Journal of Sustainable Mining 16 (2017) 127–138

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Contents lists available at ScienceDirect

Journal of Sustainable Mining

journal homepage: http://www.elsevier.com/locate/jsm

Research paper

1D resistivity inversion technique in the mapping of igneous intrusives; A step to sustainable quarry development

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ARTICLE INFO

Article history:
Received 31 May 2017
Received in revised form
28 October 2017
Accepted 7 November 2017
Available online 13 November 2017

Keywords:
Geo-electric
Diabase
Trial pit
Land degradation
Sustainability
Benue trough

ABSTRACT

The use of trial pits as a first step in quarry site development causes land degradation and results in more failure than success for potential quarry investors in some parts of the world. In this paper, resistivity, depth and distance values derived from 26 Vertical Electric Soundings (VES) and 2 profiling inversion sections were successfully used to evaluate a quarry site prior to development. The target rock Diabase (Dolerite) was observed and it had a resistivity range of 3.0×10^4 −7. 8 $\times 10^6$ Ω-m, and was clearly distinguishable from associated rocks with its bright red color code on the AGI 1D inversion software. This target rock was overlain by quartzite, indurate shale and mudstone as overburden materials. The quartzite, with its off-red colour, has a resistivity range of 2.0×10^3–2.9×10^5 Ω-m, while the indurate shale, with a yellowish-brown colour, showed resistivity values ranging from $6.1 \times 10^2 - 2.8 \times 10^5$ Ω-m. Topsoil was clayey, with a resistivity range from $8 - 8.6 \times 10^{2u}$ Ω-m and depths of 0.3–1.8 m, often weathered and replaced by associated rocks outcrops. The diabase rock, in the three prospective pits mapped, showed thicknesses of between 40 and 76 m across the site. The prospective pits were identified to accommodate an estimated **2,569,450** tonnes of diabase with an average quarry pit depth of 50 m. This figure was justified by physical observations made at a nearby quarry pit and from test holes. Communities were able to prepare a geophysical appraisal of the intrusive body in their domain for economic planning and sustainability of the natural resource.

1. Introduction

Geophysical mapping techniques have advanced from 1D to 2D to 3D, yet the potential of the 1D method in subsurface mapping is yet to be fully exploited particularly in respect to the mapping and estimation of in-place intrusive rock for commercial quarry development. This is necessary in situations where 2D/3D tools are not available. Intrusive rock's response to electrical current is very pronounced, giving relatively high resistivity values compared with associated host rocks. This makes the use of the electric resistivity method excellent in intrusive mapping. The establishment of hard rock quarries has become a booming business in Nigeria over the last two decades, following improvement in structural development, particularly in the federal capital territory (Abuja), and other state capitals. Usually, quarries are sited in a volcanic environment where igneous rocks are on the earth's surface. Very rarely is a quarry sited where the target igneous rock is subsurface (intrusive environment) as is the case in this study. Siting a quarry in an intrusive environment is inevitable in areas where volcanic activity is not present and transporting rock aggregates from a far distant volcanic quarry will be too expensive and dangerous.

Locating a commercial quarry site in an intrusive environment is therefore extremely challenging. Presently, in the Benue trough, sites are guessed, judging from notable variations in topography and vegetation, and followed by the opening of trial pits. This practice is now causing serious environmental concerns, following the presence of several trial and abandoned pits. Investors often become frustrated when trial pits fail and their initial investments and efforts are wasted. Situations also exist whereby professionals who were hired to conduct a preliminary site investigation end up presenting poor and unreliable reports. This may be because of poor knowledge of the operational requirement or use of inappropriate tools and techniques. Even where appropriate tools have been used, improper field and processing techniques could affect

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https://doi.org/10.1016/j.jsm.2017.11.001

results. Sometimes investors are in a hurry to get started and may have procured some quarry equipment in advance, before confirming how the potential of the prospective site for commercial quarry development.

This paper specifically shows a simplified method of site investigation and evaluation of intrusive bodies to reduce the problem of land degradation due to abandoned trial pits. This investigation involves the use of vertical electric sounding (VES), electrical resistivity profiling, and topographic and surface geologic mapping extended to active and abandoned quarry pits near the study area. The paper represents a guide to professionals who may face the challenges of utilizing field techniques in order to locate a viable site for the establishment of a commercial hard rock quarry in an intrusive environment. It also simplifies the procedure for estimating the quantity of rock in place and promoting sustainable quarry practices. This paper is also relevant to investors who plan to set up a quarry, but are unfamiliar with the scientific approach of selecting a site and justifying the site for business.

Not a single quarry pit has been reclaimed in the Benue trough, despite the huge number of communities and cities located along the trough. Some private investors viewed the hard rock quarries to be very lucrative, but attempted business without taking time to map-out and estimate the reserve of the rock in-place before purchasing crushers and commencing trial pits. Often they end up opening and abandoning between 2 and 5 trial pits before striking a prospective site. More often, they get frustrated and quit, causing serious land degradation and other environmental issues that threaten the socio-economic well-being of the host communities. This is not sustainable mining practice, as the host communities often do not understand the true situation or availability of the natural resource on which their present and future economic well-being depends on. This state of confusion goes on to prevent the communities from meaningful economic planning based on the natural resources available.

Quarry companies supply construction materials for road making, building construction, and the maintenance of road networks on which other industries depend. Recent studies have shown that good sustainable companies are those that provide an efficient and effective service and are mindful of all aspects of the environment and society. This is not the case with quarry companies operating in the Nigeria Benue trough. Communities accommodating quarry companies should demand that quarries be developed in a professional manner with consideration of the needs of the environment, the employees and all those who will be effected by their development, rather than only be focused on financial benefits. The general objective when planning hard rock quarries is to ensure that the aggregates produced are managed in a sustainable way so the best balance is obtained between the operational environment, the economic returns and the society. This should not only be embodied in a country code of quarry practice or mining regulations but must also be enforced accordingly.

The electrical resistivity method is used in the study of horizontal and vertical discontinuities and uses the electrical properties of the ground. It utilizes direct currents or low frequency alternating currents to investigate the electrical properties (resistivity) of the subsurface. Resistivity contrast between the target rock and the background geology must exist. Igneous rocks show the highest resistivity responses with surrounding geology. Sedimentary rocks are the most conductive due to their high fluid content and metamorphic rocks have intermediate but overlapping resistivity responses. The age of the rock is also an important factor of resistivity as young volcanic rock (Quaternary Rocks) shows lower resistivity compared with old volcanic rock (Precambrian Rocks). Electrical resistivity is commonly applied to: groundwater exploration, mineral exploration, detection of cavities, exploration of waste and engineering sites, and Oil exploration.

The study area lies in the lower Benue trough sedimentary basin of Southern Nigeria (Fig. 1a and b). The sedimentary units in this area are generally cretaceous in age and have long been studied by several researchers including Reyment (1965) and Kogbe (1975). Nwachukwu et al. (2011), worked on the petrography of the lower Benue trough intrusive rock and confirmed that it was Olivine-diabase, with a hybrid body suspected to have resulted from later recrystallization of mafic components (Fig. 1b). Their physical analysis of hand specimens showed the specific gravity (SG) of the rock to be 2.8, at the upper near surface depth, but 3.0, at lower depths, and to consist mainly of mafic minerals. From both physical and optical analysis, Nwachukwu et al. (2011) found the majority of the minerals in the lower Benue trough to be, in order of abundance: Augite, Plagioclase, Quartz, Olivine, Hornblende, Biotite and Magnetite (main accessory). Plagioclase however is more abundant at depths of ≥16.3 m. They observed that the percentage of the concentrations of the minerals vary with depth and finally described the intrusive rock as Olivine-diabase with a Laccolith structure.

The application of the geophysics method varies depending on the target and availability of the instrumentation. In this study, the target is intrusive rock. Intrusive rock mapping for commercial quarry development is not common, as a result, there is a lack of reference materials in mining-geophysics literature which can be used. This is because most quarries are established in volcanic environments where the target rock is situated on the surface and the task of exploratory mapping does not exist. This work stands as the first of its kind in recent time to discuss the task of intrusive mapping as a first step in the development of a commercial quarry in an intrusive environment located in a remote area where the choice of geophysics tools is limited.

