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Study of Subsurface Structures for the Sungai Lilin, Coal Prospect Area, South Sumatra using Active Seismic Multichannel Analysis of Surface Waves

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Abstract

Indonesia's dependency on coal, which powered ~47% of its electricity in 2018, highlights the need to optimize exploration amid rising energy demands and volatile fuel prices. This study aims to characterize subsurface structures in the Sungai Lilin coal prospect area, South Sumatra, within the coal-bearing Muara Enim Formation employing the Multichannel Analysis of Surface Waves (MASW) method. We carried out field seismic data collection using a PASI 16S24-P seismograph equipped with 24 geophones, spacing of 4 m. After having dispersion processes, which result in phase velocities (or group velocity) against frequency, we inverted phase velocities to extract subsurface structures through shear wave velocity (Vs) and density. By analyzing Vs variations, we mapped coal deposits at depths of 5–40 m with Vs values of 250–450 m/s, alongside soil, sand, claystone, and siltstone layers. Our subsurface structures derived MASW approach, integrated with borehole data, provided high-resolution 2-D models of young, shallow coal seams varying in thickness and depth. These findings highlight MASW's efficacy for cost-effective, non-invasive coal exploration, offering insights into resource delineation that support energy security for Indonesia and sustainable coal exploration in similar geological settings.

1. Introduction

Indonesia possesses vast, yet underexplored, mineral and coal resources across its archipelago, with significant reserves in Kalimantan and Sumatra (Friederich and Van Leeuwen, 2017). Globally, coal supplies approximately 40% of electricity demand and a quarter of total energy needs (Kober et al., 2020). As the world's sixth-largest holder of coal reserves, Indonesia's estimated 38,805 million metric tons in 2020 accounted for 3.6% of global reserves (Chung, 2025). Rising domestic energy demands and volatile fuel prices have intensified the need for alternatives to oil and natural gas. By 2018, coal dominated Indonesia's power generation at 47%, followed by natural gas (29%), oil (7%), and renewables (14%) (Yudiartono et al., 2018). Therefore, optimizing coal utilization is thus critical to meeting these growing energy needs.

The South Sumatra Basin, which is located on the southern part of Sumatra Island, Indonesia, is the country's premier sedimentary basin. The basin is famous due to its giant hydrocarbon accumulations, conditioned by the intense tectonic evolution of the region. Geologic development of the basin has primarily been the result of interaction between the Australian Plate, Sunda Plate, and Pacific Plate. Its tectonic evolution is significant in the context of the petroleum systems of this basin, particularly its evolution in the past by extensional and compressional tectonics.

The basin is situated along the Sunda Shelf, part of the larger Sunda Plate, and is bounded by several important tectonic features. In the west, the Barisan Mountain Belt defines the area of contact between the Sunda Plate and the Australian Plate, an area of very high tectonic activity. The basin's eastern edge is marked by the South Sumatra Fault Zone, which separates it from the Mentawai Fault System, and the Indian-Australian Plate subduction beneath the Eurasian Plate to the west also contributes to regional tectonic stresses. The tectonic history of the basin dates back to the Mesozoic and Cenozoic eras, with the development of the basin occurring during Late Cretaceous to Early Tertiary times, primarily due to extensional tectonism that resulted in rifting and the creation of deep sedimentary depocenters (Hamilton, 1979).

The evolution of the South Sumatra Basin was a combination of tectonic extension followed by compression. Extensional tectonics prevailed in the Late Cretaceous to Early Tertiary, and this produced rift basins. The basins were later filled with thick sequences of sediments, and these formed the basement for giant hydrocarbon source rocks. From Miocene to Pliocene, compressional tectonics, mainly caused by the collision of the Sunda and Australian Plates, remodeled the basin. This deformation period created thrust faults and folds that were largely responsible for the structural development of the basin (Williams and Eubank, 1995).

