

## Geothermal Prospecting of Olkaria Dome Areas in Naivasha, Nakuru County Kenya using Gravity Method

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### Abstract

The survey used Autograv.C.G 5 type Gravimeter over short wavelength by marking stations 310m intervals. The data was processed to remove all other effects independent of the subsurface changes in density. The complete bouguer anomaly was computed and Surfer 11 software has been used to draw contour anomaly map of the study area. Quantitative analysis of the contour map indicates regions of gravity highs which were analysed as bodies of high density within the earth's crust. Four profiles were drawn. The gravity anomaly was interpreted by inspection of profiles and separating the residual anomaly from the regional gravity field. 2D Euler deconvolution was done on the data profiles, indicated subsurface bodies and faults at depth between 10m and 50m. A 2D gravity model along the four profiles were generated by the computer application based on algorithm in the Grav. 2dc. The obtained results revealed presence of dense body intrusions with the contrasting density ranging from 0.22g/cm<sup>3</sup> to 0.50g/cm<sup>3</sup>. These bodies were interpreted as intrusive dykes that have higher density than surrounding rocks and probably are conduits of heat from the geothermal reservoir imaged at bottom depth of between 500m – 1000m below the surface. Advance methods of gravity data analysis such as Tensor Euler deconvolution is recommended to be carried out in Olkaria Domes to verify the results since this technique honours responses from many dimensions and deconvolution without gridding. Collection of more gravity data over steep and wild animal habitat areas is also required for deeper probing on longer profiles.

**Keywords:** Geothermal prospecting; Gravitational field; Gravity anomaly interpretation; Olkaria dome area

### Introduction

The term Rift Valley geothermal field is used for the extensive region under volcanic activities in southern, central and northern parts of Rift Valley. In Kenya many geothermal exploration sites have been established and are situated in rift system of Kenya.

Geothermal exploration began in 1950's in Kenya with major investigations in the area between Lake Bogoria and Olkaria upper rift. Wells were drilled at depth which met high temperatures. The exploration then gathered speed with support from United Nations Development Programme (UNDP) that made many more geophysical probes undertaken and more wells drilled.

The geophysical studies done in the area included various resistivity techniques (Schlumberger, eletromagmatic, dipole, headon), seismics and magnetics. These activities contributed

the building and setting up of first geothermal power plant of 45 MW capacity between 1981 and 1985. Technological advancement made it possible for the application of modern geophysical method such as magnetotellurics (MT) and Transient Electromagnetics (TEM) suitable for deep and shallow conductors to be correctly mapped and so additional geothermal models evolved. More research saw the evolution of the second, 70MW geothermal power plant North-East region. The 12 MW Olkaria III geothermal power plant in the Olkaria west region has since been built with another 2.0 MW at the nearby Oserian farm.

The Olkaria West, central and East geothermal prospect areas have been explored and their potential established. However, Olkaria dome area has not been surveyed using gravity technique to attest to other geophysical methods applied in order to locate a geothermal reservoir. The gravity survey was then carried out and dykes which are associated with heat sources have been identified. These dykes act as conduit for the heat from a geothermal reservoir located at bottom depth of 1000m below the surface.

## Geology of the Greater Olkaria volcanic complex

The larger volcanic field of Olkaria is portrayed by several centres of volcanicity with existence of comendite on the surface. Other volcanic centres include Suswa caldera to the south, Longonot to the southeast and the Eburru volcanic complex to the north of Olkaria. Volcanic complex of Olkaria does not have distinct caldera correlation whereas the other volcanoes are related to caldera of varying sizes. The occurrence of a ring of volcanic domes in the south, southwest and east has been used to invoke the occurrence of a buried caldera. Studies on Seismic wave decay in Olkaria region reveal also an anomaly in the region corresponding with the suggested caldera.

Magmatic activity of Olkaria started at the time of the late Pleistocene and continued to recent as shown by Oloolbutot comendite, which is dated at  $180 \pm 50$  years B.P using carbon 14.

