A p p l i c a t i o n of integrated geophysical techniques for groundwater potential evaluation in hard rock basement: mutito fault zone, Kenya

Muturi Njeri Esther*, Korowe Maurice Odondi and Githiri John Gitonga

Physics Department, Jomo Kenyatta University of Agriculture and Technology, P.O. Box 62000-00200, Nairobi, Kenya.

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A B S T R A C T

The lack of access to potable water in Kitui has resulted to famine and high infant mortality rates, which has risen to 9.8% and life expectancy is declining steadily. The fact that the basement system is hard Precambrian rock, ground water tends to be more localized and thus sustainable wells cannot be dug on a trial and error basis. The aim of this project was to evaluate groundwater potential located in the concealed fractured /faulted zones which act as groundwater storage and conduits, using magnetic and geo-electrical geophysical techniques. A terrameter was used to collect resistivity data and subsequently determine the subsurface layer resistivity anomalies using Wenner profiling and resistivity sounding inversion software, IP2WIN. Proton precession magnetometer was used to measure the total magnetic field intensity of the earth and 2D Euler deconvolution software was used to model the disintegrated basement. Magnetic surveys showed distinct magnetic anomalies signifying disruption of the basement rock which occur due to faulting. Resistivity surveys also showed low resistivity anomaly at points of significant magnetic anomaly. This suggests groundwater potential in the inferred fault.

Key words: Groundwater, mutito fault, hardrock, geophysical techniques.

I n t r o d u c t i o n

Groundwater exists in four main hydrogeological formations namely, crystalline rocks, volcanic rocks, unconsolidated sediments and consolidated sedimentary rocks (K’Orowe, 2009). According to a study carried out by Macdonald et al., (2001), in sub-Saharan Africa, crystalline rocks form the largest hydrogeological formations occupying 40% of the 23.6 million square kilometers of landmass with 220 million people living in areas underlain by hard crystalline rocks. These crystalline rocks comprise of compact and dense hard rock such as granite and metamorphic rocks, where occurrence of groundwater is greatly localized and limited to the existence of weathered and fractured zones within the basement. These deformations which provide for groundwater transmission and storage are highly localized and cannot be sited in a random manner.

Surface geophysical survey as an instrument in groundwater exploration has the basic advantage of saving cost in borehole construction by locating aquifer before embarking upon drilling. In this study area, the highly localized Mutito fault zone is concealed by alluvium deposits and the need to employ subsurface exploration techniques that can sufficiently locate high yielding and sustainable groundwater was necessary. Magnetic survey was employed to map out the Mutito Fault structure and to ascertain the geosynclines structure inferred in the (1957) geological report by Serggerson. The geoelectric technique was also used to determine groundwater potential and the aquifer parameters within the concealed fracture zones in the hardrock basement.
Description of Research

The area of study is Mathima location, which is within South Kitui County. It is approximately 1200 square miles in the Kitui district, bounded by latitudes 1° 30’ and 2° 00’ S and Longitudes 38° 00’E and 38° 30’E. Climatically, the area is largely semi-arid region characterized by erratic and unreliable rainfall (Fig. 1).

Fig. 1 Location of study area, Mathima district in South Kitui

Fig. 2 General geological map of Kenya showing the location of the Eastern Mozambique Belt Segment (EMBS - I, II, and III) (After Nyamai et al., 2003)
Geology

The area of study is within the Central sub-area II of the Eastern Mozambique Belt Segment (EMBS) segment, of the Precambrian age, which occurs east of the Rift System and is the largest of all the four major exposed segments of this belt in Kenya (Figure 2) Nyamaiet al., (2003). Extensive reconnaissance geological mapping carried out between 1950s and 1960s by the Geological Survey of Kenya, particularly in the EMBS, has considered the Precambrian Mozambique belt to be composed mostly of pelitic and semi-pelitic schists and gneisses, migmatites, granitoid gneisses, ortho-amphibolites and some units of marbles and quartzites; (Baker, 1954), (Dodson, 1953), (Fairburn, 1963) and (Biyajima et al. (1975).

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A geological report by Saggerson (1957) states that what is for convenience called the Mutito fault, in fact a fault-zone nearly two miles wide, and is well exposed topographically, in a river valley, West South West of Voo. The north portion of the Mutito fault has several branches, movement along which has been responsible for the displacement of small blocks near the northerly pitching Matulani syncline which was overturned during folding. South of Voo, no topographic or other field evidence of the fault is seen, but from structural evidence displayed on Mutha and adjacent hills, it is thought that the fault passes into a high-angle thrust fault which is entirely covered by alluvium deposits.

