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Recognition of boulder in granite deposit using integrated borehole and 2D electrical resistivity imaging for effective mine planning and development

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Abstract: Evaluations of a mineral resource are necessary for mineral rights, owners and investors alike. However, for resource evaluation the detail documentation of subsurface geological spatial distribution such as lateral and vertical extent of bedrock and topsoil, hydrogeological investigation and boulder characterisation is mandatory. Boulder is hard and crystalline compact rock block, which substantial presence in a deposit highly influence the drilling equipment selection. A traditional exploration technique particularly for granite resource evaluation is drilling. But even finite number of drilling sample fails in the accurate delineation of boulders because drilling is limited to small point and rock mass is heterogenous and thus immense portion of the deposit via drilling method remain discern. 2D electrical resistivity imaging (2D ERT) technique of the study area over an area of 3.5 km^2 was accomplished by six resistivity lines using a Schlumberger protocol with inner and outer electrode spacing of 5 m and 10 m respectively. Inverted resistivity images successfully identify the existence of boulders in the area of investigation in the topsoil region; characterized by high resistivity values more than 2400 Ω.m. Whereas, only one core log (BH3) out of three reported presence of boulders. Thus, the research study presented in this paper enables us to conclude that the combined application of borehole and ERT allows us to derive that 2D ERT enhances the resource evaluation efficiency and reduces the cost considerably for underlying subsurface geological characterization.

Keywords: Electrical resistivity imaging, boulders, granite, borehole, mine planning

Abstrak: Penilaian sumber mineral diperlukan untuk hak-hak mineral, pemilik dan pelabur. Walau bagaimanapun, bagi penilaian sumber mineral, dokumentasi terperinci geologi permukaan bawah seperti rentangan tegak dan sisi batu dasar, penyiasatan hidrogeologi dan pencirian batu tongkol adalah mandatori. Batu tongkol adalah blok batuan kompak keras dan berhablur, di mana kewujudannya di dalam deposit sangat mempengaruhi pemilihan peralatan penggerudian. Teknik penerokaan tradisional terutamanya untuk penilaian sumber granit ialah melalui kaedah penggerudian. Walau bagaimanapun, dengan bilangan sampel penggerudian yang banyak, masih belum dapat mengenalpasti kehadiran batu tongkol secara tepat, ini adalah kerana, kaedah penggerudian adalah terhad kepada titik kecil dan massa batuan adalah heterogen dan sebahagian besar deposit melalui kaedah penggerudian masih dapat dilihat. Pengimejan resistensi elektrik 2D (2D ERT) dari kawasan kajian sepanjang 3.5 km^2 dicapai oleh enam garis resistivity menggunakan protocol Shlumberger dengan jarak elektrod dalam dan luar masing-masing 5 m dan 10 m. Imej kerintangan terbalik berjaya mengenalpasti kewujudan batu tongkol di kawasan penyiasatan di kawasan tanah atas yang dicirikan oleh nilai resistivity melebihi daripada 2400 Ω.m. Manakala, satu log teras (BH3) daripada tiga laporan menemukan kehadiran batu tongkol. Oleh itu, kajian penyelidikan yang dibentangkan dalam makalah ini membolehkan kita menyimpulkan bahawa gabungan aplikasi lubang jara dan 2D ERT membolehkan kita membuat kesimpulan bahawa 2D ERT meningkatkan kecekapan penilaian sumber dan mengurangkan kos dengan ketara untuk pencirian geologi bawah permukaan asas.

INTRODUCTION

Mineral exploration is the initial and essential stage of a mining cycle (Figure 1), which covers prospecting, mapping and surveying of a mineral deposit (Haldar, 2012). In simple words, mineral exploration is the systematic evaluation of the mineral deposit with a view to mine it profitably and efficiently. This shows that efficient evaluation of the mineral repository is the key to successful mine planning and development. However, for successful mine planning and development the efficient delineation of numerous subsurface geological features such as determination of lateral and vertical extent of topsoil and bedrock, hydrogeological investigation and recognition of boulders is prerequisite. Boulder is a block of hard rock present in rock reserve, which immense quantity highly influence mine planning, particularly selection of drilling equipment.

