Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Identification of Permeability Controls in a Geothermal System Using Gravity Method, Menengai Case Study

Joseph Gichira and Yussuf Mohamud

Geothermal Development Company

jgichira@gdc.co.ke

Keywords: Menengai, permeability, gravity, geothermal.

ABSTRACT

Surface studies done in Menengai field have indicated a huge geothermal potential and has led to the drilling of several wells. However, some of these wells have not produced as earlier projected and there are questions as to whether this field has good permeability. The purpose of this study was to employ gravity method to understand density variations in the Menengai field by developing structural models and establishing whether there is reliable permeability. Raw data collected by Kenya Electricity Generating Company- Kengen and Geothermal Development Company- GDC was reduced to complete Bouguer data by subjecting it to all reduction procedures and gravity models developed using a Golden software program called Surfer. These models were then subjected to specific filters that helped in identification of structures responsible for permeability. These filters are: Band pass filter; applied to remove certain wavelengths and horizontal derivative filter; applied to image drastic changes. Density inversion from results of complete Bouguer anomaly readings were generated by 3D inversion Grablox1.6 programme that calculated synthetic gravity anomaly of a 3D block model. Comparison of gravity and resistivity models indicates a good resemblance of the magmatic intrusion and the Tectono-Volcanic Axis-TVA's. From this analysis, permeability controls for Menengai geothermal field were identified as follows: caldera rim faults that contribute mostly to deep vertical recharge, NNE-SSW faults along Solai graben, NNW-SSE faults along Molo axis, the southern fault extending towards Lake Nakuru and the uplifting dome in the central part of the caldera which enhance further fracturing within the caldera. This has led to a conclusion that there is good permeability in Menengai geothermal field. The research and its findings therefore have shown that gravity should be used as a key technique rather than a preliminary tool in geothermal exploration. The practice has mainly been to use gravity for deformation monitoring or as a preliminary tool. However, failure by other techniques in identifying permeability controls forms the basis of this study and from the results; it has been found that if well utilized gravity method could solve the many challenges encountered in geothermal exploration. The results from this study therefore would be of high importance to GDC if adopted and used in locating sites where geothermal wells can be drilled.

1. INTRODUCTION

1.1 Background of the study

Menengai is a field with huge geothermal potential. The field stands in an area of intra-continental crustal three-way rift intersection with the main Rift meeting the Nyanzian Rift. The main Rift is confined by North - South running rift scarps. The field covers the Ol-Banita plains towards northeast, Solai graben, Ol'Rongai and Menengai volcanoes.

This study paid more attention on the Menengai Volcano. This portion of the rift represent a splinter segment of the main lithospheric units as supported by high-pitched slopes on the flank to the east while on the west is a moderately inclined one (Bosworth, Lambiase, & Keisler, 1986). The central loop assemblies of Ol-Banita and Menengai calderas characterize failures related to withdrawal near surface magma compartments beneath. From an extract obtained from a report by Burke & Dewey, 1973, it was explained that there could be a mantle plume superimposed by Menengai – Ol-Banita zone. The surface was said to include numerous eruptive volcanoes with caldera failures and concentration of tectonic grid faulting block and fissure faults in its northern extents typical of extensional faulting related to divergence at crustal boundaries.

Massive volumes of pyroclastics shelter the gradients of Menengai and Ol-Banita areas. These differ from welded pyroclastic flows, pumice rich ash deposits, ash fall and nearby lithic tuff projections adjacent to Menengai caldera. The source of these pyroclastics eruptives is the violent eruption leading to development of Menengai caldera (Simiyu et al., 2001).

Geophysical investigations forms a key part since they are the only approach of detecting abysmal structures responsible for controlling the geothermal system which includes heat sources and conduits for geothermal fluids, with the latter being the missing link in many areas and hence a let-down in geothermal development. Gravity technique is very powerful in this regard but much attention has always been directed towards resistivity and seismic methods and even when used most workers tend to concentrate mainly on identifying heat sources. Kenya map displaying the position where Menengai lies within the Kenya Rift Valley, Figure 1.

Figure 1: The Kenya Rift section showing position of Menengai (Omenda, 2007).

1.2 Tectonic Setting

The Kenya Rift section is a prominent geographical and geological feature of interest. It is a tectonic feature running north to south. It forms a typical graben averaging 40 to 80 km wide, see Figure 1. The Kenyan section of the Rift is a portion of the great African Rift system which is an intra-continental separation region where rift tectonism accompanied by intense volcanism, has taken place from late Tertiary to Recent. The rift developed in an unchanging orogenic belt that abuts around a craton. Numerous Quaternary volcanoes occur within the Kenyan segment of the Rift floor. Within the rift floor, majority of the volcanic centers had single or multiple explosive phases which included collapsing of calderas. Several centers have scattered hydrothermal expressions and are imagined to accommodate geothermal systems driven by magmatic sources.

