HYDROCARBON POTENTIAL OF THE OFFSHORE AKIMEUGAH BASIN FROM MESOZOIC-PALEOZOIC BASED ON GEOLOGICAL AND GEOPHYSICAL ANALYSIS

POTENSI HIDROKARBON CEKUNGAN OFFSHORE AKIMEUGAH UMUR MESOZOIKUM-PALEOZOIKUMBERDASARKAN ANALISIS GEOLOGI DAN GEOFISIKA

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ABSTRACT: Akimeugah Basin is one of the basins with discovery status, however hydrocarbon production has not yet been established. One of potential petroleum play type for further investigation, estimated to contain hydrocarbon reserves in the offshore Akimeugah Basin, is the Mesozoic–Paleozoic sedimentary play, interpreted to have originated from the Australian passive margin. This study aims to analyze geological and geophysical data to delineate the sub-basin pattern and characterize petroleum system elements. The analysis integrates gravity data interpretation, geochemical evaluation of source rocks, and subsurface interpretation based on seismic and well data. Results indicate that source rocks in the Kola-1 well are primarily composed of Type III (gas-prone) and secondarily of Type II (oil/gas-prone) kerogen. Thermal maturity analysis shows that the Woniwogi, Aiduna, and Modio Formations have reached the oil window. Reservoir potential has been identified in the Tipuma Formation (Triassic), Aiduna Formation (Permian), and Modio Dolomite (Devonian–Silurian). Seal rocks consist of regional and intraformational units composed of tight siltstone and shale. Trapping mechanisms in this area include a combination of structural traps such as fault-bounded anticlines and stratigraphic traps represented by sub-unconformities. Identified exploration leads include seven within the Modio Dolomite structural play, six within the Permian Aiduna Sandstone play, and four within the Triassic Tipuma Sandstone play.

Keywords: gravity, seismic, well, hydrocarbon, offshore Akimeugah

ABSTRAK*: Cekungan Akimeugah merupakan salah satu cekungan dengan status penemuan (discovery basin), namun hingga saat ini belum terdapat produksi hidrokarbon. Salah satu tipe play migas yang diperkirakan memiliki potensi cadangan untuk diteliti lebih lanjut di wilayah cekungan offshore Akimeugah yaitu play type sedimen berumur Mesozoikum dan Paleozoikum yang berasal dari passive margin Australia. Penelitian ini bertujuan untuk menganalisis data-data geologi dan geofisika guna mendelineasi pola subcekungan serta mengkarakteristisasi elemen-elemen sistem petroleum. Analisis data meliputi interpretasi gravity, analisis geokimia batuan induk, serta interpretasi bawah permukaan berdasarkan data seismik dan sumur. Hasil yang diperoleh menunjukkan bahwa batuan induk pada sumur Kola-1 terdiri dari batuan – batuan* *induk tipe III (gas-prone) dan beberapa batuan induk tipe II (oil/gas prone). Batuan induk yang telah mencapai tingkat kematangan (oil window) meliputi batuan induk Formasi Woniwogi, Formasi Aiduna, dan Formasi Modio. Potensi reservoir terdapat di pada Formasi Tipuma (Triasik), Aiduna (Permian), dan Modio Dolomite (Devonian-Silurian). Seal rock berasal dari batuan penutup regional dan intraformasi, berupa batulanau dan serpih yang cukup rapat. Mekanisme perangkap di area ini merupakan kombinasi antara perangkap struktural (antiklin yang dibatasi patahan) dan perangkap stratigrafi (sub-unconformity). Leads yang teridentifikasi meliputi tujuh lead pada Modio Dolomite structural play, enam lead pada Permian Aiduna Sandstone structural play, dan empat lead pada Triassic Tipuma Sandstone structural play.*

***Kata Kunci:** gravity, seismik, sumur, hidrokarbon, offshore Akimeugah*

INTRODUCTION

Indonesia's petroleum potential is reflected in the presence of 128 identified sedimentary basins (Kementerian Energi dan Sumber Daya Mineral Republik Indonesia – Badan Geologi, 2022), many of which remain insufficiently explored. Updating the national sedimentary basin map through the integration of new data and comprehensive geological and geophysical studies is essential to improve the accuracy of the national hydrocarbon resource inventory. The presence of hydrocarbons in several wells within the Akimeugah Basin, including South Oeta-1, Kola-1, Buaya Besar-1, and ASM-1, indicates an active petroleum system in the region (Tim Evaluasi Data Migas, 2024). Hydrocarbon indications have been found in various types of reservoir rocks; however, no commercial production has been established in the basin to date. To identify new hydrocarbon reserves, the application of appropriate geological concepts is crucial, especially in defining the type of petroleum play, so that exploration strategies can be more focused and effective. One potential petroleum play estimated to hold significant reserves involves Mesozoic and Paleozoic sedimentary rocks originating from the Australian passive margin. A previous study by Bachri (2014) emphasized the importance of these sedimentary rocks, predominantly of Mesozoic age, which serve both as source rocks and reservoir rocks. This aligns with stratigraphic correlations of Mesozoic sedimentary rocks in northern Australia, which have been proven to contain hydrocarbons, as observed in the Bonaparte, Carnarvon, and Canning basins (Struckmeyer et al., 2006).

Stratigraphic traps are also present in the Akimeugah Basin, particularly in its southern part. In addition to the presence of source rocks, reservoir rocks, and seal rocks, the Papuan region also displays anticlinal structures and ramp anticlines (Panggabean & Hakim, 1986), which have great potential as hydrocarbon traps. The primary regional seal in the Akimeugah Basin and across most of Papua consists of thick shale layers from the Piniya Formation. Satyana (2017) stated that the Paleozoic play in the Arafura Sea and southern Papua is one of the most prospective plays, which requires the integration of geological, geophysical, and geochemical analyses to validate and confirm whether the oil generated in this region shares similarities with petroleum systems in Australia. Post

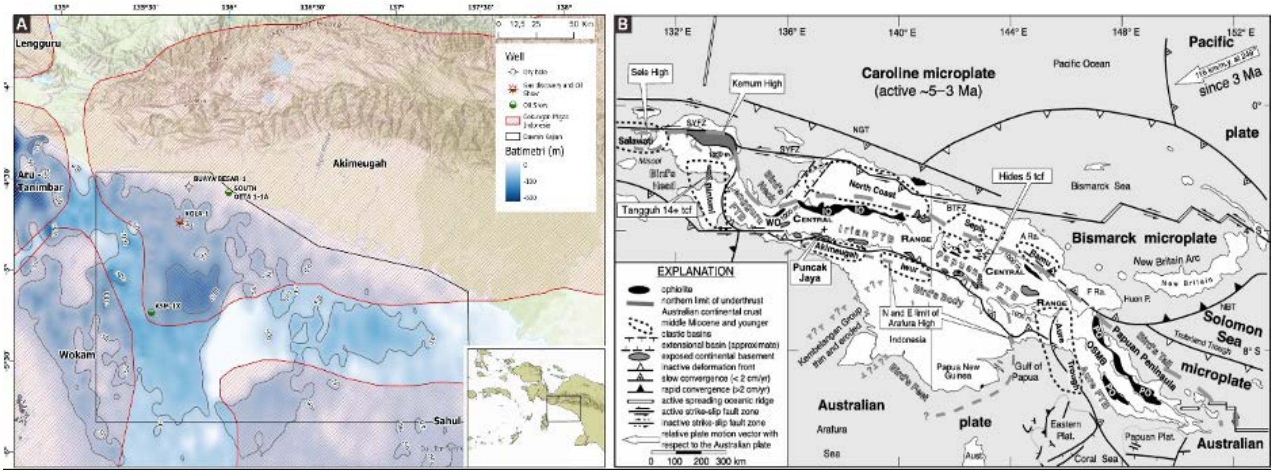

Figure 1. (A) Location of the study area in the southern part of the Akimeugah Basin, Arafura Sea, Papua. (B) Regional tectonics framework of Papua, modified after Sapiie (1998).

mortem drilling analyzes indicate that the failures of four exploration wells in the study area, which are Kola-1, ASM-1X, South Oeta-1, and Buaya Besar-1, were generally caused by structural or stratigraphic traps, seal ineffectiveness, and migration pathway issues (Tim Evaluasi Data Migas, 2024). In the Kola-1, Drill Stem Test (DST) number three (DST#3) was conducted on the Permian Aiduna interval at depths of 12,566 to 12,592 ft measured from the Rotary Kelly Bushing (RKB). The test yielded a flow of 1,825 barrels of water per day (BWPD) and 50 thousand cubic feet per day (MCFPD) of gas. Additionally, oil shows were identified in the Aiduna Formation and Modio Dolomite Formation.

The objective of this study is to analyze and re-evaluate geological and geophysical data, including gravity, seismic, and well data, in order to delineate sub-basins, characterize the petroleum system elements, and identify hydrocarbon potential within the Offshore of Akimeugah Basin in Papua. The study area is located in the southern part of the Akimeugah Basin, specifically in the offshore zone, as illustrated in Figure 1.