The application of the electrical resistivity method in engineering site investigation, groundwater exploration, and in environmental studies has been widely discussed by several authors such as: Telford, Telford, Geldart, and Sheriff (1990), Todd and Mays (2005), Parasnis (1997), Milsom and Eriksen (2011), Greenhouse and Pehme (2001), Nwachukwu and Eburukvwe (2013), etc. Like this study, Joelle et al. (2011) converted a series of VES data to obtain a 2D electrical tomography model of the Saiss basin in Morocco. They described VES as the most widely used technique in many countries because it is inexpensive, available and very useful when an in-depth investigation over a large area is required. Sultan, Fernando, and Santos (2008) used thirty-five vertical electrical soundings (VES) in a regular mesh at the north-western part of Greater Cairo to characterize different geological units and to study their quality for building foundations. Models obtained from the 1D inversion of each VES, together with borehole information, were used to construct eight geo-electrical sections that exhibited the characteristic geology of the area.

Nwachukwu & Feng (2012) condemned the use of trial pits as a first step in prospecting for an intrusive body. They recommended test drilling with or without coring, following the recommendations of detailed geophysical mapping of the intrusive rock as standard. This paper represents what could be considered affordable detailed geophysical mapping. Nwachukwu & Feng maintained that both the geophysical mapping and test drilling are complementary to the exploration and evaluation process. They also reported that quarry and trial pits abandoned along the Benue trough severally constitute environmental hazards. It is important that planning authorities should recognize that quarries (including sand-and-gravel pits) vary greatly in size, have varying environmental impacts, and that their development planning should be designed to take care of their impacts in order to achieve the level of sustainability required.

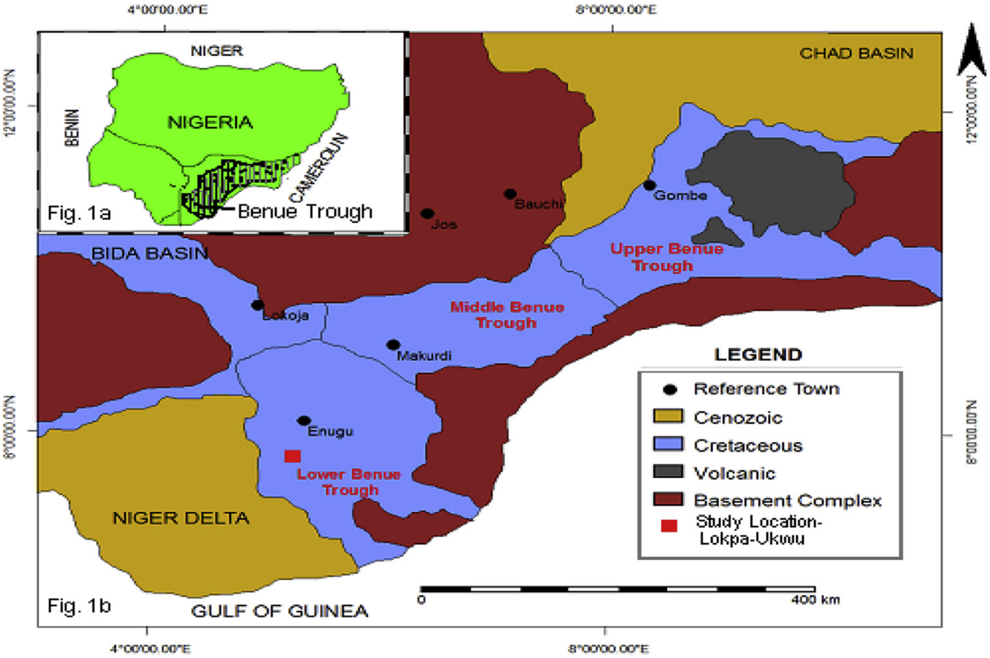

Fig. 1. (a) Map of Nigeria, showing the Benue Trough. (b) Geologic map and segments of the Benue Trough (Modified after Fatoye & Gideon, 2013).

Darwish et al. (2011) lamented the environmental impact of quarries on natural resources in Lebanon. According to them, years of unregulated mining activity left hundreds of abandoned quarries across Lebanon. The comparison of quarry distribution with a land capability map revealed that quarries are found mainly on productive soils, consuming 1314 ha in 1989 and 2192 ha in 2005 of prime lands. They state that a total of 87 per cent of the studied quarries represent serious hazards to groundwater quality. In general, a total of 272 quarries have high impact, 657 quarries have moderate impact, and 349 quarries have low impact on natural ecosystems. Analysed data revealed that around 62 per cent of the quarries are in a highly unsuitable environment. This situation is similar to that of the lower Benue Trough, where communities live with abandoned quarry pits that deprive them of their arable lands. Whereas Lebanon has stepped up efforts toward regulating quarry operations, Nigeria is yet to commence enforcement of its mining laws and regulations to reduce the negative environmental impacts of quarry operations. According to Roderick (2015), to calculate quarry reserves and resources the valuer must have a good understanding of the geology, the ownership rights and the constraints of ownership.

2. Materials and method

2.1. Procedure

- Mapping land area using the Compass and geologic method, with a construction of a 20 m interval square grid over the mapped area.
- Measuring elevation and coordinates using GPS at established grid points by triangulation helped to make the site topographic map as shown in Fig. 2a and b.
- Electric Drilling or Vertical Electric Sounding (VES) at grid points of pre-made traverses for a total of 30 VES stations were conducted using the Allied Associates Geophysical Ltd resistivity system. The field technique complied with the popular Schlumberger four electrode configurations. All necessary precautions for geo-electric measurements were taken. Generated VES data for each station was subjected to Schlumberger automatic analysis techniques using the Advanced Geophysics Incorporation (AGI) 1D resistivity inversion software. Figs. 3–15 A & B show 26 VES response curves.
- Two lateral profiles running North – South and East – West of the site which were both 180 m long were conducted following the Wenner four electrode field arrangement. The data generated was also subjected to Wenner automatic analysis using the Advanced Geophysics Incorporation (AGI) 1D resistivity inversion software (Fig. 16a and b).
- While the VES used natural resistivity variation with depth and subsurface lithology, the Wenner profiling showed lateral variation of resistivity related to lithologic variation with distance.
- The resistivity, depths and distance values were integrated to establish a 2D inversion model which enabled the estimation of rock in-place. In-place diabase was obtained by considering a density of 2.95 $g/cm^{3.}$

2.2. Operational requirements

This mapping and evaluation would not have been possible without the sponsorship of an organization that has an economic interest in the intrusive formation. The mapping lasted for 6 days, from 9.00 a.m. to 5.00 p.m. each day. Protective wear (PPE) including helmets, rain boots, and field overalls, as well as walkie-talkies for communication were provided to all workers. The resistivity meter was sensitive and came with all the accessories. All necessary precautions required in geo-electric measurement were taken. Labourers were hired from the community to cut the traverses as designed. The availability of nearby successful quarry pits enabled a comparison of the geophysics result with the result of the physical measurement of depth and the thickness of the intrusive rock and other associated rocks obtained from the nearby quarry pits.

