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Imaging subsurface fracture characteristics using 2D electrical resistivity tomography

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One of the common features of most rock bodies is the presence of discontinuities which are generally called fractures. Fractures result when applied stress overcomes the strength of the host rock. Their presences must be carefully studied as they significantly affect the engineering and strength properties of the rocks. Their presences also influence the hydraulic properties of rocks. Several tools and methods have been employed in the study of fractures both at the surface and subsurface. The Electrical Resistivity Tomography ERT method, a geophysical tool was used in this research to study and characterize fractures in the crystalline rocks at Igarra, SW Nigeria. The survey which spans a survey line of 100m and average subsurface depth of 18m imaged the presences of vertical to steep-dipping discontinuities which are interpreted as fracture planes. These fracture planes extends beyond the 18m depth of investigation suggesting that the fractures are potential conduits for leachate transport and surface water run-off infiltration in the area. This has implication for waste management disposal design and siting, as the chances of bedrock and groundwater contamination is potentially high. Hence the fracture characteristics must be taken into consideration when waste disposal management policies are being formulated and implemented.

Keywords: Fractures, electrical resistivity, lithology, groundwater contamination.

INTRODUCTION

Fractures are the commonest type of geological structures observed on rocks. They are cracks across which the cohesion of the host material is lost, and can be regarded as planes or surfaces of discontinuity. The cracks are caused by stress. In order words, fractures result when the applied stress overcomes the cohesive strength of the material or rock. Where there is significant and measurable displacement across the fracture plane, that is, where the rock block on one side of the fracture plane moves relative to the rock block on the other, the fracture is called a fault. On the other hand, where there is no appreciable displacement, the fracture is called a joint. The distinction between the fault and joint is somehow artificial, and depends on the scale of observation (Park, 1997). However, in practice, most fractures show negligible displacement and are as such classified as joints. The importance of fractures on the host rock cannot be overemphasized. Their presence significantly affects the strength and engineering properties of rocks making it imperative for them to be well studied and characterized in Civil Engineering constructions. Fractures also improve the hydraulic characteristics of rocks especially crystalline rocks that lack matrix porosity and permeability, and sedimentary rocks with low matrix porosity and permeability. Information on fracture and fracture characteristics are important input in the design, siting and management of waste disposal facilities such as landfills since fractures readily form seepage pathways for contaminant transport. Since most fractures do not have surface expressions at outcrops or are covered by topsoil, it has become imperative for Earth Scientist to develop tools and

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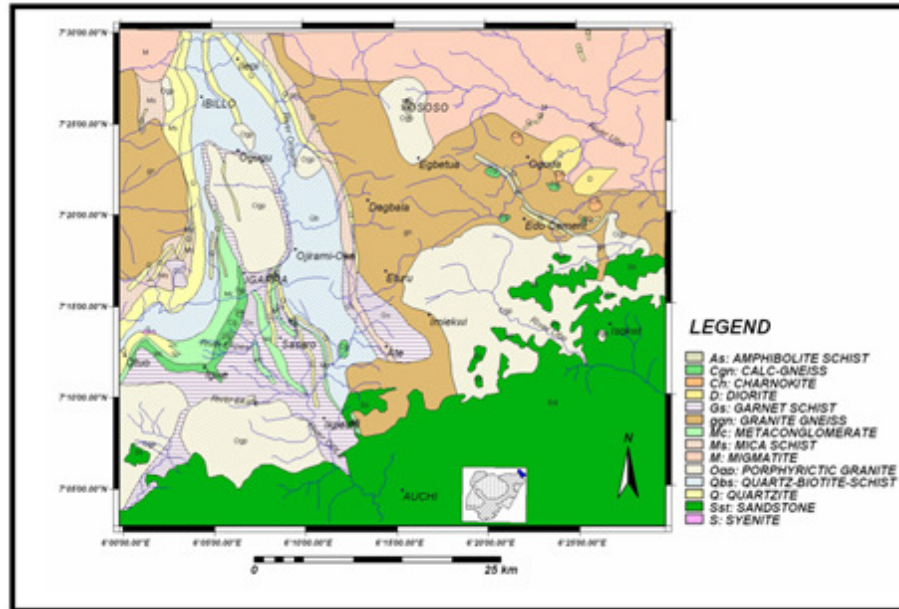*Corresponding Author E-mail: izuchukwuig@yahoo.com; Tel: +234(0)8069074221

Figure 1. Geologic map of Igarra.