Structurally, the South Sumatra Basin is characterized by a variety of geological structures, reflecting its extensional and compressional development. Normal faults dominate in the central and southern parts of the basin, signifying the initial phase of rifting. The faults are typical of the early stage of extensional tectonic development of the basin. However, in the western and northern parts of the basin, thrust and reverse faults dominate, reflecting the later compressional tectonics. Horst and graben structures are also present in the basin, typical of rift basins. These structures have created a suitable setting for hydrocarbon accumulation, with anticlines and synclines being perfect traps for gas and oil (Williams and Eubank, 1995).

The South Sumatra Basin is considered to be one of Indonesia's most productive hydrocarbon regions. The tectonic development, including a rifting phase followed by compressional folding, imposed the conditions conducive to the generation of source rocks and subsequent generation of oil and gas. During the extensional phase, sediments rich in organic matter were deposited and then thermally matured, while the later compressional phase created superb traps in the form of structural and stratigraphic traps. Significant oil fields such as the Musi, Lematang, and Tanjung fields are found within the basin, which testifies to its hydrocarbon potential (Bishop, 2000).

From the tectonic evolutionist's perspective, the basin history has been distinguished into several periods. The history of the Late Cretaceous-Early Tertiary has been characterized by the basin evolution initially through the extensional tectonics, which in turn created the deep rift basins. Compressional processes have been on the ascendant during the Miocene-Pliocene era, leading to the development of structural traps as well as folds. The region is still tectonically active, especially in relation to the ongoing collision of the Sunda Plate and the Australian Plate, which is affecting seismicity and ongoing deformation of the basin.

The geological setting of Sumatra, shaped by the collision of the Eurasian and Indian Ocean Plates, features a complex tectonic framework with large basins ideal for coal formation (McCaffrey, 2009). This interaction deformed Mesozoic and Paleozoic rock complexes along the Barisan Mountains, creating the Barisan Back Arc Basin, including the South Sumatra Basin (Ningrum, 2024) (Figure 1). Within this basin lies the Tertiary-aged Muara Enim Formation, renowned for its coal-bearing sequences (Friederich et al., 2016; Friederich and Van Leeuwen, 2017). Coal quality in this region varies due to depositional environments, temperature, and pressure over geological time (Ningrum, 2024). This study focuses on