The Menengai field is located in a zone associated with complex tectonic activity connected three way rift intersection. This section of the split is characterized by divergence forces with east -west pulls occasioned block faulting, comprising of sloping slabs as manifested in the two scarps plus the rift floor. The western region is characterized with narrow scarps that have been eroded resulting in gentle scarps, an indication of slight effects of movements. On the other hand, the eastern margins portray broader loops, with high-pitched slopes suggesting immediate dynamic activities.

There seems to be constant extension tectonics beneath the floor of the rift channel as demonstrated by several normal faults traversing this channel. Two TVA's essential in controlling Menengai geothermal system are: Molo TVA and Solai TVA.

1.3 Menengai Caldera

This large cauldron-like depression forms an oval sunken landform that has a main axes stretching for 11.5 kilometers and a minor axes estimated to measure 7.5 kilometers. The disk shaped caldera rim fault is effectively conserved with the sloping gradient measuring around 400 metres at selected places. The loop structure is disturbed on the NE end by the Solai graben faults and to SSW of the caldera wall by a fracture extending southwards, Figure 2. Notable disturbances are also evident in the NW and SE ends and could be pre caldera grabens. The floor of the caldera is covered by after caldera lavas to the level that it is impossible to approximate collapse depth and structures inside the caldera floor. On the other hand, the caldera floor is covered by lavas from fissure eruptions.

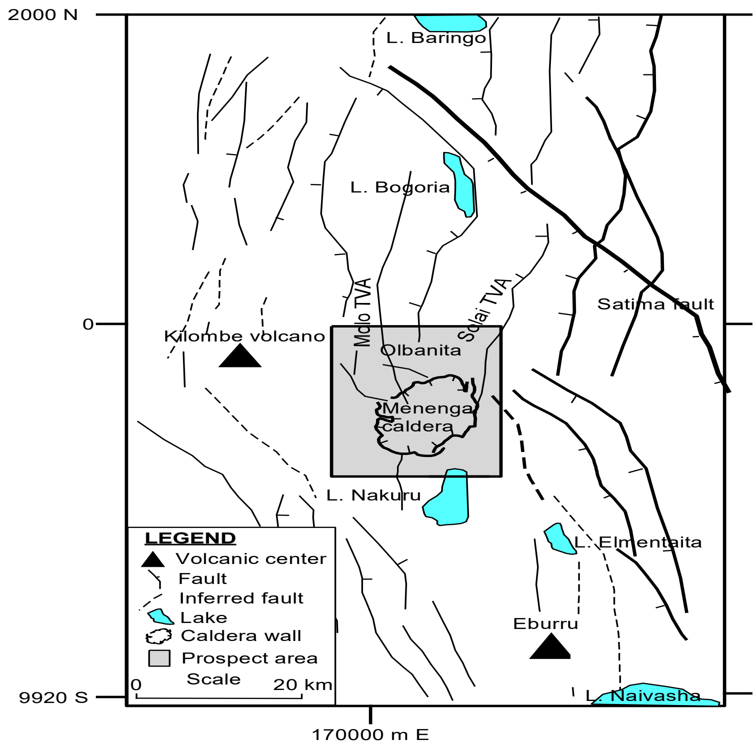

Figure 2: Structural map of Kenya (Mungania et al., 2004).

2. PREVIOUS WORKS

The rift valley is characteristic of surface indicators such as altered grounds, fumaroles and hotsprings. Previous researchers have described the origin of these features in similar ways. The findings by previous researchers are discussed as per the respective method, namely: gravity, seismology and electromagnetic method. According to (Searle, 1970), the anomaly is a high dense intrusion originating from the mantle and has a width of 20 km spreading from 20 km deep.

Hearly, 1975 explained that a system as such would have its source of heat associated to arising dyke from an intra-crustal magma reservoir. The rift axis was said to be associated with an intermittent narrow positive anomaly running from Lake Turkana to Lake Magadi in the south with varying width and amplitude.

The long-lived trachytic volcanism in the rift was explained by subsequent fractional crystallization of basalts, without the necessity of transverse structures facilitating magma ascent (Leat, 1991). The presence of hot mantle material beneath the Kenya dome since the onset of volcanism here at 15-20 ma was discovered to still be well-matched with the sudden change in mantle longitudinal wave velocities as the rift margins are intersected.