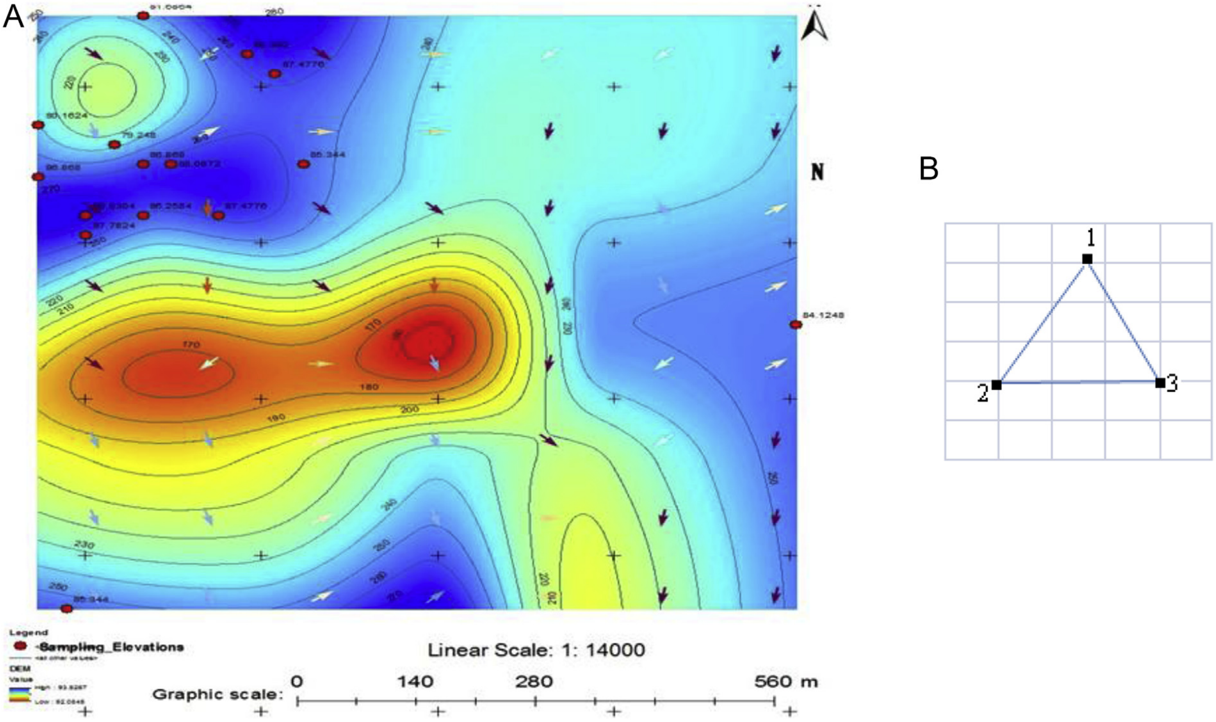

Fig. 2. A: Project map showing flow directions and spot heights. B: Determination of measurement points by triangulation using 9 square grids.

3. Results

3.1. Mapping

Geologic mapping recorded the presence of weathered indurate shale and mudstone boulders as outcrops. These rocks formed the base of the shallow stream (Iyi-Egwu) that traversed the site, running approximately in line with the general trend of the intrusive body (Fig. 2). The host rock directly associated with the intrusive body was affected by the hot temperature of the intrusive magma which resulted in baking and re-crystallization. This metamorphic process resulted in the host rock sandstone becoming quartzite, the shale became highly indurate tending to slate and clay-silt became mudstone. The study area is characterized by high and low topography ranging from 100 to 290 m above sea level. The lowest elevation corresponds with the base of the narrow stream channel. There is no farming activity in the study site, possibly due to frequent outcrops of weathered hard rocks that could hinder cultivation. This situation therefore presents the site like a forest reserve consisting predominantly of shrubs and woody vegetation.

Vertical electric sounding (VES) or electric drilling curves consistently recognized that the target intrusive rock (diabase) has

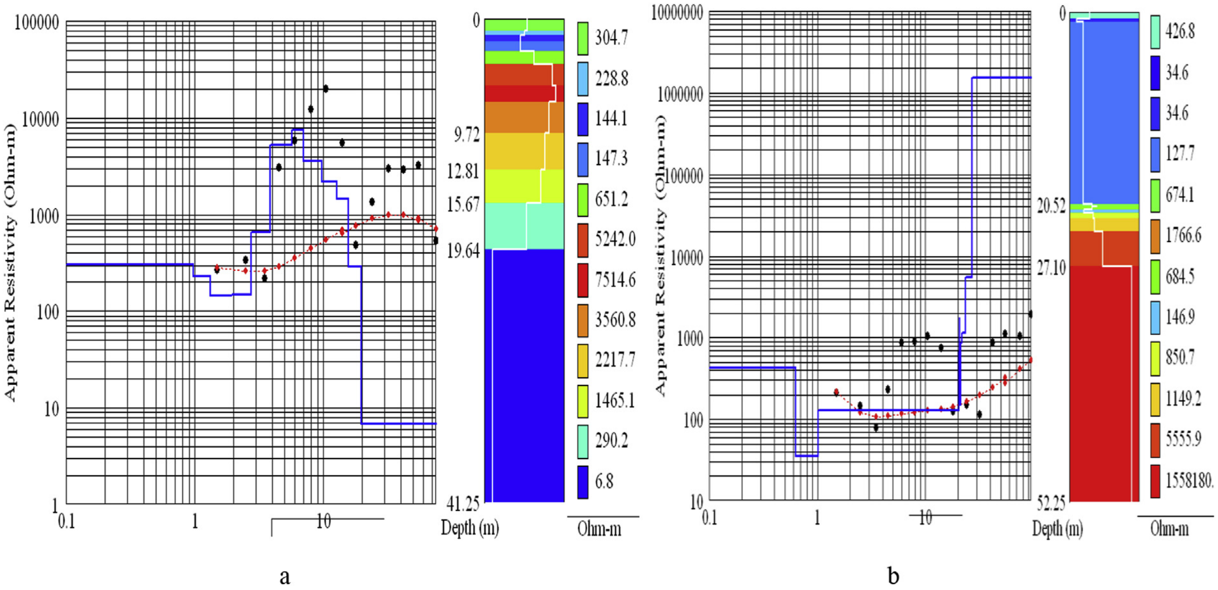

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Fig. 3. (a) CS 1C. (b) CS 2R & 1L.

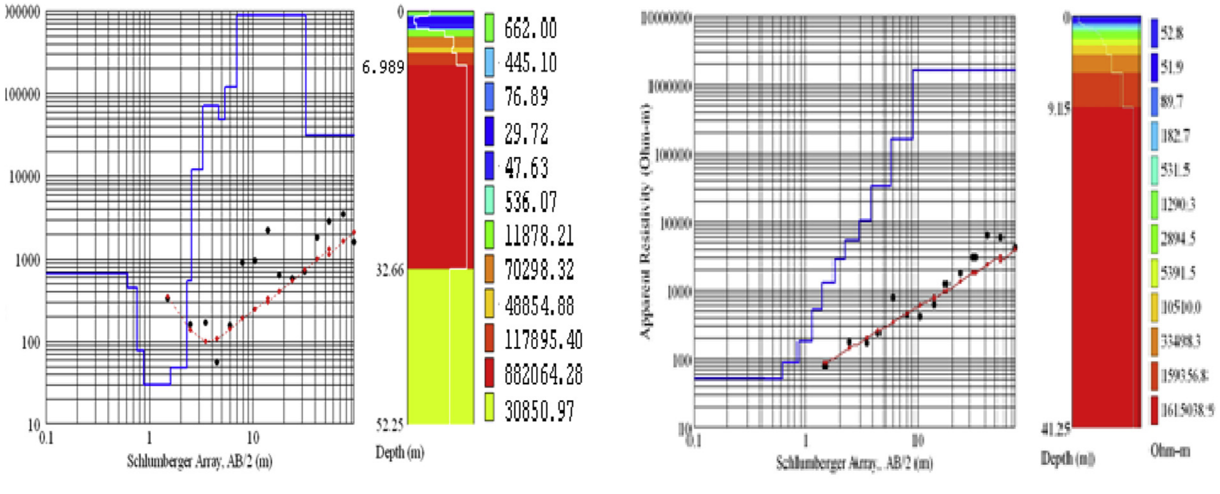

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Fig. 4. (a) CS 2L. (b) CS 2C.

