



## ORIGINAL PAPER

**INVESTIGATION OF SEDIMENTARY OUTCROPS USING GEOPHYSICAL METHODS IN LANGKAWI, KEDAH, MALAYSIA**

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**ARTICLE INFO****Article history:**

Received 27 February 2025

Accepted 7 August 2025

Available online 20 August 2025

**Keywords:**

Crustal anisotropy

Moho and Conrad discontinuities

Common Conversion Point (CCP)

stacking

410 km and 660 km discontinuities

Receiver function

**ABSTRACT**

The geological outcrop provides insight into the subsurface characteristics and history of the region. Traditional mapping and sampling techniques offer surface information but lack comprehensive subsurface analysis. To bridge this gap, 2-D Seismic Refraction and 2-D Electrical Resistivity Imaging (2-D ERI) methods were applied at Sungai Itau and Taman Helang Perdana in Langkawi, Kedah, Malaysia. These sites, part of the Singa Formation, consist of sandstone, carbonate, mudstone, and conglomerate. The study aimed to map the outcrop and determine the seismic velocity and resistivity values of the formations. Rock samples underwent thin-section and XRD analysis. Results showed sandstone had high velocity (1000–4500 m/s) and resistivity (1000–6000  $\Omega$ m), while mudstone exhibited lower values (500–2500 m/s; 20–120  $\Omega$ m). Sandstone was rich in quartz, with microcline, hematite, and dolomite. The integration of seismic, resistivity, and laboratory analyses effectively characterized the subsurface, confirming the Singa Formation's presence. This study enhances geological maps by combining surface observations with subsurface data, leading to a more comprehensive understanding of the geological setting for scientific, engineering, and environmental applications.

**1. INTRODUCTION**

Langkawi, located in northwest Malaysia, is renowned for its diverse geological formations, making it an ideal natural laboratory for studying outcrops. Outcrop is defined as exposed bedrock or an unconsolidated deposit to the surface of the ground. These outcrops are generally found along riverbanks, along the slopes of deep gorge and also on the crests of ridges. The outcrops are important for studying structural features of rocks such as orientations of bedding planes, fold axes, foliation, depositional features orientations, paleomagnetic orientations (Betlem, 2022).

Geophysical methods use high-precision sensors (e.g. geophone) that detect the arrival times of seismic waves generated by an energy source. These differences in physical properties must be measured accurately. Accuracy of measurements and their analysis rely heavily on technological development (Prowse, 2007). Combining data from different geophysical surveys, including compressional wave and electrical parameters, and integrating additional geological and geophysical information is a complex task that requires sophisticated data processing and

interpretation techniques. The inversion process for extracting elastic parameters from seismic data is inherently an inverse problem, which can be ill-posed and sensitive to noise.

Conventional geological mapping and surface observations alone are insufficient for fully understanding the subsurface characteristics, continuity, and structural complexities of these formations. Many outcrops are partially covered by vegetation, weathered layers, and modern sediments, limiting direct field observations and creating gaps in geological interpretation.

The objectives of this study are to image the subsurface outcrop using seismic refraction and electrical resistivity, determine the seismic velocity and resistivity value and to correlate geophysical results with the geological data in Langkawi Island. This study aims to integrate geophysical techniques with traditional geological approaches to improve the characterization and interpretation of Langkawi's outcrops, ultimately contributing to the broader understanding of geological setting, aiding in various scientific, engineering, and environmental applications.

## 2. LITERATURE REVIEW

Sedimentary outcrops are a major source of geological and stratigraphical history and can express environmental conditions in the past, sedimentary processes and tectonic movements. When it comes to Langkawi, Kedah in Malaysia, sedimentary outcrops are particularly important because they show the geological history of the area and can also be used for searching for natural resources (Smith and Jones, 2020). In this study, two geophysical methods had been used which are 2-D seismic refraction and 2-D electrical resistivity tomography. To determine subsurface characteristics, ERT detects changes in electrical resistivity. It has been applied to locate groundwater resources and distinguish between several sedimentary strata (Wang et al., 2021). It is appropriate for in-depth geological research due to its efficiency in high-resolution imaging of sedimentary outcrops (Wang et al., 2021). By examining the refraction of seismic waves, seismic refraction is a geophysical technique used to look into subsurface geological features. Snell's Law states that seismic waves bend or refract when they come into contact with various layers of materials moving at different speeds. This technique yields useful details on subsurface layering, such as material characteristics, thickness, and depth. Using a source like a sledgehammer or a little explosive charge, seismic waves are produced at the surface using the seismic refraction method. Placed at different distances from the source, seismic sensors, also known as geophones, log the arrival times of the refracted waves. Geophysicists can map the depths and thicknesses of the various subsurface layers and ascertain their velocities by examining these arrival times (Zhang et al., 2022).

In the previous study conducted by Muztaza et al. (2012) in Lenggong, Perak, it is demonstrated that the geophysical technique of seismic refraction and 2-D resistivity imaging is useful for the examination of the shallow surface. Field data from 2-D resistivity imaging indicate that the alluvium consists of boulders or weathered granite along with granitic bedrock phases. In addition, 2-D resistivity imaging results were successfully used to identify faults and fractures, which estimates the electrical properties of soil and rocks. Seismic refraction results show how the rocks and soil are deteriorating and rippable. At a depth of 5 to 30 m, the first layer's obtained velocity is roughly 360–1200 m/s. Granitic bedrock was discovered as the second layer, which is moving at a speed of more than 2000m/s. Rami (2014) conducted a 2-D seismic refraction survey at Ayer Hangat, Langkawi, and found that the study area contains shale and a fault associated with the hot springs. 2-D resistivity imaging and seismic refraction method had been used by Muztaza et al (2019) in identifying the structural geological contact of sedimentary lithologies at Guar Jentik, Perlis and Bukit Kukus, Kedah. The first study area's resistivity result reveals that there are two main zones: red mudstone, which has a resistivity value