Gravity maps of the central Kenya Rift show a long-wavelength bouguer anomaly minimum and axially aligned short-wavelength highs (Swain et al. 1994; Simiyu and Keller 1997; 2001). All late Quaternary trachytic volcanoes, including Menengai and Ol'rongai, are distributed along positive anomalies, rather than along the young, regional-scale left-stepping faults. Detailed analysis of gravity data showed anomaly with an amplitude of 30 milliGal, half-wavelength of 15 km and a NW-SE trending anomaly interpreted to be related to the heat source (Simiyu and Keller, 1998). Band pass filtering indicated that the NE- SW trending anomaly has two maxima with amplitude up to 15 and 24 mGal. They also identified linear positive anomalies showing control of structures in the basement and shallow bodies related to Menengai volcanic activity. During this study, a basaltic melt magma body was postulated as the main heat source directly beneath the caldera. Gravity data interpretation by analysis Bouguer anomaly map indicated presence of a high density body in the central part of the caldera (Figure 3). Since the volcano is relatively young this body could still be hot, the heat being conducted to near surface regions by dykes (Mariita et al., 2004). Tectonic activities affect geological landscape physically in the subsurface. These activities causes among others tension, compression and bending leading to fracturing of rocks (Hasanah et al., 2016).

Regional seismic studies of the crust along the Kenyan rift, showed significant differences in crust structure between the northern, Central and southern parts of the rift valley (Simiyu and Keller, 2001). The rift fill thickness varies from 1.5 km to 5 km underlain by basement material of velocity 6.05 km/s. High velocity bodies associated with the Menengai, Olkaria and Suswa Quaternary volcanic centres were mapped (Figure 4).

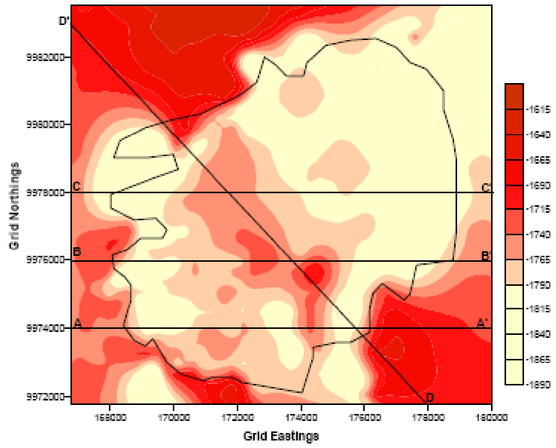

Figure 3: Bouguer anomaly map of Menengai area. The line running from east to west and the one running from the North West to South East are profiles (Mariita et al., 2004).

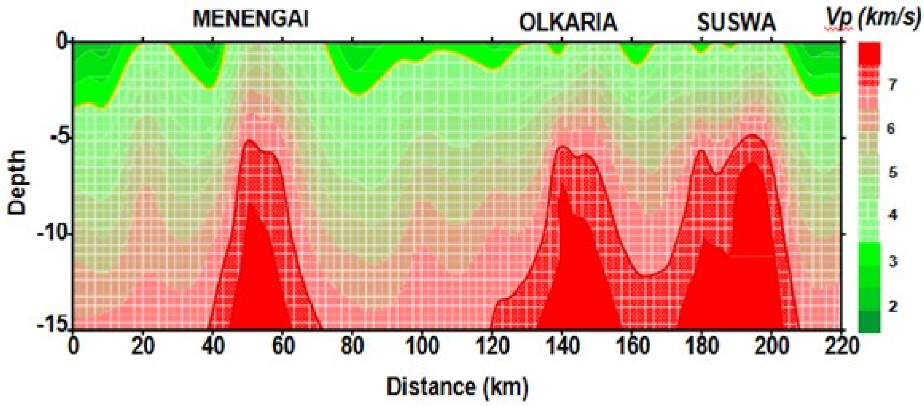

Figure 4: Seismic Velocity model along the Rift axis showing high velocity zones beneath Menengai, Olkaria and Suswa Volcanic centers based on the KRISP 1985-1990 axial model (Simiyu and Keller, 2001).

Magnitude-distance distribution for earthquakes have a greater proportion of the smallest earthquakes of magnitude 1.5 and less are recorded very close and within the network center but fewer and larger magnitude 1.5 and greater on the periphery. This result is similar to recording in other high temperature and pressure geothermal fields such as Olkaria, Kenya (Simiyu and Keller, 2001).

The amplitude and depth of the seismic activity peak is predicted to decrease with increasing geothermal gradient. Earthquakes represent a sudden slippage of rock along a fracture surface and generally should be restricted to a zone of brittle deformation. The maximum depth in a region at which earthquake intensity peaks will delineate the brittle-ductile transition zone, (Meissner and Strehlau, 1982). It was suggested that stress along the rift floor in the Central Kenya Rift area was being released by micro-seismic activities in geothermal areas but by larger earthquake sequences along the rift boundary faults. This interpretation was also supported by recent seismic intensity, magnitude and depth distribution analysis in Lake Bogoria and Olkaria (Simiyu, 1999). It was alluded that geothermal fields owe their existence to the presence of molten rock in the crust.

