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Research Paper

FORMATION OF SILALI BASIN AS A COMPLEX EXTRA-TERRESTRIAL IMPACT CRATER (ETIC)

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For a long time, Silali crater/basin has been described as a volcanic crater that formed through volcanicity. This would ordinarily entail the release of magma from inside the earth, through a volcanic pipe or vent, onto the earth's surface. A violent volcanic eruption can blast the earth to form a crater. The eruption can also pile magma all around the blasted area, forming walls of lava (cooled magma). A recent study that was carried out in Silali basin: Identification of an Extra-Terrestrial Impact Crater (ETIC): A Case Study of Silali Crater, Kenya, by Kipkiror (2016), however, has unearthed facts that give an indication that Silali basin may actually be an Extra-terrestrial Impact Crater (ETIC); formed through an extra-terrestrial impact event. This involves the impact of an asteroid, comet or a meteor on the earth's surface, leading to the formation of a crater or a meteorite. When a heavenly body impacts on the earth's surface and excavates it, a crater is formed. If the heavenly body fails to completely burn up while transiting the earth's atmosphere, it will land on the earth's surface, form a shallow crater and rest on the crater as a meteorite. The objective of this study is to explain the formation of Silali crater/basin as an ETIC. Information for the study was derived from the analysis of previous geographical and geological studies of Silali basin, with reinforcement from other research methods including interviewing, observation, sampling, laboratory testing of samples and remote sensing. Data has been presented in the form of tables, analysed remote sensing images, pictures, charts and discussions.

Keywords: Silali Basin, Extra-terrestrial, ETIC, Formation, Morphology

BACKGROUND TO THE STUDY

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)

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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.

Extra-terrestrial bodies are still falling on the earth's surface. 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 5 kg 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. Plate 1 is a photograph showing the Kimwiri meteorite as it is today, where it sits in the office of the Commissioner, department of Mines and Geology.

From Plate 1, the meteorite is about 6 cm wide. It is dark in colour, probably because it burned up as it fell. The freshly broken portions display a speckled appearance, like a granite rock. Another recent impact event on Kenyan soil is the Kuresoi-Nakuru County, fireball event that took place around 7:30 pm 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 and injuring a woman.

STATEMENT OF THE PROBLEM

Silali basin has always been described as a volcanic crater, yet the crater has many ETIC features and characteristics. Thus, the need for documentation of the formation of Silali crater as an ETIC. In addition, Silali crater, also known as Silale basin in this study, is a major geological

Plate 1: A Picture of the Kimwiri Meteorite, Taken Where it Sits at the Commissioner's Office, Department of Mines and Geology-Kenya (Kipkiror, 2013)

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). Extra-terrestrial impact cratering provides this mechanism of topographic inversion.

OBJECTIVE OF THE STUDY

This study is aimed at explaining the formation of Silali crater/basin as an ETIC and highlighting some of its ETIC characteristics.

RATIONALE OF THE STUDY

Very little information is available with regard to ETICs and extra-terrestrial impact cratering in Kenya and the rest of Africa, despite the fact that extra-terrestrial impacts on the earth's surface have significant environmental, economic and social repercussions. Again, there may be ETICs in Kenya, Silali being one of them, whose existence is not known because research has not unearthed them, yet these natural structures have immense socio-economic importance. Thus, this study is a source of information on extra-terrestrial impact cratering in Kenya, Silali basin's impact formation and imminence of space hazards and disasters in Kenya, having been excerpted from a pioneer study on ETICs and extra-terrestrial impact cratering in Kenya.

