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Unveiling Shale Gas Reservoir Structures with Seismic and MT Data: WALDIM-Based Study from East Kalimantan Indonesia

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Abstract

The Pamaluan Formation, which has a Total Organic Carbon (TOC) value of up to 1.78% and varying degrees of thermal maturity, offers the Indonesian Kutai Basin considerable potential for shale gas production. This research integrates seismic and magnetotelluric (MT) geophysical techniques to improve the knowledge of shale gas prospectivity in the area. There are nine MT sounding locations and nine 2D seismic lines in the dataset. By creating a time structure map, the anticline and syncline structures that were detected by seismic interpretation were further examined. 2D resistivity inversion models were created by processing MT data using the rho variance approach and the Python WALDIM module. A dominant anticline-syncline structural trend oriented roughly 45° from true north is indicated by the data. With an average strike of 43.5°, MT analysis demonstrates a dominant two-dimensional (2D) geoelectrical dimensionality that is in good agreement with local geological trends. At depths of 500–1000 m in anticlines and 2000–3000 m in synclines, zones of low resistivity (1–5 Ohm.m) were found, with thicknesses varying from 2000 to 4000 m. Low resistivity anomalies are interpreted to represent potential shale gas-bearing intervals, consistent with the geological framework of the Kutai Basin. The integration of seismic and MT data successfully delineates folds, faults, and low-resistivity anomalies, interpreted as potential shale gas-bearing intervals, highlighting the significance of a multidisciplinary approach in mitigating exploration risk and enhancing shale gas prospectivity evaluation in the Kutai Basin.

Keywords:
shale gas, Kutai Basin, seismic, magnetotelluric, WALDIM

1. Introduction

The shale gas potential in the Kutai Basin, East Kalimantan, is considered to be highly promising based on various research findings. **Hamdani et al. (2019)** suggested that the Pulobalang Formation in this area exhibits a wide range of organic matter richness, with Total Organic Carbon (TOC) content varying from 0.2% to 4.27%, indicating a spectrum from poor to excellent quality. The dominant kerogen type identified within this Early Miocene formation is Type III, which typically has a strong potential for gas generation. The thermal maturity zone is relatively shallow, occurring at depths between 1,100 and 2,000 meters. Furthermore, the brittleness characteristics of the rock layers within the Pulobalang Formation support favorable conditions for hydraulic fracturing, with Brittleness Index (BI) values ranging from 0.6 to 0.91. The total estimated shale gas resource within this formation reaches approximately 2.78 trillion cubic feet (TCF). **Zajuli and Wahyudiono (2018)** proposed that TOC concentrations exceeding 1.5% and varying levels of thermal maturity across different depths are key factors influencing the shale gas potential in several Indonesian shale formations, including the Pamaluan Formation in the Kutai Basin. These findings reinforce the view that the Kutai Basin, with its favorable geological conditions, holds significant potential for the economically viable development of shale gas resources. Advanced geophysical methodologies are required to accurately analyze and quantify this shale gas potential, especially in geologically complicated basins like Kutai Basin.

Geophysical methods have been used extensively over the years to look for subsurface resources, especially hydrocarbons. Due to their great resolution and capacity to accurately simulate intricate subsurface geological features, seismic reflection techniques are the most popular among these approaches (**Susilo, 2020**). Seismic imaging reconstructs subsurface geometry by analyzing elastic wave propagation (**Bashir et al., 2021;**

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Lixin, 2022). Delineating important geological structures, such as faults, stratigraphic boundaries, and structural traps, such as anticlines and synclines, is a crucial step in the interpretation phase of seismic data and is essential for evaluating hydrocarbon systems (**Zhang et al., 2022**). However, the effectiveness of seismic methods can be constrained in areas with complex geology, poor seismic data quality, or high acquisition costs. To overcome these limitations, researchers increasingly advocate for the integration of complementary geophysical methods. One such technique is magnetotellurics (MT), which measures natural variations in the Earth's electric and magnetic fields to infer subsurface resistivity distributions. MT is particularly sensitive to the fluid content and mineralogy of rocks, making it suitable for identifying potential hydrocarbon bearing formations (**Ledo and Jones, 2001**).

Prabowo et al. (2020) suggests that MT's benefits over other geophysical techniques include its deep penetration capabilities, limitless natural signal sources, and lack of the need for artificial wave transmitters. Furthermore, MT is more environmentally friendly, has higher resolution than gravity and magnetic approaches, and works well in places where seismic methods are scarce (**Likkason, 2014; Nabighian et al., 2005**). However, anthropogenic activity close to the survey location and natural phenomena like solar storms and local lightning can cause electromagnetic disturbances that affect MT results (**Hidayat et al., 2021; Hidayat and Hamdalah, 2019; Kumar and Rao, 2025; Prabowo et al., 2020**). MT interpretation has been made more reliable by the development of a number of analytical methods. The WALDIM (Weaver Agarwal Lilley Dimensionality) method is one such tool that uses seven impedance tensor invariants to calculate the dimensionality of MT data, represent one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D) subsurface conditions (**Martí et al., 2009**). Furthermore, geoelectrical strike investigations based on MT impedance data offer important information about the direction and continuity of subsurface structural trends.

Several studies have demonstrated the effectiveness and complementary nature of integrating magnetotelluric (MT) and seismic data in subsurface investigations. **Miensopust et al. (2013)** emphasized that seismic and MT methods are complementary approaches. The limitations of seismic methods, which are less effective in areas with volcanic cover or zones characterized by complex heterogeneity, can be overcome through the application of MT, which is capable of detecting lithological variations as well as geological conditions at greater depths. Therefore, the integration of these two methods provides a more comprehensive representation of subsurface structures. **Tietze et al. (2019)** argued that the joint interpretation of seismic velocity and electrical resistivity data can significantly reduce ambiguities in subsurface models by offering independent yet mutually constraining physical property datasets. This approach is especially beneficial in shale gas exploration, where delineating both structural frameworks and lithological variations is critical for reservoir characterization. Further research supports the combination of seismic and MT techniques in geothermal and hydrocarbon exploration settings. **Cinti et al. (2015**) showed that the determination of reservoir limits in structurally complicated sedimentary basins was enhanced by the combination of MT resistivity and seismic reflection data. Similarly, **Ledo and Jones (2001)** demonstrated that MT can complement seismic amplitude anomalies by efficiently imaging resistivity contrasts linked to hydrocarbon saturation. Furthermore, to improve the accuracy of geological interpretation, joint inversion techniques, albeit more computationally intensive, are being used more and more to combine MT and seismic data into a single model framework (**Gallardo and Meju, 2004; Moorkamp et al., 2011**). Integrated geophysical techniques are being used more and more in the context of unconventional hydrocarbon resources like shale gas. Multimethod approaches are necessary to properly evaluate the potential of shale formations because of their complex heterogeneity and varying maturity levels. An integrated strategy combining seismic structural interpretation and MT resistivity imaging is required to comprehend the structural framework and detect low resistivity zones associated with organic rich shales. Overall, the reliability of hydrocarbon exploration results is increased by combining seismic and MT techniques, which improve the capacity to describe the geometry and physical characteristics of subsurface formations (**Irawati et al., 2022; Ledo and Jones, 2001; Tietze et al., 2019**). In the magnetotelluric (MT) method, geoelectric dimensionality analysis plays a crucial role in determining whether the data should be modeled using 1D, 2D, or 3D approaches. The WALDIM was developed to perform this dimensionality analysis more reliably through the use of rotational invariants criteria, without requiring prior assumptions of dimensionality, while also accounting for error propagation and establishing thresholds necessary for noisy real data (**Martí et al., 2009**). Nevertheless, many previous studies have tended to apply 1D, 2D, or 3D modelling and inversion directly, without being preceded by adequate dimensionality analysis, which may lead to biased interpretations, particularly in geologically complex regions. WALDIM-based dimensionality analysis is integrated with seismic and MT methods in order to overcome the limitations of each individual technique and to achieve a more accurate, consistent, and comprehensive reconstruction of subsurface structures.

