), showing the Silali basin (courtesy of RCMRD).

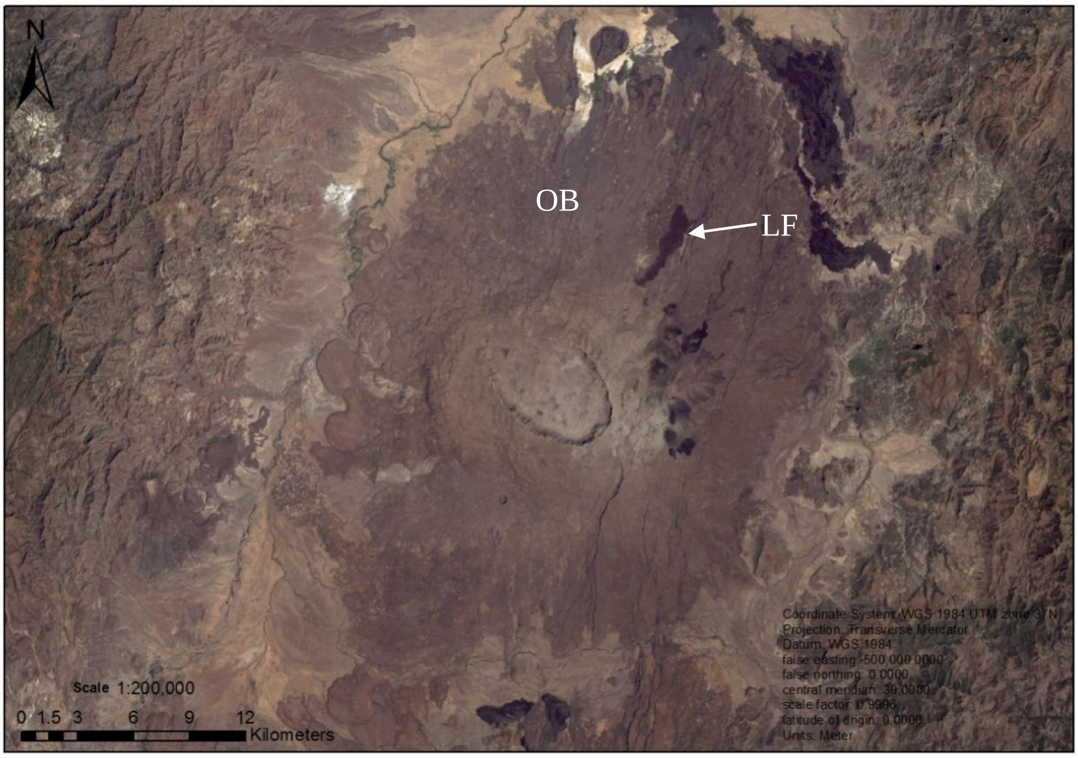
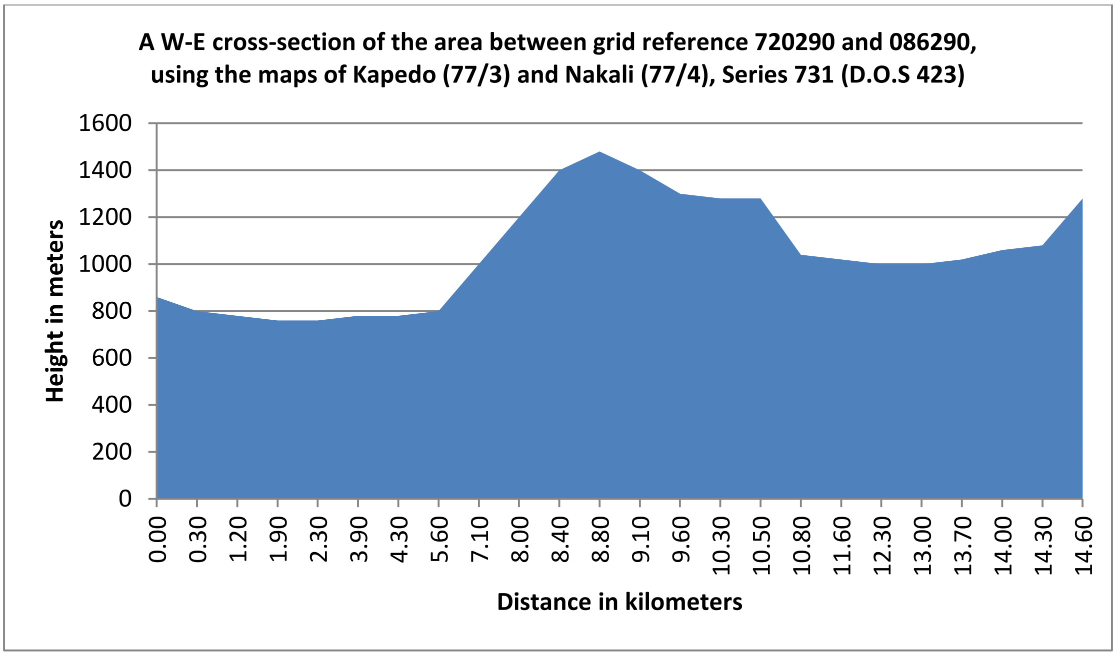


Plate 4.5: A natural color image of Landsat 8, bands 4 (Red), 3 (Green) and 2 (Blue), showing the Silali basin (courtesy of RCMRD).

The dark volcanic rock surface of sections of the outer basin (OB), can be seen on Plate 4.5, as labeled. The young lava flows (LF) to the east of the basin can also be seen from the plate and they appear to start right at the base of the Silali basin's wall.

Plate 4.6: A natural color SPOT satellite image showing the Silali crater, Marigat-Kapedo road (yellow), Suguta River (characterized by whitish sediments) and the outer basin around Silali. (A) is the Silali crater, (B) are the almost circular walls that surround the crater and (C) is the outer basin surrounding the crater. The hot springs feeding the Suguta River can be seen as white patches extending from the base of the basin's wall towards the river, westwards of the basin. Plate 4.6 was adapted from Google maps.

Figure 4.1, shows a morphological section of Silali basin and the outer basin. The section was drawn using the topographical maps of Kapedo and Nakali, which were acquired from the Survey of Kenya office (Appendix III). Similar hand drawn morphological sections or cross sections of the basin are available in Appendix V.



A | B
(720290) | (086290)

Vertical scale = 1 cm represents 200 m

Horizontal scale = 1 cm represents 2.5 km

Figure 4.1: A morphological section of the outer basin and Silali basin (Source: Author, 2015).

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From the morphological section, it appears that the outer basin's floor to the east of Silali is higher than the floor to the west of Silali. This is possible because of the recent lava flows covering the area. As stated elsewhere in this study, much of the magma that exited from Silali basin, before subsidence, appears to have poured out more to the east of the basin than to the west. The lava flows are very evident from the satellite images presented in this thesis.

Plate 4.7: A natural color SPOT satellite image showing the Silali crater. The image was adapted from Google maps.

Plate 4.7 shows the basin's raised walls, the small craters, the ridge and the volcanic cones found inside Silali basin. A crude outline of Silali's peak ring feature can also be seen from the image, at a close look. Plate 4.24 shows the peak ring more clearly. The ring feature is characterized by the ridges that are broken in places.

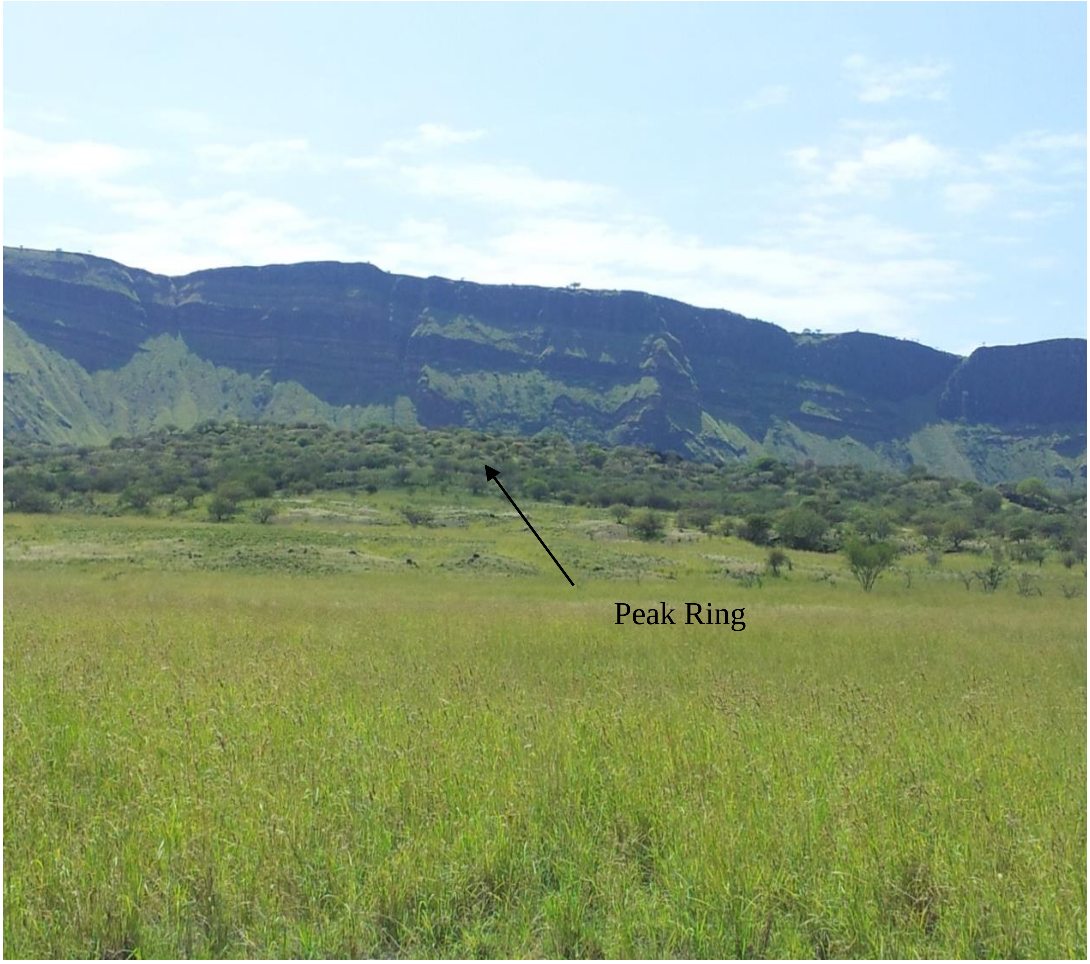

Plate 4.8: A picture showing Silali basin's stepped eastern wall (Source: Author, 2015).

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The steep stepped walls of the basin are visible on Plate 4.8. The thick acacia vegetation found right at the base of the wall is also seen more clearly, just like the thick barbed grass on the flatter areas of the basin's floor. A longer section of Silali's probable peak ring is also visible on Plate 4.8.

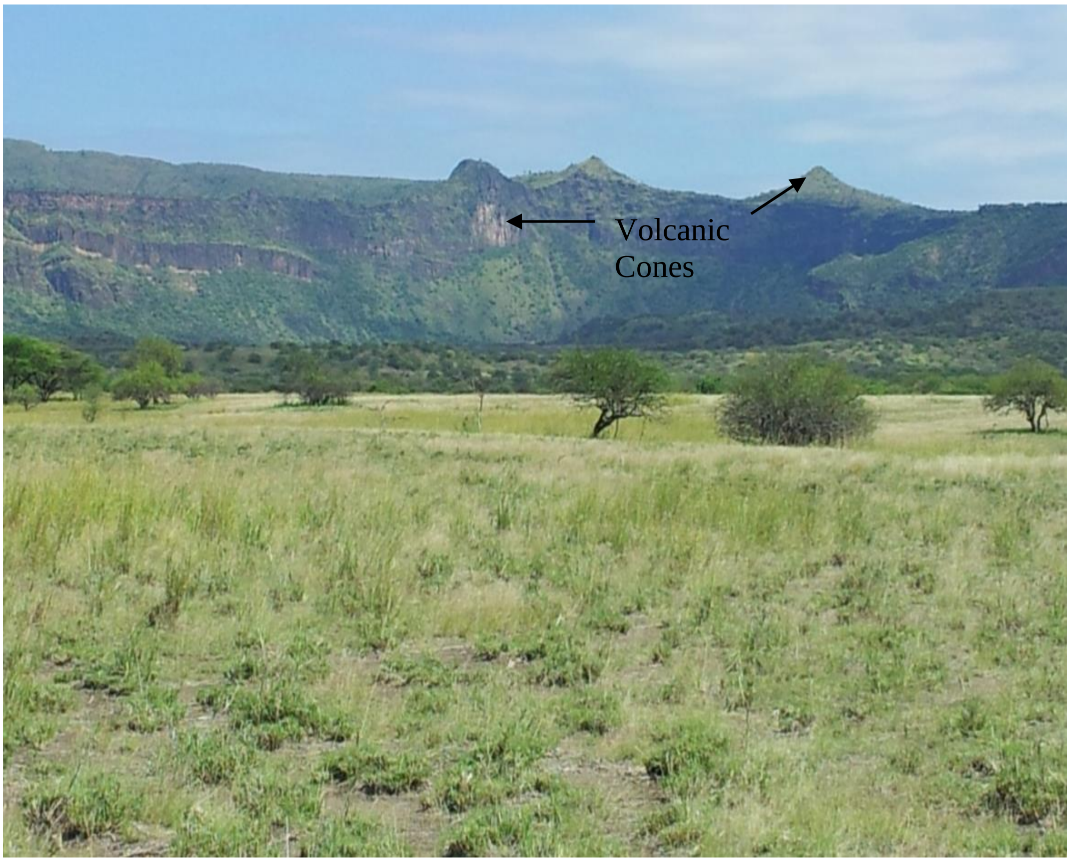

Plate 4.9: A picture showing the western walls of Silali basin, which appear whitish in color, because they are rich in breccias (Source: Author, 2015).

The image also features volcanic cones that have been split into half by the basin's wall. They may have been a part of the blasted volcanic shield. An intact cone, though, is visible further to the west of the crater, as labeled.

Plate 4.10: An aerial photograph showing a section of the western wall of the Silali basin (Survey of Kenya).

The aerial photograph, taken in 1975 by the Directorate of Overseas Survey (D.O.S), shows Silali basin’s steep and rugged wall, a section of the ridges inside the basin, volcanic cones both inside and outside the basin and fault lines. The photograph also shows lava flows to the west of the basin more clearly.

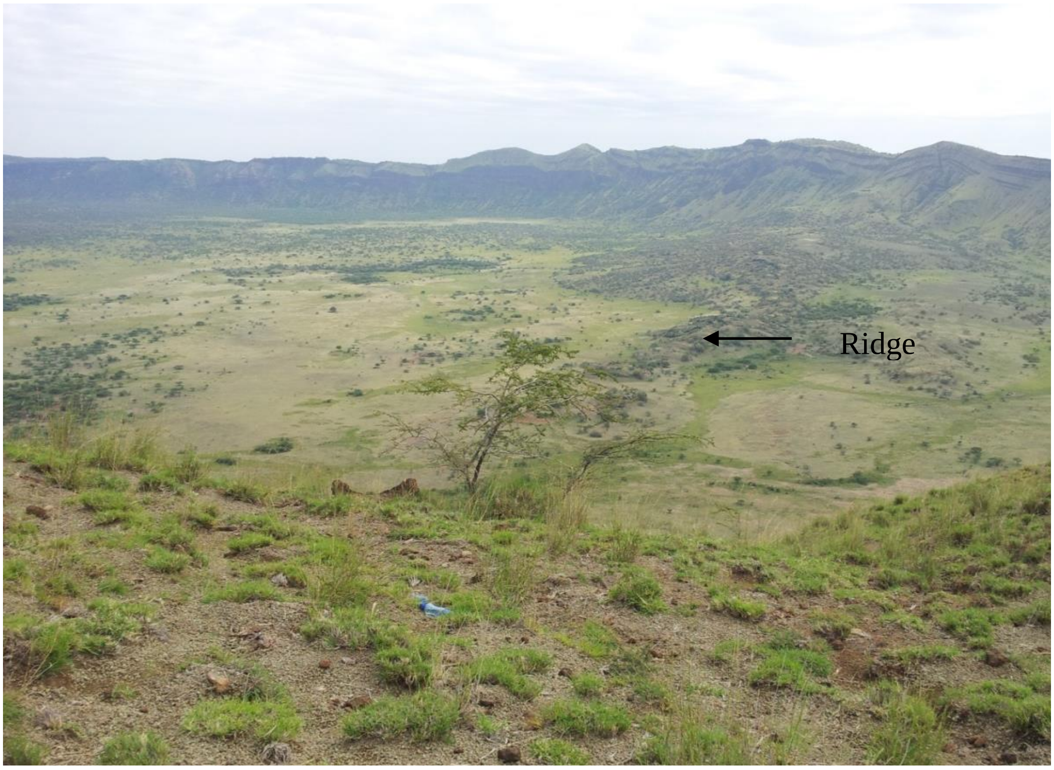

Plate 4.11: A picture showing Silali basin's northern wall (Source: Author, 2015).

A ridge lies on the eastern part of the crater. The ridge runs in a southeast-northeast direction but appears to be part of a broken ridge loop (peak ring feature) that is found on the basin's floor. The stepped walls of the crater are also visible on the plate.

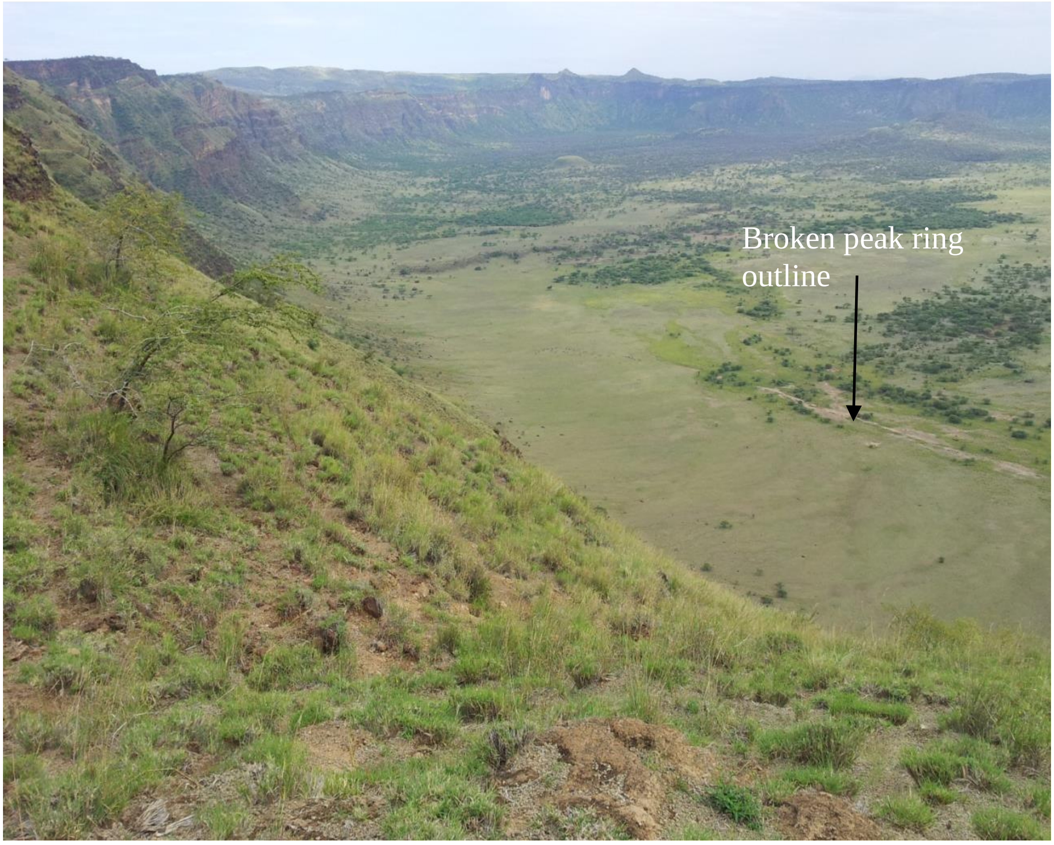

Plate 4.12: A picture showing Silali basin's southern walls (Source: Author, 2015).

The prominent volcanic cone on the floor of the Silali basin (shown on Plate 4.3) and the volcanic cones on the western shoulder of the basin are seen on Plate 4.12, alongside the basin's steep stepped walls. The outline of the basin's probable peak ring is also seen on this photo, though as a broken portion.

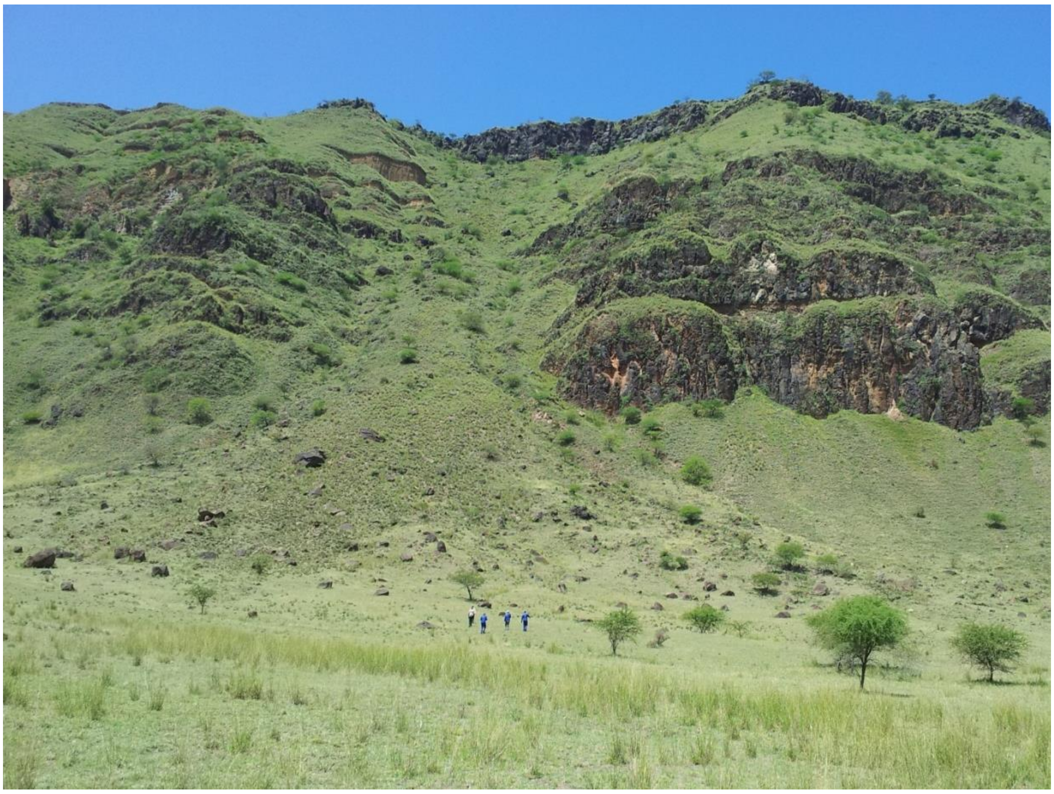

Plate 4.13: A section of Silali basin's wall that is both stepped and slumped (Source: Author, 2015).

Plate 4.13 shows the height of the basin's wall against an average human height. The field team members appear quite small at the foot of the basin's wall, seen against the wall. The picture also captures a slumped section of the wall and gives a clearer view of the wall's steps. The slumping may be an indication that Silali basin may still be in the process of subsiding, especially following the release of hot gases and steam from the basin's magma chamber.

From ground truthing, Silali basin's wall is stepped all around, though irregularly and this is ingrained in the basin's formation, as explained in Chapter Two. The basin's wall is also slumped all around, as can be seen in the ground pictures presented above (Plates 4.8, 4.9, 4.11 and 4.12). Notably, the basin's wall is extremely steep, as can be deduced from the aerial photograph and the ground photographs, especially Plate 4.13. The rim of the wall is estimated at 300 m above the crater floor, as indicated by Plate 4.18 (DEM), the cross-sections and older texts.

Plate 4.14: A picture showing a section of Silali's steep walls (Source: Author, 2015).

The steps on Silali basin's wall are seen on Plate 4.14. Any irregularity on the continuity of the steps on the basin's wall can be attributed to deformation by tectonic as well as denudation forces. Notably, the upper parts of the basin's wall are very steep while the lower parts are gentler, as modified by slumping. This is a typical ETIC characteristic though it can also be attributed to normal slumping processes, caused by the force of gravity acting on steep slopes.

Plate 4.15: A picture showing a section of Silali basin's flat floor (Source: Author, 2015).

The basin's floor is relatively flat, especially near the foot of the wall, before one reaches the wall of the basin's possible peak ring and the rest of the central hummocky floor. Plate 4.15 shows this.

The Silali basin has been said to be nearly circular, in this discussion, because its circular shape appears broken to the North-West, giving the crater an incomplete heart shape, as it appears on the satellite images (Plates 4.4, 4.5, 4.6 and 4.7). Landslides and other geological processes, such as volcanicity and tectonic movements, are responsible for the disfiguration of the Silali basin. Most sections of the basin's wall are characterized by step/terrace like features, as mentioned earlier. These appear to have formed during the crater formation, as explained in Chapter Two and shown by Figure 2.3 (the schematic diagrams showing the formation of the Silali basin). On observation, the basin's walls, in some places, are relatively higher than the 300m, given as the general height of Silali basin's rim from its floor. Incidentally, the Silali complex does not appear like a volcano *per se* because the basin does not sit on a distinctive edifice as shown by Plate 4.60.

Between Silali basin and Kapedo Town, lies the Suguta River, to the west. The river has various names upstream, for instance in East Pokot, it is called River Kinyang, around Kinyang and Amaya areas. Interestingly, the river appears to lie within a fault line and is characterized by hot water falls near Kapedo Town. The falls are fed by hot water springs on the Eastern plains, between the river and the Silali basin, which is part of the wider basin, or the 'outer basin'. Photographs of the Suguta River Valley, the hot water falls and the hot water springs are presented as part of ETIC associated features in this chapter.

Plate 4.16, summarizes some of the features found on the floor of the Silali basin. An ASTER satellite image has also been presented in this chapter, to show the circular morphology of the basin, for comparison purposes. It is the same near circular morphology that is confirmed by the DEM (Plate 4.18).

Besides showing Silali basin's appearance, the ASTER image also shows the smaller craters and volcanic cones within and around Silali basin, the different kinds of rock that make up the basin's walls, the fault lines that are found around Silali basin, among other features that are discussed under various sub headings in this study.

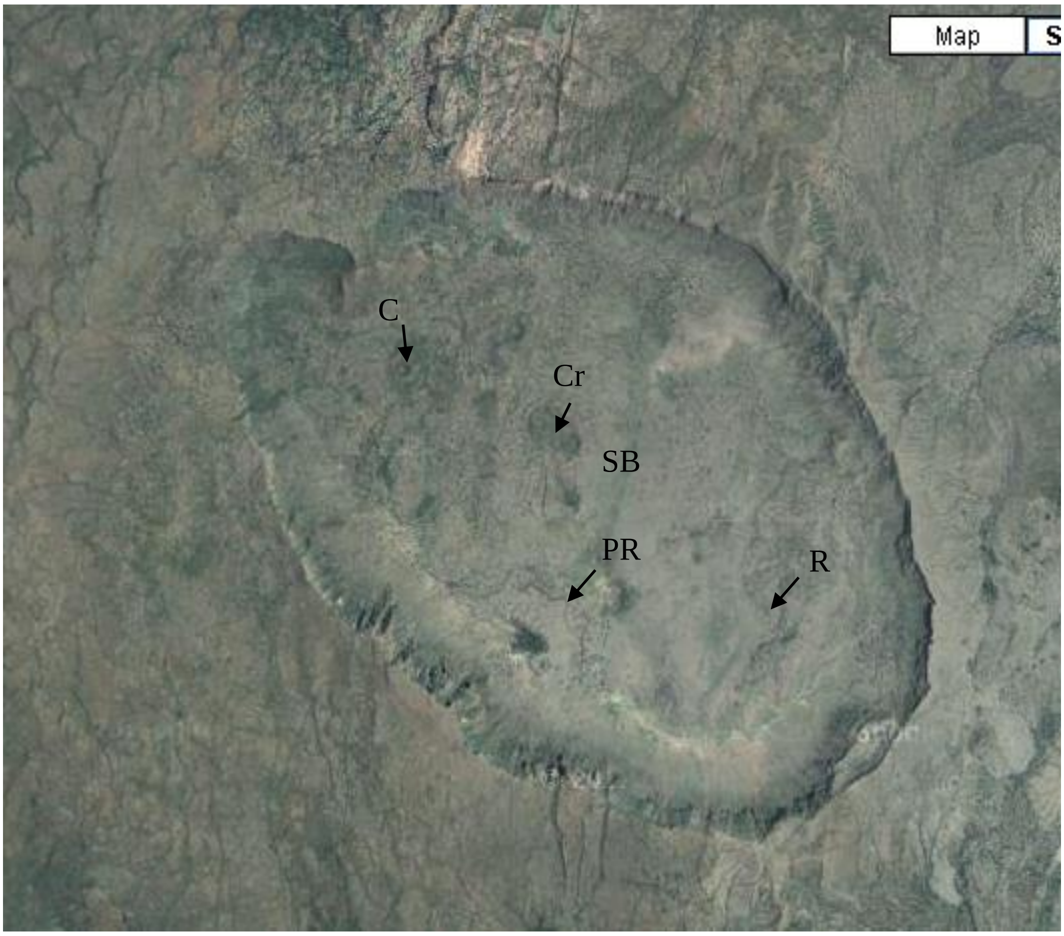

Plate 4.16: Natural color SPOT image showing Silali basin's (SB) hummocky floor (modified from www. Google.com).

From Plate 4.16, the volcanic cones (C), ridges (R) and mini craters (Cr) on the floor of the Silali basin are evident. Similarly, one can also see the outline of the basin's probable broken peak ring (PR) and the steps on the basin's wall from the image.