The location of these bodies in many fields has been mapped by analyzing regions of high S wave attenuation. It was realized there were diminished S wave amplitudes in some of the seismograms and spectral analysis of arrival times and first motion showed that the signals were of low dominant frequencies less than 3 Hz (Simiyu and Keller, 1998) . This was taken to imply that the rays were passing through a molten body or less compacted low velocity material near surface. This either suggests the axial intrusion of magma or the significance of intra-rift horst blocks to influence the gravity signal, (Simiyu and Keller 2001). Another suggestion was made that there exist intrusions below the Menengai, Olkaria and Suswa volcanoes as shown in the Bouguer map (Figure 5). Bouguer results showed a positive gravity anomaly in the middle of the caldera (Figure 6), which was interpreted as a magmatic intrusion (Wamalwa 2011).

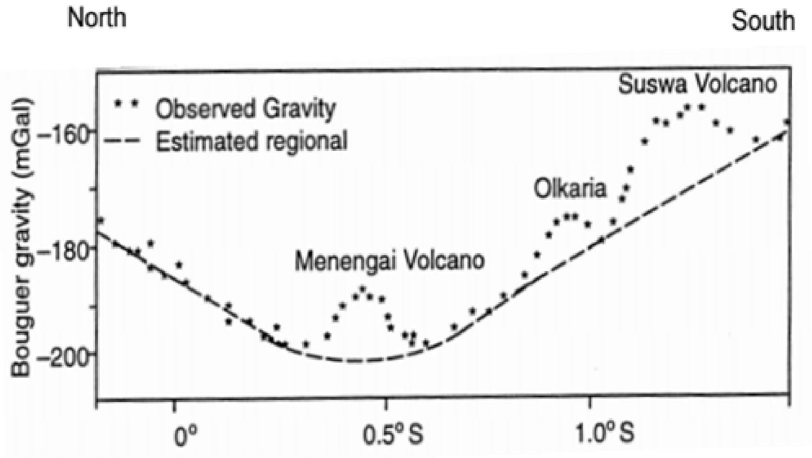

Figure 5: Anomalous bodies below Menengai volcano (Simiyu and Keller 2001).

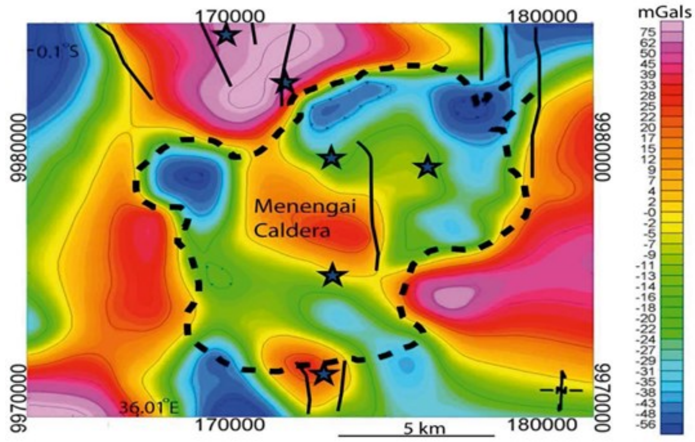

Figure 6: Bouguer anomaly of Menengai (Wamalwa 2011).

These studies led to a conclusion that the central-caldera structures were incompatible with the remainder of the structural inventory and thus were interpreted to reflect a local, magmatically driven stress-field perturbation.

Measurements and modelling of magneto telluric data recorded a less resistive zone at a depth of 3 km (Figure 7) which was associated with a molten body (Wamalwa 2011). It therefore appears likely that the observed structures are the direct result of magmatic addition into the shallow parts of the crust, associated with localized growth of topography and the generation of local structures, independent of the regional tectonic stress field.

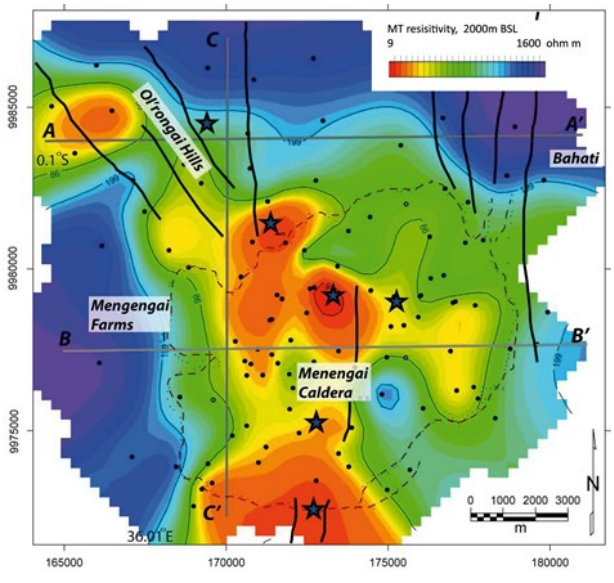

Figure 7: Resistivity map of Menengai at a depth of 3 km below surface (Wamalwa 2011).

