Effectiveness of 2D Induced Polarisation & Electrical Resistivity Tomography in Mapping Fracture Heterogeneity in Foundation Soils.

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1 **EFFECTIVENESS OF 2D INDUCED POLARISATION & ELECTRICAL**
2 **RESISTIVITY TOMOGRAPHY IN MAPPING FRACTURE HETEROGENEITY IN**
3 **FOUNDATION SOILS.**

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7
8 **ABSTRACT**

9 Inhomogeneity caused by fractures can constitute real problems in foundation soils which
10 consequently can lead to structural failure. 2D Electrical Resistivity Tomography (ERT) has been
11 exceedingly popular in mapping near surface discontinuities that can possibly affect engineering
12 structures. The effectiveness of using Induced Polarisation Tomography (IPT) in mapping
13 subsurface fractures was explored. Using the same field way out for both ERT and IPT,
14 investigations were carried out at a failed structure with foundational inhomogeneity in the Nsukka
15 area, Southeastern Nigeria. Four Electrical Resistivity Tomography (ERT) and four Induced
16 Polarisation Tomography (IPT) were carried out. Electrical Resistivity Tomography for profile
17 line one (ERT₁) and that of the opposite section, ERT₃, revealed a fault trending NNW- SSE. This
18 anomaly was also observed on the Induced Polarization Tomography for profile line one (IPT₁) as
19 well as that of profile line three (IPT₃) at the same offset distances, delineating the same fracture
20 zone. A second fault trending in NE-SW was mapped by the Electrical Resistivity Tomography
21 for profile line two (ERT₂) and Electrical Resistivity Tomography for profile line four (ERT₄). The

fault was also visible in the Induced Polarization counterparts, IPT₂ and IPT₄. Field validation along mapped trends recorded subtle cracks on the foundation along the same trend detected by the IPT as well as the ERT.

Keywords: Electrical Resistivity, Tomography, Induced Polarization, Fracture.

1.0 INTRODUCTION

Soil's suitability for engineering purposes depends largely on their ability to remain in place and to support either permanent or transient loads that may be placed on them (Roy and Bhalla, 2017). In other words, the success of any engineering structure directly placed on the earth's surface would depend on the support provided by the foundation materials that bear the load of the structure alongside other factors. (Terzaghi et al., 1996; Osinowo and Falufosi, 2018). Apart from geo-structural factors, other factors that can threaten the stability of engineering structures include poor building design, poor materials, and inexperienced personnel (Adewuyi and Philips, 2018), with a number of such failures recorded (Ayedun et al., 2012; Oyedele and Olorode, 2011; Soupois et al., 2007). A case of a failing foundation of a massive auditorium nearing completion at the University of Nigeria Nsukka is being investigated. Fractures or cavities within the earth materials bearing the structure have been proposed as likely contributors to this failure. The area is underlain by Campano-Maastrichtian earth materials belonging to the Anambra basin (Reijers, 1996; Obi and Okogbue, 2004) of which two post Santonian faults trending NW-SE and NE – SW that affected these sediments around Enugu area have been reported (Amogu et. al., 2010). Popular analysis commonly used by engineers in determining ultimate bearing capacity of soils like Prandtl's Analysis and Terzaghi's Analysis runs on the assumption of homogeneous and isotropic soil mass (Sitharam, 2013) and may not always capture the presence of cavity or fault which

constitute inhomogeneity. The use of Electrical Resistivity Tomography is a well-known technique for detecting subsurface inhomogeneity associated with fractures. (Chieh-Hou et al., 2000; Samouelian et al., 2005; Nguyen et al., 2005; Han-lun et al., 2010; Reynolds, 2011; Ugwu and Ezema, 2013; Oyeyemi, 2016; Coker, 2017; Osinowo and Falufosi, 2018).

Also, Time domain Induced Polarisation is another technique capable of detecting cavities and fractures, though it is yet to be deployed for this purpose in this region. Vogelsang (1995) described a type of polarization termed boundary-layer polarization, though weaker than metallic polarization, which develops an accumulation of cations at the boundary layer of electrolyte and then spreads over the pore walls of silicate rocks. Telford et al., (1990) also described a membrane or electrolytic polarization where it was noted that the rock structure must be somewhat porous to permit the flow of current when metallic minerals are absent. Faulting can generate this type of polarization, especially when it juxtaposes two different blocks or brings two fluids that are slightly different chemically. Aside from juxtaposition, open fractures create secondary porosity that are usually high conduits for the passage of fluid, which in turns allows for the generation of IP effect upon abrupt switching off-and-on of current supply (Telford et al., 1990). Also, fractures filled with conductive clays also generate a polarization effect when the current is abruptly terminated.