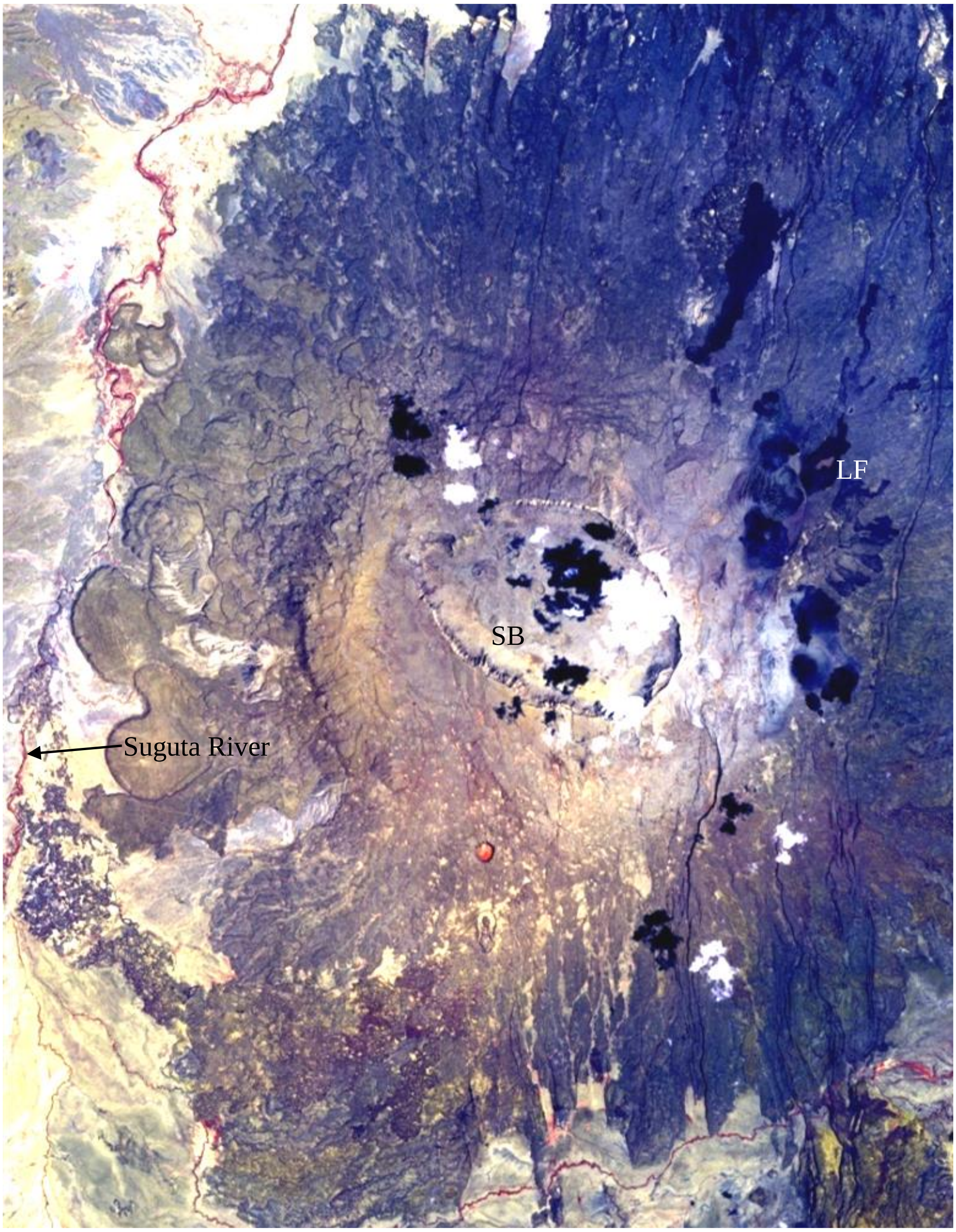

Plate 4.17: An ASTER false color satellite image of Silali Basin (SB) showing lava flow (LF) and some of the smaller craters around the basin; courtesy of Potsdam University.

The ASTER satellite image is in bands VIRN (Very near Infrared) 3N, 2 and 1 (GBR-RGB) of image 23 from NASA. It clearly shows the Suguta River to the west of the Silali basin.

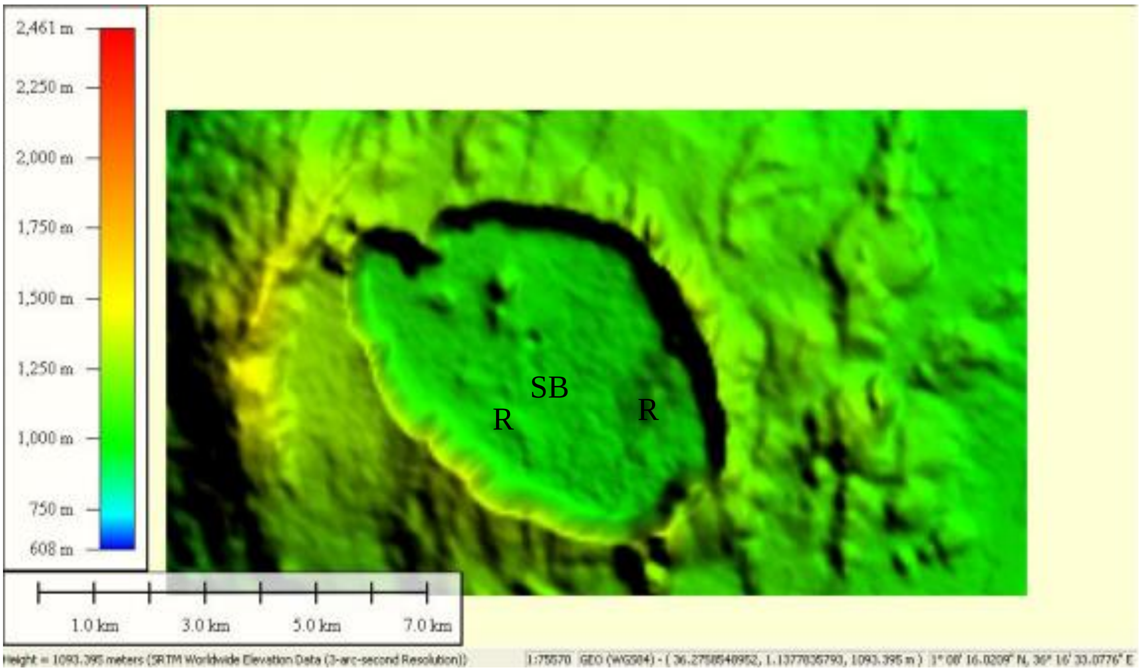

Plate 4.18 A DEM (with elevations) showing Silali basin's (SB) hummocky terrain and morphology. The DEM also shows the outline of Silali's probable peak ring (R) (Source: Author, 2015).

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A DEM represents an array of elevation points. It has been used in this research to show the morphology of the Silali basin and the height of the basin's walls. From the DEM, the height of Silali's walls is almost uniform from the basin's floor. The general height appears to be 300 m (1250 m less 1050 m) above the basin's floor. The north-western walls though appear slightly higher, even from observation, because of the presence of cones in the region. The volcanic cones on the basin's wall were probably formed during the volcanic shield stage by related fissures. Some of the craters outside the basin, however, may have been formed during the subsidence period, when magma exited the basin's floor through the various lateral fractures.

The 300 m height of Silali basin's walls, as represented by the DEM, is in agreement with what is written in the book on the geology of the Maralal area that 'the caldera walls have inner vertical drops of about 300 m; they remain unbreached and the caldera is not in filled by a lava pool' (G.o.K, 1987). This altitude of Silali's wall is also shown by the cross-sections (Appendix V) as stated earlier.

From ground truthing, the classic hallmarks of an impact crater, as borne by Silali basin include: (1) slumped walls inside the rim (2) rough irregular crater floor (3) stepped walls (4) a circular morphology (5) Hummocky deposits (ejecta) outside the basin- among other features that are discussed in this chapter. These are morphology related characteristics and are as shown by Plates 4.18, 4.19, 4.21 and 4.29).

Plate 4.19: A picture showing Silali's slumped inner walls (SW) (Source: Author, 2015).

Though slumped walls are associated with faulting, even in the rift valley where Silali basin is located, the slumping in Silali basin defines a circular basin and enhances the basin's circular morphology. There are fault lines that run through the basin as seen from the LIDAR image (Plate 2.2) and the ASTER image (Plate 4.17). These may also be enhancing slumping in the basin, if they are still widening.

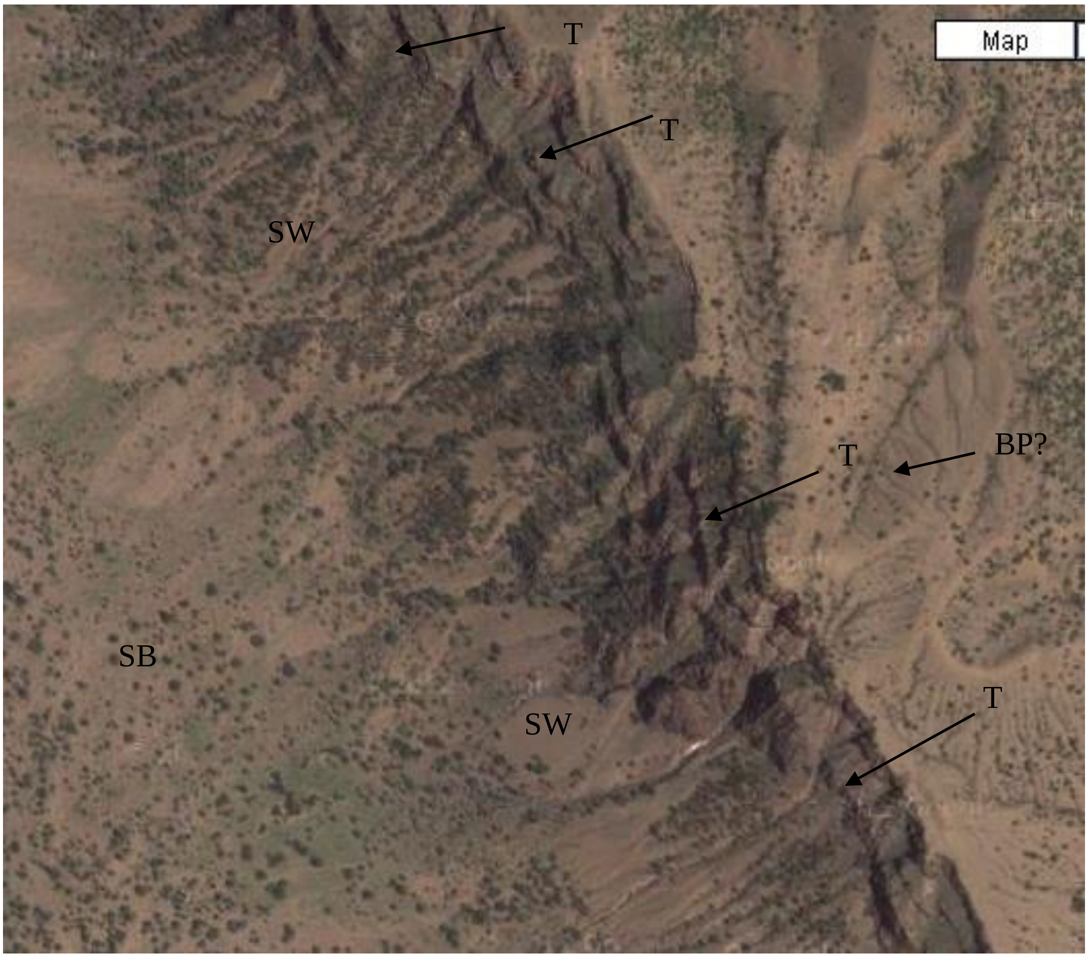

Plate 4.20: A SPOT satellite image showing terrace like features (T) on a part of the basin's eastern wall, a portion of the Silali basin (SB), butterfly pattern (BP) of ejecta spread and slumped walls (SW). Image was adapted from Google maps.

Complex craters are also said to contain terraces on their inner walls. According to Heiken and a team of other researchers, true complex craters contain terraces on their interior walls, a flat floor and a single peak or group of peaks in the center of the crater floor (Heiken et al,. 1991). For them, the interior wall terraces are products of landslides as evident in one of the craters on the moon called *Copernicus* (Heiken et al,. 1991). Terraces on Silali basin's wall are evident on most of the satellite images and ground pictures presented in this thesis and has stated earlier, they are linked to the basin's formation and effects of denudation.

Plate 4.20 also shows what appears like the butterfly pattern (BP) of ejecta spread that is displayed by ejecta on some ETICs (https://en.m.wikipedia.org/wiki/ejecta).

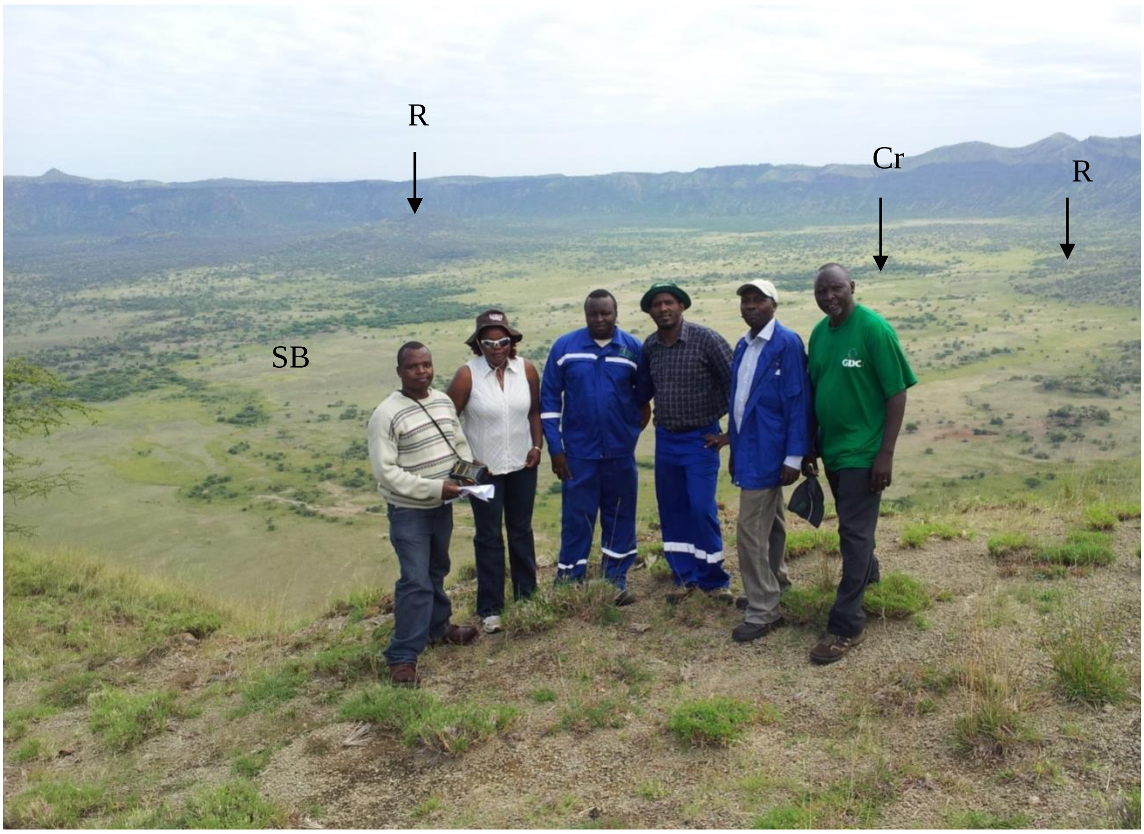

Plate 4.21: A picture showing Silali basin's hummocky floor: Craters (Cr) and ridges (R) as viewed from the southeastern rim of the crater (Source: Author, 2015).

The DEM (Plate 4.18) shows the same features.

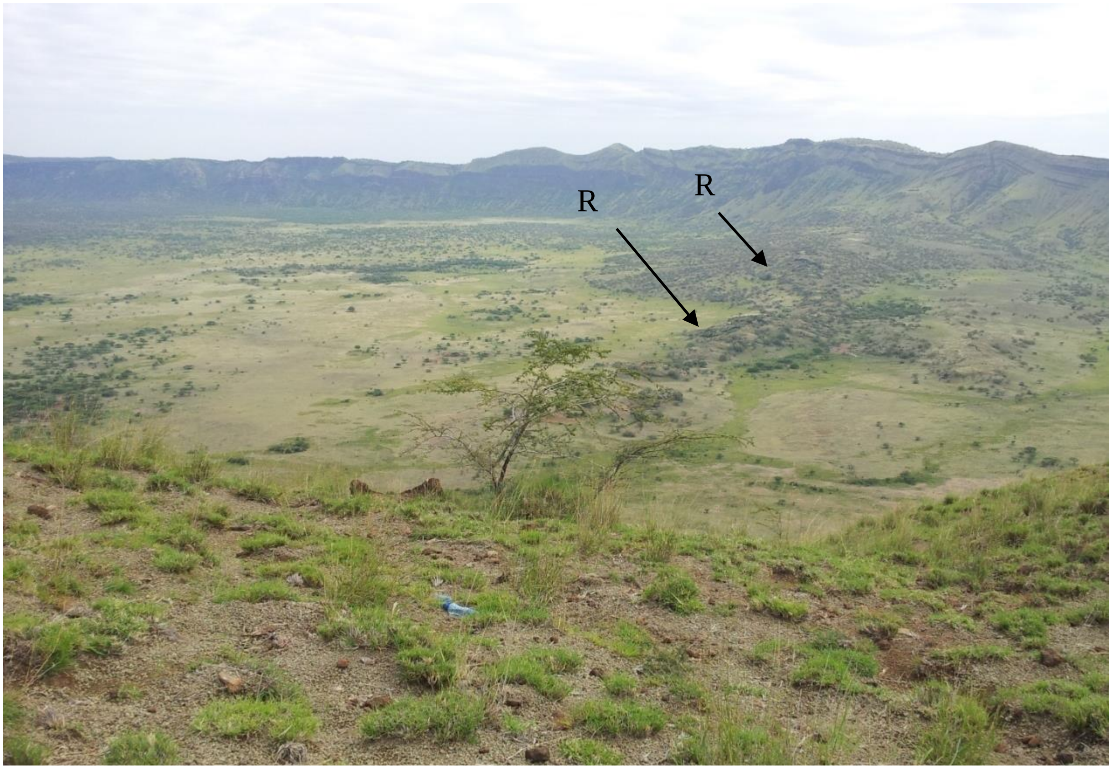

Plate 4.22: A picture showing a ridge (R) that runs around Silali basin's northeastern floor, viewed from the basin's southeastern rim (Source: Author, 2015).

The ridge (R) shown by Plate 4.22 is a part of Silali basin's broken peak ring (PR), as shown by Plates 4.8, 4.11, 4.12, 4.16 and 4.24.

Plate 4.23: A picture showing hummocky ejecta (E) on a part of Silali's outer walls (Source: Author, 2015).

The hummocky ejecta shown by Plate 4.23 is the rough mixture of dust and broken up rock material that is found on the outside wall of Silali basin. Some of the broken up rock material is of the same nature as the rocks making up the layers of Silali basin's wall. The hummocky ejecta, that qualifies to be called pseudotachylites, because of their heavy fracturing, is also evidence that an extra-terrestrial impact may have blasted rocks inside the old volcanic shield and pushed them outwards. The hummocky ejecta may be what Mc Call describes as 'syenite boulders scattered over the hill side, outside the caldera' in his 1963 studies of the crater (Mc Call, 1963).

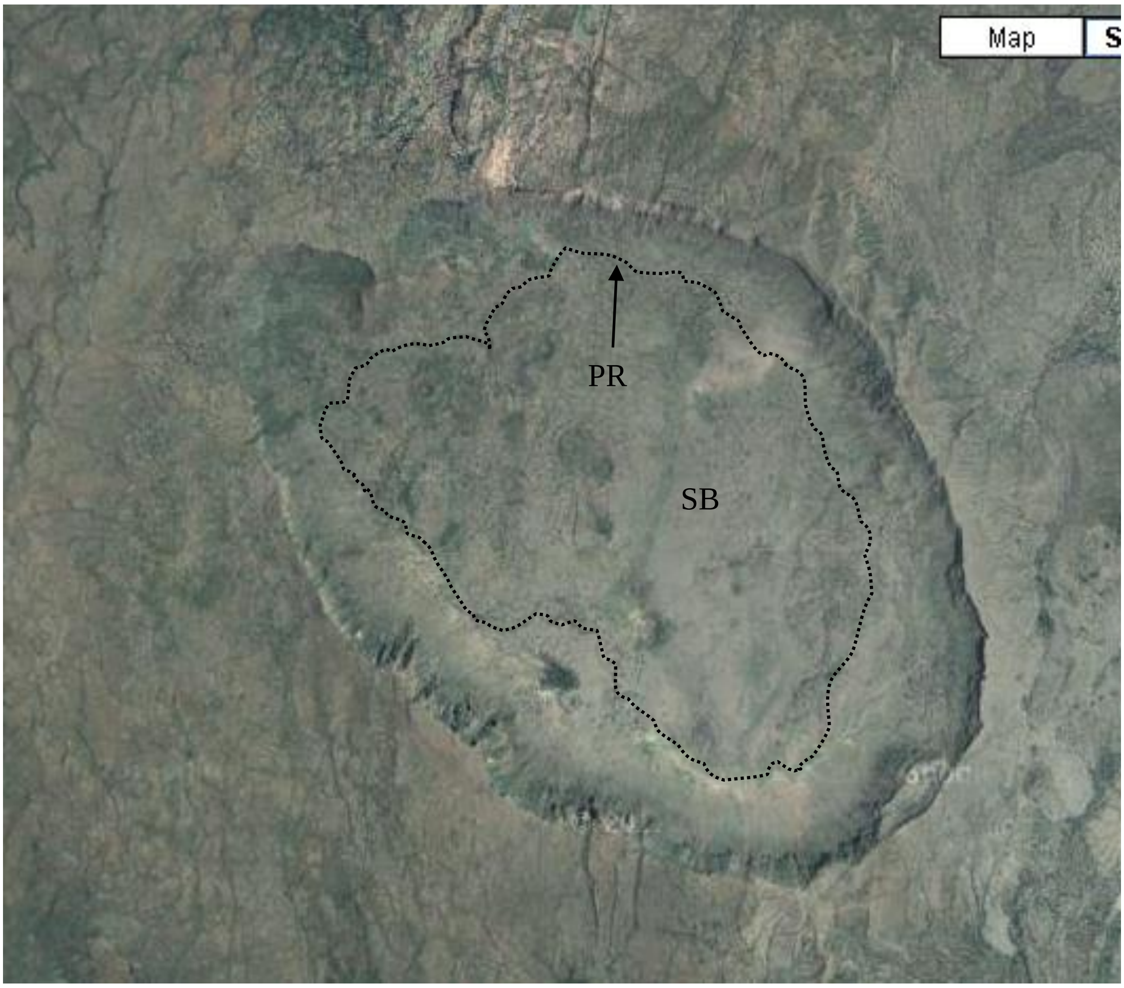

Plate 4.24: A SPOT image showing Silali basin's crude peak ring (PR). The DEM (Plate 4.18) also shows some of the ridges that form Silali's peak ring (modified from www.Google.com).

A peak ring is a feature of complex craters and extra-terrestrial impact basins. On the earth's surface, a complex crater has a diameter of 2-4 km while a basin has a diameter of more than 4 km, as stated earlier. In other complex craters, multiple peak rings or a ring of central pits are found. Silali basin's peak ring is crude because it is broken up in places and it appears to have been seriously eroded or deformed. A black line has been used to outline the possible position of the peak ring, which is a feature associated with complex impact craters. The peak ring can also be succinctly outlined from the LIDAR image presented in chapter two (Plate 2.2). Following Silali basin's subsidence, which appears to have been a block or piston kind of subsidence, it is possible that the peak ring remained intact with some deformations in some parts. Some sections of the peak ring may have fractured and got washed away, leaving the current broken ring of ridges.

4.1.2 Geophysical Evidence/ Characteristics

a) Gravity Signature

ETICs that have been studied before, register a negative gravity anomaly or a gravity low. The gravity low is circular and extends slightly beyond the crater rim. Figure 4.2 is a Bouguer gravity data image, showing the gravity mapping of Silali basin and surrounding areas. Probably because of its complex formation, Silali basin, unlike all ETICs, registers a high gravity reading of up to 100mCal, as shown by Figure 4.2. However, the data is too sparse to give a detailed picture of localized anomalies (Mariita, 2003).

The large positive anomaly, located in the central part of the area (between Lake Baringo and Emoruangikokolak volcanic centre) runs in a N-S direction, just like the faults running through Silali basin. This could be related to the axial high anomaly that could be a heat source for the area's geothermal system (Mariita and Keller, 2007).

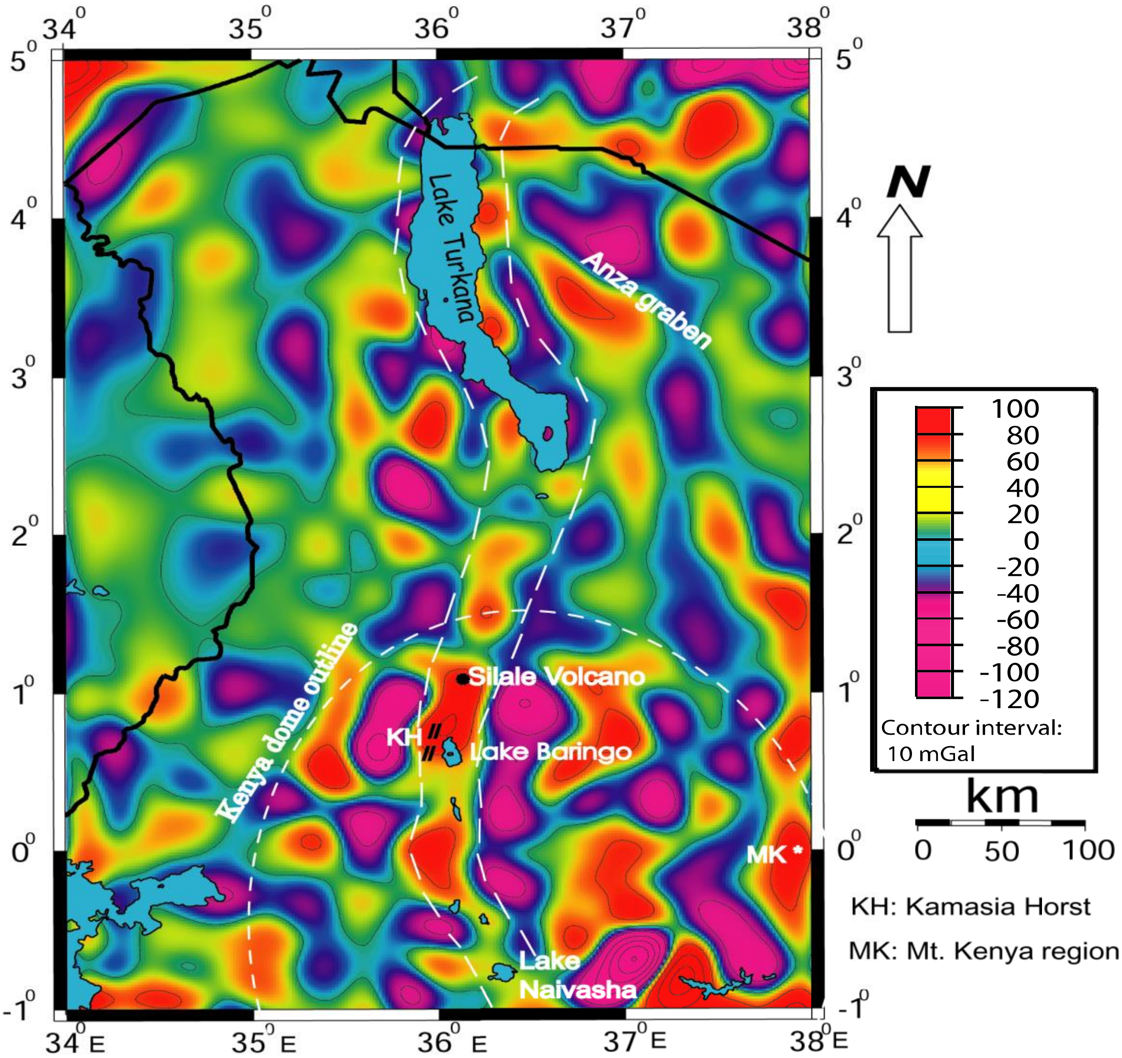

Figure 4.2: Band-pass filtered gravity map of the northern part of the Kenya rift. Wavelengths passed 30-150 km (Mariita and Keller, 2007).

b) Magnetic Signature

The magnetic anomalies associated with ETICs are usually more complex than gravity anomalies because of the complexities of rocks and their magnetism. Silali's case is even more complex because of the thermal characteristics of the crater and their effects on the rocks within and around the crater. Silali is a volcanic hot spot and the heat within it may have reset the magnetism of the rocks in the area, in relation to the earth's magnetic field. Chemical change in rocks, due to metamorphism that accrued from volcanicity or impact, may have affected the magnetism of the rocks as new chemical components were formed in the area's geology. Plate 4.25 shows evidence of rock metamorphism in Silali area, either due to impact or volcanicity. The whitish rock areas of the basin's wall are areas of metamorphic rock while the dark areas are occupied by varied volcanic rocks, which are the predominant rocks around the basin, except for the ejecta, sediments and other rocks. Ejecta are the materials that ripple away from the crater rim, all around the crater. The white rocks are breccias found on the northeastern walls of the basin, as evident on the ground and from Literature. According to Dunkley and a team of researchers, the lower layers of the north-eastern wall of the caldera comprise of massive trachyte lithic breccias (impact breccia that contains shocked and unshocked clasts in a clastic matrix) while the northern wall has up to 10 m of polymict lava lithic rich breccias (Dunkley *et al.*, 1993).

Generally, though, ETICs register a magnetic low or subdued zone ranging in amplitude from tens to a few hundred nanoteslas, looking at it regionally. Shock effects in an ETIC, though, can increase or decrease magnetism in an area (Dabizha and Fedynsky, 1975).

Figure 4.3 shows the magnetic mapping of Silali basin and the surrounding area. Regionally, the area is marked by a series of high amplitude magnetic anomalies. The wavelengths of these anomalies are less than 2.5 km, their amplitudes showing broad peaks reaching several hundred gammas and their shapes are either isometric or oval. These high magnetic markers would suggest massive basalts in the subsurface (Dabizha and Fedynsky, 1975). Silali basin has basalts around it and within its bed sediments, owing to its volcanic roots. However, it must be noted that the basin does not have an infilling of lava (G.o.K, 1975). Consequently, there may be impact melt buried beneath the basin's floor, which may be posting a high magnetic anomaly.

While in the study area, it was noted that magnetism in Silali basin is quite shifty and variable, from month to month, as indicated by hand held magnetic magnetic locators, whose blades kept crossing over each other in search of a new Magnetic North, yet there was an established Magnetic North, in the field, during the study. This can be examined more in subsequent studies.

