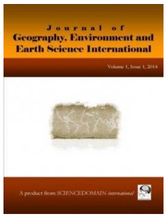

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2-D Electrical Resistivity Survey for Cassiterite Potential Mapping in Jos-Bukuru Area, North Central, Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author ESA designed the study, carried out the field work, analysed and interpreted results and wrote the first draft of the manuscript. Authors FXOU and BNG supervised the study and ensured compliance to acceptable standard, read and made corrections in draft for publication. All authors read and approved the final manuscript.

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ABSTRACT

Aim: To use 2-D Electrical Resistivity method in Cassiterite Potential mapping in Jos-Bukuru Area, North Central, Nigeria.

Methodology: Locations suspected to have very high probability for cassiterite mineralisation from the cassiterite potential map produced for the study area were selected for 2-D electrical resistivity survey. 2-D Electrical resistivity survey was carried out to obtain resistance data. The configuration used here was the Wenner-Schlumberger. The measured resistance data collected in the field was converted to apparent resistivity values which were then iteratively subjected to inversion process using RES2DINV software, to generate the 2-D resistivity sections. Inversion was carried out with the robust model constraint. Forward resistivity calculation was executed by applying an iterative algorithm based on finite element method. Rock samples were also collected near the survey lines used for the 2-D electrical resistivity survey for petrography.

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Results: The 2-D resistivity interpretation models revealed the probable average depth to cassiterite bearing alluvium to be least at Doi 2 (6 m) and greatest at Vom 1 (50 m). Suspected igneous intrusions and faults were observed within the subsurface of Kwang Rayfield 1 and 2, Doi 1 and 2, Rapkparak Shen and Kwata Zawan 1 and 2 profiles. The 2-D resistivity interpretation model for Vom 1 and 2 revealed probable depths to sub-basalt valley to be greater than 50 m and 45 m respectively. A *loto* (Hausa word for tunnel) mine was dug 295 m along Kwang Rayfield 1 survey line and was confirmed to contain some cassiterite bearing alluvium at 11.5 m deep. The probable depth to the cassiterite bearing alluvium from point A (295 m) on Kwang Rayfield 1 interpretation model is approximately 10 m. This depth in comparison with the depth in the *loto* mine at which cassiterite was found is correct to about 87%. Petrography revealed dominance of biotite, quartz and feldspar in hand specimen and thin section.

Conclusion: It can be concluded that though large lodes of cassiterite may have been extracted, there may still be some substantial amount of cassiterite deposits in the Jos - Bukuru area.

Keywords: Cassiterite; Kwang Rayfield; resistivity; depth; inversion; petrography.

1. INTRODUCTION

The Younger Granite rocks of the Jos Plateau and surrounding areas constitute a petrologically distinctive series of feldspar granites associated with rhyolites, minor gabbro and syenites. They occur in sub-volcanic intrusive complexes as ring dykes and related annular and cylindrical intrusions [1]. They are richly mineralised with cassiterite. The Younger Granites were first defined by Falconer [2]. He described them as cross-cutting alkali granites containing riebeckite or biotite and characterised by chilled margins against their country rocks. He noted their undeformed post tectonic character contrasting them with the foliated calc-alkaline Older Granites of the Basement Complex. He recognized that the Younger Granites are the source of cassiterite mineralisation of the Jos Plateau.

According to [3], there are three mineralisation models of cassiterite deposits in the study area. In the Primary mineralisation model, cassiterite is dispersed in multitudinous, narrow greisen veins, and quartz stringers in the roof zones of the biotite-granite intrusions, and is usually entrapped within the parent rock beneath an impermeable cover of roof rocks. The sub-horizontal form of the roof sections of the ring-intrusions and plutons has apparently favoured a lateral dispersion of mineralisation. In the alluvial deposit model, since the greater part of the primary mineralisation is concentrated in the horizontal roof sections of the biotite-granites, it follows that erosion rapidly uncovers an extensive area of tin-bearing granite and thus facilitates the wide distribution of cassiterite in the surrounding drainage system. Many of the source rocks are situated on or near major watersheds, so that a wide spread of alluvial is further enhanced. In the sub-basalt deposit mineralisation model, Newer Basalts overlie the main deposits of alluvium in the broad plateau valleys and this basalt can be considered to be of potential economic interest though attempts at underground mining have been met with little success [3].

Apart from cassiterite which is the major mineral found in the area, other associated minerals such as columbite, monazite and accessories like zircon and topaz are also found. As a result of the presence of these minerals, a lot of mining activities (formal and informal mining) have been carried out over the years in the area. However, it is unfortunate to note that most of the mining activities carried out at present are informal and are done using trial and error means e.g. digging of tunnels (*loto* mining).

Some geophysical survey had been carried out in the area. [4] Used electrical resistivity methods and magnetic methods to locate sub basalt valleys in the Nigerian Younger Granite province and [5] used magnetic, seismic, resistivity and gravity techniques to search for basalt covered alluvial cassiterite. [4,5] reported that the studies was not successful owing to factors such as the varying decomposition of basalt. Though, the reports of the surveys carried out by [4,5] are at present not available in the Geological Survey of Nigeria library, the resistivity survey carried out by Shaw to locate alluvial deposits was 1-D Resistivity survey. In [6], Aeromagnetic, Aeroradiometric, Geological and Topographic maps were brought into a Geographic Information System data base to produce a map of potential cassiterite deposits of Naraguta sheet 168, North-Central Nigeria. This involved digitising the hard copy maps, composing the digitised maps, processing each map to extract spatial features relevant to the prediction of cassiterite deposits to produce evidence maps which were weighted and integrated using index overlay model to produce a cassiterite potential map for the study area map. The map showed that most of Jos-Bukuru Younger Granite Complex has high or very high cassiterite potential, as well as important cassiterite mining locations like Barakinladi and Foron.