2. Methods

2.1. Reflection Seismic

In this research, an integrated geophysical approach was employed by combining seismic reflection and magnetotelluric (MT) methods to delineate subsurface geological structures. The seismic reflection technique provides detailed imaging of deeper stratigraphic horizons and structural configurations, enabling the identification of faults, folds, and potential traps. Complementing this, MT data offers insight into the distribution of subsurface electrical resistivity, which is particularly valuable for characterizing lithological variations and detecting fluid content. By integrating these complementary datasets, a more comprehensive and reliable understanding of the geological framework of the study area was achieved. The seismic reflection method is an active geophysical technique employed to delineate the Earth's subsurface structure by assessing the travel time of seismic waves that are reflected back to the surface upon encountering subterranean rock layers. Reflection seismic is an active geophysical method widely utilized to investigate deeper subsurface conditions (**Dragičević et al., 1991**). This method can be implemented both onshore and offshore, offering flexibility in various geological settings. Common applications of reflection seismics include petroleum exploration, identification of subsurface features such as faults, analysis of complex geological structures and stratigraphy, as well as the detection of earthquake sources. In the interpretation of seismic reflection data, a critical step often involves the construction of a Time Structure Map, which facilitates a comprehensive analysis of subsurface structural patterns and geometries. This map illustrates the distribution of geological structures and stratigraphic horizons within the time domain, enabling geoscientists to identify prospective zones and delineate the location and extent of subsurface features (**Sukmono and Arta, 2013**). Through the continuity of seismic reflectors and structural trends, the geometry and type of traps, such as anticlines or synclines, can be effectively recognized. Time structure maps play a vital role in identifying geological formations based on their seismic travel times, thereby supporting the detection of structural traps and enhancing resource exploration efforts (**Stark, 2008**). In order to identify subsurface structural features pertinent to the geological framework of the study area, two 2D seismic traces specifically, lines 93R-2100 Runtu Matra and K-8033 Ekali Geosin derived from Post Stack Time Migration (PSTM) processing were interpreted out of the nine seismic traces in this study.

2.2. Magnetotelluric

Magnetotellurics (MT) is a passive electromagnetic geophysical method used to estimate the subsurface electrical conductivity by measuring natural variations in the Earth's geomagnetic and geoelectric fields at the surface. The sources of these signals can be broadly categorized based on frequency: at low frequencies (below 1 Hz), the signals originate from the interaction between the solar wind and the Earth's magnetosphere, while at higher frequencies (above 1 Hz), they are primarily generated by thunderstorm, particularly concentrated near the equatorial region. The strength and quality of these MT signals vary with time and space and are susceptible to artificial noise, such as that produced by power lines, pipelines, and other man-made infrastructure. As a result, MT data acquisition typically requires long recording durations and sophisticated data processing techniques to ensure a high signal-to-noise ratio. The skin depth concept explains how the lower-frequency signals penetrate deeper into the Earth, whereas higher-frequency signals are restricted for imaging shallow structures. A broad frequency spectrum used in the MT data enables imaging subsurface from near-surface depths to several kilometers. The passive nature of MT offers significant advantages, including lower operational costs, lightweight equipment, and minimal environmental impact, especially when compared to active geophysical methods.

Synthetic modelling conducted by **Zhang et al. (2014)** demonstrated that MT is capable of delineating vertical discontinuities based on contrasts in resistivity. Therefore, in geological modelling, MT can significantly contribute to seismic inversion by clearly identifying geological features such as vertically oriented faults. In a reservoir system, MT successfully imaged anticline strucutures based on resistivity distribution. In certain settings, such as salt domes or thick volcanic sequences, MT has shown superior capability in resolving subsurface structures compared to conventional seismic methods (**Avdeeva et al., 2012; Mansoori et al., 2016; Patro, 2017**). Resistivity of rocks can be approximated by dividing the pore fluid resistivity by the fractional porosity, emphasizing the role of fluid conductivity and pore structure in governing the overall resistivity of a rock formation. This study uses nine MT data, including K03, KT04, KT05, KT06, KT07, KT08, KT09, KT10, and KT11 (see **Figure 1**).

2.2.1. Weaver Agarwal Lilley Dimensionality and Invariants Method (WALDIM)

The application of WALDIM in magnetotelluric (MT) data analysis offers several significant advantages in the preliminary stage of interpretation, particularly in geoelectric dimensionality analysis. Unlike classical methods such as *Swift's* and *Bahr's skews*, which are often unable to separate anisotropy effects from the regional structural strike, WALDIM relies on rotational invariants of the impedance tensor (**Kumar et al., 2021; Martí et al., 2009**). This approach allows for a more robust assessment without requiring prior assumptions about the dimensionality of the data (1D, 2D, or 3D), thereby reducing interpretation bias at the early stages of modelling. Another major advantage of WALDIM lies in its ability to differentiate anisotropic from isotropic media, a task that traditional techniques cannot adequately accomplish. The criteria applied in WALDIM, such as inconsistencies between the 2D regional strike direction and those derived from the impedance tensor columns, provide clear indicators of electrical anisotropy. This capability is particularly valuable in continental margins

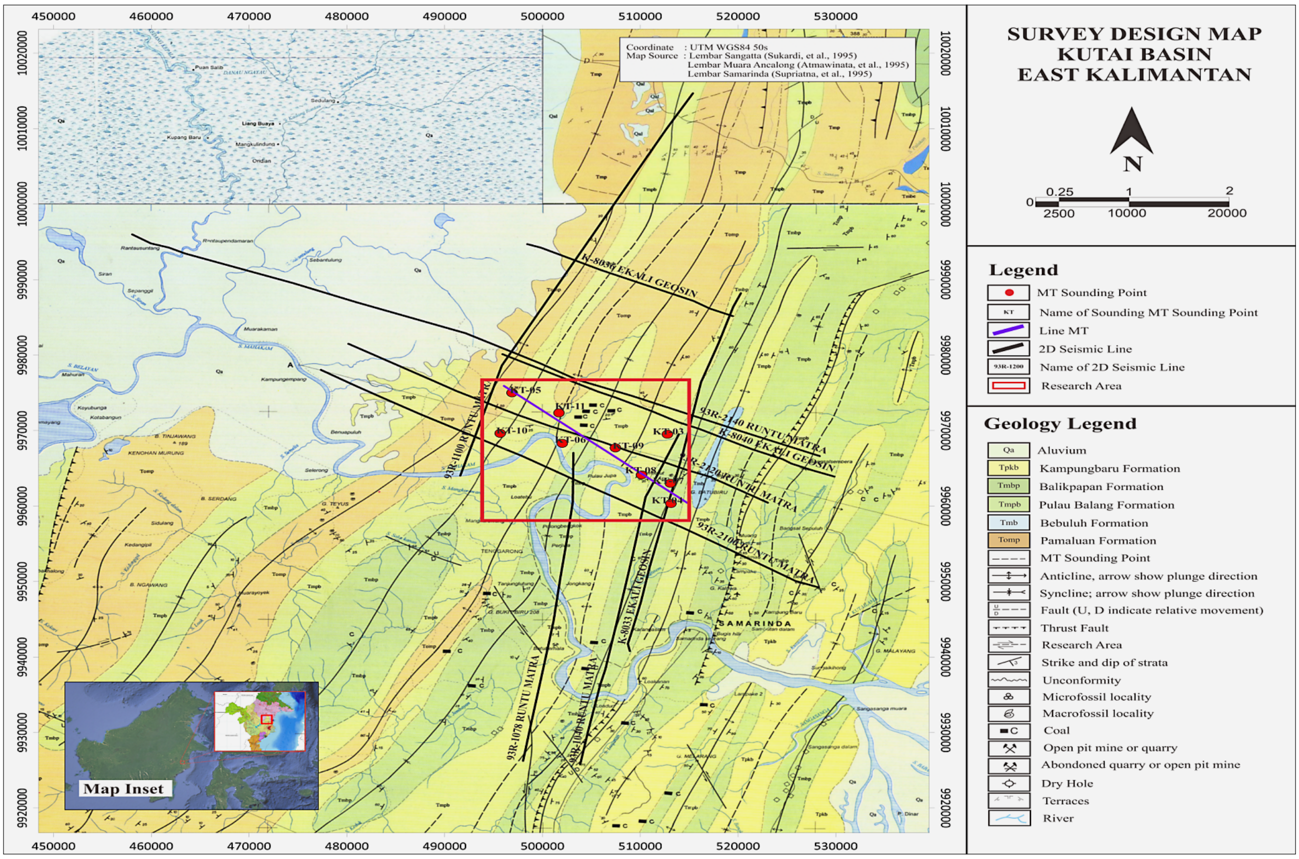

Figure 1. Design survey map The red box indicates the research region, black lines indicate seismic lines, and red dots indicate MT sounding stations overlay with geological maps sheet Samarinda (modified from **Supriatna et al., 1995**)

and tectonically active regions, where anisotropy is often associated with complex geological processes such as crustal deformation, fluid intrusions, and shear zones.

A further strength of WALDIM is its flexibility of application. The method can be applied to both synthetic and field MT data, yielding consistent results across different geological complexities. Dimensionality analysis based on invariants can also be grouped into frequency bands, enabling a more detailed characterization of variations in dimensionality with depth. Consequently, WALDIM not only assists in selecting the appropriate modelling approach (1D, 2D, or 3D) but also provides valuable guidance for data correction prior to inversion and forward modelling. Overall, WALDIM enhances the reliability of MT data interpretation, particularly in the identification of electrical anisotropy, which has important implications for understanding the evolution of geological structures, assessing economic resources, and interpreting hydrogeological systems. This advantage in detecting anisotropy makes WALDIM one of the most relevant and practical analytical tools in modern geophysical studies (**Martí et al., 2009**).