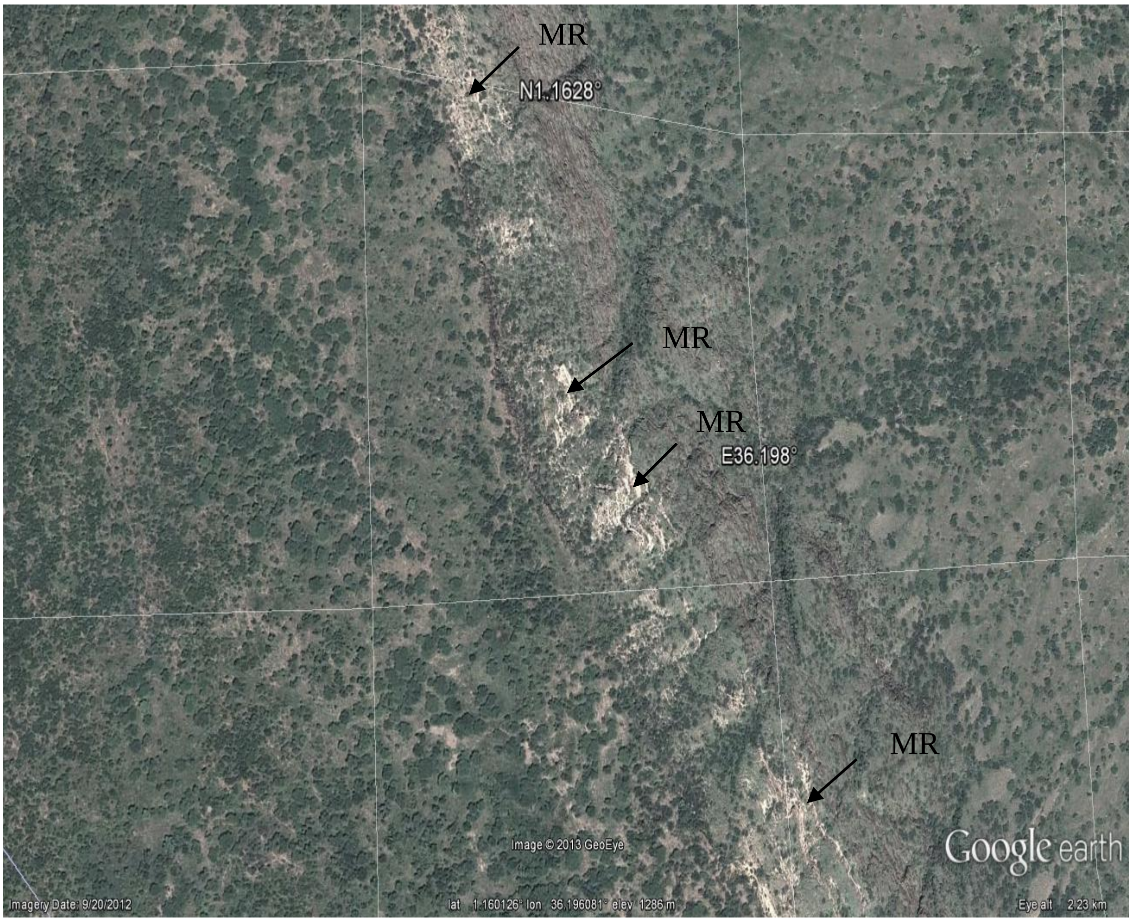

Plate 4.25: A satellite image showing metamorphosed rock (MR) on the northeastern wall of the Silali basin (Adapted from Google maps).

The metamorphosed rocks (MR) on the northeastern wall of the Silali basin are what Dunkley and team refer to as massive trachyte lithic breccias in the northeastern wall of the basin or up to 10 m or polymict lava lithic rich breccias (Dunkley *et al.*, 1993).

Plate 4.26: A section of Silali's heat altered wall (effects of thermal metamorphism) (Source: Author, 2015).

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Plate 4.26 shows Silali basin's metamorphosed rocks at close range. The metamorphism would be attributed to the volcanic activity that is evident in the basin and that may be spurring on new rock metamorphism. Notably, the picture was taken near a fumarole on the basin's wall.

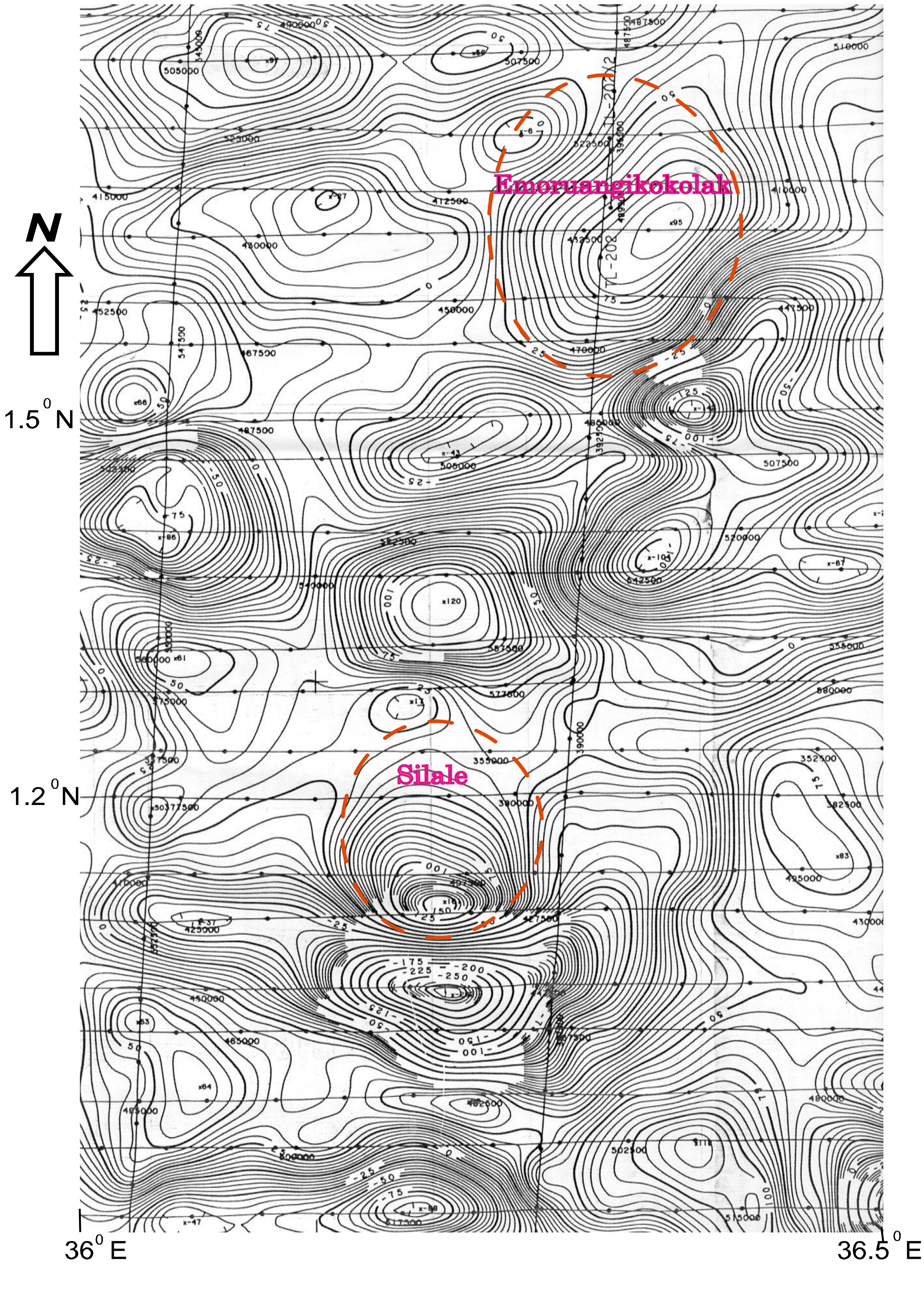

Figure 4.3: Aeromagnetic residual field intensity contour map for areas around Korosi-Chepchuk, Silali and Emoruangikokolak volcanic centres. Regional field correction used IGRF 1985 and updated to 1987 (Modified from NOCK, 1987).

c) Seismic Signature

Reflection seismic surveys allow for imaging of an ETIC's seismic signature, though the presence of rock fractures and breccias can make seismic readings complex.

Past studies have shown that the eastern Rift Valley has moderate seismic activity, except for its southern tip in Tanzania (Nyblade and Langton, 1995).

A regional seismic refraction study was carried out on a traverse covering 750km along the Rift Valley, in a N-S direction. Figure 4.4, below, shows the results.

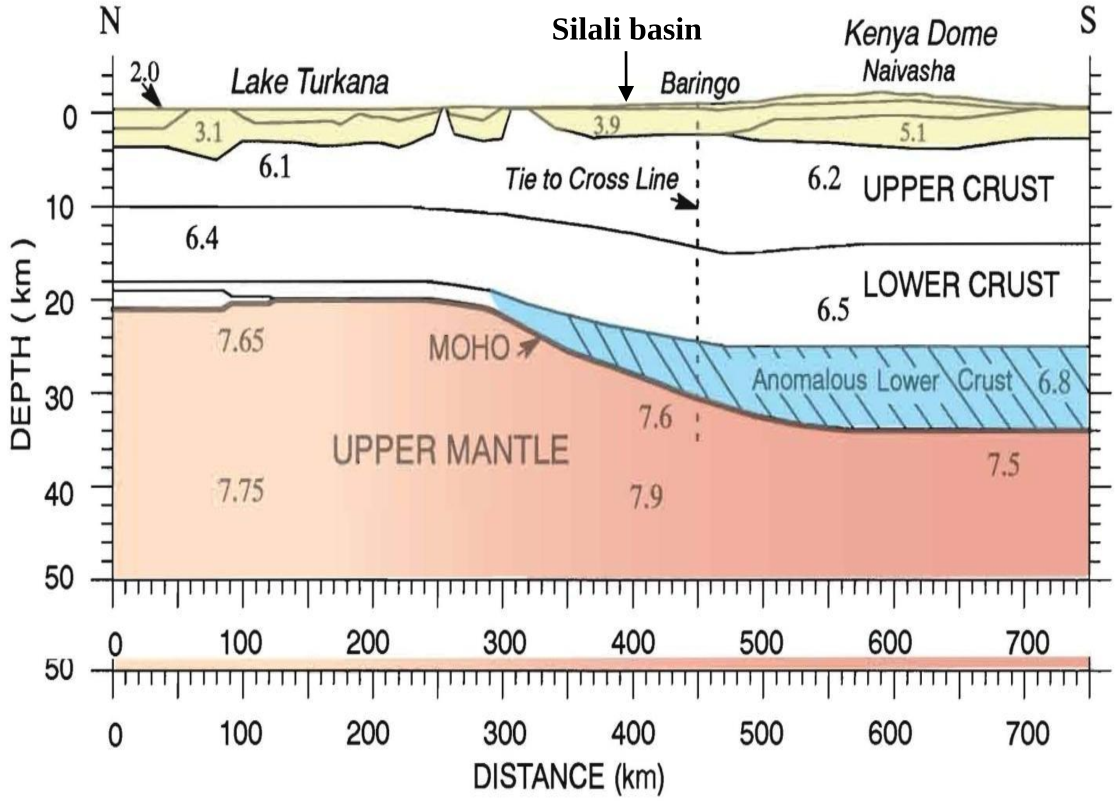

Figure 4.4: Axial crustal model showing P-wave velocities in km/s (adapted from Simiyu and Keller, 1997). Silali basin is 50 km to the North of L. Baringo, towards L.Turkana.

From the figure, it can be concluded that; the presence of a heat anomaly in the southern part of the Kenyan dome, in the southern part of the rift, is compatible with the present day observations of a steep sided region of anomalously low P-wave velocities (Simiyu and Keller, 1997).

Below the surface of the Rift Valley, there is a sharp transition of mantle material with normal P-wave velocities, down to a 100-150 km depth. A distinctive positive anomaly in the middle of the graben is due to a dyke injection related to reservoir magma (Simiyu and Keller, 1997). Put simply, Silali basin and its environs are seismically active, though the waves are not equally distributed. This may be the reason behind Silali basin's present day sinking as evidenced by massive slumping of the basin's walls. The reservoir of magma in the mid-graben could be a part of a mantle plume beneath Silali basin, which has been mentioned elsewhere in this study.

d) Electrical Signature

The conductivity of rocks is heavily dependent on their water content. The presence of fluids in impact induced structures, due to the presence of fractures and increased soil and rock pores, leads to a decreased resistivity and an enhanced conductivity. Use of resistivity sounding can help map the electrical characteristics of an ETIC, as was done by Lichoro (2013) in Silali.

Lichoro (2013) did a total of 154 TEM soundings in Silali basin since 2010. Two different TEM systems (Zonge and V8 phoenix TEM equipment) were applied to gather resistivity data for Silali basin and the results are shown by Figures 4.5, 4.6 and 4.7. Plate 4.27 shows the location of the TEM soundings and the fault lines running across the Silali basin that are severally mentioned in this study.

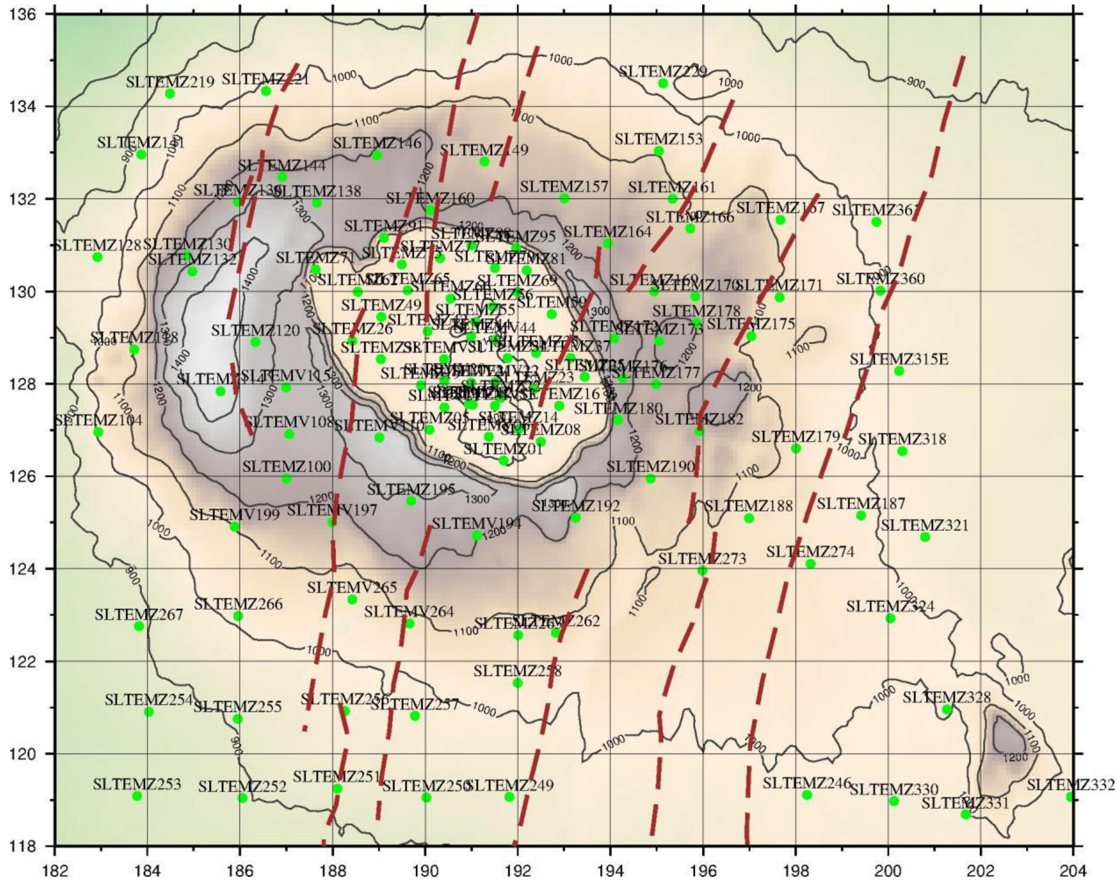

Plate 4.27: TEM sounding locations on the Silali basin, shown by green dots. The brown broken lines represent faults (Adapted from Lichoro, 2013).

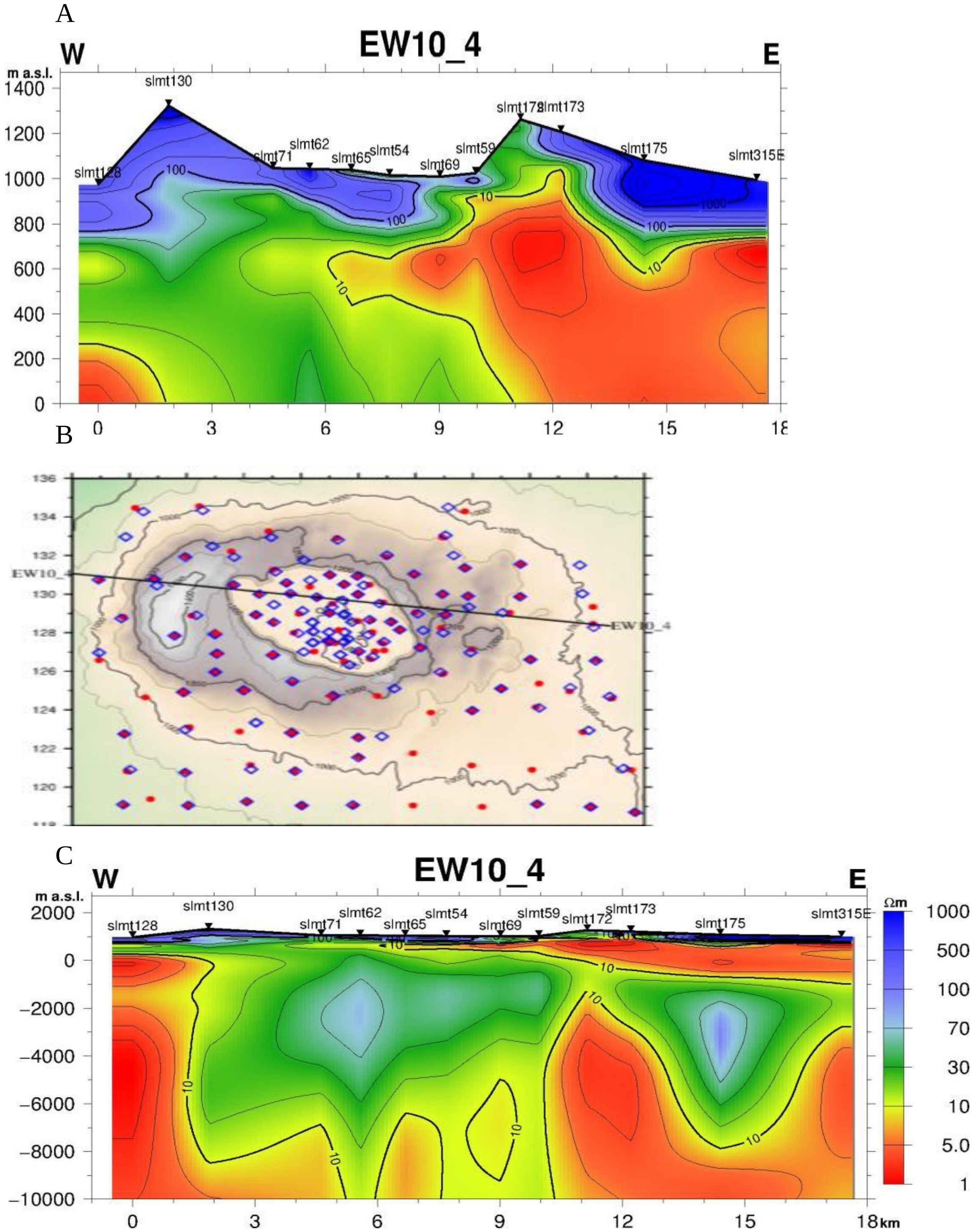

Figure 4.5: Resistivity cross-section for two different depth ranges obtained from the joint 1-D inversion of TEM and determinant MT data for profile EW10_4. Inverted triangles: MT stations; Section locations are shown by a black line at the center of the map. Red and blue points in the map are MT and TEM stations, respectively (Adapted from Lichoro, 2013).

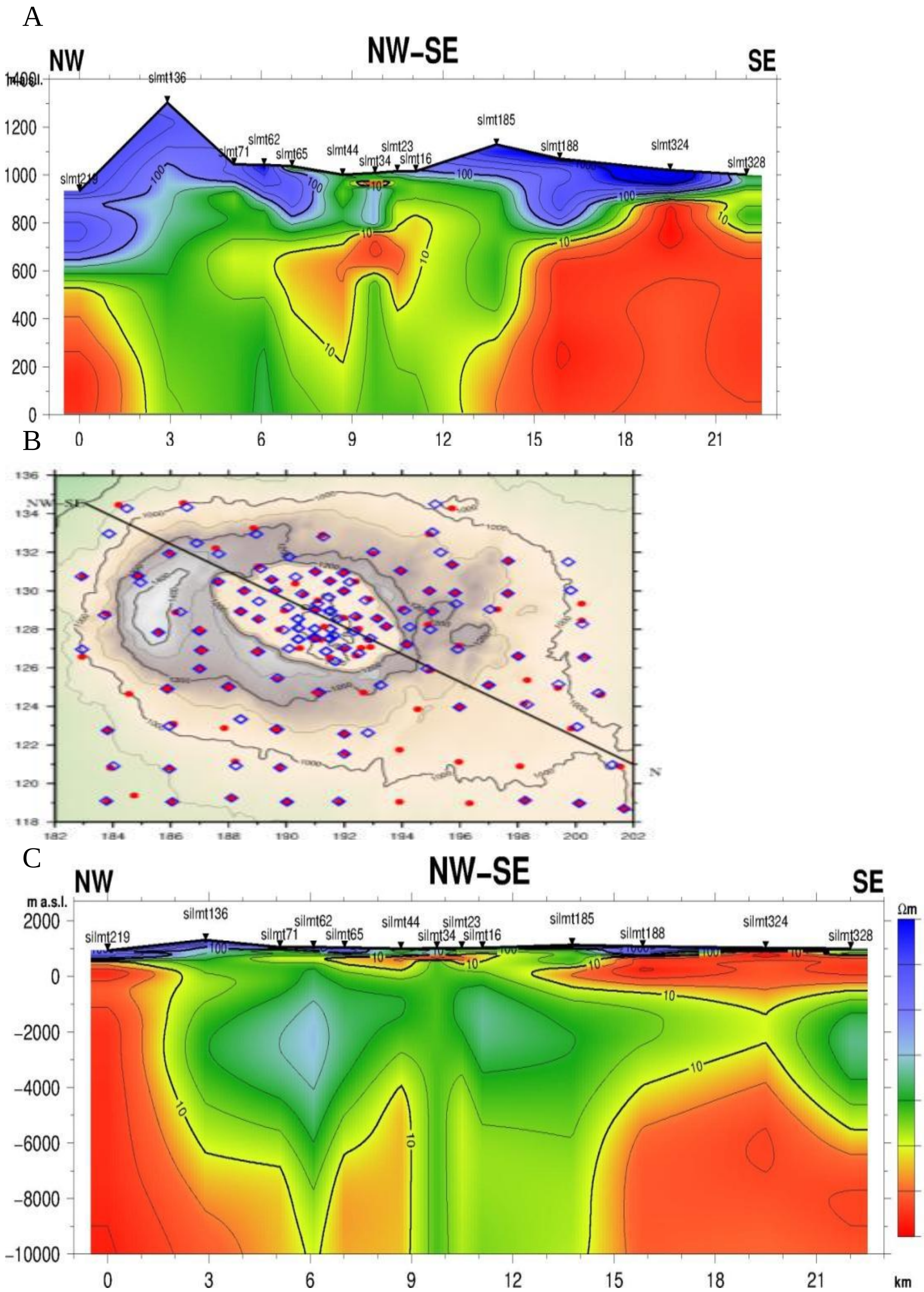

Figure 4.6: Resistivity cross-section for two different depth ranges obtained from the joint 1-D inversion of TEM and determinant MT data for profile SW-NE. Inverted triangles: MT stations; Section locations are shown by a black line at the center of the map. Red and blue points in the map are MT and TEM stations respectively (Adapted from Lichoro, 2013).

Figure 4.5, shows two plots, along an E-W cross section while Figure 4.6 shows plots along a NW-SE direction. The upper panels represent resistivity in the basin's shallower layers and the lower ones represent resistivity in the deeper structures. The top layer of about
300 m thick exhibits a high resistivity across the entire profile reflecting an un-altered rock formation, which in reality may be a block of earth built by thick sediments or impact melt. After the crater formation, for instance, the crater surface would have been porous and fractured but following several years of deposition of sediments, however, the rock fractures would have been silted up, leading to the formation of a surface that behaves like a compact rock. This 'compact rock' would then post a high resistivity reading. Alternatively, a tough layer of melted rock could be buried inside the crater, from one side to the other, as it is in Brent crater, in Ontario, Canada. This impact melt would, therefore, be responsible for the high resistivity anomaly recorded for Silali basin's about 300 m thick floor surface layer. This is the same layer that Dabizha and Fedynsky believe to be massive basalts beneath Silali basin that post a high magnetic anomaly (Dabizha and Fedynsky, 1975).

Underlying the high resistivity is a low resistivity layer, of less than 10 m thickness, which spreads to the east of the basin in Figure 4.5, but smears almost the entire profile in Figure 4.6. This low resistivity could be reflecting low temperature alteration minerals like smectite and zeolite (Lichoro, 2013) or it may be as a result of existence of fractures that have not been filled up by sediments, following the impact event, deep beneath the basin. Below the alteration layer two fairly high resistivity zones appear, one below the basin and the other more to the east. These could be probable high temperature reservoirs for the basin's geothermal field. It includes the upper parts of the magma chamber beneath the basin.

At depth of 5-6 km below sea level, low resistivity dominates the basin, rising to shallow depths at two portions of the profiles; one at the eastern edge of the basin and the other to the western edge. The eastern conductive column could be attributed to an up-flow zone or a probable existence of large fractures filled with fluids in the vicinity, which are manifested by the altered grounds and fumaroles on the surface directly above it. The altered grounds and fumaroles are also evidence of a deep circulation of hot geothermal fluids in an enhanced water-rock interaction. The western low resistivity region is not well understood but could possibly be the result of the existence of conductive sediments in the region but in the absence of other geophysical information like density, it might not be possible to attribute the low resistivity to a geothermal reservoir (Lichoro, 2013). Alternatively, these near surface low resistivity areas can also be attributed to the existence of the ring fracture structure around the basin, where rocks are heavily fractured and can hold lots of water.

Generally, all the cross-sections show evidence of a discrete low resistivity layer below Silali caldera and to the east of the caldera which is in line with the interpretation of a possible magmatic heat source (Lichoro, 2013). This magmatic heat source would be the mantle chamber beneath Silali basin or the 'localized' mantle plume in the area.

It is important to note that, Silali basin's resistivity may have been made complex by its formation and its volcanic ties so that it is not just low, as would have been expected in an ETIC, but a mix of low-high- low, as seen across the profiles.

Silali basin's low resistivity can be better seen in Figure 4.7, which is a WinGlink software image. This enhances Silali basin's ETIC nature by showing its continuous low resistivity.

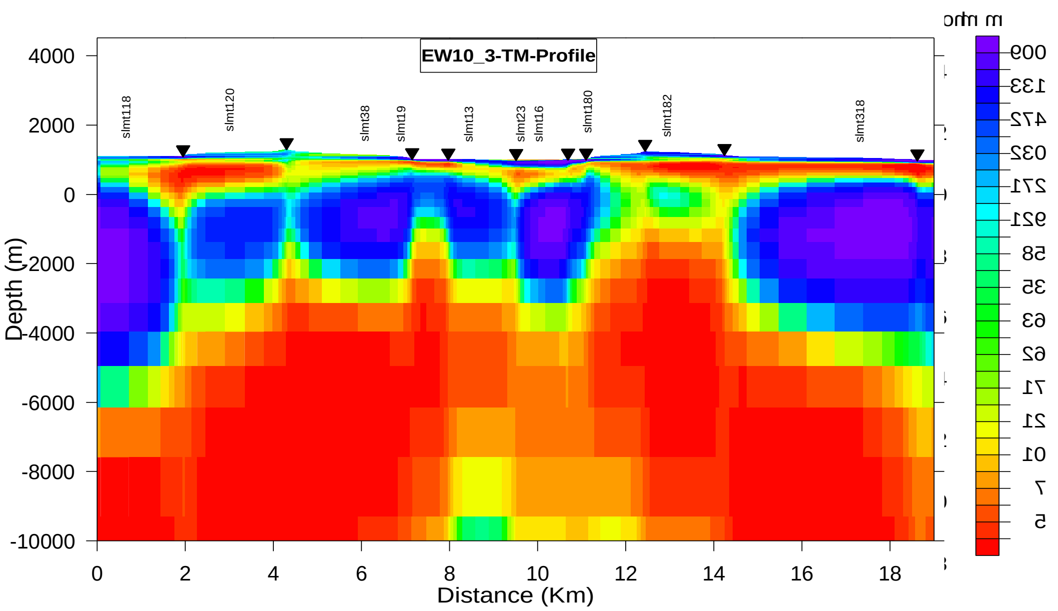

Figure 4.7: A WinGlink image showing Silali basin's resistivity

(Adapted from Lichoro, 2013).

Figure 4.7 was created using WinGlink software and it is elevation-corrected. It shows a thin resistant surface layer, underlain by a conductive second layer (a layer of low resistivity spread all over the crater). The third layer, like shown by Figure 4.5 and 4.7 above, reveals a high resistivity layer that runs across the entire profile then a deep low resistivity zone.

4.1.3 Geological Evidence/ Silali's Geologic ETIC characteristics

The ETIC related geology of the Silali basin comprises of:

a) Allochthonous

Allochthonous such as rock fragments around the rim are present in Silali basin. This is the material that appears to have been displaced during cratering. The fractured rock, on the outside walls of the basin, is very similar in appearance to the rocks found on the interior walls. This means that the rocks and the rough dust (mixture of small rock particles and fine dust) found on the outside walls of Silali basin, may be part of pulverized rock that was pushed out of the basin after impact. Plate 4.23 shows part of the hummocky ejecta on the outside walls of Silali basin. Obsidian makes up some of the rock layers on the inside walls of the basin. The presence of broken up obsidian particles in the dust/alluvial apron over Silali basin's wall indicates that the dust originated from the inside of the basin as it can happen in an impact event.

b) Impact Ejecta

According to McCall and Hornung (1972), the whole of the Silali volcano has an enveloping of an alluvial apron (sediments). Thus, the presence of massive rough dust deposition (or 'apron of alluvium') on the flanks of Silali basin, instead of magma deposition, is evidence that Silali basin may be a product of an extra-terrestrial impact rather than volcanicity. This rough dust is not volcanic tuff because it is not uniform in color or in physical composition. It is more like a juxtaposition of pulverized rock materials and dust that has been cemented together. It is important to note that the basin is rich in volcanic rocks and the broken up rock materials mentioned here, may have been cemented together by Silicate minerals that are present in the rocks or by impact melt if indeed Silali is an ETIC. Usually, ballistic sedimentation will occur first after an impact, followed by melt rich ‘ground hugging flows’ (https://en.m.wikipedia.org/wiki/ejecta).