## Geology of greater Olkaria

The litho-stratigraphic data collected from geothermal wells and regional geology revealed that the Olkaria geothermal area is categorized into six major groups; namely Upper Olkaria volcanics, Pre-Mau volcanics, Olkaria basalt, Proterozoic “basement” formation and plateau trachytes. The layouts are shortly discussed below. The “basement” rock in the region is of the Proterozoic amphibolite grade gneisses and schists and related marble and quartzites of the Mozambiquan group. The far flanks of the rift are the rocks outcrops, particularly, towards Magadi area in the south. Rock composition of gneisses and schists are largely found in the southern section of the Kenya rift. Gravity, seismic and geological correlation show that the “basement” is 6 km deep in the rift. Gravity together with seismic studies reveal occurrence of dense magmatic intrusion in the metamorphic “basement” rocks.

Pre-Mau formation is evident on the rift cliffs in the southern regions of Kenya rift as rocks outcrop. The rocks are basalts, ignimbrites and trachytes composition of undetermined thickness. The rocks are covered by the Mau tuffs. Mau tuff rocks are absent but are present in the west because of an angle dipping fault eastwards passing into Olkaria Hill. These rocks differ in texture from consolidated to ignimbritic and the main reservoir of geothermal energy bearing rocks in the Olkaria west area have been noticed from the geothermal boreholes drill fragments in the area. Trachytes are main formation of Pleistocene age and occur between 1000m to more than 2600m in depth but minor basalts, tuffs, and rhyolites are also present. The Olkaria Hill region to the east where a graben occurred before they erupted is characterized by occurrence of Plateau trachytes and are the geothermal bearing rocks in the Olkaria east. These are the geothermal bearing rocks in the Olkaria east.

The formation in upper Olkaria is composed of lavas from comendite, ashes from Longonot and Suswa volcano and trachytes

occur about 500m deep from the surface. This formation is dominated by comendite rocks of which the youngest of the lavas is the Oloolbutot comendite. The vents for these young lavas and pyroclastics were structurally controlled with many centres occurring along N-S faults and a ring structure.

## Methodology

Gravity survey method is based on the foundations of variations in the Earth’s gravitational field emanating from changes of mass within the underlying rocks. The primary concept is the idea of a causative body, which is a rock of anomalous density from the host mass. This causative body portrays a subsurface region of abnormal density and results in change in the Earth’s gravitational field known as gravity.

The gravity data was collected from about 100 gravity stations established over 10km<sup>2</sup> target areas in Olkaria Dome areas with 310m spacing. The stations were profiled at 310m interval in grid system whose positions were measured using a Global Position System (GPS) while a Gravimeter was used to conduct gravity measurements. In order to observe and monitor drifting of the instrument as well as to determine the complete gravity value in every observation point, base station readings were recorded beginning and after the survey at station interval of every three stations. The measured drifts for the instrument were then extrapolated linearly from the reading differences made at the base station. CG 5 Autograv has SCTUTIL data transfer software which was used to perform data transfer to a personal computer each day of operation.

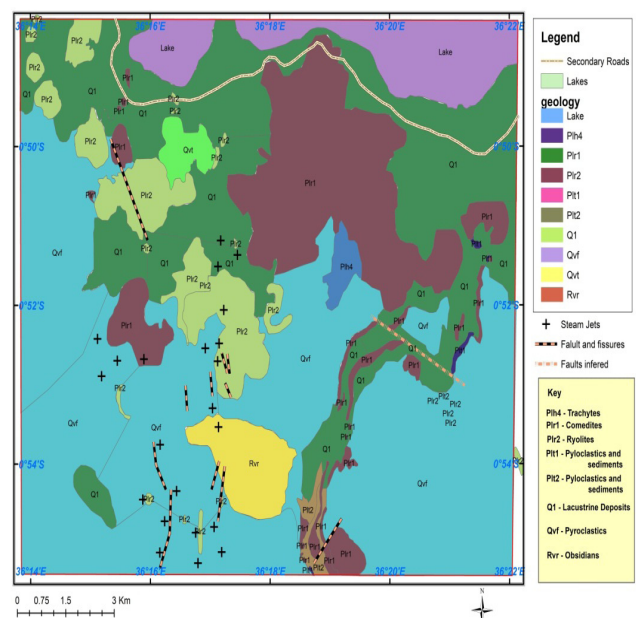


Figure 1: Map showing geology of the study area.

### The map for the Bouguer anomaly

Bouguer map of the area of study (Figure 2) reveals contours that are ascending to the centre (gravity high), giving Bouguer positive anomaly which is interpreted as caused by a body with higher density (density contrast) than the surrounding rocks. It envelops a region of about 7 km<sup>2</sup> which is under Olkaria Domes.

