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Characterizing mudstones and fault structure in Bumita Quarry, Perlis through integrated geophysical techniques

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Abstract: The parameters of seismic refraction and electrical resistivity play a crucial role in geological studies, as they provide insights into the composition of rocks or soil beneath the Earth's surface. Previous researchers have established reference ranges for seismic velocity and resistivity values based on different rock types, which are presented in tabulated forms. However, the wide variability in these values sometimes leads to challenges in interpretation due to overlapping ranges. In the region of Perlis, Malaysia, a comprehensive geophysical investigation involving seismic refraction and electrical resistivity methods was conducted within the Chepor Member of the Kubang Pasu Formation at the Bumita Quarry and Utan Aji. The results were then correlated with porosity and permeability data. The Chepor Member primarily comprises both red mudstone and grey mudstone. Interestingly, the seismic velocities of these two mudstone types are quite similar, differing only by a small margin of approximately 200 m/s. The resistivity method employed utilized a pole-dipole array configuration. In terms of resistivity values, the red mudstone exhibited lower readings (ranging from 15 to 100 Ωm) compared to the grey mudstone (ranging from 120 to 500 Ωm). Assessing porosity, the red mudstone displayed a value of 0.95%, alongside a permeability of 5.58×10^{-5} µd, while the grey mudstone indicated a slightly higher porosity value of 1.9% and a permeability of 2.06×10^{-5} µd. Consequently, the study successfully established seismic velocity and resistivity benchmarks for the mudstones within the Chepor Member geological unit.

Keywords: Chepor Member, sedimentary rocks, seismic refraction, electrical resistivity, mudstone, porosity

INTRODUCTION

The Earth's intricate composition, stemming from its lack of uniformity, hinders the complete exploitation of its resources. Therefore, it's crucial to extensively grasp the physical and chemical attributes of the Earth to thoroughly investigate its underground layers and components. Employing geophysical techniques to delve into the Earth's interior necessitates gathering measurements either at the surface or in its proximity. Geophysical analysis outcomes can provide insights into both the vertical and lateral fluctuations in the physical characteristics of the Earth's subsurface. Among the measurable attributes are the porosity and permeability of rocks, which hold significant importance in the field of earth exploration, particularly within the oil and gas industry.

The seismic velocity and resistivity range established by various geophysicists gives a wide range of values subject to the type of rocks. A type of rock having different type of facies will have its own specific range of values. Having a smaller range of values would help researchers to interpret the type of rock in a specific way thus accurately.

An outcrop is characterized as a visible section of bedrock that emerges on the Earth's surface; however, it

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Table 1: Geophysical parameters pertaining to mudstone encompassing seismic velocity and resistivity values.

Geophysical parameter of mudstone	Values
Seismic velocity (Reynolds, 1997)	1000 – 4100 m/s
Electrical resistivity (Loke, 1999)	20 – 2000 Ωm

is not widespread across the land as a significant portion is concealed by vegetation. The presence of outcrops enables the direct observation and collection of bedrock samples, facilitating in-depth geological analysis. They provide exceptionally detailed and spatially consistent insights into various aspects such as sedimentary structure, texture, petrology, facies, grain types, morphometric properties, joint patterns, fractures and their orientations, diagenetic alterations, compaction, and petrophysical as well as physicochemical properties (Van Dam *et al*., 2015). Geologists often map the geological features of an area by observing the geomorphology of the area. Sometimes, the use of logging is applied to study the subsurface lithology. The earth surface is 70% of sedimentary origin; it is formed through physical, chemical and biological processes (Tucker, 1981). This study identifies the geological outcrop of the Chepor Member at Bumita Quarry, Utan Aji, integrating seismic refraction and electrical resistivity parameters with mudstone porosity and permeability.

In general, the seismic velocity and resistivity values of mudstone, as presented by Reynold (1997) and Loke (1999) respectively, exhibit a broad range (Table 1). This study specifically focuses on characterizing the resistivity and seismic values of both red and grey mudstone within the Chepor Member at Utan Aji.