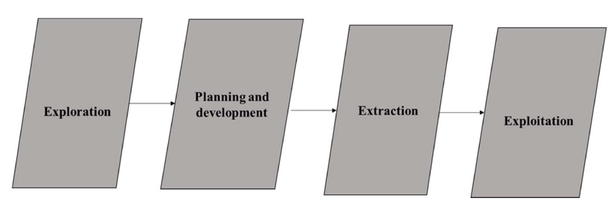

Figure 1: Mining operation stages.

Boulder is the normal geological features that associates with a granitic terrain (Twidale & Romaní, 2005). Boulder is a crystalline compact rock mass which is hard enough to be excavated easily. Therefore, the presence of boulders in rock accumulation greatly influence rock penetration (Weaver, 1975). The presence of a substantial amount of boulders in a deposit may cause the need of special drilling equipment. Hence, this cause the need of detail documentation of underlying geological characteristics, particularly, boulder layers, before commencing mining. Traditional technique for granite resource evaluation is direct method such as boreholes, trial pits and trenching (Collis & Smith, 2001; Wardrop, 2012). Despite the fact that drilling sample provides univocal and efficient vertical subsurface geological information, drilling exploration techniques have some principle limitations in detail subsurface determination. Rock mass is heterogenous and vary over a small region, whereas drilling samples are limited to a small area or even a single point. As such, even a large number of core samples may misinterpret subsurface geology since core samples are collected at regular intervals far apart from each other. Hence, massive portion of the deposit remain obscure, due to the unidentified gaps between the core samples (Baines *et al*., 2002). To add more drilling exploration technique is also time consuming and expensive. Therefore, there is an increasing intention towards novel approaches for detail subsurface geological characterization of granite deposits. To this end, geophysical exploration, particularly 2D ERT is the best non-destructive and indirect alternative technique to discern subsurface geology efficiently.

2D ERT has been found to be more efficient in various studies like hydrogeological study, ground water exploration, geotechnical site investigation, environmental assessment and archaeological site investigation (Abu-Zeid *et al*., 2004; Aristodemou & Thomas-Betts, 2000; Awang *et al*., 2016; Cassiani *et al*., 2006; Chambers *et al*., 2006; Dahlin & Zhou, 2004; Drahor *et al*., 2008; Lesparre *et al*., 2016; Loke & Lane Jr, 2004; Mansoor & Slater, 2007; Marsan *et al*., 2017; Martínez-Pagán *et al*., 2009; Metwaly & AlFouzan, 2013; Mojica *et al*., 2017; Stan *et al*., 2017; Yeh *et al*., 2002). Application of electrical resistivity imaging in realm of mineral exploration is also found to be efficient and effective (Beauvais *et al*., 1999; Cardimona, 2002; Chambers. J. *et al*., 2013; Maganti, 2008; Ritz *et al*., 1999; Zhang *et al*., 2017). Fundamental principle of electrical resistivity imaging is the injection of galvanic current via a pair of contiguous current electrodes and measuring the potential difference across other twin electrodes subsequently (Cardimona, 2002; Dahlin, 2001; Samouëlian *et al*., 2005; Zhang *et al*., 2017). The desired targeted depth is manipulated by increasing the electrode spacing, however, the resolution will be decreased (Guinea *et al*., 2014; Maganti, 2008). The increasing interest of exploiting electrical resistivity imaging for mining and geotechnical investigation in the last few decades is mainly favoured by automated computerize data acquisition resistivity instrument and rapid 2D and 3D inversion software. Furthermore, 2D ERT is simple, rapid, inexpensive and a viable technique for subsurface geological features identifications (e.g. Beresnev *et al*., 2002; Bharti *et al*., 2016; Chambers J. *et al*., 2013; Chambers J.E. *et al*., 2006; Dahlin & Zhou, 2004; Longo *et al*., 2014; Meju, 2002; Mojica *et al*., 2017; Rucker *et al*., 2012; Van Schoor, 2002).

This research attempts to image the subsurface boulder layer in a granite deposit, using a combination of 2D ERT and borehole. Few borehole data of the study area was also collected to accurately estimate the thickness of the topsoil layer. Furthermore, the comparison between core sampling and 2D ERT for identifying boulders was also made in this paper. However, this research work is mainly to demonstrate the success of 2D electrical resistivity imaging technique for recognition of underlying boulder formation in a granite resource. The resistivity anomaly due to the presence of boulder layers is also presented by the authors.