This study seeks to use 2-D Electrical Resistivity Survey in cassiterite potential mapping. Specifically it seeks to identify structures relevant to Cassiterite mineralisation, determine depth to cassiterite bearing alluvium and depth to the sub-basalt valley (valley where cassiterite bearing alluvium under lie Newer Basalts) using 2-D Electrical Resistivity survey in locations identified from the Cassiterite potential map produced by [6]. Past studies using electrical in the study area [4,5] used was 1-D as 2-D electrical resistivity survey became popular in the late eighties and early nineties due to the availability of proper equipment, methods and fast inversion software to carry out this survey [7,8]. Also studies have shown that the 1-D resistivity survey has only given useful results for geological situations where the 1-D model is approximately true such as locating the depth to water table [8]. 2-D resistivity survey has the advantage over 1-D resistivity survey of detecting both lateral and vertical changes in the subsurface resistivity.

For a geophysical technique to be useful in mineral exploration there must be contrasts in the physical properties of the rocks concerned that are related, directly or indirectly, to the presence of economically significant minerals. Resistivity method is used in the study of horizontal and vertical discontinuities in the electrical properties of the ground. It utilizes direct currents or low frequency alternating currents to investigate the electrical resistivity of the subsurface. A resistivity contrast between the target and the background geology must exist.

2. MATERIALS AND METHODS

Cassiterite potential map produced by [6] was used to select suitable sites for field work. The materials and equipment used for the field work include: ABEM Terrameter SAS 4000 with a 12V external power source; A DELL Inspiron E1505 laptop computer; Lund CVES cable in four sections (330019 25/26), including cable joints; 20 stainless steel electrodes; Garmin Global Positioning System; Geological hammer; Silva compass with clinometer; 2 (500 m) Measuring Tape; Hand Lens. The materials used for the petrographic study include: Cutting machine, Grinding machine, Silicon Carbide, Hot plate, Araldite, Carl Zeiss/JENA Microscope. Objective lens magnification 10x/0.25, Canon camera. The software used was RES2DINVx32 version 3.70.

Locations suspected to have very high probability for cassiterite mineralisation from the cassiterite potential map (Fig. 1), produced by [6], were selected for 2-D electrical resistivity survey. Fig. 2 shows the topography map for the selected locations.

2-D Electrical resistivity survey was carried out on 16 survey lines to obtain resistance data. The configuration used here was the Wenner-Schlumberger. The profile lengths varied from 300 m to 400 m depending on the nature of the terrain. The electrode spacing “a” used was 20 m. The n factor (the ratio of the distance between the C1-P1 (or P2-C2) electrodes to the spacing between the P1-P2 potential pair) varied from 7 to 9 depending on the length of the survey line. The geometric factor k for Wenner-Schlumberger is given by

$$\mathrm{k} = \pi \mathrm{n}(\mathrm{n}+1)\mathrm{a} \tag{1}$$

The measured resistance (R) data collected in the field was converted to apparent resistivity (ρ_a) values by using the k factor from equation (1) and substituting it into the equation

$$\rho_a = kR \tag{2}$$

The apparent resistivity was then iteratively subjected to inversion process using RES2DINV software, to generate the 2-D resistivity models. Inversion was carried out with the robust inversion model constraint. Forward resistivity calculation was executed by applying an iterative algorithm based on finite element method. A forward modelling subroutine is an integral part of any inversion program since it is necessary to calculate the theoretical apparent resistivity values for the model produced by the inversion routine to see whether it agrees with the measured values. The quality of the fit is expressed in terms of the Root Mean Square (RMS) error. According to [8], the model with the lowest possible RMS error can sometimes show large and unrealistic variations in the model resistivity values and might not always be the "best" model from a geological perspective. Thus the most prudent approach is to choose the model at the iteration after which the RMS error does not change significantly [8]. According to the author, this usually occurs between the 3rd and 5th iterations. Rock samples were also collected near the profiles for the 2-D electrical resistivity survey for petrographic study.

3. RESULTS AND DISCUSSION

Figs. 3 -18 show 2-D resistivity sections of the 16 survey lines. Lithological information from boreholes drilled in some of the areas surveyed was obtained from [10,11]. Representative resistivity values of earth materials used in this study area in classifying the geologic layers were derived from [12-15] and are as follows: 1 to 300 Ωm - overburden resistivity; 300 to 400 Ωm - weathered granite; 400 to 600 Ωm - cassiterite bearing alluvium; >600 Ωm - granitic rocks and fresh basement. A summary of the results is shown in Table 1.

Kwang Rayfield 1 interpretation model was confirmed with a *loto* mine (Fig. 19) dug 295 m along the profile. The tunnel revealed some suspected cassiterite bearing alluvium on reaching 11.5 m deep. At that same distance on the Kwang Rayfield 1 interpretation model (Fig. 3), the depth to the cassiterite bearing alluvium is approximately 10 m. This depth in comparison to the depth from the tunnel where cassiterite bearing alluvium was found is correct to about 87%. The lithology observed from the surface of the tunnel up to the depth of about 12.5 m (Fig. 20) were reddish brown laterite (2.5 m thick), brownish coarse grained sandy clay (3.5 m thick); light brownish clayey sand (2 m thick); light brownish clayey sand with quartz pebbles (3.5 m thick); gravels mixed with alluvium and suspected cassiterite granules (1 m thick). The suspected cassiterite granules were confirmed to be cassiterite with dilute sulphuric acid in the presence of zinc.