The gravity highs contain maximum peak of -163mgal at co-ordinates (202000, 9900000) and (204000, 9898500) in the South and peak minimum of about -170mgal to the East at co-ordinates (205000, 9901500) within Olkaria Dome area. These could be dense materials of magmatic intrusion from a geothermal reservoir. This is encircled by gravity lows of a bout -176mgal.

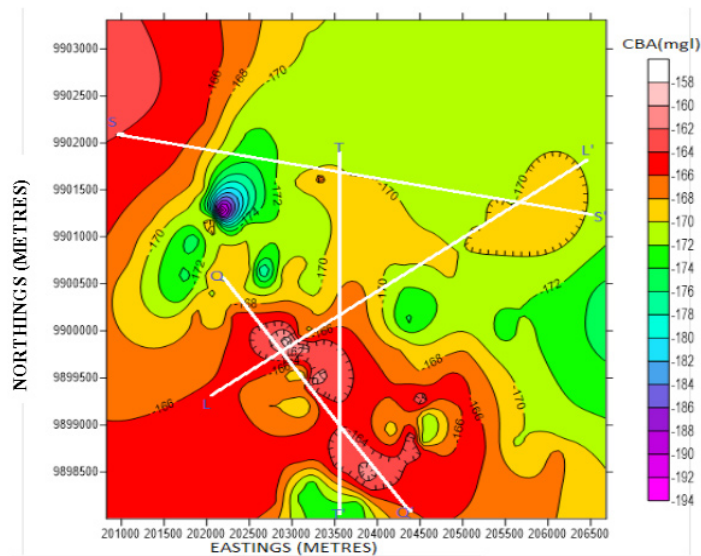


Figure 2: Complete Bouguer contour map of Olkaria Domes.

### Euler deconvolution

This method helps automatic estimation of location of a causative body and its depth within the earth's subsurface. Therefore, the boundary of the said resource and its depth from the surface was located by Euler deconvolution. Trends and depths description are the most important products of Euler deconvolution. A structural index of 1.0 was used in this study to delineate cracks and intruding dykes in the subsurface to which heat sources are related. The structural index becomes an exponential integer in a power law giving off field strength drop against source distance.

Euler's solution for profile SS' captured a shallow depth structure of between 10m and 750m (Figure 3). The top depth of the intrusion, possibly lie at 10m and 750m as its base depth. The profile density body is 500m wide (Figure 3) imaged at co-ordinate (201500, 9901900) in the anomaly map as shown in (Figure 2).

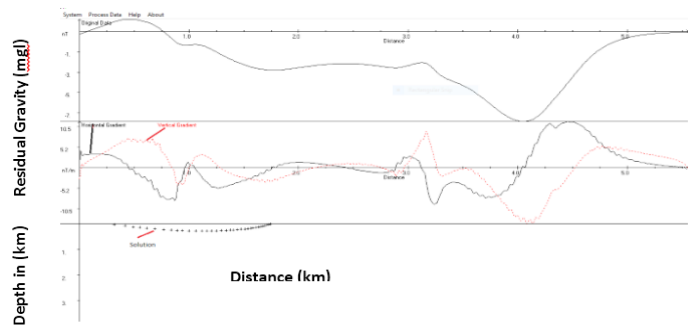


Figure 3: Euler Deconvolution solutions for profile SS'.

The depth estimation technique reveals solutions clustering as from shallow depth of 20m to deep depth of about 1000m (Figure 4) which are at co-ordinates (203500, 9899500) and (203500, 9898750) in the anomaly map. The slight gap imaged is a characteristic of formation of a fault. It has also shown few ignorable spurious solutions near the surface. Therefore, the intrusive crest is possibly lying at 20m in depth while foot depth is 1000m. The profile density structure is over 2000m broad (Figure 4).

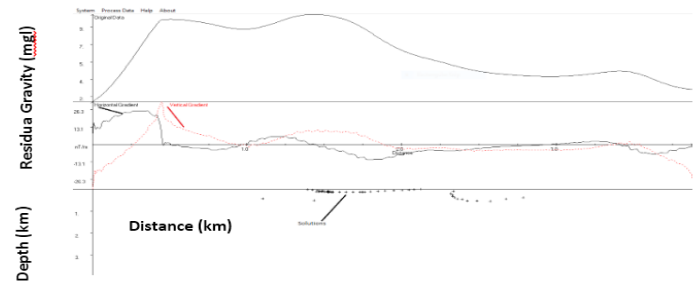


Figure 4: Euler Deconvolution solutions along profile TT'.

