Proceedings 5th African Rift Geothermal Conference 2014 (ARGeo-C5)
27th Oct to 2nd Nov 2014, Arusha, Tanzania

GIS Applications in Heat Source Mapping in Menengai Geothermal Field

Levi Shako and Antony Wamalwa
Geothermal Development Company Ltd
P.O. Box 1770 Nakuru
E-mail: lshako@gdc.co.ke, awamalwa@gdc.co.ke

Keywords: Heat Source, Geophysics, GIS, Mapping; Menengai

ABSTRACT:

Heat source mapping entails representation of the general vicinity or the environment from which heat is obtained. Geographic information systems (GIS) with its hardware and software can gather, transform and analyze information which is related to earth. In heat source mapping there are a lot of specific interrogations that need to be answered by GIS-based analysis. The system connects geographical and geoscientific data in order to put it in relation of space and time. GIS along with appropriate models and spatial analysis method was used to delineate areas with anomalous heat signatures. The project area is Menengai geothermal field in rift valley in Kenya. GIS analysis commenced with identification of important parameters in heat source mapping for the project area. The parameters considered included surface geothermal indicators (fumaroles, hot grounds, and alteration zones) and geophysical data (MT, gravity). Then, various thematic maps of project area were prepared and integrated. Boolean and index overlay models were used for integrating of maps. Possible heat source areas were defined using each model.

Geothermal indicators (fumaroles, hot grounds, and alteration zones) and geophysical data are depicted together using GIS based analysis to visualize the possible zones for heat source mapping.

This paper demonstrates the application of GIS analysis tools for heat source mapping. The Boolean and Index Overlay models were developed for processing the mapping of possible heat source areas.

Keywords: - Heat Source, Geophysics, GIS, Mapping; Menengai.

1. INTRODUCTION

For a geothermal system to exist, certain conditions and parameters must be met. These include a heat source, recharge system, permeable formation and/or structures to allow water to percolate to deeper levels and a cap rock to contain the geothermal fluids. The most critical of these conditions is the heat source. The areas with the highest underground temperatures are in regions with active or geologically young volcanoes. These hot spot regions occur at plate boundaries or at places where the crust is thin enough to let the heat through. Geothermal exploration was carried out in Menengai with a view to obtaining information about the properties of the geothermal system, prior to drilling. Such information includes temperature in the geothermal reservoir, permeability of the reservoir, areal extent of the thermal anomaly, depth to useful temperatures and location of the upflow zones. One of the main apparent indicators for the existence of a geothermal system(s) is the heat source. In Menengai field, the heat source is believed to be magmatic and reaching the surface in the form of lava intrusions, which are responsible for heating the nearby rocks and aquifers. A geothermal system is made up of three main elements: a *heat source*, a *reservoir* and a *fluid*, which is the carrier that transfers the heat. The heat source can be either shallow, with very high temperature (> 600 °C) magmatic intrusion that has reached relatively shallow depths (5-10 km) or, deep as in certain low-temperature systems, where the Earth's temperature increases with depth following the normal earth's temperature gradient. Heat source mapping involved characterization of surface and subsurface geothermal exploration datasets and various spatial sampling measurements. Surface geothermal exploration entails identifying, analyzing and mapping of geothermal manifestations, such as fumaroles, altered grounds, and hot springs and other scientific survey techniques to determine prospective geothermal resources. Menengai Geothermal field in the central rift has been targeted for the accelerated development of geothermal resource. Currently, geothermal drilling activities are going on to assess the overall potential of the field and accurately demarcate the resource area. Surface geo-scientific measurements were done in order to determine the best area for drilling for subsequent reservoir assessment. Geographic Information System (GIS) was used to link geothermal surface manifestations, geophysics and heat loss datasets for heat source mapping. Geothermal spatial decision making could benefit from more systematic methods for handling multi criteria problems while considering the physical and technical suitability conditions. Traditional decision support techniques lack the ability to simultaneously take into account these aspects which are achievable through geoprocessing and model builder tools in GIS.

2. LOCATION AND DESCRIPTION OF MENENGAI AREA

The Menengai geothermal field is located to the North of Nakuru town in the Kenya Rift Valley at approximately $0^0$20'N latitude and 36^0E Longitude (Figure 1). This area comprises several features of geographical and geological significance. These include the Menengai caldera, which is a 77 km^2 elliptical depression partially filled by young volcanic eruptives. Immediately to the North Western side is the inferred Olrongai/Olbanita ring structures whose tectono-morphological impressions are still evident despite heavy cover by younger Menengai eruptives.

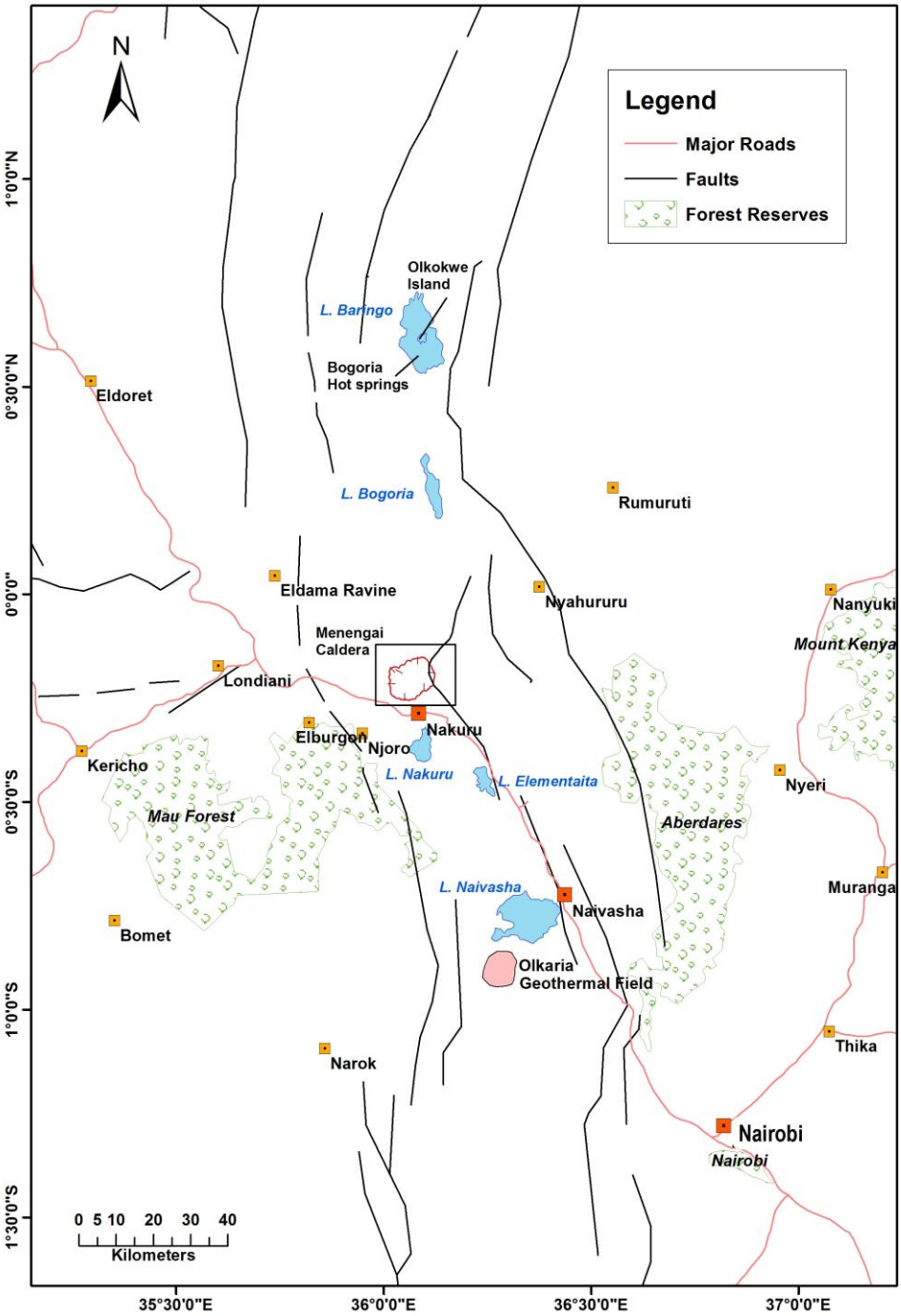

Figure 1: Map showing the location of Menengai geothermal prospect along the Kenyan Rift Valley

3. MENENGAI GEOLOGICAL SETTING:

The Menengai caldera is an elliptical depression with major and minor axes measuring about 11.5 km and 7.5 km respectively (GDC, 2010). The circular rim of the caldera ring fault is well preserved with vertical cliff. The ring structure has only been disturbed by the Solai graben faults at the northeastern end of the caldera and at the SSW end The regional surface geology of the Menengai is largely composed of late Quaternary volcanics, which are associated with the development of the Kenya Rift. The geologic studies indicate that the area north of the Menengai is characterized by lavas from N-S trending fissures (GDC, 2010). These lavas are trachytic and trachy-phonolitic in composition and mainly observed to be exposed in the scarp walls beyond the Olbanita swamps (Figure 2).