The possibility of an impact event behind the basin's formation can be inferred from the presence of broken up obsidian in the impact dust around the basin. As stated above, dense obsidian layers are found in the materials making up Silali basin’s western walls. The rock also appears as thin lines within the layers of the basin’s wall in other places. It is only an impact event that can crush or pulverize the walls of the old Silali volcanic shield, excavate a crater and push rock fragments and dust over the crater walls.

It should be acknowledged that Silali basin’s walls have no lava deposition. Secondly, the crater is not a product of a vent eruption and thirdly, the ring structure is not eruptive in terms of magma emission, as discussed in chapter two. Consequently, the material making up the dust apron around the basin, though volcanic to a large extent, is not a product of magma deposition or volcanic tuff. The material is a mix of whatever rock materials made up the volcanic shield from which Silali basin was formed, obsidian included.

Plate 4.28, shows the rough dust that covers the flanks of Silali basin, at a larger scale. Plate 4.29, shows the same dust at close range and Plate 4.30 shows obsidian particles that were collected from the dust.

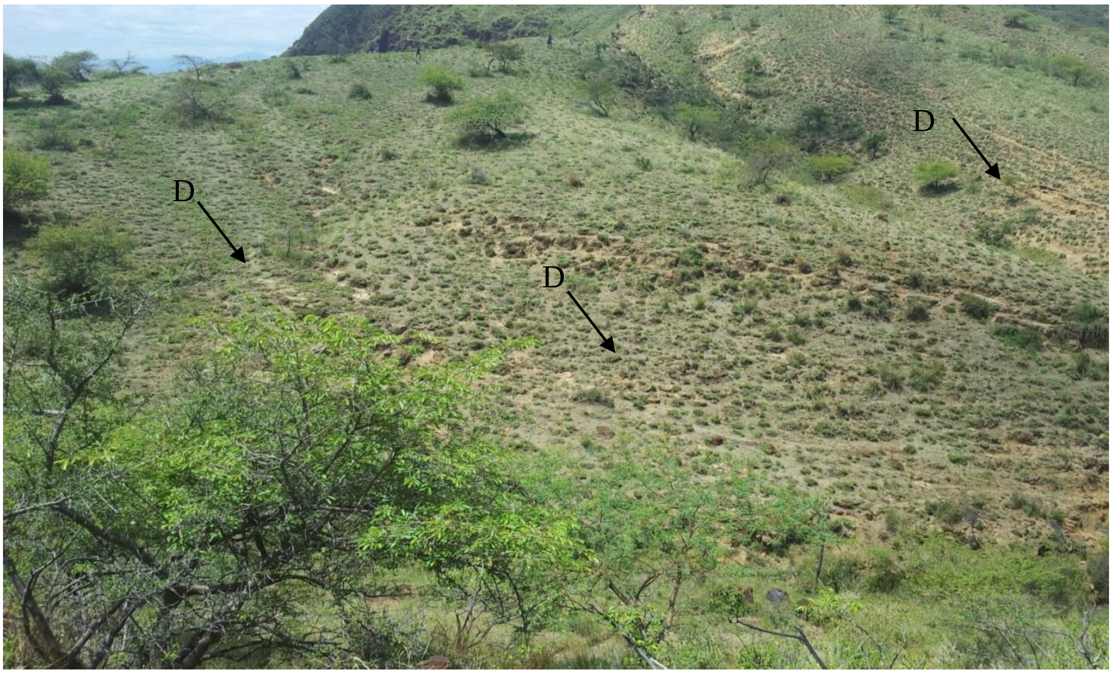

Plate 4.28: The dust (D) on the flanks of Silali basin, on the southeast and eastern walls (Source: Author, 2015).

Plate 4.29: The dust (D) at close range (Source: Author, 2015).

Plate 4.30: Broken obsidian particles found in the dust around Silali basin (Source: Author, 2015).

The obsidian particles were picked from a handful scoop of the dust that is called ejecta in this study. The dust is rich in many rock particles but obsidian was picked to show that the rocks inside Silali basin may have produced the dust around the basin.

As stated earlier, there is absence of massive lava deposition on the flanks of Silali basin, according to observation and from Lichoro's (2013) work. If Silali basin was entirely a product of volcanic activity, there would be presence of this lava within and all around the basin's flanks.

c) Breccias

Breccia is found in the crater. The lower layers of the north-eastern wall of the caldera, for instance, consist of massive trachyte lithic breccias while the northern wall has up to 10 m of polymict lava lithic rich breccias (Dunkley *et al.*, 1993). Lithic and Polymict breccias are breccias whose particles are cemented in a way that they form a matrix. In fact, lithic breccia is an impact breccia that contains shocked and unshocked clastic material in a clastic matrix.

Breccias have varied origins. They may be sedimentary, tectonic, igneous, hydrothermal and impact related. Sedimentary breccias are deposited in valleys (clastic rock) while tectonic breccias are formed on the margins of tectonic boundaries, following a collision or shearing of continental plates. Igneous breccias are volcanic bombs that have been cemented together while hydrothermal breccias are formed in areas where there are geysers. When the walls of voids containing hot water collapse, rocks implode inwards and are caught up in a churning mixture of rock, steam and boiling water. The rock fragments deminutate each other and become rounded, forming breccias with rounded particles rather than angular particles as those shown on Plate 4.31. Silali basin's fracturing and release of hot fluids may have also contributed to the formation of the breccias, on the surface rocks in and around the basin. Breccias formed by hydrofracturing have angular particles, just like impact breccias and if boiling occurs, methane and hydrogen sulfide may escape, encouraging the precipitation of mesothermal ore deposits, which often contain gold (www.thefreedictionary.com/brecciation).

Impact breccias are found on the rim or floor of an ETIC. They may also be found on the ejecta expelled beyond the crater and are identifiable by their occurrence in or around an ETIC, in association with other impact features. There is no clear explanation on how they formed but it may be because of impact heat fusing all sorts of rocks together.

Silali basin's breccias may still be impact related, whether they were formed directly by impact or by a hydrothermal fracturing activity. This is because, for the hydro fracturing to occur and form mesothermal breccias, there should have been some weakness in the area rock that encouraged the superheated fluids from deep within the basin to charge upwards under lithostatic pressure. As explained in chapter two, Silali basin's fracturing, may be impact related, especially the ring fracturing; that may be responsible for the basin's ring fracture structure.

Suevite was not found in the crater; though these may have to be investigated more during future studies. Plate 4.31 shows brecciated rock on a section of Silali basin's walls.

Plate 4.31: A picture showing brecciated rock on Silali basin's south-western wall (Source: Author, 2015).

d) Silali's Shatter Cones

As mentioned earlier, the upper layer of rock making up the inner walls of Silali basin appears like a mass of shatter cones. The broken pieces display conical fracture surfaces, just like the Chemolingot shatter cones and other shatter cones. Shatter cones form mostly on fine grained brittle rocks, just like the rock layer in question. Plate 4.32 shows the Silali rock layer shatter cones.

Plate 4.32: A picture showing Silali basin's shatter cones (Source: Author, 2015).

The rock (dark) shown on Plate 4.32 is of volcanic origin and is more exposed on the inside of the basin. On the outside of the basin, it is buried by the rough dust that envelopes Silali basin though some of its huge blocks make up part of the hummocky ejecta on the basin's flanks and a large part of the pseudotachylites littering the basin's floor and outer walls. It is made up of striated fracture surfaces and is continuous all around the basin; at an almost uniform height. The rock is rapidly breaking up and this has made it more rugged as parts of it are chipped off. Several blocks of the rock layer are found scattered along the wall of the basin, with a few on the basin's floor, as stated. The shatter cones on Silali basin (Plate 4.32) can be compared to the shatter cones in Santa Fe impact structure- Mexico (Plate 4.33). The rock formations on the two plates appear similar because the rocks on the two plates appear to be fine grained, have the same color, are striated and both have conical fracture surfaces. Interestingly, the shatter cones on Silali basin and Chemolingot shatter cones (Plate 4.41) have their conical tips facing the East. The other shatter cones cited in the study (Santa Fe-Mexico, Plate 4.33 and Beaverhead- Montana, Plate 4.42) also appear to be facing the same direction from their pictures.

Plate 4.33: Shatter cones in the Santa Fe impact structure near Santa Fe, New Mexico (Adapted from www.lpi.usra.edu).

Shatter cones are rare geological features that are only known to form in the bedrock beneath meteorite impact craters or in areas where underground nuclear explosions have occurred. They are evidence that rocks have been subjected to a HVI or high pressure shock (www.en.wikipedia.org/wiki/shatter_cone). Geologists believe that shatter cones form due to compression waves passing through rocks after an impact or as a result of tension/refraction as rocks bounce back when pressure subsides. Shatter cones range in size from microscopic to several meters large, depending on the rock type. Coarse grained rocks tend to yield less developed shatter cones but fracture more during impact. Shatter cones develop more on dense- compact- fine grained rocks that get subjected to a high velocity impact (HVI).

e) Tektites

These are also found around the crater. These are natural silica rich homogenous glasses formed by complete melting of target rocks. It is believed that the black hills to the East of the Silali basin are actually made up of pure black glass. According to McCall and Hornung (1972), 'the trachyte cones (Black Hills) to the east of the basin's wall are made of almost pure black glasses'.

Following a study on the petrogenesis of Silali that was carried out in 1995 (MacDonald *et al.*, 1995), it was concluded that the majority of Silali basalts comprise of glass and some of the trachytes are aphyric and glassy. The dolerite blocks in Silali are described as having a low amount of olivine and an increasing abundance of interstitial glass (up to 40%). The glass is said to contain quench needles of apatite and is light to blackish-brown in color and as it increases in amount, it becomes vesicular (MacDonald *et al.*, 1995).

Though access to the black hills was not possible due to insecurity, McCall and Hornung's (1972) description of the trachyte cones suggest an impact origin; first because the glasses mentioned are black to blackish brown in color, just like tektites in other ETICs. Secondly, some of the glasses have a needle like shape, such as the apatite glass mentioned above. Tektites are usually spherical in shape and therefore needle like at some point.

Siderophile elements are also associated with ETICs but were not found in Silali basin. They are Iridium, osmium, platinum and palladium. These are iron loving elements that are rare on the earth's surface but found in impact areas and meteorites. They appear as shown by the Plates 4.34-4.37.

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Plate 4.34: A picture of Iridium, adapted from Wikipedia.

Plate 4.35: A picture of Osmium, adapted from Wikipedia.

Plate 4.36: A native platinum nugget from Kondyor mine, Russia, adapted from Wikipedia.

Plate 4.37: A picture of palladium, adapted from Wikipedia.

More research will have to be carried out in Silali basin to ascertain the nonexistence of the PGMs or establish their existence. According to the Journal of Geological Society of 1995, the basalts of Silali basin are of high iron affinity (Journal of Geological Society, 1995). This may probably be as a result of the existence of PGMs.

e) Pseudotachylites

These are also found within and around the basin. They are heavily faulted or fractured rocks. Though they can be formed by tectonic fracturing, they can also be formed by impact cratering, as explained in chapter two. Generally, the area around the basin is heavily faulted but the faults are in a linear form and not likely to have formed Silali basin's ring fracture.

Silali basin's ring fracture, the caves (Plates 4.57 and 4.58), the sinkhole and the Suguta gorge, among others features in the area, all provide evidence of the massive rock faulting or fracturing within and around the basin.

f) Other Related Minerals

A study that was carried out by the Department of Mines and Geology, following a government funded project on mineral exploration and assessment of geological materials and geotourism sites in ALRMP project area of Baringo and East Pokot districts in 2009, revealed that Silali area also has other minerals that are impact related. These include iron, gold, copper and nickel.

Many large ETICs host mineral resources that range from large deposits to localized occurrences. ETIC minerals can be **progenetic**, **syngenetic** or **epigenetic**. Progenetic minerals are pre-impact minerals. These are minerals that existed in target rocks before an impact event, but may have become exposed or accessible after impact. They include iron ores, uranium and gold. Syngenetic minerals, on the other hand, are syn-impact minerals or minerals that owe their existence purely to an impact event. They include copper, nickel, PGMs and impact diamonds. Epigenetic minerals, as far as impact is concerned, are post impact minerals. These are minerals that result from impact induced thermal activity. Apart from a few metalliferous deposits and mesothermal gold, impact hydrocarbons form the bulk of many epigenetic impact deposits. This is because; impacts do not only encourage the burial of plants and animals under pressure and heat, to degrade them to hydrocarbons, but also because ETICs provide the necessary structural trap needed for localizing mineral rocks and holding mobile liquids, which may include oil.

Silali basin and the surrounding area have some iron, gold, copper and nickel. Petroleum deposits will not be expected in Silali basin because of the high temperatures. The following figures, adapted from the report produced by the Department of Mines and Geology, following the government funded project on mineral exploration and assessment of geological materials and geotourism sites in ALRMP project area of Baringo and East Pokot districts in 2009 (G.o.K, 2009), show the distribution of some of the minerals mentioned, in Silali basin and its immediate surroundings. The minerals are in ppm (parts per million).

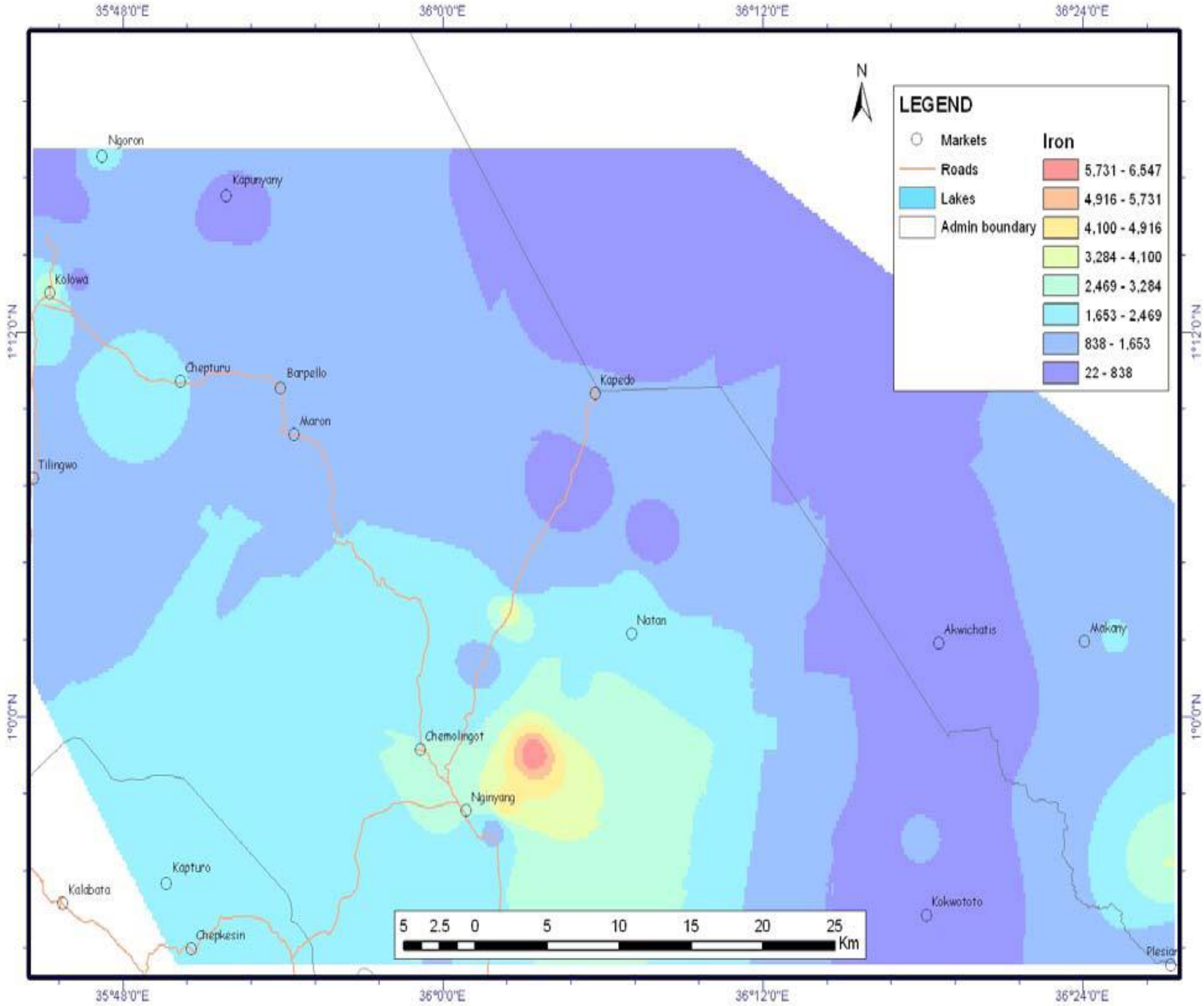

Figure 4.8: Map showing iron concentration distribution in Silali basin and surrounding area (Source: G.o.K, 2009).

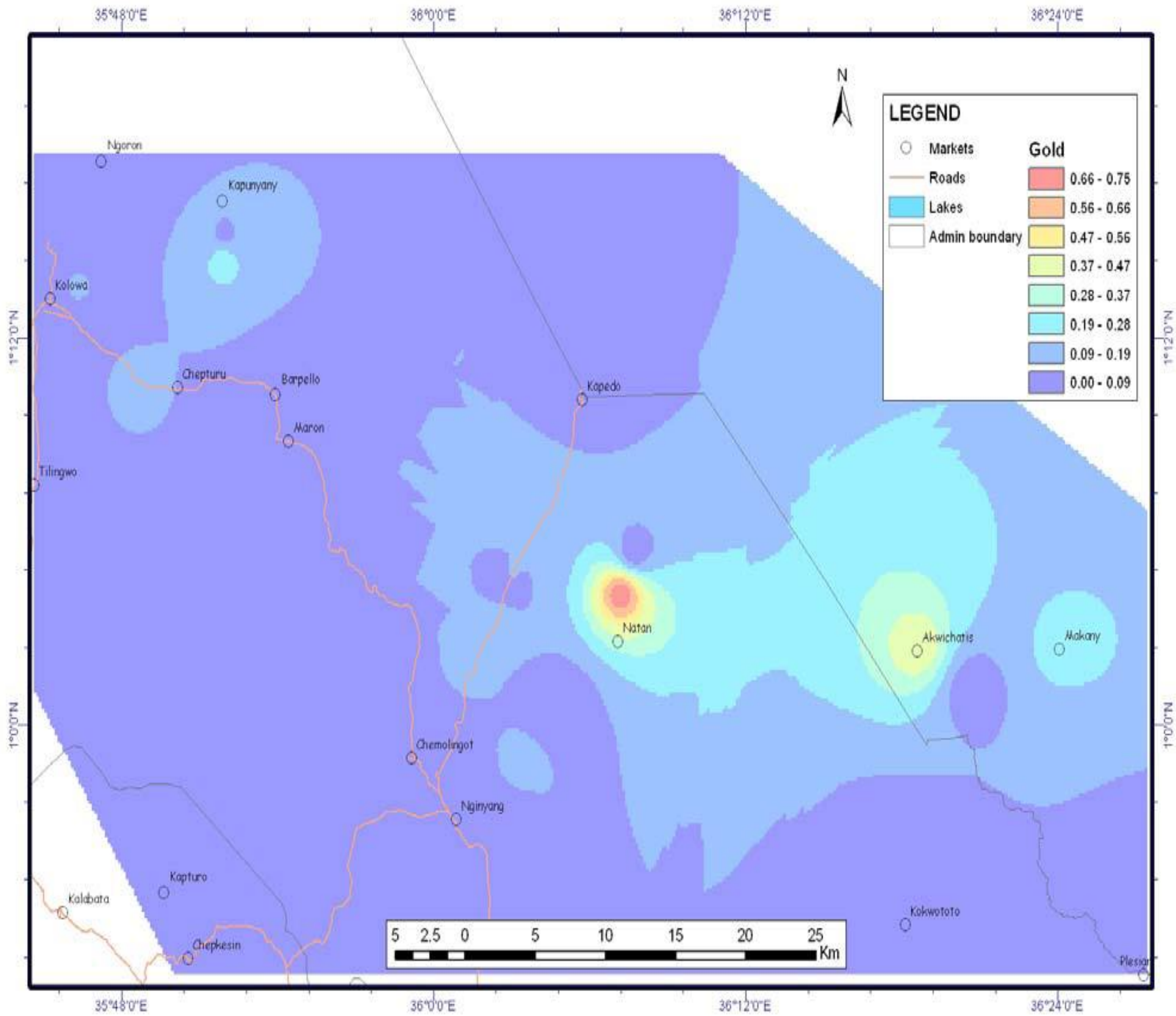

Figure 4.9: Map showing gold concentration distribution in Silali basin and surrounding area (Source: G.o.K, 2009).

Gold is associated with impact breccias.

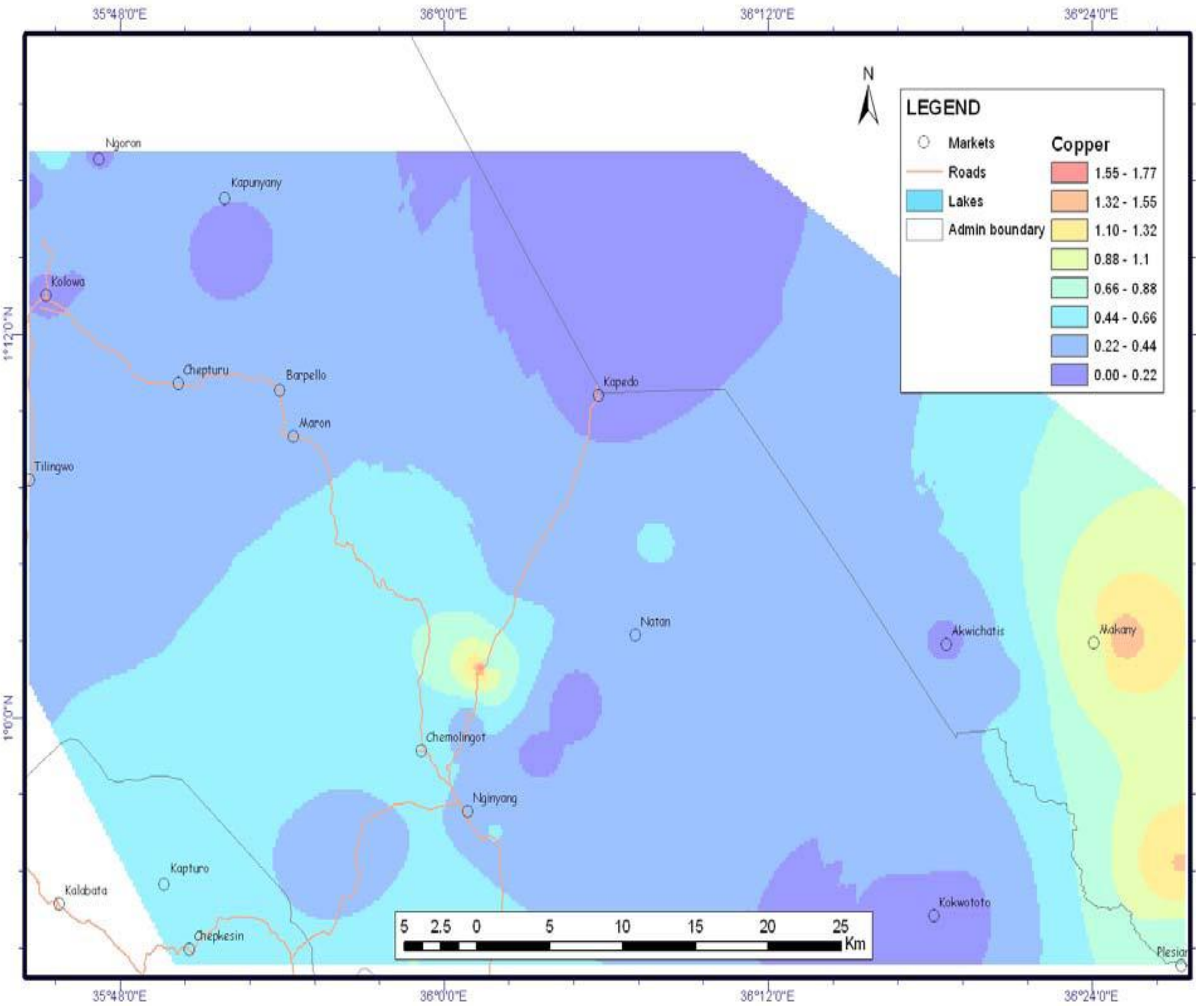

Figure 4.10: Map showing copper concentration distribution in Silali basin and surrounding area (Source: G.o.K, 2009).

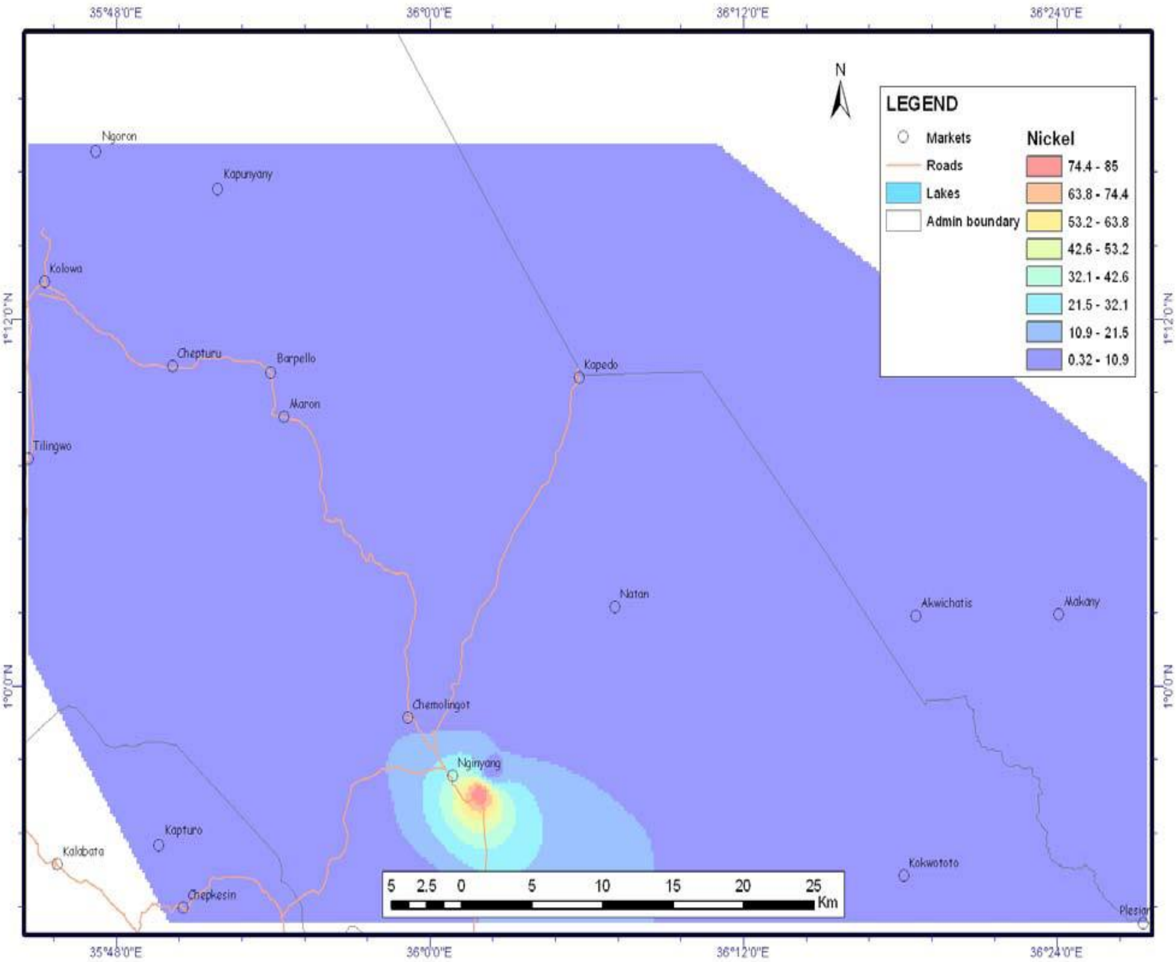

Figure 4.11: Map showing nickel concentration distribution in Silali basin and surrounding area (Source: G.o.K, 2009).

Though the minerals are in small portions, at least they prove the importance of ETICs as mineral resource areas, with all viability of encouraging mining. Located in the eastern Yilgarn, Australia, lies the Watchorn Impact Structure (WIS), which is 560km wide and about 2.6 billion years old (http://m.phys.org/news/2013-11meteorite-impact-reveals-mineral-deposit.html). The crater has gold and nickel fields. Sudbury basin in Ontario, Canada, is home to some of the world's most productive metal ore mines (http://www.galactic-stone.com/product/sudbury-crater-mine-ore-rich-in-rare-metals-iridium). More studies should be carried out to investigate the existence of nanodiamonds, mesothermal gold and other impact related minerals in Silali basin.

4.1.4 Evidence of the 'Outer Basin' and its Features

The 'outer basin' and some features which were observed in it, may support an impact formation of the outer basin and the Silali basin as well. These features include the slumped walls of the outer basin, breccias, shatter cones and a unique rock (Plate 4.38) that looks like a magma pillow.

A magma pillow is a pillow-shaped lava structure that is attributed to the extrusion of lava under water (subaqueous extrusion). It is commonly basaltic in nature and the more viscous the lava, the bigger the pillow. Magma pillows are common along marine volcanic hot spots and constructive plate boundaries (tensional boundaries) of fault areas. Due to the rapid cooling of the magma as it touches water, the magma's outer layer forms its outer coat or shell. Subsequent shells are formed as the magma cools towards its core. Thus, magma pillows are layered. The outer layers are made up of finer particles, owing to fast cooling, while the core is made up of coarse grains. The outer layer of a magma pillow is mainly glassy.

The unique rock, here known as the Chemolingot rock, the Chemolingot shatter cones, together with the slumped walls of the outer basin, are evidence that the 'outer basin' may also be an ETIC. Plate 4.38 and 4.41 show the Chemolingot rock and Chemolingot shatter cones respectively. Chemolingot area is to the south of Silali basin, near Chemolingot town on the outer basin. Since shatter cones only form inside an impact crater, their presence in Chemolingot is a likely suggestion that the Chemolingot area is an extra-terrestrial impact area. Chemolingot is on the outer basin. Consequently, the outer basin could be a product of an extra-terrestrial impact cratering. More research on the outer basin can be carried out in the future.