Regional Geology

Akimeugah Basin is located in eastern Indonesia, at the convergence of three tectonic plates: the Eurasian continental plate, the Indo-Australian continental plate moving northward, and the Pacific oceanic plate moving westward (Hamilton, 1979). The basin lies along the Australian continental margin and is classified as an intracontinental rift basin (Moore et al., 1996). Numerous studies have examined the tectonic and regional geological aspects of eastern Indonesia and northern Australia, including those by Carter et al. (1976), Bowin et al. (1980), Pigram & Panggabean (1984), Dow & Sukamto (1984), Peck & Soulhol (1986), Pigram & Davies (1987), Audley-Charles (1988), Bradshaw et al. (1988), Daly et al. (1987, 1991), Henage (1993), Struckmeyer et al. (1993), Metcalfe (1996), Hall (1996), Kendrick & Hill (2001), and Davies (2010). The Akimeugah Basin evolved from the Pre-Tertiary to the Tertiary period and is categorized as a foreland basin that has undergone rifting processes (Harahap, 2012). Miharwatiman et al. (2013) identified the basin as part of the broader Arafura Basin located on the Arafura Platform. The development of this basin began during the Proterozoic to Paleozoic era as a failed rift along the northwestern margin of the Australian continent during the Late Proterozoic.

Based on the tectonic history, most of Papua, particularly its southern region where the suture between the Pacific and Australian plates is located, is underlain by Australian continental crust. This includes overlying sediments derived from the northwestern Australian shelf (Bradshaw et al., 1988). These geological characteristics indicate a strong similarity with proven hydrocarbon systems in northern Australia. In Papua, a comparable setting is reflected in the stratigraphic framework of the Bintuni and Salawati basins, which according to Darman and Sidi (2000), contain Mesozoic sedimentary rocks as well as metamorphic Paleozoic rocks that are believed to originate from the Australian crust.

The development of the petroleum system in the Akimeugah basin occurred during the Paleozoic and Mesozoic eras, when the Australian Plate was situated at passive margin (Barber et al., 2003). The collision between the Australian and Pacific plates during the Late Miocene led to basin subsidence followed by rapid sedimentation, resulting in the deposition of thick sedimentary sequences up to 2,750 m in thickness, known as the Buru Formation. The substantial thickness of these sediments exerted significant loading on the older sedimentary rocks, promoting the maturation of hydrocarbons generated during the Paleozoic and Mesozoic. The tectonic evolution of Papua indicates that Australia, Papua, and Papua New Guinea originated from a shared geological domain. Therefore, the hydrocarbon potential identified in both Australia and Papua New Guinea can be correlated with the petroleum prospectivity of the Akimeugah Basin (Pigram & Panggabean, 1984). According to the terminology of the Australian Geological Survey Organization (Struckmeyer et al., 2006), there are three major petroleum systems in the Bonaparte Basin of northern Australia: the Larapintine System, which consists of marine facies source rocks of Early to Middle Paleozoic age (including shale and carbonate); the Gondwanan System, dominated by terrestrial facies source rocks of Permian age; and the Westralian System, composed of marine source rocks of Jurassic age. Based on age correlation, the Larapintine System is comparable to the Pre-Permian sequence in the Akimeugah Basin, the Gondwanan System corresponds to the Tipuma and Aiduna sequences, and the Westralian System aligns with the Kemblengan sequence.

Stratigraphy

The stratigraphy of the study area can be grouped based on depositional sequences (Figure 2). There are three major megasequences that developed along the

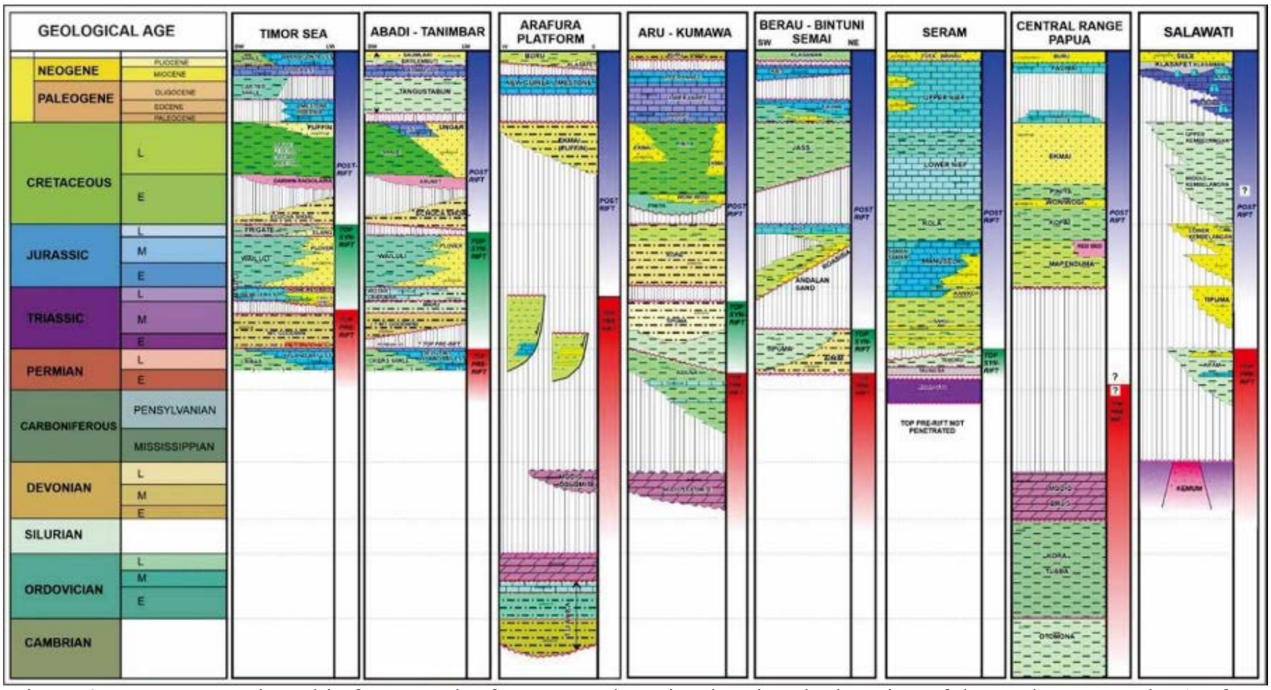

Figure 2. Tectonostratigraphic framework of eastern Indonesia, showing the location of the study area on the Arafura Platform (Siregar et al., 2024).

Australian continental margin in eastern Indonesia (Siregar et al., 2024), namely the pre rift, syn rift, and post rift megasequences. The lowermost unit is the pre rift megasequence, which formed prior to the rifting phase. In Arafura platform, this megasequence consists of the Tuaba Formation which was deposited during the Cambrian-Ordovician period, with an estimated thickness of up to 3,000 meters (Rusmana et al., 1995). The Tuaba Formation comprises quartz sandstone at the base, overlain by reddish siltstone and mudstone. Above this lies the Modio Formation, dated to the Devonian, which is characterized by dark gray dolomite with well-developed thin bedding at the base, transitioning upward into fine clastic rocks consisting of alternating micaceous siltstone and very fine to fine grained sandstone.

The syn rift megasequence includes the Aiduna Formation of Permian age and the Tipuma Formation of Triassic age. The Aiduna Formation consists of interbedded shale and siltstone, with occasional coal layers of lacustrine facies and sandstone interbeds containing shale of fluvial meandering channel facies. Overlying the Aiduna Formation is the Tipuma Formation, which consists of gray, red, and green claystone, sandstone, conglomerate, and minor micritic limestone. The thickness of the Tipuma Formation reaches up to 500 meters (Panggabean & Hakim, 1986).

Above the Tipuma Formation, during the Late Jurassic to Late Cretaceous, the Kemblengan sequence was deposited, marking the onset of the post rift megasequence. This megasequence is bounded by an unconformity of Cretaceous age. In several locations, the Cretaceous unconformity has eroded the Jurassic sequence and the upper parts of the Paleozoic sequences (Miharwatiman et al., 2013). The Kemblengan sequence is subdivided into four formations, from oldest to youngest: Kopai Formation, Woniwogi Formation, Piniya Formation, and Ekmai Formation. During this phase, the Australian Plate was classified as a stable passive margin. This sequence consists of carbonate mudstone and fine sandstone (Kopai), quartz sandstone with interbedded mudstone (Woniwogi), calcareous mudstone, fine sandstone, and nodular limestone (Piniya), as well as sandstone, clastic limestone, and shale (Ekmai). Overlying the Kemblengan Group is the New Guinea Limestone Group of Tertiary age, which is subsequently overlain by the Buru Formation of Plio-Miocene age. The Buru Formation consists of bluish gray mudstone, sandy shale, sandstone, conglomerate, limestone, and coal.

METHODS

This study utilizes subsurface data consisting of well data, 2D seismic data, and gravity data (Figure 3). The gravity dataset is a compilation from several sources, including marine gravity data acquired by the Marine Geological Institute in 2017, onshore gravity data from the Geological Survey Center database, and regional gravity data from the Arafura offshore survey in the Papua region. Seismic and well data were obtained from the Center for Data and Information Technology (PUSDATIN), Ministry of Energy and Mineral Resources. The seismic dataset includes 47 lines acquired during the 2000 and 2009 surveys. Four exploration wells were used in this study, namely ASM 1X, Kola 1, South Oeta 1, and Buaya Besar 1. Gravity analysis was carried out using spectral analysis and 2D forward modeling to delineate the configuration of the basement, basin boundaries, and depocenters. Well data were used for geochemical analysis of the source rocks to assess their maturity and hydrocarbon generation potential. In addition, petrophysical analysis was conducted to evaluate the physical properties of the reservoir rocks. Seismic data were used to map subsurface structures and characterize the reservoir through seismic inversion and sweetness attribute analysis.