Literature review

Basic geological knowledge is indispensable for evaluation and interpretation of the substrate which is important for civil engineering. Geology provides information of the exposed area while geotechnical investigations is useful to provide information of the Earth's interior but mostly involving costly destructive methods. To avoid unnecessary loss, all methods of the geosciences was taken into consideration, and recently geophysics methods have widely contributed in providing information to probe properties of the subsurface, properties of soils, sediment and rock outcrops, cost effectively and mostly related to the environmental surveys. Geophysical exploration comprises several methods and unique tools to investigate the subsurface. The methods are used for geological surveying to derive the Earth's internal physical properties. Hence, geophysical exploration is of importance to geologists and engineers, and not limited to geophysicists (Kearey *et al*., 2002). The seismic refraction method employs wave propagation through the Earth, a process influenced by the elastic properties of rocks. This quality, defined as elasticity (Telford *et al*., 1990), describes the rock's ability to resist alterations in size or shape and to revert to an undeformed state once external forces are eliminated. Seismic waves can be divided into two waves; P-wave and S-wave. P-wave travels by compressional and dilational uniaxial strain in the direction of propagation whereas S-wave travels perpendicularly to the direction of propagation (Kearey *et al*., 2002; Mohamad *et al*., 2015). Seismic refraction relies on the requirement that the velocity of sound in a deeper layer surpasses that of the layer above it. Upon fulfilling this condition, refracted waves reach the Earth's surface, detectable by a geophone. This geophone generates an electrical signal which is then transmitted to a seismograph (Haeni, 1986). Rahmouni *et al*. (2013) employed P-wave velocity (Vp) to assess the geotechnical characteristics of rock materials. The P-wave velocity of a rock exhibits a strong correlation with the properties of the rock in its natural state. In order to estimate the porosity and density of calcarenite rocks, which hold significance as historical monuments, they employed a straightforward ultrasonic velocity technique. This ultrasonic test relies on measuring the time taken for a P-wave to propagate in the longitudinal direction. Electrical imaging is a survey method developed to investigates areas of complex geology (Griffiths & Barker, 1993). The electrical survey operates by measuring the potential difference at various points in the Earth, which is generated by injecting current into the ground (Burger, 1992). Electrical resistivity tomography has proven effective in mapping the stratigraphy of sedimentary, limestone, and granite formations (Muztaza *et al*., 2013).

The quantification of empty spaces is referred to as the porosity of rock, while the assessment of a rock's capacity to facilitate fluid movement is known as permeability. Analyzing these fundamental rock characteristics is crucial prior to addressing factors such as fluid types, quantities, flow rates, and estimates of fluid recovery. The predominant characteristics of sedimentary rock texture are primarily influenced by factors such as the roundness and shape of grains, the size and sorting of grains, the orientation and arrangement of grains, as well as the chemical composition (Tiab & Donaldson, 2015). The porosity is measured in percentage (%) while the unit for permeability is in microdarcy (µd).

Previous researchers, Ismail *et al*. (2013) and Muztaza *et al*. (2013) conducted seismic refraction and electrical resistivity respectively at Kaki Bukit, Perlis to characterize the geological outcrop of limestone formation. This study focusses on Chepor Member of Kubang Pasu Formation at Bumita Quarry, Utan Aji. Both seismic refraction and electrical resistivity were conducted simultaneously on the same survey line. In their study, Meor & Lee (2004) examined the depositional setting of the Mid-Paleozoic red beds at Utan Aji, Perlis, and its implications for global eustatic sea level fluctuations. The area in the northwest of the Peninsula Malaysia features widespread Late Devonian to Early Carboniferous red-colored mudstones and sandstones. A well-preserved sequence is found at Bumita Quarry, Utan Aji, Perlis, and is detailed in this report. The identified facies suggest a marine prodelta-delta front environment for the Mid-Paleozoic red beds. Within the Bumita Quarry sequence, a relatively thin (9 m) black mudstone facies could potentially signify the occurrence of the Latest Devonian Hangenberg Anoxic Event. The presence of a Mid-Paleozoic orogeny is ruled out. It is proposed that a significant regression immediately following the transgressive episode of the global Hangenberg Event is responsible for the notable pre-Carboniferous paraconformity observed in the mid-Paleozoic successions of the Sibumasu/Shan-Thai Terrane.