The extension of the covered Mutito fault, indicated by the dashed line (Fig. 3) is inferred to pass longitudinally intersecting the Nzwanzi fault and syncline (Saggerson, 1957). Geophysical techniques were applied to establish these concealed disintegrated zones which act as groundwater conduits and whose intersection provides for high yielding potential aquifers. The syncline which also exists where the stipulated fault is inferred to be provides a perfect set up for groundwater potential (Fig. 3).

Materials and Methods

The geological parameters that indicate the inferred Mutito fault as having a NE-SW orientation intersecting the syncline structure at an angle of 290° from the true North were used in planning the surveys and designs of both magnetic and resistivity profiles.

Magnetics Survey

The instrument used for the ground magnetic survey was the Geometrics 856 Proton Precession Magnetometer. Ground magnetic data was collected perpendicularly to the geologically inferred Mutito fault. A total of 102 magnetic stations were established in the study area. Establishing and positioning of magnetic stations including base stations was done using a global positioning system (GPS). Five transects which covered a lateral distance of 4 Km each, ran in the East-West direction across the inferred fault. Each profile had a distance separation of 1 Km. Magnetic measurements were taken at every 100m meter station along each transect. Surfer 10 software was used to qualitatively analyze lateral magnetic variations within the study area. The 2D Euler deconvolution software was used to model the subsurface basement and also image the depth of the inferred fault structures within the basement. (Fig. 4)
Results and Discussion

After correcting for diurnal variations and geomagnetic field, the corrected magnetic data was uploaded to Surfer 10 software for qualitative analysis. Using the krigging technique, a magnetic Intensity Contour map was plotted. On most profiles (see figure 5), the magnetic contour map displayed hachured contours within solid contours, which represent magnetic lows and highs respectively. The variations in magnetic intensity in the Contour map (Fig 5) could be attributed to an intense shearing activity within the highly magnetic basement. The cross sections along the three profiles, A A' B B' and C C' clearly show a trend of consistent low magnetic responses along each transect, which is a distinct signature of the subsurface fault structures within the geological unit. When these profiles are interconnected, a direction of NE -SE trend is evident. This trend of magnetic anomalies within the study area seems to agree with the South Kitui geological report by Serggerson (1957), which describes the concealed Mutito fault structure as trending in a NE-SW direction (Fig. 5).

For quantitative analysis, two dimensional (2D) Euler deconvolution was used to create models of discontinuity on the faulted basement. The 2D Euler deconvolution was generated from the software developed by Cooper (2004) for constraining the subsurface geometry along the profile lines. The input data to the software was the profile magnetic data. Other input information included magnetic inclination of value 0.13°, magnetic declination of value -24.42° and the average geomagnetic field, 33548nT and the structural index of value 0.5, which is an indication of fault contacts. Four profiles, A A', B B', C C' and D D' were cut and cross sections imaging the subsurface structures were plotted, using Euler 1.0 software. The Plus (+) signs in the cross sections are Euler solutions for 0.5 structural index (Fig. 6 - 9). The variations in magnetic amplitudes and the much scattering in the Euler solutions could be attributed to an intense shearing activity and localized anomaly beneath the profiles, which is also visible in the analytical Contour map.

Transect A A' also has very well defined scattered points that define fault structures along this transect. This undulating signature and the Euler deconvolution solutions clearly show the subsurface faulting/ contacts pattern within this geological unit. Transect B B' and C C' show a grid of scattered points, signifying a grid of subsurface discontinuity across all the profiles. This is in complete coherence with the structural geological map, by Serggerson (1957), of the Mutito Fault zone, which states that the Mutito Fault may not be a single discontinuity but a grid of about 2 km wide fractures in the geological unit. Transect D D' is imaged by distinct rifts of the scattered point that signifies a fault structure whose depth is approximately 200meters. A basin structure of 250m depth is also imaged on this same transect, which could imply the geosynclines structure caused by folding, as discussed by Serggerson (1957) in the geological report. From this model also, the fault structure seems to intersect the syncline at an angle.

Therefore, from Euler solutions, the Mutito Fault is well defined at depths of about 200m. This is consistently seen in all profiles that were modeled out. These results are in agreement with the magnetic Intensity Contour map that displayed distinct hachured contours within solid contours, which represented distinct magnetic lows within magnetic highs. This continuous discontinuity was seen in each of the three profiles, which had a distance separation of 1 kilometer. This anomaly would most likely signify basement disintegration, which confirms the geological inference of the Mutito Fault.