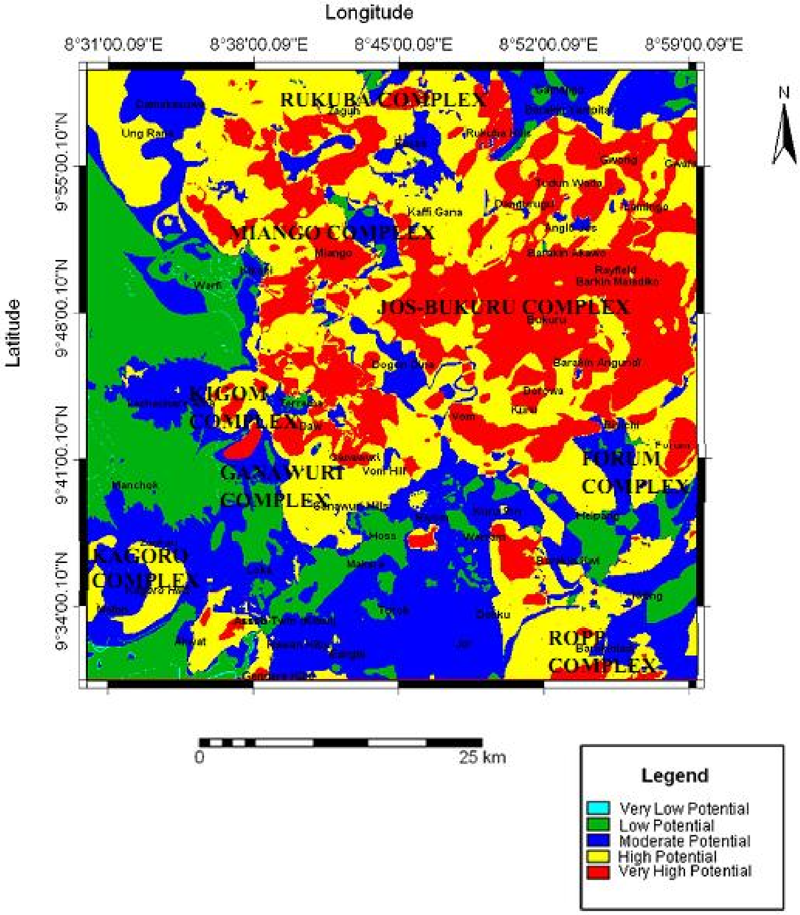

Fig. 1. Cassiterite potential map of Naraguta area, sheet 168 using index overlay method. (After [6])

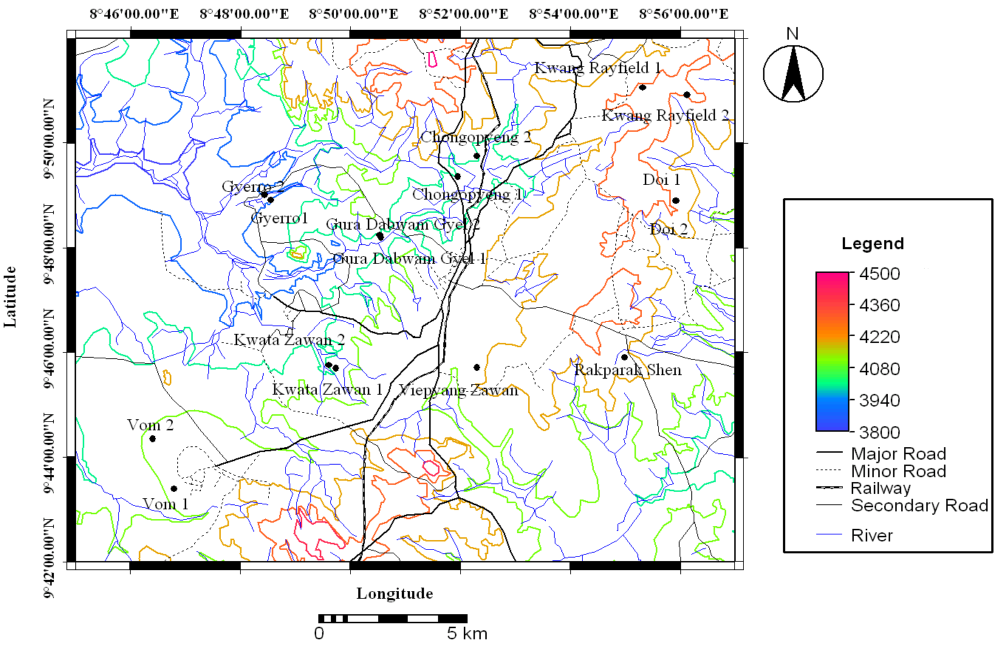

Fig. 2. Topography map showing locations covered during the fieldwork (Extracted from topography map of Naraguta sheet 168, [9]). Elevation contours in metres

The results of the petrographic study revealed that in hand specimen, the minerals present in the rock samples collected from the field are biotite, quartz and feldspar. In thin section biotite, quartz and feldspar were also present in all the rock samples (a total number of 12 thin sections – note that only three thin sections are shown here) see sample in Plate 1, along with opaque minerals (Plate 2) and Zircon (Plate 3). The rock samples were various types of biotite granite rocks from the Jos-Bukuru Younger Granite Complex. These are source rocks for cassiterite mineralisation.