between 1 and 100  $\Omega\text{m}$ , and sandstone, which has a resistivity value between 2000 and 9000  $\Omega\text{m}$ . Seismic refraction has also revealed the velocity of each zone, with the mudstone zone having a velocity of 200 to 1800 m/s and the sandstone zone exceeding 2000 m/s. The red mudstone zone and the sandstone zone are where the fault's geological contact is found. The contact zone lies between the chert zone and the mudstone zone in the second study area, where the fracture was discovered within the chert zone. Furthermore, it is discovered that the fold forms in the chert zone. The resistivity values of the mudstone and chert zones are 1  $\Omega\text{m}$  to 1500 m/s and 2600  $\Omega\text{m}$  to 35000  $\Omega\text{m}$ , respectively. Mudstone with a velocity of around 800 m/s makes up the first layer of the seismic section, and the velocity typically >1200 m/s is interpreted as chert zones for the second layer. Muztaza et al. (2024) investigates seismic refraction and electrical resistivity methods in the Chepor Member of the Kubang Pasu Formation in Perlis, Malaysia. Red and grey mudstones were identified with similar seismic velocities but differing resistivity, porosity, and permeability values. Red mudstone showed lower resistivity s (ranging from 15 to 100  $\Omega\text{m}$ ) and porosity (0.95 %) than grey mudstone ranging from 120 to 500  $\Omega\text{m}$  and a slightly higher porosity value of 1.9 %. The results provide benchmark geophysical parameters for interpreting mudstone in the region.

## 3. GEOLOGICAL SETTING AND STUDY AREA

The geology of Langkawi islands today is a result of a very long depositional history under the various sedimentological regimes and palaeoenvironmental conditions, followed by the tectonic and magmatic events and finally by surface processes that etched the present beautiful landscape. The early episode of Langkawi formation was related to the long depositional events that took place along the margin of Gondwanaland (Leman et al., 2007). Since the publication of Jones' 1966 Geological Map of Langkawi and his 1981 Geological Survey Malaysia District Memoir 17 on the "Geology and mineral resources of Perlis, North Kedah and the Langkawi Islands", many more studies had been carried out on various aspects of its geology. The Palaeozoic sedimentary rocks in Langkawi had been placed under four formations. They are, from the oldest to the youngest, the Machinchang, Setul, Singa and Chuping formations (Lee, 2014; Lee 2009).

### 3.1. LOCATION I: SUNGAI ITAU, LANGKAWI.

The Kampung Sungai Itau earth quarry is located in the southwest of Kampung Sungai Itau, about 500 m from the Kampung Sungai Itau-Durian Perangin road junction. The Sungai Itau quarry operation cut almost the entire northwestern tip of the NW-SE trending ridge connecting this quarry and the Kilim quarry described earlier in Basir et al. (1992), Leman (1996), Roslan (2017) and Shi et al. (1997). The Kampung Sungai Itau quarry mainly features





**Fig. 2** Study area at Sungai Itau, Langkawi, Kedah.



**Fig. 3** Sungai Itau, Langkawi outcrop.

The penetration depth will depend on the electrode spacing (Muztaza et al, 2013). A computer is connected to an electronic switching unit, which is connected to the multicore cable. The Signal Averaging System 4000 (ABEM Terrameter) was used by ERT to automatically take successive readings and average the findings over time. This device is an automated electrical imaging system appropriate for resistivity survey mode. The terrameter SAS 4000 is run by an external 12V battery. To create an electrical connection between the wires and the earth, stainless steel electrodes are utilised. The electrodes are connected to the cable takeouts via a jumper or connecting wire. The Pole-Dipole (PD) array utilizes a remote cable for data acquisition.

The programme utilised for the 2-D resistivity imaging is called RES2DINV. The "\*sk4\*" format was initially used for the raw data collected in the field. The acquired data is then entered into the

computer to read the terrameter's digital number records. The "\*dat\*" format will be applied to data. This format is the only one that the RES2DIN software can read. Consequently, an inverse model is generated by processing data. To find the genuine resistivity values, the inversion model is optimised using the least mean method. The contouring values are modifiable and contingent upon the geological data of the area under investigation. For interpretation, the produced data is transferred into the Surfer8 software.

One popular analytical method for figuring out a crystalline material's phase assemblage is X-ray diffraction, or XRD. It is extremely pertinent to geology and minerals since it may be used to ascertain the mineralogical makeup of sediments and other geological materials. The foundation of X-ray diffraction is the idea that X-rays interact with the atoms within a crystal lattice, producing both constructive and destructive interference of the X-ray



Fig. 4 Study area at Taman Helang, Langkawi.



Fig. 5 Taman Helang, Langkawi outcrop.

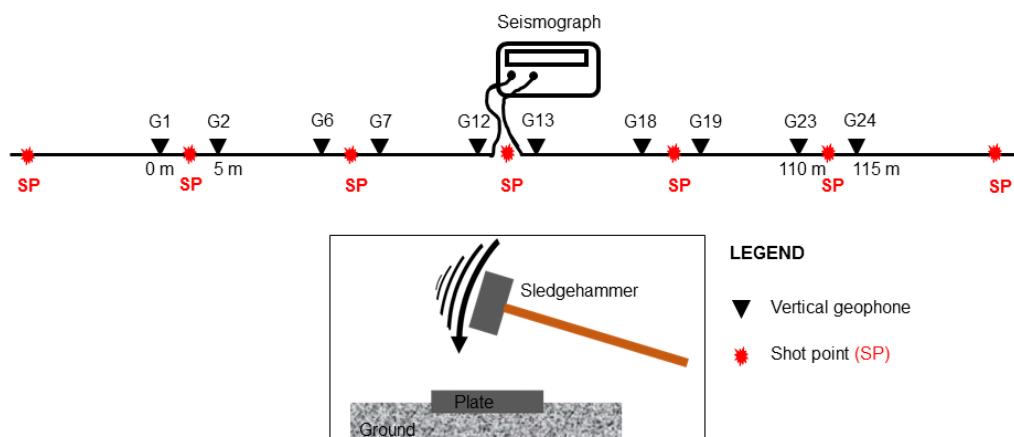
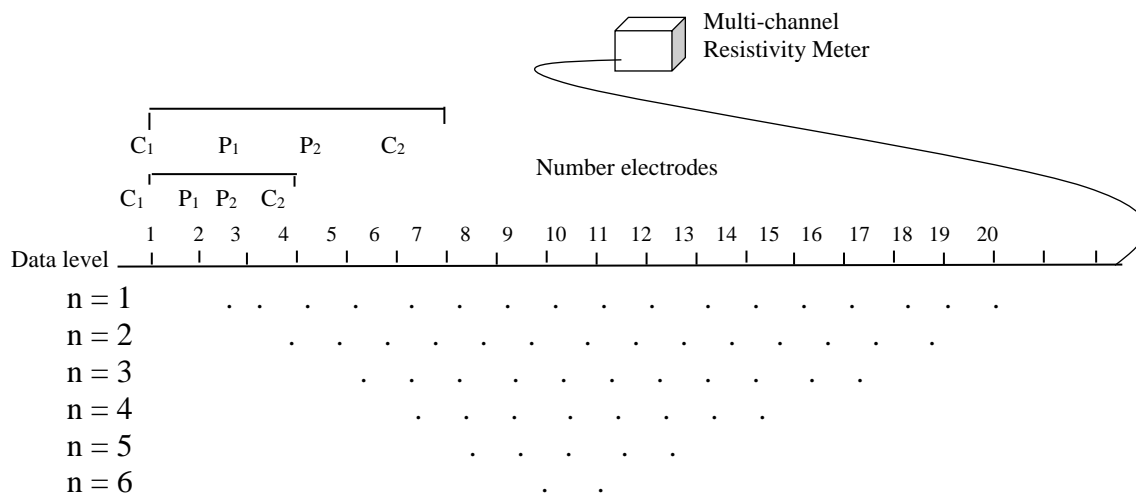