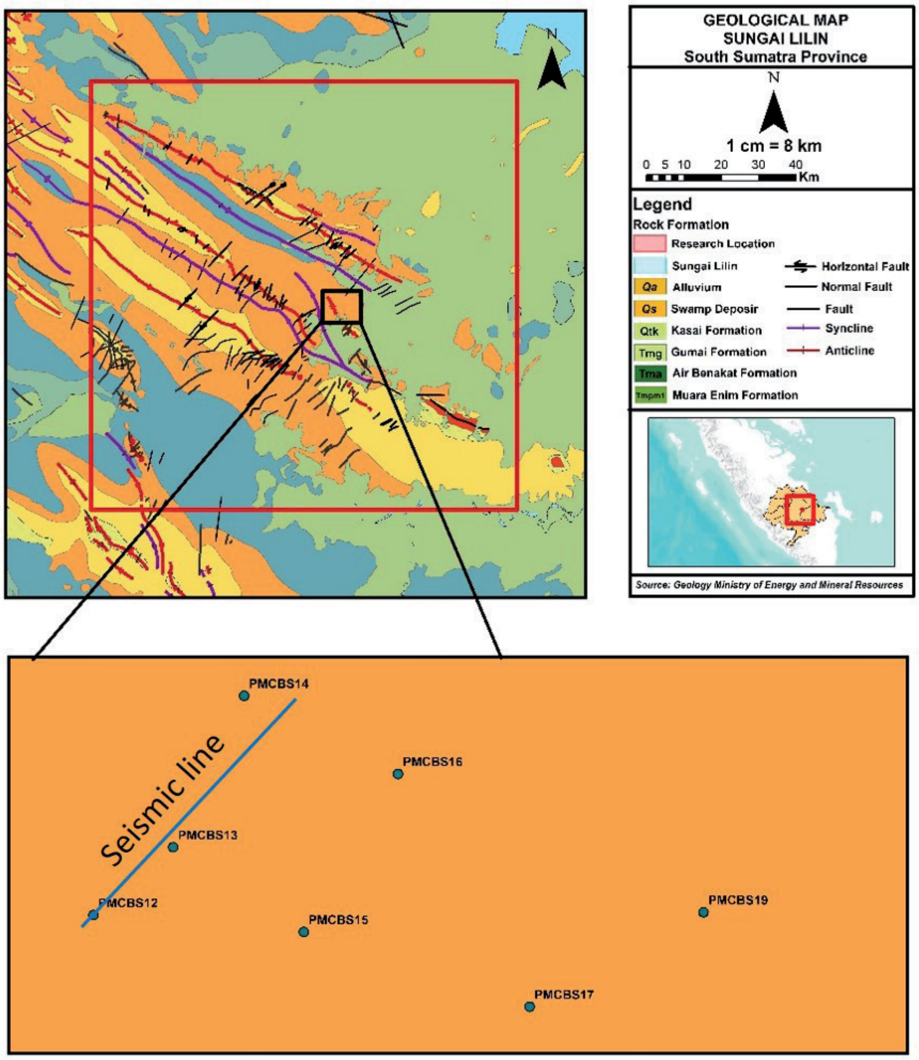

Figure 1. Geological map of study area in Musi Banyuasin, South Sumatra. Blue dots are the locations of boreholes. Blue line is seismic survey line (modified from Lubis et al., 2024).

the Sungai Lilin District within the Muara Enim Formation (Figure 1), aiming to delineate subsurface coal layers through physical properties of shear wave velocity (Vs) and density to support exploitation for domestic and industrial use.

To explore these coal prospects, we employ the Multichannel Analysis of Surface Waves (MASW) method, a geophysical technique selected for its efficiency in subsurface characterization. MASW investigates shear wave velocity (Vs) variations to map material properties and depths with high resolution (Park et al., 1999; Park, 2016). Such a study has been intensively used previously (e.g., Chandran and Anbazhagan, 2017; Lubis et al., 2021; Lubis et al., 2022). Its advantages include cost-effectiveness, non-invasiveness, and adaptability to diverse ground conditions, making it ideal for shallow coal exploration (Bessason and Erlingsson, 2011). Previous studies have successfully utilized MASW to identify coal seams and sedimentary layers, such as in Abbas and Abdelgowad (2024), who mapped subsoil structures under a damaged building; and Lubis et al. (2022), mapped subsurface structures in a coastal area. However, MASW has limitations, including reduced resolution at greater depths due to Rayleigh wave attenuation and potential challenges in detecting thin layers below the method's wavelength limit (Xia et al., 2009; Socco et al., 2010). To enhance reliability, this study integrates MASW data with borehole records, providing ground-truth validation of seismic interpretations. These approaches aim not only to locate coal deposits but also to deepen our understanding of their geophysical and geological significance in optimizing resource utilization.

2. Data and methods

Subsurface shear wave velocity (Vs) data were acquired using the Multichannel Analysis of Surface Waves (MASW) method along a single seismic profile in the Sungai Lilin coal prospect area. The survey location was selected based on a literature review of the region's geology and coal potential, with measurement points aligned to correspond with existing borehole data for validation. Field data collection utilized a PASI 16S24-P seismograph equipped with 24 geophones with a natural frequency of 4.5Hz. A space of 4 meters was chosen as the maximum space for optimum seismic data recording in the research area. The total length of 108 meters was also set to optimize the resolution of shallow coal layers (<40 m), based on the expected depth range from regional studies (Xia, 2006; Hamed et al., 2024). A 7 kg sledgehammer hitting a metal plate was utilized as an active seismic source during the data recording. A total of 28 shot points distributed in a straight line were recorded to create a 2-D figure of coal distribution. To achieve a high signal-to-noise ratio and ensure data precision, data acquisition was repeated multiple times at each point. Initially, seismic traces were examined to confirm the absence of apparent anomalies or inconsistencies caused by significant environmental disturbances during recording. A schematic of the measurement setup is provided in Figure 2A.