The breccias that were found on the outer basin are shown by Plates 4.43-4.52. The formation of breccias has been explained in the earlier pages of this chapter.

Plate 4.38: A picture showing a unique rock (Chemolingot rock) collected from Chemolingot area, in East Pokot. A brown coated probable chondrule is pointed by the black arrow (Source: Author, 2015).

This unique rock, though its chemical composition closely resembles that of an ordinary igneous rock (Table 4.2), is a suspect chondrite meteorite because it has what appears to be chondrules.

Plates 4.39 and 4.40, show one of these chondrules while Plate 4.47, shows holes that were left behind by chondrules that fell off the rock mass, probably after denudation of the rock.

Plate 4.39: A picture showing a probable chondrule in the Chemolingot rock. The chondrule is circled in black and is covered by a brownish material (Source: Author, 2015).

Plate 4.40: A picture showing a hole (one circled in black) left behind by a fallen probable chondrule on the Chemolingot rock (Source: Author, 2015).

Plate 4.41: A picture showing shatter cones (SC) around Chemolingot area of East Pokot. These compare well with the shatter cones at Beaverhead impact structure, Montana, shown by Plate 4.42 (Source: Author, 2015).

Plate 4.42: Assemblage of massive shatter cones with sizes of up to one meter, at Beaverhead impact structure, Montana (www.impact-structure.com/impact-rocks-impactites/the-shatter-cone)

The breccias presented in this chapter were all collected from flood deposits and river valleys on the outer basin and they are of greater variety than those photographed. Plates 4.43 to 4.49, illustrate these breccias, which may not be described as suevite breccias because they lack glass inclusions. Some of the pictures were taken against a background of pebbles and sand for scaling. There are breccias, though, on the northern and northeastern wall of Silali basin (Dunkley *et al.*, 1993) and some of these may have been washed into the outer basin after weathering, hence allochthonous in a way.

Plate 4.43: A picture of a greenish breccia (Source: Author, 2015).

Plate 4.44: A picture of a violet-whitish breccia (Source: Author, 2015).

Plate 4.45: A picture of a purple cum grey breccia (Source: Author, 2015).

Plate 4.46: A picture of a light purple breccia (Source: Author, 2015).

Plate 4.47: A picture of a dark brown- purple-grey breccia (Source: Author, 2015).

Plate 4.48: A picture of a purple-white-bluish breccia (Source: Author, 2015).

Plate 4.49: A picture of a purple-white-grey breccia (Source: Author, 2015).

The slumped walls of the outer basin are the materials that fell back to infill the basin after a possible impact. Photographs of the slumped walls were acquired at different parts of the outer basin especially to the south and west of Silali basin, which is accessible.

Plate 4:50: A picture showing part of the slumped walls of the outer basin; near Chemolingot (Source: Author, 2015).

Plate 4.51: A picture showing another section of the slumped walls of the outer basin; to the southwest of Silali basin (Source: Author, 2015).

4.1.5 Evidence of Associated Geomorphological Features

With all the geomorphological features within and around the Silali basin, the argument by Thompson and Turk (1992) that extra-terrestrial impact cratering is responsible for many geologic processes is highly plausible.

In their book on earth science, Thompson and Turk (1992), support a recent suggestion that lithospheric plate motion is caused by mantle plume. In itself, mantle plume is a vertical column of plastic rock rising through the mantle like hot smoke through an industrial stack. Mantle plumes originate from deep within the mantle, probably, from the mantle-core boundary, according to the two scholars and when a plume reaches the base of the lithosphere, it spreads outward, dragging the lithosphere apart and initiating a spreading center or a divergent boundary. As for the origin of the plumes, the authors above point at large meteoritic impacts on the earth, that are capable of blasting a huge crater. These impacts cause magma in the mantle to flow upwards, as an attempt to fill up the crater and enhance isostatic adjustment. This begins a mantle plume. Once started, it is believed that the upwelling may continue for millions of years. Based on this, a meteoritic impact may indeed be responsible for the volcanicity within and around the Silali basin, together with the faults around the area, such as the one followed by Suguta River. A huge extra-terrestrial impact has all the potential that is adequate to move crustal rocks apart. Part of these faults may be the vents that have created mountains like Paka or the fissures through which hot water gushes onto the earth's surface, as occurs around the Silali basin. Suguta gorge, the caves, the lava flow and the sinkhole around Silali basin are fault associated features. Consequently, this means that the Silali area is a volcanic hot spot with unending volcanic capabilities.

Plates 4.52, 4.53 and 4.54 show some parts of the Suguta River valley. Plate 4.52 shows a part of the steep Suguta River gorge. Plate 4.53 shows the hot water falls on the eastern wall of the Suguta gorge and Plate 4.54 shows the area that is the source of the hot springs that feed the hot water falls.

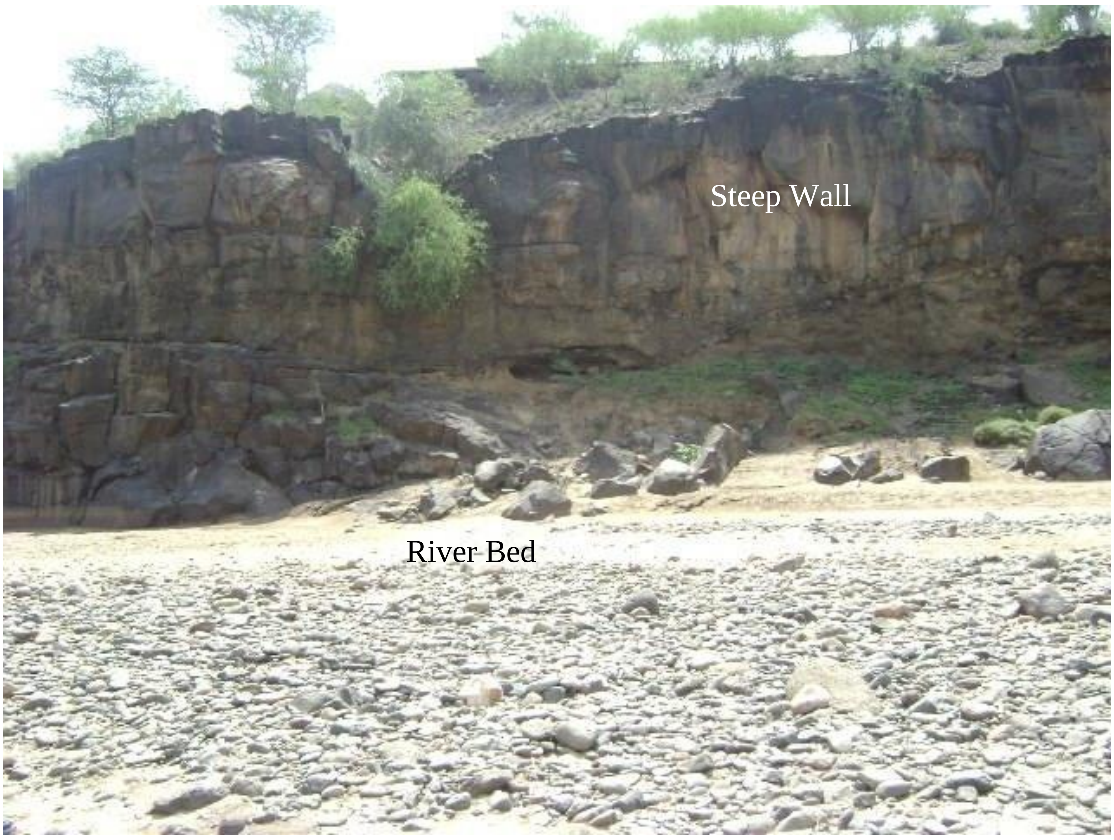

Plate 4.52: A picture showing a part of the steep walls of the Suguta River valley, which may pass for a gorge (Source: Author, 2015).

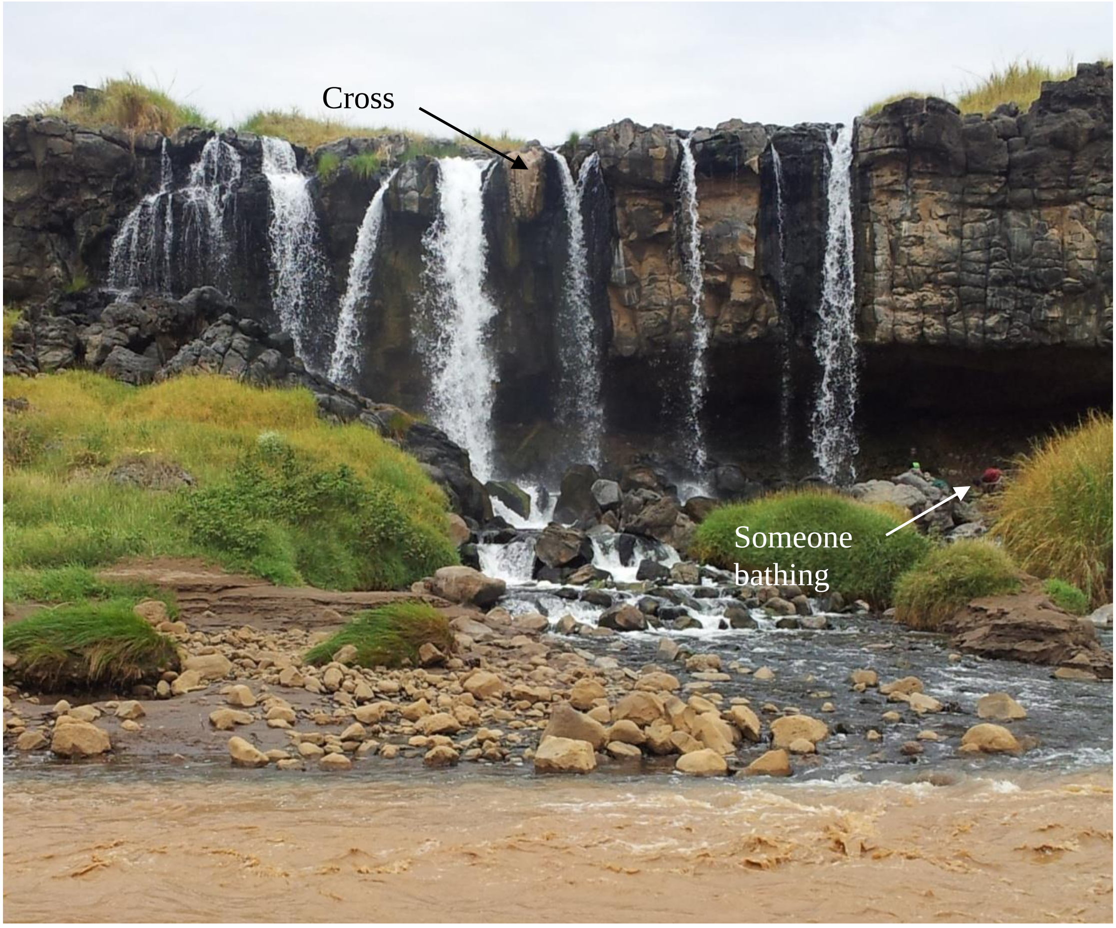

Plate 4.53: A picture showing the hot water falls of the Suguta River, near Kapedo (Source: Author, 2015).

Near the heavier water fall, on the wall, there is an engraving of the cross as known to Christians. This may have been done by Missionaries who had built a church at Kapedo. They are no longer in the area.

The picture also shows someone bathing at the water falls.

Plate 4.54: A picture showing the plain land above the hot water falls, where hot springs are found, on the outer basin (Source: Author, 2015).

To the northeast of Silali basin, there are other spectacular geological features, most of which are visible from the satellite images presented in this research thesis. Examples of these features include a sinkhole and a mass of dark volcanic rock that seems to dip towards the NE. Evidence of this is the direction of water flow from the volcanic rock. When it rains, overland flow, from the bare volcanic rock, runs northeastwards towards the sinkhole. When the sinkhole fills up, its spilled water runs further northeastwards along a valley that appears dry. Notably, the sinkhole does not retain any water for it appears dry on the SPOT satellite image (Plate 4.55) and has vegetation. There could be more sinkholes around Silali basin.

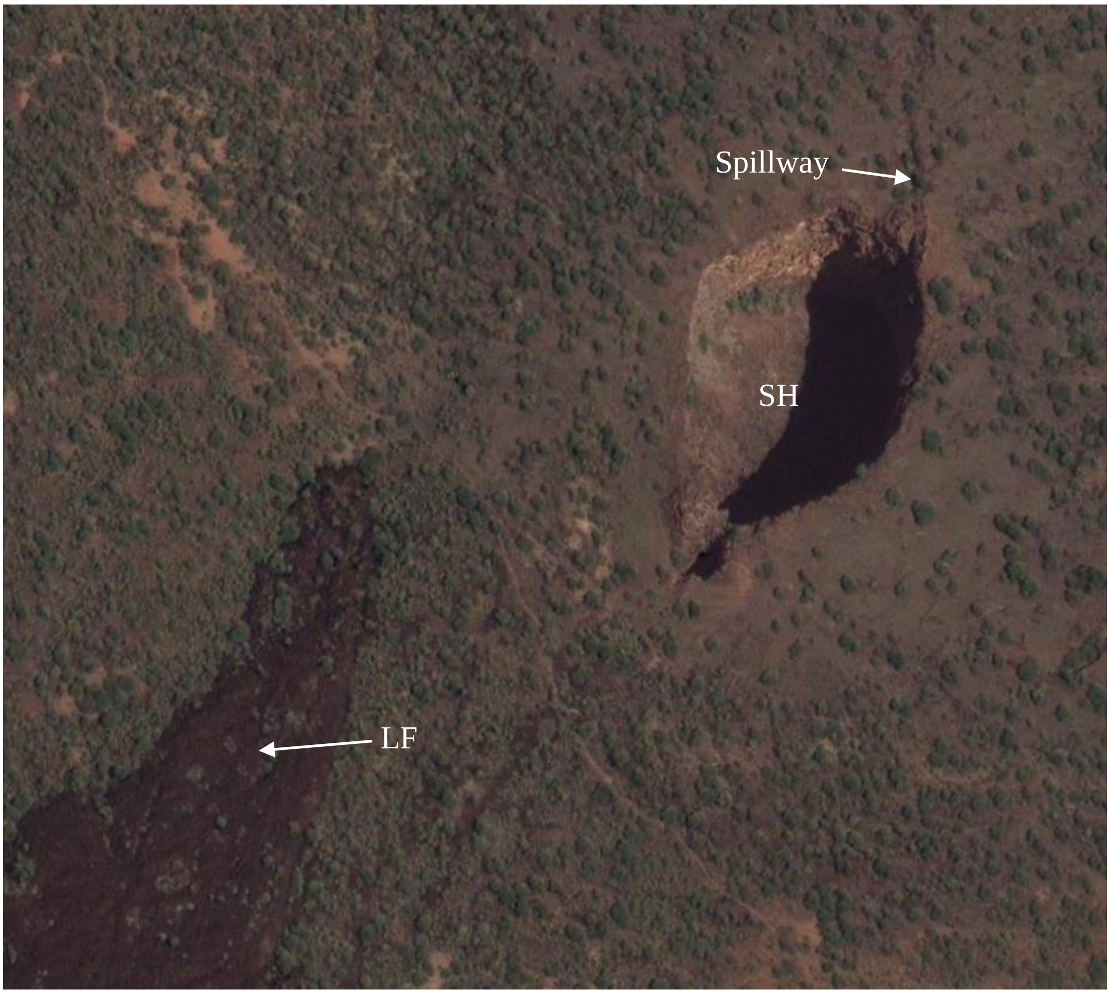

Plate 4.55: A SPOT image showing the lava flow (LF), the sinkhole (SH) and the sinkhole's spillway more clearly (Modified from www.Google.com).

The sinkhole is found to the northeast of Silali basin and the Lava flow starts right at the base of the northeastern wall, flowing outwards. This flow can be seen from the rim of the eastern wall.

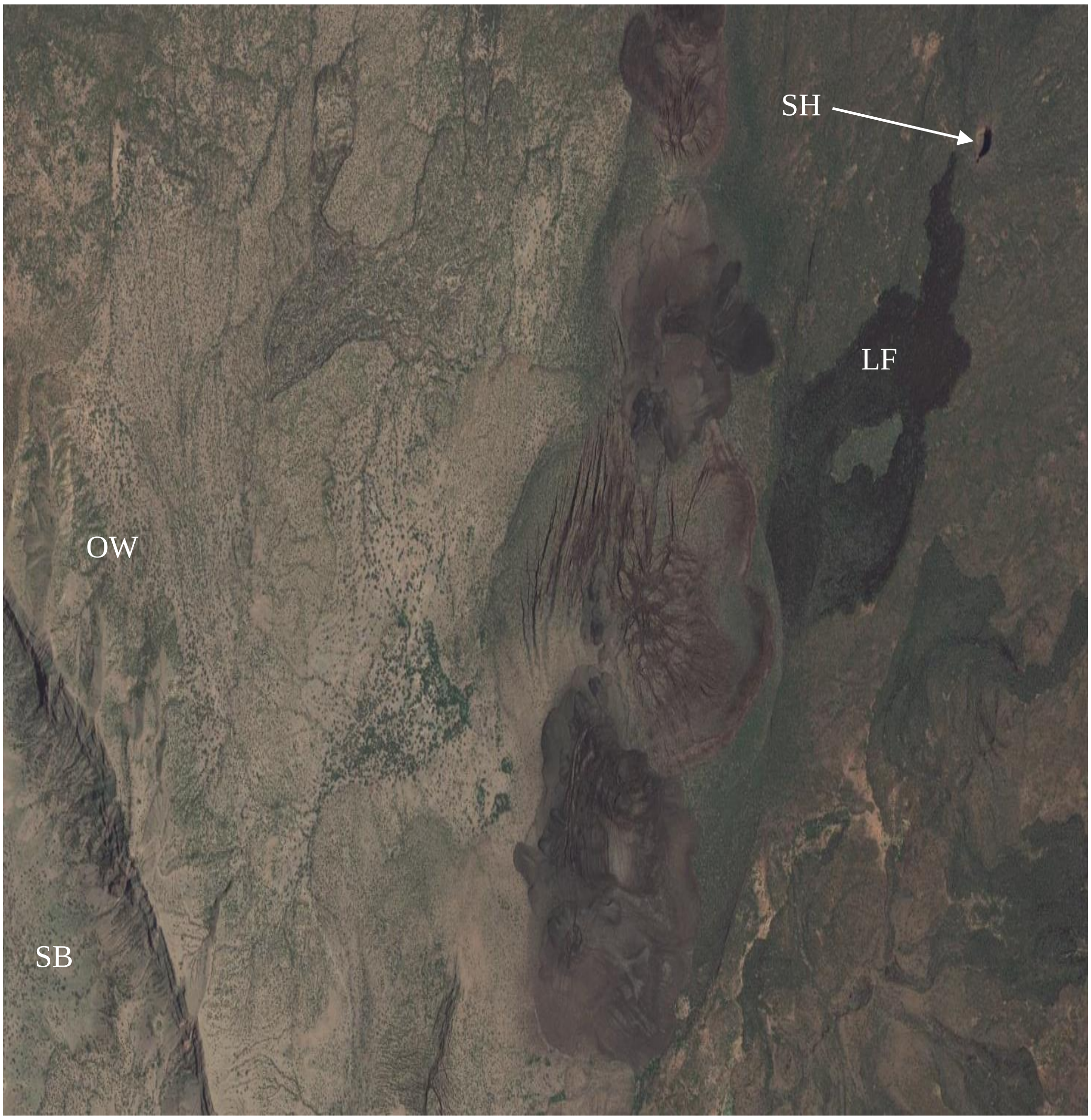

Plate 4.56: A SPOT image showing the sinkhole (SH) and lava flow (LF), Silali basin (SB) and Silali basin's outer wall (OW) (Modified from www.Google.com).

The features shown on Plate 4.56 are found to the east and northeast side of Silali basin. It is the side of the basin where massive lava outpourings appear to have occurred, near the base of the basin's wall. Though the area was inaccessible for a close study, due to insecurity, the image clearly shows the sinkhole and the lava flow, which are shown by Plate 4.55. Plate 4.56 also shows the Silali basin itself, its stepped inner walls and the basin's outer wall on the eastern side. It is important to note the rippling away appearance of the rough dust covering the basin's outer wall. This is a characteristic of the dust that could not be seen clearly while standing directly on it.

In ETICs, 'ejecta are layered thickly at the crater's rim and thin to discontinuous at the blanket's outer edge' (www.google.com). This may probably be because of the decompression wave that follows an impact event, which causes impact ejecta to shrink backwards into the crater.

Plate 4.57: The entrance (E) of one of the large caves found near Natan market, on the plains south of the Silali basin (Source: Author 2014).

The caves could have formed due to the widening up of existing faults around Silali basin, following Silali basin's possible impact. This is in relation to what Thompson and Turk (1992) say about ETICs triggering the formation of major geological features.

Plate 4.58: The cave on Plate 4.57 from the inside (Source: Author, 2014).

4.1.6 Evidence of Volcanicity and Existence of a Magma Chamber

Silali basin's volcanic features are many and splendid; ranging from the volcanic rocks found within and around the basin to the many volcanic cones. Volcanic activity within and around the basin, may have been simultaneous or intermittent and some of the features formed are old while others are young. From chapter two (Silali basin's formation), there is pre-impact volcanicity and post-impact volcanicity. There was volcanicity before the crater formed, that built a volcanic shield around 400-200ka and some volcanic cones around it. Post impact volcanicity is responsible for the volcanic cones inside and outside Silali basin, the ridges within and around, together with the numerous volcanic rocks, hot springs and fumaroles.

The hot springs and fumaroles, as they are, are evidence that Silali basin is a dormant volcanic area that is capable of erupting again in the future.

A serious extra-terrestrial impact, involving a large heavenly body that is able to excavate a crater, can be accompanied by volcanicity, especially if it hits a tectonically active area, such as an old impact crater floor (Outer Basin), upon which the Silali shield rested.

Silali basin's magma chamber is also evidence that Silali basin may be an ETIC. According to McCall and Hornung (1972), there is high and low magma reservoir beneath Silali basin. This magma chamber may be quite restless, being full of uprising and falling of currents, as is expected in any mantle plume. For this reason then, the faults within and around Silali basin exist because of ongoing faulting (evidenced by ongoing slumping), encouraged by hydothermal fracturing. The hot springs and fumaroles also survive because liquids beneath the basin are continually heated up by high temperatures therein and forced to move out of the earth's crust, fanned by the ever renewed heating from the base of the magma chamber. Beneath each impact crater, there may be a mantle plume that is responsible for continued volcanicity in an impact area, as Thompson and Turk (1992) suggested. In the case of Silali basin, the mantle plume would be expected to cover areas outside the basin (regional dimensions) because the impact seems to have been an enormous event.

Volcanism in an area impacted by an extra-terrestrial object is expected and it is quite evident in Silali. In addition, the basin is on the floor of a section of the rift valley which is tectonically active.

4.1.7 Evidence from the Absence of Massive Lava Deposition on the Walls of Silali Basin

As stated earlier, there is no lava deposition on Silali basin's outer wall nor a lava pool on the basin's floor. Lichoro (2013) observed that there is absence of massive lava deposition on the flanks of Silali basin and according to McCall and Hornung (1972), the whole of the Silali volcano has an enveloping of an alluvial apron (sediments). According to the book on the geology of the Maralal area 'the caldera walls have inner vertical drops of about 300 m; they remain unbreached and the caldera is not in filled by a lava pool' (G.o.K, 1987).

Consequently, if Silali basin was entirely a product of volcanic activity, there would be presence of this lava within and all around the basin's flanks.

As it is, the basin is surrounded by an 'apron of alluvium' which is considered to be proximal ejecta or allochthonous in this research. Indeed, an explosive volcanic eruption is capable of depositing lots of dust around a crater and Silali basin's ejecta are similar to volcanic ash because it consists of pulverized rock, minerals and volcanic glass. This would suggest that the dust on the flanks of Silali basin is pyroclastic material erupted from the Silali shield but it is not because volcanic tuff has vesicles and the particles display some distinctive shape in their looseness, such as being blocky, convoluted, vesicular and spherical or plate -like (http://en.wikipedia.org/wiki/volcanic_ash). Silali's dust is loosely crumbled and does not display any specific shape. It is just dust, broken by huge rock blocks in places. The research considers these blocks of rock to be hummocky ejecta and pseudotachylites.

According to McCall and Hornung (1972), Silali walls show a dropped fault block, some scalloping and there is negligible mantling of pumice associated with the actual caldera formation. This means that the caldera formation did not involve massive lava deposition and much of Silali basin's volcanicity either occurred during the shield period, or after the basin formed. This, again, suggests that Silali basin may be an ETIC, whose floor is covered by sediments together with impact melt and the dust around it may be impact ejecta.

4.1.8 Evidence from the Existence of an Older Caldera

In some texts on Silali, there is a belief that Silali basin's 'break off walls' are traces of an earlier caldera (Dunkley *et al.*, 1993). Though some scholars disagree with this, it can be accepted if Silali basin is an ETIC. This earlier crater would be the one that was blasted by impact. As said elsewhere in this work, the older crater is expected to have been wide and shallow, before subsidence occurred. The earlier caldera collapsed, leaving stepped walls made of different volcanic materials with different levels of resistance to denudation (refer to Figure 2.3). Unfortunately, it was not possible to determine the period between the basin's impact event and the time when subsidence occurred. Subsidence may have occurred soon after the impact, probably a few years afterwards but all the processes that led to Silali basin's formation are placed about 62-66 million years ago. Silali basin's blanket of dust, though made up of both older and younger volcanic rocks, probably together with some syngenetic materials like impact melt, may be said to be of the same age as the basin and as it is in old craters like Chicxulub crater, Silali's impact ejecta are not totally eroded because of the 'melt rich ground hugging ejecta flows' that occur after the initial ejecta deposition (https://en.m.wikipedia.org/wiki/ejecta). These cement ejecta. Silica from Silali basin's volcanic rocks also add to the cementation of the ejecta.

4. 1.9 Evidence from the Age of Silali Basin's Probable Impact/Subsidence and ETIC Formation Stage

It is possible that, an extra-terrestrial object may have fallen on the Silali volcanic shield, impacting it almost at the center and forming the Silali crater. Like all other ETICs, the old Silali ETIC, as stated earlier, must have been wide, shallow with a well-defined gentle rim and low gradient walls that were lined by impact melt (the older caldera), about 62-66 million years ago, the period when the caldera is said to have formed.

According to the Extra-terrestrial Impact Hypothesis theory and the findings of the 16 member team of international researchers who carried out research to support the theory, there are only two known continent wide layers of nanodiamonds impact spherules and aciniform soot. These are in the 65 million year old cretaceous-paleogene boundary layer (K-T Boundary) that coincided with major extinctions of many large American animals, including the dinosaurs and ammonites; and the Younger Dryas boundary event at 12,900 years ago, that is closely associated with the extinctions of many more larger North American animals like the mammoths, mastodons, saber tooth cats and dire wolves (Firestone *et al*., 2007). Although research has not been carried out to establish where the 65 million year nanodiamonds boundary in Kenya lies, Silali basin's formation may be placed in this boundary, when widespread impacts occurred on earth. Probably, Silali's nanodiamonds may have been sheared by volcanicity and thermal metamorphism, if at all they existed but, evidence of the 65 million year nanodiamonds boundary could be anywhere in the country.

If indeed Silali basin formed about 65 million years ago, it may have formed at the same time as the 65 million years old Chicxulub impact crater in Mexico and other ETICs which include; Beyenchime crater in Salaatin, Russia (65ma), Eagle butte crater in Alberta, Canada (65ma), Guesev crater in Russia (65ma), Kamensic crater in Russia (63-67 ma), Manson crater in Iowa, USA (64-66ma) and Upheaval Dome in Utah, USA (65ma). See Appendix II.

4.1.10 Myths about the Silali Basin as Evidence of Impact

An ETIC is usually known by the various factors that are associated with it and also by association, as shown by the features associated with the Silali basin, presented earlier. Silali basin though, being a major geomorphological feature in the middle graben, should have some stories about its formation, as known to the people living in or around it.

All major features of the earth's surface, craters included, have myths about their formation and Silali basin is no exception. The people around the basin were questioned about the basin's origin. Unfortunately, they seem not to have a clear view of how the basin came about. The few people who were asked questions said they found it as it is or were born with the feature in existence. One Turkana old man, at Kapedo market, however, had a different view. He said according to his grandfather, some supernatural being created Silali basin, to have a home for itself. The Pokot believe it is the origin of rains.

It must be remembered that in Africa, where literacy is a recent affair, information about major events that took place in people's lives were recorded in narratives, folktales and myths, that the people have passed down from generation to generation. The Silali event included.

4.1.11 Evidence from Laboratory Tests

Laboratory tests were carried out on the Kimwiri meteorite, Chemolingot rock, Kiptabar rock and solid rock samples from Silali basin. The tests were done by the department of Mines and Geology, Nairobi, Kenya. The results were as shown by Tables 4.1-4.5.

Plate 4.59 shows the approximate sample sites for Silali sampled rock particles (A-D).