Methods for identifying and characterizing fractures in the subsurface. One very useful innovation in the pursuit of this goal is the geophysical method of Electrical Resistivity Tomography ERT.

Electrical Resistivity Tomography is a geophysical technique for imaging subsurface structures from electrical measurements made at the surface of the ground. As with all other resistivity methods, ERT employs an artificial source of electric current (DC or low frequency AC), which is introduced into the ground through point metallic stakes (electrodes). The purpose of electrical resistivity surveys is to determine the subsurface resistivity distribution. High density ERT is receiving much attention for near-surface geophysical prospecting (Zhou, 2007; Zhou et al, 2001, 2002, 2004; Kemma et. Al., 2002). Applications either use the earth's resistivity to characterize site and understand the subsurface geologic structures and lithology (Shima, 1992, 1995; Susuki and Ohnishi, 1995) or utilize the temporal variation of the earth's resistivity to investigate underlying physical and chemical processes (Zhou et. Al., 2001, 2002, 2004).

Usually only the earth's resistivity or electrical potential data are available, so a successful application of ERT requires a reliable inversion algorithm that can convert the measured data to spatial distribution of resistivity (Zhou, 2007). Geophysical inversion seeks to find a model that gives a response that is similar to the actual measured values. The model is an idealized mathematical representation of a section of the Earth (Loke, 2004). The model has a set of model parameters that are physical quantities to be estimated from the observed data. The model response is the synthetic data that can be calculated from the mathematical relationship defining the model for a given set of model parameters. All inversion methods essentially try to determine a model for the subsurface whose response agrees with the measured data subject to certain restrictions. In the cell-based method (used in this project), the model parameters are the resistivity values of the model cells, while the data is the measured apparent resistivity values. The mathematical link between the model parameter and model response for the 2D resistivity model is provided by the finite-difference FD (Dey and Morrison 1979a, 1979b) or finite-element FE methods (Silvester and Ferrari, 1990).