More geological studies concluded that faulting was triggered by a hotspot resulted in the uplift of the region, opening up fractures, which served as conduits for Quaternary volcanic activity and the development of many large shield volcanoes of silicic composition along the axis of the rift (Baker et al., 1988).

Further detailed exploration work confirmed that structurally, Menengai is a pre-caldera low-angle volcanic shield, which has almost vertical embayed caldera walls upto 300 m high. The floor of the area depicts extensional tectonics with spatial variation in the stress field, indicated by two main orientations of fault systems. Leat (1984), found that the structures associated with Ol'rongai Tectono-volcanic axis are oriented to the NNW-SSE and are related to the NW-SE pre-caldera orientation. However faults associated with the Solai TVA system have NNE-SSW orientation, which corresponds to the orientation of the Menengai caldera.

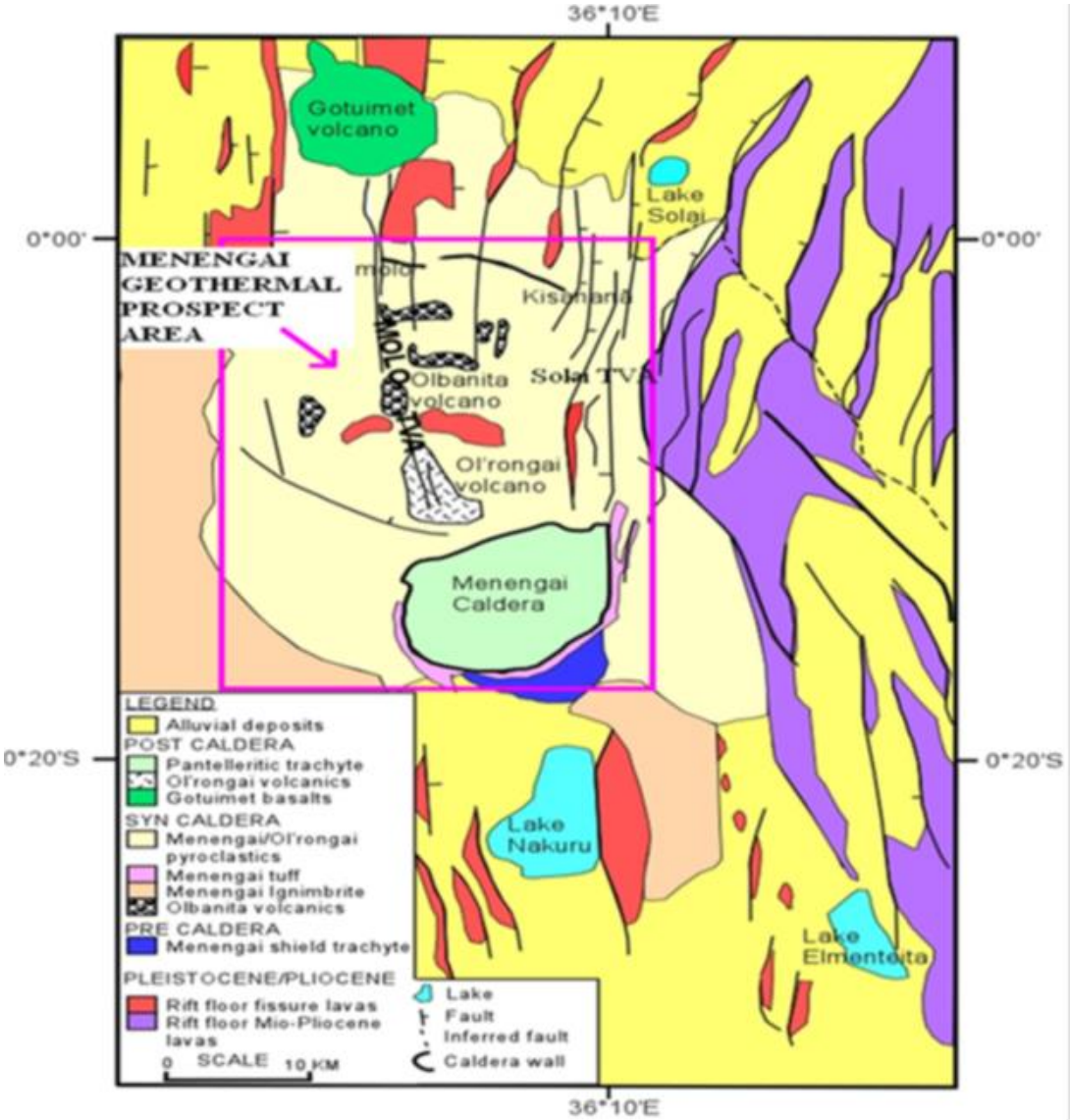

Figure 2: Map showing the geology of Menengai geothermal prospect.

4. EVIDENCE DATA LAYERS

4.1 Fumaroles Locations

These are vents in the Earth's surface from which steam and volcanic gases are emitted. The major source of the water vapour emitted by fumaroles is groundwater heated by bodies of magma lying relatively close to the surface. Carbon dioxide, sulfur dioxide, and hydrogen sulfide are usually emitted directly from the magma. Fumaroles are often present on active volcanoes and they signify the existence of geothermal activity.

In Menengai geothermal field, there are two groups of fumaroles in the central and western parts of the caldera floor. The first group are located within a fresh lava flows and close to eruption centres (Figure 3). The other group of fumaroles, located in the central eastern part of the caldera floor, are found at the young lava/pumice contact and have extensively altered the pumiceous formation. The structural control for these groups of fumaroles appears to be related to the eruption craters.