AREA OF STUDY

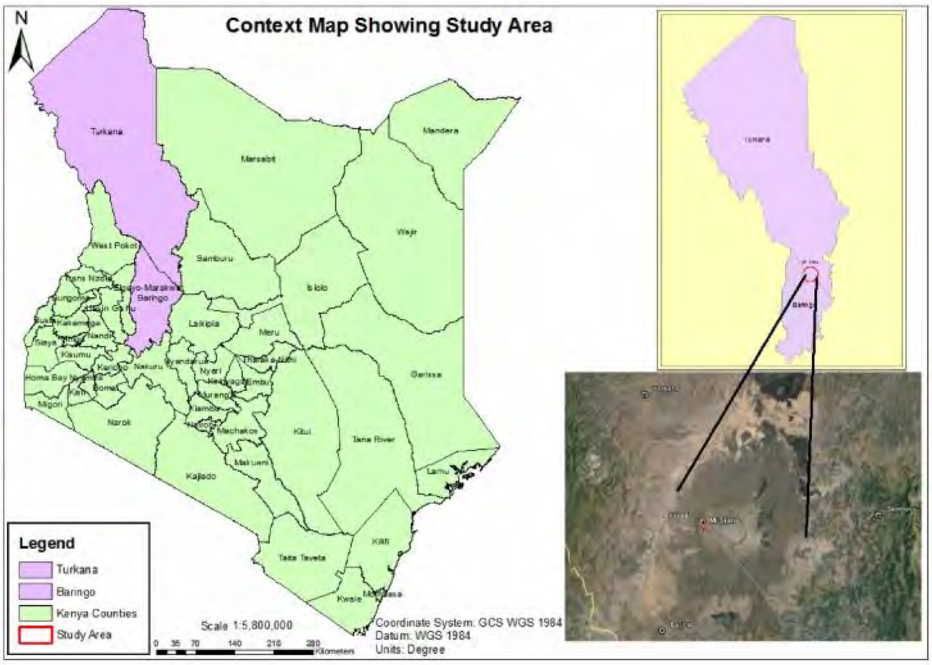
The study reported in this study covers the Silali basin and its environs. Silali basin is found in East Pokot/Turkana East, within the mid Graben of the Great Rift Valley, 50 km north of L.Baringo and near Kapedo Town. It is located on Latitude $1^{o}10'$N and Longitude $36^{o}12'$E. Turkana people call it Silali while the Pokot call it Silale. The basin covers an area of about 850 km^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 42.5 km^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). Consequently, the Silali impact event may have been a great event.

Figure 1 is a map of Kenya showing the location of Silale basin. Geographically, the area is in southern Turkana but administratively, it is at the border of Turkana East and East Pokot districts. 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 archaeological sites.

FORMATION OF SILALI CRATER/BASIN AS AN ETIC

The mechanisms associated with impact cratering are diverse but generally, when a sizable solid body strikes the earth at high speed, shock waves propagate into the target rocks. The collision speeds are very high and can squeeze dense target rocks into 1/3 of their normal volume. The target rocks then begin to flow almost like a fluid. A decompression wave follows the advancing front wave into the compressed rock, allowing target material to move sideways. As more and more of the target rock becomes engulfed in the shock wave, which expands radially from the point of impact, the flow of the target material behind the shock front, is diverted out along the wall of a now rapidly expanding crater created by the decompression wave. This flow will cease when stresses in the shockwave drop

Figure 1: A Map of Kenya, Drawn to Scale, Showing the Study Area, Pointed by a Blue Arrow and Circled in Red (Courtesy of RCMRD)



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, widening the crater formed. As for the impactor, it can be vaporized or melted to form part of an ETIC's impact melt.

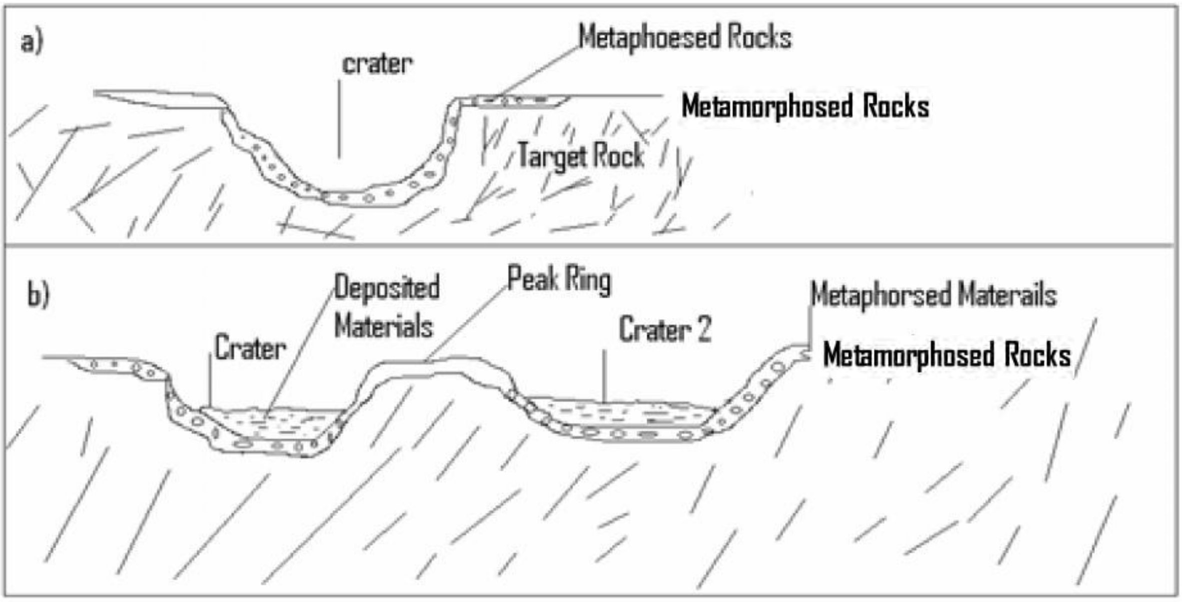
Extra-terrestrial impact Craters are divided into three categories according to their morphology, namely:

- Simple Craters
- Complex Craters
- 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 2). 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 kilometres.