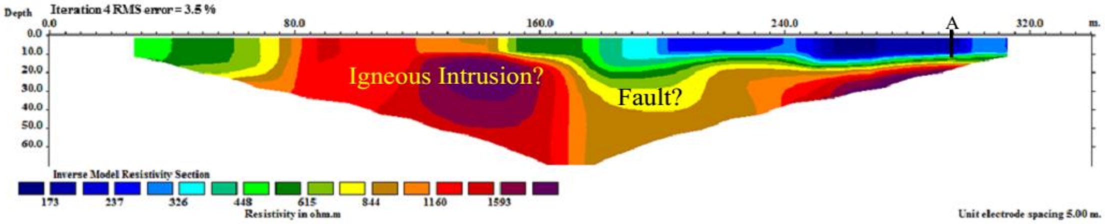

Fig. 3. 2-D Resistivity model of Kwang Rayfield 1 (depth in metres). (A represents a point where a *loto* tunnel was dug)

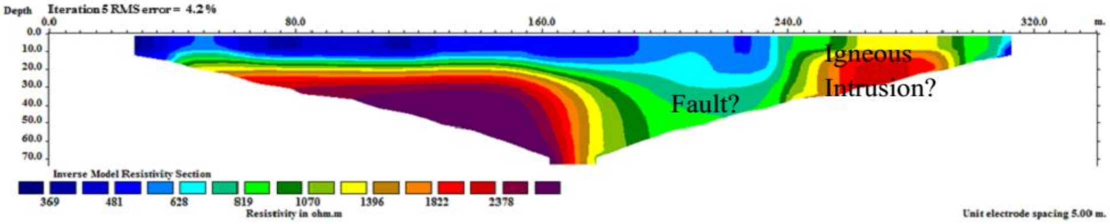

Fig. 4. 2-D Resistivity model of Kwang Rayfield 2 (depth in metres)

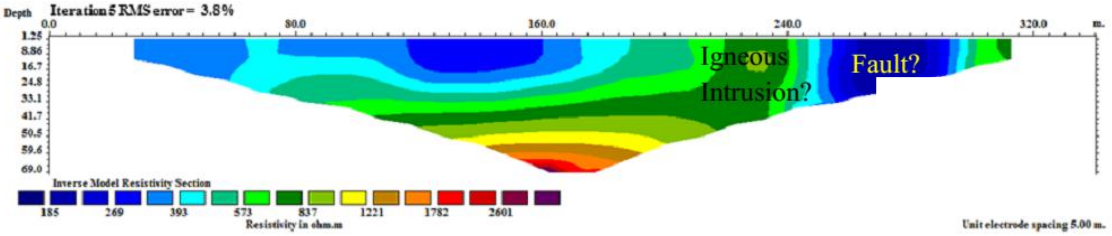

Fig. 5. 2-D Resistivity model of Doi 1 (depth in metres)

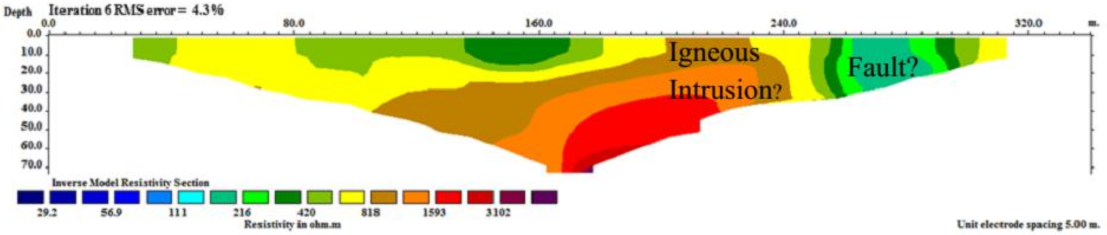

Fig. 6. 2-D Resistivity model of Doi 2 (depth in metres)

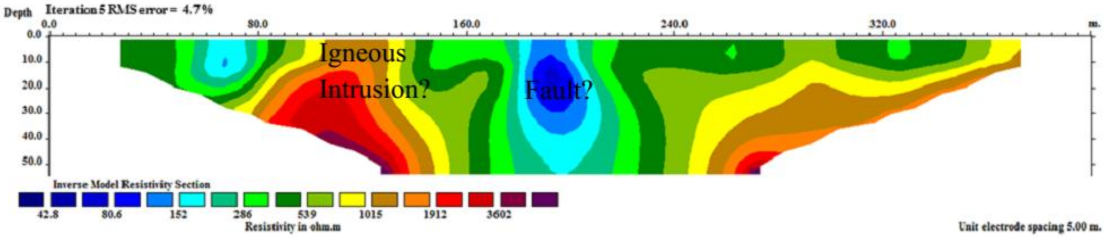

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Fig. 7. 2-D Resistivity model of Rakparak Shen (depth in metres)

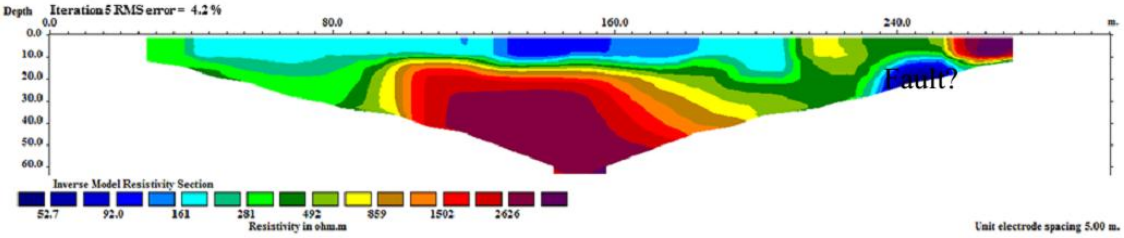


Fig. 8. 2-D Resistivity model of Viepyang Zawan (depth in metres)