The study area

The study area is Igarra, located in SW region of Nigeria and bounded by Latitudes N7^{o}14^{1} and N7^{o}18^{1}; and Longitudes E6^{o}4^{1} and E6^{o}8^{1}. Rocks in the area consist mainly crystalline rocks of the slightly Migmatised to Unmigmatised Schist Belt (Igarra Schist Belt, figure1) which are bounded and underlain by the Migmatite-Gneiss Complex and intruded in some places by the Pan-African Older Granite which forms good topographic features rising to over 100m above the surrounding terrains. The Igarra Schist belt runs for about 60km in a generally NNW-SSE direction (Rahaman, 1976) and comprises Quartz-Biotite Schist, Mica Schist, Quartzite and Quartz Schist, Calc-Silicate and Marble; and Metaconglomerate. The dominant structural features are series of antiformal and synformal folds, and extensive fractures that trend dominantly in the N-S direction.
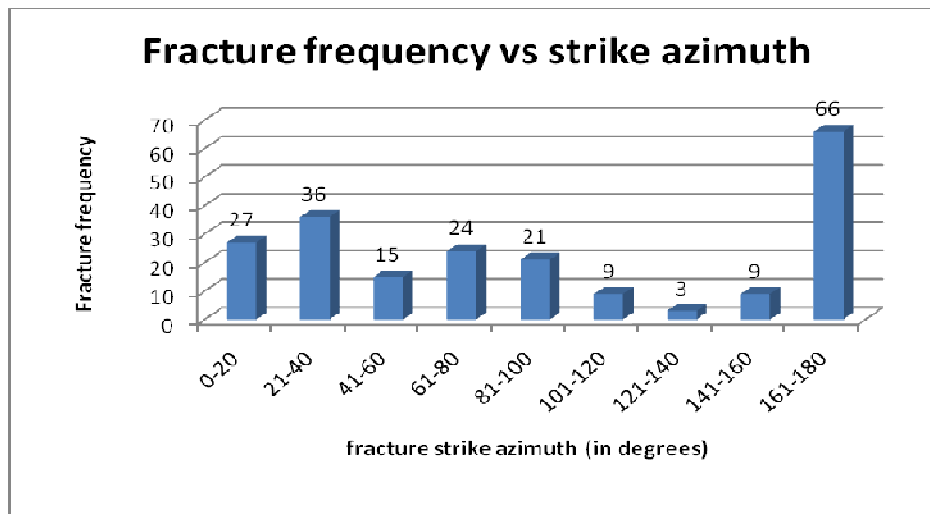
Figure 2. Plot of fracture frequency against fracture strike azimuth. Plot shows that most fractures have strike orientation in the N-S direction
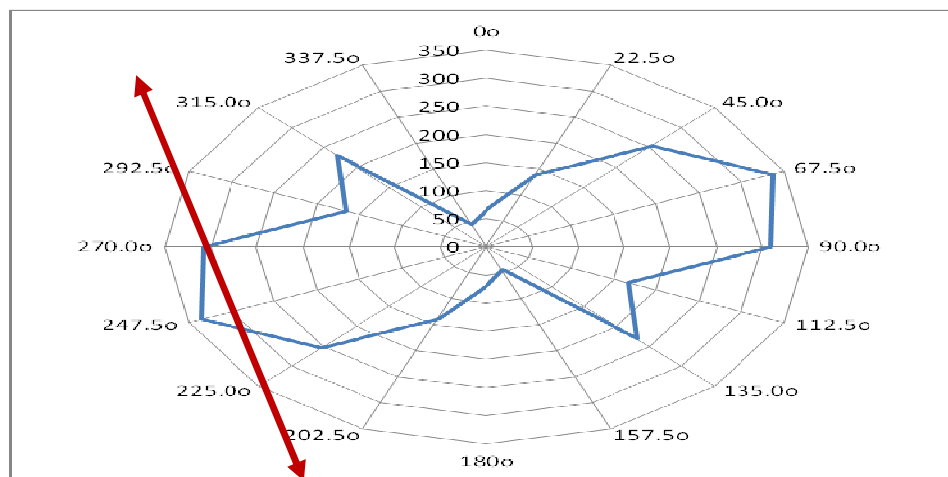

Figure 3. Polar plot of apparent resistivity value versus azimuth. The orientation of the arrow shows the orientation of the dominant fracture strike