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

Figure 2: Diagram Showing a Simple Crater (a) and a Complex Crater (b) with Associated Features (Kipkiror, 2013)



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 appears 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).

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.

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), as stated in the internet (www.google.com).

According to McCall and Hornung (1972), the whole of the Silali volcano is enveloped by an alluvial apron. According to them, 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. There is also some alluvium and lake deposits on a large part of the basin's floor, together with traces of calcrete, which comprises of a hardened deposit of calcium carbonate, containing gravel, sand, clay and silt (hardpan). The crater walls comprise of foliated mafic monzonites, syenites and granodiorites (McCall and Hornung, 1972).

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. 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). This magma reservoir beneath Silali basin would be the source of Silali basin's mantle plume and consequent features, as an ETIC.

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 5-8 km wide 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. Figure 4 is a map of Silali area that provides evidence of fractures all around the basin that appear concentric in formation, together with the many little craters within and around Silali crater/basin.

In some cases, caldera subsidence can cause ring fracture structures similar to those found in Silali basin, due to doming effects, but only for a volcano that was formed through a vent/pipe eruption. Ring fracture structures can also form as a result of an extra-terrestrial impact, where the impact 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 10 km/s or more (Therriault *et al.*, 2002). Further

Figure 3: A Cross Section of an ETIC Showing the Effects of Shockwaves on Target Rocks (Shattering and Fracturing)

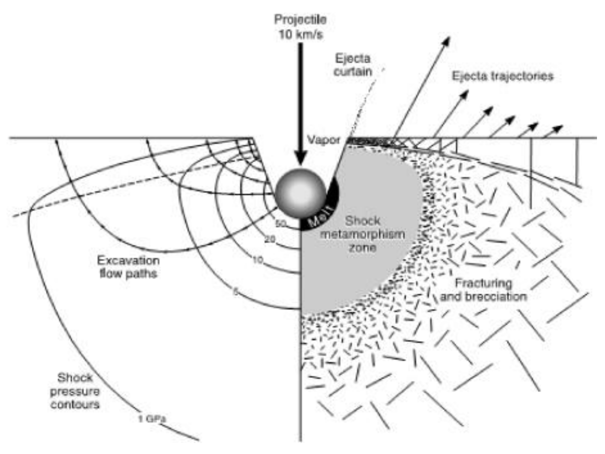
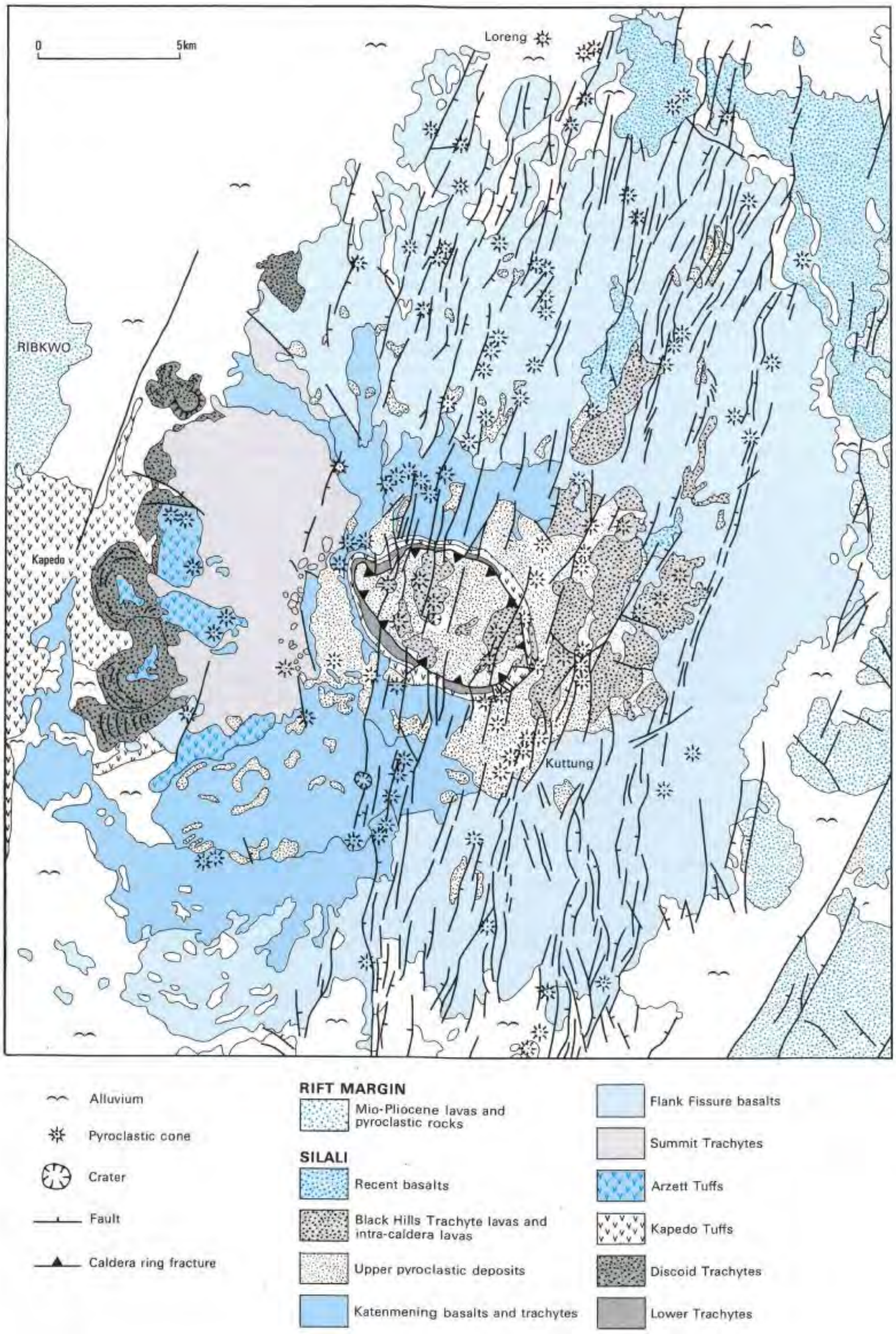


