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Facies Characteristics and Depositional Environment Reconstruction of the Minahaki Formation, "DM" Field, Banggai Basin

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Abstract

The Miocene Minahaki Formation in the Banggai Basin represented a key hydrocarbon reservoir, but its pronounced heterogeneity posed a challenge for field development. This study aimed to characterize the formation's carbonate facies and reconstruct its depositional environment in the "DM" field to establish a predictive model for reservoir distribution. The research employed an integrated subsurface analysis of core, cuttings, and wireline log data from seven wells. Four principal lithofacies (Bioclastic Coralline Floatstone, Dolomitic Algae Bioclastic Packstone, Argillaceous Dolomitic Foraminifers Bioclastic Wackestone, and Bioclastic Wackestone) were identified and subsequently grouped into two distinct facies associations: a high-energy Reef Margin Complex (FA-1) and a lower-energy Fore-Reef Slope (FA-2). Spatial correlation of these associations revealed a clear proximal-to-distal environmental gradient from west to east. The depositional architecture of the Minahaki Formation in the study area was interpreted as a rimmed carbonate platform. This model accounts for the observed reservoir heterogeneity, concluding that higher-quality reservoir bodies, characterized by moldic, vuggy, and intercrystalline porosity, are concentrated within the single reefal buildup that defines the western margin of the field. This finding provides a direct, geology-based predictive tool for optimizing future drilling activities and serves as a useful analogue for similar carbonate systems elsewhere.

Keywords: Banggai-Sula; carbonate platform; depositional environment; facies analysis; Miocene carbonate reservoir.

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Introduction

The Banggai Basin, located in the eastern arm of Sulawesi, is an established Indonesian hydrocarbon province hosting major gas and oil fields, such as the Senoro Field with estimated reserves of 362 MMBOE, within its Miocene carbonate successions (Satyana & Zaitun, 2016; Surjono et al., 2019). The primary reservoirs within the Salodik Group are characterized by high productivity but also significant heterogeneity, which presents a persistent challenge for exploration and field development (Haris et al., 2017; Hasanusi et al., 2012; Khairi et al., 2022; Ontosari et al., 2023). This reservoir variability, which manifests as rapid spatial changes in porosity and permeability, is fundamentally controlled by the distribution of primary depositional facies and their subsequent diagenetic alterations (Angkasa et al., 2024; Laya et al., 2022; Syah et al., 2019). Similar challenges in Miocene carbonate buildups across Southeast Asia, for instance in the Central Luconia province, offshore Malaysia, also highlight that the interplay between depositional facies and diagenesis represents a primary control on reservoir quality (Henglai et al., 2025). Therefore, a detailed understanding of depositional architecture is critical for predicting reservoir quality and geometry, an objective best achieved through an integrated facies analysis that combines petrographic data from cores and cuttings with wireline log responses (Laya et al., 2022; Rahadian et al., 2018).

Extensive research has established a comprehensive regional framework for the Banggai Basin. The tectonic evolution, primarily controlled by the westward drift of the Banggai-Sula microcontinent and its subsequent Mio-Pliocene collision with the East Sulawesi Ophiolite Belt, is well-documented as the primary mechanism for basin formation and trap development (Nugraha & Hall, 2018; Serhalawan & Chen, 2024). Geochemical studies have identified the Early to Middle Miocene Tomori and Matindok formations as the primary source rocks for the basin's hydrocarbons (Satyana & Zaitun, 2016).

At the reservoir scale, numerous studies have characterized the Miocene carbonate plays. In the analogous Senoro Field, for instance, facies range from high-energy reefal buildups to lower-energy platform carbonates (Hasanusi et al., 2012; Rahadian et al., 2018). This distinction is highly analogous to the stratigraphy in the study area, where the high-energy reefal facies is typically developed as the distinct Mantawa Member, often overlying or interfingering with the generally finer-grained, muddier platform carbonates of the Minahaki Formation proper (Laya et al., 2022; Rahadian et al., 2018). Detailed facies analysis has distinguished specific environmental settings such as reef margins, fore-reefs, and back-reef lagoons (Muhammad et al., 2020; Pratama et al., 2020). This work, supported by sequence stratigraphy and detailed biostratigraphy, has led to varying interpretations of the overall platform geometry, including both rimmed platforms and, more recently, a carbonate ramp model for the fine-grained Minahaki Formation (Herdiansyah et al., 2022; Laya et al., 2022). The ramp interpretation is primarily supported by the widespread fine-grained nature of the formation and seismic geometries showing low-angle progradation without a distinct shelf-edge break (Laya et al., 2022). In contrast, rimmed platform models are argued based on lithofacies evidence for a distinct, high-energy reef margin creating a significant topographic break, a condition observed in analogous buildups within the basin (Rahadian et al., 2018).