METHODOLOGY

An initial surface geological mapping was done to characterize the fractures at outcrops. The surface geological field data showed that most of the fractures have strike orientation in the N-S direction (Figure 2). This was followed by a preliminary geophysical survey using the Azimuthal Square Array Resistivity method. The survey was done by rotating a whole square array through 180° at an electrode spacing of 40m corresponding to a depth of 18m. Analysis of the Azimuthal Resistivity survey data also showed that the dominant orientation of the strike of the fractures in the subsurface is in the N-S direction (figure 3). A detailed 2D Electrical Resistivity Tomography ERT survey was then carried out at the same location where the Azimuthal Resistivity Survey was done such that both have the same center point. The ERT survey line was aligned in the E-W direction so that it will be perpendicular to the dominant fracture strike orientation. The survey design employs the use of the Wenner Array because of its high sensitivity to lateral inhomogeneity, good vertical resolution, moderate investigative depth, moderate sensitivity to geological noise and abundant interpretational materials (Reynolds, 1997). Also, compared to the other collinear array, Wenner Array requires fewer and faster measurements in pseudo-section construction (Barker, 2001). Electrode points were first carefully marked out along the profile line from West to East. By taking resistivity measurements at an
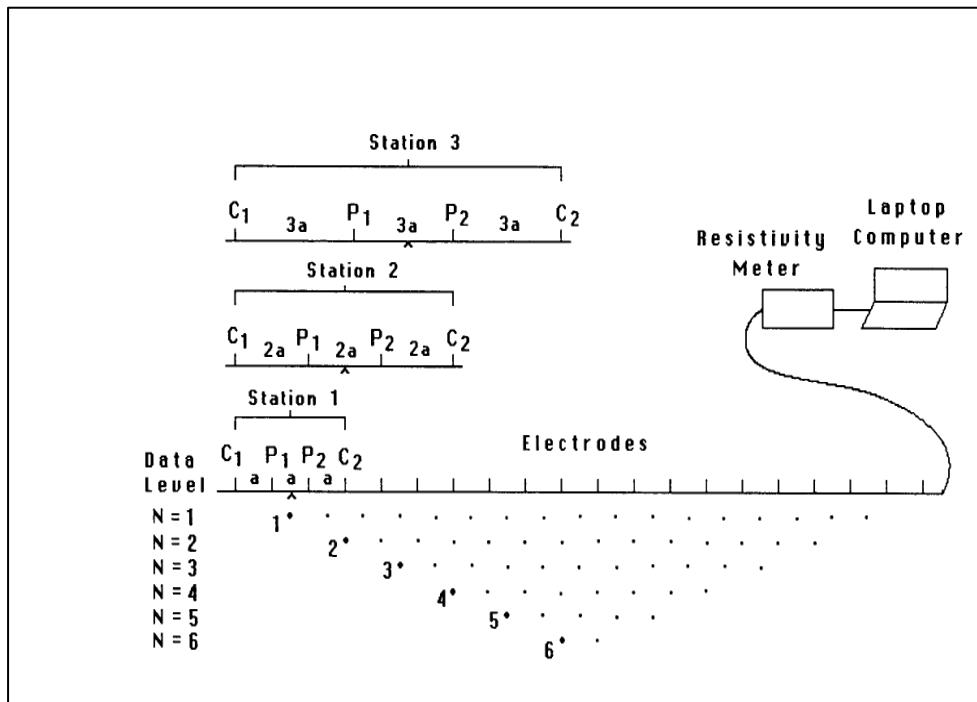
Figure 4. Measurement sequence for building a resistivity pseudo section. With an electrode spacing 'a', the first sequence of measurements are made. When this is completed, the next sequence of measurements employs the electrode spacing of '2a'. This procedure is repetitive, with increasing electrode spacing employed for each sequence. As electrode spacing increases, depth of subsurface imaged increases. Apparent resistivity values are plotted on the pseudosection with N, a multiple of the unit electrode spacing, serving as a measure of depth (Loke and Barker, 1995)

initial electrode spacing of a=3m, the subsurface was sampled. Subsequent increment of the electrode spacing to 2a, 3a, 4a and 5a led to a corresponding increase in the depth and volume of rock sampled (Figure 4). Each measurement is plotted below the midpoint of the four electrode used in making the measurement at a pseudo depth generally given as half the electrode spacing (Edwards, 1977; Barker, 1989).

Data analysis and results

The program RES2DINV™ version 3.58 was used for this analysis. Models for 2D resistivity inversion program comprise rectangular blocks (cell). The bottom of a block corresponds to a data point which is approximately equal to its effective depth (Loke, 2004). The software computes, by inversion, the true resistivity of the subsurface that agrees with the measured apparent resistivity values from the survey.

Apparent resistivity measurements recorded during the survey were entered into a text file in a format compatible with the RES2DINV™ and read into the computer with the software running. Since the maximum apparent resistivity value is more than 300 times greater than the minimum value (i.e. the spread is very large) the 'Smoothing of model resistivity value' option was enabled. A model where the cell width is half the unit electrode spacing was chosen and the inversion iterations activated.