Figure 4: Simplified Geological Map of Silali Basin, Showing the Basin's Ring Like Structure and the Fault Lines Cutting Across the Basin (The Dust Blanket Over Silali Basin's Wall is also Visible on the Map, Noting that the Material Making Up the Basin's Wall is Not Uniform) (Dunkley et al., 1993)



outwards, pressure can produce distinctive shock deformation effects (shattering and fracturing) in large volumes of unmelted target rock (Melosh, 1989). Figure 3 illustrates how an extra-terrestrial impact results in concentric fracturing of rocks.

According to Dunkley *et al.* (1993), Silali volcano was formed around 225ka and the caldera (crater or basin) collapsed around 66-62ka. Notably, Silali basin is a basin within a larger basin (the outer basin) with smaller basins within it and around 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, volcanic cones, prehistoric caves, some of the mentioned smaller craters, several swamps, hot springs, fumaroles and alluvial deposits are also found in this basin. Silali basin appears to have formed much earlier than the Great Rift Valley (66-62 ka against 25-22 ka), though the shield upon which it was formed may have formed way earlier, probably soon after the outer basin had formed, about 400-220 ka, according to Smith *et al.* (1995).

For all the previous scholars, Silali basin formed through volcanicity that entailed the formation of a volcanic shield which later subsided. This study agrees with previous studies on; the existence of Silali volcanic shield (400-220 ka), the age of Silali crater/basin (66-62 ka), Silali subsidence (66-62 ka) and volcanicity in Silali basin, but unlike previous studies, the study propagates extra-terrestrial impact as the process behind the formation of the basin. The reasons for the disjuncture include the presence of ETIC features in Silali basin (Silali ETIC characteristics), the absence of a volcanic pipe/ vent in Silali basin (as indicated by resistivity studies) and the absence of lava deposition on the floor of the basin and on the basin's walls. These also indicate that Silali basin is not a maar and the calcrete on its floor may be part of ancient 'Lake Silali' deposits, at a time when the floor of Silali basin held water (Kipkiror, 2016).

This study describes Silali basin as an ETIC, formed through an extra-terrestrial impact, 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.

Volcanic Shield Stage

It is evident that there existed a volcanic shield in Silali; 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 between 400-220 ka and 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.

The existence of a volcanic shield in Silali before the ETIC formed is favoured 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 noting that there is neither 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), as stated earlier. 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 infilled by a lava pool' (G.O.K, 1987). Consequently, if Silali basin was entirely a product of volcanic activity, there would be presence of 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 that bore this study considers these blocks of rock to be hummocky ejecta and pseudotachylites. According to McCall and Hornung (1972), Silali walls have been scalloped in some sections, appear as dropped fault blocks 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 is impact ejecta.

Subsidence Stage

To be able to understand Silali basin'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:

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.

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.

The Gas-Coring Theory

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

Sandberg's 'Mantle Pipe' Theory

This theory holds that calderas and craters are formed in the same way. The argument rests 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.

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.

Wing Easton's Cell Theory

The theory suggests 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.