Euler Deconvolution solutions for profiles LL' and QQ' give no solution for structural index of 1.0 which was used to delineate fractures and intruding dykes associated with heat sources in the subsurface

### Forward Modeling

Forward modelling involves determination of the causative body parameters such as its geometry, density contrast and the depth of burial. In the study, two dimensional forward modeling techniques was applied to generate the source body parameters using Grav.2dc software (Gordon Cooper).

Profile SS' is to model high gravity anomaly centered at co-ordinate (2035000, 9902000). Forward modelling result reveals dyke structures lying at top depth of 33m, density contrast

0.22487g/cm<sup>3</sup> and 801m wide for body 2 which is at co-ordinate (201500, 9901900) of the anomaly map, maximum top depth as 40m, contrasting density 0.245250g/cm<sup>3</sup> and a width of 501m for body 3.

The first and the fourth bodies with density contrast -0.228374g/cm<sup>3</sup>, width 1184m and density contrast -0.0051541g/cm<sup>3</sup>, width of 1854m respectively are imaged at the surface. (Figure 5) shows a fit between the calculated gravity anomaly curve and the observed anomaly curve and the observed anomaly for profile SS’

Profile TT’ models centered at grid co-ordinates (2035000, 9899000), as shown in Figure 6 reveals three subsurface intruding bodies. Body number one at co-ordinate (203500, 9899500) has density contrast 0.2415g/cm<sup>3</sup>, width of 1526m and mapped at 40m deep. The second body has a contrasting density of 0.22239g/cm<sup>3</sup>, width 1829m and imaged at 25m in depth while the third body has density contrast of 0.1488g/cm<sup>3</sup>, width 540m and mapped at maximum depth to the top as 20m at co-ordinate (203500, 9898750) in the anomaly map as shown in (Figure 2).

Models on LL’ profile centered at grid co-ordinates (2035000, 9900000) as shown in (Figure 7) maps one subsurface intruding body of density contrast 0.252g/cm<sup>3</sup>, breadth of 2697m and imaged at 40m below the surface. Bodies structures of densities -0.2335g/m<sup>3</sup>, width 1182m and - 0.03179g/m<sup>3</sup>, and width of 2480m are imaged at the surface presumed to be composed of sediments also revealed. Profile QQ’ models centered at grid co-ordinates (203000, 9899000) are shown in Figure 8 have two dense subsurface bodies intrusive revealed. The first dense body has density contrast of 0.478545g/cm<sup>3</sup> width of 1026m being imaged 44m deep. The second dense body has a density contrasting of 0.325694g/cm<sup>3</sup> width 1473m and mapped 41m in depth. The calculated anomaly curve and the observed fitting for QQ’ profile is shown in (Figure 8). At the surface are two bodies of density contrast of -0.842062g/cm<sup>3</sup>, width 1221m and -1.171403g/cm<sup>3</sup>, and width of 39m respectively which are presumed to be composed of materials of low density like sedimentary rocks.

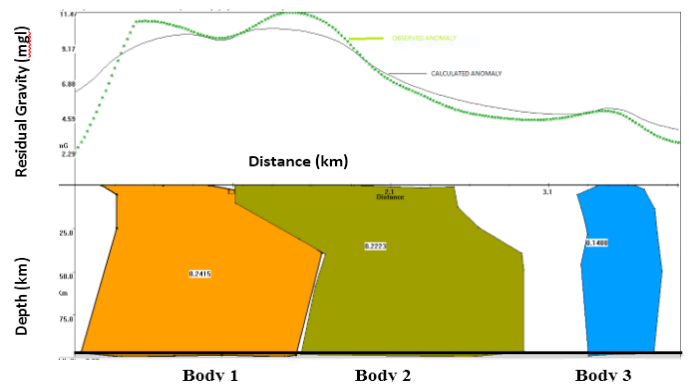


Figure 6: Observed, calculated anomaly and forward model of 2-D body for profile TT’.