GEOLOGY OF STUDY AREA

The study area is located in Senawang district, Malaysia about 7 km east of Seremban Jaya, the nearest town. The study area spreads over an area of 3.5 km^2. The ground elevation of the area is in the range of 150-250 m. The site can be accessed via an unpaved road from the Seremban-Tamping trunk road.

The study area as shown in the geological map of Senawang District (Figure 2) lies in the formation of acid intrusion (undifferentiated) igneous rocks (Hutchison & Tan, 2009). Being part of the Main Range, the rock type is classified as plutonic rock namely granite (Main Range Granite). In general, the main range granite possess restricted composition with relatively high silica content (Hutchison & Tan, 2009). Whereas the term plutonic refers to the formation of the rock by slow cooling of magma beneath the earth surface. The plutonic rock is believed to form in Late Triassic, which shows the age range of 200-300 Ma (Hutchison & Tan, 2009). The granite formation to the west is bounded by metamorphic rocks namely schist, phyllite and slate.

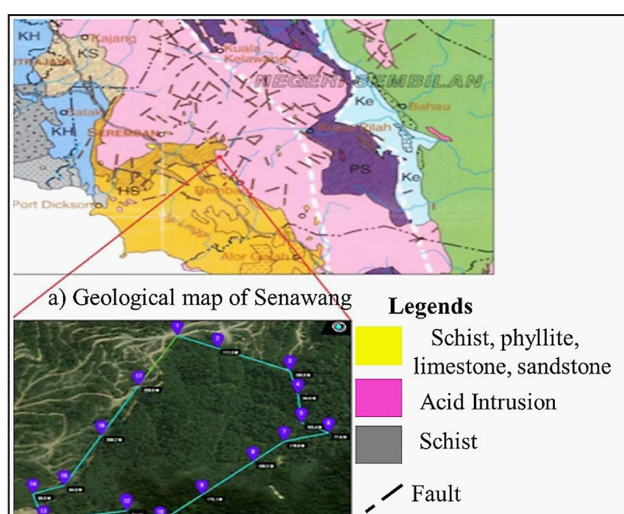

Figure 2: Geological Map of Senawang District, Malaysia (after Hutchisan & Tan, 2009; Arisona *et al*., 2017).

Figure 2a represents the geological information of the Senawang district. The major portion of the district is acidic intrusion, shown in purple colour. The study area is located in Seremban, within the acidic intrusion. The geology of the study area is majorly composed of granitic rock and also its associates - limestone, phyllite, schist and sandstone. The study area also includes a great quantity of major and minor faults as shown in Figure 2a (Arisona *et al*., 2017).

METHODOLOGY

2D electrical resistivity imaging data acquisition

The 2D ERT survey arrangement in the area of investigation comprised of six resistivity lines (R1, R2, R3, R4, R5, R6) at various locations having lengths of 400 m each, schematized in Figure 3. The subsurface apparent resistivity data was acquired by exploiting multichannel ABEM LS Terameter, connected to two multi cable system with 31 output each, allowing a total number of 62 stainless steel electrodes arrangement linearly (Lesparre *et al*., 2016; Longo *et al*., 2014; Persson *et al*., 2011). Prior to the resistivity data collection, the total number of electrodes (61 electrodes, one electrode as the center electrode) and spacing (5 m) between them was set, which remained constant throughout the survey. The resistivity data was collected using Shlumberger protocol (n=2) with inner and outer electrode spacing 5 m and 10 m respectively. The Shlumberger array configuration was employed for data acquisition, because of good compromise for both vertical and horizontal structural resolutions (Bharti *et al*., 2016; Cardimona, 2002; Samouëlian *et al*., 2005; Tejero *et al.,* 2017; Zhou & Dahlin, 2003).