Resistivity Survey

The resistivity equipment used in this research was a terrameter model Campus Tigre Geopulse. Five (5) profiles A A', B B', C C', D D' and E E' were carried out, with a total of thirty eight (38) stations measured using the Wenner electrode configuration shown in figure 10. For profiles A A', B B' and C C', electrode spacing was “a” = 100 meters while for profiles D D' and E E', electrode spacing was “a”= 30 meters. The two electrode spacing “a” = 100m and 30m was deliberately carried out so as to profile lateral resistivity variations at different depths. The profiles, which were designed to run perpendicular to the direction of the inferred fault, were intended to intercept the inferred Mutito fault. The Schlumberger Vertical electrical Sounding (VES) profiles and design were dictated by the lateral resistivity anomalies sited by the Wenner profiles. Four (4) VES soundings were carried out along the inferred fault, shown in Figure 10 (four triangle shapes). The VES stations had a distance separation of 200m while the maximum current electrode spacing (A/B/2) for each station was 130meters. Resistivities were measured at four potential electrode MN/2 spacings of 0.5 m, 2 m,
5 m and 10 m. At a point where a changeover was made from one MN/2 value to another, readings were taken at both MN/2 values. The Surfer 10 software was used to qualitatively analyse the lateral resistivity anomalies within the study area. For quantitative analysis, the IP2WIN software was used to analyse resistivity variations with depth. (Fig. 10).

Table 1 Resistivity and thickness inversion results at VES Stations

<table>
<thead>
<tr>
<th>Station</th>
<th>Resistivity (m)</th>
<th>Thickness (m)</th>
<th>Sequence of layers</th>
<th>Type of Curve</th>
<th>Fitting errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST. 1</td>
<td>202</td>
<td>4.5</td>
<td>(\rho_1 &gt; \rho_2 &lt; \rho_3)</td>
<td>H-type</td>
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<td>2</td>
<td>19.3</td>
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<td></td>
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<td></td>
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<tr>
<td>3</td>
<td>13689</td>
<td>9.31 - (\infty)</td>
<td></td>
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<td></td>
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<td>ST. 2</td>
<td>1505</td>
<td>6.79</td>
<td>(\rho_1 &gt; \rho_2 &lt; \rho_3)</td>
<td>H-type</td>
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<tr>
<td>2</td>
<td>171</td>
<td>7.07</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td>1.4 E+5</td>
<td>(\infty)</td>
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<tr>
<td>ST. 3</td>
<td>135</td>
<td>5.78</td>
<td>(\rho_1 &gt; \rho_2 &lt; \rho_3)</td>
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<td>15.6</td>
<td>5.12</td>
<td></td>
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<td>3</td>
<td>12332</td>
<td>(\infty)</td>
<td></td>
<td></td>
<td></td>
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<td>ST. 4</td>
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<td>6.89</td>
<td>(\rho_1 &gt; \rho_2 &lt; \rho_3)</td>
<td>H-type</td>
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<td>2</td>
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<td>6.17</td>
<td></td>
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<td></td>
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<tr>
<td>3</td>
<td>39937</td>
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Table 2 Computed Transverse Resistance and Longitudinal Conductance

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Easting(m)</th>
<th>Northing (m)</th>
<th>T (ohm-m²)</th>
<th>S X 10⁻³ (ohm⁻¹)</th>
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</thead>
<tbody>
<tr>
<td>Station 1</td>
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<td>980400</td>
<td>1010.968</td>
<td>2691.57</td>
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<tr>
<td>Station 2</td>
<td>422071</td>
<td>9804112</td>
<td>3177.106</td>
<td>1540.89</td>
</tr>
<tr>
<td>Station 3</td>
<td>421979</td>
<td>9804113</td>
<td>4188.074</td>
<td>4232.46</td>
</tr>
<tr>
<td>Station 4</td>
<td>422104</td>
<td>9803985</td>
<td>7365.18</td>
<td>5773.35</td>
</tr>
</tbody>
</table>

Fig. 5 Magnetic Contour Anomaly Map

Fig. 6 Processed ground magnetic data with 2D Euler solution obtained along traverse AA
Fig. 7 Processed ground magnetic data with 2D Euler solution obtained along traverse BB

Fig. 8: Processed ground magnetic data with 2D Euler solution obtained along traverse CC'