Data processing began with the application of a low-pass filter to exclude high-frequency noise, enhancing the precision of the data for the picking stage (Selim et al., 2014; Gan et al., 2015). An example of seismic data filtered is illustrated in Figure 2B. Subsequent process was performed using winMASW 5.0 Professional software, which transforms filtered seismic recordings from the space-time domain into the frequency-phase velocity (f-c) domain (Dal Moro et al., 2006). This process generates a dispersion image (Figure 2C) by analyzing Rayleigh wave propagation, capturing Vs variations across subsurface layers of differing densities and depths (Lopes et al., 2024).

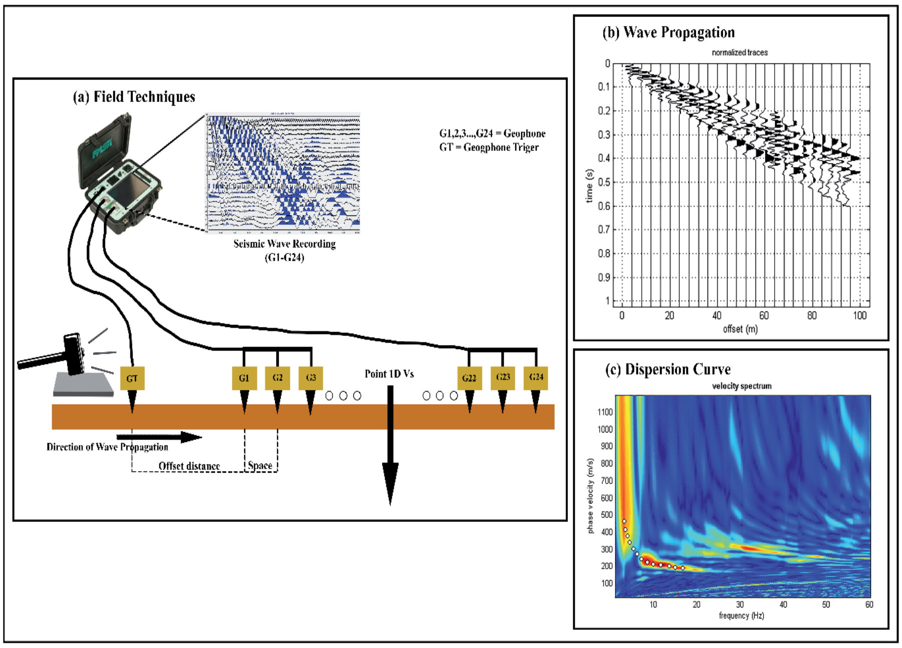

Figure 2. A) The schematic of the MASW Survey. B) A filtered seismic data. C) A dispersion curve image.

In the dispersion image (2C), a fundamental mode (M0) and higher modes (M1 to M4) can be observed. However, the clearest mode (M0) is chosen. High-amplitude surface waves were selected to construct the Rayleigh wave dispersion curve, reflecting the multimodal characteristics of wave propagation in layered media (Tian et al., 2017; Chen et al., 2019). The Rayleigh wave dispersion curves were then inverted using genetic algorithms (Dal Moro et al., 2007), which were implemented in the winMASW 5.0 Professional software. The resulting 1-D stratigraphic profiles of Vs versus depth (Figure 3) were obtained for each measurement point (Capizzi and Martorana, 2023). To create a 2-D subsurface model, these 1-D profiles were interpolated with the model exhibiting the smallest root mean square (RMS) error selected as the most reliable representation of the subsurface structure (Olafsdottir, et al., 2020). We used kriging interpolation, which gives the best linear unbiased prediction at unsampled locations, based on a Gaussian process (Le Gratiet and Garnier, 2014). Borehole data, collected from nearby wells, were incorporated to calibrate the seismic profiles, ensuring consistency between geophysical predictions and direct geological observations.

3. Results and Discussion

MASW measurements revealed a diverse subsurface structure in the Sungai Lilin coal prospect area, characterized by distinct rock types identified through their shear wave velocity (Vs) and density values. These Vs values, interpreted to a depth of 60 m, were modeled in 1-D stratigraphic profiles and interpolated into a 2-D representation, providing insights into layer composition and stiffness. The borehole data show that the subsurface comprises materials such as soil, claystone, coal, sandstone, and siltstone, with Vs values ranging from approximately 174-589 m/s across the survey area.