Collapse Theories Involving Withdrawal of Magmatic Support

The theory states 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 for Silali basin. This is because subsidence would not be a quiet event and an explosion would most likely occur, pouring out magma onto Silali basin's 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 before the collapse.

Caldera subsidence also 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 centres. 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 because it appears 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.

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 300 m 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 (400-200 ka). 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 pictures and satellite images of the basin, 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.

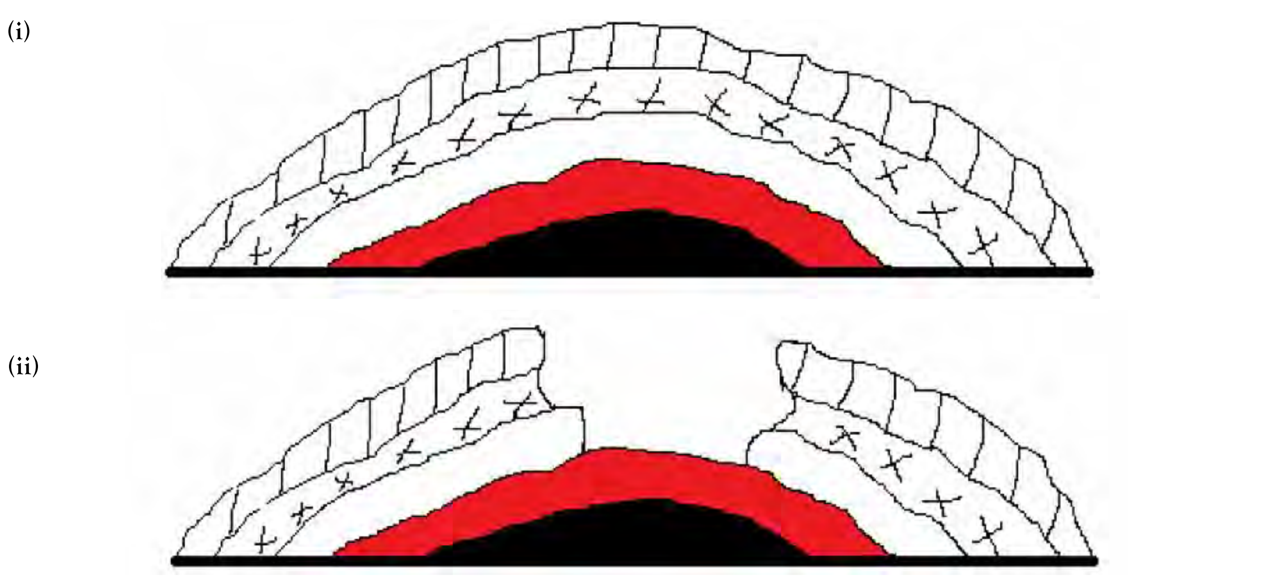
The following simplified schematic diagrams can explain the formation of Silali basin, especially the volcanic shield and impact stages.

As explained earlier, an extra-terrestrial impact could have created a crater at the centre or near centre area of the Silali volcanic shield, opening up the volcanic shield to agents of erosion and weathering. These land remodelling 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 300m thick sediments.

THE MORPHOLOGY OF SILALI CRATER/BASIN

The basic shape of an impact structure is a circular or near circular depression with an upraised rim, though other crater details may

Figure 5: Schematic Diagrams Showing the Formation of the Silali Basin, (i) Represents the pre-Impact Volcanic Shieldm, The Shield is Made Up of Different Layers of Volcanic Rock, (ii) Represents the Post Impact Volcanic Shield (Kipkiror, 2016)



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 satellite images, pictures, aerial photograph, DEM and topographical section presented in this study. 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. 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 2. 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.

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

Plate 2: A Natural Colour SPOT Satellite Image Showing the Silali Crater, Sections of the Basin's Wall and an Outline of a Peak Ring (PR), The Image was Adapted from Google Maps

Plate 3: A Natural Colour Image of Landsat 8, Bands 4 (Red), 3 (Green) and 2 (Blue), Showing the Silali Basin and the 'Outer Basin' (Courtesy of Regional Centre for Mapping of Resources for Development-RCMRD)

Plate 4: An Aerial Photograph Showing a Section of the Western Wall of the Silali Basin (Courtesy of Survey of Kenya)

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 3 and Plate 5). 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. On the satellite images, it appears as the dark and bright circular area around the Silali basin. Major fault lines in Silali area are also visible in most of the satellite images.