Schmutz et al. (2011) has used the Spectral Induced Polarization (SIP), a phase and magnitude dependent Induced Polarisation measured over a range of frequencies, to detect fractures as well as distinguish between the open and clay filled ones. In the time domain Induced Polarisation, the delay in the decay of voltage after current is turned off and then rises to its actual state after it is turned on (overvoltage) is measured as a function of time (Reynolds, 2011).

68

69 In this paper, our goal is to show that conventional 2D Time domain Induced Polarization
70 Tomography (hereafter known as IPT) is effective in delineating inhomogeneity or anisotropy
71 within foundation earth material as well as the very well-known 2D Electrical Resistivity
72 Tomography (ERT).

73

74 **2.0 THE GEOLOGY OF THE STUDY AREA**

75 The study area (Figure 1) forms a part of the Campano-Maastrichtian Anambra Basin (Reyment
76 1965; Shorts and Stauble, 1967; Obi and Okogbue, 2004; Nwajide, 2013). The geologic formation
77 of the Anambra Basin that underlies the area under study is the Maastrichtian Ajali Formation.
78 The Formation is described as medium to coarse grained sandstones and conglomerates (Nwajide,
79 1990; Obi and Okogbue, 2004). Nwajide (1990) further described the grain size as angular to
80 subangular quartz-arenites. It is whitish in colour when fresh with iron stains and brownish in
81 colour when weathered or exposed to atmospheric conditions. This is an indication of relatively
82 high iron content. The thickness of the Ajali Formation at outcrops ranges from 25m to 50m (Obi
83 and Okogbue, 2004), with sufficiently thick weathered overburden typically being reddish brown
84 in colour. Syn-depositional structures like trough and planar cross-bedding with mud-draped
85 foresets, over-turned foresets, flaser and herringbone bedding, large mud clast as well as
86 Ophiomorpha trace fossils suggest a tidally influenced fluvial-and fluvial channel environment of
87 deposition (Obi and Okogbue, 2004). Post depositional structures like fractures (joints and faults)
88 have been reported as well. Amogu et al. (2010) mapped two post Santonian faults trending NW-
89 SE and NE – SW that affected the Campano-Maastrichtian sediments around Enugu area.

90

Although Sitharam (2013) listed the presumed allowable bearing pressure for cohesionless soils – coarse grained sandstone (440 kPa) and medium grained sandstone (240 kPa) which are favourable, the presence of fractures in foundation soils can cause great harm to engineering structures placed directly on them. (Terzaghi et al., 1996; Osinowo and Falufosi, 2018). Figure 1 gives an overview of the geology in the study area.

Legend

- LGA
- LGA Boundary
- State Boundary
- Enugu State
- Study Area

Figure 1. Location and Geology of the study area

3.0 Materials and Method

3.1 Electrical Resistivity

Rocks conduct electric current in three ways, namely: electrolytic, electronic (ohmic) and dielectric means (Reynolds, 2011). In most rocks and especially clastic rocks (sedimentary rocks), conduction is carried out by pore fluids acting as electrolytes, where the mineral grains contribute insignificantly to the overall conductivity of the rock. The only condition where mineral grains will contribute sufficiently to overall rock conductivity is when the grains themselves are good electronic conductors (Reynolds, 2011). Based on the foregoing, it is

critical to comprehend Archie's Law (equation 1), which explains the bulk or effective rock resistivity model and provides geological meaning to modeled resistivity.

$$\rho = a\phi^{-m}S^{-n}\rho_w \quad (1)$$

$$\rho/\rho_w = a\phi^{-m} \quad (2)$$

where

ρ and ρ_w are the effective rock resistivity, and the resistivity of the porewater, respectively.

ϕ is the porosity; S is the volume fraction of pores with water.

a , m and n are constants where $0.5 \leq a \leq 2.5$, $1.3 \leq m \leq 2.5$, and $n \approx 2$.

F is the Formation Resistivity Factor

Equation (1) shows that with increase in porosity, a reduction in the bulk or effective resistivity is expected. As porewater saturation increases, effective resistivity reduces. For resistivity of porewater, it will increase with increasing bulk resistivity.