2.3. Design of MT data acquisition integrated with seismic lines

The MT sounding points are represented by red dots and labelled with their respective identifiers, while the seismic lines are depicted as black lines annotated with their corresponding names. As illustrated in **Figure 1**, the study area comprises three major geological formations: Balikpapan, Pulau Balang, and Pamaluan. The MT survey lines are oriented SE - NW, traversing the sounding points KT05, KT11, KT09, KT08, KT07, and KT04. In this study, the analysis is limited to seismic processing results confined within the boundaries of the research area. Seismic data processing involved fault and horizon picking, followed by time-structure analysis to generate a Time Structure Map. This map was subsequently employed to delineate anticline and syncline patterns developed across the study area. Magnetotelluric (MT) data processing began with Rho Variance analysis in the frequency domain. The next stage involved Crosspower editing using the MTEditor software, which generated two primary outputs: Tensor Impedance data in CSV format and inversion data in EDI format. Skin depth calculations were then performed on the Tensor Impedance dataset to determine which data should be retained or discarded. Subsequently, geoelectrical strike, twist, and shear were calculated using WALDIM, with the Swift method applied as a reference. The selected data were further utilized to compute the xi and eta parameters, which were then applied in constructing a Mohr Circle to interpret the real and imaginary components of each MT frequency. These parameters were also used to calculate the WAL invariants, which were subsequently plotted for statistical evaluation. The invariants provided the basis for WAL dimensional classification and were visualized in bar charts. To improve robustness, Gaussian noise was incorporated into the invariants, supported by Mohr Circle interpretation, invariant distribution, and WAL bar chart analysis. The final stage comprised model inversion and the generation of depth resistivity maps, which were integrated with interpretations derived from the previously processed seismic data (**Martí et al., 2009**).

3. Results and Discussion

The integration of seismic and MT data serves as the primary approach in this discussion, as each method offers complementary strengths seismic data excels in spatial resolution and visualization of layer geometry, while MT data penetrates deeper into the subsurface and provides information on the physical properties of rocks through resistivity (**Moorkamp et al., 2011**). By leveraging the correlation between these methods, the resulting interpretation offers a more comprehensive understanding of the subsurface geological system, including the identification of structural traps, distribution of prospective zones, and characterization of hydrocarbon bearing layers such as black shale. This chapter presents the interpretation results step by step based on the output of each method, which are then correlated to achieve a more integrated understanding.

3.1. Seismic Interpretation

A structurally complex subsurface realm characterized by severe faulting and mild folding is highlighted by the interpreted 2D seismic section along the 93R-2100 Runtu Matra line (see **Figure 2**). Undulations on a continuous marker horizon, seen at depths of around 1500–2000 meters, indicate mild anticlinal and synclinal warping. Significant vertical displacements are caused by the numerous steeply dipping faults that cut across the strata and are primarily of normal type. The central and southeast portions of the line are dominated by these faults, suggesting areas of increased tectonic deformation and potential structural compartmentalization.

The high density and varied dip angles of the interpreted faults suggest a tectonic regime predominantly influenced by extensional forces, which may be associated with rifting events or post depositional tectonic reactivation. The observed vertical offsets and segmentation of the primary seismic horizon further indicate that these faults have played a significant role in controlling sedimentation patterns. Additionally, they may serve as either conduits or barriers for subsurface fluid migration, depending on their orientation, continuity, and fault rock properties. This seismic profile provides compelling evidence for the existence of multiple structural blocks, likely bounded by fault systems associated with regional scale features such as the Buat Syncline and adjacent anticlinal structures. When correlated with regional structural mapping, these features contribute to a broader understanding of basin evolution, tectonostratigraphic development, and shale gas prospectivity. In particular, the identification of fault bounded compartments offers valuable insight into the localization of shale gas sweet spots, where structural complexity may enhance hydrocarbon trapping and preservation potential.

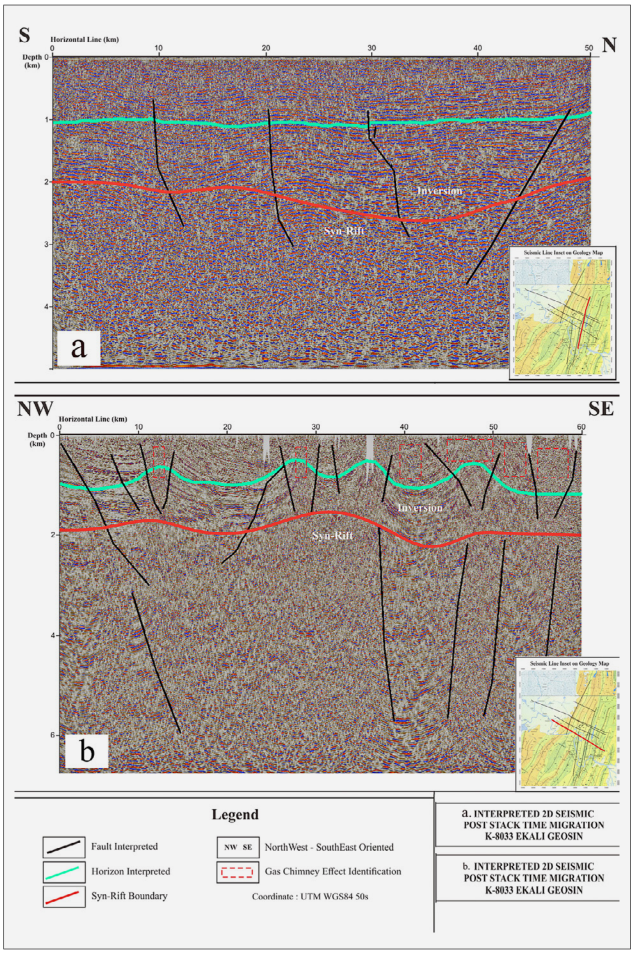

Figure 2. Interpretation of 2D Seismic Travel Time Migration Post-Stack Time Migration (PSTM). (a) 93R-2100 Runtu Matra seismic line, (b) K-8033 Ekali Geosin seismic line. The red line indicates the 93R-2100 seismic profile oriented N – S, while the K-8033 profile is oriented NW – SE. The red dashed box highlights the interpreted chimney effect, the solid black line delineates the interpreted fault, the green line represents the interpreted horizon, and the red line marks the interpreted Syn-Rift Boundary.

The interpreted 2D seismic section along the K-8033 Ekali Geosin line reveals several key subsurface structural features that contribute to the understanding of the regional geological framework. A prominent, continuous, and gently undulating seismic reflector is identified at an approximate depth of 1,000 meters. This reflector is interpreted as a major stratigraphic horizon, likely corresponding to a regionally extensive marker bed, and serves as a critical reference surface for subsequent structural and stratigraphic mapping. Multiple normal faults, predominantly dipping westward, are observed to displace this horizon, extending to various depths within the subsurface. The geometry and distribution of these faults suggest the influence of extensional tectonic processes during the basin's development. The presence of these faults results in the segmentation of the subsurface into discrete structural blocks, which may play a significant role in controlling hydrocarbon migration and trap formation. Understanding the interaction between these faults and stratigraphic units is essential for evaluating the petroleum system elements and assessing the resource potential within the study area.

The observed vertical displacement and offset of seismic reflectors in proximity to the faults indicate evidence of active tectonism, which may have contributed to the development of anticlinal and synclinal features through differential fault movement. The seismic imagery also reveals thick, layered sedimentary sequences beneath the main stratigraphic horizon, which are characteristic of synrift to postrift depositional environments. This stratigraphic pattern suggests phases of extensional tectonics followed by relative tectonic quiescence and continued sediment accumulation. When correlated with other seismic profiles across the study area, these structural features exhibit continuity with regional scale tectonic elements, including the Tenggarong Anticline, Pembulan Anticline, and Buat Syncline. These features are further delineated and spatially constrained through the construction of the time structure map.

The seismic profile has features of a positive flower structure, which is a type of geological feature often found in transpressional regimes. In these regimes, strikeslip faulting is accompanied by compressional stress. This combination results in the upward displacement of rock units, forming a structure that resembles a palm or "push up" feature. Within an anticlinal framework, the development of a positive flower structure can lead to complex uplifted zones, which often act as effective structural traps for hydrocarbon accumulation. Furthermore, geological interpretations suggest that such features may originate from positive tectonic inversion a process in which preexisting extensional (normal) faults are reactivated under a compressive stress regime and converted into reverse faults, enhancing structural complexity and trap potential (**Pace et al., 2012**). The existence of chaotic seismic reflections in the anticlinorium zones in both seismic sections, in addition to the fault patterns that have been found, could be a sign of a gas chimney effect **Figure 2b** (red dashed box). Hydrocarbons, mostly in gaseous form, migrate vertically from deeper source rocks into the reservoir or possibly even to the surface in this phenomena. Usually, this kind of migration happens along permeable channels, such as fracture networks and faults. Reservoir overpressure, active fault systems that allow fluid migration, and structural deformation that causes the creation of new or reactivated fractures are some of the contributing variables that are frequently linked to the gas chimney effect (**Aminzadeh et al., 2002**).