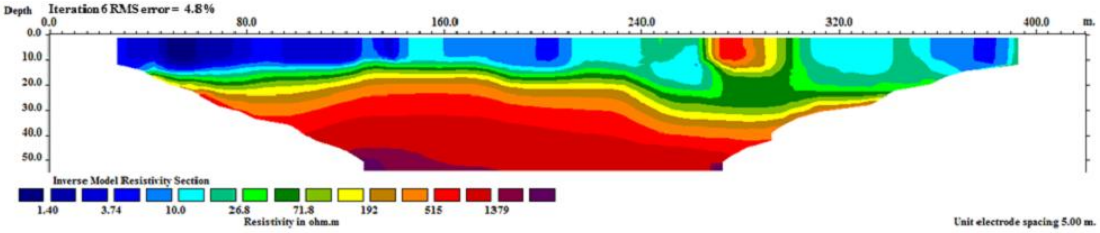


Fig. 9. 2-D Resistivity model of Gyero1 (depth in metres)

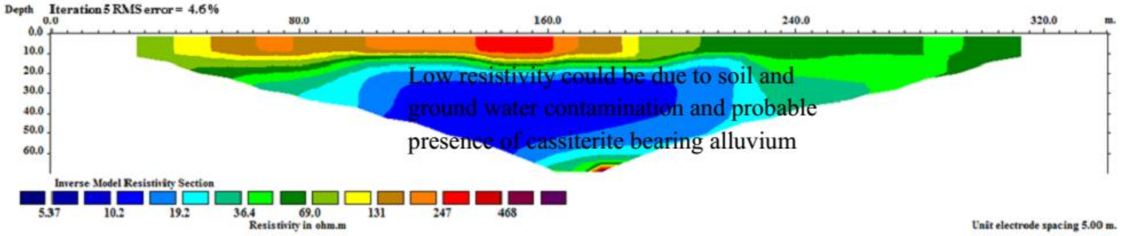


Fig. 10. Resistivity model of Gyerro 2 (depth in metres)

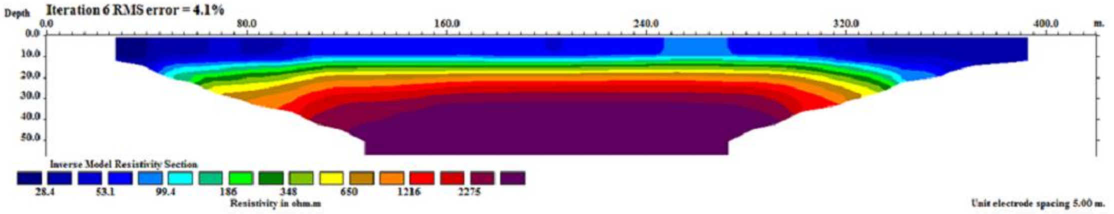


Fig. 11. 2-D Resistivity model of Gura Dabwam Gyel 1 (depth in metres)

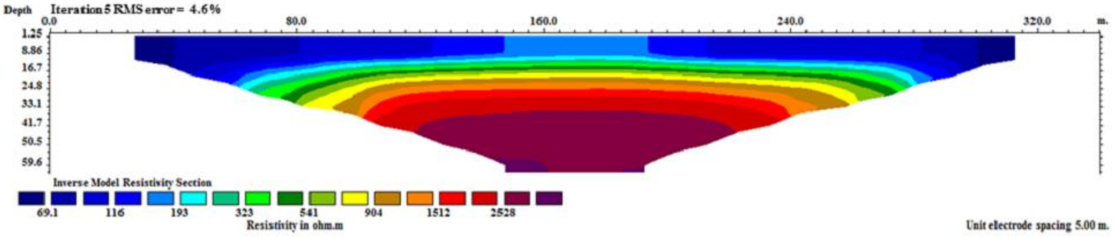


Fig. 12. 2-D Resistivity model of Gura Dabwam Gyel 2 (depth in metres)

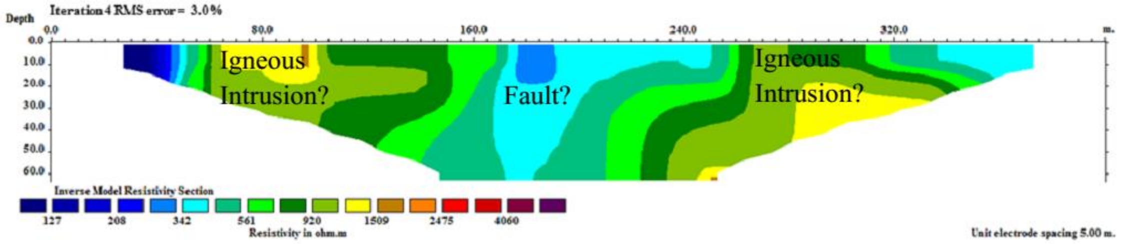


Fig. 13. 2-D Resistivity model of Kwata Zawan 1 (depth in metres)

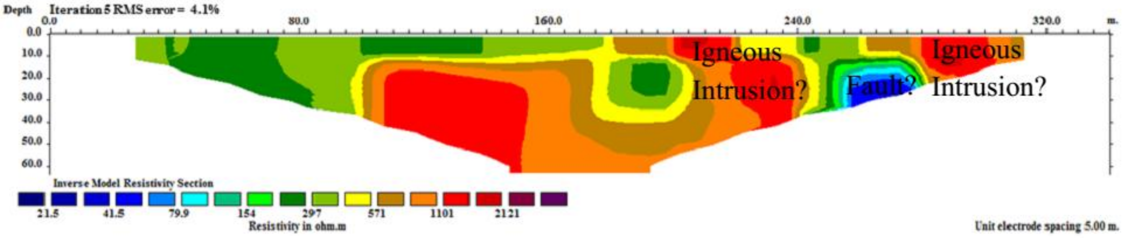
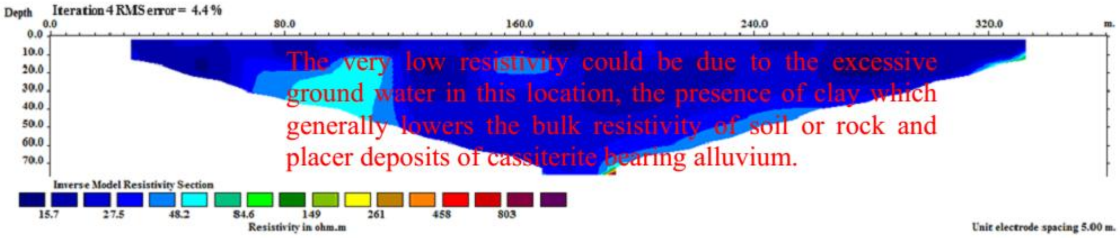


Fig. 14. 2-D Resistivity model of Kwata Zawan 2 (depth in metres)



The very low resistivity could be due to the excessive ground water in this location, the presence of clay which generally lowers the bulk resistivity of soil or rock and placer deposits of cassiterite bearing alluvium.