Geological setting

The northwestern region of Peninsula Malaysia holds an almost uninterrupted sedimentary sequence from the Cambrian to the Permian period, encompassing the entire Paleozoic era (Jones (1981); Meor & Lee (2005); Cocks *et al*. (2005); Lee (2009)). In Perlis, the arrangement of rock layers follows a pattern of gradually increasing age from west to east, commencing at the Setul Boundary Range (Jones, 1981; Meor, 2013). The lowermost segment of the Kubang Pasu Formation (KPF) is referred to as the Chepor Member. This Chepor Member is situated in areas such as Utan Aji, Guar Jentik, and Bukit Tuntung, which were previously identified as formations characterized by reddish sediments (Meor & Lee, 2005). The Chepor Member is comprised of substantial layers of mudstone ranging in color from grey to red, interspersed with flat layers of quartzitic and feldspathic sandstone, and occasionally containing stratified diamictite beds (Meor, 2013). The depositional environment for Chepor Member is of glacial marine shelf system. Figure 1 shows the geological map of Kubang Pasu Formation and Bumita Quarry, Utan Aji.

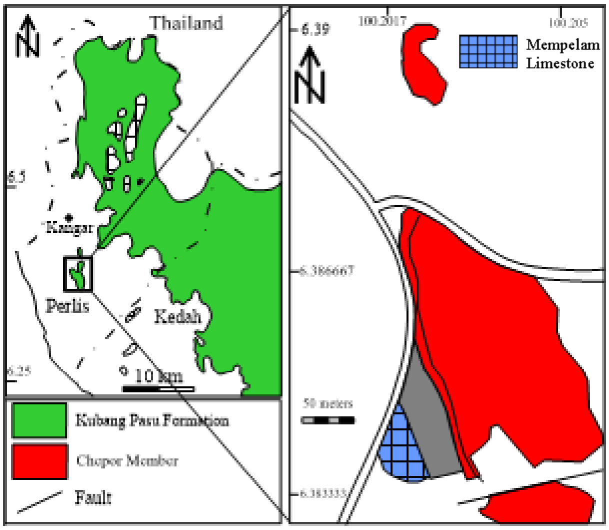

Figure 1: Geological map of Kubang Pasu Formation and Bumita Quarry, Utan Aji (Meor, 2013).

Figure 2 shows the exposed bedrock at Bumita Quarry, Utan Aji. The beds approximately dip 70 degrees eastward and complicated with folding and thrusted strata. The Chepor Member succession exposed in Utan Aji is like that exist in Guar Jentik (Meor, 2013). Figure 2 clearly shows that the rocks are tilted towards the ground and two types of mudstone exists at the area which are red mudstone and grey mudstone.

METHODOLOGY

Data acquisition took place at Bumita Quarry in Utan Aji. The survey line at this location was oriented perpendicular to the visible bedrock (Figure 3). Geophones were positioned at intervals of 2 meters, while the electrode spacing for the electrical resistivity method was set at 1 meter. Both techniques were executed simultaneously on the same survey line.

In this geophysical survey, hammer is used as the source to generate the sound waves. Geophone with frequency 14Hz is used to detect the seismic waves.

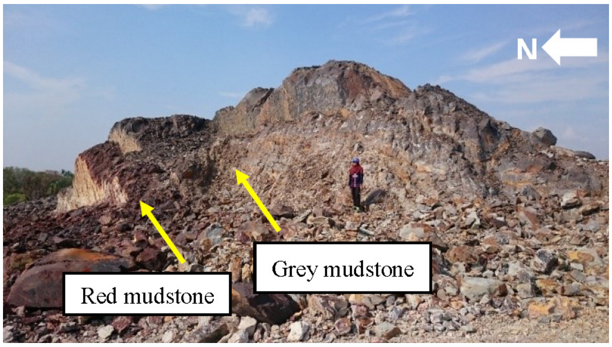

Figure 2: Outcrop at Bumita Quarry, Utan Aji. The beds approximately dip 70 degrees eastward with 40 m length.