RESULTS

Gravity Analysis

Understanding the configuration of sedimentary basins is crucial, as they represent key depositional environments that facilitate the generation, migration, and entrapment of hydrocarbons within a petroleum system. The results of gravity analysis show the presence of several sub-basins and structural patterns controlled by geological structures within the offshore Akimeugah basin, as shown in Figure 4.

This study successfully distinguishes the basinal pattern in the area and name it as West Kola High, Kola Basin and East Kola High. Kola Basin is likely the most prominent basin at the area, bounded by a ~N-S trending normal fault with a strike-slip component at the west and east. East Kola high shows a characteristic of the stable platform with a ~E-W trending shallow basin at the central. The stratigraphy of this basin cannot finely identified because the lack of well data. But, it can be the new potential basin also at that area. Spectral analysis of gravity data indicates that the depth

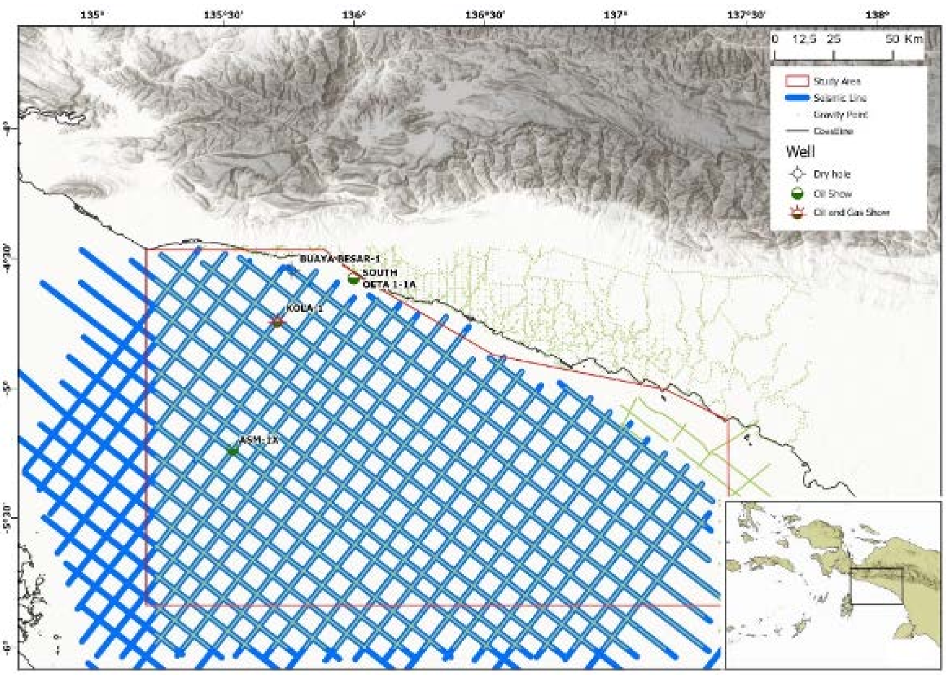

Figure 3. Distribution of wells, seismic lines, and gravity data in the Offshore Akimeugah Basin.

The integration of gravity analysis, source rock geochemical evaluation, petrophysical analysis, seismic attributes and inversion, along with subsurface interpretation, was used to define the basin configuration, identify petroleum system elements, and map hydrocarbon leads of Mesozoic and Paleozoic age in the Offshore Akimeugah Basin.

to basement varies between 2 and 6 km, with an average depth of approximately 3.61 km. These findings are further supported by the results of 2D gravity modeling (Figure 4b).

Well Log Analysis

Well evaluation in this study utilized log data from four wells located in the Offshore Akimeugah Basin: ASM-1X, Kola-1, South Oeta-1, and Buaya Besar-1. Stratigraphic correlation was conducted

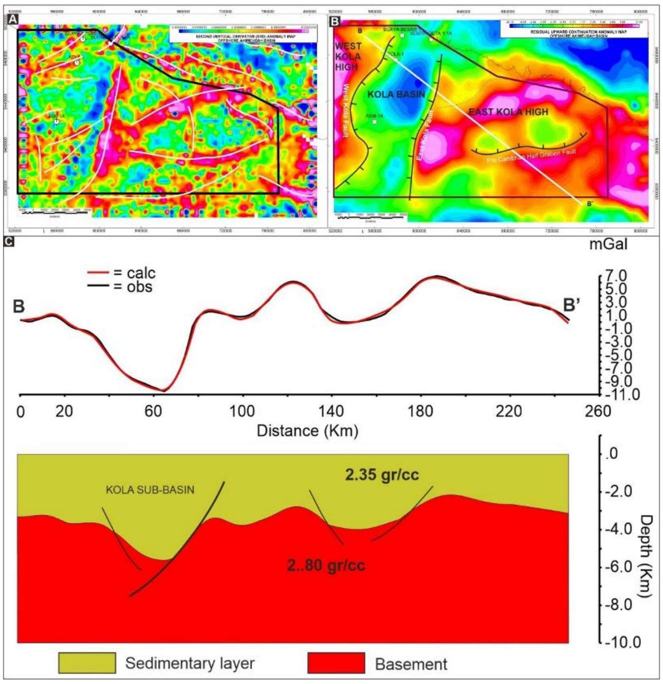

Figure 4. Gravity analysis of the Offshore Akimeugah Basin, Papua. Second Vertical Derivative (SVD) anomaly map (A); Residual anomaly map from upward continuation (B); 2D gravity model along section B–B'(C).

along a south–north cross-section passing through wells ASM-1X, Kola-1, and South Oeta-1 (Figure 5), using the base Cretaceous unconformity horizon as a flattening reference. This unconformity separates two megasequences: the post-rift megasequence above the Cretaceous unconformity, and the syn-rift megasequence below it, ranging from the Late Mesozoic to the Cenozoic. In the ASM-1X, the base Cretaceous unconformity coincides with the top of the Triassic Tipuma Formation. In Kola-1, this

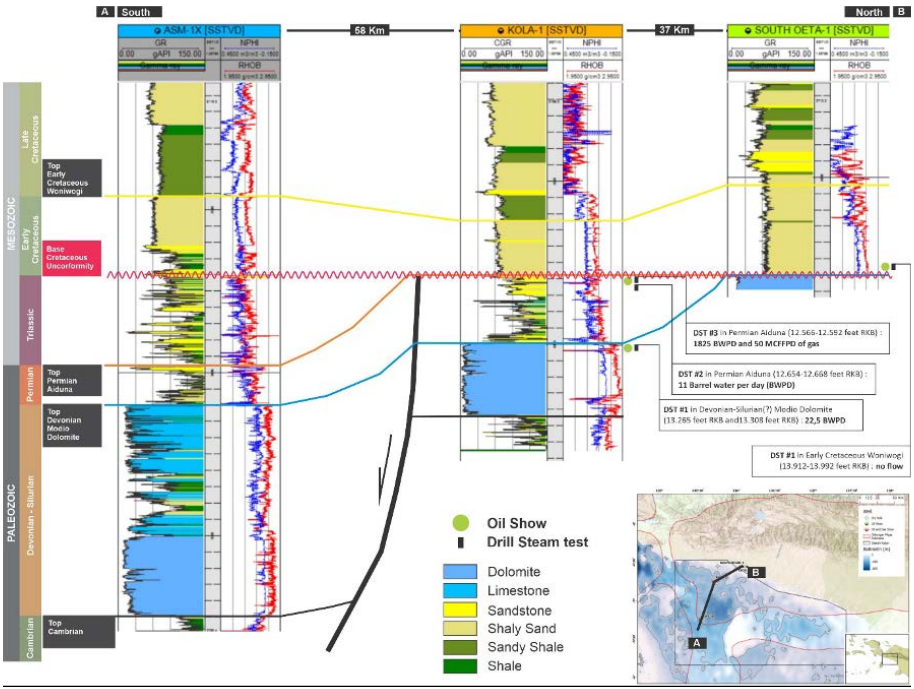

Figure 5. South–north stratigraphic correlation flattened at the base Cretaceous unconformity horizon.

Table 3. Calculated petrophysical parameters from Kola-1 and ASM-1X wells.