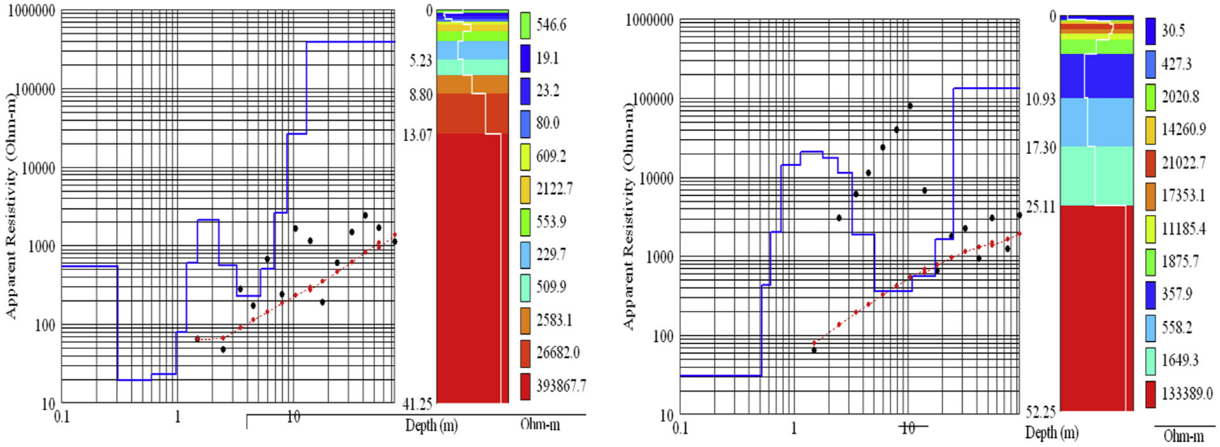

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Fig. 5. a. CS 3C & 3L. (b) CS 3R.

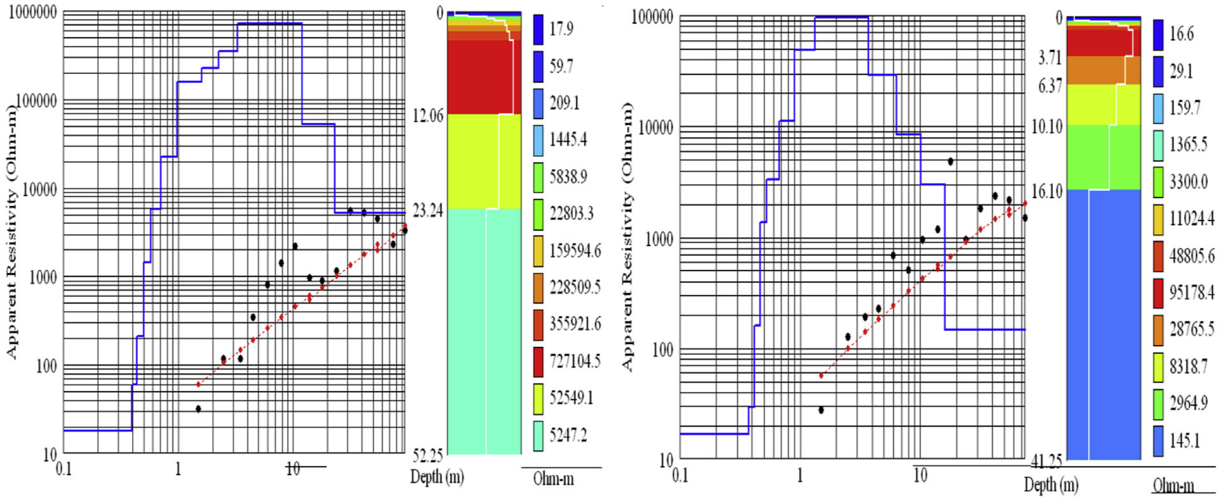

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Fig. 6. (a) CS 4L. (b) CS 4C.

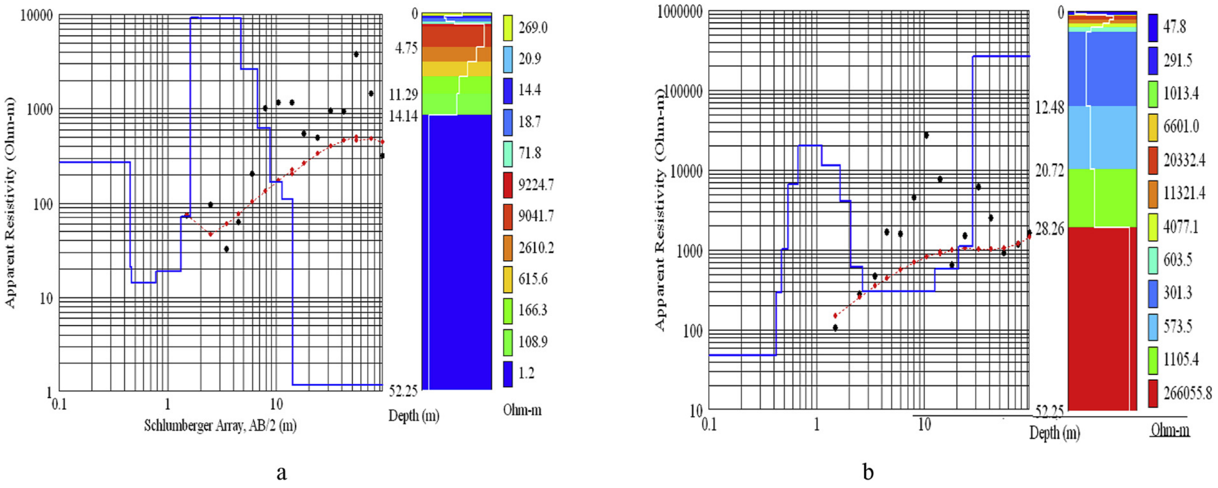

Fig. 7. (a) CS 5R. (b) CS 5C & 5L.

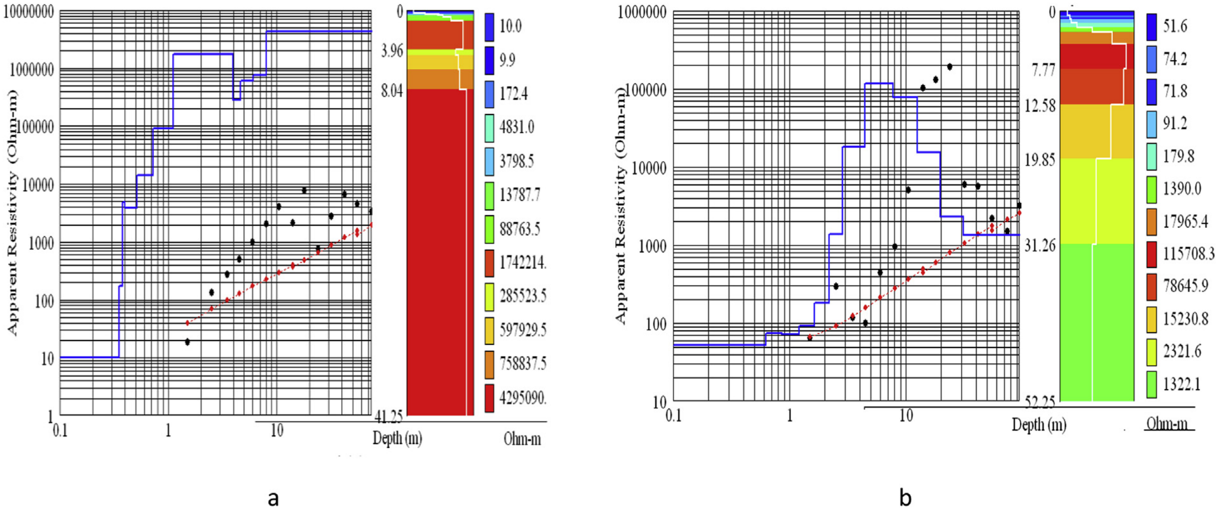

Fig. 8. (a) CS 6C. (b) CS 6L.