Fig. 6 Seismic source location and seismic refraction p-wave hammering technique.



**Fig. 7** Arrangement of electrodes for a 2D survey and the sequence of measurements used to build up an apparent resistivity pseudosection (Loke, 1999).



**Fig. 8** Thin section of rock sample was viewed under microscope.

waves. Based on the idea of Bragg's Law, this contact produces a pattern of diffracted X-rays that may be identified and examined. In the XRD method, rock samples are crushed and processed to a particle size of around 100  $\mu\text{m}$  for XRD analysis. By doing this, a test sample that is more representative of the entire sample can be produced. A suitable sample holder is carefully filled with the resulting powder. However, same as thin section analysis, the rock sample had been sent to the lab for XRD analysis.

A thin section is a carefully prepared slice of rock, mineral, or soil for microscopic examination, especially using polarising or electron microscopes (Fig. 8). This method is crucial in petrography for understanding rock characteristics and origins. The rock samples were sent to the Pusat Penyelidikan Arkeologi Global and Jabatan Mineral dan Geosains

Malaysia for processing. The process involves cutting a thin slice, mounting it on a glass slide, and polishing it to a precise thickness for clear observation. Under a petrographic microscope, the thin section is examined to identify minerals, their abundance, distribution, and relationships. This analysis helps in rock classification and diagenetic studies, revealing detailed petrographic properties and features.

## 5. RESULTS AND DISCUSSIONS

### 5.1. SUNGAI ITAU

Figure 9 shows the result of the seismic refraction profile survey. The total length of the survey line is 34.5 m and the spacing between geophones is 1.5 m. The result can be divided into two main zones which are mudstone and sandstone. The first zone, which is mudstone, has a velocity value of 500 m/s to

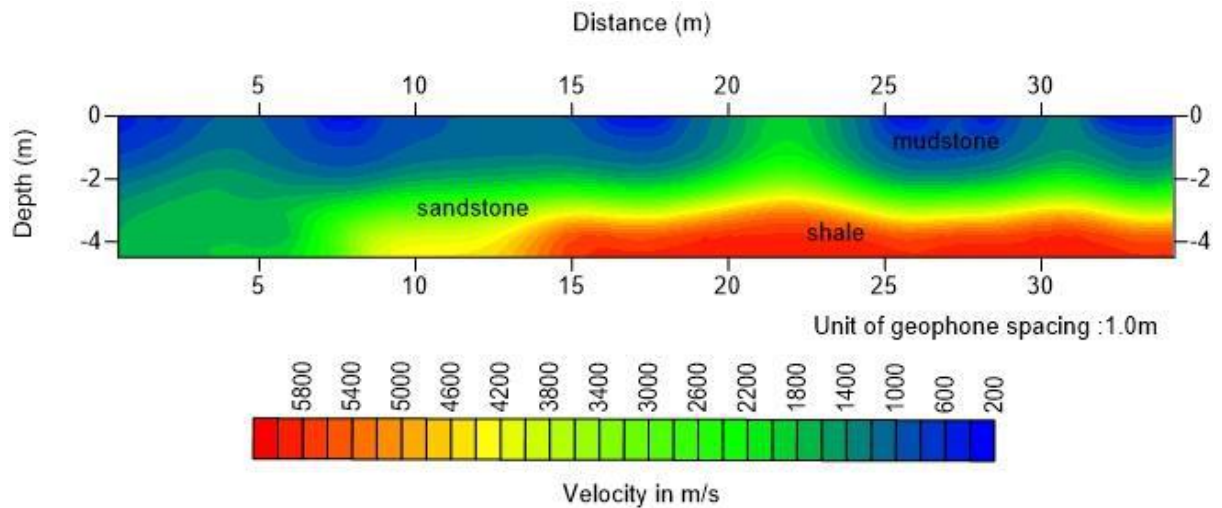


Fig. 9 The seismic refraction profile of Sungai Itau, Kedah.