3.2. Time Structure Map

The time structure map, generated through horizon and fault picking on the interpreted seismic sections, illustrates the development of key geological structures within the study area, including the Tenggarong Anticline, Pembulan Anticline, and Buat Syncline (see **Figure 3**). The Tenggarong Anticline is situated in the southwestern portion of the map and is represented by orange to yellow contour intervals with closely spaced lines, indicating a prominent structural high. In the central to eastern region, the Pembulan Anticline is identified as a secondary fold structure with a slightly lower elevation but still exhibiting significant structural potential. The Buat Syncline is seen on the map's eastern side. It is distinguished by blue to purple contour zones that indicate the deepest structural levels and a major sedimentary basin. The structural contours' overall arrangement shows a strong W - E folding trend, with possible faulting seen where there are sudden variations in contour spacing.

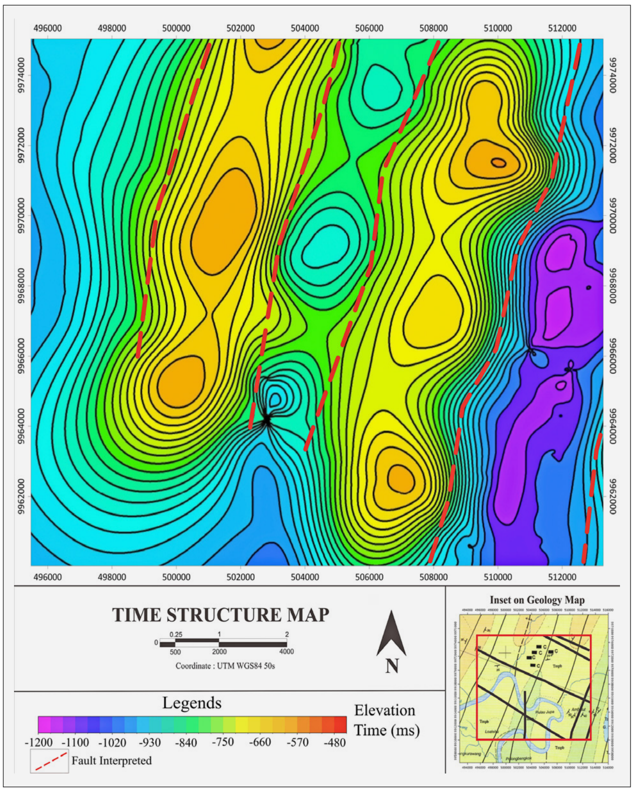

Figure 3. Time structure map research area

Figure 3 presents the time-structure map derived from horizon and fault picking on seismic sections, which illustrates the development of the main geological structures in the study area, namely the Tenggarong Anticline, Pembulan Anticline, and Buat Syncline. The fault boundaries are interpreted and represented by red dashed lines. The Tenggarong Anticline is located in the

Table 1. Presents the dimensionality classification with 0.05 and 0.15 noise of all MT point

Dimension	**Noise**	**Point**									**Total**
		KT03	**KT04**	**KT05**	**KT06**	**KT07**	**KT08**	**KT09**	**KT10**	**KT11**	
1D	*0.05*	6			1		9		9	1	26
	0.15	1					6		7	7	21
2D	*0.05*	26	24	49	52	23	48	34	24	32	312
	0.15	24	16	38	22	48	47	33	24	23	275
3D/2D twist	*0.05*			2		6			3	1	12
	0.15			1	4	1		4	3	3	16
3D/1D2D	*0.05*										0
	0.15										0
2D/1D	*0.05*										0
	0.15										0
3D/2D	*0.05*	4		1		4			2	1	12
	0.15	4		1	4				3	1	13
3D	*0.05*	17	22	7	4	13	1	24	14	23	125
	0.15	24	25	14	15	8	3	21	17	24	151
Undetermined	*0.05*	7	14	1	3	14	2	2	8	2	53
	0.15	7	19	6	15	3	4	2	6	2	64
Error	*0.05*	4.17	3.98	3.88	3.98	4.18	3.8	3.85	4.04	3.96	3.98
	0.15	12.7	12.47	12.15	11.97	11.95	11.71	11.25	11.68	12.47	12.034

southwestern part of the map, marked by orange - yellow colors and tightly spaced contours, indicating an uplifted structural high. In the Central - Eastern area, the Pembulan Anticline appears as a secondary fold with slightly lower elevation but still shows structural potential. Meanwhile, the Buat Syncline lies on the eastern side of the map, characterized by blue - purple colors representing the deepest area, serving as a sedimentary basin. The overall contour pattern suggests a dominant W – E folding trend, with indications of possible faulting in zones where abrupt contour changes occur. These structural features are significant not only in terms of conventional hydrocarbon trapping, but also in relation to shale gas potential. Anticlines such as Tenggarong and Pembulan may act as structural traps where shale formations are thermally mature and sufficiently pressured to retain gas. On the other hand, the Buat Syncline, being a deep and potentially thick sedimentary accumulation zone, may serve as a shale gas source and reservoir if the organic rich shale intervals are present and continuous. The combination of folding and faulting enhances the importance of these features as targets for unconventional gas exploration in the area.

3.3. Dimensionality of MT data

The dataset presented in **Table 1** and **Figure 4**, consisting of 540 frequency samples spanning from 320 Hz to 0.011 Hz, includes 60 analyzed frequency values at each measurement point. Overall, the average error is 3.982, while an additional analysis under higher noise conditions (0.15) yields a greater average error of 12.348. **Table 1** presents the dimensional classification results under both conditions in an integrated manner. Across the data, 2D remains the dominant dimensionality in the study area, indicating a prevailing complexity in subsurface structures that can generally be interpreted using 2D models. However, several points exhibit distinct behaviors. KT08 and KT10 show a strong dominance of 1D responses, suggesting homogeneous and laterally consistent subsurface characteristics at those locations. In contrast, KT04, KT09, and KT11 consistently display significant 3D classifications, pointing to complex geological conditions, likely influenced by galvanic distortion, local structural anomalies, or sharp resistivity contrasts.

The proportion of undefined dimensionality increases with higher noise levels, accompanied by a general decline in 1D and 2D classifications. Under these noisier conditions, 3D anomalies become more prominent, particularly at KT03, KT04, and KT11, where 3D classifications often exceed 2D. This suggests the presence of complex subsurface heterogeneity or enhanced resistivity anisotropy at depth. Despite these variations, 2D dimensionality remains the most dominant across the survey area, supporting its suitability for regional-scale interpretation while highlighting localized zones that may require more advanced 3D modelling. Results of the WAL analysis are illustrated in a bar chart, where colors represent different dimensional categories: red (1D), yellow (2D), brown (3D/2D twist), green (3D/1D2D), light purple (2D/1D), dark purple (3D/2D), blue (3D), and black (undefined). Dimensionality is classified using

