THE MENENGAI CALDERA STRUCTURE AND ITS RELEVANCE TO GEOTHERMAL POTENTIAL

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ABSTRACT

Calderas are considered to be depressions resulting from an underpressure and/or overpressure within the magma chamber and can be used to interprete the conditions of the subsurface Menengai caldera is located on the floor of the Kenya Rift Valley, 24 km south of the equator and is seen to be of great geothermal potential. Its location on major structures is seen to be advantageous in terms of a highly productive high temperature geothermal system.On the basis of geology the caldea is seen to have undergone multiple block collapse and is thus classified as a piecemeal caldera. The stages of its development include pre caldea volcanism, caldera susidence, post caldera volcanism and hydrothermal activity. The structure of the caldera and post caldera volcanism anf hydrothermal alteration imply a shallow and active magma chamber respectively.

INTRODUCTION

The word caldera in derived from the Latin word *caldaria* which means boiling pot (Cole et al, 2005). It is thus simple to understand in layman terms the basic features of a caldera and these comprise heat, a chamber and a conduit. A caldera is a cauldron-like volcanic feature usually formed by the collapse of land normally following a volcanic eruption. Acocella (2007) considers calderas to be depressions resulting from an underpressure and/or overpressure within the magma chamber. This term is sometimes used interchangeably with crater but the distinction is in the mode of formation. Calderas vary in size and shape based primarily on geological setting/tectonic control and composition of eruptives although the latter is not proven.

Calderas are thus interesting sites for geologists since they give information of the geological processes that have taken place on the surface and the subsurface. In the geothermal sector calderas are key indicators of the very sort after geothermal activity because they more or less imply an underlying heat source. Direct witnessing of the formation of a caldera is a minor setback in the formulation of a comprehensive model but is overcome with the use of geophysical methods and subsequent models.

Menengai caldera is located immediately north of Nakuru town and a few kilometres south of the equator (figure 1). It is one of five calderas in the Kenya Rift valley and is seen to be of great geothermal potential.

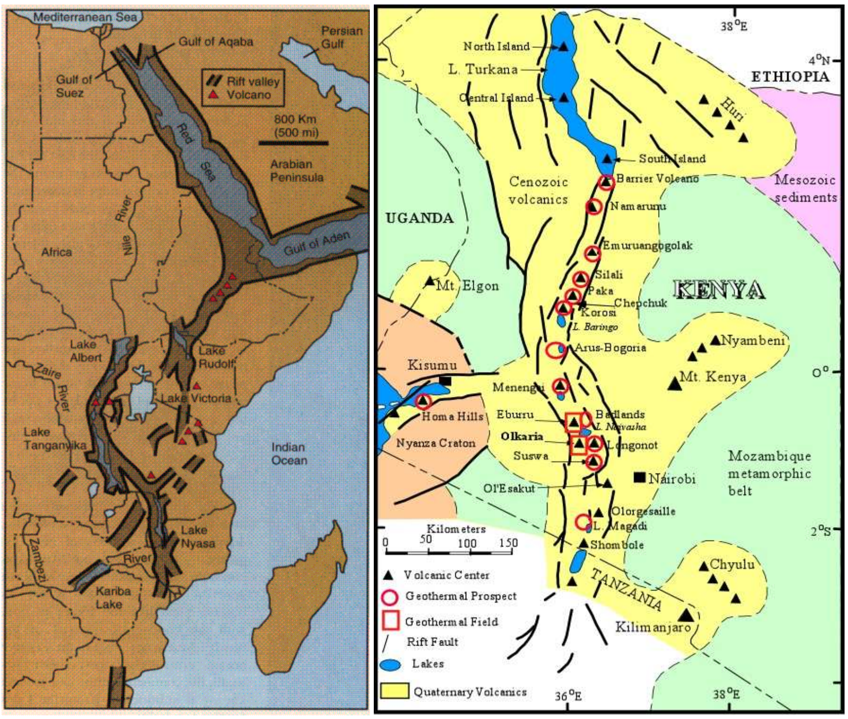
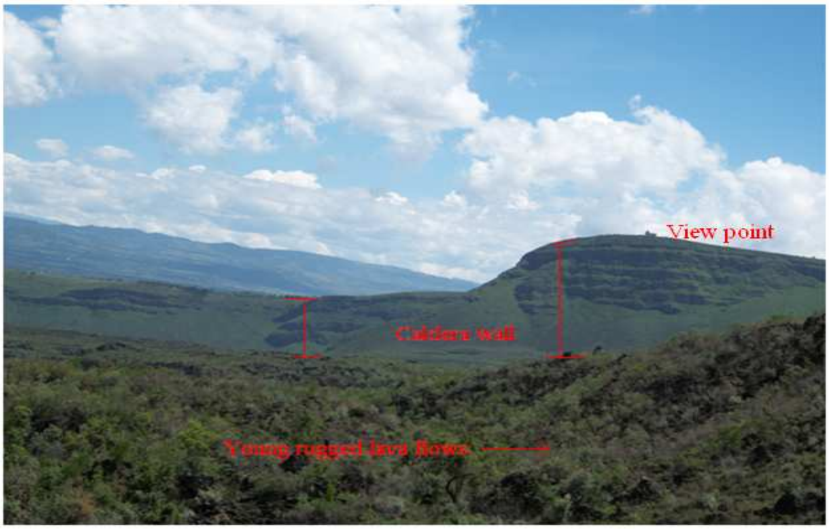