Despite this comprehensive regional understanding, a detailed, facies-based depositional reconstruction specifically for the Minahaki Formation in the “DM” field remains a gap in the published literature. Regional models, while providing excellent context, often lack the granular resolution required for accurate field-scale prediction. This lack of resolution translates directly into higher exploration and development risk, as the precise location of high-quality reservoir bodies, such as porous reef margins, versus lower-quality, muddier facies remains unpredictable. What has escaped detailed attention is a well-calibrated, multi-well reconstruction that validates and refines these regional models at a local scale, particularly explaining the observed west-to-east facies transition within the "DM" field.

To address this gap, this study aims to characterize the lithofacies of the Minahaki Formation in the "DM" field and reconstruct their depositional environments through an integrated analysis of core, cuttings, and wireline log data. This integrated approach is essential because it allows the direct rock observations from limited core intervals to be used to calibrate the continuous wireline log data, enabling a reliable extrapolation of facies interpretations across all wells in the field. This approach allows for the creation of a spatially coherent geological narrative to explain observed reservoir heterogeneity. The goal is to develop a robust depositional reconstruction that serves as a predictive framework for understanding reservoir distribution. Ultimately, this research provides not only a field-scale refinement to the regional depositional model of the Minahaki Formation but also delivers a direct, geology-based predictive tool for optimizing future hydrocarbon exploration and development in the Banggai Basin.

Materials and Methods

Geological Setting

The "DM" field is situated within the Banggai Basin, a foreland basin located on the eastern arm of Sulawesi, Indonesia (Figure 1). The basin's architecture and stratigraphy are direct products of a complex Cenozoic tectonic history dominated by the interaction between the Eurasian, Indo-Australian, and Pacific plates, which involves multiple subducting slabs (e.g., Sula Spur, Halmahera, and Celebes Sea Slabs) beneath the island (Greenfield et al., 2021; Hall, 2019; Kesumastuti et al., 2025; Serhalawan & Chen, 2024; Wibowo et al., 2025). The basin itself formed atop the Banggai-Sula microcontinent, a continental fragment that rifted from the northern margin of Gondwana (present-day Australia) during the Late Jurassic (Advokaat & van Hinsbergen, 2024; Garrard et al., 1988; Hall, 2012; Satyana & Zaitun, 2016). This microcontinent drifted westwards before its eventual collision with the East Sulawesi ophiolite belt, a major tectonic event that occurred from the Early Miocene to Early Pliocene (Nugraha & Hall, 2018; Patria et al., 2023).