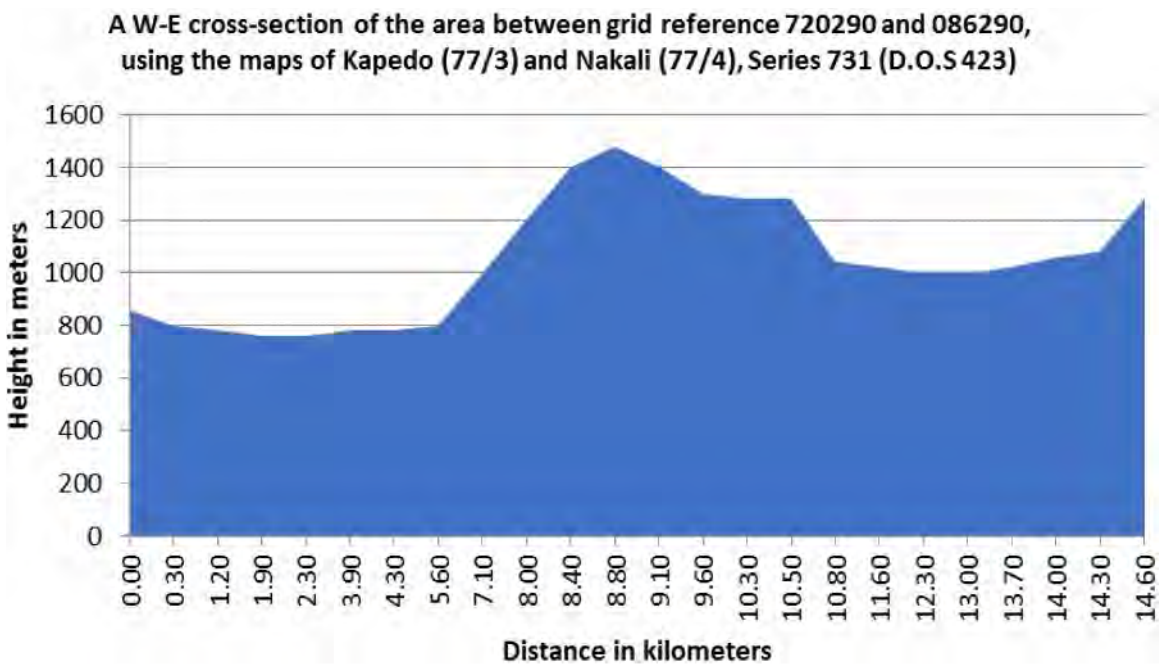
The outer basin (OB) has dark volcanic rock surfaces in many sections and young lava flows (LF) that appear to start right at the base of the Silali basin's wall, especially to the East.

Plate 5: A Natural Colour 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, The Image was Adapted from Google Maps

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.

Between Silali basin and Kapedo Town, lies the Suguta River, to the west, which is also called River Kinyang around Kinyang and Amaya areas. 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

Figure 6: A Morphological Section of the Outer Basin and Silali Basin (Kipkiror, 2016)



Note: A: (720290); B: (086290); Vertical scale = 1 cm represents 200 m; Horizontal scale = 1 cm represents 2.5 km.

basin, which is part of the wider basin, or the 'outer basin'.

Figure 6, 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.

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. This is possible because of the recent lava flows covering the area. Following Silali basin's formation, it appears that much of the magma that exited Silali basin's magma reservoir, before subsidence, poured out more to the east of the basin than to the west. Plate 6 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 picture, at a close look.

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. 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.

Plate 7 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

Plate 6: A Picture Showing Silali Basin's Southern Walls (Kipkiror, 2016)

Plate 7: A Section of Silali Basin's Wall that is Both Stepped and Slumped (Kipkiror, 2016)

Plate 8: 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) (Kipkiror, 2016)