Fig. 9: Processed ground magnetic data with 2D Euler solution obtained along traverse

Fig. 10: Resistivity profiles: Plus signs represent wenner profiling stations; Triangular symbols represent Schlumberger VES sounding stations

Fig. 11 2D Contour map of the wenner profiles with electrode spacing a=100m
(Resistivity Contour map with Wenner profiles of electrode spacing a=100 meters)
Fig. 12 Cross Sections AA’, BB’ and CC’

Fig. 13 Wenner profiles at a = 30meters

Wenner profiles with electrode spacing a=30

Fig. 14 Resistivity (ρ) against AB/2 (m) : VES Station 1

Fig. 15 Resistivity (ρ) against AB/2 (m) ; VES Station 2

Fig. 16 Resistivity (ρ) against AB/2 (m) ; VES Station 3

Fig. 17 Resistivity (ρ) against AB/2 (m) ; VES Station 4
At electrode spacing of a=100m and a=30m, the 2D contour maps showed the contour map (figure 11 and 13) displayed hachured contours within solid contours, which represent resistivity lows and highs respectively. On profiles A A’, B B’, and C C’ a trend of low resistivity anomalies within highly resistivity environment is a possible indication of the disintegrated basement rock which may contain highly conductive infills, in this case, groundwater. As inferred from geology, the concealed Mutito fault trends at an angle of 290° from the true North. A similar trend of distinct low resistivity affirms the prediction of groundwatery flowing in this fault structure. The cross sections below (Profiles A A’, B B’, and C C’) , with a similar reference point, have been drawn from within the Contour map below (Figure 11). These profiles clearly show the low resistivity anomalies at specific points, which, when interconnected reveal a NW-SE trend, which is the same direction that the geology report, by (Sergerson, 1957) infers the fault direction to be. These resistivity lows shows that groundwater, which has low resistivity signature, could be flowing within the fault structure, in this case, the Mutito fault (Fig. 11-13). The location and design of the V E S sounding indicated by the bold dots (Figure 13) were constrained by the Wenner profile results which showed areas with distinct lateral resistivity anomalies; regions of distinct low resistivity values being the areas of interest. To quantitatively analyze the V E S results, the calculated apparent resistivity, A B/2 and M N/2 electrode separations were uploaded to the IP2WIN software. Below are the sounding
The total transverse resistance \( T \) and longitudinal conductance values were computed, plotted and contoured to produce the total transverse resistance map of the area (Fig. 18). High \( T \) and \( S \) values were obtained at geo-electric sounding (VES) station four (4) (422104 Easting, 98039853 Northing) with values of 7365.18 ohm-m². This depicts that the aquifers or aquiferous zones delineated at the VES station four (4) might have the highest transmissivity values and thus a more sustainable aquifer at this point (Table 2 & Fig 18-19).

From previous studies of nearby borehole logs (Kenya Ministry of Water, 1987) shallow unconfined aquifers seem to overlay deep confined aquifers, where water was first struck at depths of between 12 to 14 meters and subsequently, deeper and more sustainable aquifers were struck at greater depths of between 80 to 145 meters. Therefore, the shallow unconfined aquifer signified by the low resistivity within the second layer is a good suggestion of deeper and sustainable aquifers.

**Conclusion**

In conclusion, significant geophysical evidence of the existence of the Mutito fault has been indicated in both magnetic and resistivity surveys. Comparing previous geological findings and the geophysical results, great coherence in the trend of the inferred fault is evident. According to previous geological report, the fault trends at a 290° bearing (clockwise from the true North), in a North-West South-East direction (Fig. 22-23). This trend is seen in both magnetic and resistivity, whose anomalies, indicated by the hachured contours, trend in a similar direction, at a similar bearing. These results confirm the presence of the inferred Mutito Fault, which could potentially act as a groundwater conduit in the Kitui hard rock environment. Resistivity surveys also showed low resistivity anomaly at similar points of significant magnetic anomaly. This suggests groundwater potential in the inferred fault.

**Recommendations**

Therefore, from analysis of the two geophysical techniques, the locations with the similar correlations of the two data sets are indicated in the topographical map below. The best location however, with the best correlation is point 9803500 Northing 421700 Easting. This would be the area with the highest chance of
groundwater drilling success (Fig. 23). However, further geophysical investigations should be carried out so as to further constrain the areas of most probable success. Follow-up test borehole should be subsequently drilled to ascertain the geophysical findings and to understand the lithological stratigraphy of the area.

A cknowledgements

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R eferences