3. RESULTS AND DISCUSSIONS

3.1 Discussions

The Bouguer anomaly map that was developed shows an almost complete circular gravity low within the caldera associated with permeability and notable relative high gravity in the central part of the caldera (Figure 8). The high amplitude gravity gradients in this map could indicate contact zones that separate this high gravity anomaly and the faulted zones. The dense body in the central part of the caldera coincides with the dome area. It is deduced that this anomaly represents a magmatic intrusion. To perform trend surface analysis, band pass filter was applied to filter low and high wavelengths and this slightly improved interpretation.

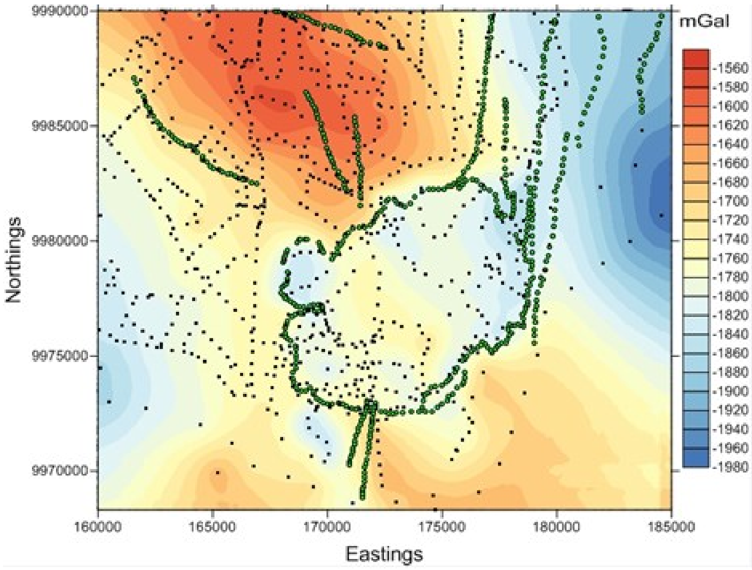

Figure 8: Gravity Bouguer anomaly map of Menengai Geothermal field. Black dots denote gravity sampling points.

A band pass filter of 50-3000 m was applied to the Bouguer data and some changes could be observed (Figure 9). This filter effectively removed the effect of deep seated dense bodies that had made the NNW part of the study area appear very dense in Figure 8.

This study was interested with a depth of upto 3000 metres (m) and anything below this therefore had to be removed. The filter also removed any possible effect of surface bodies above 50 metres (m). Attempts to improve resolution further for better interpretation led to application of 100-3000m filter (Figure 10) but this did not change the interpretation. To overcome this huddle, regional effects had to be removed and a residual gravity anomaly map was constructed. The regional effects had magnified short wavelength anomalies to deep seated anomalies leading to wrong interpretations and therefore had to be removed (Figure 11). The resulting residual anomaly map filtered these effects leading to reduction in size of the highly positive anomalous body notable in the NNW orientation (Figure 12).

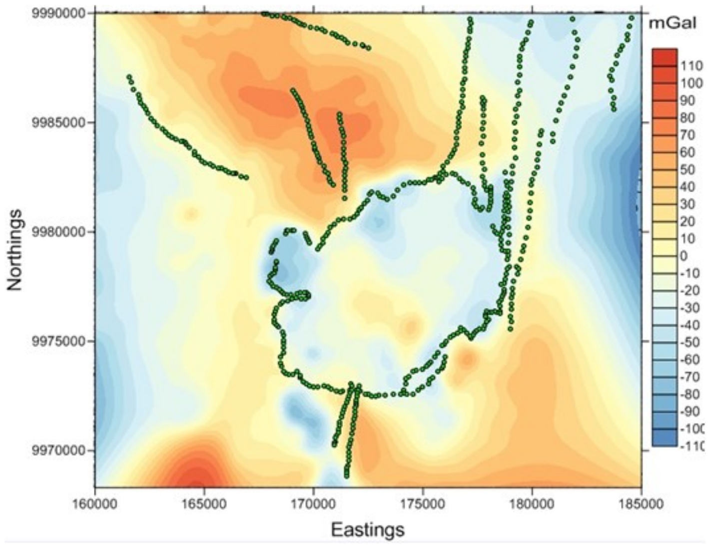

Figure 9: 50 – 3000 metres Band pass map of Menengai.