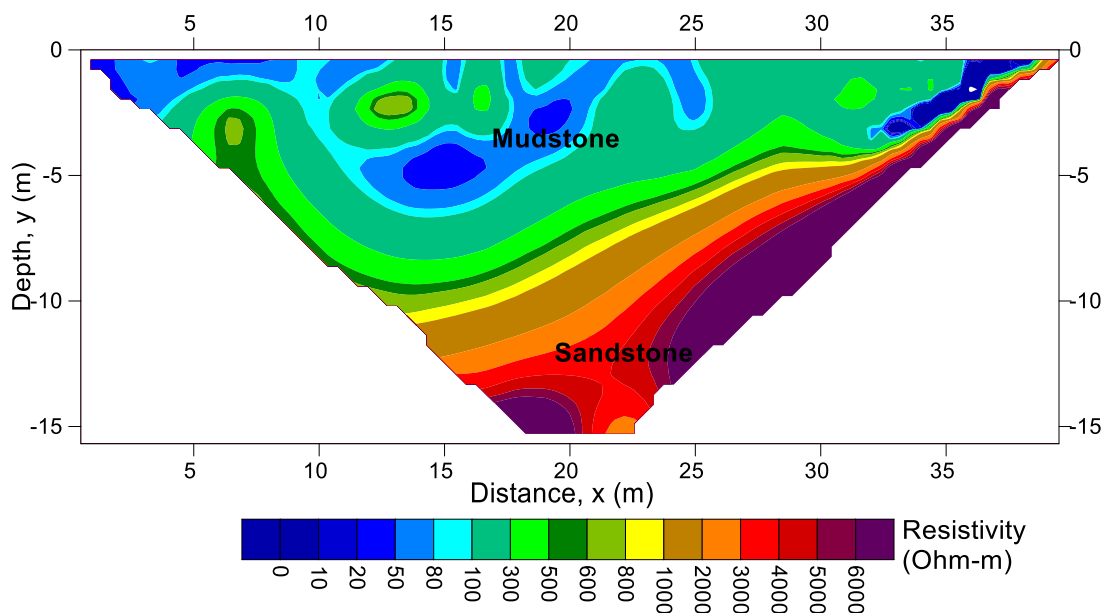


Fig. 10 Inversion model of electrical resistivity tomography (ERT) value of pole dipole array at Sungai Itau, Langkawi, Kedah.

2500 m/s. The second zone is sandstone/ shale with a velocity value of 2000 m/s to 4500 m/s (Rami, 2014). The velocity contrast of high-low value is indicating the contact zone between two different types of rock (Nisa et al., 2012).

Based on Figure 10, the depth of current penetration is around 15 m. The resistivity value is between 1  $\Omega$ m to 6000  $\Omega$ m. There are two distinct ranges of colour mudstone. Sandstone/shale with the obvious high resistivity 1000  $\Omega$ m – 6000  $\Omega$ m, that refers to sandstone/shale. Contrary to the low resistivity value between 20  $\Omega$ m -120  $\Omega$ m which belongs to mudstone. Sandstone is often composed of quartz grains, a good insulator. Mudstone in Langkawi's Singa Formation might contain clay minerals that can conduct electricity to some extent, further lowering its resistivity compared to sandstone (Makoundi et al., 2014).

Based on Figure 11, the X-ray diffraction pattern of sandstone sample, this sample contains minerals of quartz and dolomite. The composition of quartz is higher than dolomite. Quartz is very common in sedimentary rocks due to durability and its resistance to the weathering process. Dolomite, although less resistant than quartz, is abundant in the Earth's crust and thus a common component of sandstone (Sulistiyo et al., 2020).

Based on Figure 12, the X-ray diffraction pattern of the quartz sample. The XRD analysis of quartz provided information on mineralogical properties of a quartz sample. This sample formed from sandstone and was dominated by quartz minerals. In some cases, quartz can be found in association with minerals that are characteristic of specific geological environments (Bonewitz, 2012).

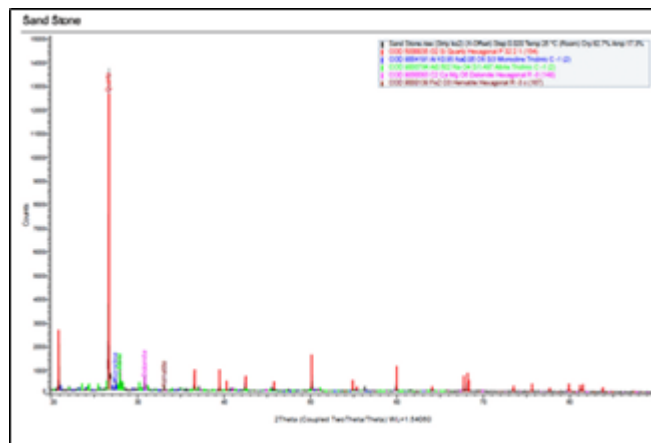


Fig. 11 XRD pattern of sandstone sample at Sungai Itau, Langkawi, Kedah.

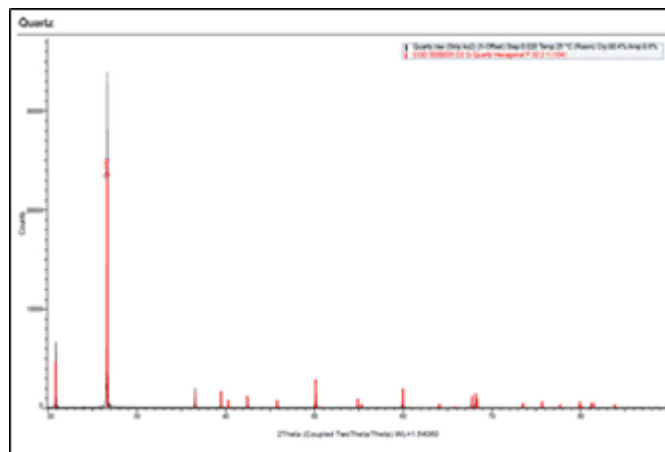


Fig. 12 XRD pattern of quartz sample at Sungai Itau, Langkawi.