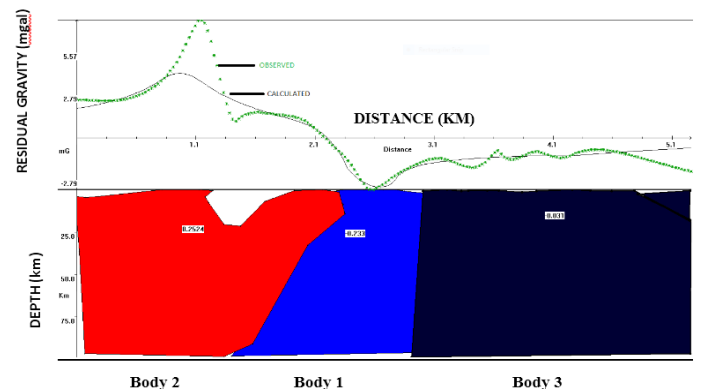


Figure 7: Calculated, Observed anomaly and forward model of 2-D body for profile LL’.

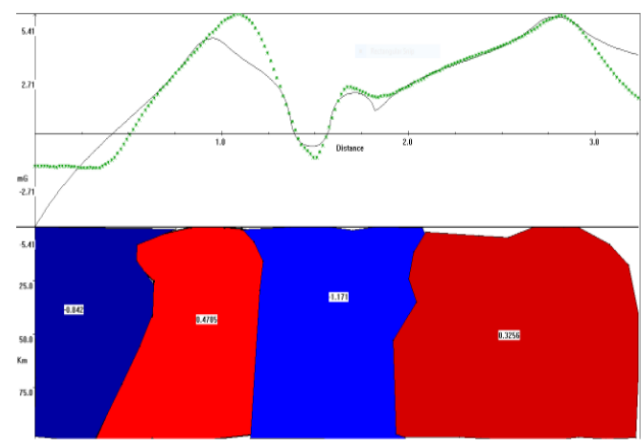


Figure 8: Computed, Observed anomaly and model of 2-D body for profile QQ’.

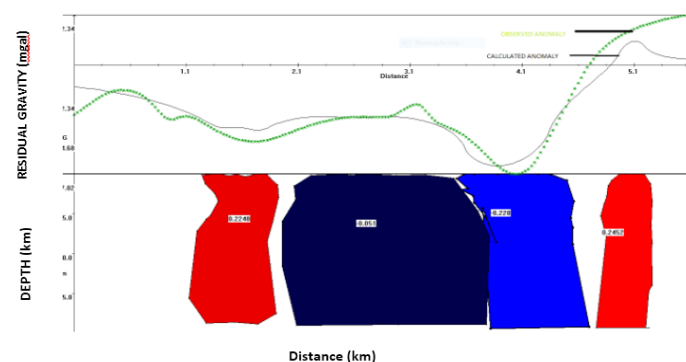


Figure 5: Observed, Computed anomaly and forward model of 2-D body for profile SS’.



## Discussion

Profile SS' is inclined towards NWSE on the upper part of the study area and traverses the high and low areas centred at (203500, 9902000) as shown in Figure 2. The direct analysis that is curve shapes dependant and the limiting depth approach, approximates the SS' profile body to be less than 267.5m in depth. This is in line with the top depth of the modelled structures which is at about 40m. The outcome of the forward modelling reveals dyke like structures at the maximum depth to the top as 33m, density 2.89g/cm<sup>3</sup> and a width of 801m for body 2, maximum depth to the top as 40m, density 2.92g/cm<sup>3</sup> and a width of 501m for body 3. The structures are lying slightly vertical and spread to 801m in breadth. This as was revealed earlier by Euler's results that estimated depth of 40m below the surface and a width of 800m (Figure 3). The first and the fourth bodies with density 2.34g/cm<sup>3</sup>, width 1184m and density 2.66g/cm<sup>3</sup>, width of 1854m respectively are imaged at the surface (Figure 5). These positive gravity anomalies could be hot intrusives of density high at 800m in depth emanating from the mantle under the volcanic complexes located at co-ordinate (201500, 9901900) of the anomaly map which agree well with the geology of the area and quantitative analysis results, hence they could be the heat sources at the basin.

The TT' profile is inclined towards NS direction on the central part of the study area and centred at grid co-ordinates (2035000, 9899000) as shown in Figure 2. It targets the NW-SE fault of high gravity area possibly the geothermal reservoir along the Easting 203500. It reveals a subsurface relatively dense body whose direct analysis, has average crest depth of 287.5m.