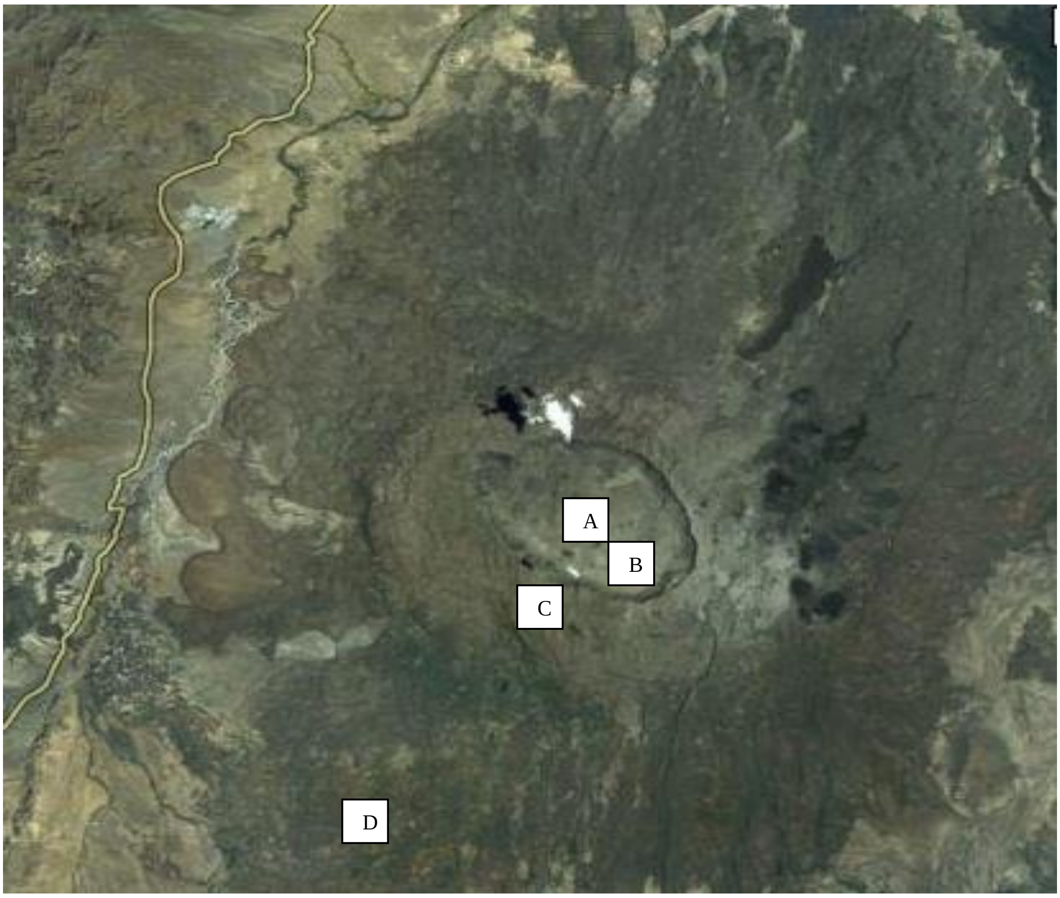

Plate 4.59: A natural color SPOT satellite image showing the sample sites for Silali's sampled rocks (Modified from www.Google.com).

Table 4.1: Chemical composition of the Kimwiri meteorite (Department of Mines and Geology, 2014).

Application	Manual
Sequence	1 of 1
Measurement time	20th July 2011 at 10.04 am
Position	1

Oxide	SiO_2	Al_2O_3	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	SO_3	NiO
Conic Unit (%)	40%	8%	3%	0.4%	0.5%	0.6%	52.4%	0.6%	1.9%

Table 4.2: Chemical makeup of the Chemolingot rock (Department of Mines and Geology, 2014).

Application	Manual
Sequence	2 of 1
Measurement time	17th and 18thDecember 2012 at 13.05 pm and 2.00pm.
Position	1

Oxide	SiO_2	Al_2O_3	SO_3	TiO_2	CaO	MnO	Fe_2O_3	K_2O	CuO
Sample 1	44%	21%	0.10 %	3.0%	12%	0.20 %	17.6 %	1.1%	0.3%
Sample 2	50.32 %	17.12 %	0.90 %	2.62 %	9.0%	0.60 %	17.0 %	0.77 %	0.2%
% Average	47.16 %	19.06 %	0.5%	2.81 %	10.5 %	0.40 %	17.3 %	0.94 %	0.25 %

Table 4.3: Chemical composition of the Kiptabar rock (Department of Mines and Geology, 2014).

Application	Manual
Sequence	1 of 1
Measurement time	17th December 2012 at 13.02
Position	1

Oxide	SiO_2	Al_2O_3	SO_3	TiO_2	CaO	MnO	Fe_2O_3	K_2O	CuO
Conic Unit (%)	93.8 %	4%	0.53 %	0.09 %	0.11 %	0.06 %	0.7%	0.5 %	0.07 %

Table 4.4: Chemical composition of some rock particles from Silali basin (Department of Mines and Geology, 2014)..

Application	Manual
Sequence	4 of 5
Measurement time	17th December 2012 at 14.00
Position	(refer to Appendix IV)

Oxide	SiO_2	Al_2O_3	SO_3	TiO_2	CaO	MnO	Fe_2O_3	K_2O	CuO
Silali A	60.47%	14.45 %	-	1.66 %	0.20 %	0.40 %	12.90 %	2.50 %	-
Silali B	60.43.0 %	14.68 %	-	2.0%	0.57 %	0.40 %	7.80%	3.30 %	-
SilaliC	60.65%	16.70 %	-	0.20 %	1.43 %	0.50 %	6.99%	4.60 %	-
SilaliD	60.99%	14.37 %	-	0.54 %	1.38 %	0.50 %	9.72%	4.30 %	-
% Average	60.64%	15.05 %	-	1.10 %	0.90 %	0.45 %	9.35%	3.67 %	-

Bar graphs were used to show the chemical compositions of the rocks sampled and the results are as shown in Figures 4.12- 4.15.

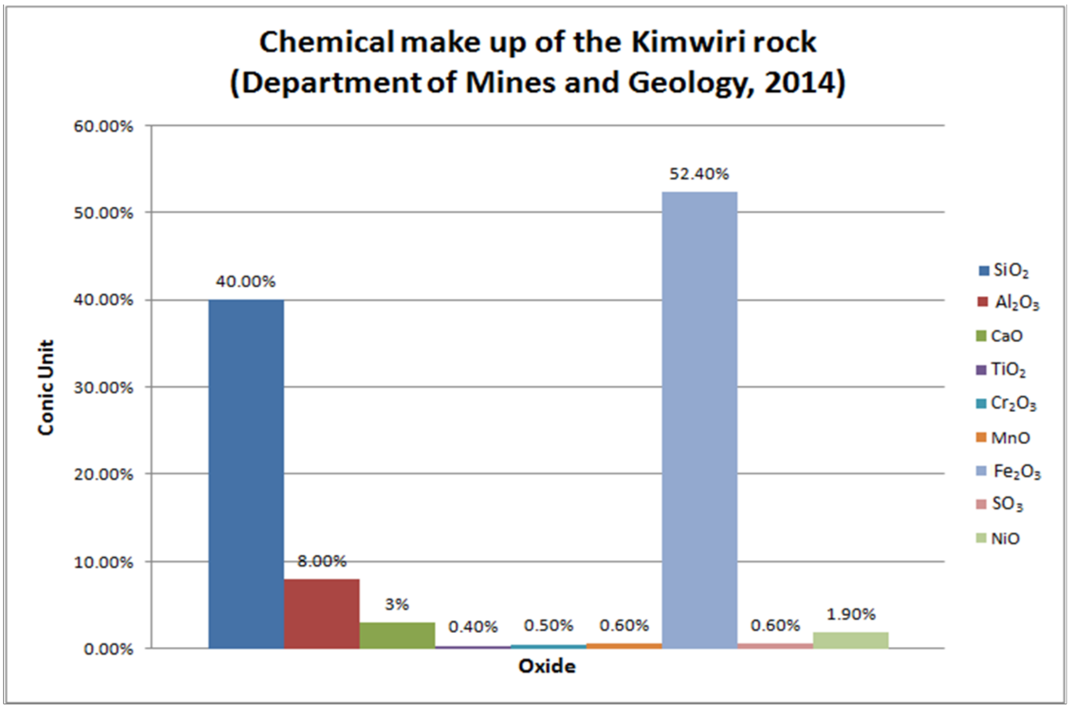

Figure 4.12: Chemical composition of the Kimwiri meteorite (Source: Author, 2015).

From the study, the chemical composition of Kimwiri meteorite was as summarized by Figure 4.12. The rock showed it is made up of 52.4%, Fe_2O_3, 40% SiO_2 and negligible TiO_2 and MnO, among the other elements. Fe_2O_3, thus, is more prevalent in the rock, followed by SiO_2, SO_3 and the other elements shown by Figure 4.12. Generally, the Kimwiri meteorite comprised of a higher proportion of Fe_2O_3 and SiO_2.

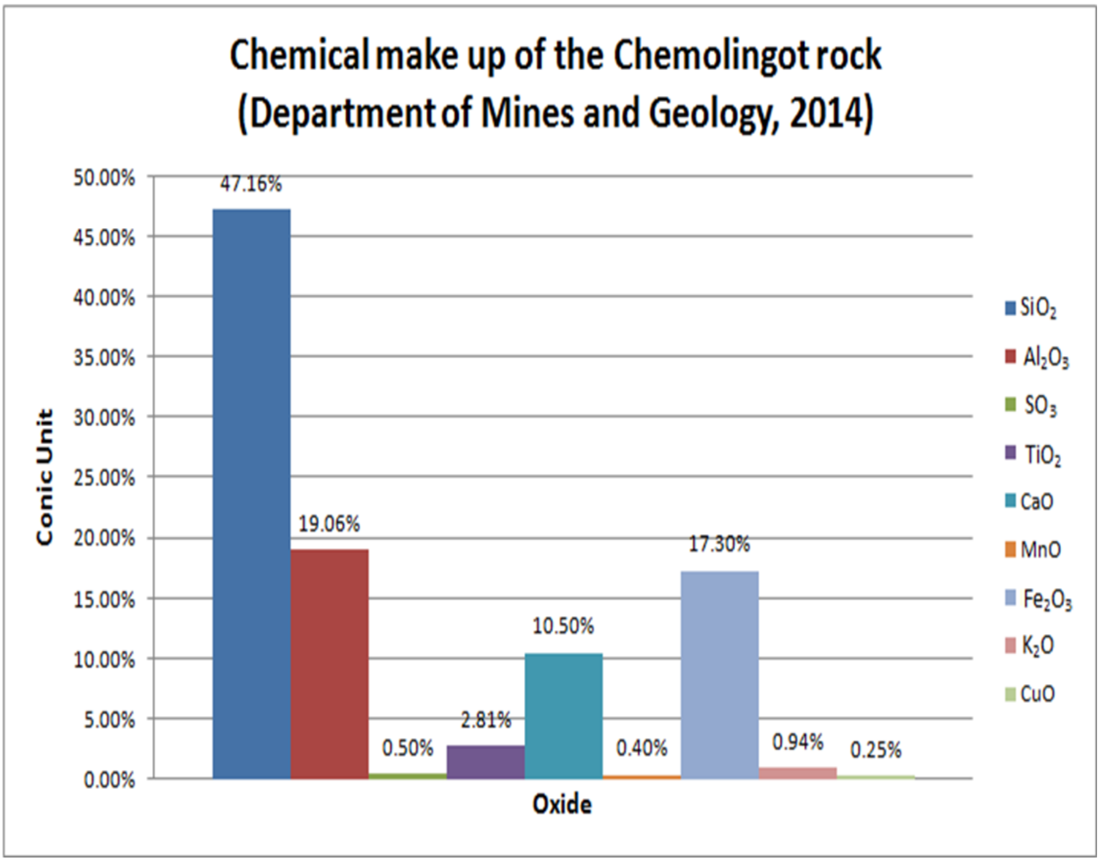

Figure 4.13: Chemical composition of the Chemolingot rock (Source: Author, 2015).

From the study, the chemical composition of the Chemolingot rock was as summarized by Figure 4.13. It comprised of 47.16%, SiO_2 and 17.3% Fe_2O_3. This shows that, like the Kimwiri meteorite, the Chemolingot rock comprised of higher proportions of Fe_2O_3 and SiO_2. Interestingly, the Chemolingot rock has a high percentage of Al_2O_3, at 19.06%, similar to the Silali rocks.

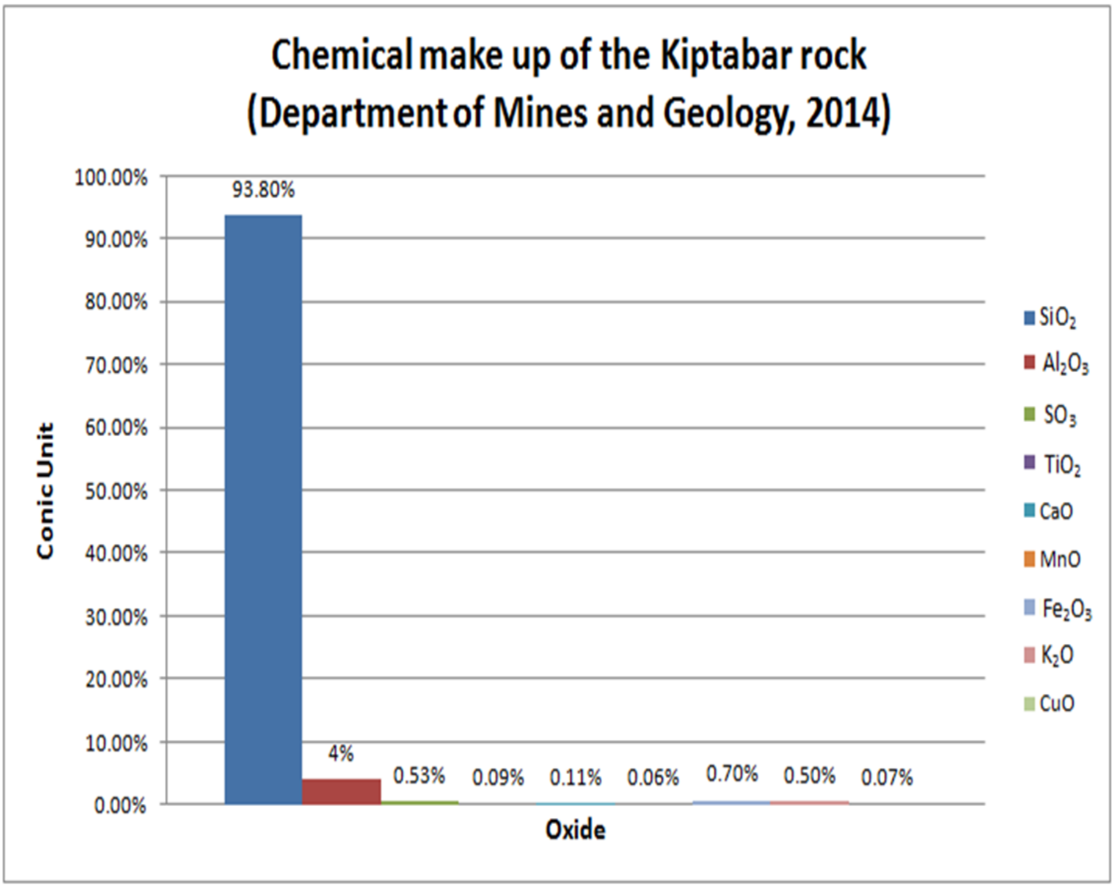

Figure 4.14: Chemical composition of the Kiptabar rock (Source: Author, 2015).

From the study, the chemical composition of the Kiptabar rock was slightly varied as summarized by Figure 4.14. The rock comprised of 93.8% SiO_2, 4% Al_2O_3 and other elements in very small percentages. This showed that the Kiptabar rock comprised of a higher proportion of SiO_2. With a percentage of 93.8% SiO_2, rock appears to be an almost pure silicate rock. Indeed, it is brilliant white in color with a few impurities.

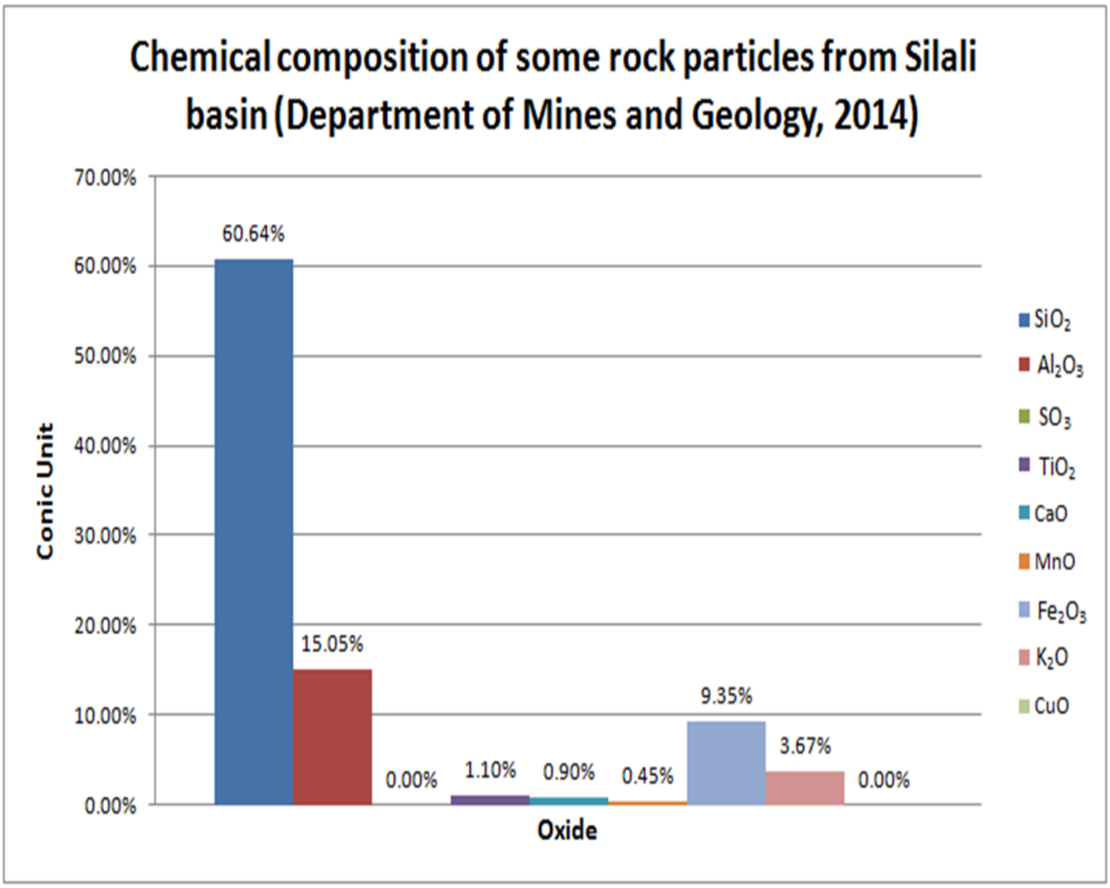

Figure 4.15: Chemical composition of some of the rocks from Silali basin (Source: Author, 2015).

From the study, the chemical composition of rocks from the Silali basin was varied as summarized in Figure 4.15. Using a percentage average, the rocks comprised of 60.64% SiO_2, 15.05% Al_2O_3, 9.35% Fe_2O_3 and 3.67% K_2O. This showed that the rocks from the Silali basin comprised of a higher proportion of SiO_2, followed by Al_2O_3 and Fe_2O_3, almost like the Chemolingot rock. A similarity with the Kimwiri meteorite is in the higher percentages of SiO_2 and Fe_2O_3.

4. 2 Discussion

4.2.1 A Comparison of the Chemical Composition of the Kimwiri Meteorite, the Chemolingot Rock and Silali Basin Rocks

A table and a comparative bar graph were used to compare the chemical composition of the rocks sampled by the study and the results were as follows:

Table 4.5: A comparison of the chemical composition of some of the rocks sampled (Department of Mines and Geology, 2014).

Oxide	**Sample Rock**		
	Chemolingot	**Silali**	**Kimwiri**
SiO_2	47.16%	60.64%	40.00%
Al_2O_3	19.06%	15.05%	8.00%
TiO_2	2.81%	1.10%	0.40%
CaO	10.5%	0.90%	0.50%
MnO	0.40%	0.45%	0.60%
Fe_2O_3	17.3%	9.35%	52.4%
K_2O	0.94%	3.67%	0.60%

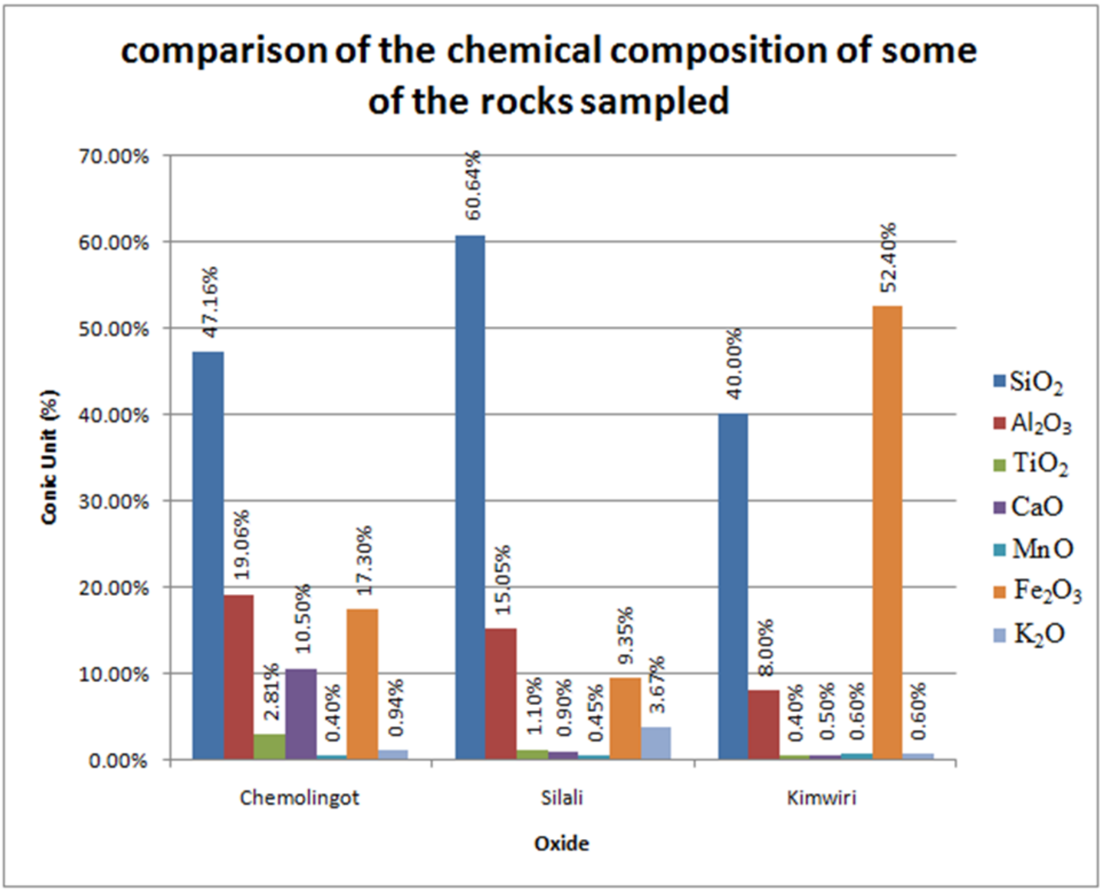

Figure 4.16: A comparative bar graph of the chemical composition of the rocks sampled (Source: Author, 2015).

From Figure 4.16, Kimwiri meteorite, the Chemolingot rock and the rocks from the Silali basin shared certain characteristics that include: All the three rocks having similar chemical elements, among the sampled ETIC related oxides, though in varied percentages. The rocks also had higher percentages of SiO_2. Again, Al_2O_3 is present in all the three rocks at very close percentages and the rocks are rich in Fe_2O_3. This shows that meteorites, at times just look like common igneous rocks.

4.2.2 Summary of the Laboratory Test Findings

From the tables and the graphs, the following observations can be made: Kimwiri meteorite is a stony-iron meteorite. It is also a fall because it was observed as it transited the skies and impacted on the earth's surface. It has large amounts of iron and rocky material, like silica. The Chemolingot rock is very similar to an igneous rock. It compares well with the Silali rock as shown by Figure 4.15 but unlike the Silali rock, the Chemolingot rock is rich in iron at 17.3% compared to 9.35% posted by the rocks from Silali. Interestingly, the Chemolingot rock has rounded brown particles that may be taken to be chondrules, making the rock a suspect chondrite meteorite, as stated earlier. In fact, from the definition of a meteorite in the preliminary pages of this research, a meteorite is rich in silica and iron, as in the case of the Kimwiri meteorite and the Chemolingot rock. This enhances the possibility that the Chemolingot rock may actually be a meteorite.

Kiptabar rock, on the other hand, may indeed be a stony meteorite. It is rich in silica (93.8%), being an almost pure silicate rock. It must then be an achondrite because it lacks chondrules and because of the general belief that most of the meteorites found on the earth's surface are achondrites that are similar to igneous rocks such as basalts (http://en.wikipedia.org/wiki/meteorite). It is said that stony meteorites consist mainly of silicate minerals and most achondrites are from planet Mars and the moon (www.nhm.ac.uk/nature online on 20th April 2014). Kiptabar rock, thus, may have come from a closer source, such as the moon or planet Mars, as mentioned earlier.

The Silali rock is a typical volcanic rock; rich in varied minerals. Comparison of the chemical composition of the Chemolingot rock and the Kimwiri meteorite, indicates that the two rocks are very similar. They both have silica of almost similar proportions (47.16% for the Chemolingot rock and 40% for the Kimwiri meteorite) and both are rich in Fe_2O_3 (52.4% for Kimwiri meteorite and 17.3% for the Chemolingot rock). Kimwiri meteorite, probably because of its recent age and less exposure to oxidation and other forms of weathering, has more iron as opposed to the Chemolingot rock. The rocks also share similar chemical elements at varied percentages. A point of difference is Chemolingot rock's 19.06% Al_2O_3 percentage as compared to 8.00% percentage for the Kimwiri meteorite. This may be because the rocks are two different meteorites from different sources. The Kimwiri rock is an iron-stony meteorite while the Chemolingot rock could be a chondrite meteorite, as mentioned earlier. If the Chemolingot rock is a meteorite, it means that the Silali basin, the outer basin and the other smaller craters may all be ETICs.

4.2.3 Silali Basin is not a Maar

Silali basin is quite similar to a maar because it has very steep walls that have been made gentle by slumping, has a raised rim, has volcanic rocks and has alluvial deposits on its floor. The basin, in fact, has one maar characteristic; it has lake deposits on its floor, especially calcrete, which is a calcium carbonate rock. It appears that Silali basin may have been occupied by a lake in the past (L. Silali) and this is not uncommon in ETICs as there are ETICs with lakes even presently. Examples are the Clear water lakes of Quebec, Canada.

Silali basin, though, does not qualify to be a maar because, unlike a maar, Silali basin's floor is hummocky and not flat. Again, the basin is not currently filled with water and does not have indications of a diatreme; a breccia filled volcanic pipe that was formed by a gaseous explosion. This is because according to past studies carried out in the area, Silali basin was not formed by a central pipe or conduit. According to Mc Call and Hornung (1972) for instance, Silali volcano was built by clustered vents and not a central pipe. From the book on Geology of the Maralal area (G.O.K 1987), Silali is a composite volcano; a dome built by clustered vents. Similarly, from resistivity studies (Figures 4.4-4.6), Silali basin does not show a cylindrical portion of high resistivity at its center, beneath the subsurface layer of low resistivity. The basin is not also backfilled by volcanic fragments as it is the case with most volcanic craters. It may not also be considered a volcano because it is not found at the top of a volcanic edifice the way summit craters are found at the top of volcanic cones, such as the nearby Mt. Paka. The lack of a cone shape in the raised area surrounding the basin is clearly visible, even from the side captured in Plate 4.60.

Plate 4.60: A picture showing the outside western walls of the Silali basin, *per se* in the background, at a distance (Source: Author, 2015).

Upon crossing the wall, there is a descent into the Silali basin. Notably, the basin lies to the East of Mt. Tiati, an extinct volcano, which is quite high (about 3000 m above sea level) and endowed with the usual climatic conditions that are prevalent in most of the Kenyan highlands. From the Kerio Valley, the bamboo covered summit of the mountain can be seen clearly. To the south of Silali basin, is Mt. Paka, which is a dormant volcanic mountain, alive with fumaroles and steam jets in addition to a crater on its summit and parasitic craters on its sides.

4.3 Environmental Effects of Silali Basin's Cratering

A major impact event releases the energy of several million nuclear weapons detonating simultaneously when a heavenly body of a few kilometers, in diameter, collides with the earth (https://en.m.wikipedia.org/wiki/impact_event).The energy released by an impact event and the impact itself has different effects on the environment; both physical and human environment. These effects may be local, regional and global, in terms of scale. Notably, the effects decay with an increase in distance from the impact area.

As mentioned earlier, many impact events known today occurred millions of years ago so that there is no one alive to tell about their environmental effects. Consequently, the effects of impact cratering can be deduced from scientific studies and from recent impact events. This applies for Silali basin.

It must be noted though that an extra-terrestrial impact event takes place in the environment and affects both the physical and the human environment vertically and horizontally. The possible effects of an extra-terrestrial impact event on an area's physical environment would include:

i) Dust Displacement and Climate Change

The dust that is displaced by an impact event can blanket the earth's atmosphere, preventing terrestrial radiation from escaping the earth's surface. This causes global warming and its many problems. The same dust, in the long run, may reduce solar radiation reaching the earth's surface enhancing cold temperatures and glaciation, even globally. Silali's impact may have contributed to climate change 62-66 million years ago if it occurred alongside other impacts such as the Chicxulub impact (65 million years ago).

ii) Volcanicity

Impact cratering can initiate or enhance volcanicity in an area. Volcanicity can occur in an impact area, if a hypervelocity object deeply fractures target rocks, providing conduits for magma to explode. Extra-terrestrial impact can also enhance volcanicity if it deepens or widens existing fault lines, causing volcanic eruptions to occur. This appears to have happened in Silali basin, causing the crater to subside.

iii) Fire Breakouts

Fire ball impact events, such as the Tunguska fire ball in Siberia or the recent Kuresoi (Kenya) impact event (Thursday 27th February 2014), can cause massive fire break outs that can destroy life on earth. This may have happened in Silali basin, especially with the proposition that Silali basin and the craters around it may have been formed by a heavenly body that exploded above the area, causing multiple impacts.

iv) Earthquakes

Impact events are associated with tremors and earthquakes because of their ability to shift rocks. The Kahuho farm-Thika impact event (Kimwiri meteorite) was reported to have caused a tremor when a small heavenly rock fell on a dusty maize field near Thika town, on Saturday 16th July 2011. Silali's impact event, from the impactor's size (0.25-0.4 km wide) may have caused a serious earthquake in the area.

v) Landscape Remodeling

Extra-terrestrial impact cratering can alter the face of the earth by constructing new geomorphological features or destroying existing landforms. In Silali, impact cratering may have led to the formation of Silali basin and the other craters, ejecta deposits, gorges and caves. According to Thompson and Turk (1992) extra-terrestrial impact cratering is responsible for many geological processes on the earth's surface.

vi) Disruption of Life on Earth

Huge impact events can have negative biospheric effects that include collapse of food chains and ecosystems with a single swipe. The formation of the Chicxulub crater 65 million years ago, for instance, is associated with the extinction of dinosaurs and other mega fauna (Kring, 2000). This is because mega impact events can cause coast to coast fires that can kill plants and animals or bring about glaciation. Both ways, plants will die and the food shortage that will ensue will kill animals. This may have happened following Silali basin's formation, noting that Silali basin appears to have formed about the same time as the Chicxulub crater (between 62-66ma).

vii) Ozone Depletion

Besides ordinary dust, impact ejecta are associated with chemically active gas components such as aerosols that produce SO_2, SO_3 and greenhouse gases especially H_2O and CO_2. Impact events are also associated with ozone depleting gases such as Br and Cl (Kring 2000). Aerosols yield acid rain that can cause chlorosis in plants and poison water bodies. Br and Cl are produced from the projectile-target water or target rocks interaction and post impact wild fires (Kring, 2000). Acid rains may have occurred in Silali basin but without eye witnesses, further scientific studies in the area may be relied upon to unearth ancient chlorosis.

viii) Tsunamis

Impact events are known to cause tsunami waves which are destructive in their own way. Silali's impact may have caused an earthquake that would have affected the whole of what is Kenya's landscape today and possible tsunamis in the nearby Indian Ocean and lakes.