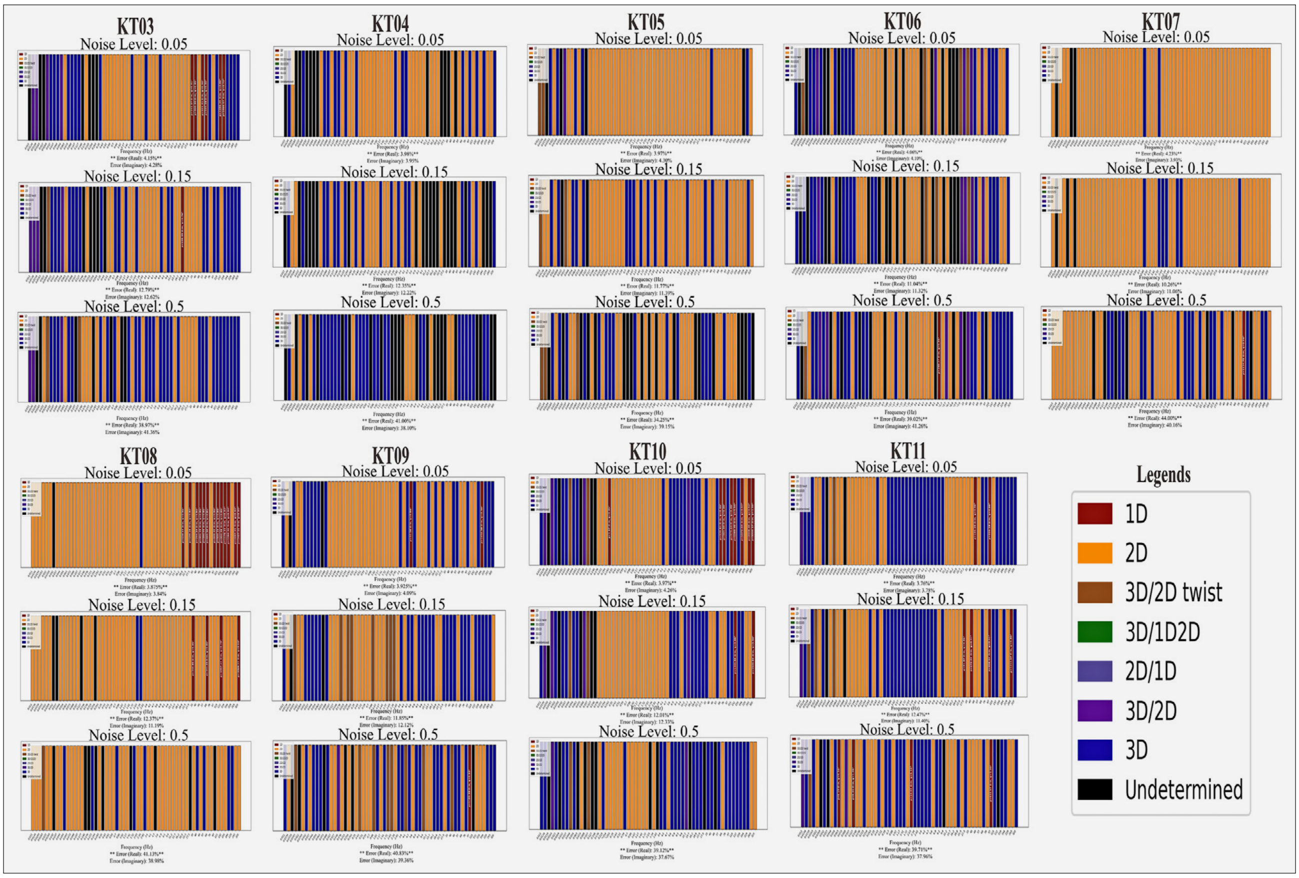

Figure 4. WALDIM bar chart dimensionality classification with 0.05, 0.15, and 0.5 noise of all MT point

threshold criteria from WALDIM (**Weaver et al., 2000**), and the resulting categories are examined both quantitatively and qualitatively to guide interpretation and inversion modelling. As shown in **Figure 5**, the chart is dominated by yellow, indicating that 2D anomalies are most common. Nonetheless, certain sites—such as KT05 and KT07—exhibit 3D characteristics at higher frequencies. At KT04 and KT06, 3D dimensionality is especially dominant in the mid-frequency range, while at KT08, high-frequency data are primarily 1D (red). Overall, anomalies display increasing inconsistency as frequency decreases, a trend observed across all measurement sites.

3.4. Geoelectrical strike of MT data

Geoelectrical strike refers to the dominant direction of resistivity anisotropy, which may differ from the orientation of the measured electric or magnetic fields. It plays a crucial role in determining the directional variability of subsurface resistivity within geoelectrical layers. According to **Groom and Bailey (1989)**, additional components contribute to the continuity of subsurface anomalies, namely twist and shear. As stated by **Martí et al. (2009)**, geoelectrical twist is a galvanic distortion parameter that represents the alteration in the orientation of the electric field due to localized distortions near subsurface structures. Twist quantifies the angular deviation between the measured electric field direction at a given point and the ideal geoelectrical strike direction. In this context, twist refers to the rotation or angular shift of the electric field orientation caused by surface irregularities or near-surface resistivity anomalies. Geoelectrical shear is another parameter associated with galvanic distortion, which describes the angular difference or shear in electric field orientation between two dominant directions. Shear indicates the presence of non-uniform resistivity distribution along these principal axes. **Table 2** presents the strike angle, which represents the predominant direc-

Table 2. Presents the geoelectrical strike, twist, shear of all MT point

Point	Average Angle (dominant)		
	Strike	Twist	Shear
KT03	47.42	-65.49	24.00
KT04	41.83	11.38	28.75
KT05	40.76	13.89	25.12
KT06	42.17	-38.97	23.45
KT07	44.71	-7.60	26.02
KT08	47.58	-11.04	26.98
KT09	40.67	-63.00	24.54
KT10	41.78	-38.03	25.16
KT11	44.73	20.66	26.00
Average	**43.52**	**-19.80**	**25.56**

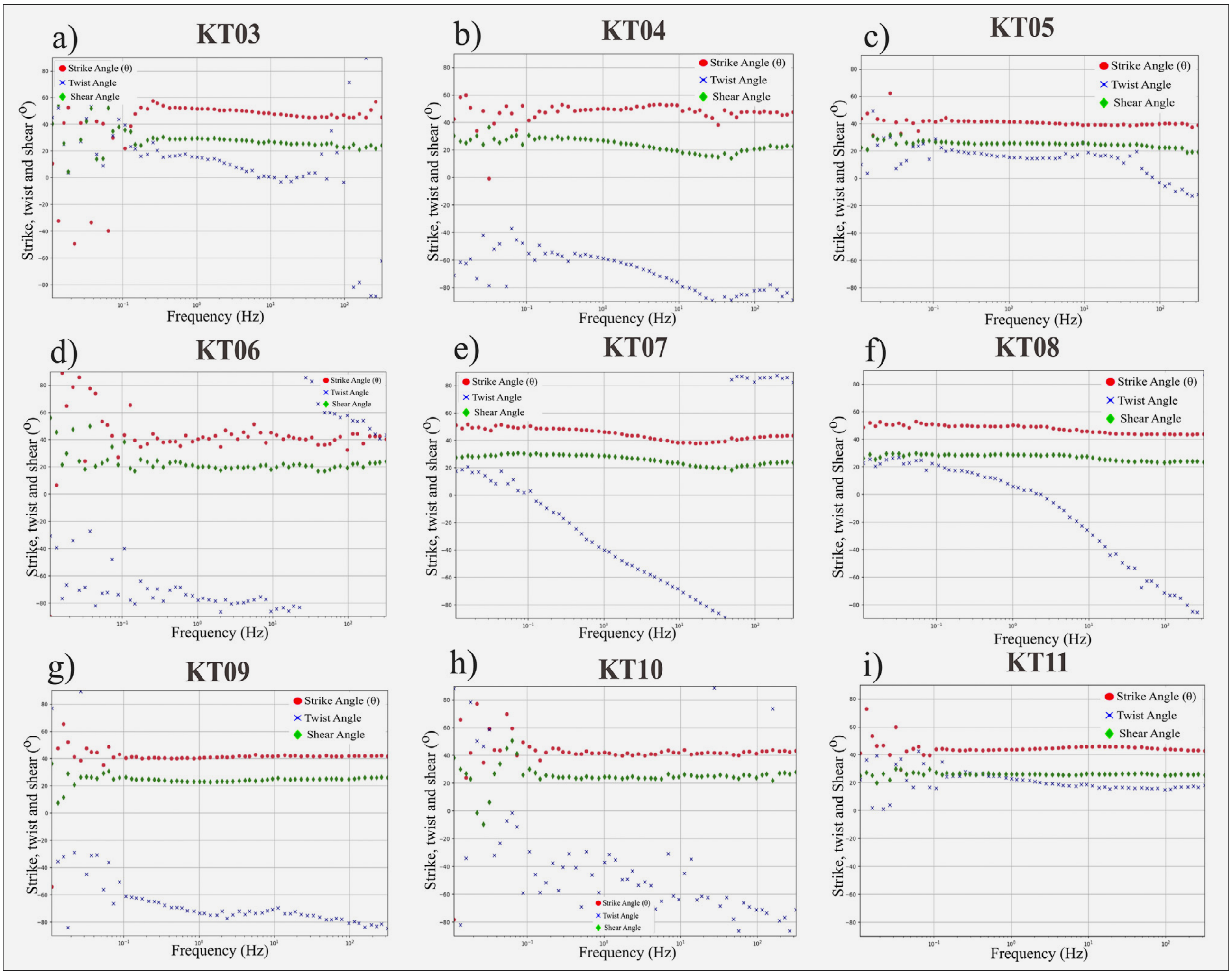

Figure 5. presents the plots of the relationships between the geoelectrical strike angle (q) (red), twist angle (green), and shear angle (blue) for each MT station: (a) MT point KT03, (b) MT point KT04, (c) MT point KT05, (d) MT point KT06, (e) MT point KT07, (f) MT point KT08, (g) MT point KT09, (h) MT point KT10, and (i) MT point KT11.

tion of subsurface resistivity anisotropy, with an average value of approximately 43.52°. This indicates that the subsurface structure exhibits a relatively consistent orientation across the measurement sites. The strike angle varies between 40.67° (KT09) and 47.42° (KT03), with locations such as KT03 and KT08 displaying relatively higher strike values. This suggests that these areas may possess more pronounced structural alignment or greater resistivity contrast compared to other sites. Given the overall consistency in strike orientation, it can be inferred that the electromagnetic field aligns with a uniform resistivity pattern, thereby supporting the validity of subsequent 2D inversion analysis.