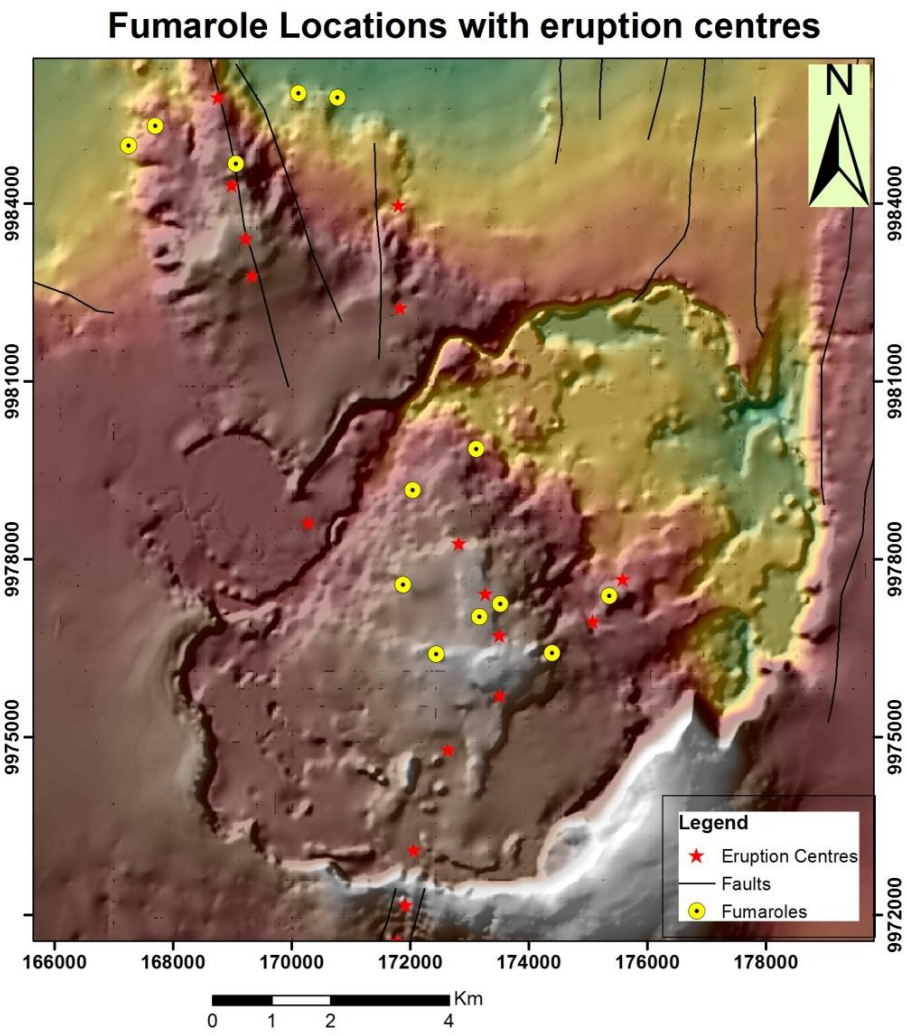

Figure 3: Map showing the fumarole locations

Mapping of a fumarole field can give an indication of an area of thermal springs and gas vents where magma probably exists at shallow depth. It is generally assumed that surface manifestations are associated with geothermal resources

4.2 Hydrothermal alteration zones

Hydrothermal alteration is a general term embracing the mineralogical, textural, and chemical response of rocks to a changing thermal and chemical environment in the presence of hot water, steam, or gas (Henley and Ellis, 1983). By mapping alteration mineral assemblages at the surface it is possible to locate the zones with highest temperatures, pressures, or permeability, all of which are important in geothermal exploration.

For the purpose of heat source mapping in Menengai field, two types of hydrothermal alteration minerals were considered in the GIS model; Wollastonite and Actinolite. These types of alteration minerals are directly associated with existence of very high temperatures, probably caused by the presence of magma at the near surface.

Wollastonite is a calcium silicate mineral, which was noted at depth of the some productive geothermal wells in Menengai and was associated with the diminishing calcite. Wollastonite is a metastable mineral at temperatures above $\geq 270^0$C. It is an alteration mineral which is usually associated with contact metamorphism and therefore its occurrence is probably related to the numerous intrusions in the caldera summit area. The intense CO_2 reported from the Menengai wells can be explained as a result of magma degassing and disintegration of calcite and the formation of wollastonite. It occurs mainly from 1450 m depth, in well MW-04 and from 1780 m in well MW-06, and prevails down to the bottom of the wells. *Actinolite* is a member of amphibole group, which is a high temperature mineral, mostly found in altered and metamorphic iron rich basic rocks. It is an intermediate solid solution member between ferro-actinolite and tremolite. Usually, it appears as green to grey-green groundmass mineral, although the colour varies depending on the amount of iron. The interference colours of actinolite depend on the iron and magnesium content and are usually green or brown. It is formed by the replacement of ferromagnesian minerals in association with epidote and chlorite. Actinolite appeared from 2020 m in well MW-06 and at 1964 m in well MW-07. Actinolite is a high temperature mineral which indicates temperature of above 280^0C and occurs as a replacement product of chlorite or pyroxene

Hydrothermal alteration zones covered by the two mentioned minerals were digitized and assigned as a polygon data layer in ArcMap (Figure 4).

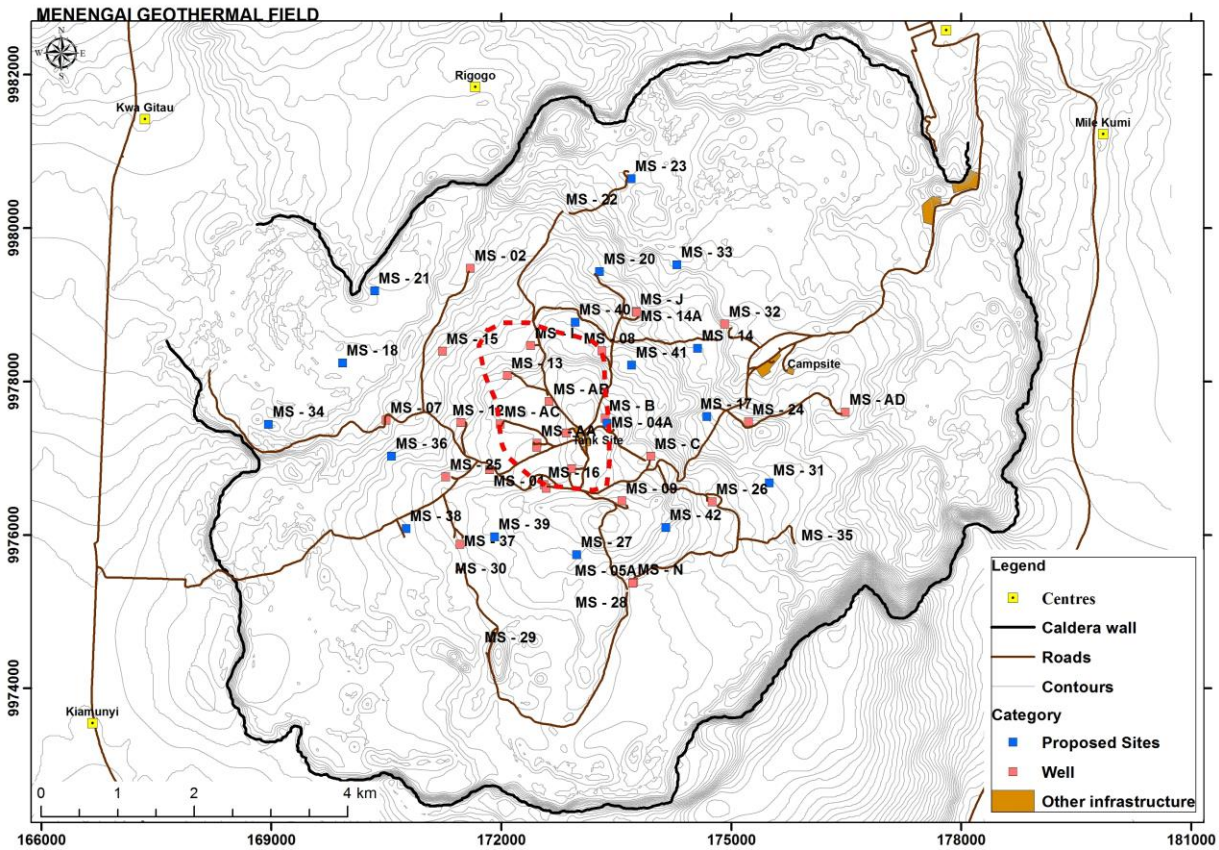

Figure 4: Actinolite-wollastonite zones in Wells MW-13, MW-12, MW-04, MW-06, MW-8 and MW-11

4.3 Geophysics Data

Geophysics survey that was done in Menengai geothermal field included gravity and Magnetotellurics. Magnetotellurics (MT) measurements were done to infer the depth and extent of the possible heat source and geothermal reservoirs. MT techniques measure over a frequency range. The lower the frequency, the greater the depth of investigation at a given site. MT techniques acquire data in frequencies ranging from about 400 Hz to 0.0000129 Hz (a period of about 21.5 hrs.), and are suitable for deeper investigations. Figure 5 reveals low resistivity bodies at depth that could be related to magmatic heat sources.