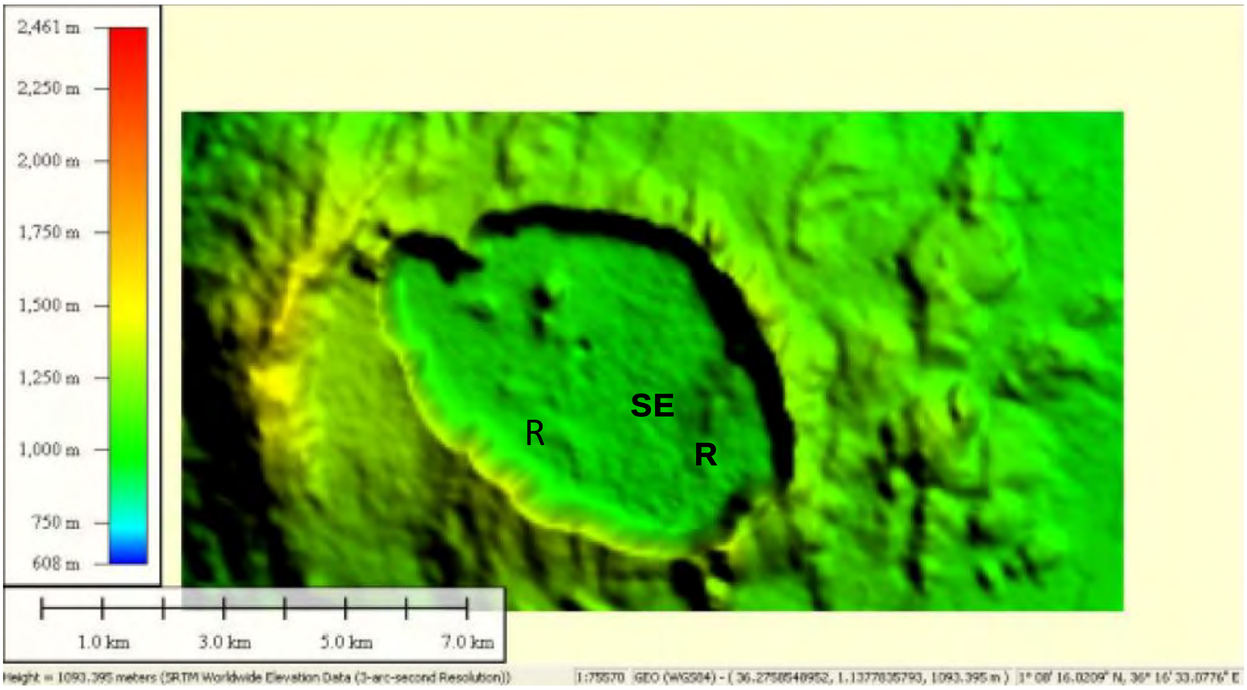


Plate 9: A Picture Showing Silali's Irregular, Slumped (SW) and Stepped Inner Walls (Kipkiror, 2016)

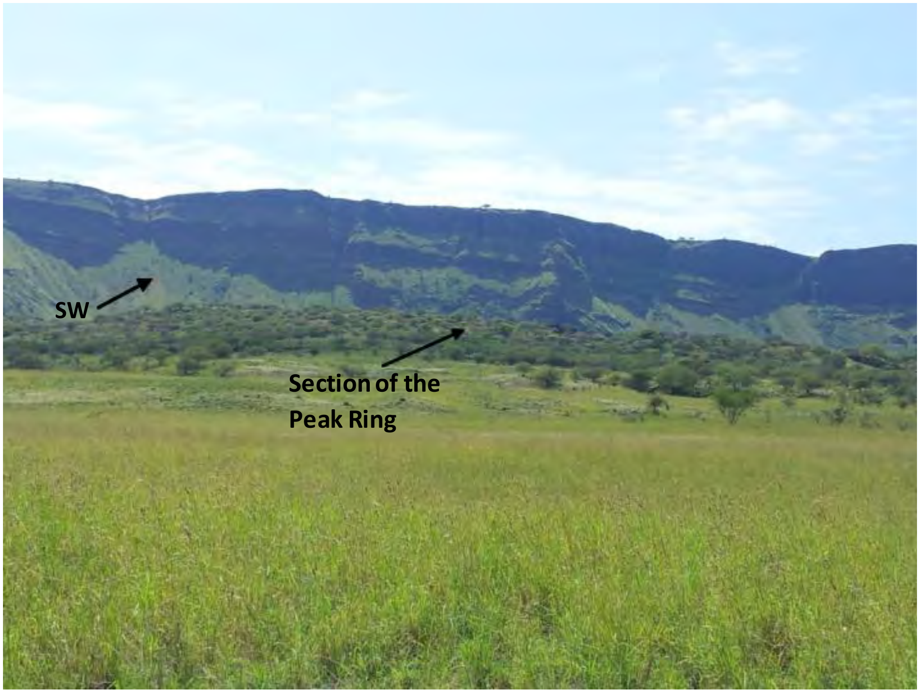
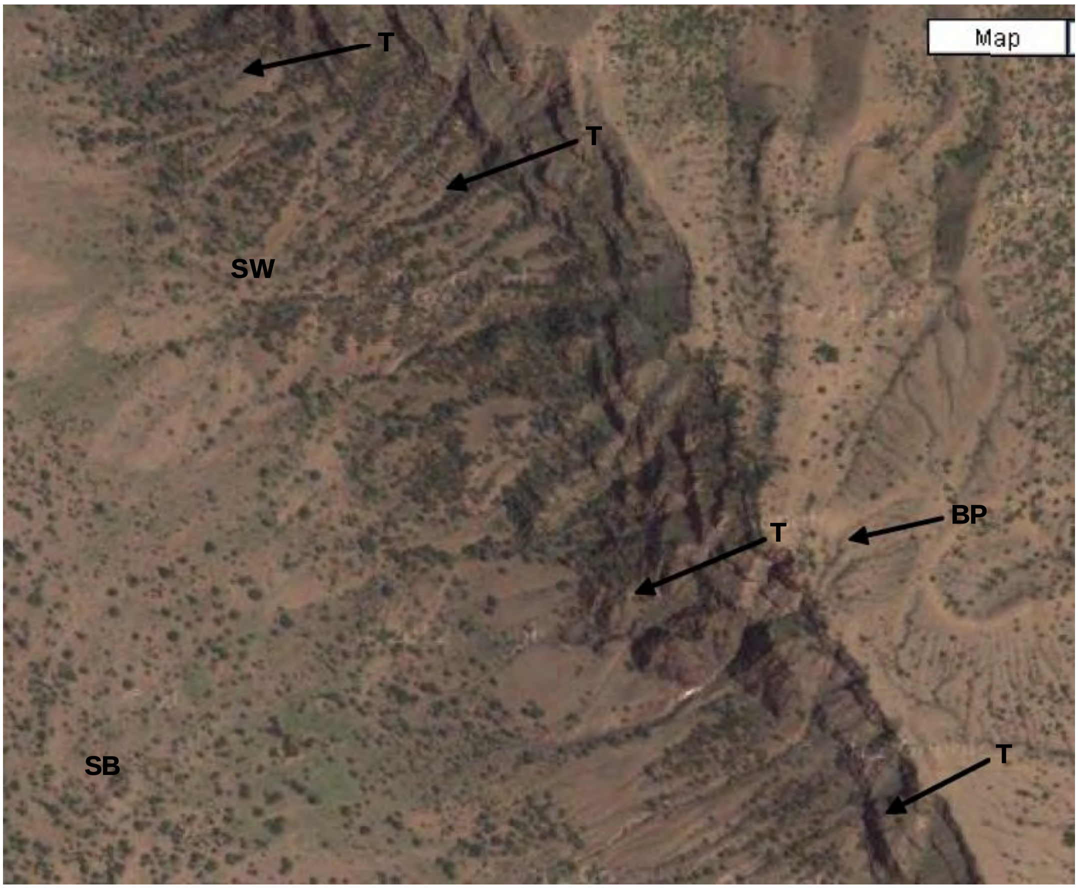