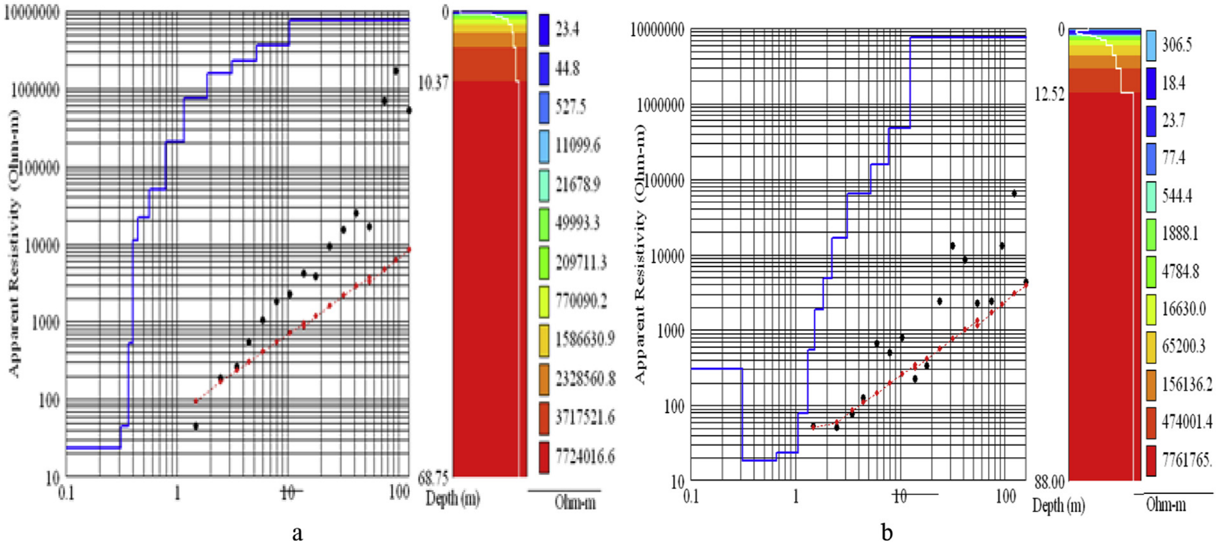

Fig. 9. (a) CS 7C. (b) CS 7R.

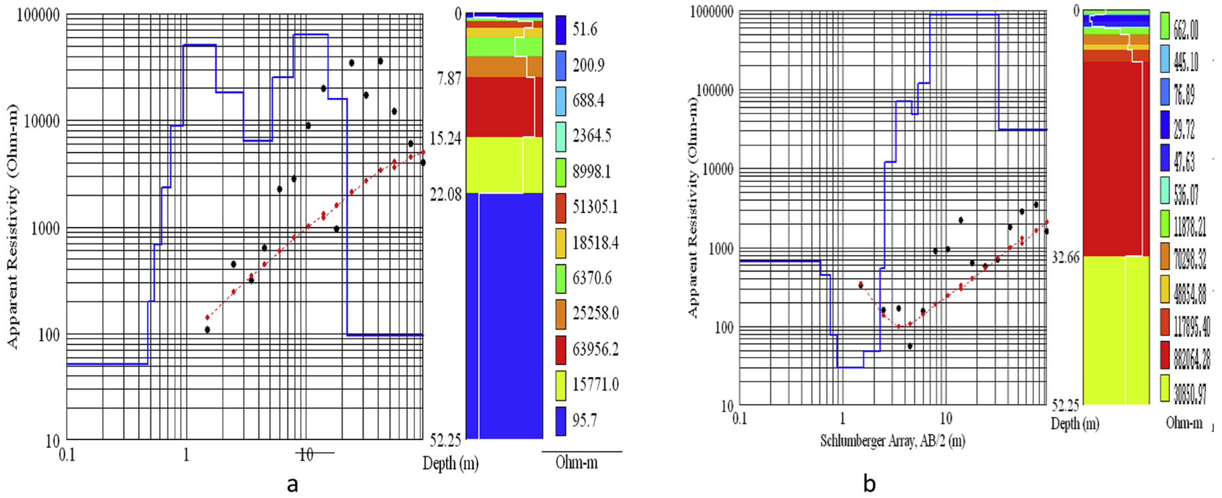

Fig. 10. (a) CS 8R. (b) CS 8C & 8L.

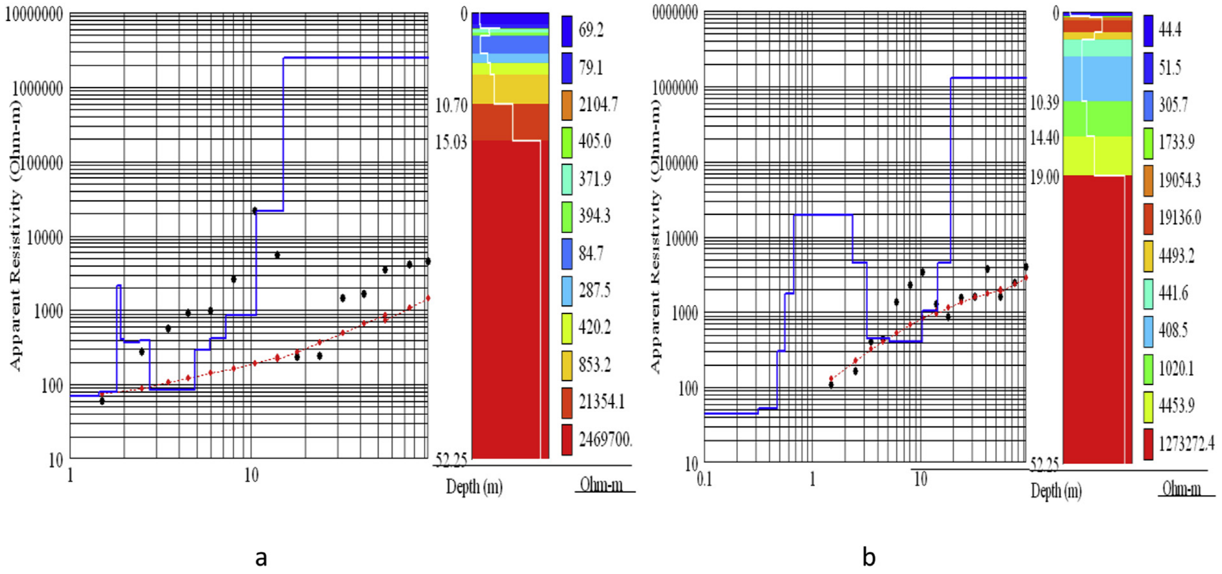

Fig. 11. (a) CS 9C. (b) CS 9L.

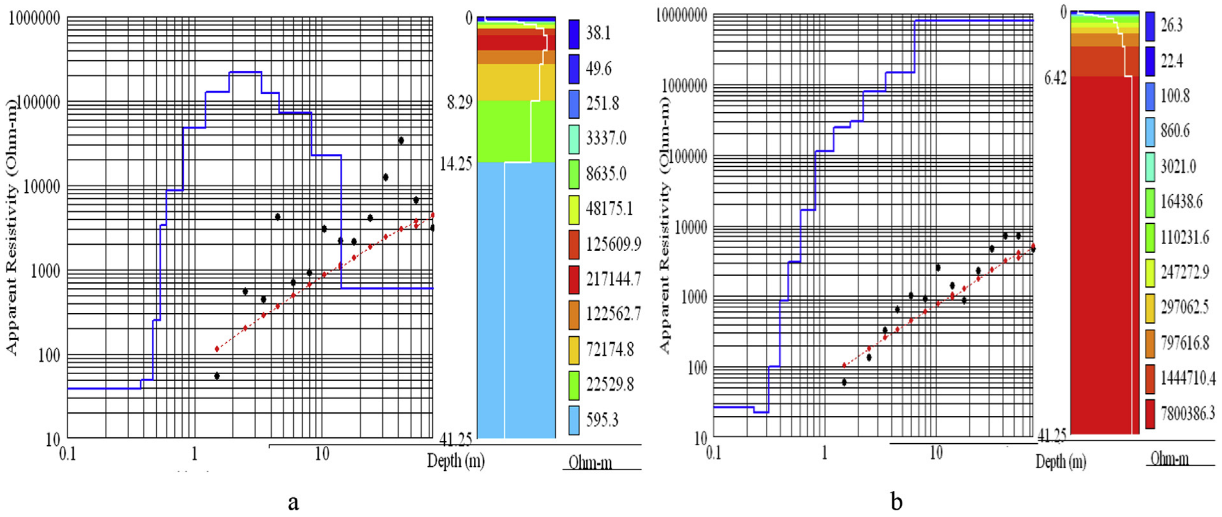

Fig. 12. (a) CS 10R. (b) CS 10C.