Figure 5 illustrates the plots of the relationships between the electrical strike angle (red), twist angle (green), and shear angle (blue) for each MT station: (a) MT point KT03, (b) MT point KT04, (c) MT point KT05, (d) MT point KT06, (e) MT point KT07, (f) MT point KT08, (g) MT point KT09, (h) MT point KT10, and (i) MT point KT11. The results illustrate that the geoelectrical strike derived from the WALDIM analysis closely corresponds to the surface geological strike, with both orientations situated within the first quadrant. This correspondence reinforces the reliability of the subsurface resistivity model and indicates a strong structural control on the observed anisotropic properties. The consistency between the geophysical and geological strike directions further highlights the coherence between subsurface and surface features, thereby supporting a more comprehensive and integrated interpretation in the regional structural and tectonic framework.

3.5. 2D MT model inversion

Figure 6 presents a 2D resistivity model extending approximately 22 km laterally and reaching a depth of up to 15 km, illustrating a subsurface resistivity range between 1 and 300 Ohm.m. This resistivity range is categorized into three main zones: low resistivity (1–5 Ohm.m), represented by purple to light blue colors; moderate resistivity (6–135 Ohm.m), shown in green to yellow; and high resistivity (136–300 Ohm.m), indicat-

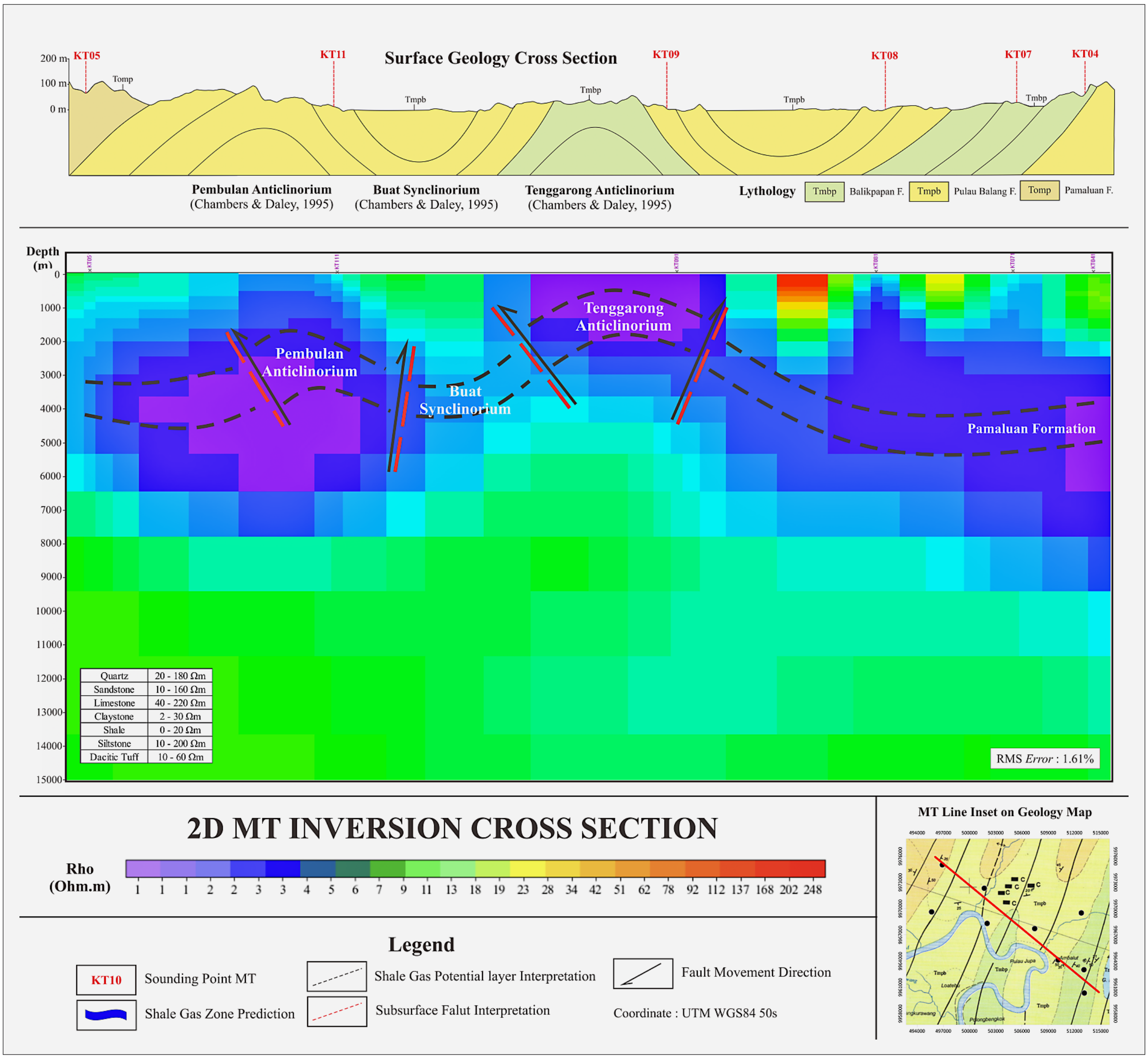

Figure 6. 2D MT model inversion with survey geological section

ed by orange to red tones. The resistivity values of rocks are interpreted as follows: quartz ranges from 20–180 Ohm.m, sandstone 10–160 Ohm.m, limestone 40–220 Ohm.m, claystone 2–30 Ohm.m, shale 0–20 Ohm.m, siltstone 10–200 Ohm.m, and dacitic tuff/alluvium 10–60 Ohm.m (**H. Hidayat et al., 2021**). Overall, the area is predominantly characterized by low to moderate resistivity zones. Based on the results of the 2D inversion model along the MT survey line, a low resistivity anomaly (1–5 Ohm.m) is observed, visualized in shades of purple and light blue in the crosssection of **Figure 6**. Based on the resistivity analysis, the Pamaluan Formation exhibits low-resistivity anomalies that can be interpreted as indications of shale gas presence. This anomaly is further interpreted as representing a black shale layer within the Pamaluan Formation (**Zajuli and Wahyudiono, 2018**). Such conditions are consistent with the general characteristics of high-potential source rocks, where organic-rich clay-rich layers are typically associated with unconventional petroleum systems. The anomaly pattern suggests that the layer has undergone deformation in the form of folding, resembling an anticlinal structure, consistent with features observed in the surface geological map. In addition to the fold structure, four fault lines previously unrecognized in the geological map were also identified. The MT survey line traverses several surface exposed geological formations, including the Pamaluan Formation (Tomp), the Pulau Balang Formation (Tmpb), and the Balikpapan Formation (Tmbp), as identified by **Umar et al. (2018)**. The Samarinda Anticlinorium within the study area comprises several major structural features, namely the Pembulan Anticline, Buat Syncline, Tenggarong Anticline, and Sebulu Anticline. According to **Chambers and Daley (1995)**,

