Journal of Himalayan Earth Sciences Volume 54, No. 1, 2021 pp. 11-32

2D Electrical Resistivity Tomography an advance and expeditious exploration technique for current challenges to mineral industry

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Submitted date: 09/02/2020 Accepted date: 24/02/2021 Published online: 31/03/2021

Abstract

The rapid urbanization and industrialization are spurring a rising demand for building materials, base metals, and industrial minerals. This causes the need of increasing exploration activities of greenfield mineral deposit. While, in contrary mining industry in recent years discover fewer greenfield deposit, due to the high costs of traditional exploration (drilling and trenching) methods and low success rate in discovery of the mineable deposit. Whereas, the substantial growth in demand for mineral commodities increased the need for more new discoveries. To this end, innovations in exploration strategies are required. This paper attempts and overview of available techniques (drilling, geochemical and geophysical) for evaluation of mineral deposits, focusing on fundamental principles, and the advantages and disadvantages of each technique. The paper also presents a critical comparison of these exploration techniques, considering equipment cost, time required for data collection and interpretation and also the efficiency of deposit assessment of each method. The major advantages and disadvantages of the techniques presented is discussed in text and as well as tabulated. Finally, the future challenges in exploration are discussed and recommendations for alternative techniques is mooted.

Keywords: Mineral exploration, 2D electrical resistivity imaging, Drilling, Geochemical, Geophysical.

1. Introduction

The rapid urbanization and industrialization are spurring a rising demand for building materials, base metals, and industrial minerals. The increasing trend of mineral commodities is predicted to not ceased by 2050 (Xiang, Chen et al. 2018). This growing demand for mineral commodities necessitates the need of exploration of greenfield deposit. Therefore, the holy grail of mineral industry is to identify new subsurface mineral resources in order to meets the global mineral commodity demand. In other words, the ultimate aim of the mineral industry is to make it possible to identify clearly below a mine site and to localize and map the extent of the resources aiming at reduced exploration investment and time and increased profit.

However, currently the mining industry faces several challenges such as low success rate in the discovery of economic mineable deposits, high costs associated with exploration activity, shortage of exploration budget and increasingly high demand for mineral commodities. According to published data, the rate of success is 1:20-24 for brownfield (known deposits) and 1:200-3333 for greenfield (unknown deposits) exploration (Kreuzer 2007). These numbers indicate a huge exploration cost with using conventional boring and trenching. For example to make a project successful for mining approximately 20,000 exploratory holes (cost USD 1,000 million) are required for a major discovery, 2000 holes (USD 200 million) for a moderate discovery and 200 holes (USD 30 million) for a minor discovery (Schodde 2003, Kreuzer 2007). Thus, due to the high costs tailored with traditional drilling exploration technique, many exploration companies face deficits in their exploration budget Fig 1a (Wilburn and Bourget 2010). The insufficiency of exploration budget results from the rising cost of instruments, expensive labour, high cost related to environmental regulations when using conventional drilling exploration technique (Minings 2016, Junaid, Abdullah et al. 2019). This has caused decrease in exploration activities and has ultimately resulted in fewer discoveries of new mineral resources in recent years. On the other hand, the production of mineral commodities has shown an increase Fig 1b in the last few years (Survey 2012, Survey 2015). The growing demand of minerals necessitates an increasing pace of new mineral discoveries. However, the real scenario is in contrast, because many exploration companies seized exploration activities resulting in lower pace of new mineral resource discoveries than is required.

To cope with increasing demand for mineral commodities, the pace of exploration activities should be increased. For these purposes an innovation in exploration strategies are required, to reduce the time and cost involved in the quality assessment of a mineral district. The key problem for the mining industry is to obtain enough subsurface information based on a small amount of drilling core data. Since, the end of 18th century the fundamental technique used for mineral exploration was drilling (Ma et al. 2016). The drilling technique is considered no more feasible because of high investment and more time required to completely assess the subsurface mineral resources. However, in the beginning of 19th century the development of various geophysical exploration techniques such as gravity, magnetic, seismic, 2D electrical resistivity tomography (2D ERT) and electromagnetic makes it possible to obtain required subsurface information with limited core data. These aforementioned techniques contribute a lot to subsurface geological investigation in last decades (Eckhardt 1940, Hinze 2013, Alsadi and Baban 2014). The geophysical exploration techniques particularly 2D ERT provide a promising approach to diagnose subsurface geology rapidly, efficiently and economically. This paper presents an overview of various geological and geophysical exploration techniques considering applicability, efficiency and limitations of each technique available for mineral exploration. Recommendation of alternative inexpensive and expeditious technique other than drilling for subsurface mineral exploration has also been made by the authors.

Exploration drilling

Exploration drilling is the collection of samples of soil or bedrock by vertical deep drilling through the bedrock followed by laboratory analysis (Marjoribanks 2010, Coal 2011). Drilling technique involve the collections of samples of rocks in the form of rock cores or rock chips followed by qualitative analysis of the rock samples in the laboratory. Drilling for mineral exploration is a two-stage process. Initially, more widely spaced narrow diameter holes are drilled to confirm the presence of a mineral anomaly. Once, the presence of the mineral anomaly is confirmed, then more closely spaced holes are drilled to precisely evaluate the economic viability of the deposits.

Exploration drilling have greater depth of investigation (up to several kilometers) compared to other techniques. In contrast the principal limitation of exploration drilling is that it provides discrete lateral information. Since, rock mass is heterogeneous and vary within a small region, while, drilling samples are limited to a small area or even a single point, therefore core sample cannot be rely as representative of whole mineral repository (Baines, Smith et al. 2002). Because, immense subsurface geology leftovers undiscerned due to several unidentified gaps between the core samples. Hence, despite having good vertical investigation depth, rock core sampling is considered insufficient for detail subsurface geological characterization of the deposit. Furthermore, exploration drilling data collection and analysis is slow and costly (GWA , Hinze 1990, Heller 1993, Minnesota 2014, Tejero, Gomez-Ortiz et al. 2017). The high cost associated with exploration drilling is due to site preparation before and rehabilitation after exploration activity. In addition, application of drilling method is restricted to specific areas, due to the large space

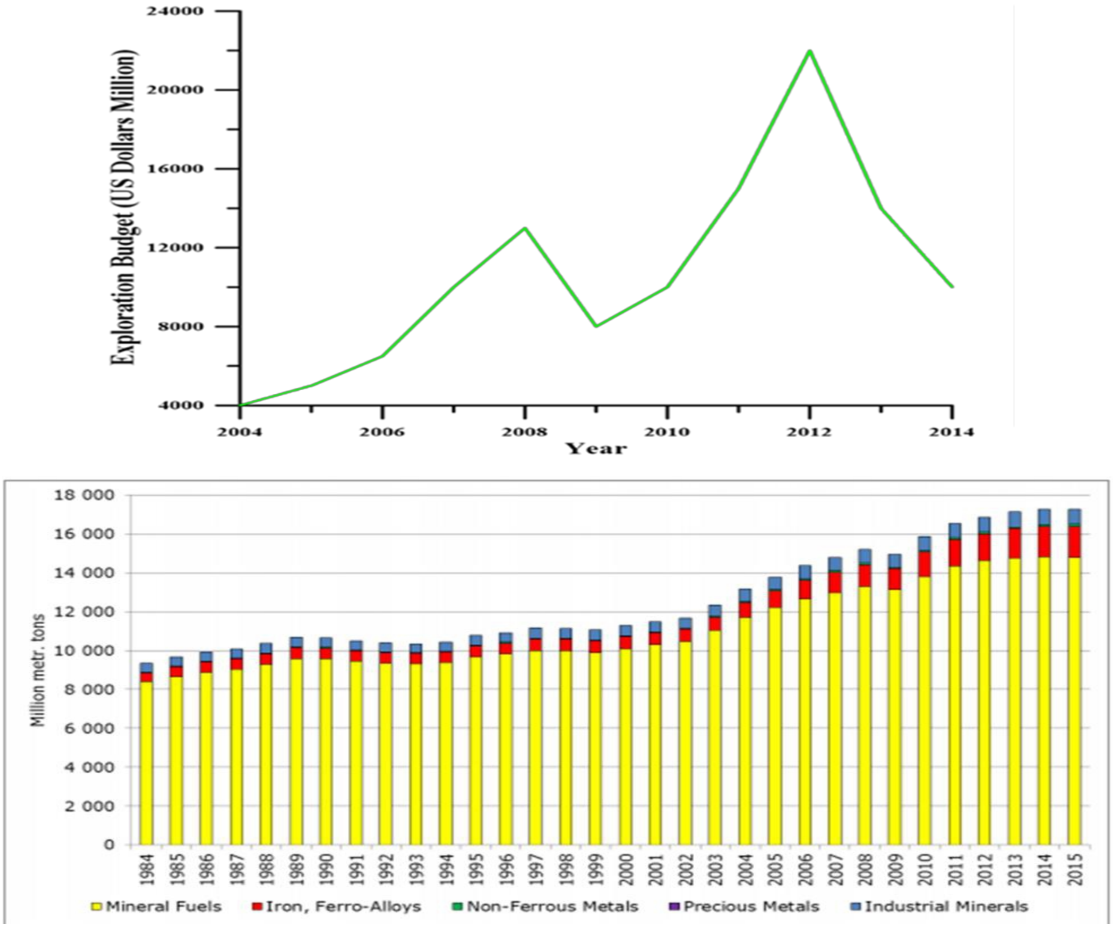


Fig. 1. World mineral exploration budget versus mineral production [Wilburn et al., 2010]

requirements for equipment. Moreover, high safety precautions are required in drilling operation, as many serious and fatal cases have been reported, because of heavy equipment involved in drilling sampling (Heller 1993, Chambers, Wilkinson et al. 2012, Minnesota 2014). The critical evaluation of pros and cons mention above, drilling exploration techniques is considered costly and time consuming.