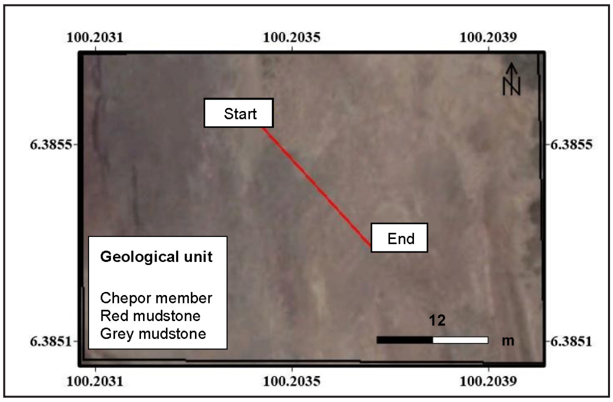

Figure 3: Location of the survey line from top view (Google earth, 2016).

Seismic refraction tomography (SRT) employs the transmission of waves through the Earth's subsurface. This wave propagation is contingent upon the elastic characteristics of the underlying rock formations (Telford *et al*., 1990). At its core, seismic exploration operates on a fundamental concept: it involves the creation of seismic waves and the subsequent measurement of the travel time for these waves as they traverse from emission points to an array of geophones, typically arranged linearly in alignment with the source (Figure 4).

In electrical resistivity survey, the pole-dipole array was employed due to its capacity for deeper current penetration and its effectiveness in providing extensive horizontal coverage (Loke, 1999).

Resistivity measurements entail the injection of electrical current into the Earth through a pair of current electrodes, labeled as C1 and C2. Consequently, the resulting potential difference is recorded by two potential electrodes, designated as P1 and P2. Figure 5 depicts the representation of electric current distribution within a uniform subsurface. In this scenario, when electric current is introduced into the ground through a pair of current electrodes, it disperses outward from the electrodes in a radial manner and also travels between them. By employing voltmeters, the potential differences between two potential electrodes are measured. It's important to note that as the distance between the electrodes increases, the depth at which the current penetrates also increases.

The raw data from seismic refraction is processed using several software. Firstly, IXRefraX is used to transfer the data from seismograph to the computer. The software is also used to filter the noises of the seismic wavelets. After the filters, it is imported to FIRSTPIX v4.21 for picking the first break of each of the seismic traces. Lastly, the time of the first break is imported to SeisOpt2D for imaging the depth versus distance. For electrical resistivity, the data is automatically processed using Res2Dinv software. Both seismic refraction and electrical resistivity imaging section are imported to Surfer8 software for final editing.

Rock samples are extracted from the visible outcrop using a rock hammer, after which they are transported to the laboratory for further testing. The conducted test involves determining the porosity and permeability values of the rocks. Prior to conducting any tests, the rock specimens were shaped into cylindrical forms using a diamond drill bit core driller (Figure 6). The nitrogen permeability test was employed for measuring

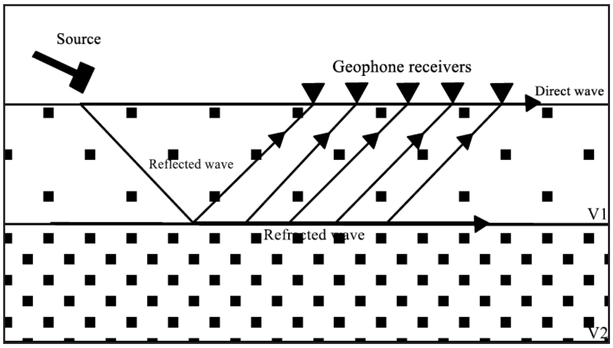

Figure 4: Ray paths for seismic waves (after Anderson &Croxton, 2008).