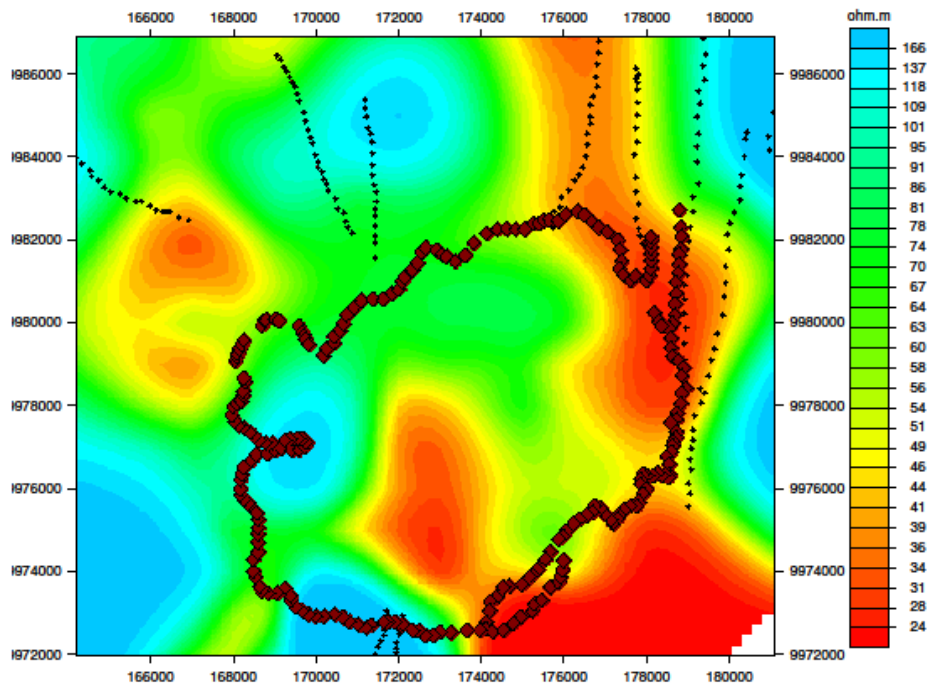

Figure 5: Map showing MT resistivity anomaly at 1km below sea level

Gravity data interpretation by KRISP (Simiyu and Keller, 1994) along a regional profile that runs across Menengai show gravity high with an amplitude of 40 mgal and an EW wavelength of 35 km. This anomaly was modeled as an intrusive body, about 13 km wide and coming to within 4 km depth below surface. Gravity prospecting method was used to define and delineate possible heat sources and other geologic features that could give an indication of the size and the potential of geothermal energy in Menengai area.

In gravity data analysis, a high pass filter was applied then upward continuation to the complete Bouguer data (Figure 6), aimed at further investigating the shallow crustal anomalies. That could be of interest to the geothermal system in terms of materials that could provide the heat for the geothermal resource within the caldera. The results (Figure 6) show a high density material under the summit region while the rest of the caldera shows gravity low.

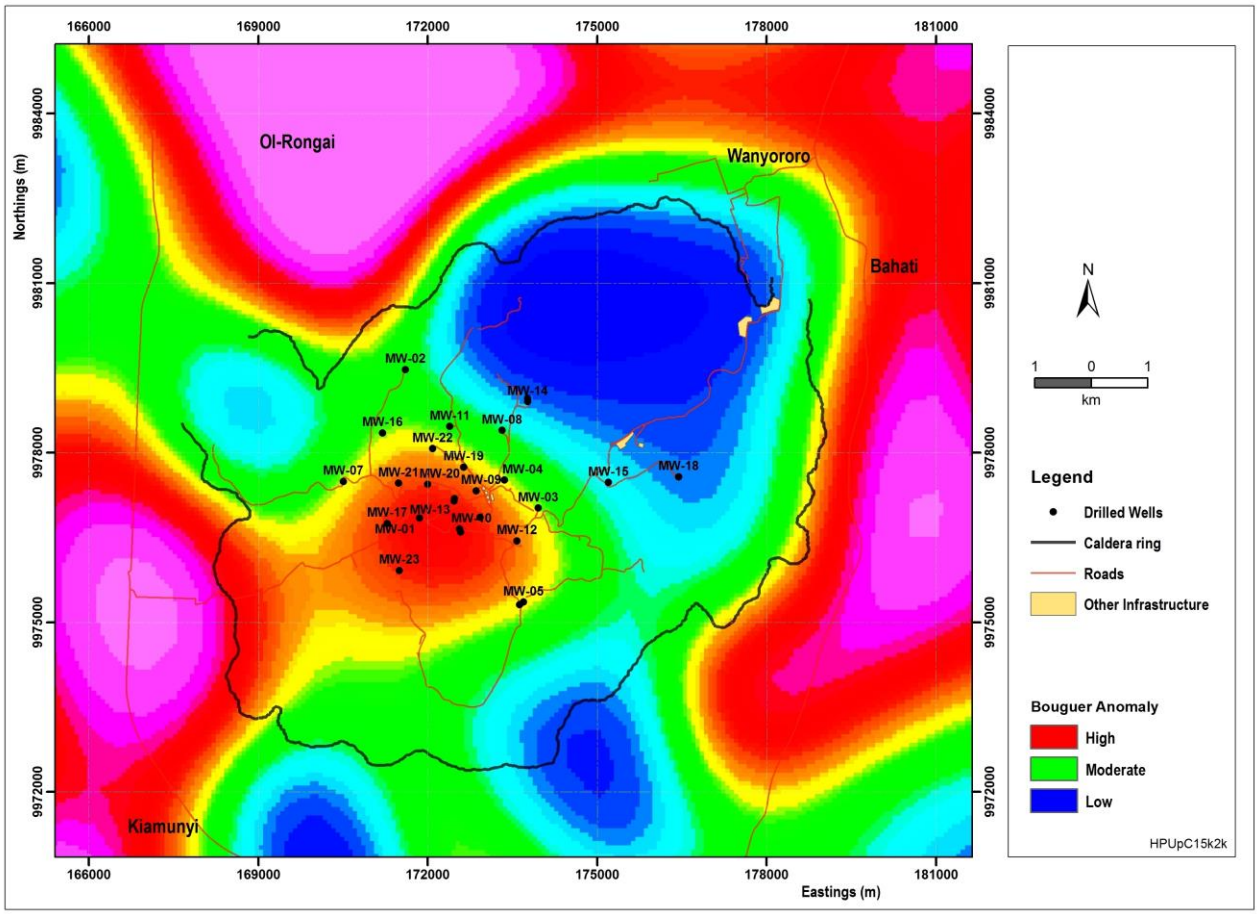

Figure 6: High pass filtered then upward continued gravity anomaly map

Geophysics data used were MT anomaly maps integrated with Bouguer gravity map to derive geophysical positive areas for mapping heat source.

4.4 Heat Loss

Heat flow survey was conducted with an aim to estimate the natural heat lost at Menengai geothermal field and also to map the ground temperature distribution in the prospect area. Natural heat loss by conduction was estimated by obtaining temperature gradients from shallow 1 m depth holes drilled manually. Temperatures were measured at the surface, at 50 cm and at 100 cm depths by a digital thermometer (thermocouple) with a hardened penetrating probe. Location of these holes was read from a portable hand held Global Positioning System (GPS). Thermally active area was later estimated from 40°C isotherm at 1 m depth (Figure 7).