Figure 1: Tectonic setting of Menengai Caldera

The approximately 12 x 8 km summit caldera was formed about 8000 years ago following volcanic activity which begun almost 200,000 years ago (Seach 2009). This caldera is the major geological feature in the area and also an important structure in terms of occurrence of geothermal potential. The large caldera floor is partially covered by young rugged lava flows as shown in slide 1 below. The caldera rim forms a complete circular cliff that breaks at very few locations which makes it perfectly visible in areal and satellite images.

The apparent signatures of geothermal potential include the young volcanism represented by the numerous recent eruptions both inside and outside the caldera, the large caldera collapse and intense tectonics resulting in intense faults marking the area. Occurrence of active fumaroles, steaming ground, hot/warm water from boreholes and geothermal grass indicate hydrothermal activity and possibility of existence of geothermal reservoirs in this area.



SLIDE 1: Image of Menengai caldera wall and some young lava flows.

TECTONIC SETTING

The Kenya Rift valley (Figure 1) is a very distinct feature of geographic and geologic interest that has developed along a rift, especially one bounded by normal faults in an area of lithospheric thinning. It is a tectonic feature that runs from Lake Turkana to the North down to Lake Magadi in the south splitting the country almost in half. It forms a classic graben averaging 40-80 km wide, is deepest at Naivasha area and shallowest at Lake Turukana area where there is no clear distinction between the rift and the surrounding desert. The Kenyan rift is part of the East African Rift system, which is an intra-continental divergence zone where the Somali and Nubian plates are rifting apart at a rate of 2cm per year (1cm in each direction) and creating a much thinner crust. Rift tectonism accompanied by intense volcanism, has taken place from late Tertiary to Recent (Kengen, 2004). Several Quaternary volcanoes occur within the rift floor of the Kenya segment of the rift. The extensional deformation occurs because the underlying mantle is rising from below and stretching the overlying continental crust. Upwelling mantle may melt to produce magmas, which then rise to the surface, often along normal faults produced by the extensional deformation (Odhiambo, 2010). Menengai is one of the volcanic centres that has had one or more explosive phase(s) including caldera collapse.

Menengai caldera is located within an area characterized by a complex tectonic activity associated with the rift triple junction. This is a zone at which the failed rift arm of the Nyanza rift joins the main Kenya rift. The Kenya rift is characterized by extension tectonism where the E-W tensional forces resulted in block faulting, which include tilted blocks as evident in both the floor and scarps of the rift (Jones and Lippard 1979).