Porosity is a major influencer of effective resistivity especially when the resistivity of porewater is tending towards unity as can be deduced from Equation (2) (Archie, 1942; Jackson et al., 1978; Ioannidis et al., 1997; Keary et. al, 2002; Chen et al., 2008; Reynolds,

2011). Bulk resistivity has been observed to be approximately equal to the inverse of the square of porosity as shown in equation 3 below.

$$\rho \approx 1/\phi^2 \quad (3)$$

Fractures enhance secondary porosity of rocks. As a result, they are expected to display lower effective resistivity than the unfractured blocks in a 2D resistivity section.

However, Apparent resistivity, ρ_a , is directly measured during field and it is derived by the product of measured resistance (R) and a geometric factor (K) as shown in equation 4 (Reynolds, 2011). The geometric factor is dependent on the electrode configuration used in data collection which is governed by ohmic law. Geometric factor for Werner array is given in equation 5. True resistivity is derived by the inversion of the apparent resistivity.

$$\rho_a = R * k \quad (4)$$

$$K = 2\pi a \quad (5)$$

Where:

ρ_a is the apparent resistivity;

R is measured resistance

K is Geometric Factor;

a is electrode spacing;

143

144 3.2 Time Domain Induced Polarisation

145 Upon applying current to the ground and switching it off after a moment, an overvoltage builds up
146 which decays (Reynolds, 2011; Telford et al., 1990) as shown in Figure 2. The magnitude of the
147 observed voltage (V_o) is equal to the actual voltage (V) as a result of the passage of current and in
148 addition, a polarization voltage (V_p) is caused by either grain, electrolytic, macroscopic, or ionic
149 processes. These processes are well documented (Reynolds, 2011; Vogelsang, 1995; Telford et al.,
150 1990). Switching off the applied current, the voltage drops within an imperceptibly brief period of
151 time by an amount V , leaving a residual voltage called overvoltage (V_p) that decays with time. A
152 measure of the generated induced polarization (IP) effect is the ratio V_p/V_o , which is known as
153 Chargeability which is normally expressed in terms of millivolts per volt or percent. Measurement
154 of overvoltage (V_p) via instrument is usually done at a fixed time, typically 0.5s when current
155 cutoff and decay would be noted at discrete intervals of about 0.1s (Reynolds, 2011). Integral of
156 the values with respect to time gives the area under the curve (Figure 2a). Mathematically, it is
157 expressed as shown in equation 4.

158 **Figure 2. Two forms of measurement of overvoltage (V_p) at (a) discrete time interval and (b)**
159 **by the area below the overvoltage curve, A.**

160

$$161 \quad M = \frac{1}{v_0} \int_{t_1}^{t_2} v(t) dt \quad (4)$$

162 Where:

163 M is Chargeability

164 V_o is observed voltage

165 V_p is the polarization voltage or overvoltage; t is time

166 Field measurement of true chargeability described by equation 4 is usually not very practical
167 (Reynolds, 2011) however, a ratio of the integral with V_o gives the apparent chargeability (Ma)
168 which is measurable and has its units in time (milliseconds). The expression is given in equation
169 5.

170

$$Ma = \frac{1}{v_0} \int_{t_1}^{t_2} v_p(t) dt = \frac{A}{v_0} \quad (5)$$

172

173 Where:

174 Ma is Apparent Chargeability

175 V_o is observed voltage; V_p is the polarization voltage or overvoltage.

176 t is time; A is area beneath the decay curve.

177 One main advantage of recording Ma is that it reduces noise from cross-coupling cables alongside
178 those from background potentials (Reynolds, 2011). Field data used for the modeling IP
179 tomographic sections in the study utilized the Ma values recorded with ABEM SAS 1000.

180

181 **3.3 Data Acquisition and Processing**

Reconnaissance studies carried out at the study area aided the design of the survey as shown in Fig. 3. Resistivity and Induced Polarization data were acquired along the designed profile lines using ABEM Terrameter SAS 1000. Each of the profile lines was executed using a Werner (Alpha) Array method (Nguyen et al., 2005) with a minimum electrode spread (a) of 10m and a maximum of 30m i.e. $n=3$. The ratio of the median depth of investigation (Z_e) of Werner Alpha to the minimum electrode spread (a) is 0.519 (Loke, 2000). A maximum electrode spread of 30m should give an estimated depth of investigation of about 15m. This depth of investigation seemed satisfactory for foundation soil investigation since most foundations do not exceed 7m depth except for high rising structures.