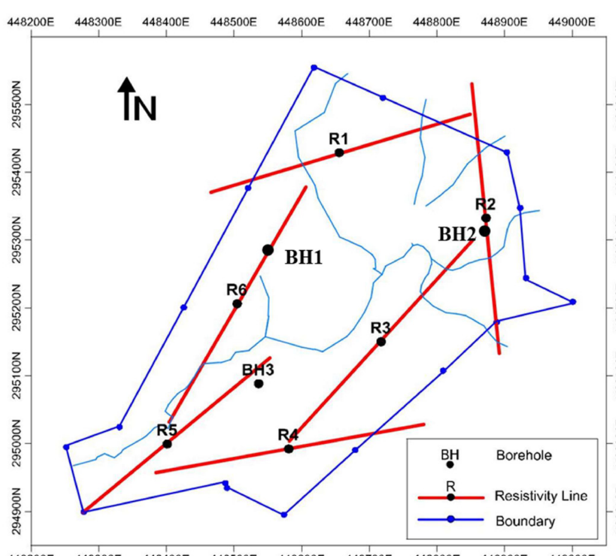

Figure 3: Resistivity survey line and borehole location.

Figure 4: rock core samples obtained from boreholes.

Borehole data collection

Boreholes were also drilled for providing hard data to compliment and assist in interpreting the 2D ERT results. Three boreholes (BH1, BH2, BH3) as shown in Figure 3 were drilled at various location of the site exploiting YWE-D90R boring plant.

Borehole investigation of the site was made in accordance with BS 5930:1981. The topsoil thickness was inferred by using information from three boreholes BH1, BH2, BH3 located at different points. Identification of different rock strata from core samples was made based on the color of return water and washed drill cuttings. The diameter of recovered borehole samples of BH1, BH2, BH3 was 54 mm and the core lengths were 10.50 m, 16.50 m and 32.50 m respectively, depicted in Figure 4 (a-c).

RESULTS AND DISCUSSION

Inverted resistivity images of 2D ERT survey line (R1, R2, R3, R4, R5, R6), spread at various locations show huge resistivity contrast, presented in Figure 5(a-c) and Figure 6(a-c). Three different geological strata types have been identified i.e. topsoil (800 Ω.m), fracture granite (800-1800 Ω.m) and solid granite (>1800 Ω.m). The different resistivity range of these geological strata shows the effect of weathering and presence of water content and impurities. Resistivity of the rock mass is a function of porosity, permeability, weathering and presence of water content, as well as mineral composition,

Table 1: 2D ERT and borehole survey results.

Type of survey	Survey no	Result	Characterised by
2D ERT	R1	Boulder detected	High Resistivity Value (2400 ohm.m)
	R2	Boulder detected	High Resistivity Value (2400 ohm.m)
	R3	Boulder detected	High Resistivity Value (2400 ohm.m)
	R4	Boulder detected	High Resistivity Value (2400 ohm.m)
	R5	Boulder not detected	-
	R6	Boulder detected	High Resistivity Value (2400 ohm.m)
Borehole survey	BH1	Not detected	-
	BH2	Not detected	-
	BH3	Boulder detected	Continue free bore in soil after reamed casing in to boulder

texture and structure of soil and rock. As topsoil is more exposed to the weathering and is composed of sandy soil, it shows low resistivity values. However, an unexpected high resistivity value more than 2400 Ω.m, represented by dark greenish colour was reported by inverted resistivity imagines. This high resistivity value layer near the earth surface reveals the presence of boulders because topsoil resistivity value should be less than 800 Ω.m. The high resistivity value of boulders is inherited from the fresh granite resistivity that was formed by solid crystallization of mineral and unaffected by weathering. The trend of unexpected high resistivity values in topsoil is shown by five resistivity lines namely R1, R2, R3, R4 and R6. On the other hand, only one bore hole (BH3) among the three borehole samples (Figure7(a-c)) was successful in detection of boulder formation.