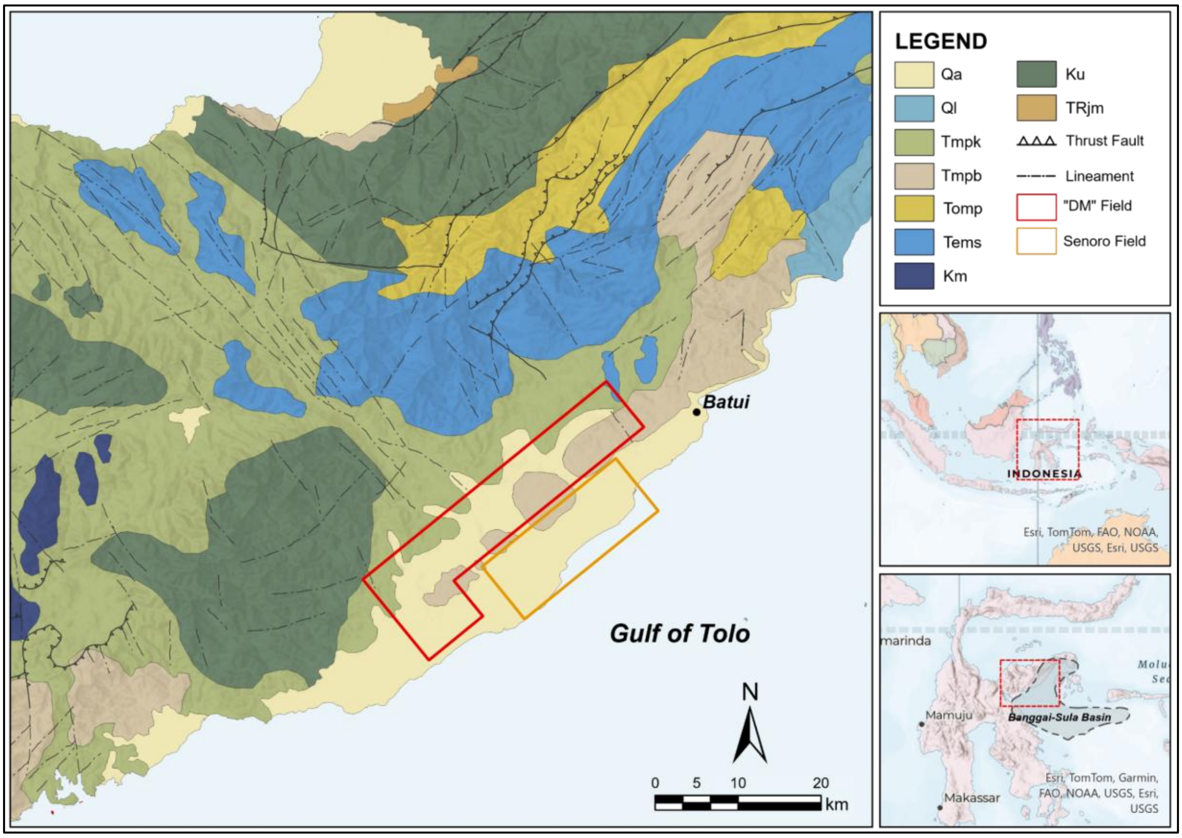


Figure 1. Regional geological map of the eastern arm of Sulawesi showing the location of the "DM" Field (this study) and the analogous Senoro Field. Inset maps illustrate the regional context and the outline of the Banggai Basin. (Geological map modified from the Geological Agency of Indonesia (Badan Geologi, ESDM); inset base maps from Esri and contributing partners).

This tectonic evolution resulted in a distinct tectonostratigraphy that governs the petroleum system of the region (Figure 2). Prior to the main collisional event, which initiated in the Early Miocene, a period of relative tectonic quiescence during the Miocene allowed for the widespread development of a shallow-marine carbonate system known as the Salodik Group (Titu-Eki & Hall, 2020). This group comprises three main successions: the Lower Miocene Tomori Formation, the Middle Miocene Matindok Formation, and the Upper Miocene Minahaki Formation (Jambak et al., 2024). The Minahaki Formation, the focus of this study, is a key carbonate unit within this group, characterized by extensive platform development (Laya et al., 2022; Nugraha & Hall, 2022). Recent high-resolution biostratigraphic studies using nannoplankton have constrained the age of the Minahaki Formation to the Middle to Late Miocene (Nurhidayah et al., 2024). The subsequent collision terminated this carbonate production phase and initiated a compressional regime, creating complex fold-and-thrust structures that now serve as the primary hydrocarbon traps (Titu-Eki & Hall, 2020). This compression was followed by rapid subsidence and the deposition of thick Pliocene-Pleistocene syn-orogenic sediments of the Sulawesi Group, often referred to as the Celebes Molasse, which provide both the regional seal and the necessary overburden for the maturation of Miocene source rocks (Nugraha et al., 2022; Satyana & Zaitun, 2016).