The main rift is bounded by N-S running major rift scarps that depict different tectonic style on the two sides due to their morphological difference. Geotermica Italiana Srl (1987) proposes that this whole section of the rift is a crustal detachment generating a sequence of faults, which merge at a low angle at depth. Two rift floor tectono-volcanic axes Molo and Solai (TVA) that are important in controlling the geothermal system.

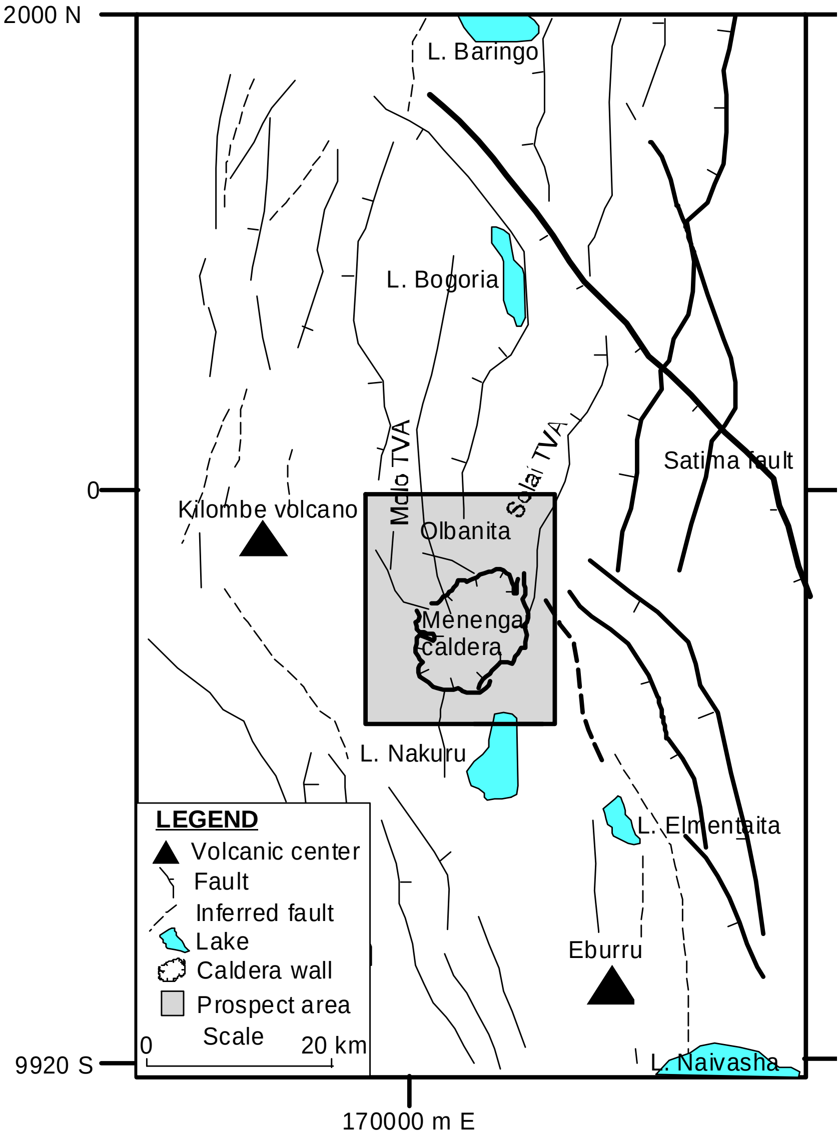


Figure 2: The tectonic setting of Menengai caldera

Although there is no direct link between type of eruptive and the type of caldera formed, there seems to be one between the type of eruptive and the tectonic setting. Peralkaline calderas such as menengai are associated with zones of rifting.