Field data, exemplified by time-domain wave propagation images (Figure 2A), show a normal dispersion pattern in the Rayleigh wave dispersion curves (Figure 2C). This pattern, where phase velocity decreases with increasing frequency, indicates a stratified medium with stiffness increasing progressively with depth. The dominance of the fundamental mode in the dispersion curve suggests a relatively simple, stratified subsurface with gradual increases in stiffness, typical of unconsolidated sedimentary sequences. Higher modes, if present, could indicate more complex layering or discontinuities not resolved in this study (Park et al., 1999; Fu et al., 2021). This observation aligns with the expected geological setting of the Muara Enim Formation, where unconsolidated sediments overlie more compact layers.

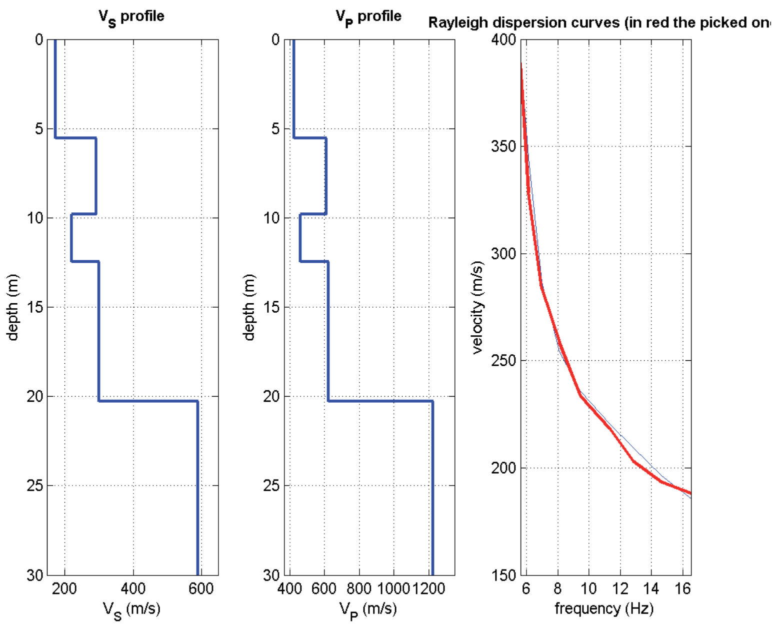

Figure 3. Example of 1-D Vp and Vs profiles, and also Rayleigh dispersion curve profile at point 8.

At point 8, for instance, the Vs profile (Figure 3) shows values increasing with depth, reflecting a transition to denser, harder materials. Shear wave velocity serves as a reliable indicator of soil stiffness and strength (Wair, et al., 2012; Tsai and Kishida, 2015; Hussien and Karray, 2015), with higher Vs values correlating to greater hardness and density, as supported by regional studies (Lubis et al., 2022; Hamed et al., 2024). The Vs range of 174–589 m/s (point 8) corresponds to a medium soil classification (175 < Vs ≤ 350 m/s) in the shallow layers, transitioning to stiffer materials below. The average Vs over the upper 30 meters (Vs30), a standard metric for site classification, falls within the medium soil category, consistent with the observed lithology (SNI 1726:2019, 2019). The Vs range at point 8 includes coal at approximately 250–450 m/s, alongside claystone, sandstone, and siltstone, with variations in thickness and density evident across the profile. The Vs range of 250–450 m/s for coal layers reflects their relatively low stiffness and density due to high organic content and porosity, contrasting with the higher Vs values (> 550 m/s) observed in denser rock layers. This aligns with theoretical expectations for young, shallow coal deposits, where compaction and diagenesis are minimal (Lu et al., 2023; Ningrum, 2024). In general, the inversion process to obtain Vs values provides a good confidence level with an average of root mean square (RMS) values less than 10%.