3. Geochemical exploration

Geochemical method works on practical application of geochemical and biological prospecting and data, to investigate the mineral deposit and hydrocarbon accumulation (Boyle and Garrett 1970). The fundamental principle of the geochemical exploration is that the earth crust in vicinity of mineral deposit will have a different chemical composition than the similar material where there is no mineral deposit.

Geochemical exploration method is less expensive technique but is not widely used because it only confirms presence of a mineral anomaly or hydrocarbon constituents. This limits the application of geochemical exploration technique for reconnaissance survey that is for identification of mineral anomaly only. The primary requirements for describing the economic potential of the mineral inventory is to identify the vertical and lateral extent of the deposit. Geochemical exploration technique can-not provide this information and thus lacks the capability to describe the economic potential of the hydrocarbon reservoir or mineral deposit. This makes it unreliable technique for mineral exploration (Govett 2013). The geochemical method also fails to provide the structural information about the source rock (Philp and Crisp 1982). Geochemical explorations only provide information on the mineralogical composition of the deposit, whereas, various lithological features such as faults, folds and discontinuities cannot be obtained by geochemical survey.

4. Geophysical exploration:

Geophysical exploration broadly covers various exploration techniques such as gravity, magnetic, seismic, 2D ERT and electromagnetic, which use the physical properties of rock for subsurface geology documentation, hydrological study and geotechnical and environmental site investigation at or near-earth surface. The fundamental principle and operative physical properties of various geophysical exploration techniques are summarized in Table 1 (Robinson 1988, Kearey, Brooks et al. 2013, Scott and Eng 2014). The range of physical properties of numerous rocks measured by various geophysical techniques are listed in Table 2.

4.1. Gravity method

Gravity is a potential field, which is a force of attraction that acts at a distance (Pit Hil 1997, Mariita 2007). The gravity method provide the subsurface geological and geotechnical information based on the variation in earth gravitational field,due to change in rock densities laterally in the vicinity of measuring point. In other words gravity survey measures the variation in acceleration due to gravity.

Gravity method is reported to be an inexpensive and suitable technique for studying earth structure feature laterally, after diversified applications such ground water, mineral and hydrocarbon exploration, geotechnical and environmental investigation, (Leaman 1973, Carmichael and Henry Jr 1977, Ali and Whiteley 1981, Aboud, Selim et al. 2011, Reynolds 2011, Lelièvre, Farquharson et al. 2012) . The principle advantage of gravity method is its less susceptibility to cultural noise and hence gravity survey can be carried out in heavily populated areas. Ground vibration is the only noise which may affect gravity data, which may result due to vehicular traffic, low flying aircraft, heavy equipment or wind.

The gravity method requires several readings at a single station in order to survey precisely for latitude and elevation. This makes surveying large areas using gravity method uneconomical and time consuming. The quality of gravity data is also affected by many temporal variations such as free air, bouguer, earth tides and topographic anomalies and many corrections and reductions for these errors are required in interpretation of gravity data (Ali and Whiteley 1981, Hinze 1990, Kana, Djongyang et al. 2015, Thomas 2016) .

4.2. Magnetic method

Magnetic method is passive geophysical exploration method, which provide subsurface geological information based on magnetism. Magnetism like gravity is a potential field, which is the force that acts on another magnetic body or electrically conducting material at a distance (Hinze, Von Frese et al. 2013). The operative physical property for magnetic method is the magnetic moment per unit volume, which is the vector sum of induce magnetization obtained by the product of magnetic susceptibility and permanent or remnant magnetization (Sharma 1987, Hinze, Von Frese et al. 2013, Yassonov and Nurgalieva 2013).

Magnetic method an indirect geophysical technique that is considered useful in characterizing and mapping geological structures (Aboud, Selim et al. 2011, McClenaghan 2011, Kana, Djongyang et al. 2015, Khan, Bilali et al. 2018). Magnetic exploration may detect directly some iron ore deposits (magnetite or banded iron formations). It is often useful for deducing subsurface lithology and structure. Comparative to other geophysical method, the magnetic method is less expensive, having operation cost three times less than the gravity method (Hinze 1990, McClenaghan 2011, Kana, Djongyang et al. 2015). The survey requirements for magnetic method are not as stringent and therefore data collection is comparatively faster and inexpensive.

However, magnetic method makes a limited contribution in mineral exploration, because of low vertical depth of investigation compared to other geophysical techniques (Hinze 1990, Bevan 1998, Kana, Djongyang et al. 2015). For mineral resource evaluation, subsurface geological identification is required to a greater extent both laterally and vertically. Whereas, a limited subsurface investigation depth makes it inappropriate for detail evaluation of a mineral deposit. Furthermore, the high sensitivity to cultural noise due to various sources such as man-made structures made of ferrous material, traffic and high voltage electric cables have greater effects on the quality of magnetic data. This makes the magnetic method inappropriate for mineral exploration covering large and populous areas. Although, being the rapid data collection ability, the interpretation of the data is complex due to high sensitivity to noise that is the: inability in interpretation method to differentiate between various steel objects (Clark 1983, Hinze 1990, Telford, Telford et al. 1990, Kana, Djongyang et al. 2015). Therefore, the complex interpretation due to several corrections and reductions associates with magnetic data, reduces its application in mineral exploration. Furthermore, magnetic and gravity method are mostly used combinedly to complement each other prior to the use of other geophysical techniques.

4.3. Seismic method

Seismic method for subsurface geological investigation exploits propagation of strain energy, as an elastic wave (artificially generated seismic waves) in subsurface ground. Elastic waves are generated by sledgehammer striking a plate or block, weight drop, or an explosive charged in buried hole. The transmitted elastic waves, refract or reflect at boundary having varying density or elasticity. Measuring the arrival time of the transmitted wave back to the surface and velocity of the wave, provides base for geological interpretation (LANGE , Weller 1974, Sengbush 2012).

In comparison to other geophysical methods, seismic method has maximum depth of investigation (up to 3000m) and high vertical resolutions (Milkereit, Berrer et al. 2000, Salisbury, Milkereit et al. 2000, Salisbury and Snyder 2007, Al-Anezi, Al-Amri et al. 2012). The greater depth of investigation and low operative cost compared to drilling, makes seismic method appropriate technique for deep hydrocarbon explorations.

Seismic method compare to other geophysical technique is considered expensive for mineral exploration (Salisbury and Snyder 2007, Lelièvre, Farquharson et al. 2012, Sengbush 2012). As, most minerals lie at depth up to 200 m, which can easily be investigated by other inexpensive geophysical techniques. Therefore, seismic method is limited to hydrocarbon exploration. The other serious limitation of seismic method in mineral exploration is that most minerals occur in sedimentary geology, seismic data in such areas have high noise (Van Overmeeren 1981, Eaton 2003, Salisbury and Snyder 2007), because sedimentary geology is usually hard rock. To overcome noise problem in sedimentary geology using seismic method, dynamite is usually practiced to produces high frequency seismic waves, which makes seismic method uneconomical and unreliable technique. Compare to 2D ERT, seismic data collection and interpretation is slow and time consuming. It is therefore argued that for mineral exploration other than hydrocarbon, 2D ERT is expeditious and inexpensive technique compare to seismic method.

4.4. 2D electrical resistivity tomography (2D ERT)

2D ERT is the study of earth response to the current. The subsurface geological characterization using 2D ERT is carried out by galvanic injection of DC current in to the ground surface by pair of electrodes and measuring resultant potential difference simultaneously by other pair of electrodes. Depending on the electrodes arrangement 2D ERT survey may be carried out either Schlumberger, Wenner, Dipole-Dipole or Pole-Dipole array, however that is not within the scope of this paper (Loke 1999, Cardimona 2002, Bentley and Gharibi 2004, Samouelian, Cousin et al. 2005, Auken, Pellerin et al. 2006, Maganti 2008, Karaaslan and Karavul 2018).