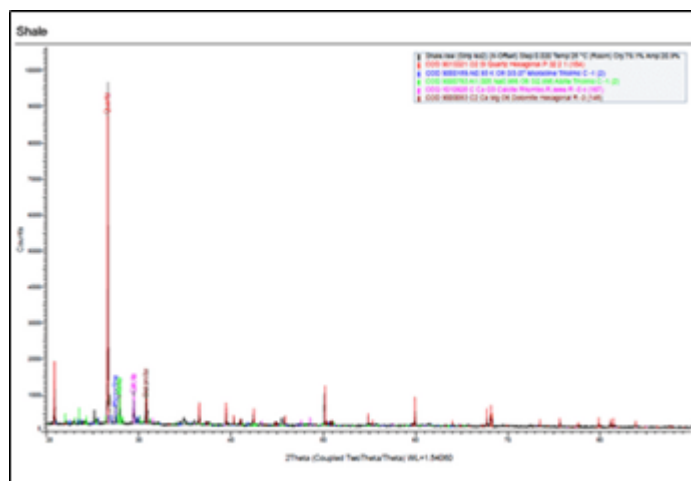
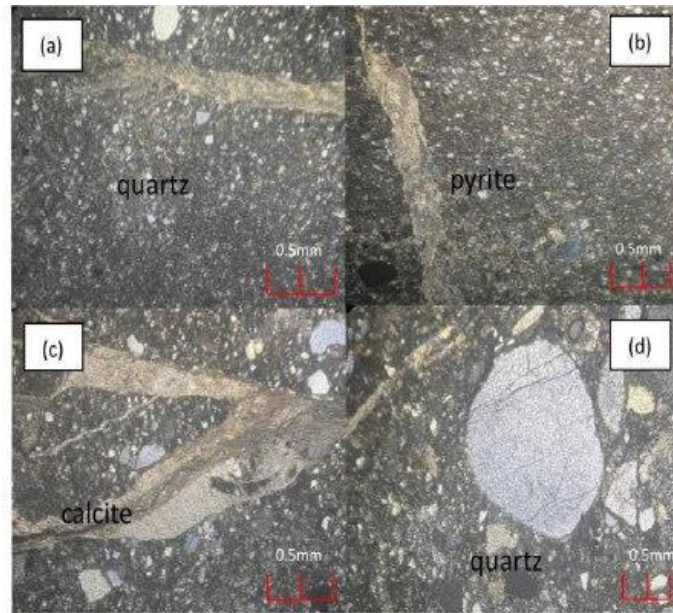


Fig. 13 XRD pattern of shale sample at Sungai Itau, Langkawi, Kedah.

Based on Figure 13, the X ray diffraction pattern of the shale sample. This sample contains minerals of quartz, dolomite and calcite. Shale is often formed from weathering and erosion that tend to have a higher of quartz compared to dolomite and calcite (Sulistiyo et al., 2020)

Thin section, also known as a petrographic thin section, is a thin slice of a rock or mineral sample that has been created in a lab for use with an electron microscope, polarising petrographic microscope, and electron microprobe in optical mineralogy and petrography. Since quartz is one of the most common minerals, it is usually used as the thickness gauge



**Fig. 14** Thin section photomicrographs of shale rock which consists of a) quartz, b) pyrite, c) calcite, and d) quartz minerals.

when determining thickness using the Michel-Lévy interference colour chart.

The thin section of shale is viewed under a microscope with magnification  $4 \times 0.1$ . Shale is a sedimentary rock with fine grains that is made from mud, which is a mixture of clay particles and minute pieces of other minerals, mostly calcite and quartz. The rock readily splits into thin, parallel layers, exhibiting a laminated structure. Shale differs from other kinds of mudstones in that it has a feature called fissility, which makes it more likely to split. Silt and clay-sized mineral particles, which are often carried by wind and water, consolidate to create shale. These fine-grained sediments build up over time and undergo lithification and compaction, which turns them into shale. Although shale's mineral composition varies, it usually consists primarily of quartz, feldspar, calcite, and iron oxides in trace amounts, as well as clay minerals including kaolinite, illite, and montmorillonite. Shale's colour can vary based on its exact composition; frequent colours include black and grey, but they can also be green, red, or brown depending on the amount of organic material and iron compounds present.

Figure 15 shows the thin section of sandstone 1. Based on the figure, the composition of the sandstone includes quartz and vein. Sandstone is one of the clastic sedimentary rocks which is made of mineral grains or grains of sand size or bigger, all held together by a mineral matrix. It is easy to agree with the opinion about siltstone as one of the most widespread forms of the sedimentary rock which is typical for the sedimentary basins in the different parts of the Earth. Sandstone is formed through the process of sedimentary layers, where gravel is compacted with cementing of combined sand-sized particles that are in the range of 0.0625 to 2 millimetres. A high seismic

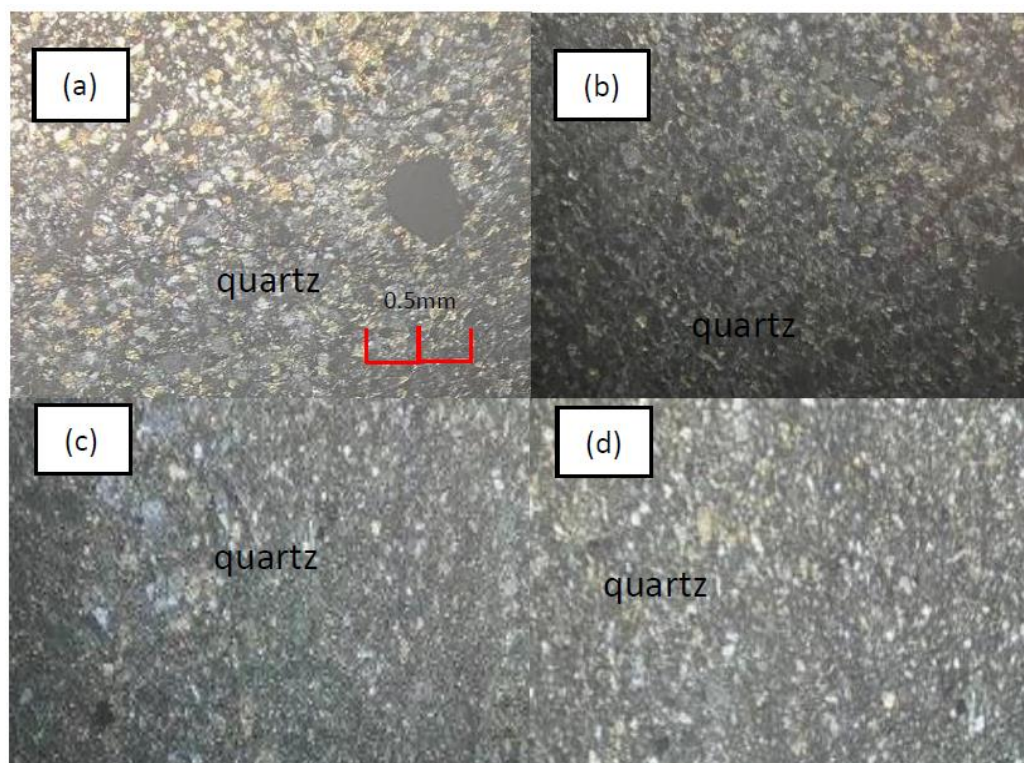
velocity may indicate tightly interlocked grains with low porosity in a thin section, as seen in well-cemented sandstone. These particles are commonly spherical, and they may consist of other rock fractions or minerals like quartz and feldspar. While it is subject to the effects of weathering some of the characteristics of this sedimentary rock of sandstone, it is fundamentally composed of quartz, feldspar and lithic fragments.