The multidisciplinary research methodology presented in this paper allows us to conclude that 2D ERT describes the subsurface geology more rapidly, efficiently and economically. The 2D ERT results are of subsurface geology until 90 m deep, while the borehole investigation is only to a maximum depth of 32.5 m. Moreover, 2D ERT has effectively diagnosed the possible boulders in the granite district. On the other hand, only one of the three rock core samples reported boulder existence in the study area. The core samples therefore had misinterpreted the substantial presence of boulders in the study area. The boulders throughout the strata were found in the upper region that is topsoil, confirmed by the concordant results of both 2D ERT and borehole survey. As mentioned earlier, boulder is the solid compact rock strata which is difficult for ordinary core drilling. As such, after the boulder detection at BH3, drilling was continued by reaming casing into the boulders. This suggests that drilling in boulders strata is quite difficult, but the accurate information of boulder location in deposit is extremely important before commencing mining. To this end, 2D electrical resistivity imaging compared to borehole survey was justified as most effective and the efficient technique. But for accurate recognition of boulder formation in a strata, the knowledge of its influence on resistivity of rock mass is prerequisite. The boulders being solid and compact and having no probability of fracturing and containing any impurities is less conductive. Hence, the resistivity of topsoil that is naturally less than 800 Ω.m. is increased to 2400 Ω.m. with the presence of boulders.The increasing resistivity trend due to boulder existence in granite deposit is shown in Figure 8 (a-e). Thus, according to the results obtained by 2D ERT imaging and borehole survey (Table 1), there are boulders in the study area but not at a significant level to influence drilling equipment selection. The study also shows that the resistivity of granite solid bedrock and boulders overlaps and can be incorrectly mapped if using 2D ERT independently. The borehole survey reduces the ambiguity in inverted resistivity images by being able to estimate the thickness of the topsoil. This shows that for efficient subsurface geological characterization, 2D inverted resistivity imaging must be carried out in integration with borehole or other geophysical technique.

CONCLUSION

The research work presented in this paper enables us to conclude that 2D ERT has successfully revealed the existence

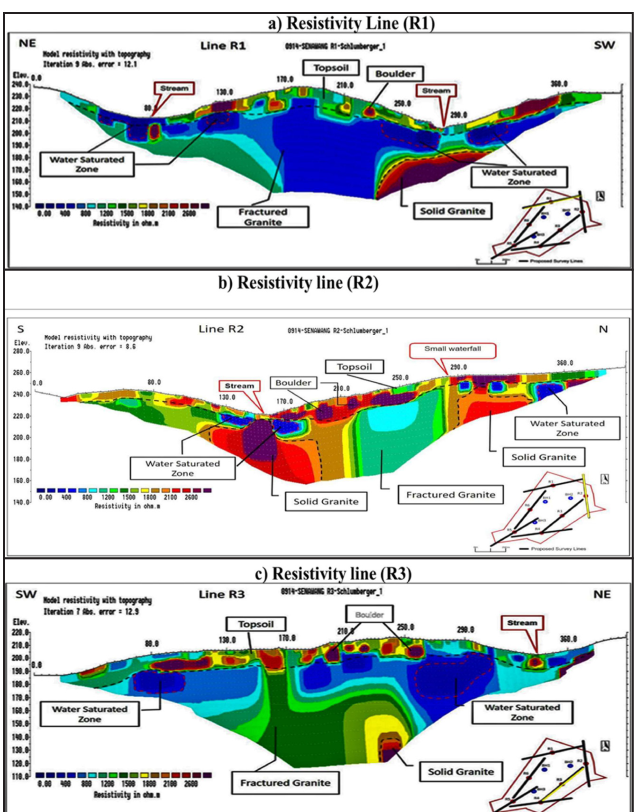

Figure 5: Inverted resistivity images.

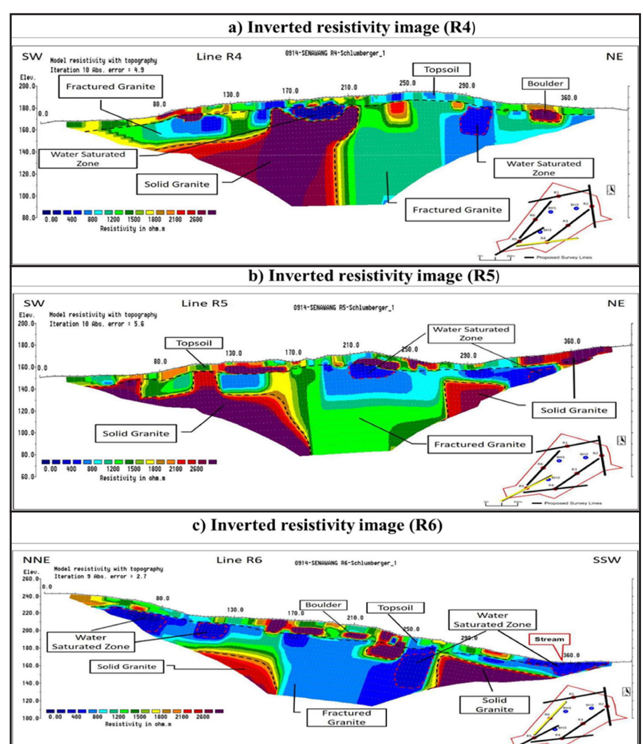

Figure 6: Inverted resistivity images.