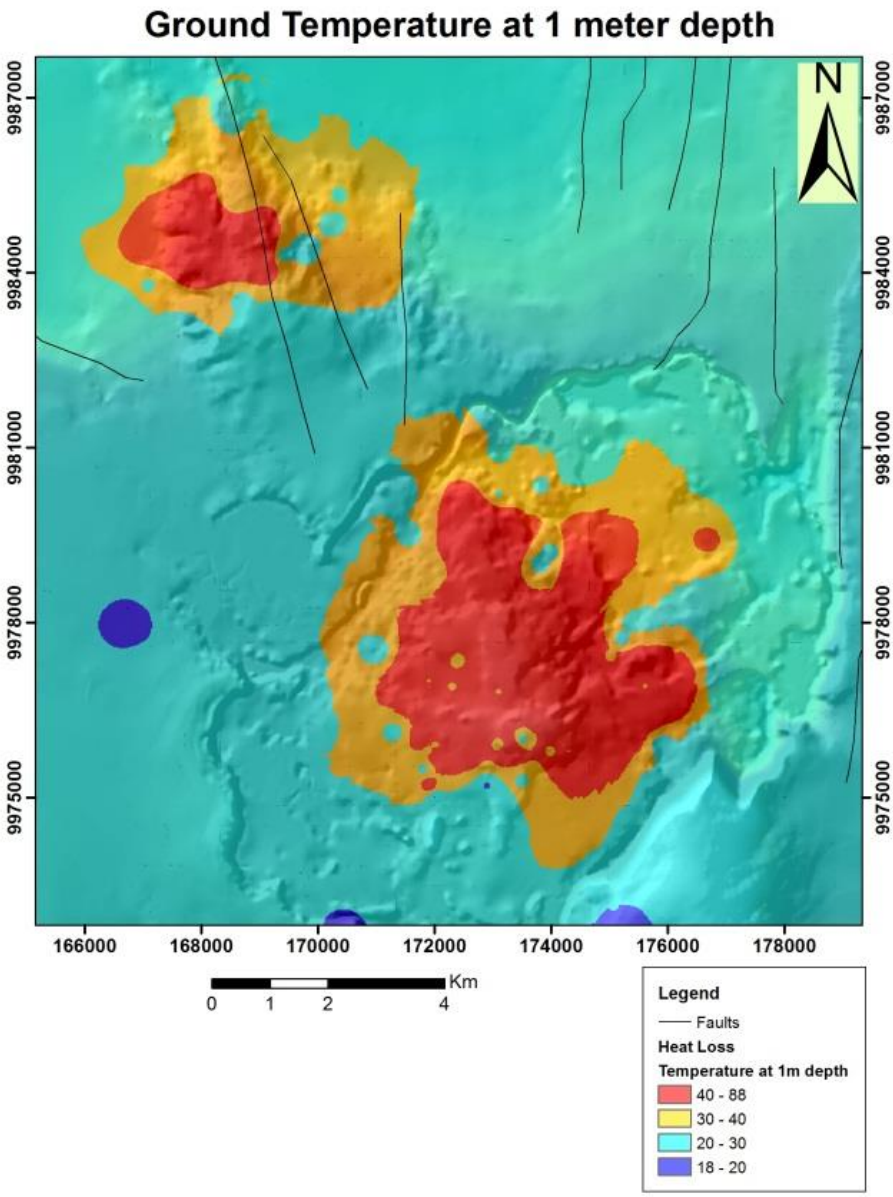

Figure 7: Map showing temperature anomaly at 1km below sea level

5. GIS DATA INTERGRATION MODEL

Data integration modeling started with the identification of evaluation criteria or parameters needed for heat source mapping. All these parameters have been identified based on their relevance and direct connectivity with the heat source in a geothermal system. Knowledge driven weighted index overlay integration model was used with the aim of providing evidence on the applicability of GIS in defining the most likely areas for mapping the heat source based of data collected. According to Clarke (1997), Index Overlay is a GIS operation that the layers with a common area are joined on the basis of their occupation of space.

During data integration, it is crucial to assign appropriate weightage of the classes of each parameter. Consideration of relative importance leads to a better representation of the actual field situation. This methodology entails having the data layers in same category combined using Boolean logic “OR” operation and the targeted areas are defined. Afterwards, the derived map layers from different categories are weighted, overlaid, combined and analyzed by Index Overlay method and the resultant map displays areas that are defined as per the objective of the project.

GIS can handle a large amount of data, and is a powerful tool to visualize new and existing data, which can help produce new maps while avoiding human errors made during decision-making and allows the effective management of the GIS data (Noorollahi et al., 2007).

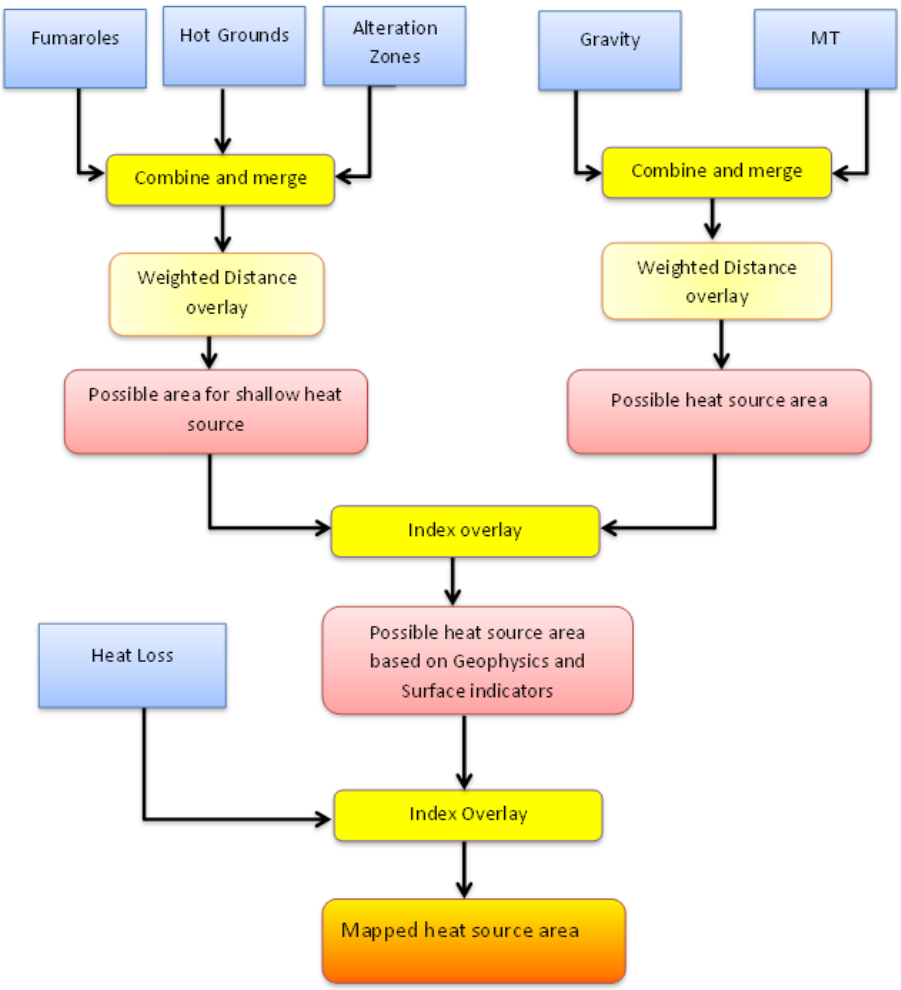

Figure 8: GIS data integration schema

To map areas with possible heat source suitability in Menengai field, weighted overlay integration model was used. The model entails applying a common scale to the datasets, and the higher values are given attributes that are considered suitable. The datasets were weighted, giving each a percentage influence. The higher the percentage, the more influence a particular dataset will have in the model.

Data integration models application to geothermal exploration requires expertise in the selection of the maps that will provide predictor keys of the resource. Knowledge-driven Index Overlay model was proposed for heat source mapping. Assignment of weights in the Index Overlay model depends on the conceptual model of the system under exploration. In this model the input data used certified certain conditions, i.e. the heat source areas are assumed to be located;

(i) in the vicinity of fumaroles and hot grounds marked by surface manifestations at a distance of less than 500 m
(ii) in the vicinity of altered alteration zones (at a distance of less than 200 m)
(iii) within a distance of less than 100 m from areas that present a high density of surface fracturing according to structural studies
(iv) In areas where resistivity is lower than 49 ohms
(v) Areas where bouguer gravity anomaly high
(vi) In areas where the soil temperature at 1m depth is above 40c

For performing weighted overlay model, a tool found in Arc Toolbox, called raster calculator, was used to integrate the datasets in the prospect area. Raster calculator builds and executes a single Map Algebra expression using Python syntax in a calculator-like interface. The main objective of GIS integration model for heat source mapping is to provide evidence on the GIS applicability on defining the most likely areas where heat source can be demarcated based on the available data on geothermal. Factor maps on fumaroles distances, and hot grounds were integrated to produce a map showing areas with presence of shallow heat source. Based on integration of factor maps on gravity and magneto-telluric (MT), areas with geophysics suitability on heat source mapping were identified. The two layers were integrated using index overlay tool to determine the possible areas where the heat source responsible for geothermal system in Menengai, could be in existence (Figure 8). Common weighted areas to all input data layers are selected using this method (Bonham-Carter, 1994). This infers that the designated area is meets the purpose of the work based on all input data layers, and the selected area receives the highest suitability ranking in terms of heat source mapping.