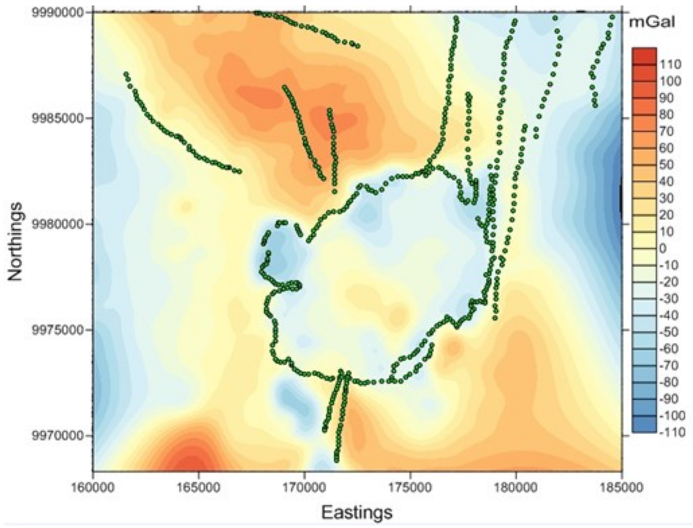

Figure 10: 100 – 3000 metres Band pass map of Menengai.

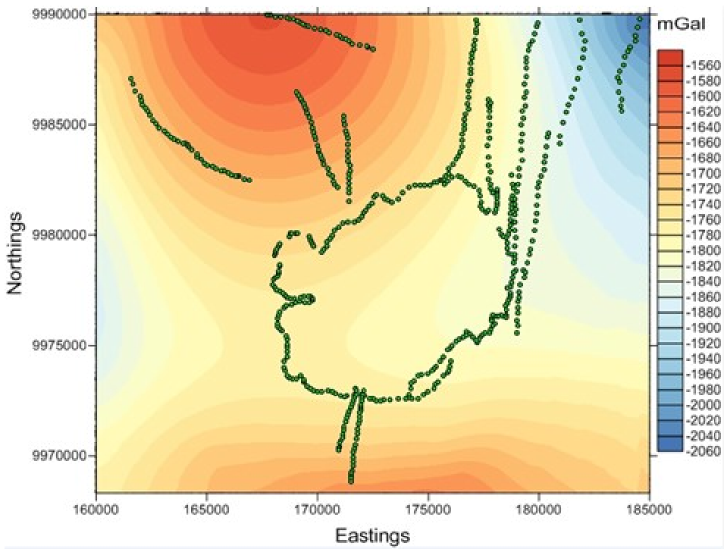

Figure 11: Regional anomaly map of Menengai Geothermal field.

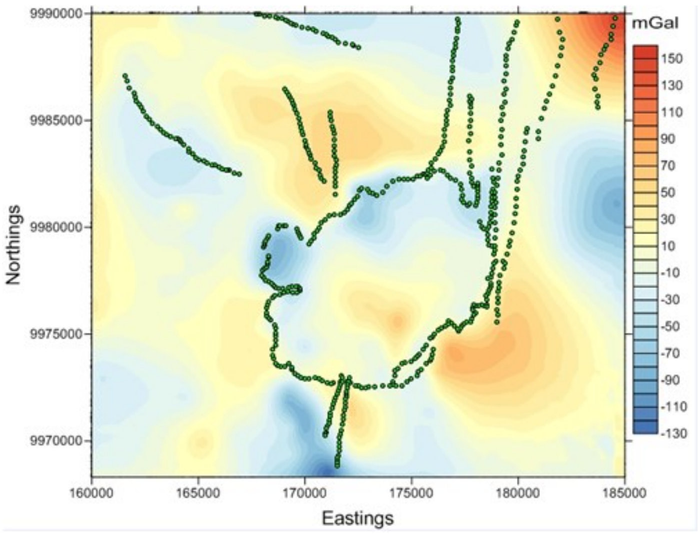

Figure 12: Residual anomaly map of Menengai Geothermal field.

To improve clarity and establish whether there is enough permeability, more terrain surface analysis were carried out. 200- 3000 m Band pass filtered anomaly map was subjected to horizontal first derivative filter. This filter allows for better delineation of discontinuities by focussing mainly on the points of sharp gradients, thus delineating fractured zones (Figure 13). The same was done for the residual map and a map developed (Figure 14). These two figures show anomalous areas that are interpreted as local geologic features. The high amplitude gravity gradient which represents the major fault areas forms the basis of this research. These features are the highly fractured areas which are paths controlling fluid flow in and out of the caldera. The axis of the caldera is one clear area where geology is in complete agreement with these findings. The Molo TVA is another clear faulted area while the Solai TVA could not be captured by this filter.