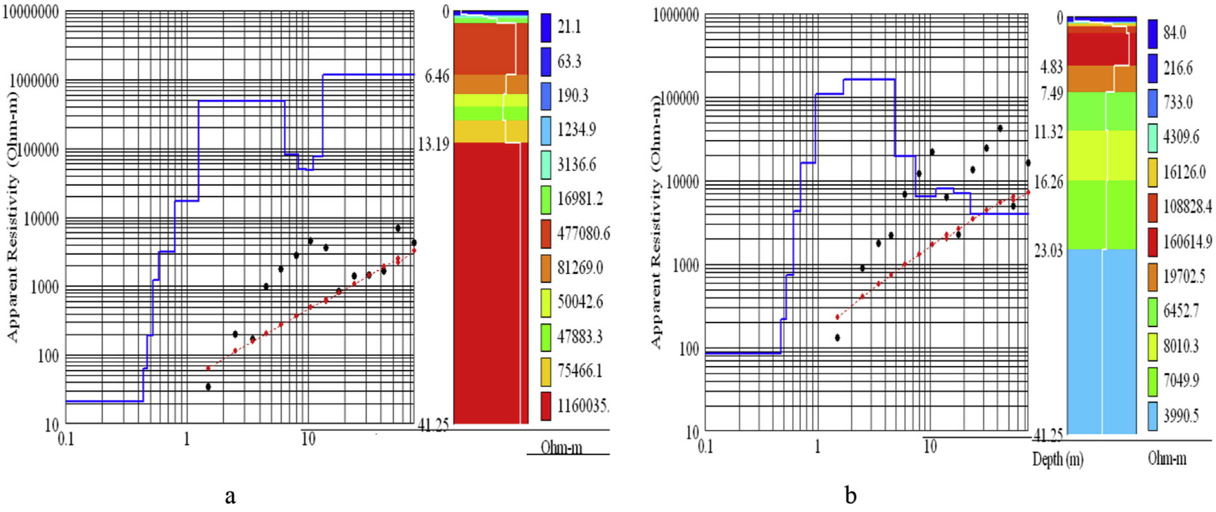

Fig. 13. (a) CS 11R. (b) CS 11C.

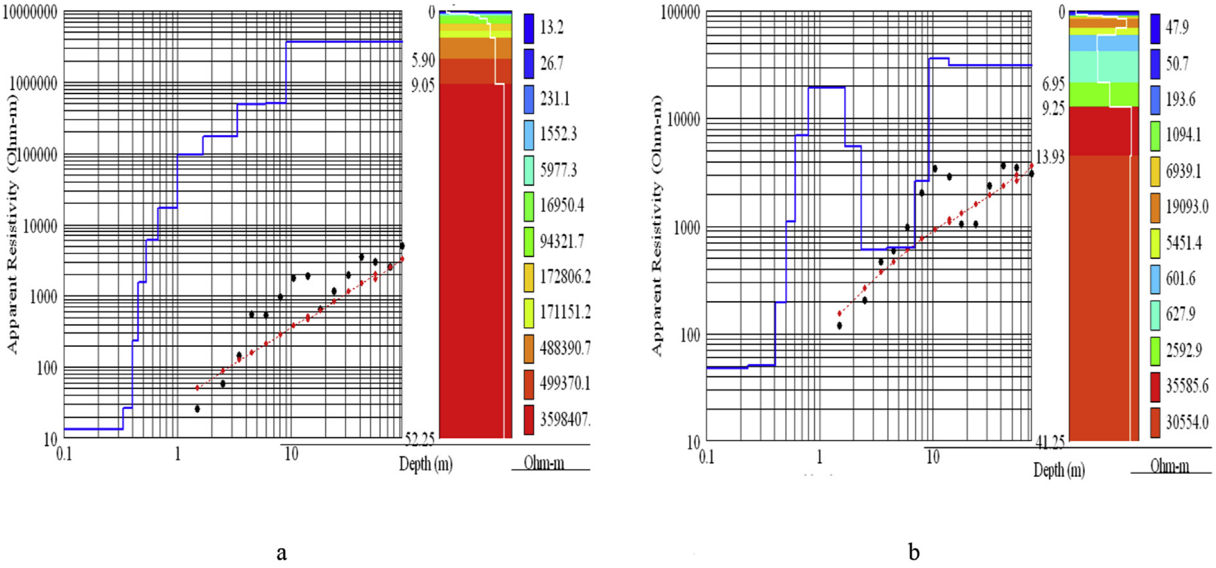

Fig. 14. (a) CS 12L. (b) CS 12C.

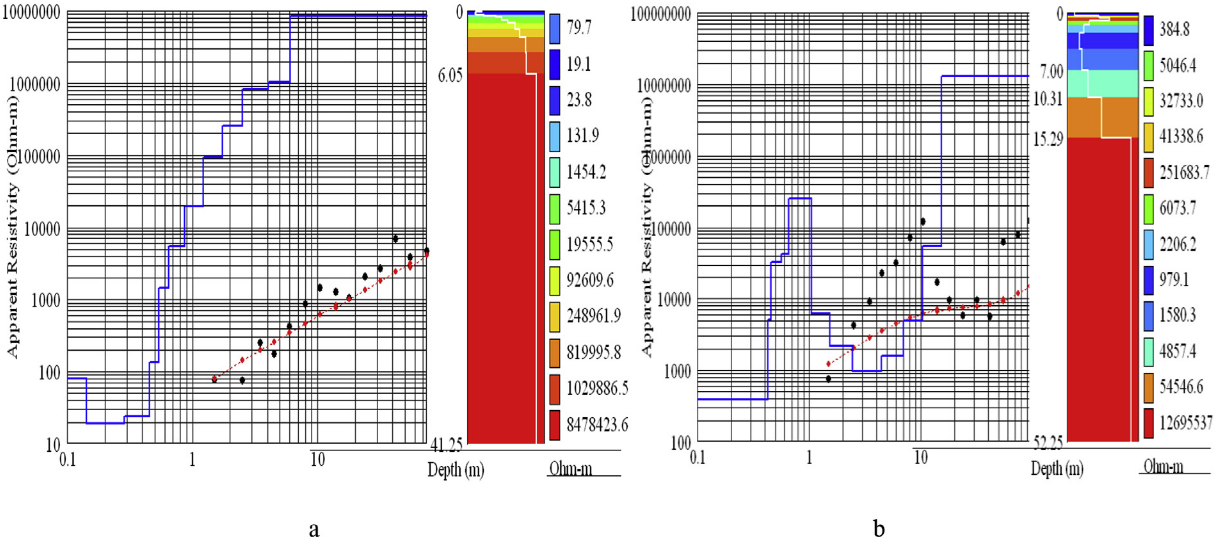

Fig. 15. (a) CS 13C & 13L. (b) CS 13R.