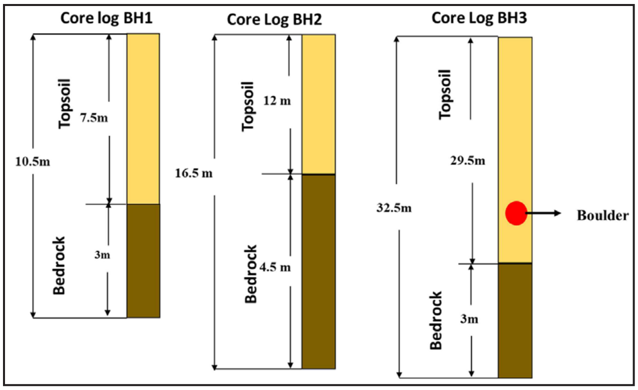

Figure 7: Core samples identifying boulders.

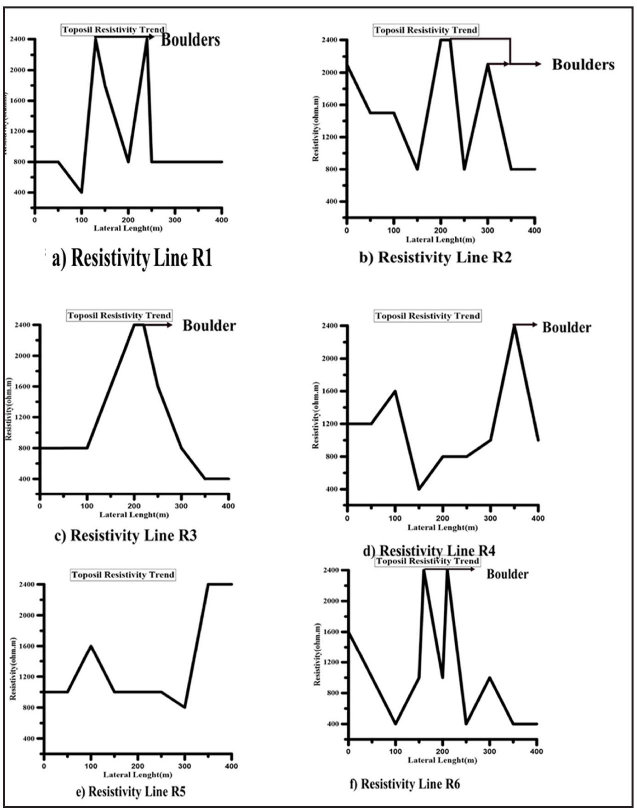

Figure 8: Trend of boulder effects on topsoil resistivity.

of boulder formations in the study area. All the boulders were encountered in the topsoil region. As the topsoil has less than 30% rocks and is mainly composed of sandy soil, it has low resistivity values, less than 800 Ω.m. But the unexpected encounter of high resistivity value of about 2400 Ω.m in this region indicates the presence of compact, hard and unweathered rock block called boulders. 2D inverted resistivity images compared to borehole data encountered immense existence of boulders in the study area. Thus, the integrated application of borehole and 2D ERT presented in this paper allows us to argue that the borehole survey for boulder identification was found to be less efficient, due to the reason that the depth of investigation by core samples was not considered enough for detail subsurface delineation. Nevertheless, borehole survey was found to be efficient in estimating thickness of topsoil which helps avoid ambiguity in inverted resistivity images. Because the resistivity of solid granite bedrock and boulder strata can be overlapping, the results may be misguided. Thus, the accurate estimation of topsoil thickness by the borehole survey diminished the ambiguity from 2D inverted resistivity images. This allows us to conclude that the integrated application of borehole survey and 2D ERT enhanced the resource evaluation efficiency and reduce the cost considerably for underlying subsurface geological characterization.

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