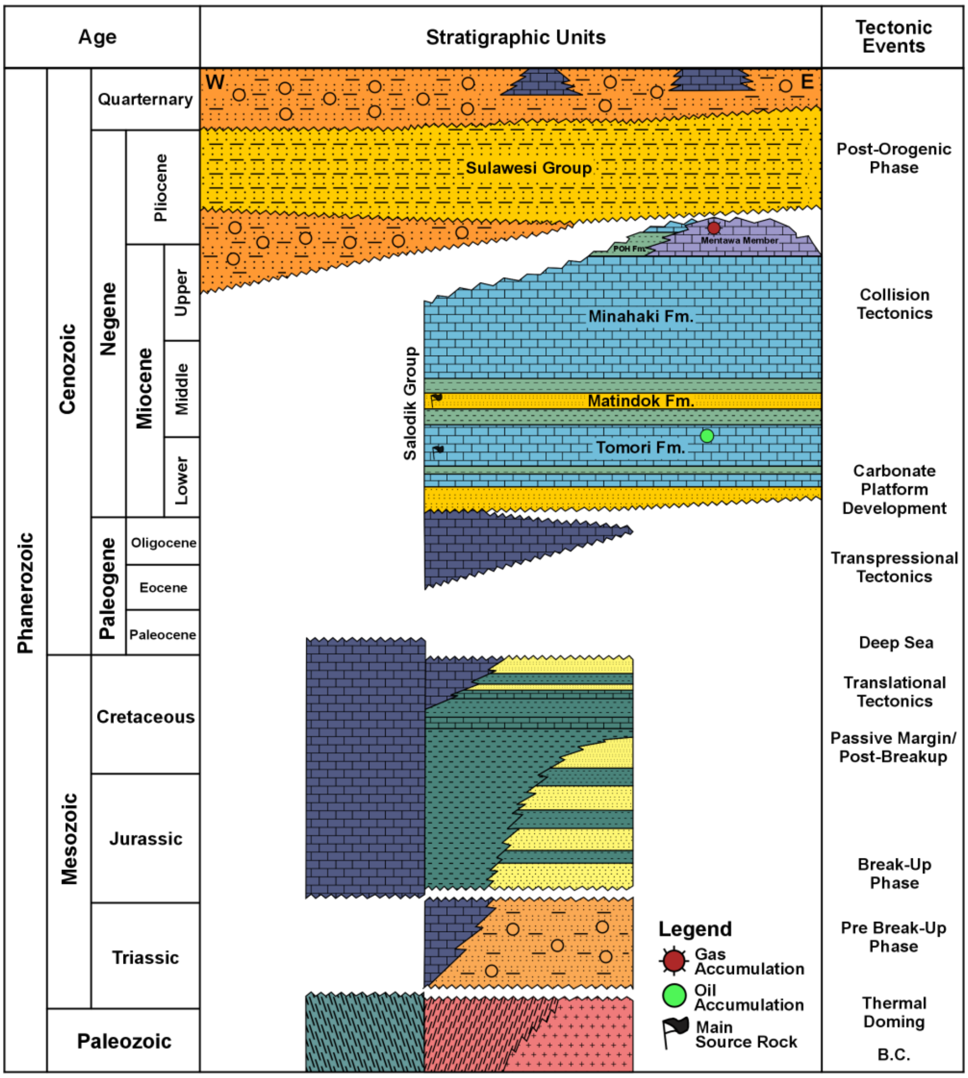


Figure 2. Generalized tectonostratigraphic column of the Banggai Basin, showing the Miocene Salodik Group as the primary carbonate succession (Compiled and modified from Advokaat & van Hinsbergen, 2024).

Data and Methods

The analytical workflow was conducted in three sequential stages using an integrated subsurface dataset from seven wells in the "DM" field (IUS-1 to IUS-7). The primary analysis was based on a 10-meter conventional core interval (2075.08–2084.20 m MD) from well IUS-1, which included visual core description, petrographic analysis of 11 thin sections, and supporting mineralogical and textural analysis using Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX) and X-Ray Diffraction (XRD). Carbonate rock classification followed the depositional texture framework of Dunham (1962), as modified by Embry & Klovan (1971). This framework was specifically chosen because it classifies rocks based on depositional texture, which directly reflects the energy conditions of the depositional environment. The Embry & Klovan (1971) modification is essential for this study to accurately classify coarse-grained and framework-supported reefal carbonates (Flügel, 2010). Subsequently, the identified lithofacies were grouped into genetically related facies associations, which then formed the basis for a field-wide spatial framework constructed through well-to-well correlation using AspenTech Geolog™ 14.2 software. The primary correlation datum was picked at the top of the Fore-Reef Slope (FA-2), a key lithofacies surface consistently identified across all wells.

To extrapolate these findings, electrofacies were identified from Gamma Ray (GR) log patterns and calibrated against the core- and cuttings-derived lithofacies. This calibration is a proven method that enabled the robust interpretation and mapping of facies belts across the entire study area (Khazaie et al., 2022). Finally, the resulting spatial distribution of facies associations was used to reconstruct the paleo-depositional environments. Based on the initial identification of high-energy, reef-derived facies in the core data, the classic rimmed carbonate platform model of Wilson was chosen as the primary analog framework, as it accounts for a distinct, high-energy margin, which is a feature not present in alternative models such as a carbonate ramp (as modified and presented in Flügel, 2010).

Results and Discussion

Carbonate Lithofacies

Four distinct lithofacies were identified within the Minahaki Formation in the study area (Figure 3). These are distinguished by their texture, grain composition, and diagenetic features.