The software produces a pseudosection of the subsurface by contouring the apparent resistivity values from the geophysical survey and this is presented as the first image of figure 5. The calculated apparent resistivity values was also produced and contoured, and presented as the second image of the same figure. Pseudosection gives very approximate picture of the true subsurface resistivity distribution. However, the pseudosection gives a distorted picture of the subsurface because the shape of the contours depends on the type of array used and the true subsurface resistivity. The third image of figure 5 is the inverse model resistivity section which represented the most accurate picture of the subsurface that can be produced from the measured or observed apparent resistivity distribution. One very useful application of the pseudosection plot is for picking out bad apparent
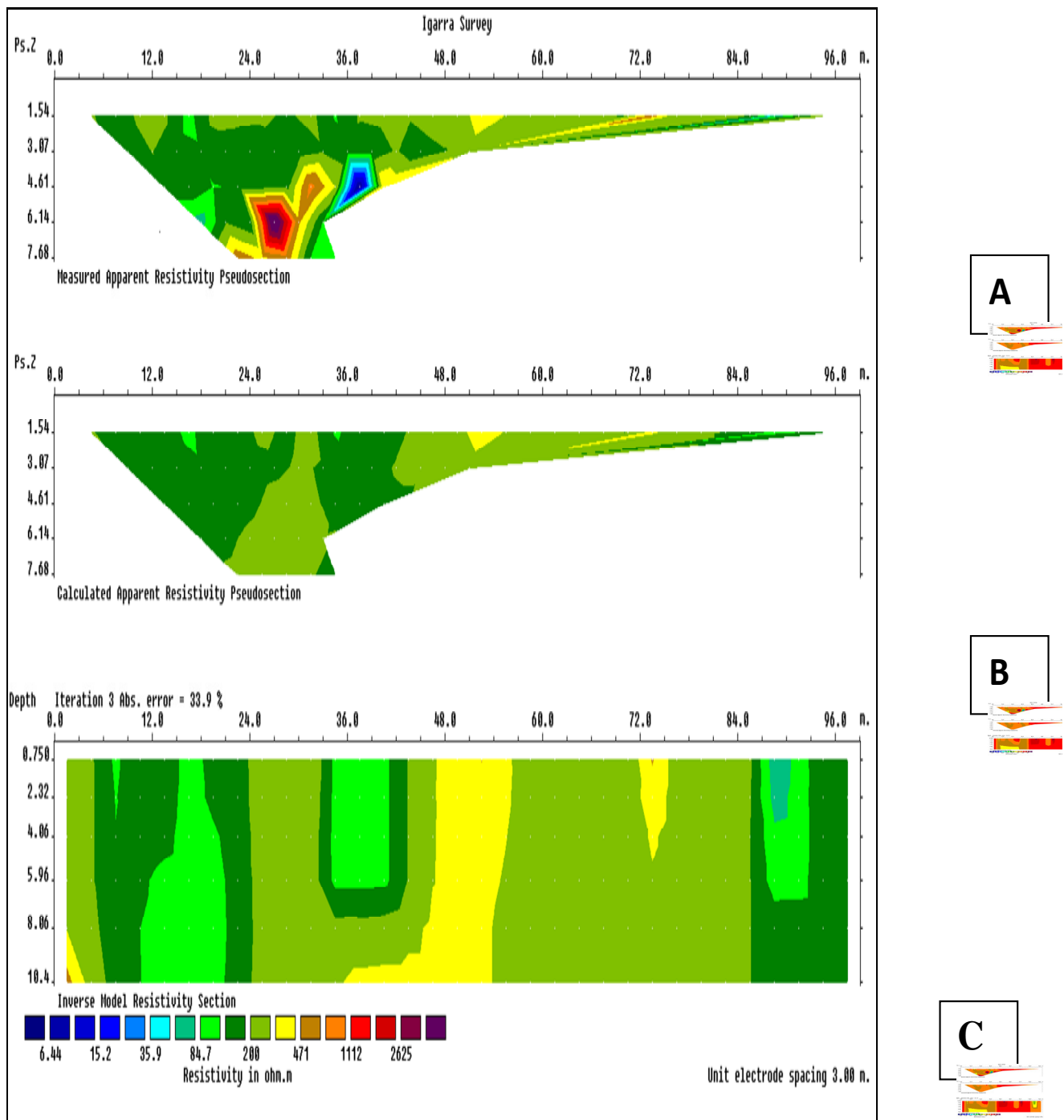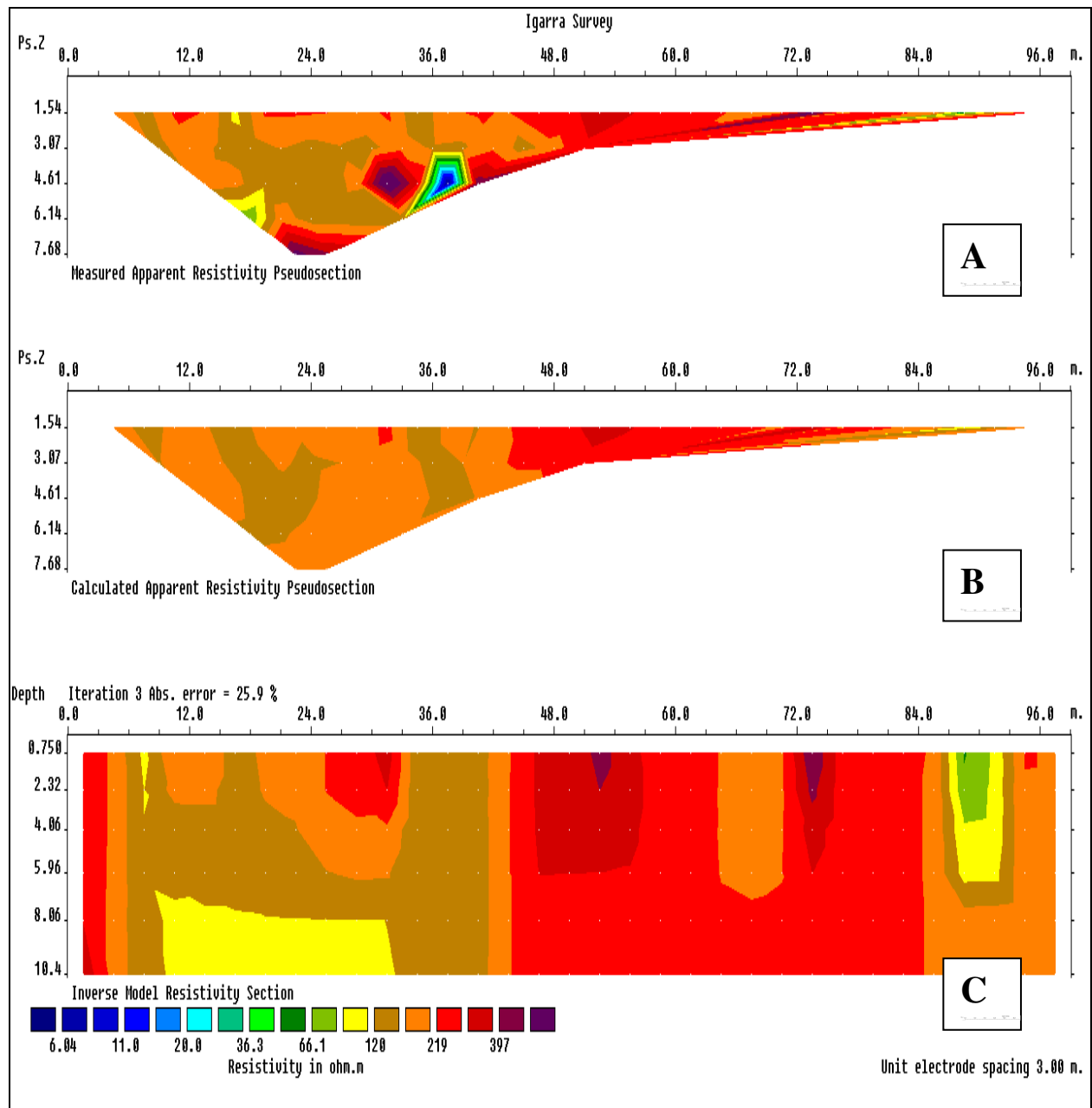
Figure 5. Measured apparent resistivity pseudosection (A), calculated apparent resistivity pseudosection (B) and inverse model resistivity section (c) for Igarra survey line (depth in meters)