CALDERA CLASSIFICATIONS

Various caldera classifications have been suggested, published and adopted over time in an effort to reduce the numerous variations in their descriptions. The distinction of these classes is becoming more apparent with the availability of additional data and simulation of experimental models. The end member approach by Lipman (1997) is the most realistic as it recognizes and assimilates the wide range of features associated with these structures.

Classifications based on volcanic events, geophysical gravity anomalies and nature of magmas do not put clear boundaries on the calderas where for example a rhyolitic caldera may contain some mafic volcanism.

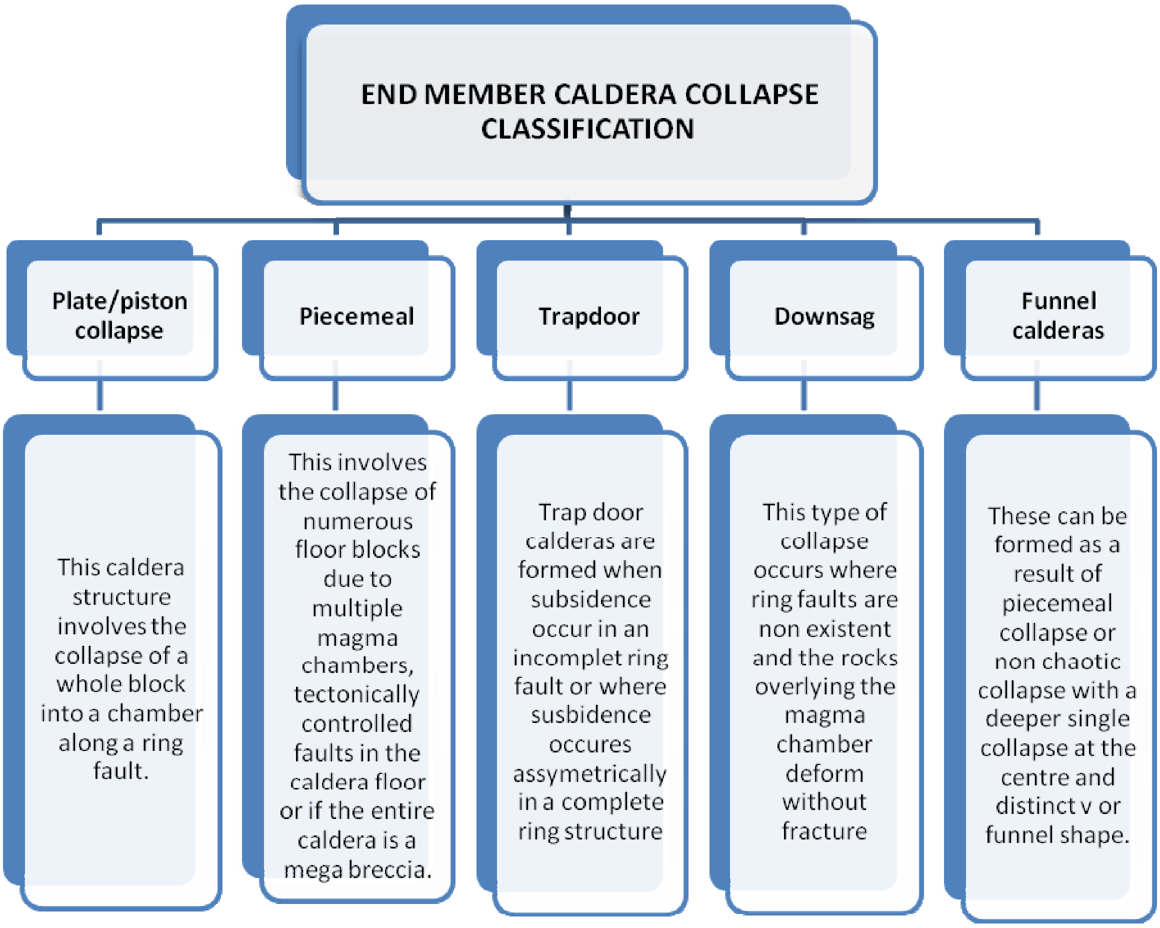


Figure 5: End member caldera classification after Lipman (1997)

The Menengai ring structure has only been disturbed by the Solai graben faults on the NE end and one another fracture at the SSW end. The caldera floor is covered with post caldera lavas such that it is not possible to estimate the collapse depth or any structures that may be marking the caldera floor (KenGen 2004). However, most of the caldera infill lavas are fissure eruptions that prefer fracture openings. These features therefore suggest a piecemeal collapse caldera as do the rock types and their respective ages.