The 1-D Vs profiles, such as that at point 8, reflect medium properties along the survey path, while the 2-D interpolation highlights spatial variability in layer thickness and composition (Figure 4). The increase in Vs with depth indicates greater compaction, a trend consistent with the depositional history of the Muara Enim Formation, where shallow, young coal deposits overlay more consolidated sediments (Nasution et al., 2017; Ningrum, 2024). These findings underscore the utility of MASW in mapping coal-bearing sequences, though the method's reliance on Rayleigh waves, which decrease in amplitude exponentially with depth, suggests potential limitations in resolving deeper or thinner layers (Foti et al., 2014).

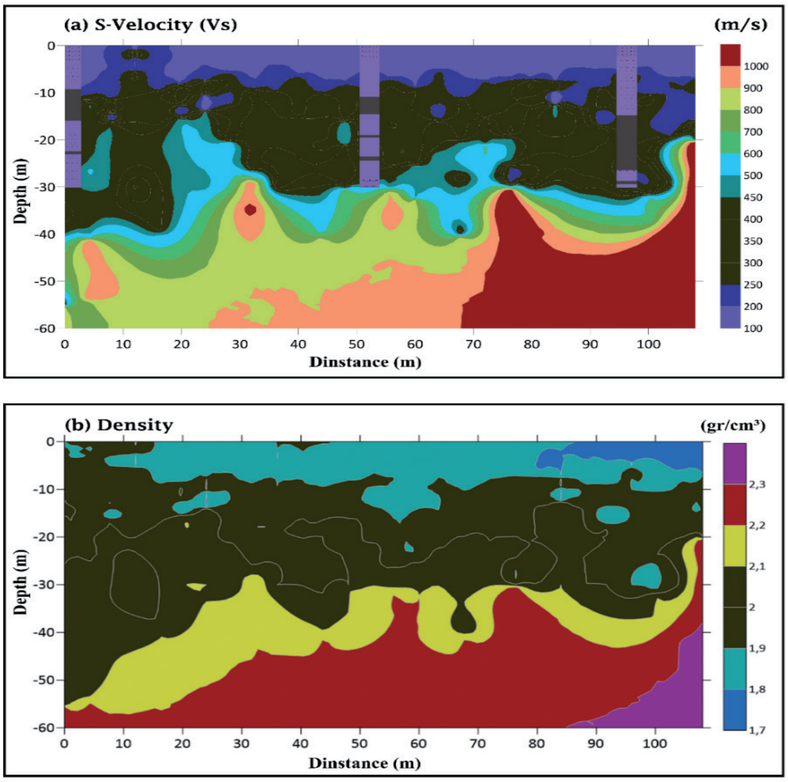

Figure 4. 2-D Interpolation Model of the 1-D Stratigraphy.

The Vs values from the 2-D model in the figure clearly indicate the presence of coal in the prospect area, with coal layers found at depths ranging from 5 to 40 meters, alongside other rock types such as soil, sand, claystone, and siltstone. The coal layers at each point vary in thickness and depth. These layers are classified as young coal, characterized by relatively thin layers and shallow depths. However, some areas also feature thicker layers with potential for mining. The thin, shallow coal layers (5–40 m) identified in the 2-D model are consistent with the Miocene–Pliocene peat-forming environments of the Muara Enim Formation, where rapid subsidence and sediment influx in a back-arc basin setting limited coal seam thickness compared to deeper, more mature basins like those in Kalimantan (Sosrowidjojo and Saghafi, 2009; Nasution et al., 2017).

This data interpretation is further supported by the region's geological conditions, which include coal outcrops, and by the Muara Enim formation, which contains at least 11 main coal seams (Lubis et al., 2024). The depths and thicknesses obtained from the results differ slightly from the borehole data due to variations in the topography at the study location. While the depths and thicknesses obtained from the results slightly differ from borehole data due to topographical variations at the study site, it is important to note that the vertical height difference between geophones does not exceed 10% of the geophone span length to avoid significant disruptions in surface wave propagation (Park et al.,1999; Xia et al., 2009).