Model on profile TT' as shown in figure 6 reveal three subsurface intruding bodies. Body one has density 2.92g/cm<sup>3</sup> extensive width of 526m and imaged at a shallow depth of 40m. Body two has a density 2.89g/cm<sup>3</sup> width 1829m and imaged at a shallow depth of 25m while the third body has density 2.82g/cm<sup>3</sup>, width 540m and imaged at maximum depth to the top as 20m. These were presumed to be hot dense bodies composing phonolitic trachytes imaged under magma at bottom depth of 1000m which are attesting to a heat source at the basin. The trachytes occurring in the east of Olkaria Hill are the host for the geothermal reservoir (Omenda, 1994, 1998) could also be the heat bearing rocks in the dome areas under the survey. The formation of these rocks has pyroclastic minor and basalt flows. Thickness of the formation changes from 100m - 500m and is regarded as the rock cap for geothermal system of Olkaria (Haukwa, 1984).

Profile LL' is inclined SWNE towards positive anomaly, centered at co-ordinates (203500, 9900000), shown in Figure 2. Models on LL' as shown in Figure 7 mirrors one subsurface intrusive body of density 2.92g/cm<sup>3</sup>, extensive width of 2697m and imaged at a depth of 40m. Body structures of densities 2.44g/

m<sup>3</sup>, width 1826m and 2.63g/m<sup>3</sup>, width of 2480m are imaged at the surface, presumed to be composed of sediments also revealed.

Profile QQ' is drawn in the NWSSE direction and traverses the positive gravity anomaly centred at grid coordinates (203000, 9899000) as in Figure 2. Profile QQ' models shown in figure 4.13, displays three dense intrusive structures below the surface. First dense structure bears 3.049g/cm<sup>3</sup> density, width of 1026m, detected at 44m deep. The second dense body bears 3.096g/cm<sup>3</sup>, width 1473m and mirrored at 41m deep.

At the surface are two bodies of density 1.649g/cm<sup>3</sup>, width 1221m and 1.498g/cm<sup>3</sup>, and width of 993m respectively which are presumed to be composed of materials of low density like sedimentary rocks.

## Conclusion and Recommendation

The map of anomaly shows large area with anomalies encircling most of the area, while three dimensional map gives a view of 3-D gravitational field changes in the study area. Olkaria Dome prospect area possess high geothermal gradient, which is evident by presence of hot springs and steaming, has a potential heat source covering approximately 10km<sup>2</sup>. It is characterized by major faults, veins, sills, fractures, craters dykes, gorge and inferred ring structures.

The possible source of heat imaged at co-ordinate (201500, 9901900) and (203500, 9899500) in the area has shallow sharp dykes manifestation, modelled at 10m, 25m, 30m, and 50 m deep as in Figure 5 and 6 according to Euler deconvolution results and 11m, 20m, 25m, 33m and 40 m according to results obtained by Forward modelling shown in Figure 7 through 8. These depth results are attest to what empirical methods have postulated and agree with the geology of the area. The shallow imaged fault by Euler deconvolution Figure 4 directs the flow of water from the rift scarps to the hot masses underground. This possibly led to the trapping of a heat source in the area as evidenced by the hot springs. The low lying dykes causing heating effect on the geothermal fluid in Olkaria Dome were well captured. Due to radioactivity within the crust and great pressure the over lying rocks exert, these dykes gradually cool down. Gravity method was able to locate these body dykes as positive gravity anomalies within Earth's subsurface.

It is postulated that intrusive, in the form of dykes could be the conduit of heat from large magma bodies at few kilometres from the surface. Therefore, this study was able to detect gravity highs that show evidence of a buried dense body compared to the surrounding rocks along profiles SS' and TT'. The buried dense bodies were interpreted as intruding dyke injections within the subsurface which could be heat sources.

This gravity study was conducted to gather information on the possible existence of geothermal heat sources in Olkaria

Dome area. It has provided information which will be used as a start point for future detailed geophysical study. This study recommends the application of other geophysical techniques like seismic, resistivity, magneto telluric (MT) and magnetic to map heat sources for outcome comparisons. This ensures confirmation of this gravity results before drilling is done which is expensive.

Advance techniques of gravity data analysis such as Tensor Euler deconvolution approach to be carried out in Olkaria Domes to verify the results. Usage of calculated gravity gradients in convectional Euler is overcome by Tensor Euler deconvolution that deploys the measured ones. This honours responses from many dimensions and the, the deconvolution can be executed minus gridding. Over the steep and wild animal habitat areas, collection of more gravity data is required for deeper probing on longer profiles.

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