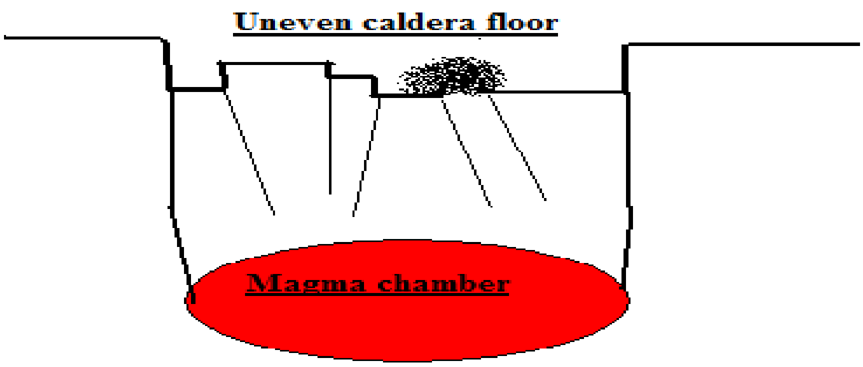


Figure 4: Piecemeal caldera

In the geothermal sector where structures are primary constituents of a good geothermal system, a piecemeal caldera is certainly ideal as the structures increase chances of recharge and permeability. Targeting these structures in the exploration drilling phase would certainly be an excellent plan as they also give additional information for use in the geothermal model.

MENENGAI CALDERA DEVELOPMENT

Lipman (1984, 2000) identified four stages which result in the development of a caldera based on his study of rhyolitic calderas in North America. This four stage cycle although applicable to other caldera types is not standard as some stages may not be pertinent to all formations.

TABLE 1: Stages in the formation of calderas (from Lipman 1984)

	Stage	Activity
1	Pre-collapse volcanism	Surface volcanism, frequently accompanied by tumescence, but this tumescence is not easily preserved and formation of pre-caldera lava domes and small explosive eruptions are often the only record of magma accumulation and migration to shallow crustal levels.
2	Caldera subsidence	Collapse associated with large-scale magma withdrawal (eruption). Eruptions often begin with a central vent phase and proceed to a ring vent phase coincident with caldera collapse
3	Post-collapse magmatism and resurgence.	Volcanism after caldera formation can be randomly scattered within the caldera or localised along regional structural trends. Renewed rise of magma may uplift the central portion of the caldera either by doming or block uplift. This uplift may also be caused by intrusion of sill complexes.
4	Hydrothermal activity and mineralisation.	This may occur throughout the life of the caldera, but begins to dominate activity late in the cycle creating geothermal systems.

The Menengai caldera although a peralkaline caldera fits perfectly into the four stages of formation described above with pre, syn and post caldera group volcanics being used to describe the geology of the area in various studies. The geology is subdivided into 3 based on caldera activity; rocks exposed at the surface, mainly the Menengai massif building lava (pre-caldera formations), the pyroclastics that accompanied the caldera collapse (syn-caldera) and glassy lavas that erupted after the collapse (post-caldera).