Fig. 15. 2-D Resistivity model of Vom 1(depth in metres)

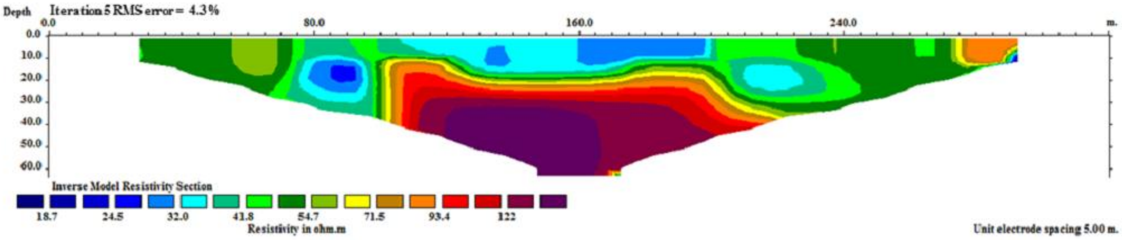


Fig. 16. 2-D Resistivity model of Vom 2 (depth in metres)

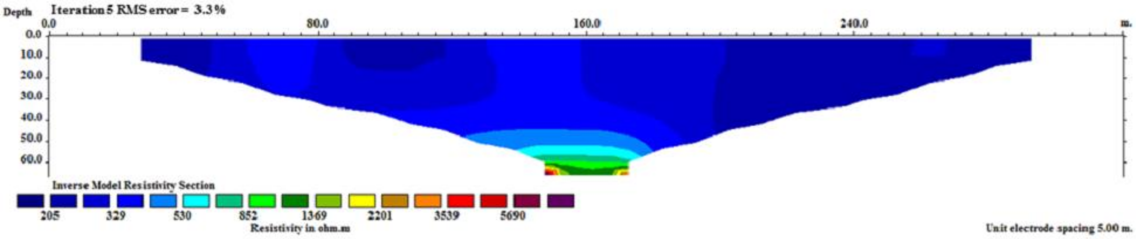


Fig. 17. 2-D Resistivity model of Chongopyeng 1 (depth in metres)

Table 1. Summary of 2-D resistivity survey result

Profile	Probable depth to cassiterite bearing alluvium (m)	Probable depth to fresh basement (m)	Notes
Kwang Rayfield 1	10	13	Igneous Intrusion/Fault?
Kwang Rayfield 2	8	10	Igneous Intrusion/Fault?
Doi 1	16	22	Igneous Intrusion/Fault?
Doi 2	6	12	Igneous Intrusion/Fault?
Rakparak Shen	10	14	Igneous Intrusion/Fault?
Viepyang Zawan	19	25	Fault?
Gyerro 1	33	38	
Gyerro 2	N/A	N/A	Soil and Ground water contamination?
Gura Dabwam Gyel 1	18	22	
Gura Dabwam Gyel 1	18	21	
Kwata Zawan 1	N/A	N/A	Igneous Intrusions/Fault?
Kwata Zawan 2	N/A	N/A	Igneous Intrusions/Fault?
Vom 1	N/A	50	Excessive Ground water and clay?
Vom 2	N/A	45	Excessive Ground water and clay?
Chongopyeng 1	36	44	
Chongopyeng 2	N/A	N/A	

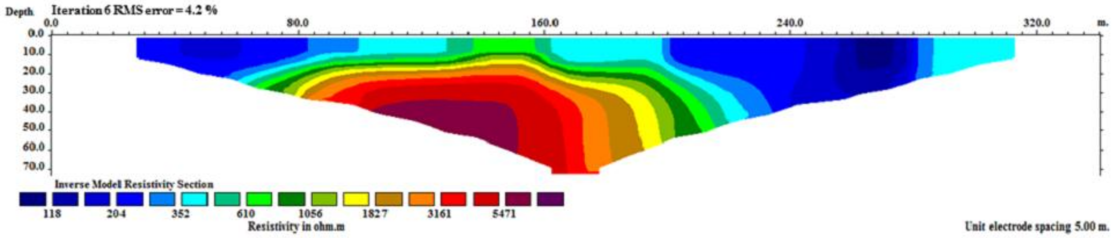


Fig. 18. 2-D Resistivity Model of Chongopyeng 2 (depth in metres)