5.1 Thematic maps

The input datasets introduced in the model are surface manifestations (fumaroles, hot grounds), hydrothermal alterations, gravity and resistivity data. Various thematic and factor maps were produced from these datasets.

5.1.1 Fumaroles and Hydrothermal Alteration Proximity distances

One of the most significant criteria that should be considered in heat source mapping could be proximity to fumaroles and hydrothermal alteration zones (Figure 9 and 10). Consequently, in fumarole and alteration mineral factor maps, values are decreasing when the distance from the fumarole and alteration zone are increased. In a factor map, areas can be given different weights according to their suitability for mapping of heat source.

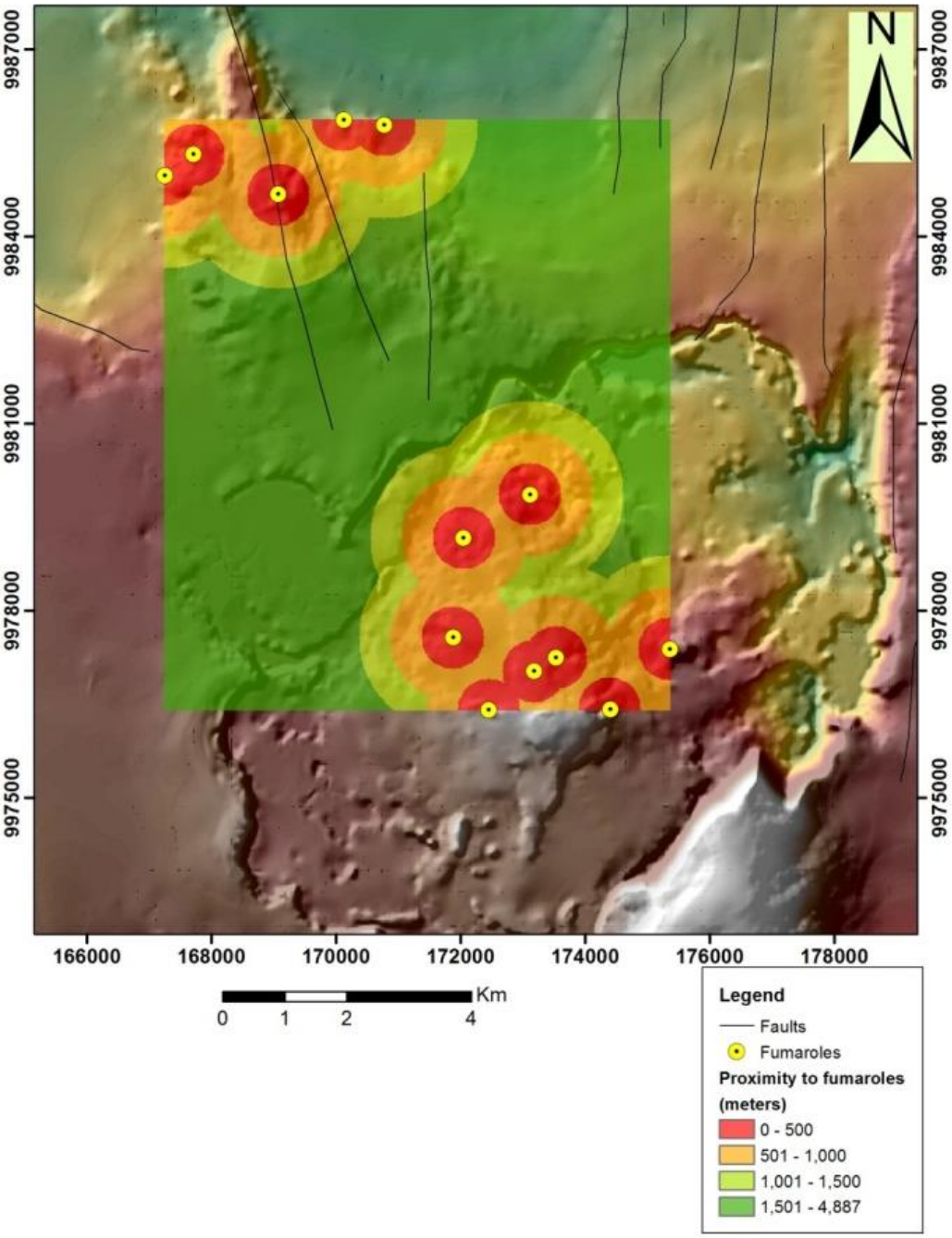

Figure 9: Map showing proximity distances to fumaroles

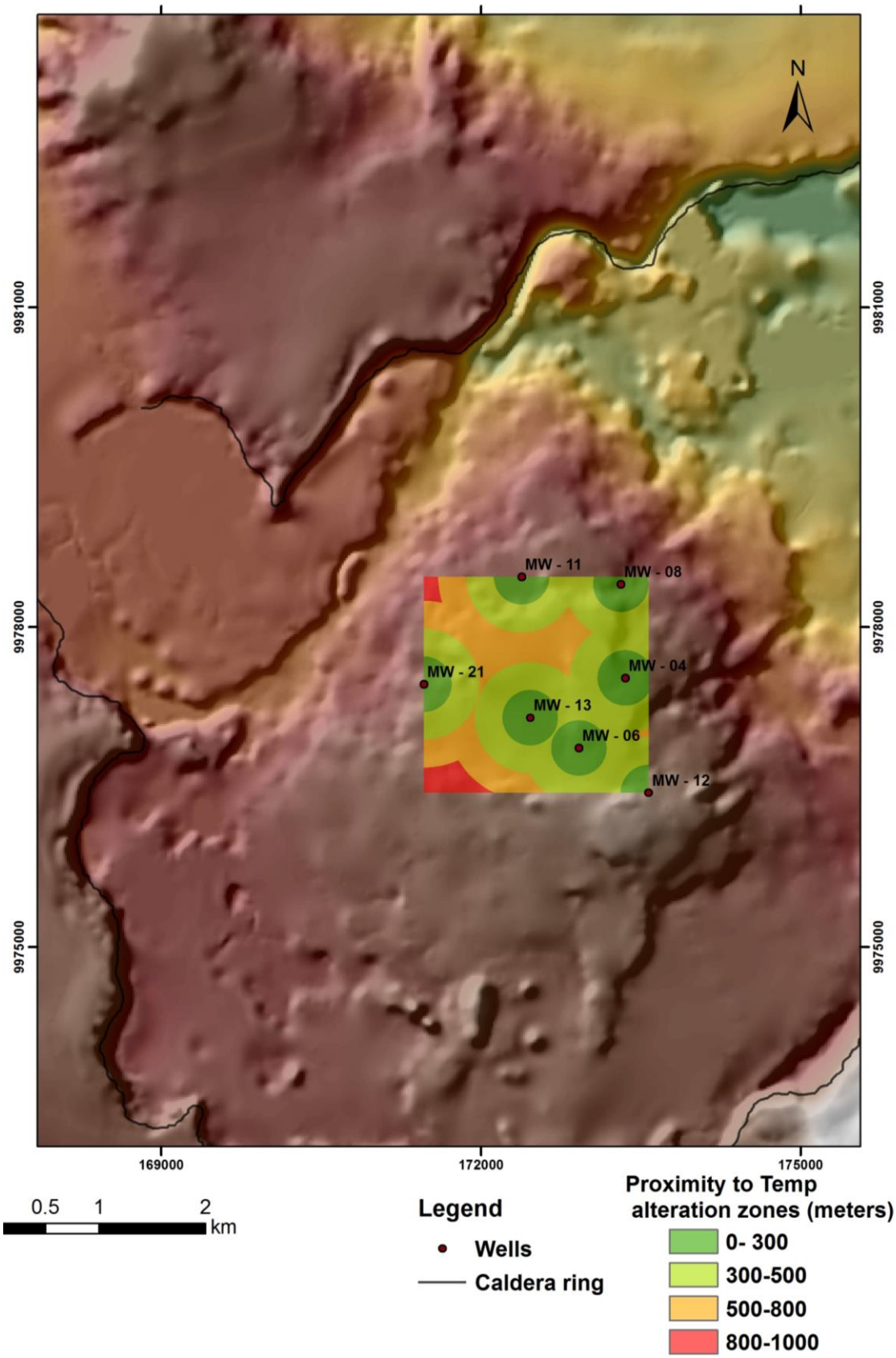

Figure 10: Map showing proximity distances to alteration zones

5.1.2 Gravity and Magnetotellurics

The geophysical data layer comprised both MT and gravity. The layer was assimilated in the overlaying process in heat source mapping data integration. The best indicators of the heat source area are the low apparent resistivity areas at depth, and high bouguer gravity anomaly which are related to the presence of magmatic intrusion.