Pre- caldera volcanism

Activity in Menengai started shortly before 0.18 Ma, with the growth of a low-angle trachyte lava shield having a volume of about 30 km^3 (Leat 1984). These volcanics are typical of any lava shield volcano where sequential piles of lava flow overlie each other (Slide 4). These rocks can be seen on the caldera walls such as at the lion hill where up to 250m of these lava piles are exposed despite the caldera wall being approximately 300m high. The rocks are trachytic in nature with the groundmass being comprised of mainly sanidine crystallites although riebeckite/ arfvedsonite are also present (Kengen, 2004). The chemistry of the rocks implies that there was periodic addition of new magma batches to the growing system. A series of Trachytic tuffs of similar age to the trachytes suggest that the chamber was zoned at that point of the chamber evolution (Mcdonald 2009).

Caldera Subsidence

Growth of the lava shield was truncated, at ~29 ka, by a period of caldera collapse, accompanied by the eruption of an ash flow tuff, preceded by pumice falls. The ash flow tuff had a volume of 20 km^3 and was erupted as a single flow unit (Leat, 1984). The rocks are exposed both at the upper parts of the caldera rim (east and northern rim), where they resemble an agglomerate deposit, which is rich in poorly sorted angular lithic and glassy/semi-pumiceous material (Kengen, 2004). Leat et al. (1984) inferred that the sequence was erupted from a compositionally zoned magma chamber. The ash shows flow texture indicative of pyroclastics flow mode of emplacement. This is the proximal phase indicating the source was at the caldera and its rim.

A second period of collapse occurred at ~8 ka, with the formation of a 12 × 8 km caldera associated with the eruption of 30km^3 of magma. A speculative sequence of the caldera formation during eruption of the second ash flow is shown below. The dot-dash area represents the volume of magma erupted as ash flow.