In comparison to other geophysical exploration techniques, 2D ERT have low operation cost, fast and easy data collection and interpretation and less sensitivity to culture noise (Meju 2002, Rucker, Crook et al. 2012). Furthermore, the wide range of earth material resistivities also makes the method applicable to identification of earth lithologies and structures that control identification. 2D ERT is reported a reliable and efficient technique by several authors after being applied for wide spread purposes such as mineral exploration, environmental, hydrogeological and archeological site investigation (Griffiths and Barker 1994, Macnae 1995, Dahlin 1996, Van Schoor 2002, Yeh, Liu et al. 2002, Abu-Zeid, Bianchini et al. 2004, Lapenna, Lorenzo et al. 2005, Auken, Pellerin et al. 2006, Cassiani, Bruno et al. 2006, Papadopoulos, Sarris et al. 2009, Chambers, Wilkinson et al. 2012, Mojica, Pérez et al. 2017). 2D ERT gives the quantitative model of subsurface geology, which can provide the accurate estimate of thickness, depth and resistivity of subsurface of layer.

Serious limitations of 2D ERT is that unlike other geophysical methods, direct contact of electrodes with ground surface is required (Frederick D. Day-Lewis). If any electrode lacks direct contact with the ground surface the quality of the data is affected significantly. To add more, the resistivity data can be affected by various non geological sources such as (pipelines, buried utility cables and ground power lines), lateral near surface geological variation and lightening or natural earth current (Sheriff 2002, Lucius, Langer et al. 2007). Therefore, larger area, far removed from these sources of noise is required for 2D ERT survey. Another consideration regarding 2D ERT is that the data collection requires at least three crewmembers, which make it labor intensive compare to gravity and magnetic method. However, although 2D ERT have low vertical depth of investigation as compared to seismic and electromagnetic methods, the simplicity of operation, low cost and sophisticated results, 2D ERT is the most widely used technique for shallow mineral exploration.

4.5. Electromagnetic method

The fundamental principle of electromagnetic method is, that an electromagnetic field is generated by a transmitter coil which propagates into the subsurface. As the electromagnetic wave travels through the ground, eddy current is induced in the ground. The eddy current result in the generation of secondary magnetic field which is detected by the receiver. The receiver usually detects both the primary and secondary field (West and Macnae 1991, Cheng, Smith et al. 2009).

The major advantage of electromagnetic method is its good depth of investigation and diversified data collection ability such as surface, marine and airborne for various purposes for example mineral and groundwater exploration, geotechnical and environmental site investigation (Spies 1989, Gough 1992, Macnae 1995, Karlık and Kaya 2001). The electromagnetic data can easily be collected rapidly with fewer personnel required.

The key disadvantage of electromagnetic induction is complexity in data collection and interpretation (West and Macnae 1991, Karlık and Kaya 2001). Because, in electromagnetic method both electric and magnetic fields are involved which makes it highly sensitive to cultural noise. This makes the interpretation of electromagnetic data complex because the corrections associate with both electric and magnetic field. Thus, like seismic method electromagnetic method is not considered economical for shallow mineral exploration, due to high associated costs and complex data collection and interpretation.

5. Critical comparison of various explorations techniques

Based on the literature Table 3 summarizes multi-criteria critical comparison of various exploration techniques, considering numerous parameters, such as efficiency in term of depth, efficacy, time and personnel required for data collection and interpretation.

Table 3 makes us to assume that each technique possesses some pros and cons. Not even a single technique can be considered appropriate for subsurface investigation of all type of geological environment. This means that the efficiency of these methods is highly influenced by the deposit type and type of study sought. The type of deposit refers to the type of anomaly to be identified. For example, for hydrocarbon exploration, seismic method is better option because deep subsurface information is usually needed. In hydrocarbon exploration gravity and magnetic surveys can also be used for studying the lithological features prior to seismic survey. On the other hand, as most minerals usually lie in sedimentary geology and seismic survey associated high noise in such geological environment. Therefore, for mineral exploration in sedimentary environment 2D ERT is more reliable then seismic survey. In addition, 2D ERT is considered the most appropriate exploration technique for mineral exploration compared to other geophysical techniques, because of its simplicity and low cost compare to seismic, and better efficiency than gravity and magnetic methods. The type of study to be sought means whether the target is shallow or deep and the area to be investigated extended larger or small. For shallow subsurface investigation over a small lateral extent, gravity and magnetic methods can be considered as inexpensive and fast techniques. Whereas, for deep investigation seismic is more appropriate. For lithological and structural mapping gravity and magnetic methods are consider most appropriate, whereas, for detail mineral resource evaluation 2D ERT and electromagnetic methods gives better results. However, electromagnetic method compare to 2D ERT is costly and complex, because of the high associated cultural noise. Therefore, for mineral resource exploration 2D ERT is the most appropriate option, because, in mineral resource evaluation we are more interested in lateral and vertical geometry of bedrock and topsoil, which can easily be obtained by 2D ERT. Moreover, most metallic and non-metallic minerals lie at depths up to 200 m, in such case 2D ERT is consider most inexpensive and expeditious technique.

2D ERT is used routinely for subsurface mineral documentation. The low operational cost and simplicity in data collection favours its application for mineral exploration a lot. Although, it is widely accepted that the success of 2D ERT depend on strong resistivity contrast. The wide spread application of 2D ERT in the realm of mineral exploration such as graphite (Ramazi, Nejad et al. 2009), bauxite (Bi 2009), nickel (Robineau, Join et al. 2007), boron (Bayrak and Şenel 2012), hydrocarbon exploration (Davydycheva, Rykhlinski et al. 2006) and coal seam identification (Singh, Singh et al. 2004) has proved it to be a viable technique. A few case histories of application of 2D ERT for mineral exploration is provided in section below.

Table 1. Fundamental principle and instrument detail of various geophysical techniques

Types of Method	Fundamental physical principle	Measured Parameter	Operative Physical property	Equipment used	References
Gravity	Newton Gravitation Law	variation in earth gravitational field	Density	Gravitometer	
Magnetic	Columb's Law	Spatial variation in earth magnetic field	Magnetic susceptibility	Magnetometer Magnetic Compass	
Seismic	Snell's Law	Reflected/refracted seismic waves travel time	Elastic modulii	Seismography Seismic source Geophone	[25-27]
Electrical resistivity	Ohm Law	Earth resistivity	Resistivity	Resistivity Meter Digital multimeter Power battery Electric wires and electrodes	
Electromagnetic	Max Law	Response to Electromagnetic radiation	Conductivity	Electromagnetic inductionmeter Transmitter,Reciever	

Table 2. Physical Properties Ranges of Various Rocks [Kearey et al., 2013]

Rock Class	**Rock Type**	**Density (gm/cm^{3})**	**Magnetic Susceptibility**	**Seismic (m/sec)**	**Resistivity (Ωm)**	**Conductivity (sm/m)**
Igneous	Granite	2.5-2.8	0-50,000	3300-6000	30-500	10^{-6}-$2*10^{-4}$
	Basalt	2.7-3.30	250-180,000	2800-6000	10^{3}-10^{6}	10^{6}-10^{-3}
	Rhyolite	2.35-2.70	250-37700	2500-5000		
	Andesite	2.40-2.80	200-3500	3000-6000	$4.5*10^{7}$-$1.7*10^{2}$	
Sedimentory	Clay	1.63-2.60	0-360	1000-2500	1-100	
	Sandstone	1.61-2.76	0-21000	1400-4500	1-$7.4*10^{8}$	
	Limestone	2.4-2.7	5-25000	3300-6000	50-$4*10^{2}$	$2.5*10^{3}$-0.02
	Shale	1.77-3.20	63-18600	2000-4100	20-2000	$5*10^{-4}$-0.05
Metamorphic	Marble	2.6-2.9	0-73000	3700-7000	10^{2}-$2.5*10^{3}$	$4*10^{9}$-10^{-2}
	Slate	2.7-2.9	0-38,000	2500-5000	$6*10^{2}$-$4*10^{7}$	$2.5*10^{-8}$-$1.7*10^{-3}$
	Shist	2.39-2.90	315-3000	2000-3000	10-100	

Table 3. Efficiency Comparison of Various Exploration Techniques [Kana et al., 2015]