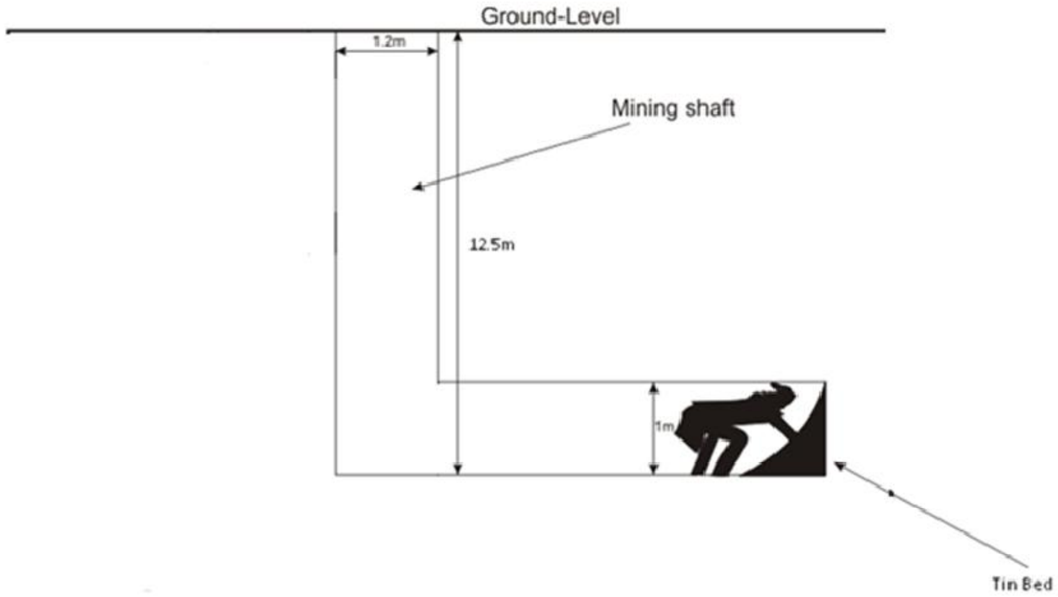


Fig. 19. Diagram showing the *loto* mine dug by informal miners at Point A of Fig. 3. Not drawn to scale

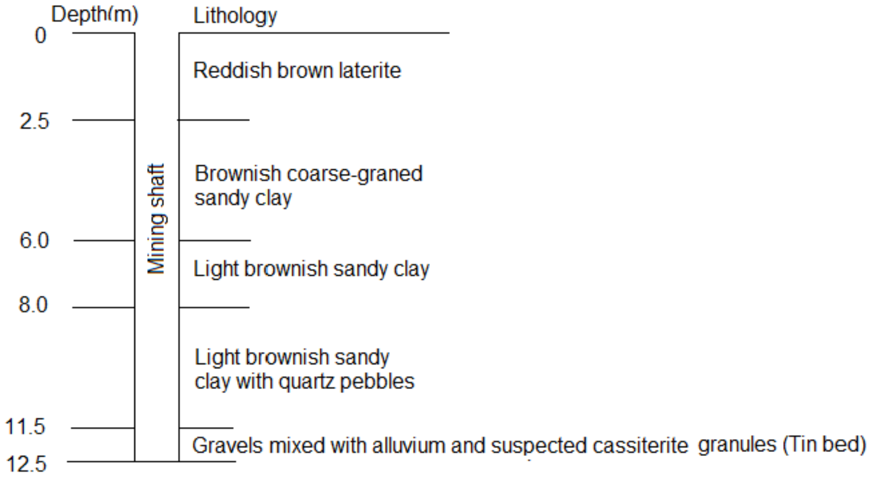


Fig. 20. Drilling record of *loto* mine

In the Primary mineralisation model, cassiterite is dispersed in multitudinous, narrow greisen veins, and quartz stringers in the roof zones of the biotite-granite intrusions, and is usually entrapped within the parent rock beneath an impermeable cover of roof rocks dykes [3].

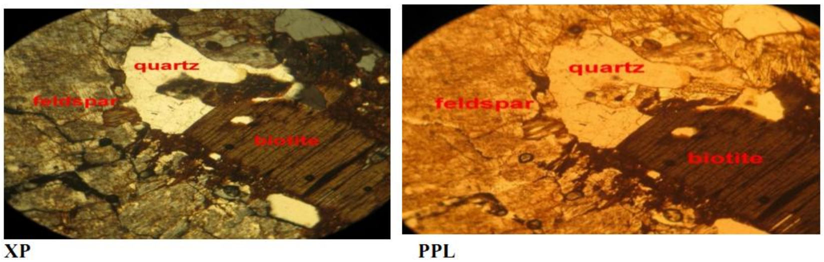

XP PPL

Plate 1. Photomicrographs taken with Cross Polarised Light (XP) and Plane Polarised Light (PPL) showing the thin section of a Biotite Granite rock sample collected from Kwang Rayfield 2

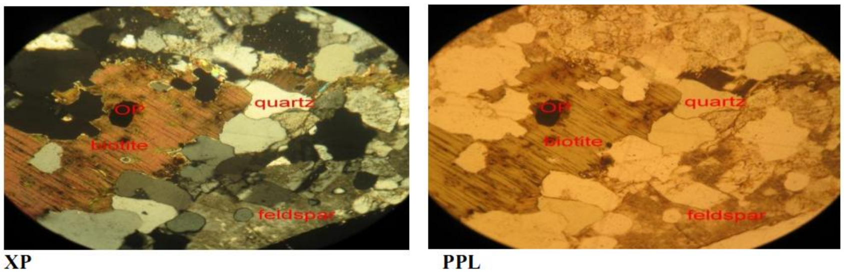

XP PPL

Plate 2. Photomicrographs taken with Cross Polarised Light (XP) and Plane Polarised Light (PPL) showing the thin section of a Biotite Granite rock sample collected from Doi. OP is an Opaque Mineral