On the human environment, the effects of Silali's impact cratering was inferred from what has happens to human environments in the event of an extra-terrestrial impact, especially HVIs. The reason for this is the fact that humans are about 200,000 years old on the earth's surface and consequently, there is no one alive in Silali area who was alive 66-62 million years ago when the impact would have occurred.

The effects of Silali basin's extra-terrestrial impact cratering on the human environment, from literature and looking at the future, may include:

i) Destruction of property due to acid rains that destroy crops and kill animals through poisoning of water bodies, impact events that collapse buildings and infrastructure and wildfires that destroy the human environment.

ii) Death of People, which may result from some impact related episodes such as: Impact shock and trauma, burial by impact ejecta, propulsion by impact explosion, noxious gases and impact related accidents. On 15th September 2007, for instance, a chondrite meteor crashed near the village of Carancas in southeast Peru, near L. Thicaca, leaving a water filled hole and spewing gases across the surrounding areas. Many residents became ill from the poisonous gases (http://en.m.wikipedia.org/wiki/impact_event). Similarly, on 15th February 2013, an asteroid airburst occurred over the city of Chelyabinsk, Russia, at an altitude of 30-50km above the earth's surface. About 1500 people were injured by broken window glasses and the fireball cost $30 million in losses (http://en.m.wikipedia.org/wiki/impact_event). This shows that impact airbursts as well as earth surface collisions can cause death. Silali basin's impact may have killed some people, if the area was inhabited 65 million or so years ago.

iii) Sickness, poor health and injury as it happened in Russia following the extra-terrestrial impact fire ball event over the city of Chelyabinsk on 15th February 2013 and the meteorite impact that occurred in Peru, near the village of Carancas on On 15th September 2007.

Impact cratering also has positive effects on both the physical and the human environment. Some scholars believe that impact craters provide shelter for early life forms especially microbes (Charles, 2014). Impact events are also associated with rare minerals such as PGMs and important minerals like gold, nickel and diamonds. Petroleum can also be found in an impact crater, probably because an impact crater can trap migrating petroleum or because of impact ejecta burying massive vegetation and creating hydrocarbons. The spectacular landforms that are created by impact cratering, such as the gorges, craters and volcanic cones can be used for economic purposes, such as tourism.

4.4 Summary of Chapter Four

It is worthwhile noting that it is difficult, at times, to differentiate between volcanic calderas and ETICs. For this reason, some ETICs are called calderas and this is not wrong as long as volcanicity is not invoked and because basically, a caldera is a huge crater. Crater Lake, in Canada, is referred to as a caldera in some texts (Traver, 2007). The following are the characteristics of volcanic calderas that make them similar to ETICs:

- Inner topographic wall; a steep wall on its upper parts but concave to flat down the slope. This is a scarp modified by mass wasting. Silali basin has such a wall.
- Collapse collar; the volume of rock lying between the topographic wall and the boundary of the caldera floor (Marti *et al*., 1994). It is a product of mass wasting and wall retreat. This is the slumped material in an ETIC.

- Bounding faults (ring faults); which in many calderas are attributed to doming and can accommodate uplift or subsidence. This, for Silali basin, may be the product of impact cratering.
- A caldera floor; which comprises of subsided pre-caldera land surface and volcanic materials. For an ETIC, it is hummocky and can contain sediments, as in the case of Silali basin, where more complex rocks may be buried beneath the sediments. Volcanic rocks are also found around the cones, the small craters and the ridges.
- Intra-caldera fill; the material that is erupted during and after the caldera forming event or deposited due to the subsidence of the magma chamber. It is composed of volcanic tuff and grit. This material can be expected in a volcanicity riddled ETIC, such as Silali basin. Notably, Silali basin is not infilled by a lava pool (G.o.K. 1987).
- Sub-caldera magma chamber; which is in the form of a solidified pluton or batholith that is a few kilometers from the crater floor, with a roof zone protruding onto the crater floor. It is associated with uplift and tensile stresses that encourage ring faulting in a volcanic crater that is associated with a vent eruption. For an ETIC, though, a mantle plume would be inferred. This may be deep within the area of impact and spreading for many kilometers, but its roof would be felt just beneath the ETIC's floor. It is equally associated with uplifting, as the magma attempts to flow out to fill the crater created by impact. It may be the factor behind the construction of the volcanic cones found inside and outside the Silali basin.

As a result of these characteristics, many ETICs have been considered volcanic craters. Tenoumer impact crater in Mauritania, for example, was considered an ancient volcano in 1950s because of scattered basalt rocks around the crater. It remained so for years but in 1970s, following fresh investigations, PDFs were found within the basaltic rocks around the crater and the crater's origin was confirmed to be impact related. Tenoumer ETIC is filled with a 200-300m thick layer of sediments and its inner walls are very steep, just like in the case of the Silali basin.

To conclude Chapter Four and as stated earlier, Silali basin is a possible ETIC that is rich in volcanic features. Old and recent volcanicity has created many volcanic features in Silali basin to an extent that the basin can easily pass for a volcano and it would have been so if this study had not been conducted. The study, thus, has introduced a new perspective into the basin's formation through extra-terrestrial impact cratering. It has also revealed the ETIC characteristics of the basin, proving that the basin may indeed be an ETIC.

Silali basin, as mentioned earlier, is a basin within an older basin and it sits on volcanic rocks of different ages, some older than the basin, such as those that built the Silali shield (400-200ka). According to McCall and Hornung (1972), the foundation upon which Silali rests comprises of lower pleistocene and older intermediate/acid volcanics. In fact, Silali basin may have formed as an ETIC, not only on an area of volcanic rock but on a volcanic shield. For this study, Silali basin is a possible ETIC that formed on a volcanic shield, that itself formed on a tectonically unstable volcanic ground, as evidenced by the faults that run across the basin, in a North-South direction, as shown by the simplified geological map of Silali basin (Figure 2.1) . It would be expected that the faulting in Silali was not only influenced by localized forces, but by regional forces that link up to the Great Rift Valley formation. From the available data, Silali basin seems to have a complex formation involving volcanicity, extra- terrestrial impact and subsidence, as explained in chapter two.

Silali basin is surrounded by a larger outer basin, which has smaller craters in some parts. If Silali basin and the small craters around it were formed by an extra-terrestrial impact cratering event, then it is possible that a heavenly body might have exploded in space, just above the area, fractured into smaller fragments with a larger piece creating the Silali basin, while smaller pieces created the craters around and within the outer basin.

The study had two specific objectives which were to:

i) Map and characterize the Silali basin/crater and provide evidence on the nature of its formation.
ii) Document the effect that the cratering of Silali had on the environment in the area.

Chapter Four has addressed these objectives and the study has made it possible to map out and characterize the Silali basin, besides providing evidence on the nature of the basin's formation as a possible ETIC. It has also brought to light the possible environmental effects of Silali's basin's possible impact cratering.

The various satellite images, topographical maps, the DEM, the LIDAR image and the morphological sections all show Silali basin's near circular morphology and morphological related features such as the stepped walls of the basin, slumped walls, the hummocky terrain of the baisn's floor and impact ejecta.

The basin has been characterized as a possible ETIC; a complex crater or basin, that has been heavily affected by tectonic movements, volcanicity and denudation. The various ETIC characteristics of Silali basin, as discussed in this chapter, include:

1) **Circular Morphology and Related Features**

   The satellite images, the topographical sheets, the LIDAR image, the morphological sections and the DEM all show that Silali basin has a circular morphology, just like other ETICS all over the world. The basin also has ETIC-related features such as those discussed in the chapter. It is a depression as shown by the cross-sections or morphological sections.

2) **The basin's Geophysical Characteristics**

   Silali basin's complex seismic and magnetic character, together with the layer of low resistivity beneath the surface layer, all indicate that Silali basin is an ETIC. The high gravity signature though, is an anomaly for an ETIC because ETICs post a low gravity signature. As Mariita (2003) observed, the gravity data over Silali basin is too sparse to give a detailed picture of a localized anomaly.

3) **The Basin's Geology**

Gold, copper, iron and nickel are minerals associated with ETICs and they are found around Silali basin. According to Dunkley *et al*., (1993), breccias make up the north eastern walls of the basin. There are breccias on the outer basin as well. The basin is also associated with pseudotachylites, allochthonous (especially ejecta), tektites and shatter cones, such as the Chemolingot shatter cones on the outer basin. The top most rock layer of Silali basin's wall also appears to be made up of shatter cones (Plate 4.32).

4) The Geological Features of the Outer Basin

According to Thompson and Turk (1992) extra-terrestrial impact cratering is responsible for many geological processes on the earth's surface. The Suguta gorge, the sinkhole, the cave, lava flows and volcanic cones, all found on the outside basin, may all be associated with Silali's extra-terrestrial impact.

5) Absence of Massive Lava Deposition on the Walls of Silali Basin and Floor

Plate 2.1 (Silali's simple geological map) shows that the rock/soil material making up Silali basin's walls is not uniform. For a crater as large as Silali basin, one would expect massive lava flows on the caldera walls, if the caldera was as a result of volcanicity. The glaring absence of massive lava flows on Silali basin's walls has also been noted by other scholars who have visited the area. According to Lichoro (2013), there is absence of massive lava deposition on the flanks of Silali basin and according to the study on the geology of the Maralal area; there is no lava pool in the basin (G.o.K, 1987).

6) Presence of Impact Ejecta

According to McCall and Hornung (1972), the whole of Silali volcano has an enveloping of 'alluvial apron'. This alluvial apron is the dust on Silali's wall, which has been described as comprising of pulverized volcanic rock and volcanic glass. It is what the study calls 'impact ejecta' on the walls of the basin. The ejecta are loosely crumbled and do not display any specific shape as in the case of volcanic ash that can be blocky, convoluted, vesicular, spherical or plate-like.

7) Volcanicity and Existence of a Magma Chamber

Silali basin is rich in volcanic features such as the cones, ridges and volcanic rocks inside and around the basin. This may be the reason why all earlier scholars concluded that it is a volcanic crater. Tenoumer crater, in Mauritania, was also known as a volcanic crater for twenty years until PDFs were found in its rocks in 1970 (Dunkley *et al.*, 1993). Like Silali basin, Tenoumer crater is filled with a 200-300 thick layer of sediments and its inner walls are very steep. As explained in chapter two, Silali's volcanic characteristics are related to the basin's origin that includes a volcanic shield that was blasted by an extra-terrestrial object. This is possible because heavenly objects can fall anytime and anywhere on the earth's surface. There is ongoing volcanicity in Silali basin and this may be attributed to the mantle plume beneath the basin (if it is an ETIC) or the magma chamber that many authors have alluded to. According to McCall and Hornung (1972), there is a high and low magma reservoir beneath Silali basin. According to Simiyu and Keller (1997), the distinctive positive seismic anomaly in the middle of the graben is due to a dyke injection related to reservoir magma.

8) Existence of an Older Caldera

Early scholars of Silali basin suggested the existence of an older caldera before the current one. According to them, Silali basin's break-off walls are traces of an earlier caldera (Dunkley *et al*., 1993**.** This theory was rejected by other scholars who proposed that for the theory to be plausible, some mechanism of topographic inversion is required (Williams *et al*., 1984). For the study at hand, the mechanism of topographic inversion that can explain the existence of an older caldera is an extra-terrestrial impact which created a wide shallow crater on a volcanic shield. Later, the crater sudsided to form the current one, that narrows inwards, as shown by the cross-sections.

9) Silali Basin's Formation

The study at hand is in agreement with older studies, especially pertaining to the existence of an old volcanic shield on Silali and crater subsidence. The point of divergence is on the crater formation process and the origin of the grid faults found within the precincts of the basin. For all the earlier scholars, Silali crater is a volcanic crater that was formed by alternate periods of faulting, subsidence and infilling that is associated with volcanic activity (Dunkley *et al*., 1993). According to McCall and Hornung (1972), Silali volcano was built by clustered vents and not a central pipe. From the book on the geology of the Maralal area (G.o.K 1987), Silali is a composite volcano; a dome built by clustered vents through a first phase of quiet trachyte effusion, followed by emission of trachyte pyroclasts and a return of quiet effusion. Later, the shield suffered some sagging in which a fine grid of normal faults developed, following the extensive emissions of thin basalt from many small vents situated along these fracture lines (G.o.K, 1987). From this explanation, one would expect multiple centers of rock layers making up Silali basin's wall. As it is, the basin's walls have continuous uniform layers of different rocks which are neither of the same age nor composition. This alone, shows that Silali volcanic shield existed and it was not built by a cluster of vents but by a central fissure and probably a few parasitic fissures that built the old cones on the western walls of the Silali basin. The book does not state whether the fine grid of normal faults are on the floor of the crater or on the walls, where Silali basin's ring fracture is evident. If they are on Silali's walls, then it would mean that lava would build up the outer walls of Silali basin, which is not the case. If they were on the crater's floor, it would mean that the basin's floor would consist of a network of criss-crossing ridges or fault lines, which is also not the case because the floor has cones, craters and broken ridges that seem to be a part of a ring formation (Silali's peak ring). Consequently, while the book attributes the formation of the grid faults to subsidence, the study pegs their existence on rock fracturing following an extra-terrestrial impact. The study also does not support the existence of a central pipe in Silali basin but suggests the existence of a central fissure with minimal branches. Again, for the study, there was no major volcanic eruption in Silali to create a caldera. Instead, a volcanic shield was hit by an extra-terrestrial object that blasted a hole on it and enhanced fracturing in the area. The impact created a ring of fractures which did not emit magma. In time, following an active mantle plume, magma was fired out of Silali basin's floor, through fractures that existed on the basin's floor. The outward extrusion of magma caused the basin's subsidence. The ring fracture of Silali basin, thus, was not active in emitting magma out of the basin's floor. Currently, Silali basin is experiencing quiet volcanicity, which may be attributed to the active mantle plume or magma chamber beneath the basin. The basin also appears to be undergoing continued subsidence as evidenced by continued slumping of the walls.

From chapter two, Silali basin's formation is via three processes: Volacanicity, extra-terrestrial impact and subsidence. Support for these processes comes from previous studies that have been carried out in Silali area (especially for volcanicity and subsidence) and the various evidence of Silali's ETIC nature as presented in this chapter (Chapter Four) of the study.

Objective two, which was to document the effect that the impact cratering of Silali had on the environment of the area, has also been met by the study as discussed above; to include the effects that the impact cratering of the basin would have had in the physical and human environment of the area, with reference to extra-terrestrial impacts in other areas.

The extra-terrestrial impact that may have occurred in Silali area did not only create the Silali basin and the other basins, but affected the environment of the area in many ways. Because of the age of the event, it is not possible to succinctly explain the effects of the impact on the human environment because there is no one alive today who witnessed the event 62-66 million years ago. Such effects may be speculated to entail the usual hazards and disasters that accompany an extra-terrestrial impact. These include; massive deaths of people, collapse of structures, loss of property, environmental pollution, migration and its social problems, as explained.

There is a cave to the southeast of Silali basin that may hold secrets about ancient human settlement in Silali area. The cave has an old homestead and paintings on its walls. Unfortunately, as stated elsewhere in this thesis, it was not possible to visit the cave because of the unfriendly terrain.

Besides building the Silali basin and the other basins, the possible extra-terrestrial impact of Silali may have affected the physical environment in more ways than explained earlier including the following ways:

i) It led to the metamorphism of rocks around the area, such as seen on Plate 4.25 and Plate 4.26. Both thermal and kinetic metamorphism would have been experienced in Silali basin after the impact, leading to the formation of breccias and heat altered grounds.

ii) The impact may also be responsible for the minerals that have been mentioned in this research and others that are yet to be discovered in Silali area. The minerals include impact glass or tektites (black hills), gold, copper, iron and nickel (see Figures 4.8-4.11).

iii) Silali's impact may also be responsible for the post impact volcanicity that was experienced in the area and that is ongoing, together with its resultant features; such as the various volcanic rocks, volcanic cones and the ridges. Active volcanicity in Silali, by itself, is responsible for the hot water springs and hot water falls at Kapedo area.

iv) The extra-terrestrial impact may be linked to the massive rock fracturing within and around Silali basin, together with its associated features. The ring fracture of the basin is an example of faulting in Silali basin, apart from the many fractures that are visible from the LIDAR image (Plate 2.2). The Suguta river gorge is a wide fault and the caves and sinkhole presented in this study may all be products of rock fracturing. The caves, though, may be products of areas where faulted rocks have been eroded and opened up. It must be noted that grid faulting in Silali basin is in existence because impact cratering encourages it as shown by Figure 2.2. The pseudotachylites found within and around Silali basin are a product of the massive rock fracturing that occurred in the area, following the possible impact.

v) Silali basin's impact may also have led to the creation of impact related features, such as all those listed in this chapter including the shatter cones at Chemolingot area (Plate 4.41), Silali shatter cones (Plate 4.32), the impact ejecta around the basin and other features which may be discovered in later studies that involve impact investigation in the area.

vi) The impact may have introduced heavenly rocks into Silali area, as an older impact did on the outer basin, if the Chemolingot rock is indeed a meteorite (Plates 4.38- 4.40). There may be meteoritic rocks in Silali area that were not discovered during the study.

The formation of Silali basin and the many other smaller craters within and around the basin is a major geological event by itself. The creation of the major crater (Silali basin) and the other smaller craters changed the appearance of the earth's surface in the area. It can be said that the possible impact cratering in Silali did not only create new geological features in the area (Silali basin, the smaller basins and the features stated above) but it blasted a volcanic shield creating a depression where a mountain would have been. This is crustal alteration, deformation or reformation as it would suit a geologist.

The Silali crater is a major geological feature in the mid-graben's physical environment. Its presence has sparked ownership disputes between the Turkana and the Pokot. This in itself is a social issue that enhances war and general insecurity in the area, making it inaccessible to researchers and developers.

Economically, Silali basin can be a wonderful tourist attraction feature, together with all its associated features and terrain. The various breccias can be harvested for home decoration or construction purposes, Breccias are associated with various mineral elements, such as the mesothermal gold ore and can form over large areas. The rocks also have ornamental uses and can be used for architectural as well as sculpturing purposes. In 1800 BC, for instance, breccia was used to create the columns of the famous Minoan palace of Knossos in Crete. The ancient Egyptians curved their goddess 'Tawaret', found in the British museum, from breccias and the Romans included breccias in their construction of high profile public buildings (www.thefreedictionary.com/brecciation). The other minerals found in Silali can also be assessed for mining.

The volcanicity that must have ensued following the formation of Silali basin has created a rich geothermal field in the area that GDC is considering for the generation of geothermal power.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Silali basin has suffered its share of deformation by tectonic, volcanic and denudation forces, just like all the other ETICs of the earth. The effect of tectonic forces on Silali basin is even more pronounced because the basin lies between the two arms of the Great Rift Valley, in a region that is tectonically active. The basin also appears to have undergone serious subsidence after impact. Some more dating of the basin’s rocks and floor drill cores may need to be done to determine the time lapse between the impact event and the time of subsidence. Despite this, Silali basin still retains some ETIC characteristics such as those discussed in Chapter Four, for instance; its shape is nearly circular, its inner walls are slumped, it has breccias, it has ejecta around it, it has an active magma chamber and volcanic features, it has a ring fracture, has terraces and its floor is hummocky. At the same time, the basin has some volcanic characteristics such as the presence of volcanic rock, volcanic cones, hot springs and fumaroles. Although the volcanic nature of Silali basin has been explained in chapter two of this study; as a product of a possible extra-terrestrial impact on a volcanic shield, the basin needs to be investigated more for its impact origins, with focus on finding PDFs, siderophile elements and establishing a more regional gravity signature. As it is, the basin may be said to be a possible ETIC with volcanic roots. It may also be an ETIC whose formation triggered volcanic activity. Its formation is thus complex and this may be the reason why some of the scholars who have studied it proposed the existence of an older crater before the current one, a proposition that others disagreed with but one that the study at hand agrees with.

Table 5.1, shows a comparison of Silali basin’s ETIC characteristics against common ETIC characteristics that are displayed by studied ETICs (from literature review in Chapter Two).

Table 5.1: Comparison of Silali basin's ETIC characteristics against common ETIC characteristics (Source: Author, 2015).

Common ETIC Characteristics	Presence or Absence in Silali Basin
1. Circular morphology	√
2. Hummocky floor	√
3. Impact ejecta	√
4. Allochthonous	√
5. Breccia	√
6. Complex magnetic anomalies	√
7. Low gravity signature	X (inconclusive data)
8. Complex seismic characteristics	√
9. Low resistivity	√
10. Shatter cones	√
11. PDFs	X (inconclusive data)
12. Siderophile elements	X (inconclusive data)
13. Impact glass	√
14. Pseudotachylites	√
15. Related Minerals	√
16. Slumping	√

Key

√ - Presence

X– Absence

There are other ETIC characteristics that are unique to different ETICs. Thus, only the most common characteristics have been listed in Table 5.1. Out of the 16 stated common ETIC characteristics, Silali basin has 13, noting that findings on the 3 other characteristics are inconclusive.

The 13/16 common ETIC characteristics that are displayed by Silali basin, in percentage, is 81.25% (13/16 x100) and with such a high percentage, there is all likelihood that Silali/Silale crater or basin is an ETIC.

Unfortunately, even with the high number of common ETIC characteristics, it is not possible to state conclusively that Silali/ Silale basin is an ETIC. This is because PDFs and siderophile elements were not netted satisfactorily by the study (due to the factors stated earlier) yet their presence would have nailed Silali basin's identity as an ETIC.

Tests were carried out to ascertain the presence of PDFs in the basin. Some of the results show what appears to be PDFs, as shown by Table 5.2 and Figure 5.1. The samples that were tested were collected from the basin's floor. However, the samples were few and cannot be taken summarily.

Table 5.2: A table showing the results of a petri-graphic study of a rock sample from Silali basin, courtesy of the Department of Mines and Geology, 2015.

Petrographic study in thin section	
Major constituents (%)	Cryptocrystalline pyroxenes -50% Quartz 35% Opaque -10% Others 5%
Accessory (% or trace)	-
Secondary (% or	-
Lithology	The rock is interpreted as volcanic trachyte
Petrographic descriptions	
Quartz (35%), Cryptocrystalline pyroxenes -50% and other minerals. Individual grains of quartz are fractured.	

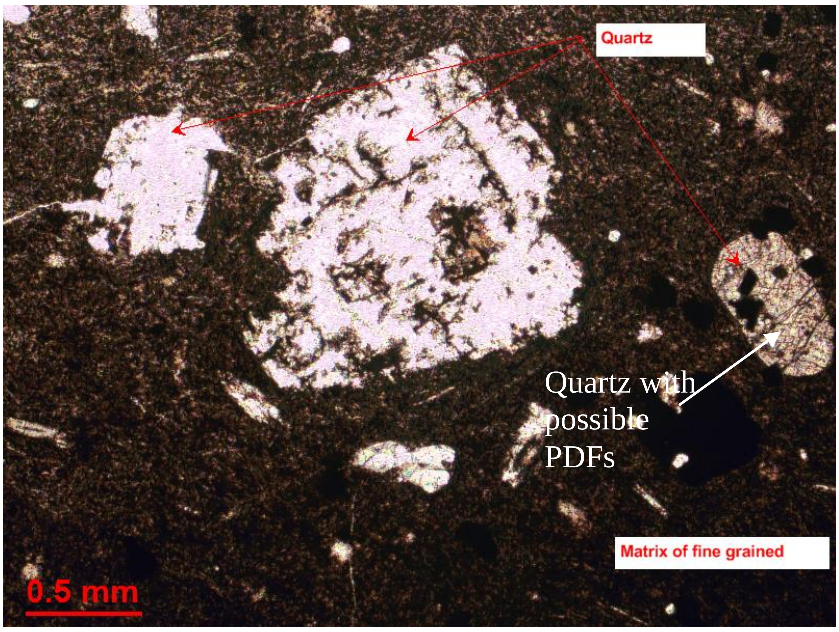

Figure 5.1: A thin section of one of Silali basin's sampled rocks, courtesy of the Department of Mines and Geology, 2015.

With improved security and accessibility of Silali basin, more studies should be carried out, with the aim of finding PDFs and siderophile elements- noting that rock and soil samples have not been collected from the northwest and northern parts of the basin.

In conclusion and in line with Table 5.1, Table 5.2 and Figure 5.1, Silali/ Silale crater or basin has a high percentage (81.25%) of common ETIC characteristics. Consequently, it can aptly be said that the crater/ basin is a possible ETIC; a complex impact crater, which has both ETIC as well as volcanic characteristics, pending further scientific research. The volcanic characteristics, as stated earlier, can be attributed to the basin's origin and formation; as an ETIC that formed on a volcanic shield, enhancing volcanicity within and around itself. The volcanic cones within and around the basin, as mentioned elsewhere in the study, are products of solidified magma that exited the floor of the earlier crater via the many fractures that were widened by the possible impact, on the basin's floor. It is this outflow of magma from the floor of the older crater that caused the crater's subsidence and produced the present crater, the Silali basin, 62-66 million years ago. Consequently, the hypothesis that Silali basin is a dried up maar is null. The calcrete on the basin's floor may have been formed on the floor of the older crater, at a time when water filled the crater (Lake Silali). The present Silali basin appears to be very porous (mostly around the sides) because there is no evidence of stagnant rain water on the basin's floor.

The following can also be true; that because Silali basin is a possible ETIC, there may be other ETICs in Kenya that are waiting to be unearthed. Again, Kiptabar rock may be a stony meteorite, meaning that there may be other meteorites and meteoritic rocks in Kenya. The Chemolingot rock is most likely a chondrite meteorite.

5.2 Recommendations

Although Silali basin is already of use to the Turkana and Pokot communities sharing it, this environmental resource has not been fully utilized for commercial purposes. GDC has carried out studies to determine Silali basin's geothermal potential and there is a possibility of the organization harvesting geothermal power from the basin soon. Besides harnessing of Silali basin's heat for geothermal power, the study recommends that:

1) The Silali area and the whole of former Turkana East and East Pokot districts be opened up for development and research. This can be done through infrastructural development including construction of good road networks, establishment of social amenities and provision of communication structures. Currently, there is only one poor road leading to Kapedo and no road to Silali basin. Mobile phone use is not also possible within and around the basin because of poor connectivity to mobile phone networks. A good transport and communication network in the area will certainly boost national unity and development in Silali area.
2) Insecurity in the area be completely erased so that the area is safe for the residents, developers and researchers. As stated earlier, Silali basin is a social hot spot because of cattle rustling and ownership disputes. Good infrastructure in the area, alongside government security, will make the area accessible and secure hence easy to develop and study.
3) Silali basin be tapped for more economic purposes such as tourism and mining of the multicolored breccias. As mentioned elsewhere in this study, Silali basin is a beautiful place with many tourism and sport capabilities. The basin can be visited for health as well as social development and for air sports such

as paragliding and parachuting. The Kenyan government should thus develop and market Silali basin for such purposes.

5.3 Further Research

1) There is need to investigate Silali's past climate from evidence provided by the prehistoric cave dwellings and paintings found to the southeast of the basin. This will yield information on Silali's past and more information on the basin's formation. The only challenge is that the area is very inaccessible because it is in a deep jungle and can only be accessed on foot or by a chopper.
2) McCall and Hornung (1972), mentioned that the 'black hills' to the northeast of Silali basin are made up of pure black glass. It was not possible to access these hills for sampling, because of insecurity. Knowing that ETICs are associated with diaplectic glass or impact glass and tektites, it is important to check out the black hills and ascertain their glass mining potential. The whole 'outer basin' and beyond should also be prospected for glass because impact glasses are known to form thousands of kilometers away from their impact origin (http://www.unb.ca/passc/impactDatabase/Africa.html). Lake Bosomturi, in Ghana, is an ETIC that is believed to be the source of Ivory Coast's tektites and microtektites in the nearby ocean sediments (http:www.unb.ca/passc/impactDatabase/Africa.html).
3) There is also need for more research on ETICs in Kenya and the rest of Africa to enhance the continents and country's geological data, as it is in the rest of the world.
4) There is need for Silali basin's more detailed scientific research with a focus on establishing the presence or absence of PDFs and siderophile elements. More gravity mapping of the area should also be conducted to establish Silali basin's localized gravity signature for a better understanding of the basin's origin. According to Mariita (2003), Silali basin's existing gravity data is too sparse to give a detailed picture of localized anomalies.

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APPENDIX I: A SAMPLE OF THE QUESTIONS THAT WERE ASKED DURING FIELD INTERVIEWS

Qn 1. What is the meaning of the term ‘Silali or Silale’ to your community?

Qn 2. How did the basin form according to your community?

Qn 3. When did the basin form?

Qn 4. Is Silali basin important to your community in anyway?

APPENDIX II: A LIST OF ALL THE IDENTIFIED EXTRA-TERRESTRIAL IMPACT CRATERS AND THEIR GLOBAL LOCATION (from www.google.com).