Figure 16 shows the thin section for sandstone 2. The magnification is  $4 \times 1$  with scale of 0.5 mm. This rock sample consists of mica and quartz minerals. The grain is fine-grained sandstones as it has small, closely packed grains which give them a smoother texture. Finer-grained sandstones generally have lower porosity because smaller grains pack tightly together, leaving less room for pore spaces. Figure 17 shows the thin section of the quartz rock. Under cross-polarized light (XPL), quartz displays low interference colors, usually ranging from grey to very pale yellow. This is because it is a weakly birefringent mineral. Quartz may show undulose extinction, where the crystal goes dark and light in patches as the microscope stage is rotated. This phenomenon indicates deformation of the quartz, usually from tectonic stress (Quartz, 2024).

The primary origin of quartz is in places rich with silica where molecules of silicon dioxide ( $\text{SiO}_2$ ) gather to form complex structures. This solidifying phase has different manifestations ranging from the gradual solidification of molten lava in deep underground Earth layers to silicon-rich liquid deposits in fault surfaces resulting in silica deposition. Such ways facilitate the development of variously shaped crystals of quartz in the absence of different sizes attributes like dimensionality in view of factors like thermal influence, pressure and other minerals. Quartz exhibits a mesmerising spectrum of colours,



**Fig. 15** Thin section photomicrographs of sandstone 1 rock which consists of vein and quartz minerals.



**Fig. 16** Thin section photomicrographs of sandstone 2 rock which consists of vein and quartz minerals.

each indicative of its unique geological history and chemical makeup. For clear quartz, it is transparent and colourless for its clarity and brilliance. Amethyst quartz has radiant purple, owing to the presence of iron impurities and irradiation during formation. rose quartz delicate pink tones which are attributed to the presence of quartz, titanium, iron, or manganese and smoky quartz ranging from light grey to deep brown, caused by natural radiation or aluminium impurities.

Table 1 shows the parameter of geophysical method integrated with rock properties. At Kampung Sungai Itau, an active earth quarry exposed a good lithological section consisting of limestone, silty shale, and mudstone interbedded in sandstone. This quarry section has a number of known sedimentary facies, the combination of which suggests an offshore marine depositional environment heavily impacted by sea level fluctuations. This fluctuation in sea level may

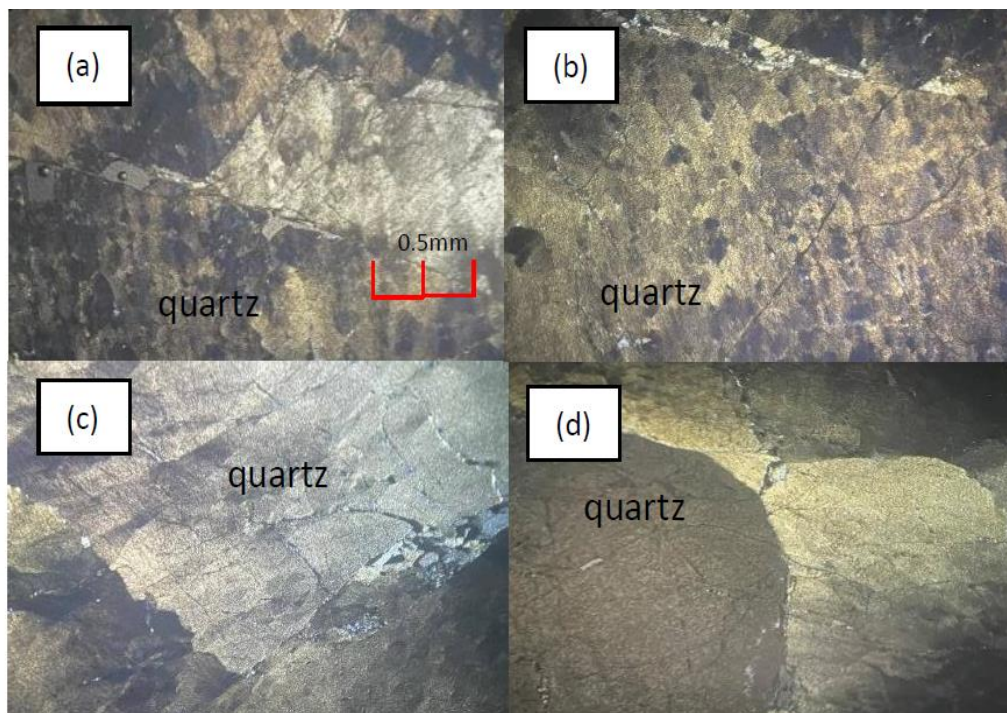


Fig. 17 Thin section photomicrographs of quartz.

Table 1 Geophysical parameter with rock properties at Sungai Itau, Langkawi.