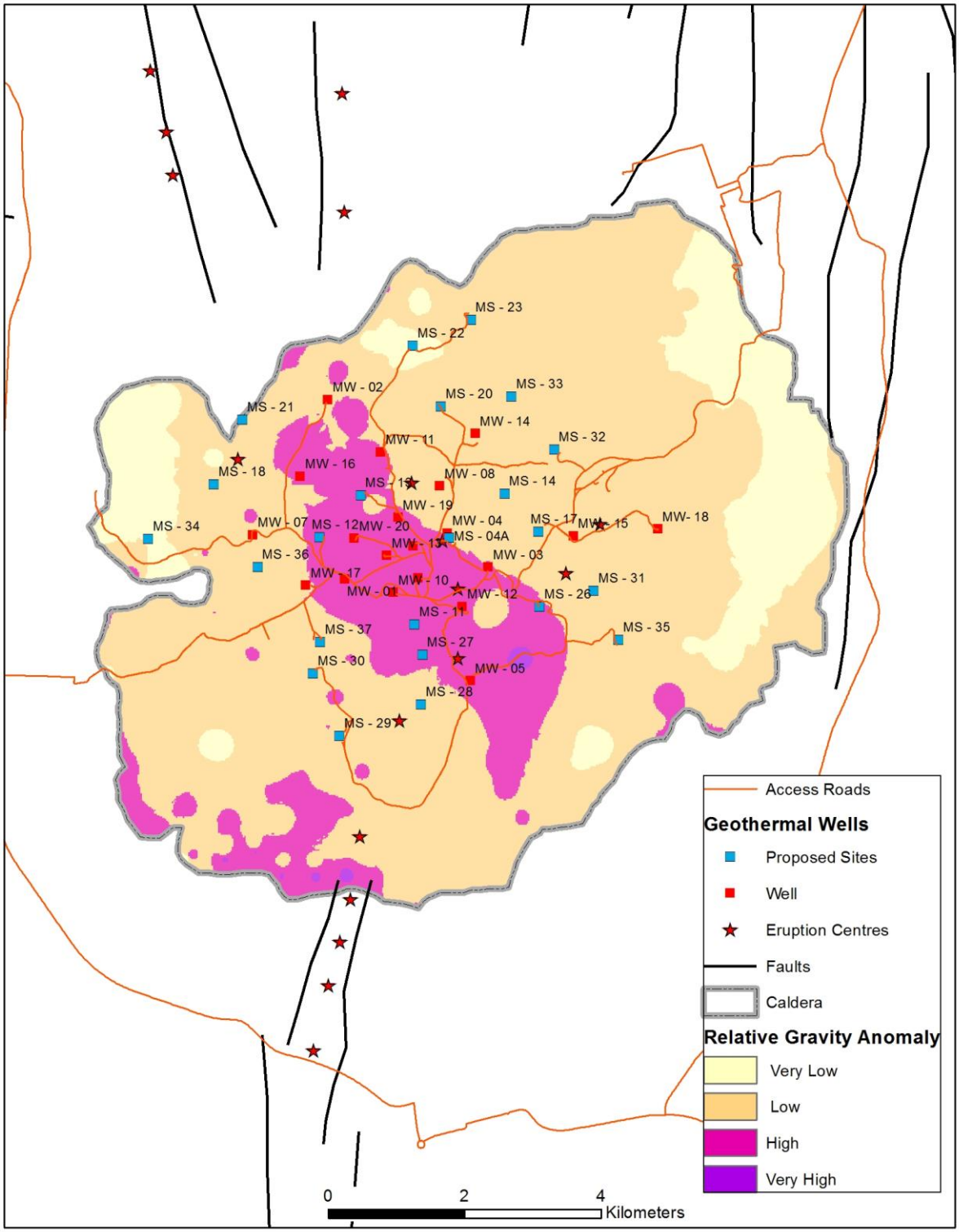

Figure 11: Map showing geophysics (Gravity anomaly) evidence layers

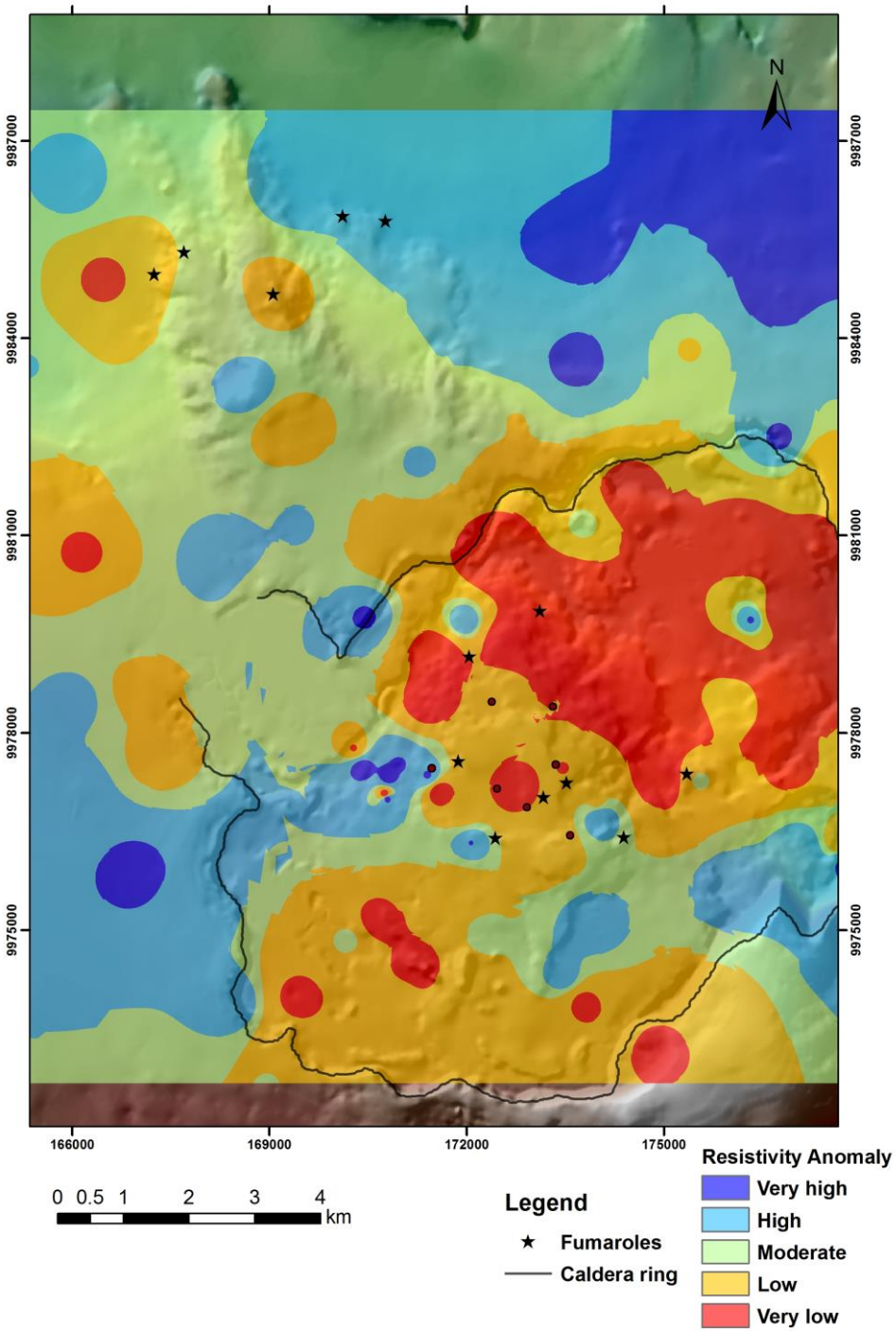

Figure 12: Map showing geophysics (Resistivity Anomaly) evidence layers

6. RESULTS

The weighted index model generated an area for locating and mapping the heat source from input evidence layers that included geothermal manifestation evidence data (fumaroles, hot grounds) , geophysics data (MT and Gravity), and heat loss data layer. The fumaroles and hydrothermal alteration proximity distance layers were combined to produce an area of possible shallow heat source. Resistivity anomaly at 2km below sea level was combined with gravity anomaly to produce a geophysics suitable layer that indicated possible magmatic heat source from depth. The two evidence layers, that is, geophysics suitability and the combined fumarole and alteration layer, were integrated to demarcate a zone of possible location of heat source. To enhance this model, heat loss evidence layer was at a later stage, integrated to produce defined heat source areas. (Figure 13)

GIS models are quite flexible and can always change depending on the input data in consideration and also the aim of the model shall determine the kind of data that is required.

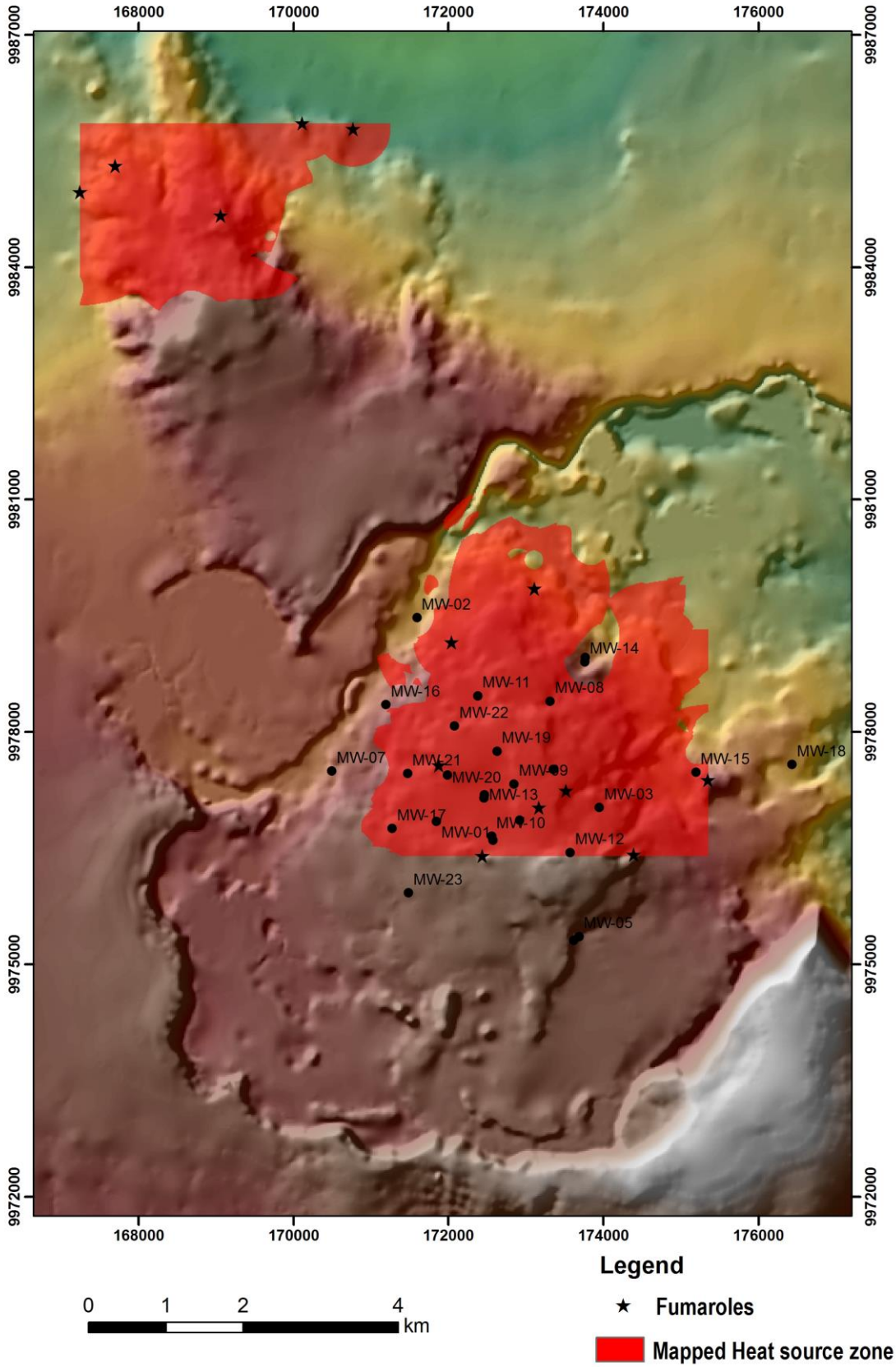

Fig.13. Favorable areas for geothermal energy production as identified by the index Overlay model.

Output from the Index Overlay model designates an area of possible shallow heat source. Most of the area mapped by the model includes some drilled production wells in Menengai that have recorded extremely high temperatures. This model can provide helpful data for planning further drilling, and can also be used to plan for detailed exploration.

7. CONCLUSION