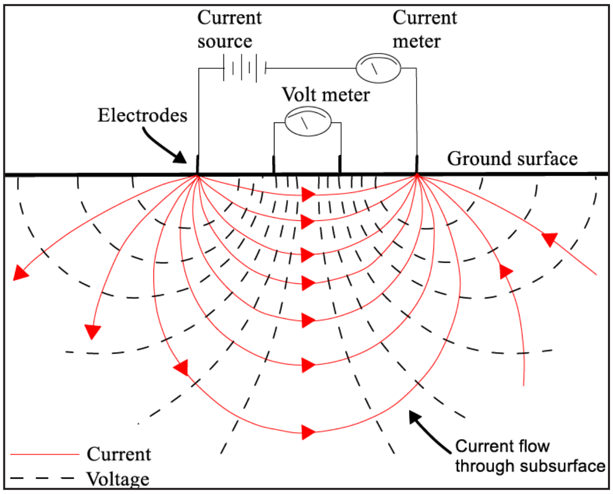

Figure 5: Electric current is generated between the paired electrodes, as indicated by the red lines. The potential difference between the potential electrodes, which are also paired, is then measured (after Anderson & Croxton, 2008).

Figure 6: Cutting the rock sample into cylindrical shapes. a) the sample is placed in a jig specifically designed to hold the sample in place for both the trimming and facing, b) trimming the sample and c) cylindrical blocks.

permeability, while water immersion under vacuum was utilized for porosity determination. Additionally, the rock samples were transported to the Department of Mineral and Geosciences Malaysia (JMG) in Ipoh for the creation of thin sections.

RESULTS AND DISCUSSION

The lowermost segment of the Kubang Pasu Formation (KPF) is referred to as the Chepor Member (CM). This specific unit, known as the Chepor Member, is situated at Utan Aji and Guar Jentik. In earlier descriptions by Meor & Lee (2005), these locations were categorized as formations characterized by 'red bed' deposits. The Chepor Member is composed of substantial layers of mudstone ranging in color from gray to red. These mudstone layers are interspersed with flat, tabular deposits of sandstone that are rich in quartz and feldspar. In certain instances, bedded diamictite can also be observed within this member (Meor, 2013). The depositional environment for Chepor Member is of glacial marine shelf system. Both red mudstone and grey mudstone are fresh rock which exist under the survey line contrast to the beds of quartzitic and feldspathic sandstone which shows moderately weathered condition on the outcrop.

Figure 7 shows the seismic refraction (SR) at Bumita Quarry, Utan Aji. The tomography gives depth of approximately 15 m. At the right side of the section, the velocity is slightly higher compared to the left. The SR value for red mudstone is between 1500 m/s – 2100 m/s whereas for grey mudstone also from 1500 m/s to 2300 m/s. At the center of the line, the layering starts to fall which might indicate the contact or fault line between red mudstone and grey mudstone. The difference in seismic velocity of the red mudstone to grey mudstone is within 200 m/s.

Figure 8 depicts the inversion model of electrical resistivity (ER) obtained from the pole-dipole array survey conducted at Bumita Quarry, Utan Aji. The boundary between the red mudstone and grey mudstone is indicated by the black dashed line. As inferred from the results, the rock is observed to be inclined or dipping beneath the ground surface. It can be directly deduced that the two major colors which are blue and green in the inversion model resistivity represents two types of mudstone. The green color having higher resistivity (120 – 500 Ωm) value is the grey mudstone, while the low resistivity value (15 – 100 Ωm) with blue color is the red mudstone. The depth of the result is approximately 16 m.

Figure 9 shows the SR and ER results are compared together. The red dashed line shows the centre of the survey line as at distance 22 m of SR is equivalent to 20 m ER survey line. Observing the possible fault or contact line between red mudstone and grey mudstone indicated by black dashed line, both SR and ER results shows quite good correlation. Correlation between seismic refraction and electrical resistivity results shows the subsurface imaging is agreeable to one another.

The difference of seismic velocity between red mudstone and grey mudstone is within 200 m/s, the range for red mudstone is slightly lesser than the grey mudstone.

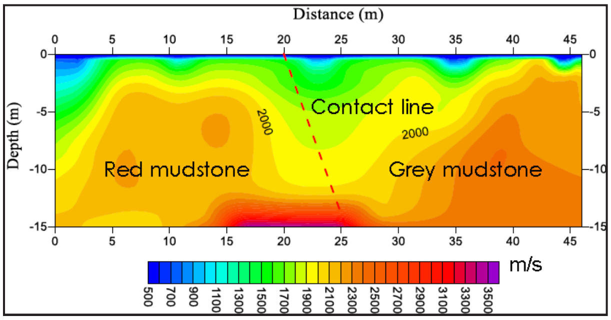

Figure 7: Seismic refraction profile at Bumita Quarry, Utan Aji.