Locality	Velocity (m/s)	Resistivity ( $\Omega\text{m}$ )	Rock	Mineral
Sungai Itau	500 - 2500	20 - 120	Mudstone	Quartz
	2000 - 4500	1000 - 6000	Sandstone	Quartz

have a direct correlation to the alterations in the Langkawi islands' paleoclimatic conditions during the deposition (Leman and Yop, 2002)

5.2. TAMAN HELANG PERDANA

The seismic cross section in Figure 18 shows the result of the rock available at Taman Helang Perdana. Generally, the seismic cross section profiles show that the outcrop has two main zones. The boundary between two different velocity contrasts is the geological contact (Nisa et al., 2013). The first zone is the mudstone with the range of seismic velocity between 600 m/s to 2600 m/s. The thickness of the first zone is about 2 m from the top of the surface. The second zone is the sandstone rock with the velocity of more than 2200 m/s.

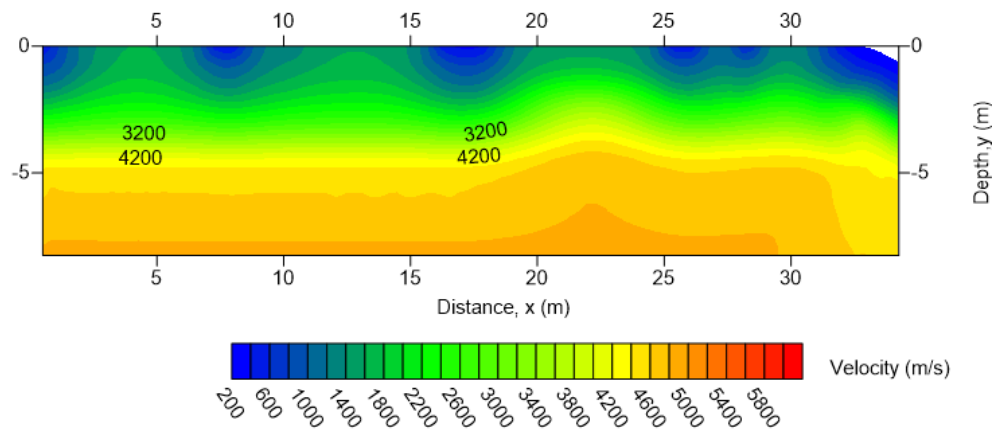
Based on the inversion model of 2-D electrical resistivity shown in Figure 19, there are two distinguished layers that can be interpreted, consisting of sandstone and mudstone rocks with an approximate depth of around 20 m. The sandstone/shale gives higher resistivity value of 500  $\Omega\text{m}$  to 3000  $\Omega\text{m}$  at depth varying from 5-15 m, whereas the mudstone gives low resistivity value below 100  $\Omega\text{m}$  -300  $\Omega\text{m}$  at depth less than 5 m.

Taman Helang Perdana might reveal additional clues about the origin of the sandstone layers there. This could involve analysing the composition of the

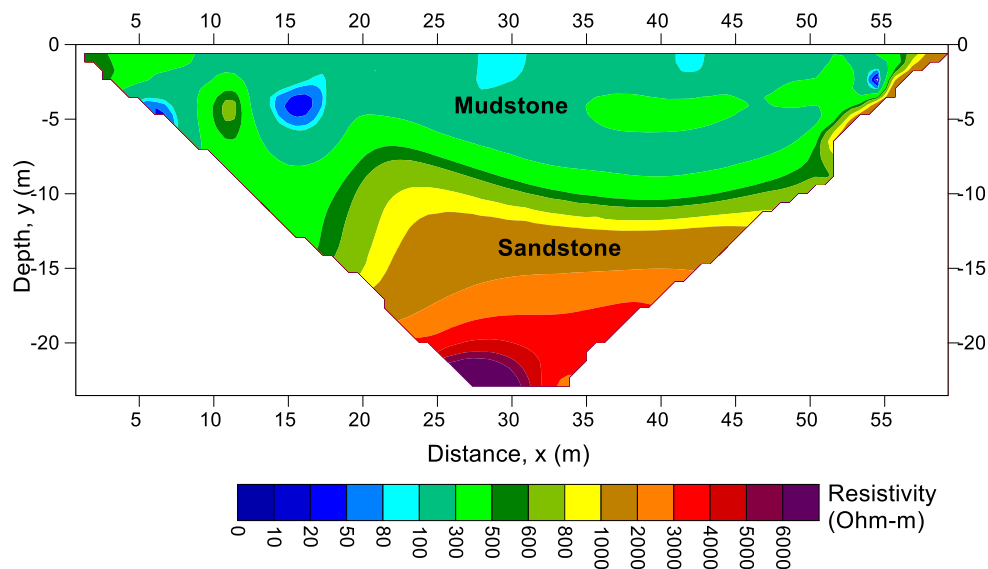
sand grains, such as the presence of specific minerals, to infer the source rocks that were eroded. Mudstone deposition suggests calm periods, while sandstone layers might signify times with stronger currents or wave action (Rahman et al., 2022). Hard rock layer gives a resistivity value greater than 3000  $\Omega\text{m}$ . Hard rocks generally have high resistivity compared to softer or more porous rocks. (Sivaramakrishnan et al., 2015).

Figure 19 shows the inversion model of the electrical resistivity tomography. Most of the line is covered with sandstone/shale 500  $\Omega\text{m}$ -3000  $\Omega\text{m}$ . Sandstone/shale is a porous rock, meaning it has spaces between the sand grains. The amount of water filling these pores significantly impacts resistivity. This is due to their low porosity and the absence of fluids that can conduct electricity (Sivaramakrishnan et al., 2015). Low value (1  $\Omega\text{m}$ - 100  $\Omega\text{m}$ ) is a saturated zone. It may be due to the water from raining that seep through the underground causing the low resistivity value. This is the part of the subsurface where all the pores and cracks in the rock or soil are filled with water (Nor et al., 2023).