Electrodes were laid at 10m intervals along each profile line and their coordinates were taken with the help of a Global Positioning System (GPS). These coordinates were further plotted in Google Earth application to quality control their spatial positions. With the accurate determination of the electrode positions, observed anomalies on profile sections would easily be tied to the zone of foundation instability.

The apparent electrical resistivity and chargeability data collected were arranged to Block Model data format, displayed, and dispiked where necessary using RES2DINV© software. Block Model format is reported to yield a good result for fault modeling (Genelle et al., 2012). Subsequently, data were inverted employing a least-squares inversion technique (Loke and Barker, 1996; Loke, 2004; Osinowo and Falufosi, 2018). Half-cell width model refinement (Loke, 2004) was applied due to larger resistivity values observed at the uppermost layer for better inversion results. The process displayed acceptable tomographic sections for both Electrical Resistivity and IP sections.

Figure 3. Design of Geophysical Survey Lines

4.0 RESULTS AND DISCUSSION

The result of electrical resistivity for profile line one is given in Figure 4a. Figure 4a (i) is the apparent Electrical Resistivity data displayed in a pseudo-section while Figure 4a (ii) is the theoretically calculated section. Figure 4a (iii) is the inverted section which is the true resistivity image of the subsurface termed ERT1. A good resemblance exists between the apparent and the calculated sections revealing high input data integrity (Loke, 2004). ERT1 shows a vertical anomalous zone of relatively low resistivity ($<600 \Omega\text{m}$) at an offset distance of about 70 - 90 m. This vertical anomalous zone most likely possesses higher porosity or a very conductive interval, thereby causing a drastic drop in the resistivity (equation 1- 3). Based on the geology a probable geologic event that could yield such a phenomenon is a fracture. Fractures increase secondary porosity and as well create conduits for fluid migration. Fluid like groundwater is generally mineralized and can serve as a weak electrolyte which in turn reduces the bulk resistivity of materials. Figure 4b is the result of the 2D Induced Polarization survey for profile line one. Figure 4b (i) is the pseudo-plot of the apparent chargeability while Figure 4b (ii) is the theoretically calculated section. A good match observed in both images shows good data quality which subsequently yields a reliable inversion (Loke, 2004). The inverted section is given in Figure 4b (iii) which is the true chargeability result for the Induced Polarisation survey for profile line one, hereafter referred to as IPT1. Figure 4b (iii) shows anomalously high chargeability at the same spatial position observed in ERT1 (Figure 4a (iii)). The IPT1 anomaly ranges from 7.77 msec – 8.98 msec, as against the background values of 0.5 msec to 3.0 msec. IPT1 further supports the presence of fracture in the region of profile one. Conductive interval acts as capacitors that tend to

build up charges which will decay with time after the induced current is turned off. In the case of groundwater filling fracture conduits, the stored electrical charges tend to decay over time after the current is put off, giving rise to higher chargeability within the zone of occurrence.

Figure 4 (a) Legend

Figure 4 (b) Legend

Figure 4 Tomography Result for Profile line One. (a) Electrical Resistivity Tomography for profile line one (ERT1), (b) Induced Polarization Tomography for profile line one (IPT1)

The result of surveys on profile line two is shown in Figure 5. Figure 5a (i) is the pseudo-plot of the apparent resistivity while 5a (ii) is the theoretical calculation for the same section. Similarities in the patterns displayed by the pseudo and the calculated section justify the inversion result shown in Figure 5a (iii) which is the Electrical Resistivity Tomography for profile line two (ERT2). Two anomalous zones appeared on this section at an offset distance of 65 m – 75 m and 90 m – 105 m possessing a resistivity value ranging from 107 Ωm – 695 Ωm, lower than the adjacent resistivity values. The depth of the anomalous zone in the first offset seems to be deeper than 16 m. This vertically inclined anomalous zone at offset distance ranging from 65 m – 75 m in ERT2 seems to be mimicking the resistivity behavior typical of a fault zone.

The Induced Polarisation result for profile line two is given in Figure 5b. A pseudo-section of the measured apparent chargeability is displayed in Figure 5b (i) while that of the calculated apparent

chargeability is shown in Figure 5b (i). The inversion result for the measured apparent chargeability for profile line two (IPT2) is given in Figure 5b (iii). At offset distance of 65 m – 90 m, higher chargeability values (200 msec – 395 msec) exceeding the background lower values are noticed. IPT2 reveals an anomaly on profile line two at offset distance and orientation similar to that of ERT2.