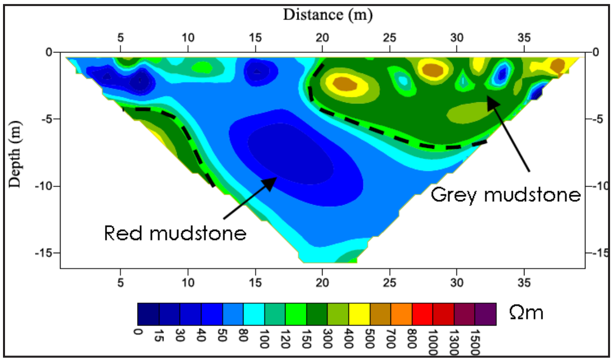

Figure 8: 2-D inversion model of Pole – dipole array at Bumita Quarry, Utan Aji.

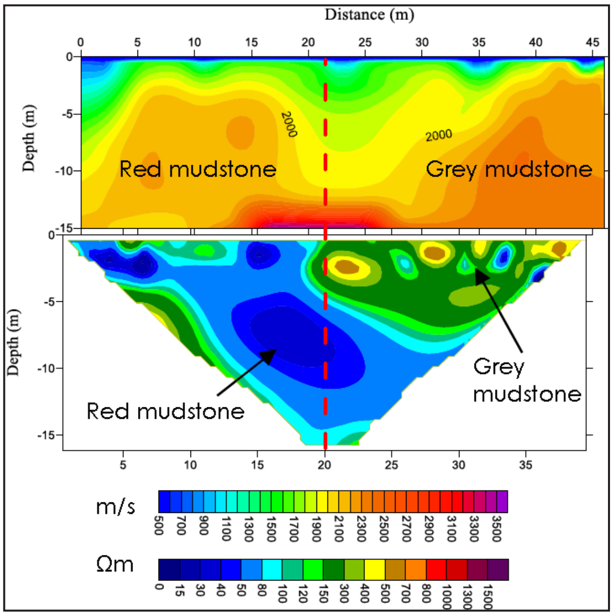

Figure 9: Comparison between seismic refraction and Pole – dipole array of electrical resistivity.

Table 2: Table describing geophysical parameters and their corresponding facies of the Chepor Member at Bumita Quarry, Utan Aji.

Facies	Velocity (m/s)	Resistivity (Ωm)
Red mudstone	1500 – 2100	15 – 100
Grey mudstone	1500 – 2300	120 – 500

Whereby resistivity results show a great distinct value between the two mudstones. Table 2 shows the mudstone facies with its respective geophysical parameter.

Mudstone are brittle rocks that needs a hammer to remove the sample from quarry faces or any rock exposures. The color of mudrock is related to its mineralogy and geochemistry. The color can be quite useful in field mapping to differentiate between mudrock formations. The main controls of the color are the organic matter and pyrite content and the oxidation state of the iron (Tucker, 1981).

The mudstones can be divided into two referring to its color; red mudstone and grey mudstone as shown in Figure 10. The difference in color of the mudstone is because of the chemical weathering processes of each of the mudstone has undergone. Brown or red mudstone typically consist of oxidized ferric iron minerals like hematite (Fe_2O_3), primarily present as coatings on grains and intertwined with clay particles. On the other hand, mudstone exhibiting shades of grey generally suggest a substantial clay content along with a limited presence of non-oxidized ferrous minerals. As the clay content increases, there tends to be a higher proportion of organic matter and pyrite in such grey-hued mudstone (Tucker, 1981; Merriman *et al*., 2003).