Based on the thin section shown in Figure 20, mudstone consists of quartz and mica. The magnification used is 4 x 0.1 and the scale for each thin section observed is 0.5 mm. The easiest way to characterise mudstone is as a sedimentary rock



**Fig. 18** The seismic refraction profile of Taman Helang Perdana.



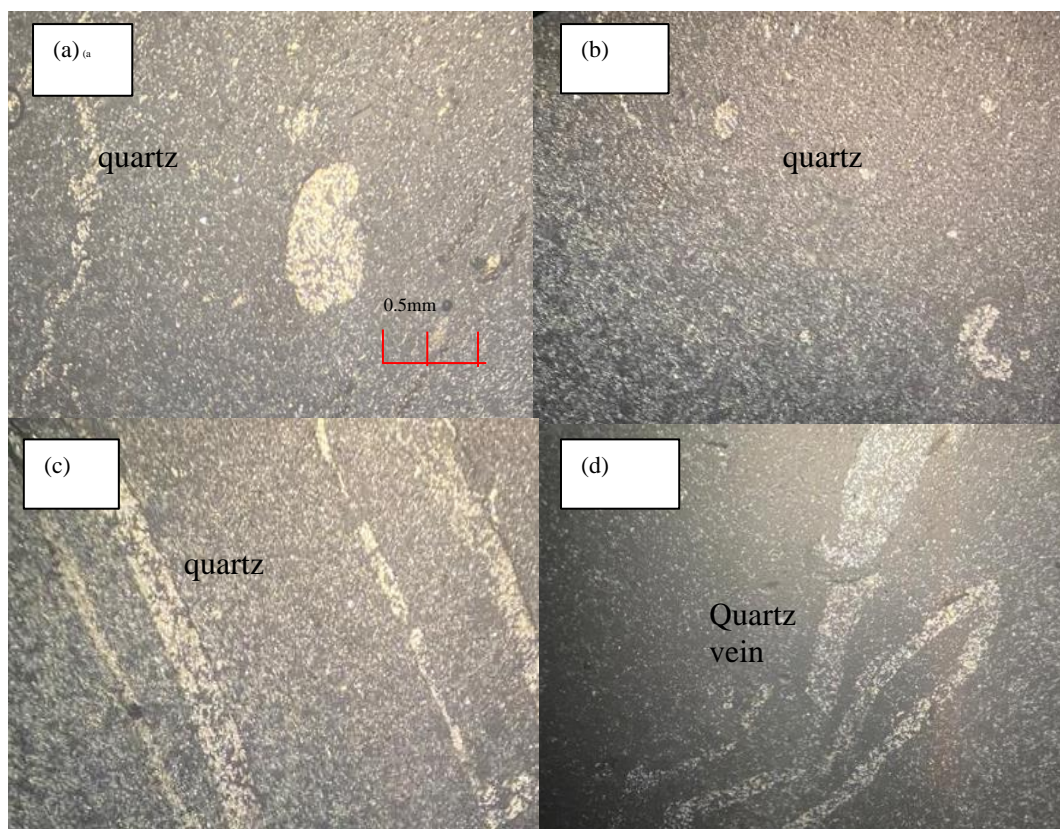
**Fig. 19** ERT inversion model of pole dipole array of Taman Helang Perdana, Langkawi, Kedah.

composed of silt and clay particles that range in size from 1/256 to 1/32 mm and is typically more complicated and thinly stratified. Mudstone is frequently created by the lithification process, which compresses silt, clay, and water to create sedimentary rock. Over extended periods of time, the process of compaction and cementation shrinks the size of the sand and gravel particles to create a rock. However, the nature and content of mudstone depends on the types of sediment that originated it and the depositional settings. Which consists of fine to coarse particles of clay minerals, quartz and feldspar. A little amount of organic matter, iron oxides and many other minerals that may vary the colour and other characteristics of rock is often present in the formation of mudstone. For instance, the organic content in some mudstones is high, and they are dark grey or black, and there are reddish brown mudstones related to iron content.

Table 2 shows the parameter of the geophysical method integrated with the rock properties. Taman Helang Perdana is indicated to have offshore to transition shallow marine depositional environments (Abidin, 2020).

## 6. CONCLUSION

This research study has effectively employed seismic refraction method, electrical resistivity method, thin section analysis and XRD analysis to investigate sedimentary outcrops using geophysical and geological methods in Langkawi, Kedah, Malaysia. Higher velocities indicate denser and more compact materials while lower velocities suggest softer materials. High resistivity values indicate quartz-rich rocks or dry compact materials, while low resistivity suggests clay-rich formations, fractures, or water-saturated zones. The analysis of the rock samples revealed that mudstone generally has lower



**Fig. 20** Thin section photomicrographs of mudstone which consists of quartz.

**Table 2** Geophysical parameter with rock properties at Taman Helang Perdana.

Locality	Velocity (m/s)	Resistivity ( $\Omega\text{m}$ )	Rock	Mineral
Taman Helang	600 -2600	100-300	Mudstone	Quartz
Perdana	>2200	500-3000	Sandstone	
		3000-6000	Conglomerate	

seismic velocities (600 to 2600 m/s) and resistivity values (20 to 120  $\Omega\text{m}$ ) compared to sandstone (2000 to 4500 m/s for seismic velocity and 500 to 6000  $\Omega\text{m}$  for resistivity).

A high seismic velocity may result in a thin section revealing tight interlocking grains with low porosity, such as well-cemented sandstone. A low resistivity value can indicate the presence of clay minerals, fractures, or high porosity, contributing to increased water content. When both high seismic velocity and resistivity are observed, XRD analysis may confirm quartz-rich minerals like sandstone. Conversely, low resistivity and seismic velocity often correspond to clay minerals such as kaolinite and smectite or alteration minerals like sericite and chlorite, suggesting weathering or hydrothermal alteration.

Overall, by integrating seismic refraction, resistivity, thin section, and XRD data, rock type, porosity, and mineralogy can be interpreted. This combined approach enhances the understanding of geological outcrops, subsurface conditions, and material properties for applications in engineering geology, hydrogeology, and mineral exploration.

#### ACKNOWLEDGEMENT

We extend our gratitude to the Ministry of Higher Education Malaysia for Fundamental Research Grant Scheme with Project Code: FRGS/1/2022/STG08/USM/03/1 entitled "Performance-Based Multimodal Geophysical Design for Soil Dynamic properties to Improve Visualisation of Subsurface Conditions". We also acknowledge the research to Industry Grant by Global GeoExpert Sdn. Bhd entitled "Mineral Exploration Using Integrated Geophysical Methods", account project number: R504-LR-GAL007-0000001507-G121

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