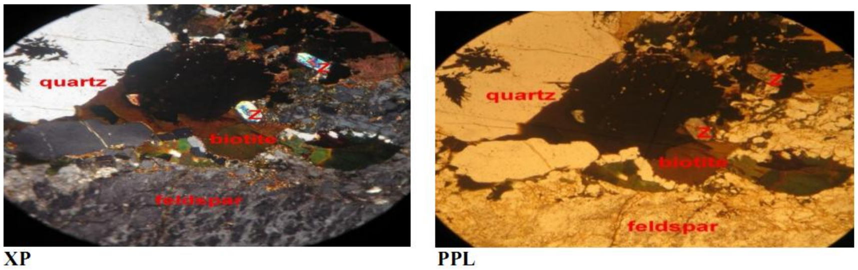

XP PPL

Plate 3. Photomicrographs taken with Cross Polarised Light (XP) and Plane Polarised Light (PPL) showing the thin section of a Biotite Granite rock sample collected from Vom. Z is Zircon

Suspected igneous intrusions and fractures were observed within the subsurface along the following profiles: Kwang Rayfield 1 and 2, Doi 1 and 2, Rapkparak Shen and Kwata Zawan 1 and 2, this suggests a possible relationship between these fractures and igneous intrusions. Ring fracturing and cauldron subsidence are the major tectonic controls governing the emplacement of these igneous intrusions. It is clear that the fractures extended to the surface and provided zones of weakness that facilitated the upward flow of magma. These same ring fractures have frequently served as the loci of the intrusion of granitic ring dykes [3]. The form and distribution of most of the Younger Granite Complexes have been determined by extensive and frequently overlapping zones of ring fracturing. The faults observed in the resistivity sections could have resulted as magma intruded by injection into the initial ring fractures of the basement rock during formation of the igneous intrusions and can act as host or passage to minerals and fluids. The suspected igneous intrusions observed in the 2-D resistivity models could be dykes and/or granite plutons. Frequently, these rocks are extremely resistant to weathering compared to the surrounding rocks [16] and as a result it may be left standing by itself when the surrounding country rocks have weathered away. Thus, Younger granite rocks may cause prominent high resistivity zones compared to the surrounding country rocks because they are less weathered than the rocks in which they intrude. The surrounding rocks commonly develop secondary porosity and permeability resulting from fracturing and weathering and will make it more conductive and less resistive than the Younger Granite rock. In this study these Younger Granite intrusions are revealed as high resistive bodies. Dykes and granite plutons form structural controls of the Younger Granite ring complex [3]. The Jos-Bukuru Complex where the 2-D electrical resistivity was carried out and Sha-Kaleri Complex have the most extensive occurrence of important intrusions of biotite granites which occur as ring dykes but are more commonly found in the form of large circular and crescentic plutons and as small stocks [3]. Hence these intrusions could be biotite granite intrusions and according to [3,17] cassiterite occurs only in association with biotite-granite.

For the alluvial deposit model, many of the cassiterite bearing source rocks (Biotite Granite rocks) are situated on or near major watersheds, so that a wide spread of alluvium is further enhanced. From the 2-D resistivity models, the probable depth to cassiterite bearing alluvium is least at Doi 2 (6 m) and greatest at Vom 1 (50 m). The rock samples collected from the outcrops near the profile for petrographic study were observed to be Younger Granite rocks; in hand specimen and thin section, they were shown to contain biotite. Cassiterite occurs only in association with Biotite granite intrusions [3,17]. Erosion of these rocks over would have rapidly uncovered some extensive area of cassiterite-bearing granite and thus facilitate the wide distribution of cassiterite in the surrounding drainage system. Hence the cassiterite granules discovered at a depth of 11.5 m, 295 m along Kwang Rayfield profile. The 10 m depth obtained from the 2-D resistivity interpretation model which is 1.5 m different from the actual depth obtained from the tunnel for the spot, has revealed a pitfall in using geophysical methods, it is well known that more than one model can produce the same response that agrees with the observed data within the limits of the data accuracy. The accuracy of the result is only as good as the accuracy of the assumptions made. The resulting model thus depends to a significant extent on the constrain used, and will closely approximate the true subsurface resistivity only if the constrains correspond to the real situation [10]. The depth of 10 m obtained from the 2-D resistivity model in comparison to the depth from the tunnel where cassiterite was found is correct to about 87%.

For the sub basalt deposit model, previous studies using 1-D electrical resistivity survey [4] and [5] to detect the sub basalt valley met with little success owing to so much water and varying decomposition of basalt. Applying 2-D electrical resistivity survey to detect the sub basalt valley and hence sub basalt cassiterite alluvium revealed very low resistivity values probably because of the waterlogged nature of the location (though survey was carried out in January there was evidence of location being flooded during the rainy season), varying decomposition of basalt and the sub basalt cassiterite bearing alluvium. The average depth to fresh basement from the 2-D resistivity model for Vom 1 and 2 is beyond 50 m and 45 m respectively. These could be the average depths to the sub basalt valley for these locations. These depths for these locations could be combination of the thicknesses of various forms of decomposed basalt, basement rocks and placer deposits of alluvium. These depths though large are possible because the thickness of basaltic flow according to [3] is limited by the depth of the pre-existing valleys and rarely exceeds 61 m (200 feet)). This study agrees with the conclusion drawn by [4] and [5] with regards to mining Sub-Basalt deposits of cassiterite that with this depth and nature of overburden, underground mining with will be very difficult and mechanical stripping of the overburden using draglines or other means will leave the environment in a devastated state. Other methods of mining this sub basalt deposit need to be devised to still tap this large potential cassiterite deposit and also the save the environment.

4. CONCLUSION

The 2-D electrical resistivity sections revealed suspected igneous intrusions and faults which are structures relevant to cassiterite mineralisation. It also revealed the average depth to cassiterite bearing alluvium and to the basement.

Based on the findings of this study, it can be concluded that though the large lodes of cassiterite may have been extracted, there may still be cassiterite in the Naraguta area and if the mining activities are well coordinated it can generate income for the state, minimize environmental degradation and boost sustainable development.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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