WELL	AGE/FORMATION	ZONA	FACIES	PETROPHYSICAL PARAMETER								
				TOP	BOTTOM	GR_MAX	GR_SH	GROSS	NET	NTG	VSH	POR
KOLA-1	Permian Aiduna	KP-1A	Mouth Bar dan Distributary Channel	3829,9	3850	131	42	20,1	9,6	0,48	0,38	0,125
		KP-1B	Mouth Bar dan Distributary Channel	3856,7	3886,3	114	64	29,6	0	0,00	0,4	0,143
		KP-2A	Braided Channel	4007	4032	148	31	25	14	0,56	0,36	0,09-0,188
	Devonian-Silurian Modio Dolomite	KD-1A		4205,6	4224,7	103	4	19,1	3,9	0,20	0,17	0,058-0,27
ASM-1X	Triassic Tipuma	AT-1A	Distributary Channel	2792,3	2813,7	119	58	21,4	18	0,84	0,36	0,145
		AT-2A	Mouth Bar	2874,6	2888,9	110	12	14,3	9,7	0,68	0,15	0,189
		AT-2B	Distributary Channel	2893,4	2920	118	40	26,6	26	0,98	0,36	0,145
		AT-2C	Mouth Bar	2923	2933	103	61	10	9,7	0,97	0,38	0,133
	Permian Aiduna	AP-1A	Braided Channel	3067,8	3093,9	152	46	26,1	20	0,77	0,49	0,08
	Devonian-Silurian Modio Dolomite	AD-1A		3424	3500	112	16	76	14,8	0,19	0,4	0,017

horizon aligns with the top of the Permian Aiduna Formation, while in South Oeta-1, it corresponds to the top of the Devonian–Silurian Modio Dolomite. Based on the correlation section, the Triassic sequence is only developed in the ASM-1X. The Permian sequence is observed in both ASM-1X and Kola-1, whereas in South Oeta-1, the pre-rift megasequence is represented by the Devonian–Silurian Modio Dolomite Formation.

Petrophysical evaluation of wells Kola-1 and ASM-1X is summarized in Table 1. In the Tipuma Formation, analysis from ASM-1X indicates four reservoir zones, with effective porosity values ranging from 0.133 to 0.189 and water saturation between 0.68 and 0.768. Depositional facies within these zones include mouth bars, distributary channels, and braided channels.

The Aiduna Formation, evaluated from both ASM-1X and Kola-1, also reveals four reservoir zones. Zone AP-1A in ASM-1X and zones KP-1A, KP-1B, and KP-2A in Kola-1 exhibit net-to-gross values ranging from 0.048 to 0.56 and effective porosity values between 0.125 and 0.188. Identified facies in this formation include distributary channels and mouth bars.

Meanwhile, the dolomite and limestone of the Modio Formation, interpreted from ASM-1X and Kola-1, reflect a shallow marine depositional environment. These carbonates display an average effective porosity of approximately 0.27 and water saturation of around 0.8. The most favorable reservoir potential is associated with karstified zones formed through diagenetic processes or with intervals showing fractured structures, making them prime targets for hydrocarbon exploration.

Geochemical Analysis

Geochemical analysis was conducted by Maxus Aru Inc on well Kola-1, which reaches a total depth of 14,300 ft (4,358.64 m), penetrating as deep as the Silurian-aged Pre-Modio Formation. The analytical methods employed include Total Organic Carbon/Rock-Eval Pyrolysis (TOC/REP), vitrinite reflectance, gas chromatography (GC), gas chromatography–mass spectrometry (GC-MS), and carbon isotope analysis.

The TOC vs. PY cross-plot (Figure 6a) indicates that the majority of source rocks in well Kola-1 exhibit gas-generating potential with fair quality. Source rocks from the Aiduna Formation demonstrate fair to excellent gas potential. Several source rock samples with excellent gas-generating potential originate from the Buru, Piniya, Woniwogi, and Aiduna formations. Meanwhile, the Pre-Modio Formation has been identified as an oil-prone source rock but with poor generative quality.

Thermal maturity assessment based on the Tmax vs. Hydrogen Index (HI) cross-plot (Figure 6b) reveals that source rocks from the Woniwogi, Aiduna, Modio, and Pre-Modio formations have reached the oil window. The plot also shows that most source rocks contain Type III kerogen (gas-prone). Two Permian-aged source rock samples (Aiduna Formation) indicate mixed Type II/III kerogen, capable of generating both oil and gas, while one Lower Miocene–Pliocene sample (Buru Formation) contains marine Type II kerogen, indicating oil-prone characteristics.

Furthermore, the vitrinite reflectance (Ro) vs. depth cross-plot (Figure 6c) demonstrates that source rock maturity begins to be reached at around 3,320 m, particularly in rocks from the Piniya, Woniwogi, Aiduna, Modio, and Pre-Modio formations. Two samples from the Pre-Modio Formation have even attained the wet gas maturity level. Between depths of 3,150 and 2,700 m, Ro values decrease to around 0.3, indicating possible tectonic uplift and erosion. Unconformities are also indicated at intervals of 3,836–3,838 m and 4,175–4,280 m.

The burial and thermal history modeling results for well Kola-1 are presented in Figure 7. Based on the model, the Permian Aiduna source rock began to enter early maturity (Ro = 0.55) during the Early Cretaceous, around 132 Ma. Peak oil maturity (Ro = 0.7) was

Seismic Interpretation

Seismic interpretation was carried out on several seismic lines available in the Offshore Akimeugah area and its surroundings. The interpretation process involved several stages, including seismic mistie analysis, well-to-seismic tie, horizon and fault interpretation, and the construction of subsurface structural maps. The stratigraphic markers used in the interpretation were derived from well data analysis (Figure 5), and include the following key horizons: Base Cambrian, Modio Dolomite (Devonian), Aiduna Formation

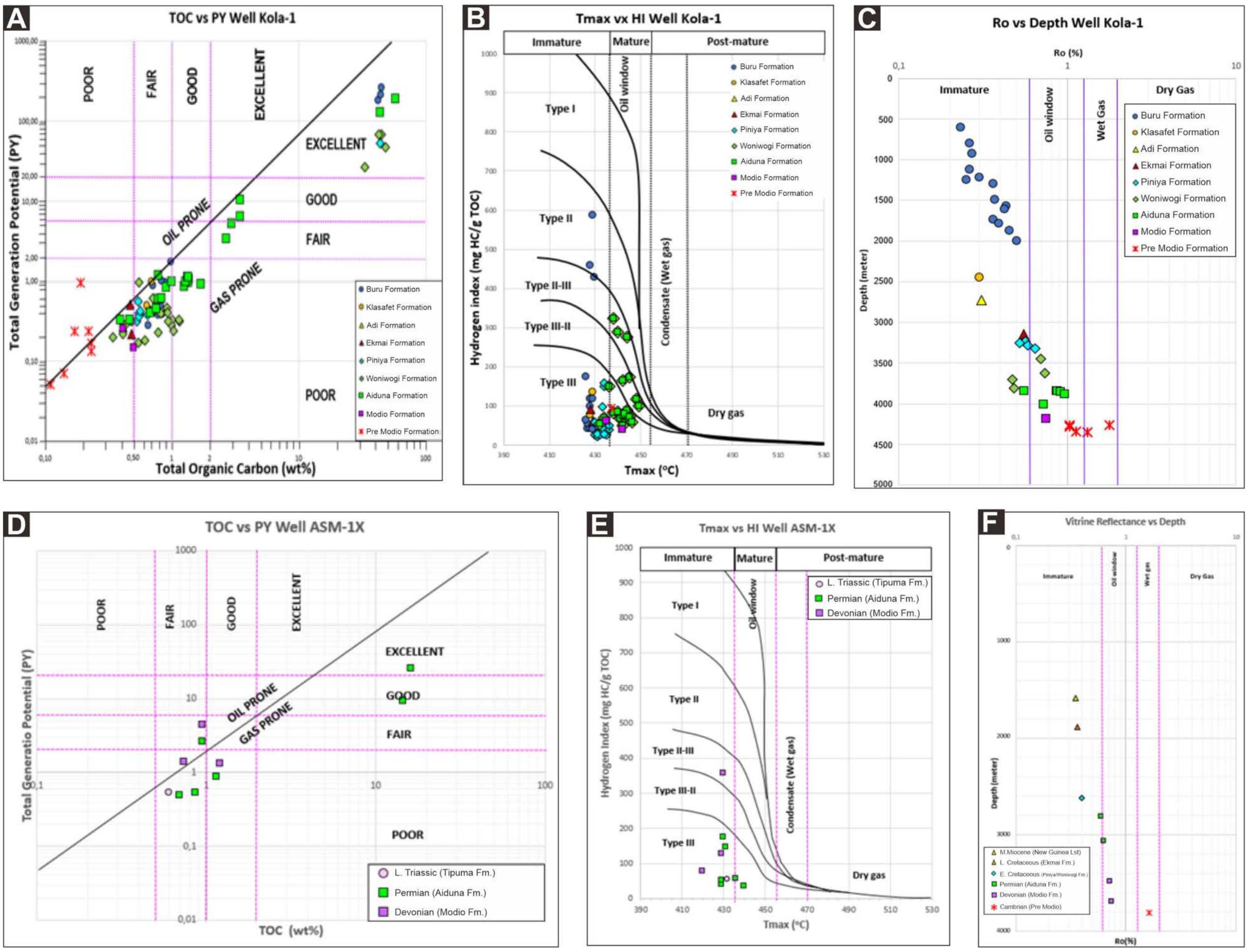

Figure 6. Cross-plot of TOC vs Pyrolysis Yield (PY) for well Kola-1 and ASM-1X (A and D); Cross-plot of Tmax vs HI for Kola-1 and ASM-1X (B and E); Cross-plots of Tmax and vitrinite reflectance (Ro) vs depth in Kola-1 and ASM-1X (C and F).

reached between 119 and 89 Ma, and late oil maturity (Ro = 1) was achieved in the Late Cretaceous, around 85.9 Ma. At present, the early oil window is identified at 3,609 meters depth, peak oil maturity at 3,849 m, and late oil maturity at 4,043 m.