Figure 5 (b) Legend

Figure 5. Tomography Result for Profile Line Two. (a) Profile Line Two Electrical Resistivity Tomography (ERT2), (b) Profile line Two Induced Polarization Tomography (IPT2).

The result of surveys conducted on profile line three is given in Figure 6. The measured apparent resistivity for profile line 3 is displayed in Figure 6a (i). The theoretically calculated apparent resistivity for the same section is presented in Figure 6a (ii). Good similarity exists in the patterns observed in both Figure 6a (i) and (ii) showing a reliable inversion process whose result is displayed in Figure 6a (iii). At offset distance ranging from about 75 m – 105 m, an anomalous zone with a resistivity of about 203 Ωm and less is observed on ERT3 (Figure 6a (iii)).

Figure 6b contains the result of the chargeability survey performed on profile line 3. The measured apparent chargeability is displayed in a pseudo-section given in Figure 6b (i). Figure 6b (ii) is the calculated apparent chargeability section for the same profile line. The inverted result is presented in Figure 6b (iii). The chargeability section suggests a good inversion. At an offset distance of 80 m – 105 m, an anomalously high chargeability ranging from 203 msec – 24.8 msec is observed in IPT3 (Figure 6b (iii)).

Figure 6 (b) Legend

Figure 6. Tomography Result for Profile Line Three. (a) Profile Line Three Electrical Resistivity Tomography (ERT3), (b) Profile line Three Induced Polarization Tomography (IPT3)

Profile line four results are displayed in Figure 7. The Electrical Resistivity results in Figure 7a while that of Induced Polarization in Figure 7b. Figure 7a (i) is the measured apparent resistivity for the profile line four survey while the calculated apparent resistivity for the same profile line is given in Figure 7a (ii). The inversion of the measured apparent resistivity data yielded a true resistivity section for the profile line, ERT4, presented in Figure 7a (iii). A good resemblance in the pseudo-section of the measured and the calculated apparent resistivity implies a stable

inversion process. At an offset distance of 40 m – 55 m, an inclined zone of anomalously low resistivity is observed on the ERT4. The resistivity of this zone ranges from 169 Ωm - 388 Ωm (Figure 7a (iii)).

Figure 7b (i) is the measured apparent chargeability pseudo-section for profile line four. The calculated apparent chargeability is given in Figure 7b (ii). The inversion result (IPT4) of the measured apparent chargeability for profile line four is presented in Figure 7b (iii). The good similarity between the measured and the calculated apparent chargeability suggests a reliable inversion process. Main Anomalous chargeability was observed at an offset distance of 50 m – 65m with values ranging from about 195 msec – 296 msec. Another anomalous zone of a smaller scale was noticed at 70 m – 85m. Although the latter anomalous zone is smaller in terms of size, higher chargeability (over 603 msec) is recorded at this interval.

Figure 7 (a) Legend

Figure 7 (b) Legend

Figure 7. Tomography Result for Profile Line Four. (a) Profile Line Four Electrical Resistivity Tomography (ERT4), (b) Profile line Four Induced Polarization Tomography (IPT4)

Inclined anomalous zones of low resistivity observed on the Electrical Resistivity Tomography (ERT) sections suggest that these surveys intercepted fractures within the foundation soils. The

outcome of correlating results of opposite profile lines validates the presence of fractures (Figures 8 & 9).

Figure 8 compared the results of profile line one and that of line three (Figure 8d). Figure 8a is a 3D representation of the measured apparent resistivity of profile line three (Figure 8a (i)) and that of profile line one (Figure 8a (ii)). At an offset distance of about 80 m, low measured apparent resistivity ran from profile line one to profile line three. This is represented by a blue-coloured depression in Figure 8a (ii) and Figure 8a (i) respectively. Figure 8b correlates the ERT3 (Figure 8b (i)) and ERT1 (Figure 8b (ii)). This correlation model the fracture plane indicated by the broken line (Figure 8b). The trend of this fracture is NNW-SSE.

Figure 8 (a) Legend

Legends for Figure 8 (b) same as ERT1 (Figure 4 a) and ERT3 (Figure 6a)

Legends for Figure 8 (c) same as IPT1 (Figure 4b) and IPT3 (Figure 6b)

Figure 8. Fracture Zone ‘A’ delineation. (a) A 3D plot of measured apparent resistivity for profile line Three and Profile line one revealing fracture zone. (b) 2.5D view of ERT1 – ERT3 revealing

fracture zone (c) 2.5D view of IPT1 – IPT3 revealing fracture zone, (d) Google earth image showing profile lines I and 3.