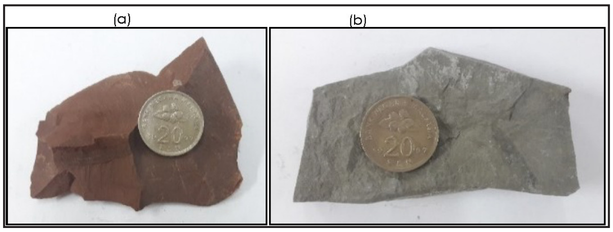

Figure 10: Rock samples representing (a) red mudstone and (b) grey mudstone of the Chepor Member.

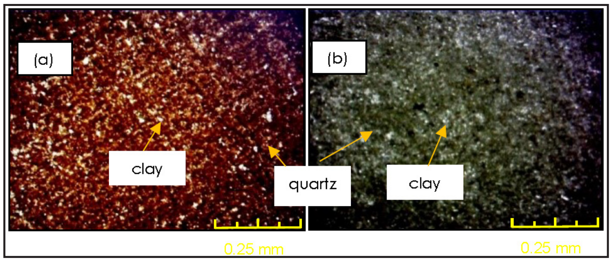

Figure 11: Thin section photomicrograph of (a) red mudstone and (b) grey mudstone.

Figure 11 illustrates the thin sections of red mudstone and grey mudstone from the Chepor Member located at Bumita Quarry, Utan Aji. Looking at both thin sections, the mineral crystals are extremely fine, making it very difficult to identify the type of minerals present with the petrological microscope (Tucker, 1981). Generally, the minerals present in a mudstone are clay minerals and quartz.

Both mudstone of Chepor Member has nearly the same seismic velocity because of its physical properties. Generally, mudstone is a fined grain encompassed of clay minerals and silt-grade quartz. The only difference that can be seen clearly is the color of the mudstone. Seismic velocity does not get affected by the difference in color, since both mudstone show the same physical properties therefore the seismic velocity shows nearly the same.

The main reason on why the low resistivity values of red mudstone is because of the chemical processes it had undergone which is oxidation and the ferromagnetic properties itself. The chemical composition of the red mudstone is iron (III) oxide (Fe_2O_3) which can be seen by the red color. Dynamically, the ferromagnetic property of Fe_2O_3 creates an environment which caused electrons to easily move around the material, this reduces the resistivity properties as current can move through the mudstone easily.

The resistivity of grey mudstone is higher because of the deficient in iron compared to the iron content in red mudstone which is higher. The chemical composition of grey mudstone is iron (II) oxide (FeO). Resistivity value greater than the resistivity of mudstones is consider as sandstone.

Upon integrating the porosity and permeability values derived from the laboratory tests, it has been observed that the results for both red mudstone and grey mudstone are nearly the same. The porosity of red mudstone is 0.95% compared to grey mudstone which is 1.9% (Table 3). The permeability value for red mudstone is 5.58×10^{-5} µd while grey mudstone is 2.06×10^{-5} µd.

CONCLUSION

The study has effectively employed seismic refraction and electrical resistivity surveys to investigate the geological exposure of the Chepor Member at Bumita Quarry, Utan Aji. The seismic velocity and resistivity values of both red mudstone and grey mudstone from the Chepor

Table 3: Comparing parameters between red mudstone and grey mudstone.

Parameters	Red mudstone	Grey mudstone
Seismic velocity (m/s)	1500 – 2100	1500 – 2300
Resistivity (Ωm)	15 – 100	120 – 500
Porosity (%)	0.95	1.9
Permeability (µd)	5.58×10^{-5}	2.06×10^{-5}

Member were combined with their respective porosity and permeability values. These are useful benchmarks for the mudstones within the Chepor Member geological unit.

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AUTHOR CONTRIBUTIONS

NMM: Investigation, data curation, writing original draft. HH: Investigation, data curation, formal analysis, writing – editing. TYJ: Validation, formal analysis. MTZ: Conceptualization, formal analysis, methodology, software. NAI: Conceptualization, formal analysis, methodology, software. MFMD @ AMDMFM: Conceptualization, validation. TA: Review and editing.

CONFLICT OF INTEREST

The authors affirm that there are no conflicts of interest in relation to this research, nor are there any personal relationships that could be perceived as potentially exerting influence on the findings presented in this paper.

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