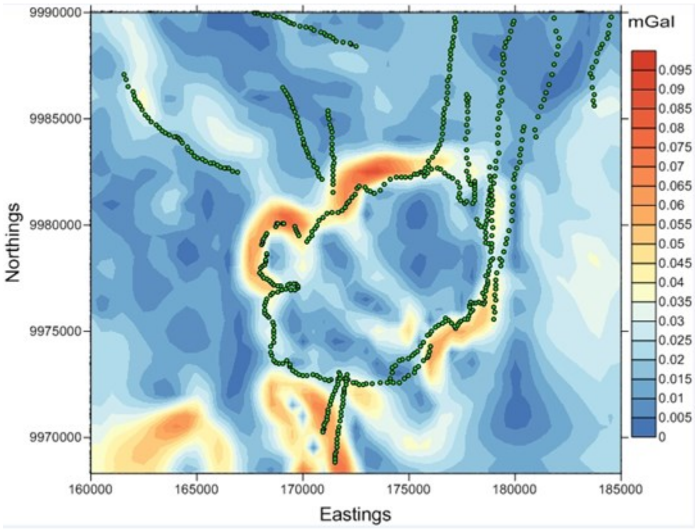

Figure 13: Horizontal derivative filtered 200-3000 Band Pass anomaly map of Menengai Geothermal field.

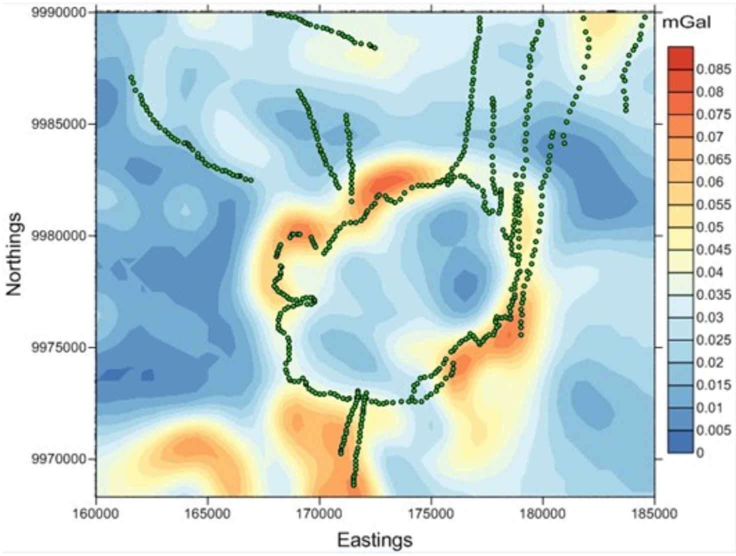

Figure 14: Horizontal derivative filtered Residual anomaly map of Menengai Geothermal field.

Density inversion from results of simple Bouguer anomaly readings were generated by 3D inversion Grablox1.6 programme that calculates synthetic gravity anomaly of a 3D block model. The programme then generates files with inverted densities at each location where gravity readings were recorded with sets of varied depth. The inverted densities were then presented in 3-D visualization platform i.e. Voxler by Golden software (Figure 15). This figure summarises the results of gravity survey in mapping subsurface density contrast to locate structures (low density lineament) that channel geothermal fluids at depth in Menengai geothermal field. When density is set to zero (0) during filtering, it enhances the contrast between negative and positive density boundaries at iso-dense contour of zero. The low density lineaments are fracture areas while the high density ones are intrusions. From this analysis, four groups of faults are identified, which include caldera rim faults that contribute mostly to deep vertical recharge, NNE-SSW faults along Solai graben, NNW-SSE faults along Molo axis and Southern fault extending towards Lake Nakuru.

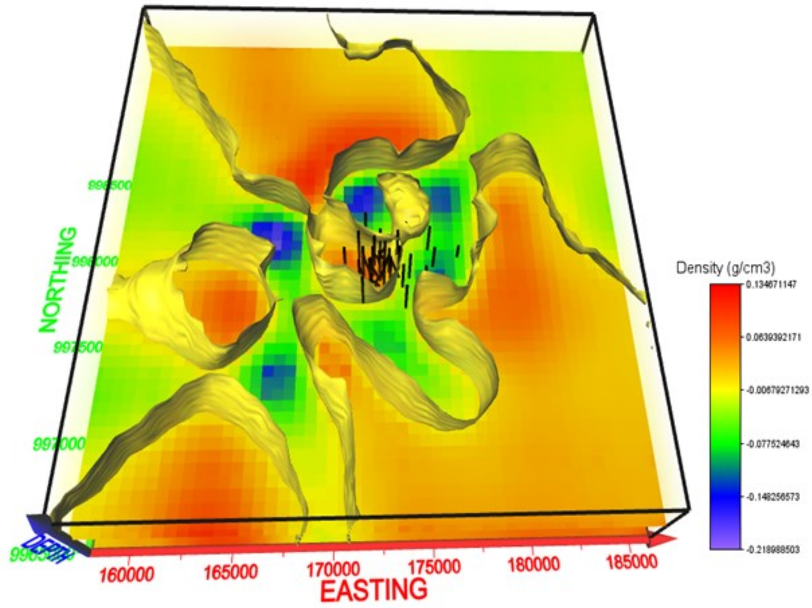

Figure 15: 3D iso-dense values at zero (0) to enhance structural boundaries.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

A complete geothermal system mainly comprises of heat sources, fractures and the capping. In many areas, heat source is easily identified but the major task is usually to identify the permeability controls. To achieve this, gravity structural models were developed and interpreted. Permeability is represented by fractures which form conduits for fluid flow. Compact zones are mainly represented by gravity high denoting limited or no permeability; however gravity high could also be used to denote molten magmatic material. Fractures permit movement of fluids, and heat transfer by convection nearer to the surface where they can be tapped.