Plate 10: A SPOT Satellite Image Showing Terrace Like Features (T) on a Part of the Basin's Eastern Wall, a Portion of the Silali Basin (SB), Butterfly Pattern (BP) of Ejecta Spread and Slumped Walls (SW)



gives a clearer view of the wall's steps. Slumping, in Silali basin, may be an indication that the basin may still be in the process of subsiding, especially following the ongoing 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. The basin's wall is also slumped all around, as can be seen in the ground pictures presented in this study. Notably, the basin's wall is extremely steep, as can be deduced from the aerial photograph and the ground photographs, especially Plate 9. The rim of the wall is estimated at 300 m above the crater floor, as indicated by the DEM and the cross-section.

The steps on Silali basin's wall are seen on Plate 10. 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. 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. The basin's floor is relatively flat, especially near the foot of the wall, before one reaches the edge of the basin's possible peak ring and the rest of the central hummocky floor. 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 DEM and the satellite images. Landslides and other geological processes, such as volcanicity and tectonic movements, are responsible for the disfiguration of the Silali basin.

A DEM represents an array of elevation points and in this study, it shows 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 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; all of which are morphology related characteristics.

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, just like Silali basin's ring fault structure. There are fault lines that run through the basin as seen from the satellite images, the aerial photograph and the general map of Silali area (Figure 4).

Complex craters are also said to contain terraces on their inner walls, as it is in Silali basin, Telemzane crater and Quarkziz Crater in Algeria. 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 centre 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 study and as stated earlier, they are linked to the basin's formation and effects of denudation.

Plate 10 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).

CONCLUSION

Silali basin's volcanic features can easily lead a scholar into classifying it as a volcano without bearing in mind that volcanicity can be a by-product of an extra-terrestrial impact. 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, Planar Deformed Feature's (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 200-300 m thick layer of sediments and its inner walls are very steep, just like in the case of the Silali basin. As it is, Silali basin has numerous ETIC characteristics that include its morphology; that is circular or near circular. The other ETIC characteristics of Silali basin include: The basin's geology that entails breccias, shatter cones, minerals, impact glass and PDFs; the basin's active magma reservoir that enhances volcanicity (because of the mantle plume beneath the basin); the basin's complex geophysics and the morphological features around Silali basin- all of which point to an extra-terrestrial impact origin for the basin. Consequently, Silali basin may be an ETIC and not a volcano. However, more scientific research should be carried out in Silali basin and its environs to ascertain its extra-terrestrial impact origin beyond all doubt.

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