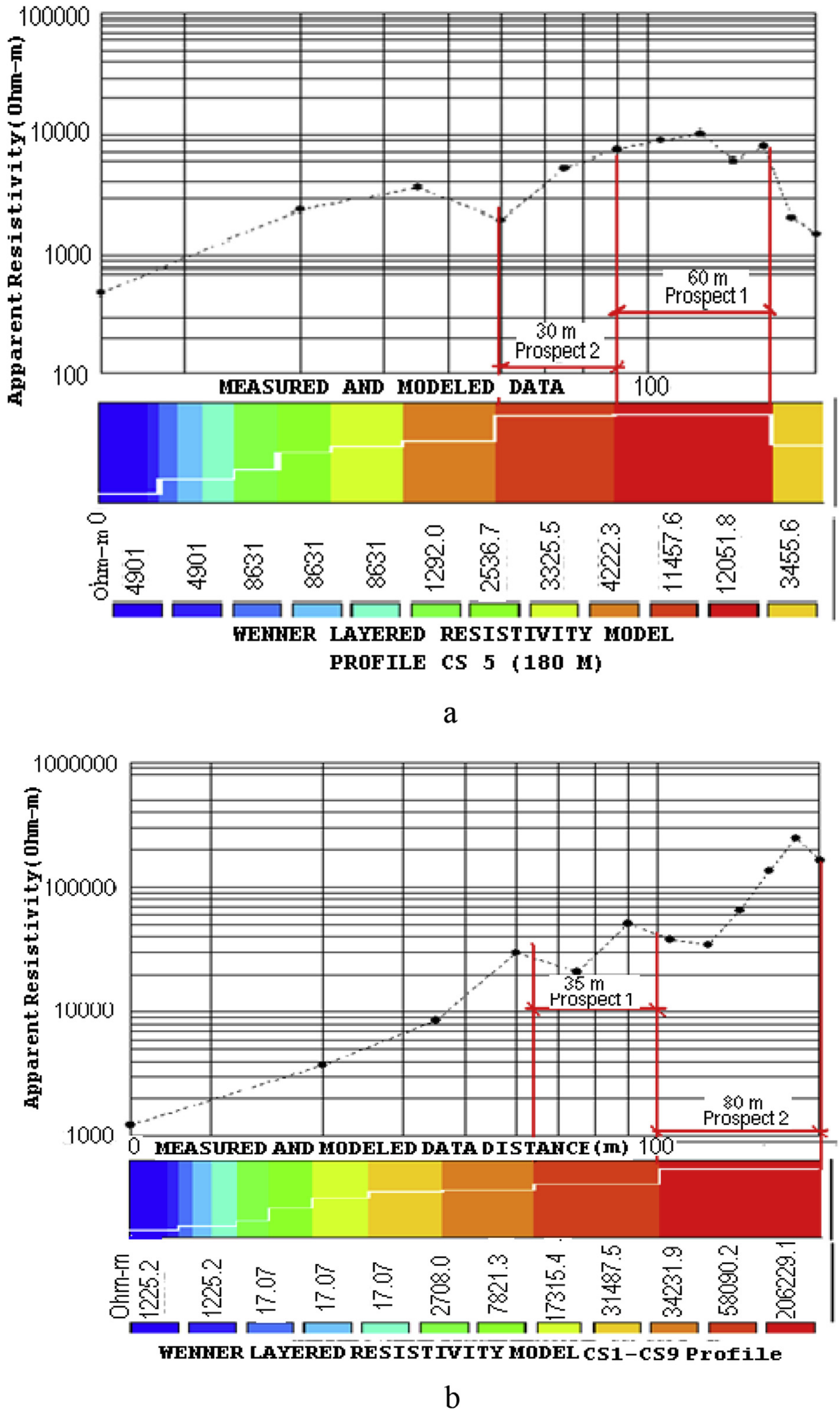

Fig. 16. (a). Profile 1, E-W. (b). Profile 2, N-S.

high resistivity values and is of a very bright red color code which distinguishes it from other associated rocks (Figs. 3–16). The associated host rocks responded with high, but lower, resistivity values, and off-red to yellow-brown colour codes that were easily distinguished.

The results are shown by 26 selected VES curves (Figs. 3–16) and the 2 profiling curves (Fig. 17) used in the evaluation. Out of the 30 VES stations, 23 showed a significant presence of the target rock, representing about 76.6% of the total area investigated. The VES result summarized in Table 2 indicates three sizes of intrusive body based on thickness as follows:

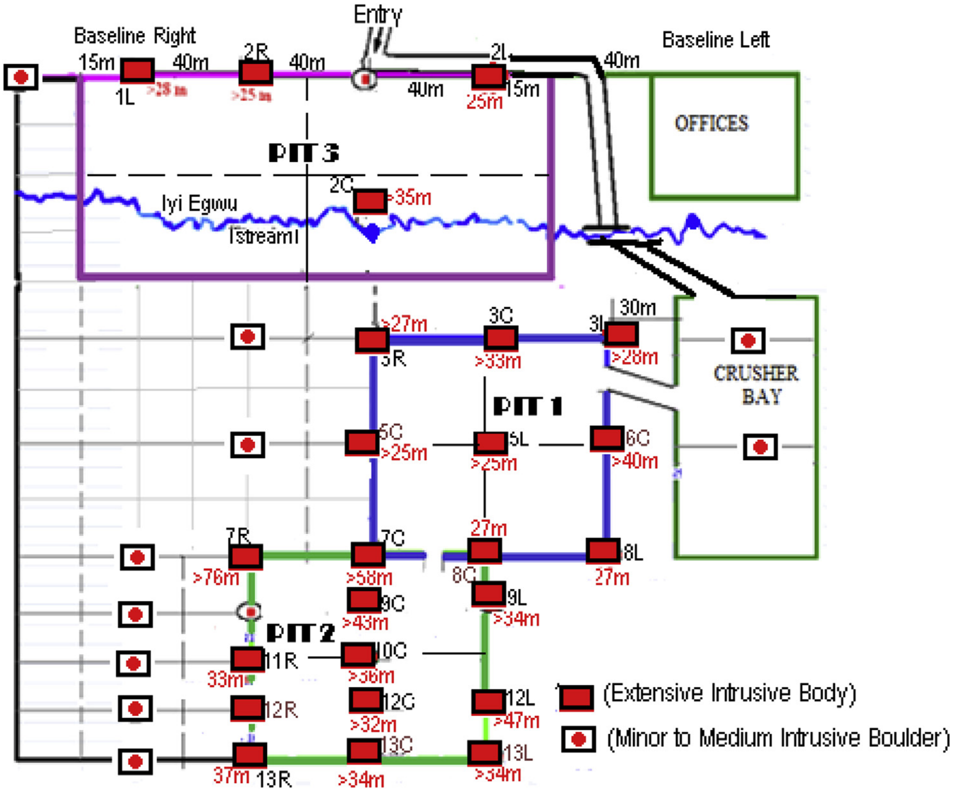

Fig. 17. 1D to 2D concept diagram.

(a) Minor (boulders); thickness varying between 1.75 m and 4.0 m,
(b) Medium; thickness varying between 5 m and 25 m
(c) Massive (extensive); thickness varying between 25 m and >70 m or indeterminate.

This result gave an average depth of between 50 and 60 m across the area of the three potential quarry pits (Fig. 17).

As in the VES responses, the very bright red color code on the profile sections indicated lateral distance containing the target rock. The N-S profile showed that the lateral distance of the target intrusive rock was 90 m, which represented the width of prospective area, and the E-W profile showed a distance of 125 m representing the length of the target area (Table 3). Measurements were also made on land to confirm the distances and in nearby quarries to verify the depth and thickness estimates. The surface environment of the site was swampy, as the survey was conducted in the rainy season. The clayey topsoil could have resulted from the weathering of intrusive outcrops.

3.2. Analysis

A detailed analysis of the VES results is presented in Table 2. The two Wenner profiles showed the lateral distance of the target intrusive rock to be 90 m running N-S and 125 m running E-W as shown in Table 3. The target rock Diabase (Dolerite) was observed and had a resistivity range of 3.0×10^3–8.4×10^6 Ω-m (Table 2), and was clearly distinguishable from associated rocks due to its bright red color code on the AGI 1D inversion software. The target rock was usually overlain by quartzite, indurated shale and topsoil constituting the overburden materials. The thickness and structure of the overburden varied between the measurement points. The quartzite has a resistivity range of 2.0×10^3–2.9×10^5 Ω-m while clay-stone and siltstone constituting the indurate Shale showed resistivity values ranging from $6.1 \times 10^2 - 2.8 \times 10^5$ Ω-m. Clayey topsoil was found at depths between 0.3 and 1.8 m across the area, with a resistivity range from $8 - 8.6 \times 10^2$ Ω-m.