Exploration Techniques	**Depth (m)**	**Weight (KG)**	**Person Required**	**Data Collection per Day (10 working hours)**	**Data Interpretation Per Field Day**	**Application**
Drilling	1000-3000	1000-3300	3-5	200-300 m/day	Many include laboratory analysis	Mineral exploration and geotechnical study
Gravity	<50		1-2	40-120 station/day	3-4	Geological structure mapping
Magnetic	<50	1.5-2.5	1-2	10 lines Km/day	1-2	Geological structural mapping
Seismic	100-1000	12-15	2-4	40-12 shots/day Or 0.2-0.6 lines Km/day	2-4 days	Geological and geotechnical investigation, hydrocarbon and mineral exploration
Electrical Resistivity	50-200	5-13	2-3	1-2 lines km/day	2-3	Mineral exploration, environmental study, geological and geotechnical study
Electro-magnetic	100-300	12-24	1-3	(FDEM) 1-5 lines kilometres (TDEM) 6-20 sounding station	2-3	Mineral exploration, environmental study, geological and geotechnical study

5.1. Case histories

5.1.1. Application of 2D ERT for Gravel Prospecting

The potential site for fieldwork is in Story County, central Iowa shown in Fig 2a (Beresnev, Hruby et al. 2002). The key source of natural aggregate in Story County is glacio-fluvial deposits associated with the Des Moines Lobe of the Laurentide Ice Sheet (Bettis et al., 1996). The most common of these deposits is outwash concentrated in former meltwater channels, which occur as terraces or point bars. These deposits are usually found near modern streams that have exploited these pre-existing channels. Terraces occur within the margins of the channels, generally at intermediate elevations between the Quaternary flood plain and the till uplands. Less commonly, ice contact deposits including kames, eskers, and crevasse fillings are also found to be potential sources of coarse material. These deposits occur as isolated topographic highs and may consist of a variety of mixed or sorted materials including sand, gravel, till, and, occasionally, clay.

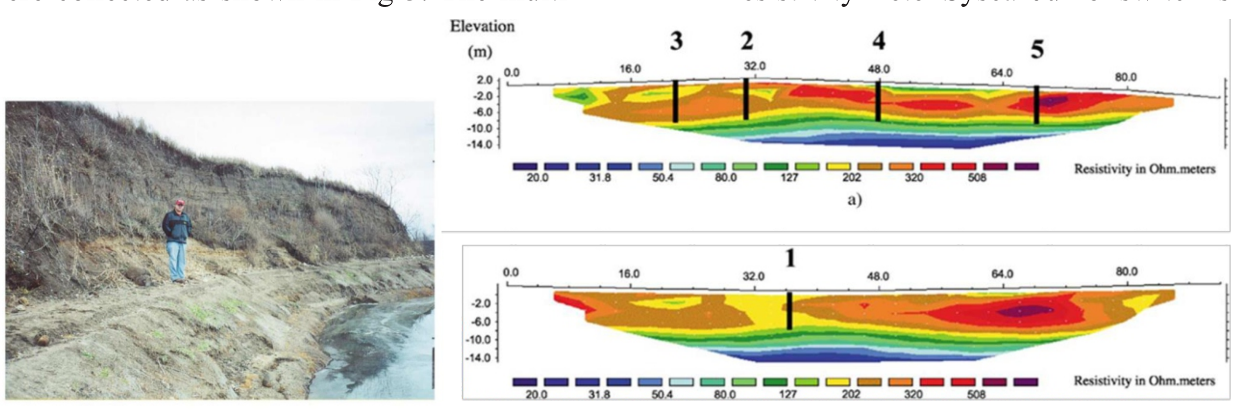
The 2D ERT data was carried out utilizing Wenner-Schlumberger electrode array arrangement. Total number of 24 electrodes spaced at 4 m were used to achieve a 92 m total length of a resistivity survey line depicted in Fig 2b. A layout of two resistivity lines was carried out to investigate the subsurface geology of potential site. The Borehole data was also collected to confirm resistivity results. On resistivity survey Line (a) four drill holes whereas, one drill hole on resistivity line (b) were collected as shown in Fig 3. The multi-electrode apparent-resistivity readings were written on the disk file and transferred to an external PC. The files are then inverted using RES2DINV software (Loke, 1997, 1999). Nonlinear least squares optimization technique was adapted by a program to obtain the inversion of apparent resistivities (Griffiths and Barker, 1993; Loke and Barker, 1996). The inversion program allows control of the accuracy of final inverted sections; this accuracy is defined as the root-mean-square (RMS) difference between the observed and calculated pseudo-sections. The inversion stops when this difference decreases below a user defined tolerance level, given in percent.

All the subsequent inverted sections have the RMS error of less than 5%, typically 1– 2%. The resistivity ranges 300-500 Ωm represented by reddish to dark reddish colour identified the thickness of gravel layer. Thus, the same depth estimated by both 2D ERT and borehole survey confirms that 2D ERT is successful applicable technique for sand and gravel subsurface characterization.

5.1.2. Application of 2D ERT for coal seam identification

East Basuria colliery is situated in the northern part of Jharia Coalfield of Dhanbad district(Singh, Singh et al. 2004). All the active coal seam lies in Barakar formation of lower Gondwana. Barakar formation predominantly consist of sandstone of varying grain size. Intercalation of shale and sandstone, grey and carbonaceous shale and coal seams.

A resistivity meter Syscal Junior switch is



a) Geological study area

b) Inverted resistivity images of the area

Fig. 2. Geological area and Inverted resistivity images of the gravel deposit [Beresnev et al., 2002]

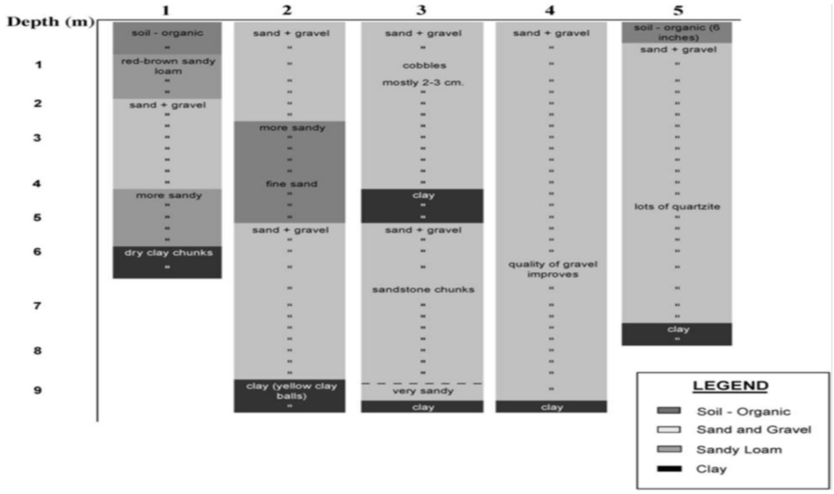


Fig. 3. Thickness of various geological layers obtained by core sample

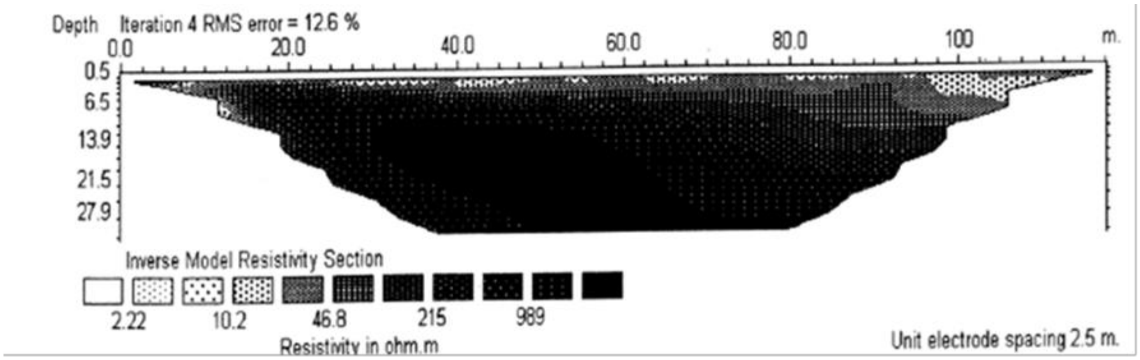
used in the current study. With 48 electrodes connected to the meter through a multielectrode channel. Pole-dipole array configuration with unit electrode spacing 2.5 m is adapted for data collection. After the interpretation of the obtain resistivity data, along Line R1 Shown in Fig 4, high resistivity zone over 989 Ωm shows an incline coal seam of black colour located at 30-80 m. The depth of coal seam at this position vary in between 10-31 m. Whereas, along the tracers R2 (Figure 5) it is noticed that a high resistivity zone over 1632 Ωm exist at surface position from 32.5- 82.5 m at the depth of 10-31 m. Since both the resistivity lines lies along the same coal seems but the coal bed resistivity detected by resistivity Line R2 is more than the resistivity Line R1. This may be due to the presence of air-filled fractures in traverse R2 because the air-filled fractures reduce the resistivity considerably.

The case histories mentioned above shows that 2D ERT successfully identified the thickness of topsoil and bedrock based on resistivity contrast. However, for feasibility assessment of a deposit only the identification of boundary between topsoil and bedrock is not enough. Whereas, the accurate estimation of volume and bedrock is mandatory. Therefore, this review article shed light on recent advance in application of 2D ERT for accurate estimation of volume of bedrock and topsoil to assess the feasibility of the deposit for mining.