resistivity data points. Such bad measurement points usually stand out as points with usually high or low resistivity values. This was noticed and the bad points removed manually, and re-processed to give the inverted model presented in figure 6.

RESULT, INTERPRETATION AND DISCUSSION

Electrical Resistivity Tomography produces images which give fairly accurate picture of the subsurface that can be produced from the measured apparent resistivity distri-
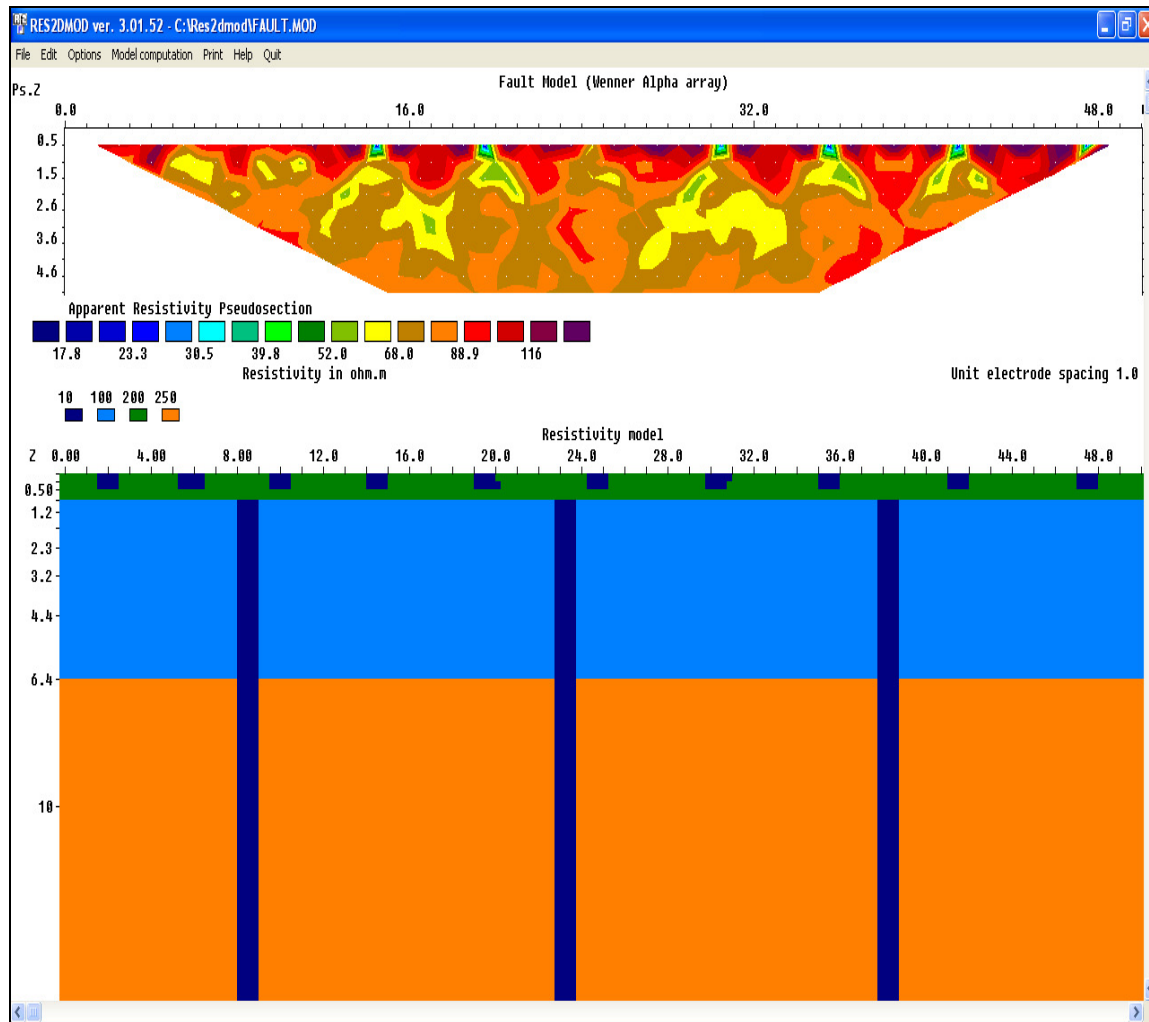
Figure 6. Measured apparent resistivity pseudosection (A), calculated apparent resistivity pseudosection (B) and inverse model resistivity section (c) for Igarra survey line after the bad data points have been manually edited (depth in meters)