Diabase resident in the three prospective bands (pit 1–3) had a thickness of 40–76 m, and generally was indeterminate across the site. The prospective pits were identified to accommodate an estimated diabase of **2,569,450** tonnes for an economic quarry pit of depth 50–60 m (Table 1). This can sustain a small-medium scale quarry operation for between 5 and 8 years. This result was confirmed by physical observations made at an active quarry pit next to the site. Further confirmation was made by drilling test holes and physically examining the drill cuttings, as coring was not possible.

Table 1
Estimating target rock reserve at average density 2.95.

Pit No.	Area of pit (m^2)	Economic working depth (m)	Tonnage estimate
1	50 × 100	50	737,500
2	60 × 90	55	876,150
3	60 × 90	60	955,800
Estimated In-place Rock			**2,569,450**

4. Discussion

A viable quarry site is measured by the income that can be derived from the limits of its operational depths. Many prospective quarry investors and operators think that the way to value the resource is to multiply the total tonnage obtained by the prevailing market value per ton. They go beyond this to crusher capacity, for example they could consider purchasing a 300 ton per hour plant and divide the reserve by 300, and believing to obtain the life span

Table 2
Detail analysis of VES result.

VES #	Elevation (ft.)	Top of TR (m)	Bottom of TR (m)	Thickness of TR (m)	Resistivity Ohm-m	Size of TR
Fig. 3a; CS 1C	287	4.0	5.75	1.75	7.5×10^3	Minor Boulder
Fig. 3b; CS 2R/1L	280	27	>52	>25	1.5×10^6	Extensive
Fig. 4a; CS 2 L		7	32	25	8.8×10^5	Medium
Fig 4b; CS 2 C		5.6	>41	35.4	1.5×10^6 -1.6×10^6	Extensive
Fig. 5a; CS 3C/3L	269	13	>41	>28	3.9×10^5	Extensive
Fig. 5b; CS 3R		25	>52	>27	1.3×10^5	Extensive
Fig. 6a; CS 4L		1.6	12	10.4	1.5×10^5 –7.2×10^5	Medium
Fig. 6b; CS 4C	201	1	3.7	2.7	9.5×10^3	Minor Boulder
Fig. 7a; CS 5R	267	1.65	4.75	3.1	9.2×10^3	Boulder
Fig. 7b; CS 5C/5L	284	28	>53	>25	2.6×10^5	Extensive
Fig. 8a; CS 6C	285	1.0	>41.5	>40.5	1.7×10^6-4.2×10^6	Extensive
Fig. 8b; CS 6L	285	3.0	7.0	4.0	1.1×10^5	Boulder
Fig. 9a; CS 7C	211	10.0	68	>58	2.3×10^6-7.7×10^6	Extensive
Fig. 9b; CS 7R	220	12.0	>88	>76	4.7×10^6-7.7×10^6	Extensive
Fig. 10a CS 8R	269	8.0	15	07	6.3×10^4	Medium
Fig. 10b CS 8C/8L	290	5.0	32	27	1.1×10^5-8.8×10^5	Extensive
Fig. 11a CS 9C	281	10.0	>53.0	>43.0	2.1×10^5-2.4×10^6	Extensive
Fig. 11b CS 9L	280	19.0	>53	>34.0	1.2×10^6	Extensive
Fig. 12a CS 10R	281	1.0	05.0	4.0	1.2×10^5-2.1×10^5	Boulder
Fig. 12b CS 10C	285	6.0	>41.0	>36.0	1.4×10^6-7.8×10^6	Extensive
Fig. 13a CS 11R	287	1.0/13.0	06/>41.0	05/>28	4.7×10^6 -1.1×10^6	Minor/Extensive
Fig. 13b CS 11C	247	1.0	4.8	3.8	1.6×10^5	Boulder
Fig. 14a CS 12L	320	6.0	>53.0	>47.0	3.5×10^6	Extensive
Fig. 14b CS 12C	292	9.0	>41.0	>32.0	3.0–3.5×10^5	Extensive
Fig. 15a CS 13C/13L	315	6.0	>41.0	>34.0	1.0×10^6-8.4×10^6	Extensive
Fig. 15b CS 13R	270	15.0	>52.0	>37	1.2×10^6	Extensive

Table 3
Analysis of profiling result.

Profile #	Direction layout	Measured distance (m)	Prospect interval (m)	Prospect distance (m)
1	N-S	180	50–140	90 (Width)
2	E-W	180	55–180	125 (Length)

of the quarry and income from the quarry through this method. This is poor practice as several operational factors must be put in place. They quickly forget they have no control over weather and seasonal variations. They have no strong control over equipment breakdown and community disagreements over land ownership, and possible industrial action periods. This is clearly inaccurate as there is no regard given to the output or market demand or the speed at which the resource is worked and the risk involved within the market place.

Identifying an economically viable quarry site and estimating in-place rock should not be the work of land surveyors as some investors would think. It requires the expertise of a seasoned geologist/geophysicist. The use of surface features: Topography, vegetation and possible surface exposures followed by trial pits as a step to opening a quarry pit is unsustainable mining practice. The consequences go beyond disappointing the investors and the operators when their expectations are not met as it can also lead to environmental hazards. Nwachukwu and Eburukvwe (2013) found that trial pits are capable of causing gully erosion and road failure. Nwachukwu & Feng (2012), found such pits to be danger zones for human beings and roaming animals. They observed that these pits when wet could breed mosquito and when dry could become hideouts for criminals. They also observed that the pits are often used for dumping waste that can cause groundwater contamination.

Be it as it may, in these countries the most dangerous threat to environment and society is the reckless use and abandonment of trial pits for the exploration of intrusive bodies. Quarry companies make millions of dollars of profits within five years of operation, yet not a single pit has been reclaimed in the lower Benue Trough area where communities are subjected to living with abandoned pits. These trial pits cause obstructions to future rural development, such as the construction of rural roads and the development of prospective quarry sites. In this way, abandoned trial pits can deceive potential investors to conclude in error that an adjacent site does not have potential. Aside from environmental degradation, trial pits are neither cheap nor fast when compared with the method in this study. They do not allow proper conservation of the natural resources on which the economic well-being of the present and future generations of the host communities depend on. The use of trial pits as an exploration method to investigate and assess prospective quarry sites therefore constitutes unsustainable mining practice. There is a need for global attention to be placed on the formulation of a base-line hard rock quarry best management practice.

5. Conclusion and recommendations

Geo-electric 1D inversion VES and profiling methods combined with surface geologic measurements have been applied successfully in the mapping of intrusive bodies for the development of a commercial quarry. In-place diabase (dolerite) was estimated using resistivity, depth and distance values, and the transformation of 1D geo-electric sections to a 2D model (Fig. 17). The target rock was distinguished from other associated rocks using resistivity variation and the results were verified by measurements obtained from nearby successful quarry pits. This was followed by trial drilling, to finally confirm the viability of the site for a commercial quarry. In the lower Benue trough, a number of suburban communities exist and there is dense population. Respective communities are advised to conduct a geophysical appraisal of their intrusive bodies into prospective quarry bands and submit this to the bureau of mines. Since land ownership still belongs to the communities, the communities could use these appraisal reports for economic planning and ensuring the sustainability of the natural resources. This will make potential quarry investors and operators depend on the communities (land owners) for mining lease rather than the communities depending on the operators. This will provide the communities with greater bargaining power with the aim of the land being restored by the operators after mining is complete.

Acknowledgements

The authors are grateful to GEOPROBE Int'l Consult Ltd for sponsoring this research through providing field equipment, logistics, field personnel and the AGI 1D software used in the data processing.

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