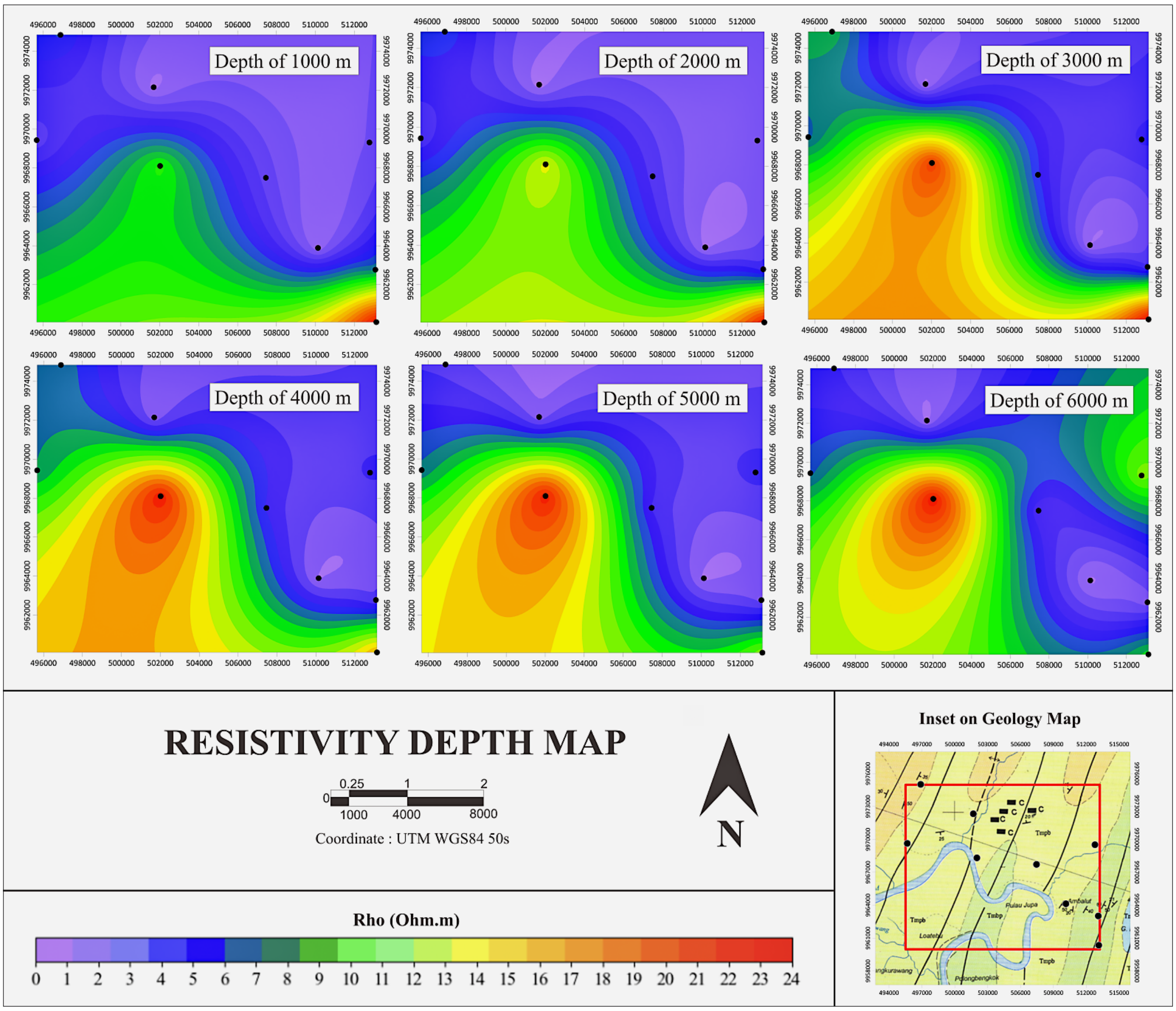

Figure 7. Resistivity depth map from 1000 to 6000 meters

interpretation of the MT survey line suggests that the black shale layer is associated with the structural features of the Pembulan Anticline, Buat Syncline, and Tenggarong Anticline, with an estimated thickness ranging from 2,000 to 4,000 meters. This layer begins to appear at depths of approximately 500 to 1,000 meters; however, due to folding and faulting processes, it is also detected at greater depths between 2,000 and 3,000 meters. The black shale is interpreted as acting as a reservoir within the anticlinal structures and as a potential gas generating source rock within the synclinal zones.

To estimate the shale gas resource potential, mapping the lateral distribution of shale gas is a crucial aspect. Magnetotelluric (MT) data can be visualized in the form of horizontal resistivity maps, which depict the electrical characteristics of various subsurface lithologies (see **Figure 7**). These maps are constructed based on measurements from nine MT sounding points distributed across three surface exposed geological formations: the Pamaluan Formation (Tomp), the Pulaubalang Formation (Tmpb), and the Balikpapan Formation (Tmbp). The interpolation method used for mapping is kriging. The complexity of structures and the depth of anomalies observed in the 2D resistivity sections served as the basis for generating resistivity maps at multiple depths namely 1,000 m, 2,000 m, 3,000 m, 4,000 m, 5,000 m, and 6,000 m. These maps reveal a resistivity range of 1–24 Ohm.m within the study area. The color classification is divided into three categories: low resistivity anomalies (1–5 Ohm.m) shown in purple to dark blue, moderate anomalies (6–15 Ohm.m) in dark green to yellow, and high anomalies (16–24 Ohm.m) in orange to red.

The different resistivity patterns with increasing depth are used to estimate the presence of shale gas. Low resistivity zones are widely dispersed at depths of 1,000 to 2,000 meters, especially in the study area's central and southern regions. This implies that the strata of shale gas are somewhat shallow and may be connected to faulting and bending, among other structural characteristics. Low resistivity anomalies are still discernible at depths of 3,000 to 4,000 meters, but they get smaller and begin to mix with moderate to high resistivity zones that show up in certain places. The presence of more compact or resistant rock formations, which change the resistivity properties, or lithological changes may be connected to this phenomena. Low resistivity zones, on the other hand, become more localized and less extensive at depths of 5,000 to 6,000 meters, suggesting that the shale gas there may have experienced substantial compaction or thermal modification as a result of high subsurface pressures (**Hidayat et al., 2021; Zajuli and Wahyudiono, 2018**).

3.7. The correlation of seismic and magnetotelluric

In this research, seismic data are utilized as supporting information to identify fault patterns and stratigraphic horizons within the study area. Seismic data are employed due to their higher resolution compared to magnetotelluric (MT) data, making them a valuable reference for enhancing the interpretation. The seismic lines used are oriented linearly, parallel to the MT survey line, following a S- N direction. The specific seismic lines incorporated in the analysis are 93R-2100 Runtu Matra and K-8040 Ekali Geosin. **Figure 8a** presents a three-dimensional section of the seismic line, which serves as a primary reference for subsurface structural interpretation. **Figure 8b** shows the magnetotelluric (MT) resistivity section, correlated with fault systems and the syn-rift boundary as interpreted from the seismic section. In **Figure 8c**, a direct comparison between the seismic section and the MT profile is provided, illustrating the structural correspondence of folding and faulting features identified by both methods. Meanwhile, **Figure 8d** displays an overlay of the time structure map with the MT profile, reinforcing the geological interpretation and highlighting the delineation of major anticline–syncline structures within the research area. Spatially, this seismic line is located to the north of the MT survey line and shares a similar SE - NW orientation. Fault interpretation reveals the presence of several faults exhibiting various structural patterns. These faults are associated with folding structures, forming anticline–syncline configurations within the study area. Specifically, the faults create folded structures that resemble a positive flower structure pattern. Horizon interpretation is based on the reservoir depth within the Kutai Basin, which ranges between 500 and 600 meters. Within the anticline structures, irregular patterns indicative of gas chimney effects are observed.

The correlation between the resistivity data derived from the magnetotelluric (MT) method and the seismic data from line 93R-2100 Runtu Matra, as shown in **Figure 8d**, demonstrates a strong relationship in delineating subsurface structures. The seismic method, with its higher resolution, provides more detailed imagery of subsurface layering and faulting compared to the MT method. In the seismic section, reflection patterns suggest the presence of folds and possible faults that influence the distribution of subsurface lithologies. Hence, the folded layers shown in the seismic data seem to correspond with the low resistivity zones in the MT resistivity section, which are indicated by blue hues. This implies that lithologies with a high fluid content or shale gas deposits may be connected to the low resistivity zones.

Several geological features identified through seismic data show folding patterns that express as anticlines and synclines in the research area. Fold geometries that are congruent with a positive flower structure pattern have developed as a result of fault activity, which is the primary cause of these structural traits. **Figure 8c** shows the comparison of seismic and magnetotelluric (MT) resistivity data, which shows a good correlation in describing subsurface structures. Stratigraphic layering and fault structures are more precisely delineated by the seismic approach than by the MT method because of its higher resolution. The distribution of underlying lithologies is influenced by folding and potential faulting, which are shown by seismic reflection patterns.

The integration of both geophysical methods demonstrates that the major structural features observed in the seismic data, such as folds and faults, are also recognizable in the MT resistivity model. The low resistivity anomalies in the MT data are consistent with seismic reflections that indicate anticline and syncline structures throughout the area. Furthermore, several fault features identified in the seismic section correspond to changes in resistivity observed in the MT data, underscoring the MT method's capability in detecting potential reservoir or source rock zones. Although the MT method has lower resolution compared to seismic data, its ability to penetrate deeper into the subsurface provides valuable complementary information. Additionally, **Figure 8d** which overlays the Time Structure Map with MT data, reinforces the consistency between the datasets, showing coherent anticline–syncline patterns. This integrated interpretation strengthens the delineation of key fold structures such as the Tenggarong Anticline, Pembulan Anticline, and the associated synclinal features.