(Permian), Unconformity/Lower Triassic Tipuma, Kemblengan Group Woniwogi (Early Cretaceous), Kemblengan Group Piniya-Ekmai (Late Cretaceous), Intra New Guinea Limestone Group (Late Oligocene), Batugamping Nugini (Late Miocene), and Buru Formation (Pliocene).

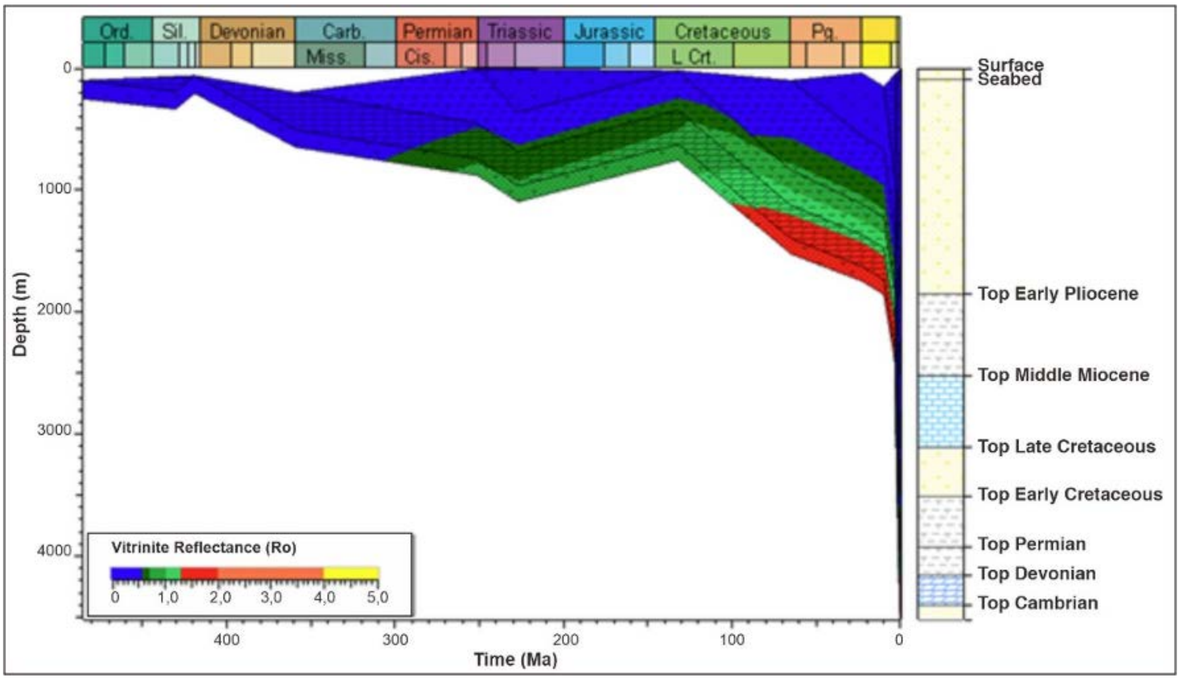

Figure 7. Burial history diagram of Kola-1

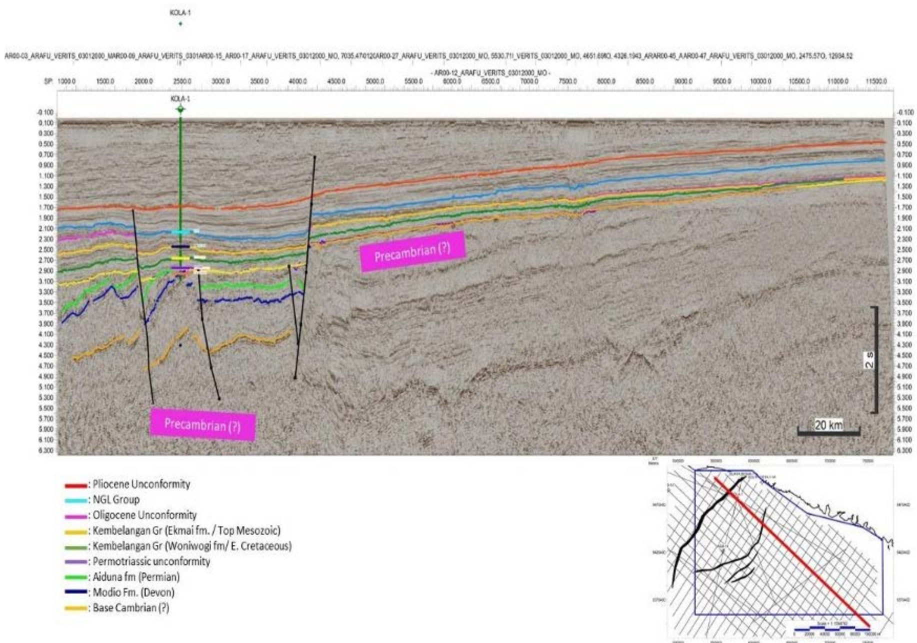

Figure 8. Seismic interpretation of Line AR00-12 crossing the Kola-1. Paleozoic rock units are observed in the western part of the seismic section.

Figure 8 illustrates the internal structures of various stratigraphic intervals. Several types of seismic reflector terminations were identified, including onlap, downlap, and toplap (erosional truncation). These patterns suggest depositional sequences and transgressive surfaces. The Devonian Modio Dolomite exhibits a parallel internal configuration with toplap terminations, indicating deposition in a carbonate platform environment followed by erosion due to tectonic uplift.

The deposition of the Permian Aiduna Formation and the Lower Triassic Tipuma Formation occurred in a continuous sequence, as evidenced by the parallel reflectors and lack of erosional truncation. After the deposition of the Tipuma Formation, a major tectonic event caused folding and partial erosion of the Modio, Aiduna, and Tipuma

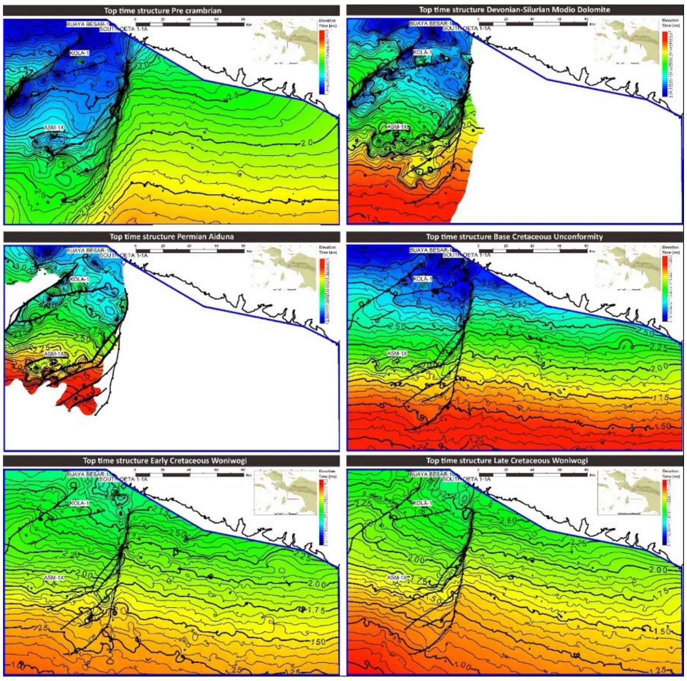

Figure 9. Seismic-derived time structure map of the Offshore Akimeugah Basin.

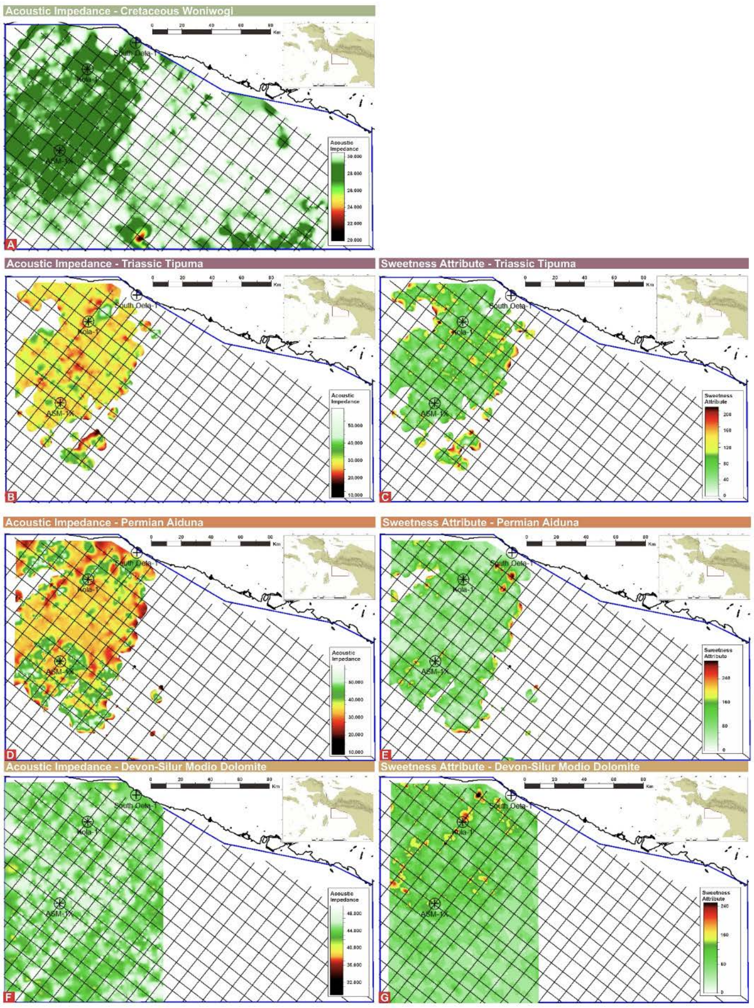

Figure 10. AI and sweetness attribute maps for the Tipuma (B, C), Aiduna (D, E), and Modio Dolomite (F, G) intervals.