bution. The image of the inverted model of ERT showed the presence of steep-dipping to vertical discontinuities in the subsurface. These discontinuities are interpreted as fracture planes. The minor contrast in the resistivity values of the fracture bounded rock blocks maybe due to the effects of the fracture infill which maybe water and/or finely dispersed clay material from the weathering of the fracture surface and/or leaching of weathered overburden materials into the fracture spaces. The relatively high lateral variation in resistivity close to the surface as imaged in the inverted model section may

reflects inhomogeneity and weathering effects which can also be observed at outcrops. These effects may be structurally controlled as observed from the inverted images.

To further constrain the interpretation of the Electrical Resistivity Tomography model (i.e. the presence and influence of steep dipping fractures in the mapped rocks) a forward model of the inverted model was carried out using the Res2DMOD™ software and based on the data obtained from the Vertical Electrical Sounding VES done at the location, and the Electrical Resistivity Tomography

Figure 7. Generated 2D forward modeling diagram of Igarra survey line. Note the close resemblance of the simulated forward model apparent resistivity pseudosection to that of the real field data (depth in meters)

surveys. Information on the geology of the area was also used in designing the forward model. The software codes calculate the apparent resistivity values for a simulated survey carried out over a specified subsurface resistivity distribution. The main purpose is to compute the apparent resistivity that would be measured over such a structure using the finite – difference method (Loke, 2004). Data from the Vertical Electrical Sounding and the Electrical Resistivity Tomography survey showed that the mean apparent resistivity in the area decreases from the top to a depth of about 6m and thereafter starts to increase with depth. This electro-stratigraphy was simulated in the forward model by the use of three model resistivity of 200Ωm for the topmost unit, decreasing to 100Ωm and increasing to 250Ωm beyond the 6m depth. Relatively low 10Ωm model resistivity discrete blocks was fitted into the topmost unit to simulate inhomogeneity and weathering effects as observed from the geology of the study area. Three vertical fractures that extend

downwards from the base of the topmost units were simulated by the use of vertical continuous blocks of low model resistivity of 10Ωm. The low resistivity is used because the fractures are zones of high conductivity occasioned by the fluid and/or clay infill. The simulated fractures extend from the base of the topmost electro-unit because the fractures mapped by the surface geophysical survey were not observed to extend to the surface in the field. The forward modeling was done using the Wenner Array configuration which was the same configuration used to acquire the Electrical Resistivity Tomography data. The apparent resistivity pseudosection generated from the simulated subsurface distribution (Figure 7) showed a high resemblance and similarity to the apparent resistivity pseudosection generated by the field data (figure 5 and 6). This supports the interpretation of the occurrence of steep dipping fractures from the Electrical Resistivity Tomography field data analysis.

CONCLUSION

Fractures are common post-formational structures found in most rocks. Their presence has a lot of influence on the rock properties, and must be carefully studied in engineering construction works, groundwater development and waste disposal management. 2D Electrical Resistivity Tomography was used to image and study the fractures in the study area. Images of the inverted model of the subsurface showed the presence of vertical to steep-dipping discontinuities which are interpreted as fracture planes. These fracture planes extend beyond the depth of investigation of the ERT survey suggesting that the fractures are potential conduit for leachate transport and surface water run-off infiltration. The average fracture density of the area was estimated to be $0.19m^{-1}$.

This research has once more shown that surface geophysical method such as the electrical resistivity method can be used satisfactorily in the structural characterization of subsurface rocks and hence can be employed for site investigation studies.

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