Terrestrial Impact Crater Structures				
Name	**Latitude**	**Longitude**	**Diameter (kilometers)**	**Age (Ma)**
Acraman, Australia	32°1'S	135°27'E	160.000	570.00
Ames, Oklahoma, USA	36°15'N	98°10'W	16.000	470.00 ± 30.00
Amguid, Algeria	26°5'N	4°23'E	0.450	0.10
Aorounga, Chad, Africa	19°6'N	19°15'E	17	200
Aouelloul, Mauritania	20°15'N	12°41'W	0.390	3.10 ± 0.30
Araguainha Dome, Brazil	16°46'S	52°59'W	40.000	249.00 ± 19.00
Avak, Alaska, USA	71°15'N	156°38'W	12.000	100.00 ± 5.00
Azuara, Spain	41°10'N	0°55'W	30.000	130.00
B.P. Structure, Libya	25°19'N	24°20'E	2.800	120.00
Barringer, Arizona, USA	35°2'N	111°1'W	1.186	0.049
Beaverhead, Montana, USA	44°36'N	113°0'W	60.000	600.00
Bee Bluff	29°2'N	99°51'W	2.400	40.00
Beyenchime-Salaatin, Russia	71°50'N	123°30'E	8.000	65.00
Bigach, Kazakhstan	48°30'N	82°0'E	7.000	6.00 ± 3.00
Boltysh, Ukraine	48°45'N	32°10'E	25.000	88.00 ± 3.00
Bosumtwi, Ghana	6°32'N	1°25'W	10.500	1.30 ± 0.2
Boxhole, North Territory, Australia	22°37'S	135°12'E	0.170	0.03
Brent, Ontario, Canada	46°5'N	78°29'W	3.800	450.00 ± 30.00
Campo Del Cielo, Argentina	27°38'S	61°42'W	0.050	0.00
Carswell, Saskatchewan, Canada	58°27'N	109°30'W	39.000	115.00 ± 10.00
Charlevoix, Canada	47°32'N	70°18'W	54.000	357.00 ± 15.00

Chesapeake Bay, Virginia, USA	37°15'N	76°5'W	85	35.5 ± 0.6
Chicxulub, Mexico	21°20'N	89°30'W	170.000	64.98 ± 0.05
Chiyli, Kazakhstan	49°10'N	57°51'E	5.500	46.00 ± 7.00
Clearwater East, Quebec, Canada	56°5'N	74°7'W	22.000	290.00 ± 20.00
Clearwater West, Quebec, Canada	56°13'N	74°30'W	32.000	290.00 ± 20.00
Connolly Basin, Australia	23°32'S	124°45'E	9.000	60.00
Crooked Creek, Missouri, USA	37°50'N	91°23'W	7.000	320.00 ± 80.00
Dalgaranga, West Australia	27°45'S	117°5'E	0.021	0.03
Decaturville, Missouri, USA	37°54'N	92°43'W	6.000	300.00
Deep Bay, Saskatchewan, Canada	56°24'N	102°59'W	13.000	100.00 ± 50.00
Dellen, Sweden	61°55'N	16°39'E	15.000	110.00 ± 2.70
Des Plaines, Illinois, USA	42°3'N	87°52'W	8.000	280.00
Dobele, Latvia	56°35'N	23°15'E	4.500	300.00 ± 35.00
Eagle Butte, Alberta, Canada	49°42'N	110°35'W	19.000	65.00
El'Gygytgyn, Russia	67°30'N	172°5'E	18.000	3.50 ± 0.50
Flynn Creek, Tennessee	36°17'N	85°40'W	3.550	360.00 ± 20.00
Garnos, Norway	60°39'N	9°0'E	5.000	500.00 ± 10.00
Glasford, Illinois, USA	40°36'N	89°47'W	4.000	430.00
Glover Bluff, Wisconsin, USA	43°58'N	89°32'W	3.000	500.00
Goat Paddock, Western Australia	18°20'S	126°40'E	5.100	50.00
Gosses Bluff, North Territory, Australia	23°50'S	132°19'E	22.000	142.50 ± 0.50
Gow Lake, Canada	56°27'N	104°29'W	4.000	250.00
Goyder, Northern Territory, Australia	13°29'S	135°2'E	3	>136

Granby, Sweden	58°25'N	15°56'E	3	470
Gusev, Russia	48°21'N	40°14'E	3.500	65.00
Gweni-Fada, Chad, Africa	17°25'N	21°45'E	14	<345
Haughton, Northwest Territories, Canada	75°22'N	89°41'W	20.5	21.5 ± 1.00
Haviland, Kansas, USA	37°35'N	99°10'W	0.015	0.00
Henbury, North Territory, Australia	24°35'S	133°9'E	0.157	0.01
Holleford, Ontario, Canada	44°28'N	76°38'W	2.350	550.00 ± 100.00
Ile Rouleau, Quebec, Canada	50°41'N	73°53'W	4.000	300.00
Ilumetsa, Estonia	57°58'N	25°25'E	0.080	0.00
Ilyinets, Ukraine	49°6'N	29°12'E	4.500	395.00 ± 5.00
Iso-Naakkima, Finland	62°11'N	27°9'E	3	>1000
Janisjarvi, Russia	61°58'N	30°55'E	14.000	698.00 ± 22.00
Kaalijarvi, Estonia	58°24'N	22°40'E	0.110	0.00 ± 0.00
Kalkkop, South Africa	32°43'S	24°34'E	0.64	<1.8
Kaluga, Russia	54°30'N	36°15'E	15.000	380.00 ± 10.00
Kamensk, Russia	48°20'N	40°15'E	25.000	65.00 ± 2.00
Kara, Russia	69°5'N	64°18'E	65.000	73.00 ± 3.00
Kara-Kul, Tajikistan	39°1'N	73°27'E	52.000	25.00
Kardla, Estonia	58°59'N	22°40'E	4.000	455.00
Karla, Russia	54°54'N	48°0'E	12.000	10.00
Kelly West, Northern Territory, Australia	19°56'S	133°57'E	10.000	550.00
Kentland, Indiana	40°45'N	87°24'W	13.000	300.00
Kursk, Russia	51°40'N	36°0'E	5.500	250.00 ± 80.00
Lac Couture, Quebec, Canada	60°8'N	75°20'W	8.000	430.00 ± 25.00
Lac La Moinerie, Canada	57°26'N	66°37'W	8.000	400.00 ± 50.00

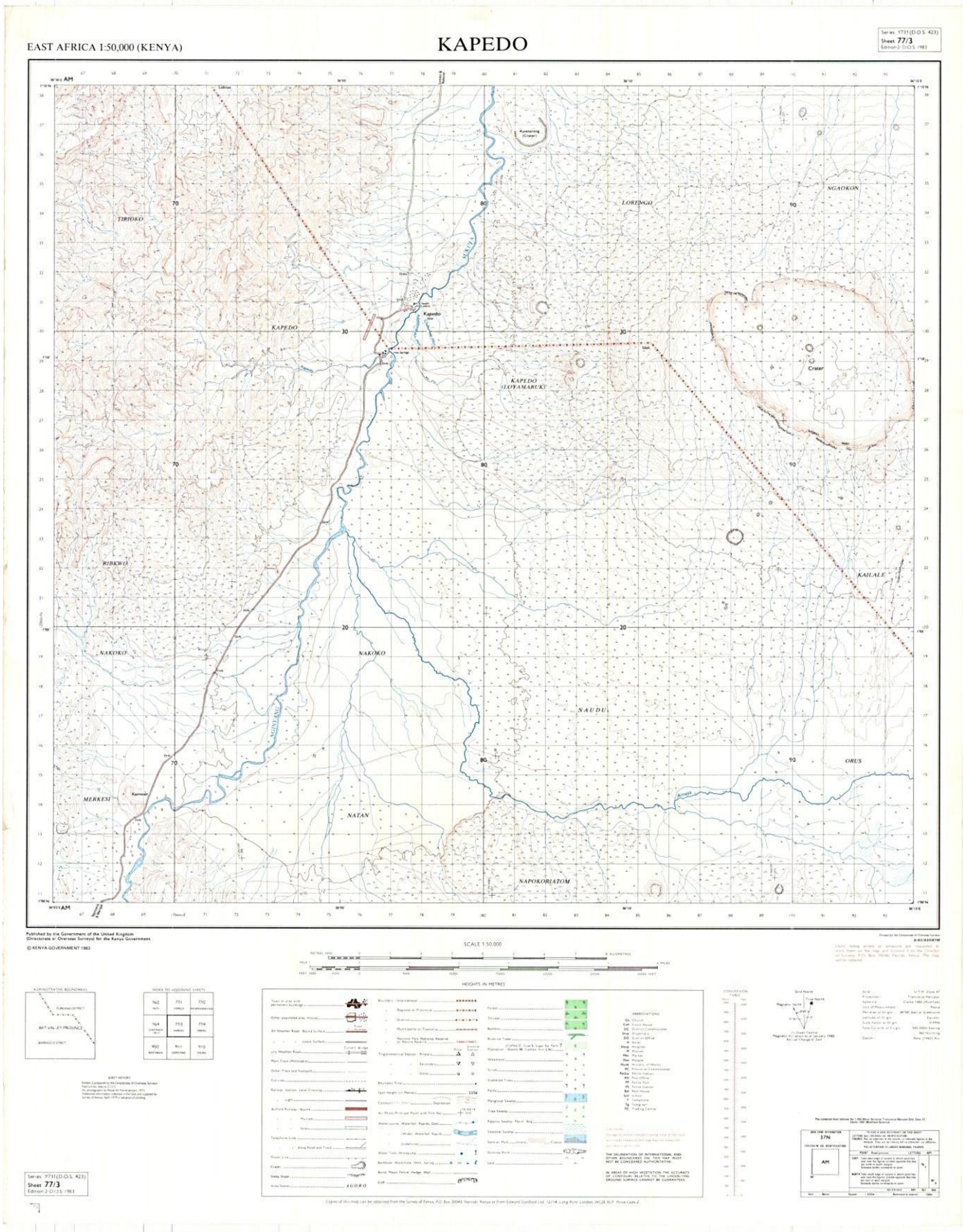
Lappajarvi, Finland	63°9'N	23°42'E	17.000	77.30 ± 0.40
Lawn Hill, Queensland, Australia	18°40'S	138°39'E	18.000	515.00
Liverpool, Northern Territory, Australia	12°24'S	134°3'E	1.600	150.00 ± 70.00
Lockne, Sweden	63°0'N	14°48'E	7.000	540.00 ± 10.00
Logancha, Russia	65°30'N	95°48'E	20.000	25.00 ± 20.00
Logoisk, Belarus	54°12'N	27°48'E	17.000	40.00 ± 5.00
Lonar, India	19°59'N	76°31'E	1.830	0.052 ± 0.01
Lumparn, Finland	60°12'N	20°6'E	9	1000
Macha, Russia	59°59'N	118°0'E	0.300	0.01
Manicouagan, Quebec, Canada	51°23'N	68°42'W	100.000	212.00 ± 1.00
Manson, Iowa	42°35'N	94°31'W	35.000	65.70 ± 1.00
Marquez, Texas, USA	31°17'N	96°18'W	22.000	58.00 ± 2.00
Middlesboro, Kentucky	36°37'N	83°44'W	6.000	300.00
Mien, Sweden	56°25'N	14°52'E	9.000	121.00 ± 2.30
Misarai, Lithuania	54°0'N	23°54'E	5.000	395.00 ± 145.00
Mishina Gora, Russia	58°40'N	28°0'E	4.000	360.00
Mistastin, Labrador, Canada	55°53'N	63°18'W	28.000	38.00 ± 4.00
Mjolnir, Norway	73°48N	29°40'E	40	143 ± 20
Montagnais, Nova Scotia, Canada	42°53'N	64°13'W	45.000	50.50 ± 0.76
Monturaqui, Chile	23°56'S	68°17'W	0.460	1.00
Morasko, Poland	52°29'N	16°54'E	0.100	0.01
New Quebec, Quebec, Canada	61°17'N	73°40'W	3.440	1.40 ± 0.10
Newporte, North Dakota, USA	48°58'N	101°58'W	3	<500
Nicholson Lake, Canada	62°40'N	102°41'W	12.500	400.00
Oasis, Libya	24°35'N	24°24'E	11.500	120.00

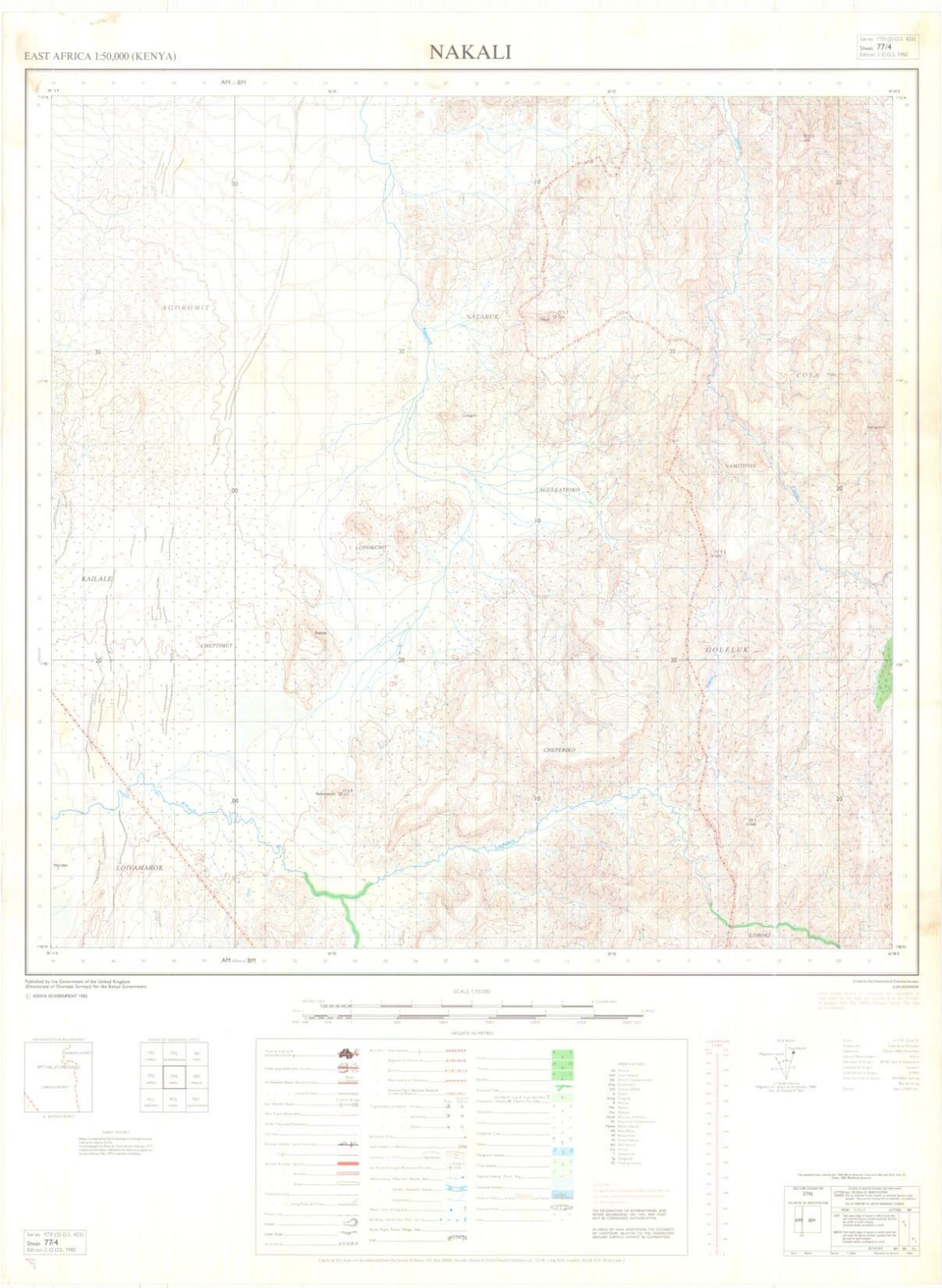
Obolon, Ukraine	49°30'N	32°55'E	15.000	215.00 ± 25.00
Odessa, Texas, USA	31°45'N	102°29'W	0.168	0.05
Ouarkziz, Algeria	29°0'N	7°33'W	3.500	70.00
Piccaninny, Western Australia	17°32'S	128°25'E	7.000	360.00
Pilot Lake, Canada	60°17'N	111°1'W	5.80	445.00 ± 2.00
Popigai, Russia	71°30'N	111°0'E	100.000	35.00 ± 5.00
Presqu'ile, Quebec, Canada	49°43'N	78°48'W	12.000	500.00
Pretoria Salt Pan, South Africa	25°24'S	28°5'E	1.130	0.20
Puchezh-Katunki, Russia	57°6'N	43°35'E	80.000	220.00 ± 10.00
Ragozinka, Russia	58°18'N	62°0'E	9.000	55.00 ± 5.00
Red Wing, North Dakota, USA	47°36'N	103°33'W	9.000	200.00 ± 25.00
Riachao Ring, Brazil	7°43'S	46°39'W	4.500	200.00
Ries, Germany	48°53'N	10°37'E	24.000	14.8 ± 1.00
Rio Cuarto, Argentina	30°52'S	64°14'W	4.500	0.10
Rochechouart, France	45°50'N	0°56'E	23.000	186.00 ± 8.00
Roter Kamm, Namibia	27°46'S	16°18'E	2.500	5.0 ± 0.30
Rotmistrovka, Ukraine	49°0'N	32°0'E	2.700	140.00 ± 20.00
Saaksjarvi, Finland	61°24'N	22°24'E	5.000	514.00 ± 12.00
Saint Martin, Canada	51°47'N	98°32'W	40.000	220.0 ± 32.00
Serpent Mound, Ohio, USA	39°2'N	83°24'W	6.40	320.00
Serra da Cangalha, Brazil	8°5'S	46°52'W	12.000	300.00
Shunak, Kazakhstan	47°12'N	72°42'E	3.100	12.00 ± 5.00
Sierra Madera, Texas, USA	30°36'N	102°55'W	13.000	100.00
Sikhote Alin, Russia	46°7'N	134°40'E	0.027	0.00
Siljan, Sweden	61°2'N	14°52'E	55.000	368.00 ± 1.10

Slate Islands, Ontario, Canada	48°40'N	87°0'W	30.000	350.00
Sobolev, Russia	46°18'N	138°52'E	0.053	0.00
Soderfjarden, Finland	63°0'N	21°35'E	6.000	550.00
Spider, Western Australia	16°44'S	126°5'E	13.000	570.00
Steen River, Alberta, Canada	59°31'N	117°37'W	25.000	95.00 ± 7.00
Steinheim, Germany	48°40'N	10°4'E	3.800	14.80 ± 0.70
Strangways, Northern Territory, Australia	15°12'S	133°35'E	25.000	470.00
Sudbury, Ontario, Canada	46°36'N	81°11'W	200.000	1850.00 ± 3.00
Suvasvesi N, Finland	62°42'N	28°0'E	4	<1000
Tabun-Khara-Obo, Mongolia	44°6'N	109°36'E	1.300	3.00
Talemzane, Algeria	33°19'N	4°2'E	1.750	3.00
Teague, Western Australia	25°52'S	120°53'E	30.000	1685.00 ± 5.00
Tenoumer, Mauritania	22°55'N	10°24'W	1.900	2.50 ± 0.50
Ternovka, Ukraine	48°1'N	33°5'E	12.000	280.00 ± 10.00
Tin Bider, Algeria	27°36'N	5°7'E	6.000	70.00
Tookoonooka, Queensland, Australia	27°0'S	143°0'E	55.000	128.00 ± 5.00
Tvaren, Sweden	58°46'N	17°25'E	2.000	0.00
Upheaval Dome, Utah, USA	38°26'N	109°54'W	5.000	65.00
Ust-Kara, Russia	69°18'N	65°18'E	25.000	73.00 ± 3.00
Vargeao Dome, Brizil	26°50'S	52°7'W	12.000	70.00
Veevers, Western Australia	22°58'S	125°22'E	0.080	1.00
Vepriaj, Lithuania	55°6'N	24°36'E	8.000	160.00 ± 30.00
Vredefort, South Africa	27°0'S	27°30'E	140.000	1970.00 ± 100.00
Wabar, Saudi Arabia	21°30'N	50°28'E	0.097	0.01 ± 0.00
Wanapitei Lake, Ontario, Canada	46°45'N	80°45'W	7.500	37.00 ± 2.00
Wells Creek, Tennessee, USA	36°23'N	87°40'W	14.000	200.00 ± 100.00

West Hawk Lake, Manitoba, Canada	49°46'N	95°11'W	3.150	100.00 ± 50.00
Wolfe Creek, Western Australia	19°18'S	127°46'E	0.875	0.30
Zapadnaya, Ukraine	49°44'N	29°0'E	4.000	115.00 ± 10.00
Zeleny Gai, Ukraine	48°42'N	32°54'E	2.500	120.00 ± 20.00
Zhamanshin, Kazakhstan	48°24'N	60°58'E	13.500	0.90 ± 0.10

APPENDIX III: TOPOGRAPHICAL MAPS OF SILALI BASIN





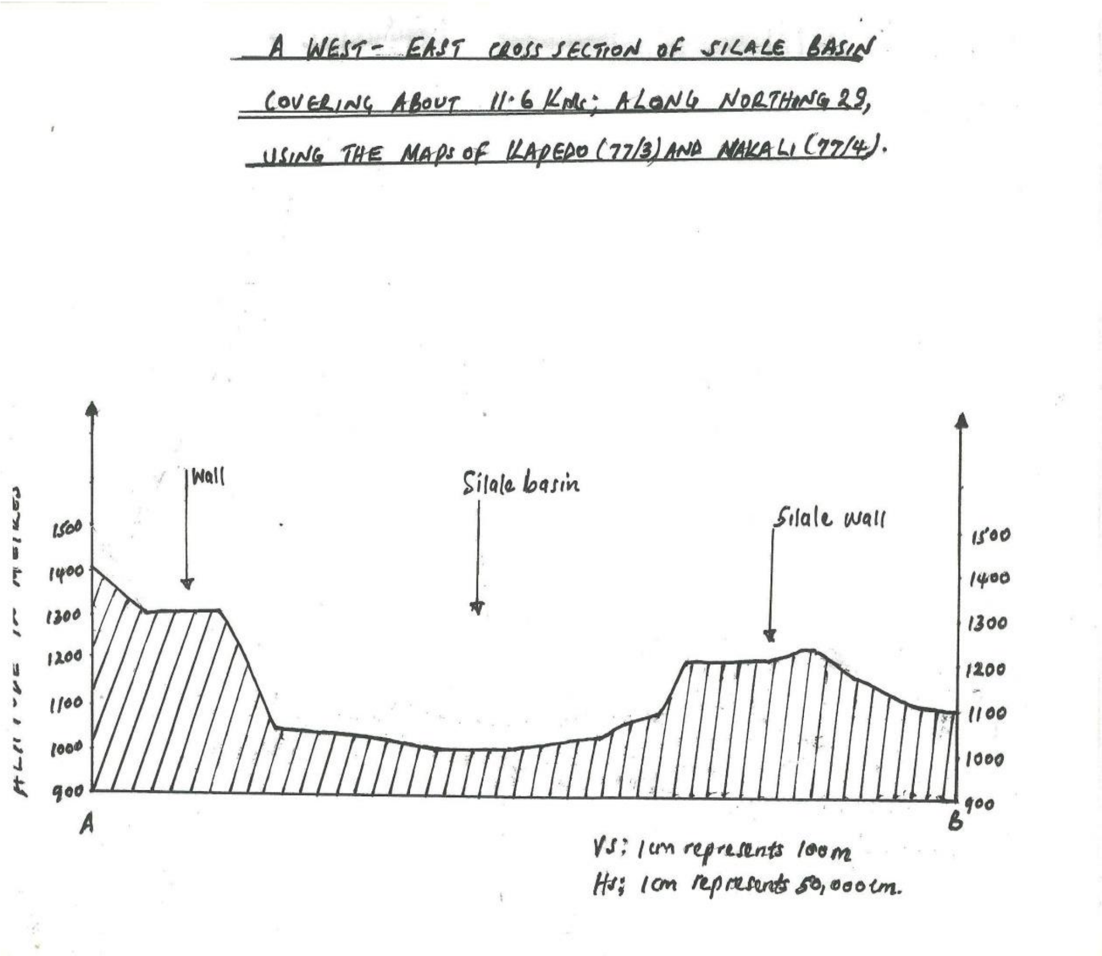
EAST AFRICA 1:50,000 (KENYA)
NAKALI
Sheet 77/4
AM BM
AGOROMIT
NATARUK
KAILALE
CHEPTIMET
GOLELUK
CHEPERIKO
LOIYAMAROK
SCALE 1:50,000
HEIGHTS IN METRES

APPENDIX IV: RESULTS OF SILALI ROCK SAMPLES

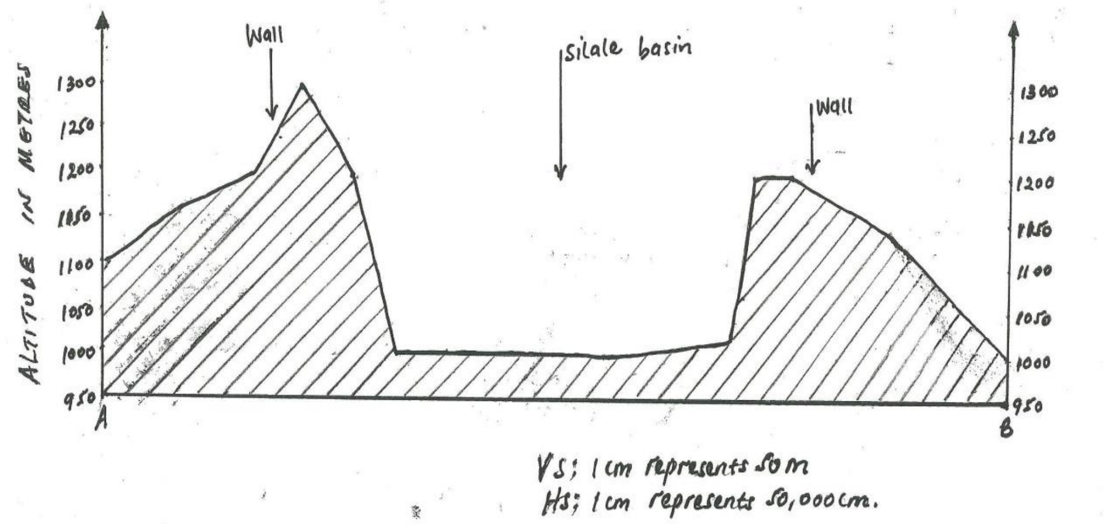
Oxide	SiO_2	Al_2O_3	CaO_3	MgO	Na_2O	K_2O	MnO	Fe_2O_3	TiO_2	LOI
Chemolin-got Rock	50.32	17.12	9.10	5.39	3.34	0.77	0.60	6.90	2.62	0.59
Silali A	60.47	14.55	0.20	0.22	0.62	2.50	0.40	12.9	1.65	5.83
Silali B	60.43	14.68	0.57	0.32	3.80	3.30	0.40	7.80	0.53	7.0
Silali C	55.99	13.10	0.10	0.17	0.55	4.00	0.40	0.60	0.51	24.02
Silali D	60.65	16.70	1.43	0.44	7.12	4.60	0.50	6.99	0.20	1.73
Silali E	60.99	14.37	1.88	0.38	6.86	4.30	0.50	9.72	0.58	0.52

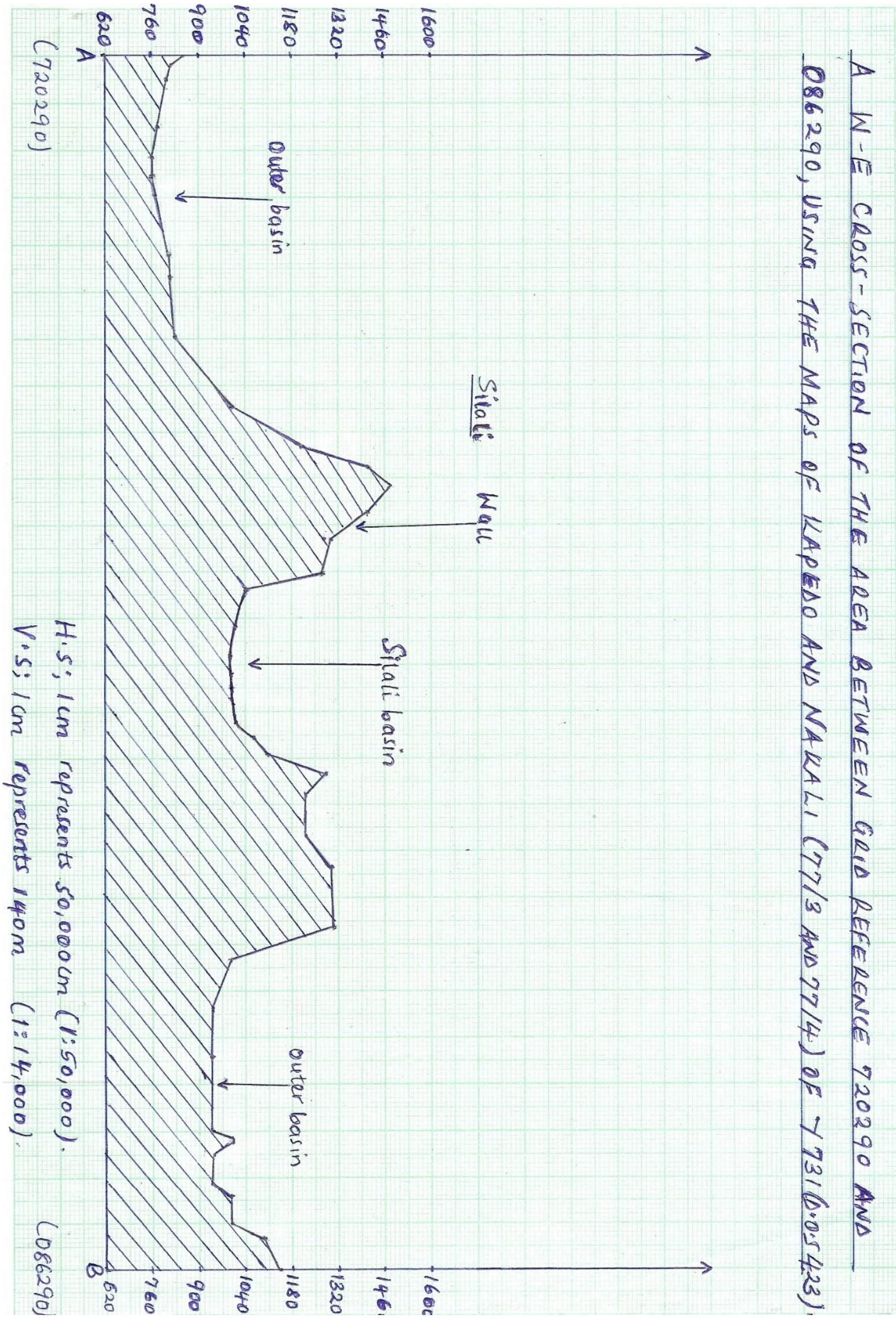
Note: The results are represented in percentages (%).

APPENDIX V: SILALI BASIN'S MORPHOLOGICAL SECTIONS (CROSS SECTIONS)



A SOUTH - NORTH CROSS-SECTION OF THE SILALE BASIN COVERING 12.1 KMS: ALONG EASTING 91, USING THE MAPS OF KAPEDO (77/3) AND NAKALO (77/4).




A N-E CROSS-SECTION OF THE AREA BETWEEN GRID REFERENCE 720290 AND 086290, USING THE MAPS OF KAPEDO AND NAKALI (77/3 AND 77/4) OF Y731 (D.O.S 423).
1600
1460
1320
1180
1040
900
760
620
A
(720290)
Outer basin
Silali
Wall
Silali basin
Outer basin
H.S; 1cm represents 50,000cm (1:50,000).
V.S; 1cm represents 140m (1:14,000).
B
(086290)