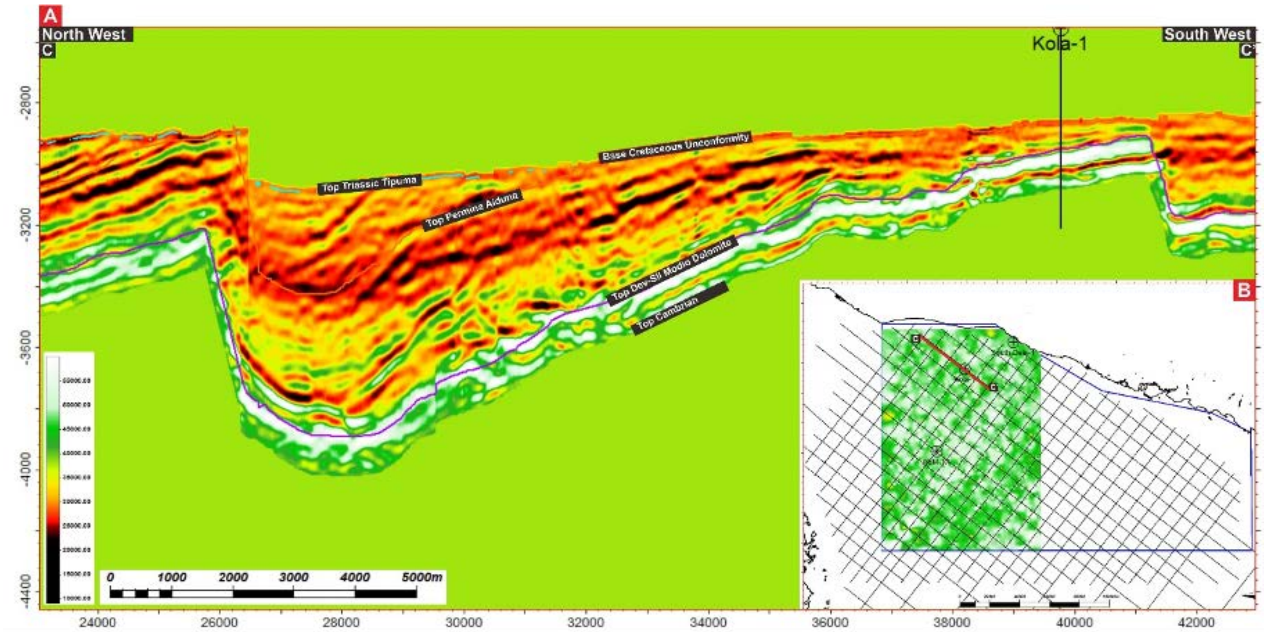

Figure 11. Distribution of low-impedance zones embedded in high-impedance settings (A); AI map of the Modio Dolomite Formation from seismic inversion (B).

Formations. This is reflected in toplap terminations toward overlying Lower Cretaceous sediments, forming a pop-up structure and an unconformity known as the Mesozoic Unconformity. Time-structure maps for key interpreted horizons are presented in Figure 9.

Seismic interpretation reveals that the Cretaceous interval, which unconformably overlies the Paleozoic sequences in the Arafura Basin, has the potential to function as a regional seal. Seismic inversion results for the Late Cretaceous to Jurassic Unconformity interval indicate acoustic impedance (AI) values ranging from 10,000 to 33,000 ft/s*g/cc. The main target within this interval is the Woniwogi shale (Base Cretaceous), characterized by AI values between 29,000 and 30,000 ft/s*g/cc, as indicated by green to white colors in the inversion results (Figure 10a). The AI distribution suggests that Woniwogi shale is primarily concentrated in the eastern and northern parts of the study area.

In the AI distribution maps of the Tipuma and Aiduna Formations (Figures 10b and 10d), potential lead zones are represented by red to dark hues, and are located northwest of Kola-1 and north of ASM-1X. Similar lead patterns are observed in the sweetness attribute maps (Figures 10c and 10e), which largely coincide with the inversion anomalies. Although additional anomalies appear in the southern region in the sweetness attribute map, they are less pronounced than those seen in the AI inversion.

In the Modio Dolomite Formation, seismic inversion results (Figure 11a) show low impedance zones interspersed within high-impedance areas. These high impedance zones may function as internal seals, enabling hydrocarbon entrapment within porous dolomite. The distribution of low impedance zones, mapped within 150 ms below the Top Modio Dolomite, are shown in yellow to brown shades. Sweetness attribute analysis (Figure 11b) reveals similar trends, and black outlines mark inversion derived leads that correlate well with sweetness anomalies. However, in the southern part of the study area, sweetness anomalies appear less distinct (Figure 10g).

DISCUSSIONS

Basin Configuration

Gravity analysis delineates the structural configuration of the Akimeugah Basin (Figure 12), revealing two prominent highs; West Kola High and East Kola High, separated by a north–south trending depocenter known as the Kola Basin. This basin is bounded by two major fault systems; the East Kola Fault to the east and the West Kola Fault to the west. Several exploratory wells (Buaya Besar, South Oeta, Kola-1, and ASM-1X) are located within the Kola Basin, confirming its significance as a key exploration target. A notable feature on the East Kola High is a west–east trending sub-basin, which appears as a half graben on seismic sections, bounded by north dipping normal faults (Figure 12). The formation of this pre-Cambrian half graben and the Kola Basin reflects distinct tectonic regimes and kinematic histories, requiring further evaluation. Limited well data over the East Kola High poses challenges in fully resolving the tectonic evolution of this sub-basin.

To reconstruct the basin history, palinspastic restoration was performed along regional seismic line B–B′, oriented NW–SE, across the Kola Basin. The restoration indicates that basin development commenced during the pre-Cambrian with the deposition of units Pre-Cambrian-1, Pre-Cambrian-2 and Pre-Cambrian-3 under extensional tectonics,