The GIS-analysis approach is encouraged technically to identify and locate areas where heat source can be mapped for a better understanding of the conditions that make up a geothermal system. Demarcating areas where the heat source nears the surface in geothermal areas can be realized by means of a geographical information system based on evidence layers that included surface manifestation features like fumaroles and hot grounds, hydrothermal alteration minerals and geophysical data from MT and gravity surveys. Weighted index overlay integration method was applied to combine the evidence layers in GIS environment.

Finally, a map displaying zones of possible existence of heat sources was realized. Mapped zones included the summit area inside and the North Western part of the Menengai caldera as shown in figure 13.

8. REFERENCES

Baker, B.H., Mitchel, J.G., and Williams, L.A.J., 1988: Stratigraphy, geochronology and volcano-tectonic evolution of the Kedong-Naivasha Kinangop region, Gregory Rift Valley, Kenya. Geological Society of London, 145, 107-116.

Clarke, K., C. (1997), “Getting Started With Geographic Information Systems”. Upper Saddle River, NJ: Prentice Hal

Bonham-Carter, G.F., (1994). “Geographical Information Systems for Geoscientists: modeling with GIS”. Computer Methods in the Geosciences 13, Pergamon, New York, 398 pp.

GDC. 2010: Menengai geothermal prospect; an investigation for its geothermal potential. Geothermal Development Company (GDC); Geothermal resource assessment project, unpubl. Report.

Henley, R W and Ellis A J; (1983): Geothermal systems ancient and modern: a geochemical review. *Earth Science Reviews*, 19: 1-50.

Leat, P.T., 1984: Geological evolution of the trachytic volcano Menengai, Kenya Rift Valley. *J Geol Soc London, 141: 1057-1069*.

Noorollahi, Y., R. Itoi, et al. (2007). "GIS model for geothermal resource exploration in Akita and Iwate prefectures, northern Japan." Journal of Computers & Geosciences 33(8): 1008-1021

Simiyu, S.M. & Keller, G.R., 1997. An integrated analysis of the lithospheric structure across the east African plateau based on gravity analysis and recent seismic studies. *Tectonophysics Vol. 278.*