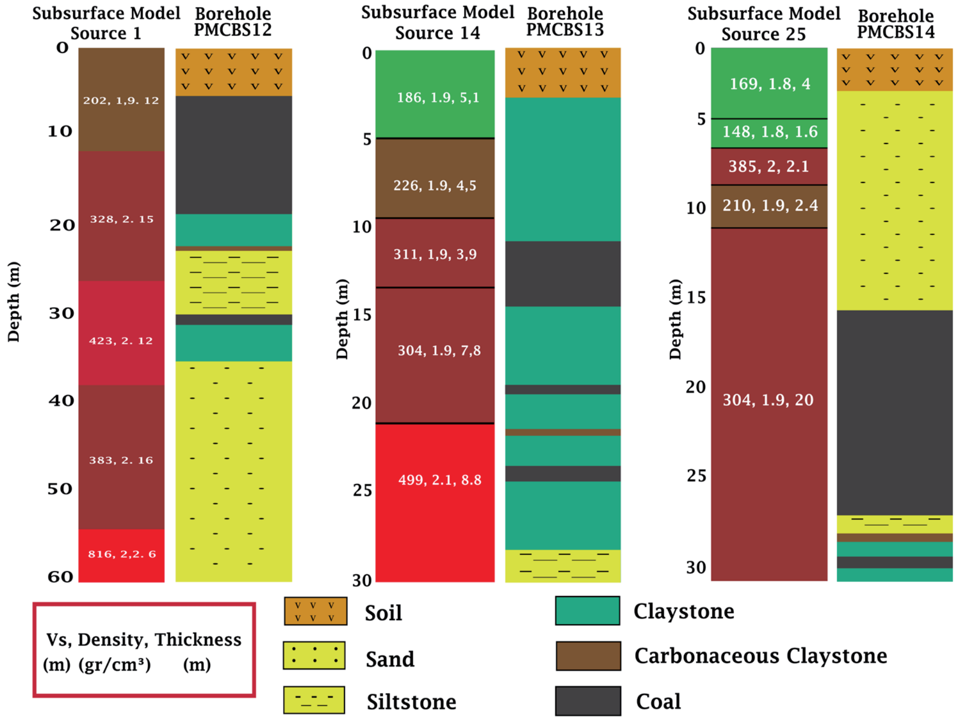

Figure 5. 1-D Stratigraphic model and borehole data.

Based on the interpretation of the 1-D stratigraphic model and borehole data (Figure 5), the shear wave velocity (Vs) values for coal layers range between 250 and 450 m/s, corresponding to various types of coal with differing moisture content and energy characteristics. Several other materials are present as constituents, including organic material, fine sand, medium soil rich in carbonaceous content, compact soil, and rock, found at varying depths. The Vs range of 250–450 m/s suggests variability in coal compaction and moisture content, potentially affecting its energy potential (Lu et al., 2023). Shallow depths (5–40 m) make these deposits accessible for small-scale mining, though their thinness may limit large-scale exploitation unless thicker seams are identified in adjacent areas. While MASW effectively delineates coal layers at 5–40 m, its resolution decreases with depth due to the attenuation of high-frequency Rayleigh waves, potentially missing thin seams or deeper deposits (Park et al., 1999; Xia et al., 2009). Topographic variations may also introduce minor errors in Vs interpolation, as noted by Du et al. (2024). Future studies could integrate passive MASW or borehole seismic to enhance deeper imaging.

4. Conclusions

The interpretation of the 1-D stratigraphic model and borehole data reveals that the shear wave velocity (Vs) values for coal layers range from 250 to 450 m/s, corresponding to different coal types with varying moisture content and energy properties. Additionally, the layers contain several other materials, such as organic matter, fine sand, carbonaceous-rich medium soil, compact soil, and rock, distributed at different depths. MASW revealed coal layers at 5–40 m with Vs of 250–450 m/s, indicative of young, porous deposits in the Muara Enim Formation. Overall, our result shows a good correlation with borehole data. These findings highlight MASW's efficacy for shallow coal exploration while underscoring the need for complementary methods to resolve deeper or thinner seams.

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