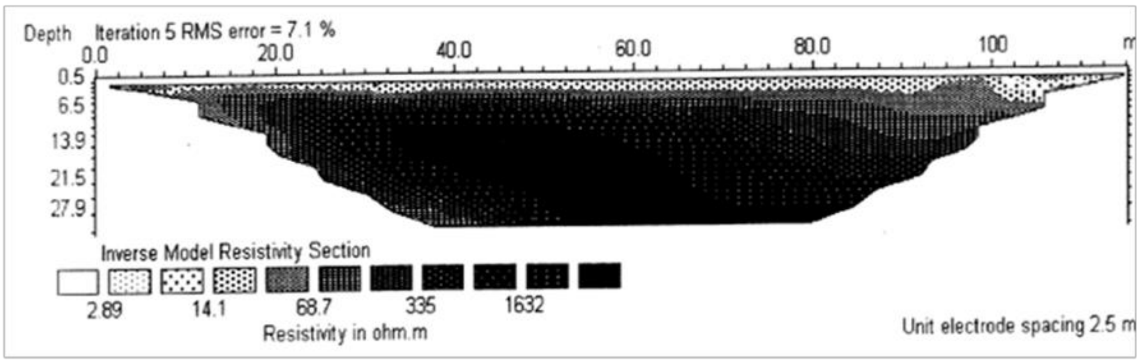
5.1.3. Identification of coal seam using 2D ERT:

2D ERT survey was carried out at Nam Nao District, Phetchabun Province, Thailand for identification of coal seams. SYSCAL PRO by an IRIS Instrument were utilized using Wenner -Schlumberger electrode configurations (Phengnaone, Arjwech et al. 2020). The length of the survey profile was 177.5m using 72 electrodes at 2.5 m spacing. A core log at study area was also collected to validate the results of 2D ERT shown in Fig 5.

The 2D ERT data was processed using Res2DInv software. The obtained ERT tomogram (Figure 6) shows the geological distribution of at site. The maximum depth of penetration was ~40 m at the middle of the profile, with a shallower penetration depth towards the ends of the profile. A heterogeneous zone of relatively low resistivity (<100 Ωm) from surface to 25 m depth over entire profile was identified. The surface layer, which is marked by the black dashed line in Figure 6a, is interpreted as calcareous mudstone intercalated with siltstone and lignite. The core log collected on the resistivity profile identified core seam at 15-20 m depth. The relatively homogeneous zone of higher resistivity (>100 Ωm) extending from the beginning to the end of the profile below ~25 m depth is interpreted as calcareous mudstone. The depth to the calcareous mudstone appears to be anomalously shallow in the interval about 30–45 m along the profile. The cause of this anomalous shallowing of the calcareous mudstone is not known but may. The study reveals that 2D ERT successfully discern the coal seams.



a) Resistivity Line R1



b) Resistivity Line R2

Fig. 4. 2D Inverted resistivity images of coal seems [Singh, 2004]

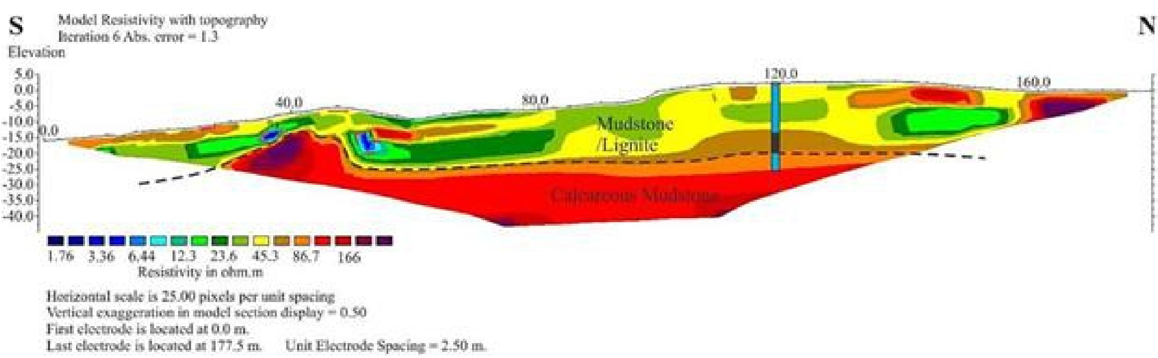


Fig. 5. Coal Identification using 2D ERT [Phengnaone et al., 2020]

5.1.4. Application of 2D ERT for granite resource evaluation

The study area is located in Senawang district, Malaysia about 7 km away from nearest town, Seremban Jaya towards east. The study area spread over 3.5 km2. The ground elevation of the area is in the range of 150-250m. The site can be accessed by an unpaved road from Seremban-Tamping trunk road. The potential site for mineral resource evaluation for granite deposit is shown in Fig 6.

The 2D ERT survey arrangement of the area of investigation consisted of three resistivity lines (R1, R2, R3,) at various locations having 400 m length each. 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. Prior to resistivity data collection the total number of electrodes [61 electrodes, one electrode as centre electrode] and spacing (5m) between them was set, which remained constant throughout the survey. The resistivity data was collected using Schlumberger protocol (n=2) with inner and outer electrode spacing 5 m and 10 m respectively. The field data (apparent resistivity) collected were downloaded from resistivity meter and processed further, using Res2inv Geotomo Software. First, the area under study was divided in series of rectangular cells and assigned an electrical resistivity (model parameter) value to each cell based on the collected measurements, by solving for forward modelling by finite element method. In this study, the desire results were obtained after nine iterations with a varying RMS error of 12.1%, 8.6% and 12.9% for R1, R2, and R3 respectively.

Borehole investigation of the study area was performed in accordance with BS 5930:1981. Topsoil thickness were inferred by three boreholes BH1, BH2 and BH3 located at different points. The borehole samples were collected on the resistivity survey line for the purpose to compare both results and avoid ambiguity in 2D ERT data due to resistivity overlap of subsurface geological features. The type of soil from core samples were distinguished by colour of returned water and wash drill cuttings. Thus, three core sample (BH1, BH2 and BH3) shown in Fig 7(a-c) were obtained to identify different geological strata based on the colour of return water and washed drill cuttings. In addition to borehole and 2D ERT survey topographic survey was also carried out to estimate the volume of bedrock and topsoil.

The inverted resistivity images of ERT survey line (R1, R2, R3,), spread at various locations indicate huge resistivity contrast. Thus, the high variation in subsurface resistivity represents different geological strata in the form of different colours. Therefore, topsoil being most exposed to weathering and is usually composed of sandy soil is characterized by low resistivity values ranging 20-800 Ωm identified by greenish to reddish colour with varying thickness of 17-25m. The low resistivity values shown by topsoil is because it associates sandy soil and highly exposed to weathering. The solid granite recognized by dark red colour was assigned high resistivity values greater than 1800 Ωm. The high resistivity shown by solid granite is due to crystallized mineral formation which makes compact material and thus have less probability of presence of impurities or water content. However, fractured granite due to presence of cracks and pores, which may accumulate water content or other conductive impurities shows resistivity in between solid granite and topsoil ranging from 800 Ωm to 1800 Ωm distinguish by greenish to yellow orange. The volume of topsoil and bedrock estimated by combine topographic, borehole and 2D ERT was 2344505 m3 and 7449072 m3 respectively shown in Figure 8. The combine results of all the methodologies shows that the bedrock is 3.2 times to the topsoil and the deposit is feasible for mining. Whereas, the estimated volume of topsoil (2978263 m3) and bedrock (6815944 m3) by borehole (Figure 9) and topographic survey shows the bedrock volume is 2.2 times to overburden and hence the deposit is not feasible for mining. 2D ERT survey calculated the volume of topsoil and bedrock 2387031 m3 and 7407176 m3 respectively given in Figure 10. While, based on the results obtained by 2D ERT and topographic survey the volume of bedrock is 3.2 times to the topsoil volume therefore, the deposit is feasible to be mined.

6. Discussion

This paper presents a review of various exploration techniques that are used for the discovery of new mineable deposit. The paper also presents the challenges that are faced by mining industry in terms, high exploration cost and low available exploration budget. This results in fewer exploration activities and thus cause low pace of discovery of new mineable deposit. The success mining project is determined by accurate estimation of topsoil and bedrock volume along with the cost, time and efficiency of exploration technique. The cost in term how much investment is carried out in preparing the feasibility study of the mineral venture. 2D ERT is considered simple and inexpensive technique for mineral resource evaluation because, the operational and capital cost of 2D ERT is comparatively low. Time represent the duration required for economic analysis of mineral venture. With time the economic worth of the mining project may vary, because the minerals commodities prices fluctuate significantly with time. The critical comparison of all exploration techniques based on literature enable us to conclude that 2D ERT is fast and expeditious technique for mineral resource evaluation. While, efficiency is termed used for the accuracy and precision of estimating the grade and rock reserve of the mineral deposit. Considering the case study in section 4.3, 2D ERT successfully diagnose subsurface geology based on resistivity contrast. The bedrock to topsoil ratio obtained by 2D ERT (3.2) was more accurate compare to borehole (2.2). Hence, based on the cost, time required and accuracy, 2D ERT is consider inexpensive, rapid and efficient technique for mineral resource evaluation.