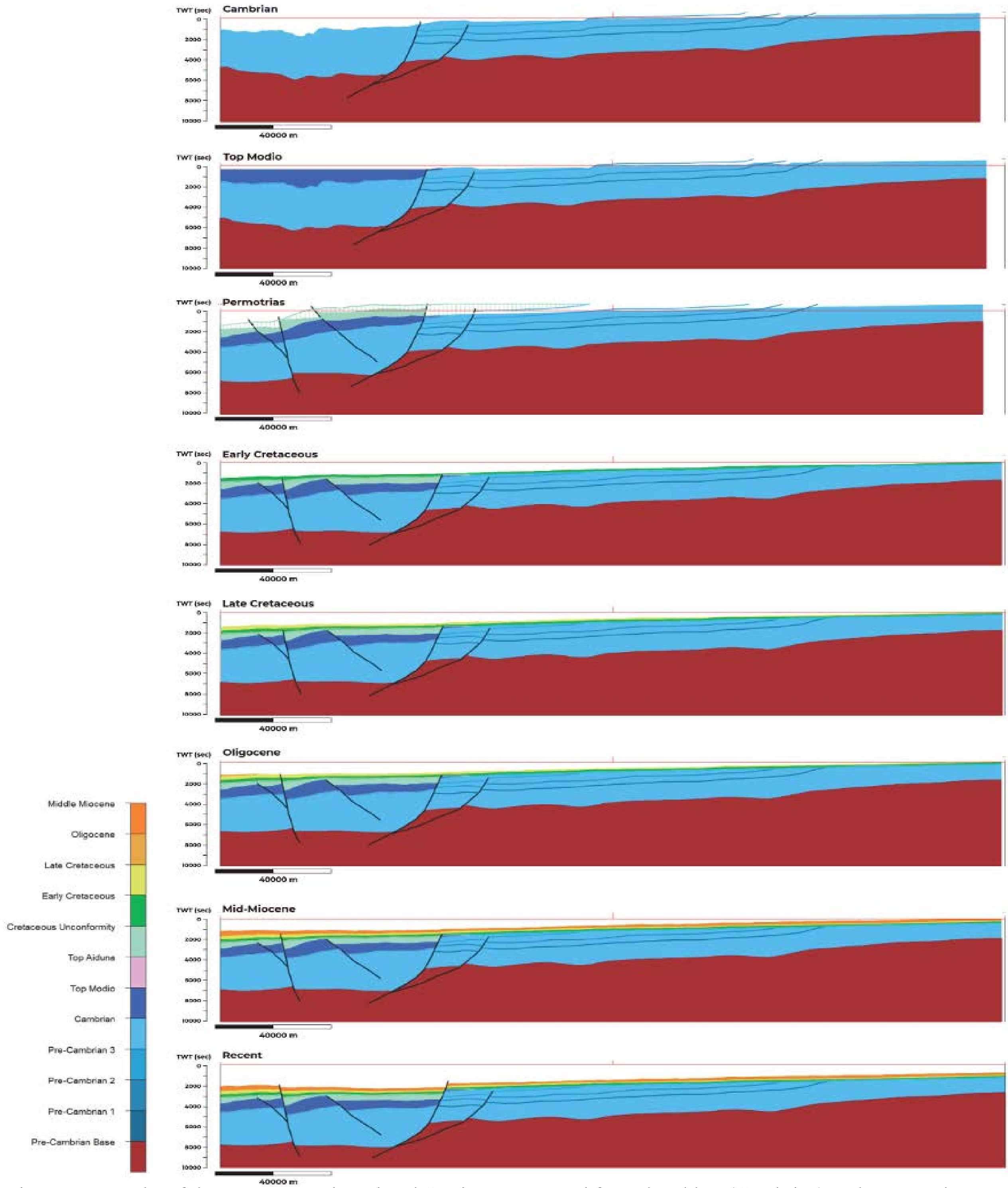

Figure 12. Results of the reconstructed Regional Section 1, arranged from the oldest (Cambrian) at the top to the youngest (Recent) at the bottom. The section line corresponds to B–B′ shown in Figure 4b.

forming normal fault-bounded depressions. Continued extensional activity during the Cambrian resulted in the initiation of the Kola Basin and deposition of the Modio Formation. Sedimentation persisted through the Permo-Triassic until a Permo-Triassic unconformity developed, associated with uplift and erosion.

During the Early Cretaceous, inversion occurred as a consequence of the extensional regime affecting Regional Line B–B′. The resulting accommodation space led to basin sagging, as evidenced by the continued deposition of sedimentary units up to the Recent. This long-term sagging since the Early Cretaceous reactivated pre-existing normal faults within the Kola Basin and its surroundings due to overburden loading. Palinspastic analysis indicates that the Akimeugah Basin has remained generally tectonically stable. No evidence of compression was observed, as typically indicated by negative extension/ shortening values. Strain analysis along regional sections 1 show exclusively positive values, confirming that basin development has been dominated by extension and sagging. These characteristics are typical of an undisturbed passive-margin setting.

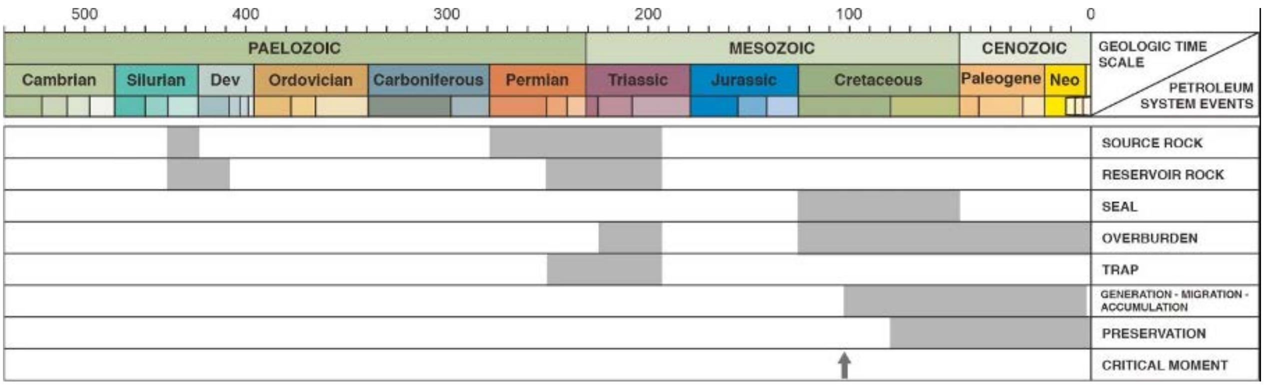

Figure 13. Petroleum system elements and processes in the Offshore Akimeugah Basin.

Petroleum System

The petroleum system of the Offshore Akimeugah Basin is characterized by identified source rocks, reservoirs, seals, and traps, integrated from seismic interpretation, petrophysical analysis, and geochemical evaluation (Figure 13).

Source Rocks

The Aiduna Formation ranges from fair to excellent as a gas-prone source rock. Based on crossplots of Tmax and vitrinite reflectance (Ro) versus depth (Figure 6b and 6c), source rock intervals within the Aiduna Formation in the Kola-1 well enter the oil window at approximately 3,619 m (Tmax) and 3,450 m (Ro). Geochemical analyses including gas chromatography (GC), gas chromatography–mass spectrometry (GC-MS), and carbon isotope studies of samples at 3,843.5 m depth indicate that the organic matter is predominantly of terrestrial origin, deposited under anoxic to suboxic conditions, supporting its potential for gas generation at relatively mature levels.

Based on the similarity of facies and depositional environment between the Aiduna and Tipuma Formations (Figure 5), Tipuma Formation exhibits significant potential as a hydrocarbon source rock, with a predominance of gas-prone characteristics. Organic matter within this formation is primarily Type III kerogen, with minor contributions of Type II kerogen capable of generating both oil and gas The organic input is largely of terrestrial origin, deposited in deltaic to estuarine environments under oxic to suboxic conditions. Source rock quality varies from fair to good, as indicated by total organic carbon (TOC) content and hydrogen index (HI), both of which reflect the hydrocarbon generation potential (Figure 6d, 6e, and 6f).

In terms of thermal maturity, Tipuma Formation is generally capable of reaching gas-mature levels, particularly at intermediate to greater burial depths or in areas with a history of elevated geothermal gradients. This implies that, under suitable burial and thermal conditions, the Tipuma Formation is more likely to enter the gas window rather than the oil window, making it a promising candidate for natural gas exploration. Further geochemical analyses, including Rock-Eval pyrolysis and vitrinite reflectance, are required to confirm hydrocarbon generation capacity within specific areas.

Reservoir Rocks

Reservoir potential in the Offshore Akimeugah area has been identified within three primary formations: the Triassic Tipuma, the Permian Aiduna, and the Devonian–Silurian Modio Dolomite. Evidence includes oil shows observed in the Kola-1 well, where native hydrocarbons (oil stain and chlorotene cut) were recorded in the upper Permian Aiduna interval (12,581–12,589 ft RKB). Minor oil shows were also reported in the upper Devonian–Silurian(?) Modio Dolomite (13,255–13,270 ft RKB) as dull yellow-brown fluorescence, dark brown staining, and very slow solvent cuts. Drill Stem Test (DST) #3 conducted on the Permian Aiduna (12,566–12,592 ft RKB) yielded 1,825 barrels of water per day (BWPD) accompanied by 48.4–56.6 thousand cubic feet per day (MCF/D) of gas. Chromatographic analysis of the produced gas indicated the presence of methane (C1), ethane (C2), propane (C3), iso-butane (C4), n-butane (C4), pentane (C5), and nitrogen.

In addition to mud log and test data, reservoir potential was further evaluated through facies analysis and petrophysical interpretation (Table 1). The Permian Aiduna and Triassic Tipuma, deposited during the syn-rift phase, are characterized by deltaic reservoir facies dominated by distributary channels and mouth bars, as indicated by log character and moderate porosity values. In the Modio Dolomite, reservoir quality is supported by oil shows, petrophysical analysis, and seismic inversion, which reveal low-impedance zones in the lower part of the formation associated with enhanced porosity, possible fracture development, and karstification due to diagenetic processes. These features collectively identify the Modio Dolomite as a key exploration target within the regional petroleum system.

Seal Rocks

Seal effectiveness in the study area is attributed to both regional and intraformational seals. The regional seal in the offshore Akimeugah Basin is identified as the Cretaceous Klembengan Group (Woniwogi, Piniya, and Ekmai formations), supported by seismic inversion results showing high impedance values. Additionally, tight limestone and dolomite layers act as effective intraformational seals. The Arafura Platform is entirely overlain by Cretaceous and Tertiary sequences that unconformably overlie the Palaeozoic. Well data from Kola-1 and ASM-1 indicate that the lowermost part of the Cretaceous consists predominantly of tight siltstones and shales, further enhancing the sealing effectiveness.

Traps

Tectonic events during the Middle Jurassic induced extensive faulting, folding, and erosional truncation affecting pre-existing units, including the Modio Dolomite, Aiduna, and Tipuma formations. Hydrocarbon trapping mechanisms in this area are a combination of structural traps, mainly fault-bounded anticlines, and stratigraphic traps associated with sub-unconformities.

Play Concept

Petroleum plays identified in the offshore Akimeugah Basin, based on seismic interpretation, petrophysical evaluation, and geochemical analysis, include the Devonian Modio Dolomite stratigraphic–structural play, the Permian Aiduna Sandstone structural play, and the Triassic Tipuma Sandstone structural play. A schematic overview of the petroleum play concepts in the Offshore Akimeugah Basin is shown in Figure 14.

Modio Dolomite stratigraphic–structural play

The Devonian Modio Dolomite serves as the primary reservoir, structurally associated with southwest–southeast trending faults. Source rocks are inferred to originate from Cambrian intervals and shales of the Aiduna Formation. Seismic attribute analysis reveals high impedance zones, suggesting the presence of internal seals within the Modio Dolomite, enhancing hydrocarbon entrapment potential.