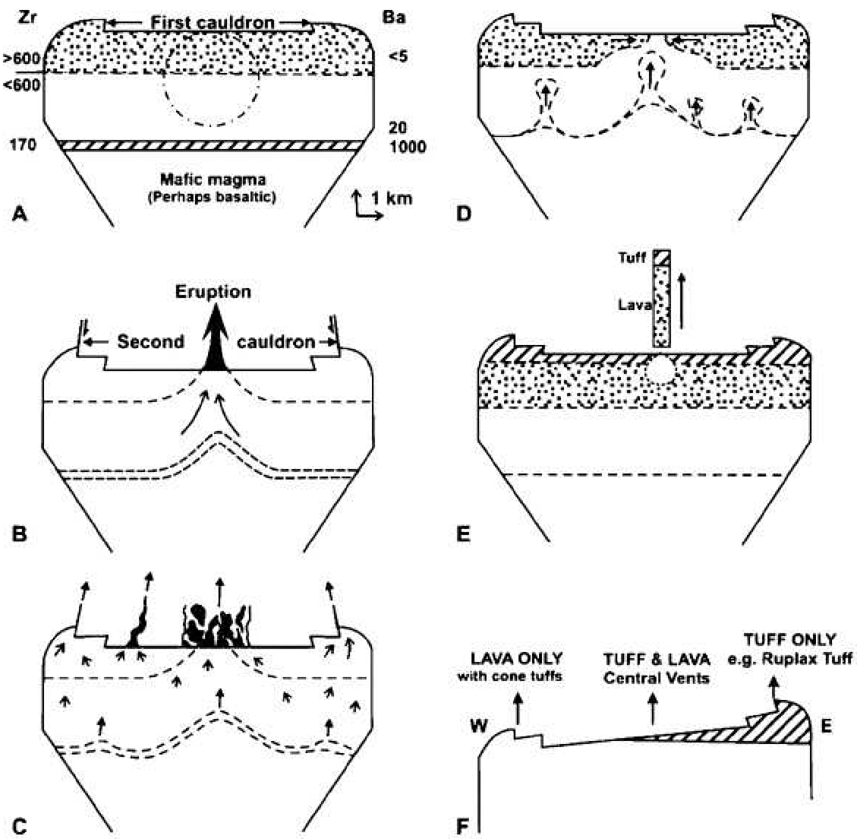


Figure 6: Phase two caldera collapse and post caldera volcanism

Post-collapse magmatism and resurgence

During post-caldera times, some 25 km³ of magma was erupted, mostly as lava flows which now cover the caldera floor and the eruption of these post caldera lavas may have been preceded by explosive episodes due to presence of ash and pumice products in the caldera floor (figure 4). About seventy distinct lava flows can be identified on the caldera floor, with most of the eruption centres emitting the flows being located in the central and the western parts. These lavas have built a huge pile inside the caldera rising to 2160 m.a.s.l. The lowest part of the caldera floor, which is also infilled with the same lavas stands about 1700 m.a.s.l. The lavas are dark in colour, holocrystalline, glassy and are vesicular (Jones 1985). The ropy flow texture, and the small undisturbed lava tubes which are still intact, indicates a young age and the low viscosity of the lavas. The groundmass is mainly made up of sanidine feldspar laths and occasional riebeckite crystallites.

SLIDE 2: Satellite image showing the post caldera lavas (darker in colour)

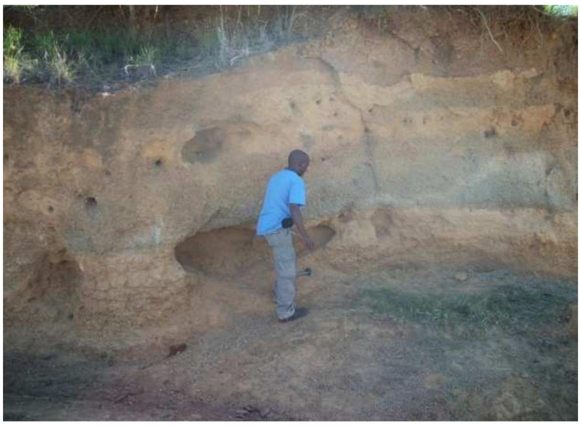
SLIDE 3: Lava tube.

Hydrothermal activity and mineralization

Hydrothermal activity is mainly what leads scientists to show interest in a geothermal field. The good thing is that in the feasibility stage of any mapping work, aerial photographs are required. Hydrothermal manifestations can be identifies from aerial photographs and thus thermal mapping mission was conducted in the Menengai area. Until then airborne exploration methods have scarcely been applied. As a result of this mission a total number of 2,400 thermal images with 5m pixel size were collected for an area of 510 km² (30 x 17 km) in the Menengai and surrounding areas. Additionally, 220 stereoscopic aerial photographs (1:20,000) were recorded. Eight thermally anomalous areas or "hot spots" were identified by KenGen. The digitally processed photographs were thereafter linked with temperatures from fumaroles steam discharge sampling, soil gas sampling and with several hundred temperature measurements in shallow boreholes (1m deep). The aerial thermal mapping technique proved to be a valuable additional exploration tool, particularly in relatively unknown prospect areas with limited vegetation. (BGR 2009)

Hydrothermal activity is manifested in this area by the occurrence of fumaroles, warm springs, steaming/gas boreholes, hot/warm water in boreholes and altered rock/grounds. Fumaroles are however located mainly inside the caldera floor (Slide 7) with some weaker ones outside the caldera. The fumaroles appear to be structurally controlled and are marked by silica and or chalcedonic deposition.

SLIDE 4: Pre caldera Trachytic lavas



SLIDE 5: Syn caldera ignimbrite and tuff

SLIDE 6: Post caldera lava flows

SLIDE 7: Hydrothermal activity and mineralization

CONCLUSION

Regional and local structures are envisaged to be what created lines of weakness which lead to formation of the menengai caldera. These faults are also likely to be potential sites of magma accumulation and dyke formation which in turn provide heat to the geothermal system. The large diameter and circular shape of the caldera implies that the magma chamber is wide and shallow. Seismic studies in Menengai indicate that a dense body lies within 10 km below the surface (Simiyu and Keller, 2001). Studies further show that the caldera size is by no means an indication of the size of the magma chamber. This means that the chamber in Menengai is much larger and still active based on the active hydrothermal activity.

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