However, 2D ERT may result ambiguity by overlapping of resistivities of various geological layer. For example, in section 4.2 the two different resistivity values of same coal seam were recorded. Whereas, in subsurface geological characterization of granite deposit (section 4.3), two different geological layers such as topsoil and water filled layer showed same resistivity values. This shows that the present of various impurities in geological layers, fluctuate the resistivity values considerably and makes the resistivity imaging results ambiguous. Therefore, 2D ERT may misinterpret the various geological layers in some geological environment and cannot be relied on independently. However, the ambiguity in 2D ERT results can be overcome by integrating few drilling samples to obtain the accurate thickness of various geological layers. Even though, the cost and time of integrated application of drilling and 2D ERT is low compare to the drilling exploration to be applied independently. It is because the combined application of 2D ERT with drilling reduce the need of drilling samples significantly, which in other words reduce the time and cost of exploration and increase the performance efficiency. Thus, in this way the success rate of finding potential mineral deposits can be increased with low risk of failure and reduced exploration cost.

The critical analysis of literature available on various exploration techniques makes us to argue that 2D ERT in conjunction with borehole drilling efficiently analyse the feasibility of a mining project with reduced exploration costs and time. The technique compared to borehole provide the subsurface information in more detail and efficiently estimate the volume of bedrock. The application of 2D ERT for mineral exploration will successfully enable the mining companies to increase the discovery of new mineable deposit with low exploration budget. Thus, the challenge to mining industry such as low exploration activities can be cope with the application of expeditious and inexpensive 2D ERT technique.

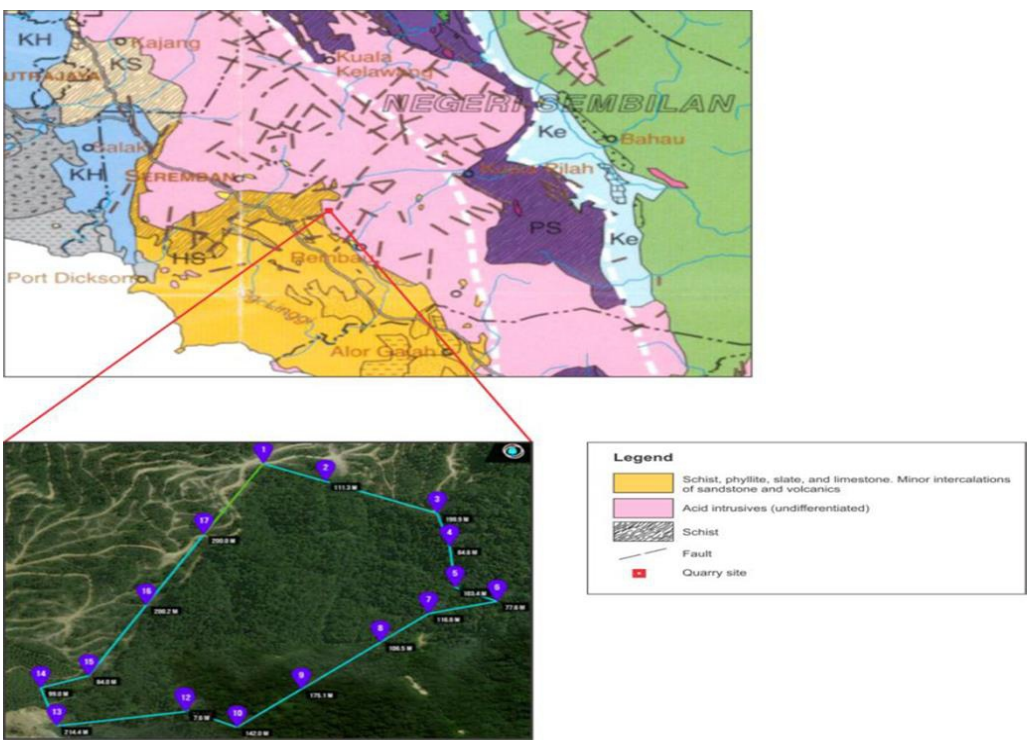


Fig. 6. Geological map of study area.