Legends for Figure 9 (a) same as ERT2 (Figure 5a) and ERT4 (Figure 7a)

Legends for Figure 9 (b) same as IPT2 (Figure 5b) and IPT4 (Figure 7b)

Figure 9. Fracture Zone ‘B’ delineation. (a) 2.5D view of ERT2 – ERT4 revealing fracture zone (b) 2.5D view of IPT2 – IPT4 revealing fracture zone.

The correlation of the IP results of profile line three and profile line one is presented in Figure 8c. This result clearly shows the strength of Induced Polarization Tomography (IPT) in imaging the same fracture trend identified by the ERT.

More so, the correlation of results of profile line two with that of profile line four detected another fracture trending in the NE-SW direction (Figure 9). Figure 9a images the fault from ERT4 (i) and ERT2 (ii). Figure 9b reveals that the same fault can be imaged using Induce Polarization techniques.

Field validation (Figure 10) shows visible cracks on the foundation of structures further confirming the presence of fractures in the site area. Although most of the cracks reveal a north-southerly (Figure 10 i-iv, vii) trending fractures, some east – westerly (Figure 10 v-vii) are present. Based on the ERT and IPT results, two fracture (fracture zone A and B) trends are delineated as shown in Figure 11. This deduction agrees with Amogu et al. (2010) who mapped two post-Santonian faults trending NW-SE and NE – SW that affected the Campano-Maastrichtian sediments.

Figure 10. Field photographs validating the presence of a fracture.

Figure 11. Delineated fracture zones on Google Map view.

5.0 CONCLUSION

This study demonstrates the suitability of the 2D Induced Polarization technique as well as 2D Electrical Resistivity in mapping inhomogeneity introduced by fractures in foundation soils; both techniques mapped the two major fracture zones (trending in an NNW- SSE direction, as well as NE-SW direction) in the study area.

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486 **Figure captions**

487 **Figure 1.** Location and Geology of the study area

488 **Figure 2.** Two forms of measurement of overvoltage (V_p) at (a) discrete time interval and (b) by
489 the area below the overvoltage curve, A.

490 **Figure 3.** Design of Geophysical Survey Lines

491 **Figure 4.** Tomography Result for Profile line One. (a) Profile Line One Electrical Resistivity
492 Tomography (ERT_1), (b) Profile Line One Induced Polarization Tomography (IPT_1)

493 **Figure 5.** Tomography Result for Profile Line Two. (a) Profile Line Two Electrical Resistivity
494 Tomography (ERT_2), (b) Profile line Two Induced Polarization Tomography (IPT_2)

495 **Figure 6.** Tomography Result for Profile Line Three. (a) Profile Line Three Electrical Resistivity
496 Tomography (ERT_3), (b) Profile line Three Induced Polarization Tomography (IPT_3)

497 **Figure 7.** Tomography Result for Profile Line Four. (a) Profile Line Four Electrical Resistivity
498 Tomography (ERT_4), (b) Profile line Four Induced Polarization Tomography (IPT_4)

499 **Figure 8.** Fracture Zone A delineation. (a) 3D plot of measured apparent resistivity for profile line
500 Three and Profile line one revealing fracture zone. (b) 2.5D view of $ERT_1 - ERT_3$ revealing
501 fracture zone (c) 2.5D view of $IPT_1 - IPT_3$ revealing fracture zone, (d) Google earth image showing
502 profile lines I and 3.

503 **Figure 9.** Fracture Zone B delineation. (a) 2.5D view of $ERT_2 - ERT_4$ revealing fracture zone (b)
504 2.5D view of $IPT_2 - IPT_4$ revealing fracture zone.

Figure 10. Field photographs validating the presence of fracture.

Figure 11. Delineated facture zones on Google Map view.

Declarations

- **Availability of data and materials**

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

- **Competing Interests**

The authors declare that they have no competing interests.

- **Funding**

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- **Authors' Contribution**

Okechukwu Nnebedum coordinated the data acquisition, analyses, and interpretation. He also compiled the manuscript. Ogbonnaya Igwe designed and supervised the work. He also attracted the funds. Stanley I. Ifediegwu was instrumental in data collection and analyses as well as map production. All authors read and approved the final manuscript.

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