A similar fault pattern, known as a positive floral structure, is seen in both seismic sections. A positive floral structure is a type of geological formation that usually forms in transpressional tectonic settings, where rock layers are displaced upward by compressional force on strike-slip faults. This produces a structure that looks like a palm tree, often known as a "push-up structure." These characteristics are frequently seen in strike-slip fault zones, especially in regions with stepovers or restraining bends where compressive forces combine horizontal and vertical displacements. Positive floral structures help create intricate uplift zones in an anticlinorium and are frequently important structural traps for the buildup of hydrocarbons. Positive tectonic inversion, in which pre existing normal faults that were initially created under extensional regimes are reactivated as reverse faults due to compressional stress, is another way that these structures can emerge, according to earlier research (**Pace et al., 2012**). Despite the fault pattern, the gas chimney effect is responsible for the uneven reflec-

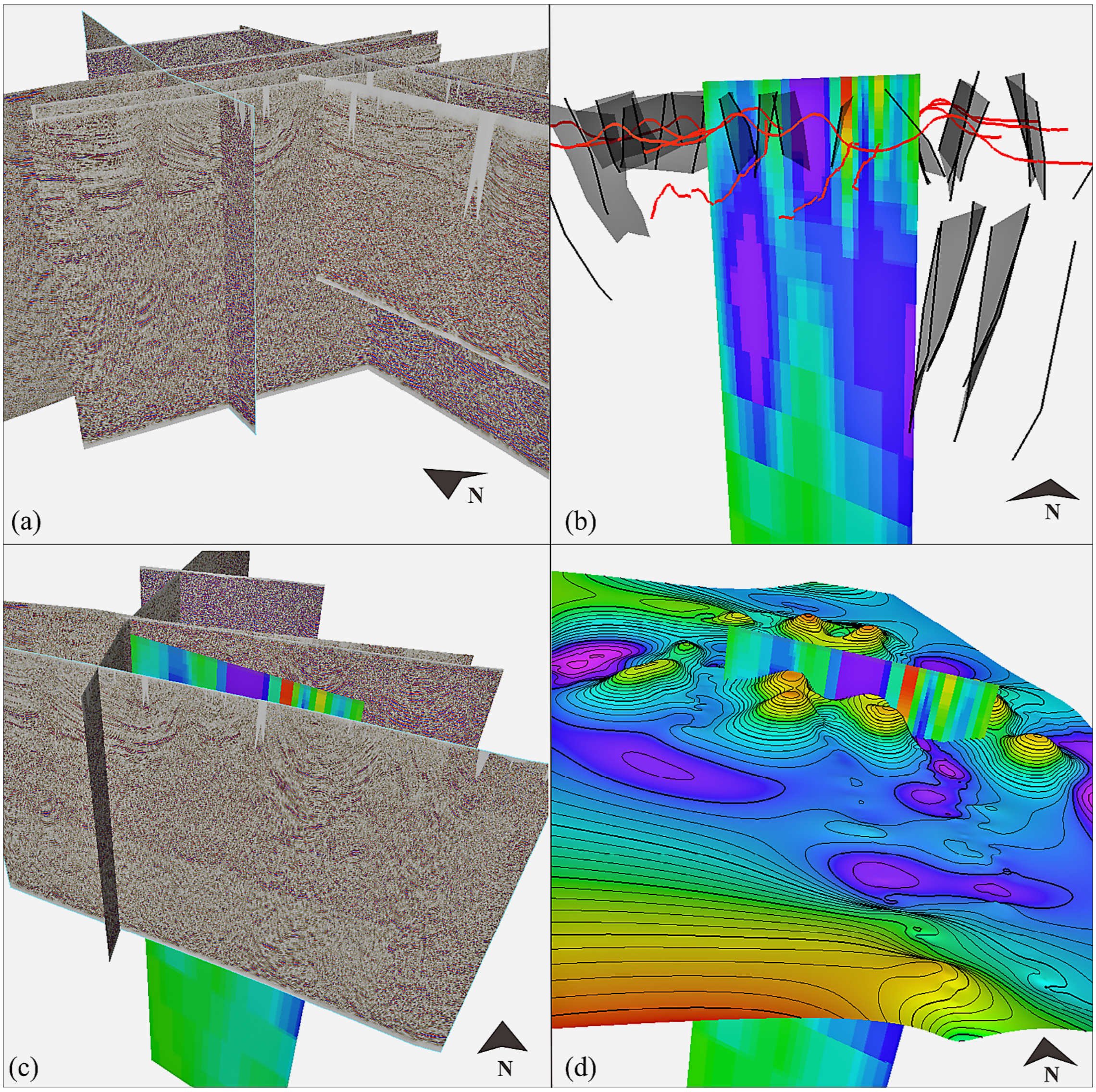

Figure 8. Correlation seismic section and MT interpretation; (a) corelation MT and selected fault horizon, (b) corelation MT and time structure map.

tion characteristics seen in the anticlinorial zones of both seismic sections. This phenomenon shows how hydrocarbons, especially gas, migrate vertically from source rocks to reservoirs or even to the surface via permeable channels like faults and fractures. Overpressure in the reservoir, migration routes along active faults, and structural deformation that creates new fracture networks are the main sources of this phenomenon. According to **Aminzadeh et al. (2002)**, gas chimneys are important markers of active hydrocarbon migration pathways.

5. Conclusions

The 2D Magnetotelluric (MT) resistivity modelling results reveal the presence of low-resistivity anomalies (1–5 Ohm.m), which are interpreted as black shale layers within the Pamaluan Formation. These anomalies exhibit folding patterns resembling anticlines and are influenced by several previously unmapped fault lines. Correlation with seismic data strengthens this interpretation, as folds and faults identified in seismic sections correspond with low-resistivity zones in the MT data. Major structural features in the study area, including the Pembulan Anticline, Tenggarong Anticline, and Buat Syncline, play a significant role in controlling the distribution of black shale. This layer appears at depths of 500–1,000 m and extends to 2,000–4,000 m due to folding and faulting processes. Resistivity depth maps (1,000–6,000 m) indicate that low-resistivity zones are predominant at shallow depths (1,000–2,000 m) but diminish with increasing depth as a result of compaction and thermal alteration. This suggests that shale gas potential is concentrated at shallow to intermediate depths. The integration of MT and seismic data also reveals positive flower structures (push-up structures) formed by transpressional strike-slip faulting. These structural features act as hydrocarbon traps, while the occurrence of gas chimney effects indicates active hydrocarbon migration pathways from source rocks to reservoirs. Overall, the combined application of MT and seismic methods successfully delineates the relationship between folds, faults, and the distribution of black shale as both a source rock and a potential reservoir. Therefore, the study area demonstrates significant indications of shale gas prospectivity controlled by the major geological structures of the Kutai Basin.

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SAŽETAK

Otkrivanje struktura ležišta plinonosnih šejlova seizmičkim i MT podatcima: WALDIM studija iz Istočnoga Kalimantana, Indonezija

Pamaluanska formacija, s vrijednošću ukupnoga organskog ugljika (engl. *Total Organic Carbon*, TOC) od 1,78 % i različitim stupnjem termalne starosti, predstavlja izniman potencijal za proizvodnju iz plinonosnih šejlova u indonezijskome bazenu Kutai. Ovo istraživanje objedinjuje seizmičke i magnetotelurske (MT) geofizičke tehnike u svrhu povećanja znanja o potencijalima plinonosnih šejlova u tome području. U sklopu istraživanja obrađeni su podatci s devet lokacija MT sondiranja i devet linija 2D seizmičkih ispitivanja. Izrađenom strukturnom kartom dodatno su istražene antiklinale i sinklinale koje su utvrđene interpretacijom seizmičkih podataka. Obradom MT podataka, primjenjujući pristup varijance koeficijenta korelacije rho i modul WALDIM računalnoga programa Python, stvoreni su 2D modeli inverzije otpornosti. Podatci upućuju na dominantan smjer antiklinalnih i sinklinalnih struktura orijentiran otprilike 45° od pravoga sjevera. S prosječnim nagibom od 43,5° MT analiza pokazuje dominantnu dvodimenzionalnu (2D) geoelektričnu dimenzionalnost, koja se poklapa s lokalnim geološkim trendovima. Na dubinama od 500 do 1000 m u antiklinalama i 2000 do 3000 m u sinklinalama pronađene su zone niske otpornosti (1 – 5 Ohm·m), s debljinama koje variraju od 2000 do 4000 m. Anomalije niske otpornosti interpretiraju se kao potencijalni intervali plinonosnih šejlova, što je u skladu s geološkim karakteristikama bazena Kutai. Objedinjeni seizmički i MT podatci vjerno prikazuju bore, rasjede i anomalije niske otpornosti koji se tumače kao potencijalni intervali plinonosnih šejlova ističući važnost multidisciplinarnoga pristupa u ublažavanju rizika istraživanja i poboljšanju procjene perspektivnosti plinonosnih šejlova u bazenu Kutai.

Ključne riječi:
plinonosni šejlovi, bazen Kutai, seizmika, magnetotelurska metoda, WALDIM

Author’s contribution

Suharsono: conceptualization, supervision, methodology, wriing and interpretation, **Yustisio Dianwiyono**: validation, processing and visualitation, **Edy Wijanarko:** data curation, software, resources supervision, and validation, **Wahyu Hidayat:** original draft and writing and review and editing. **Muhammad Fachrul Rozi Kurniawan:** project administration and review and editing, **Yudha Agung Pratama:** data curation and project administration.
All authors have read and agreed to the published version of the manuscript.