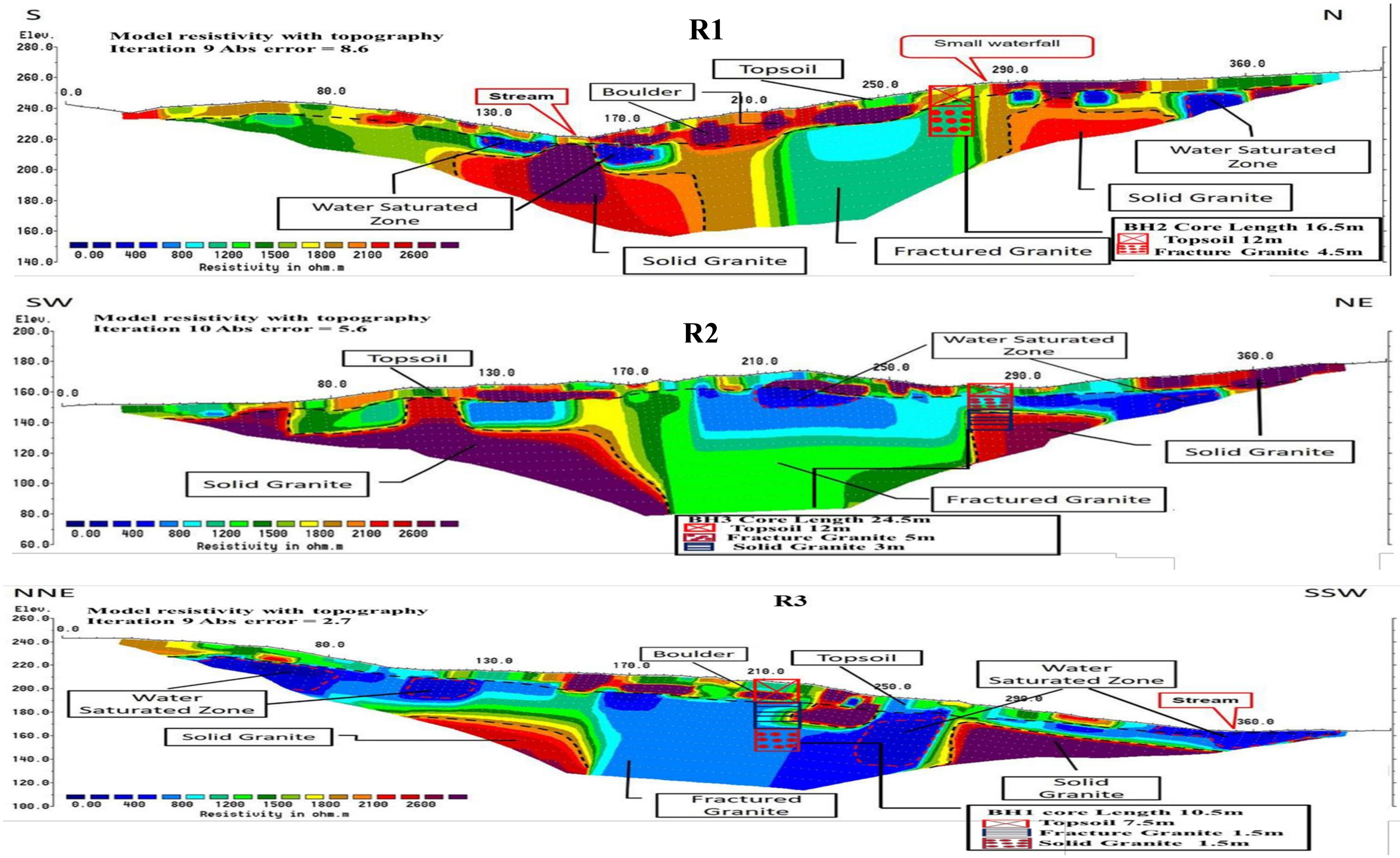
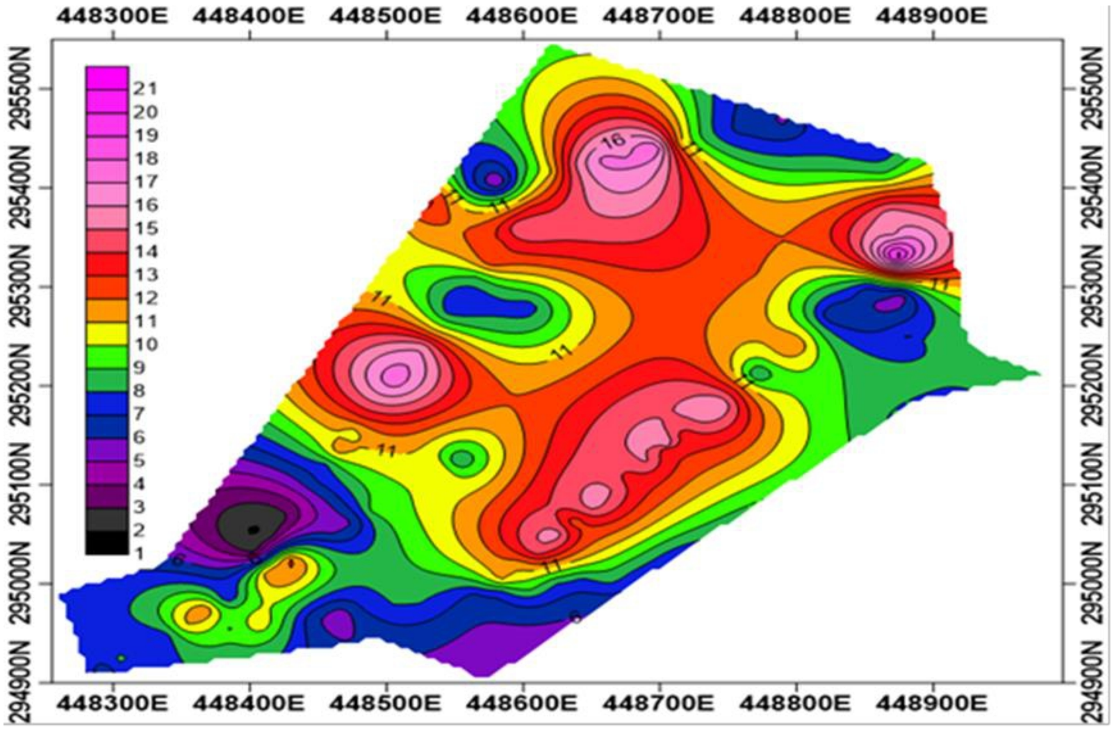
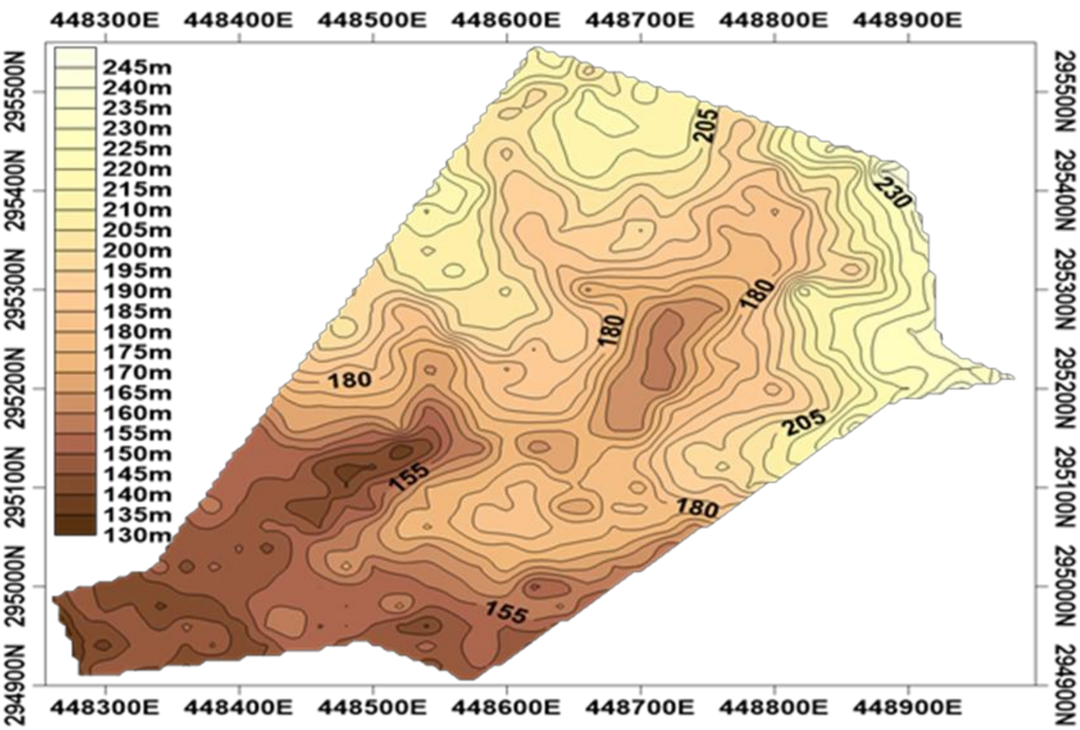