This study identified four main permeability controls for Menengai, these are: The axis of the caldera, Molo TVA, Solai TVA, Southern fault extending towards Lake Nakuru and the magmatic intrusion in the central part of the caldera. The caldera axis faults, Southern fault and the TVA's are conduits that facilitate fluid flow and therefore convective heat transfer while the magmatic intrusion was identified a permeability control due to tensional and compressional forces that would result from intruding magma. These forces are expected to have an impact on the host rocks creating new fractures. The fractures are seen to the depth of 3 km. From these interpretations of the Bouguer and filtered maps, it was therefore concluded that Menengai has permeability based on the well-developed fracture networks. The indication of good permeability and the presence of a possible heat source is therefore a good encouragement for continued geothermal resources exploitation in Menengai.

In summary, good gravity models were developed by subjecting data to all necessary procedures and applying important filters for better interpretation. Permeability controls for Menengai geothermal field were identified as follows: The uplifting dome, regional fractures i.e. Solai TVA and Molo TVA, southern fault extending towards Lake Nakuru and the axis of the caldera. This has led to a conclusion that there is enough permeability in Menengai geothermal field.

4.2 Recommendations

It is recommended that more studies be done on this subject to minimize any possible chances of failure in future. This research has made a contribution to practice where it has been found to locate permeability controls that have been an elusive component using other geophysical methods e.g. resistivity. This research therefore informs the decision makers to adopt gravity method in structure identification whenever undertaking surface exploration.

REFERENCES

Bosworth, W., Lambiase, J., & Keisler, R. (1986). A new look at Gregory's Rift: the structural style of continental rifting. Eos, Transactions American Geophysical Union, 67(29), 577-583.

Burke, K. and Dewey, J.F. (1973). Plume generated triple junctions: Key indicators in applying platetectonics to old rocks. J. Geol., 81: 406-433.

Hasanah, L., Aminudin, A., Ardi, N. D., Utomo, A. S., Yuwono, H., Wardhana, D. D., Gaol, K.L., & Iryanti, M. (2016). Graben Structure Identification Using Gravity Method. Paper presented at the IOP Conference Series: Earth and Environmental Science (Vol. 29, No. 1, p. 012013). IOP Publishing.

Hearly, J. (1975). Geothermal field zones of recent volcanism." Proceedings at the 2nd UN symposium on Development and use of geothermal resources. San Francisco, California, 1: PP 415-422.

Leat, P.T. (1991).Volcanological development of the Nakuru area of the Kenya rift valley. Journal of African Earth Sciences 13, 483-498.

Mariita, N. O., Otieno, C.O. and Shako, J. W. (2004). Gravity studies of Menengai geothermal prospect, Kenya. Kengen Internal Report. 15 p.

Meissner, R., & Strehlau, J. (1982). Limits of stresses in continental crusts and their relation to the depthâ□frequency distribution of shallow earthquakes. Tectonics, 1(1), 73-89.

Mungania, J and Lagat, J.K. (2004). Menengai volcano: investigations for its geothermal potential a geothermal resource assessment project, Kengen internal report.

Omenda, P. A. (2007). Status of geothermal exploration in Kenya and future plans for its development. Short Course II on Surface Exploration for Geothermal Resources. UNU-GTP and Kengen, at Lake Naivasha, Kenya: 2-17.

Searle, R.C.(1970). Evidence from gravity anomalies for the thinning of the lithosphere beneath the Rift valley in Kenya. Geophysical Journal.21: pp. 13-31.

Simiyu, S. M. (1999). Induced micro-seismicity during well discharge: OW-719, Olkaria, Kenya rift. Geothermics, 28(6), 785-802.

Simiyu, S. M., & Keller, G. R. (1998). Upper crustal structure in the vicinity of Lake Magadi in the Kenya Rift Valley region. Journal of African earth sciences, 27(3-4), 359-371.

Simiyu, S.M., & Keller, G.R. (2001). An integrated geophysical analysis of the upper crust of the southern Kenya rift. Geophysical Journal International 147, 543-561.

Swain, C.J., Maguire, P.K.H., Khan, M.A. (1994). Geophysical experiments and models of the Kenya rift before 1989. Tectonophysics 236, 23-32.

Wamalwa, A.M. (2011). Joint geophysical data analysis for geothermal energy exploration. PhD thesis. University of Texas at El Paso, El Paso, Texas.