Permian Aiduna Sandstone structural play

This play involves Permian Aiduna sandstones as the reservoir, associated with southwest–southeast trending fault systems. Source rocks are likely Cambrian intervals and Aiduna shales. Seismic inversion indicates that the overlying Woniwogi Formation provides an effective top seal, allowing for hydrocarbon retention in the Aiduna reservoir.

Triassic Tipuma Sandstone structural play

The Triassic Tipuma Sandstone, similarly associated with major southwest–southeast trending faults, serves as the reservoir. Potential source rocks include Cambrian intervals and shales of both the Aiduna and Tipuma formations.

Lead Potential

Lead identification and petroleum system play mapping are supported by seismic sweetness attribute analysis and seismic inversion of the

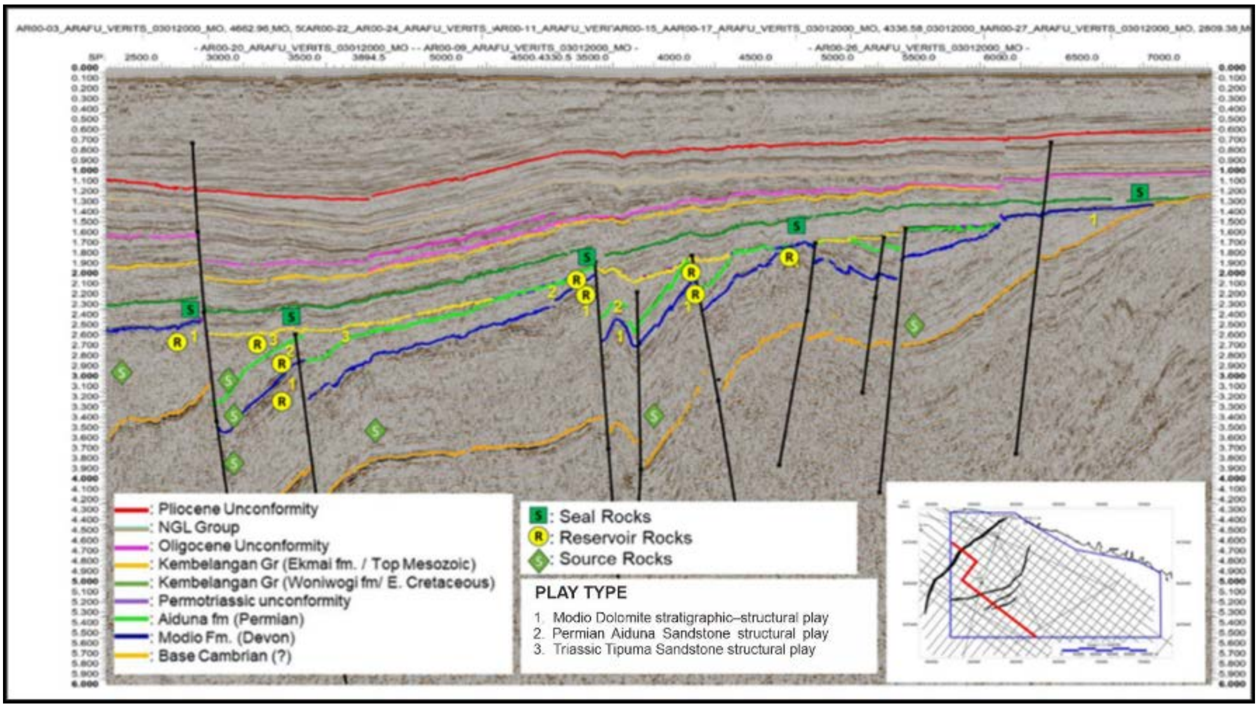

Figure 14. Petroleum play concept in the Offshore Akimeugah area.

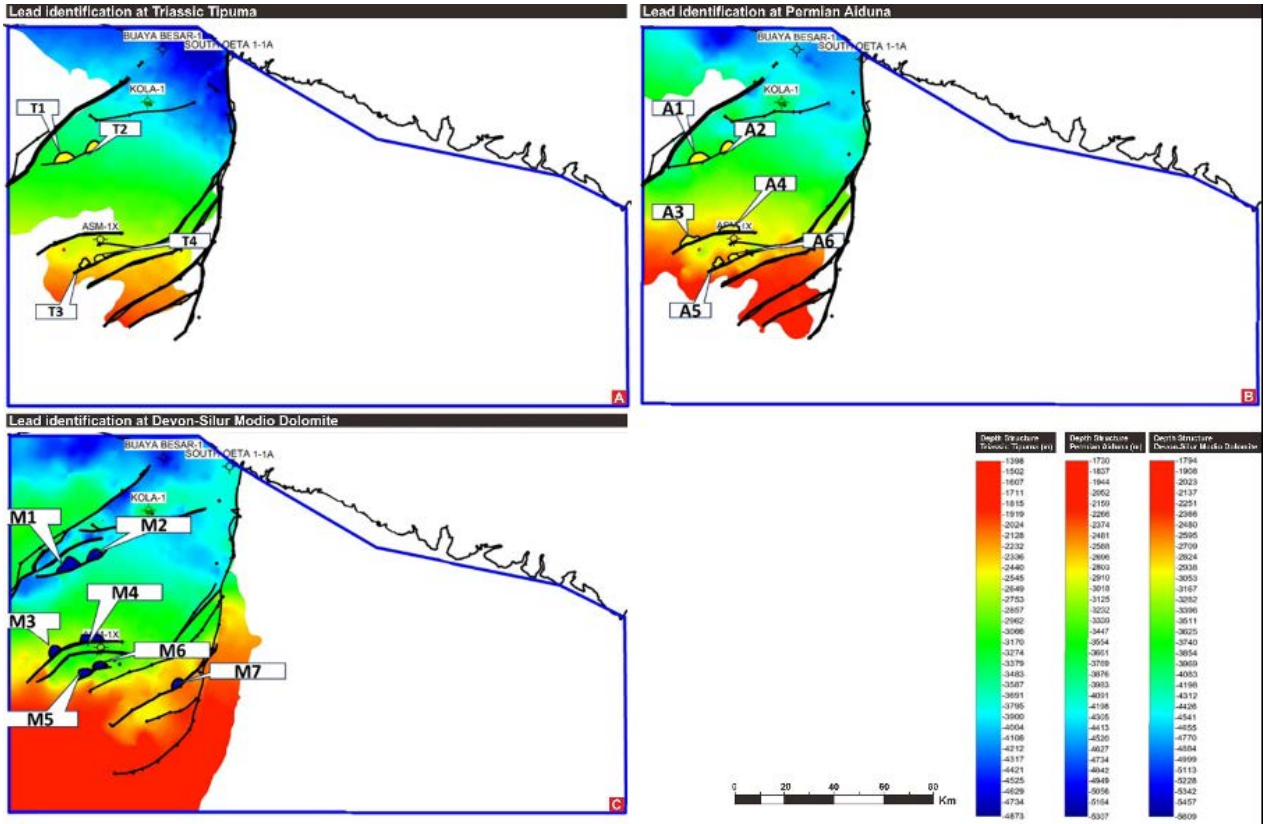

Figure 15. Lead identification in the Offshore Akimeugah Basin

Tipuma, Aiduna, and Modio Dolomite formations. The integration of seismic interpretation with sweetness attribute and inversion results enabled the delineation of potential leads in the Offshore Akimeugah area. A total of four leads are identified in the Triassic Tipuma Sandstone structural play (Figure 15a), six leads in the Permian Aiduna Sandstone structural play (Figure 15b), and seven leads in the Modio Dolomite structural play (Figure 15c).

CONCLUSIONS

Based on gravity data analysis, a total of five sedimentary sub-basins have been delineated in the study area. The underlying basement rocks consist of metamorphosed Australian continental crust with an estimated density of approximately 2.8 gr/cc. Gravity modeling results indicate that the basement depth ranges from 2 to 6 km, with an average depth of about 3.61 km. Source rocks identified in several wells within the study area are dominated by Type III (gas-prone) kerogen, with some intervals containing Type II (oil/gas-prone) kerogen. Mature source rocks within the oil window include the Woniwogi, Aiduna, Modio, and Pre-Modio formations. Reservoir potential, as indicated by petrophysical and seismic inversion analyses, resides in the Triassic Tipuma Sandstone, Permian Aiduna Sandstone, and fractured Devonian–Silurian Modio Dolomite. Sealing effectiveness in the area is provided by both regional and intraformational seals. The Lower Cretaceous section in the Kola-1 and ASM-1 wells consists of tight siltstone and shale, while the widespread Woniwogi shale is interpreted as the primary regional seal. Hydrocarbon trapping mechanisms comprise a combination of fault-bounded structural anticlines and stratigraphic sub-unconformity traps. Identified petroleum plays in the Offshore Akimeugah area include the Modio Dolomite stratigraphic–structural play, Permian Aiduna Sandstone structural play, and Triassic Tipuma Sandstone structural play. A total of seven leads have been delineated in the Modio Dolomite, six in the Aiduna Sandstone, and four in the Tipuma Sandstone.

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