Fig. 7. 2D Inverted tomogram of granite deposit

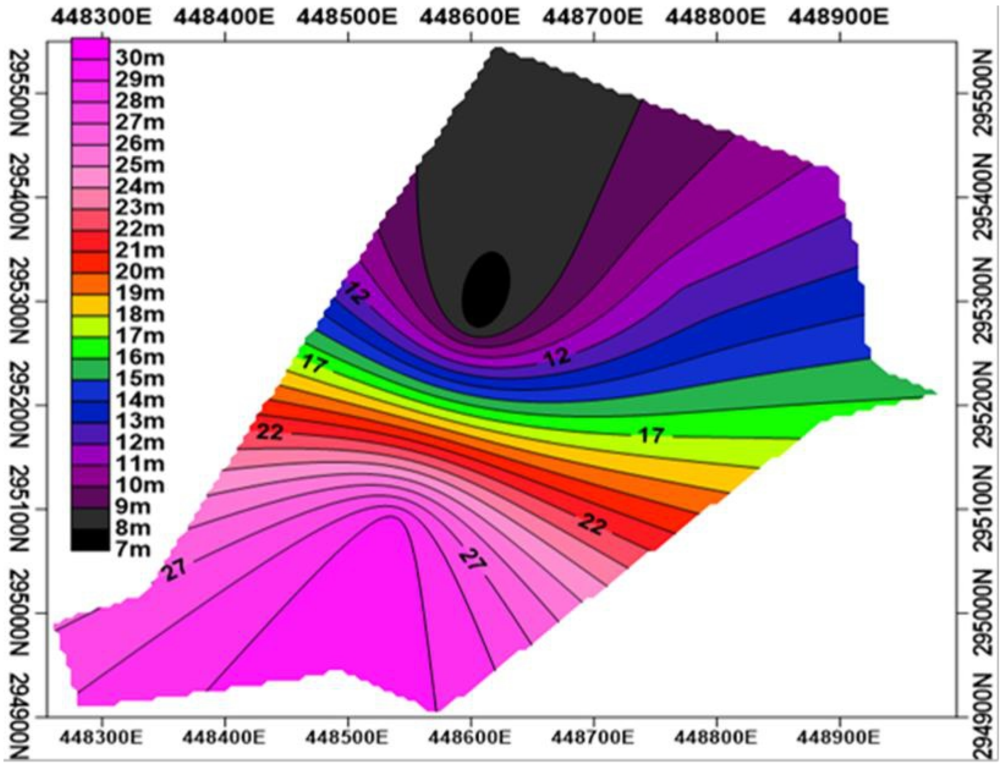


a) Topsoil contour of combine borehole and 2D ERT

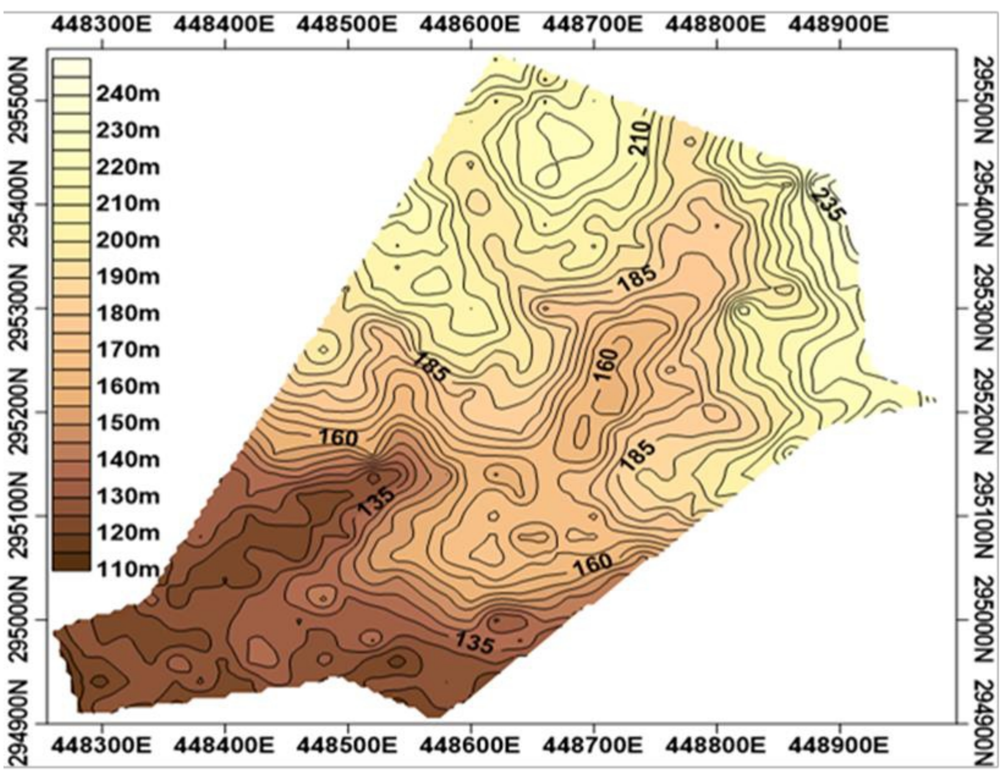


b) Bedrock contour of combine borehole and 2D ERT

Fig. 8. Contour map of topsoil and bedrock obtain by combine topographic, 2D ERT and borehole survey

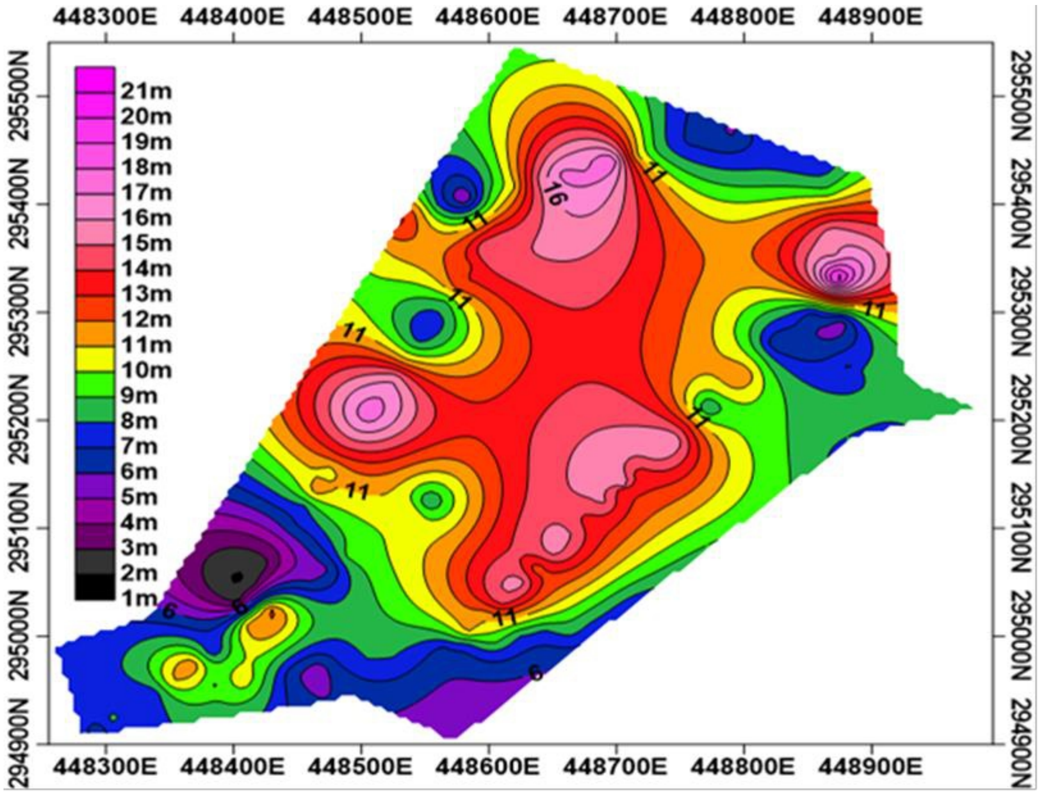


a) Contour of topsoil by borehole

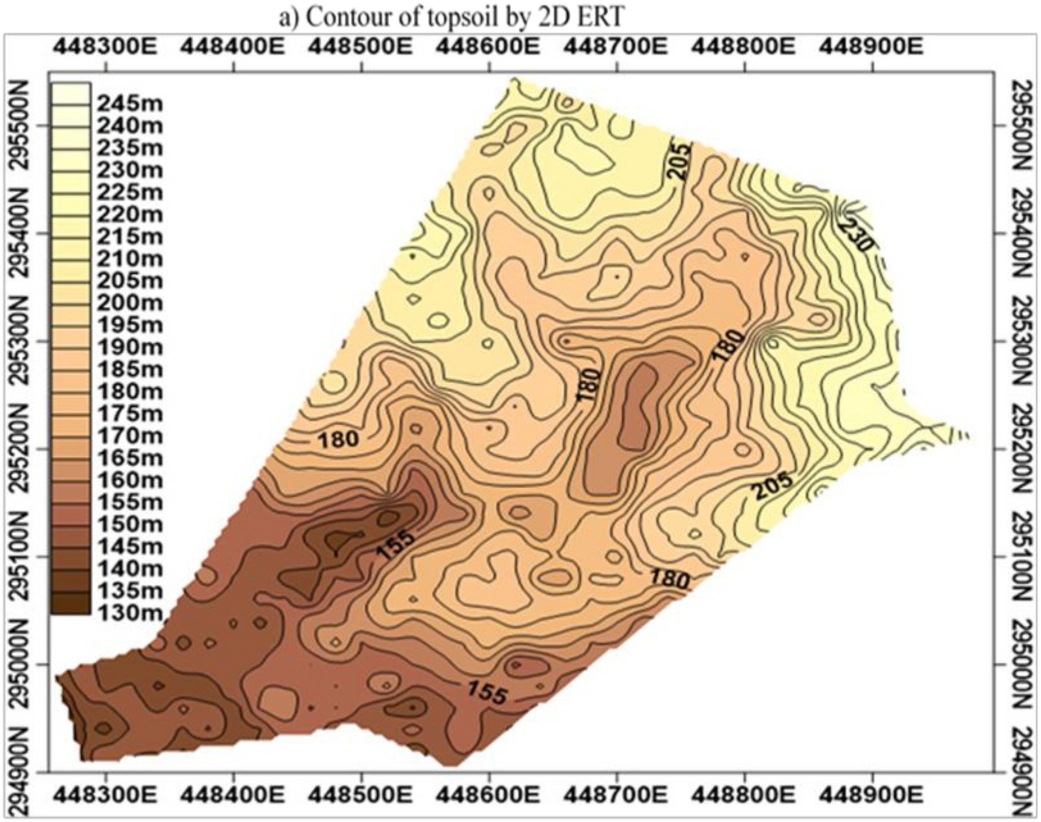


c) Contour of bedrock by borehole

Fig. 9. Contour map of topsoil and bedrock obtain by combine topographic and borehole survey



a) Contour of topsoil by 2D ERT



b) Contour of bedrock by 2D ERT

Fig. 10. Contour map of topsoil and bedrock obtain by combine topographic and 2D ERT survey

7. Conclusion

The paper presented the various factors influencing the success of mining project. The essential parameters responsible for leading a project to acceptable level of success are cost, time and efficiency. The cost, time and efficiency of various geological and geophysical techniques vary widely from one technique to another. Therefore, it is important to select carefully a method for mineral resource evaluation, in order to reduce cost and time required for exploration, and increase performance efficiency. 2D ERT provide an inexpensive and rapid approach for feasibility assessment of shallow mineral deposit. In addition, the demand for mineral commodities increases significantly, whereas, the exploration of new mineable deposit is low. This is due to the fact that mining industry have low exploration budget and thus reduced the exploration activities. Because the cost of exploration using conventional drilling technique is high. 2D ERT is capable of reducing exploration cost and time by reducing or illuminating drilling or trenching. Furthermore, as it is stressed that most of the mineral lies at shallow depth about 100-200 m. The application of 2D ERT up to certain depth is logical, inexpensive and expeditious.

Acknowledgement

This study is supported by Universiti Teknologi Malaysia and Ministry of Higher Education Malaysia under Research University Grant R. J130000.7316.4B431.

Author's Contribution

Muhammad Junaid as a first author has prepared the draft of the paper. Rini Asnida Abdullah reviewed and proof read the manuscript. Radzuan Saari, checked the sequence stratigraphy of the article. Mohd Nur Asmawisham Alel provided the relevant literature and proof read the paper. Wahid Ali and Hafeez Rehman proof read and help in improving the language of the paper. Usman Ghani contributed to the paper in improving the figures and arrangement of the article.

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