Bioclastic Coralline Floatstone (BCF)

Observed in 4 of the 11 thin sections analyzed, this facies is characterized by a mud-supported texture containing a significant volume of large, visibly abraded coral fragments (ranging from 8% to 18%). Fragment size, measured petrographically, ranges up to 7.5 cm. These fragments appeared to float within a fine-grained carbonate mud matrix (13–17%). Other bioclasts form a diverse accessory assemblage, including various types of foraminifera, red and green algae, echinoderms, and mollusks (Figure 3a). The total visual porosity for this facies is moderate, ranging from 10.5% to 14.0%, and is predominantly composed of fabric-selective moldic porosity (3–9%), including honeycomb textures from dissolved coral frameworks, and non-fabric selective vuggy porosity (3.5–4%), with minor contributions from microfracture, intercrystalline, and pint-point pores. The textural characteristics, particularly the poor sorting, the chaotic orientation of fragments, and the mixture of coarse skeletal debris in a fine matrix, were indicative of deposition by high-energy, short-duration events such as debris flows (Flügel, 2010). This lithofacies corresponds well with Standard Microfacies Type 5 (SMF 5), which represents allochthonous bioclastic floatstones containing reef-derived biota deposited on slopes (Flügel, 2010). The occurrence of such deposits is consistent with observations in analogous Miocene buildups within the Banggai Basin, where facies comprising coral-algal fragments are developed adjacent to reefal buildups in the Senoro Field (Rahadian et al., 2018) and are considered part of the fore-reef slope system (Muhammad et al., 2020). This facies generally exhibits good reservoir quality, with routine core analysis measuring porosity values of 18–29% and horizontal permeabilities ranging from 4 to 63 mD.

Dolomitic Algae Bioclastic Packstone (DABP)

Observed in one of the 11 thin sections analyzed, this facies is characterized by a grain-supported texture with a low mud matrix content (approximately 10%). Its dominant allochems are reef-derived algal fragments (>10%), accompanied by coral debris and a diverse assemblage of other bioclasts (Figure 3b). The facies has undergone significant dolomitization, estimated at ~13% based on petrographic point counting, which imparted a sucrosic texture. The total visual porosity is approximately 13.5%, comprising a mix of vuggy (5%), moldic (4.5%), and intercrystalline (2%) pores. The grain-supported fabric, combined with the presence of coarse reef-derived bioclasts, is indicative of deposition from high-concentration sediment gravity flows originating from a nearby carbonate factory, likely on a proximal slope setting (Flügel, 2010; Hasanusi et al., 2012; Pratama et al., 2020). This lithofacies corresponds well with SMF 5, which represents allochthonous bioclastic packstones or grainstones deposited on a proximal slope setting (Flügel, 2010). This interpretation is consistent with the description of similar reef-associated facies in the analogous Senoro Field, where they are described as having excellent reservoir quality (Rahadian et al., 2018). This claim is substantiated by routine core analysis data from this facies, which measured a porosity of 24.5% and a permeability of 52 mD.

Argillaceous Dolomitic Foraminifers Bioclastic Wackestone (ADFW)

Observed in 2 of the 11 thin sections analyzed, this facies is characterized by a mud-supported wackestone texture with an abundant matrix (26%) that is notably argillaceous. The presence of detrital clay was identified petrographically and later quantified at 3–4% by XRD analysis. The grain assemblage is dominated by foraminifera (>10%), comprising a mix of planktonic, small benthic, and large benthic forms (Figure 3c). Notably, the abundance of planktonic forms is 1.5 to 3 times greater than that of large benthic foraminifera. This high ratio indicates a setting distal from the shallow-water environments where large benthic foraminifera typically thrive (Flügel, 2010; Pratama et al., 2020). The fine-grained, mud-dominated texture, combined with suspended clays and the significant presence of planktonic foraminifera, indicated deposition from suspension in a low-energy, open marine setting. This interpretation aligns with Standard Microfacies Type 3 (SMF 3), which represents a pelagic wackestone with planktonic microfossils characteristic of basinal and deep shelf environments below the storm wave base (Flügel, 2010). This finding is consistent with regional descriptions of the wider Minahaki Formation as a "foraminifera-rich wackestone with an argillaceous matrix" (Laya et al., 2022), however, this study further specifies that the high ratio of planktonic to large benthic foraminifera is a key indicator of a direct connection to the open sea. This facies exhibits moderate reservoir quality, with routine core analysis measuring porosity values of 18–22% and permeabilities ranging from 3 to 7 mD.

Bioclastic Wackestone (BW)

Observed in 4 of the 11 thin sections analyzed, this facies is characterized by a mud-supported wackestone texture with a variable matrix content (6–20%). Its constituent grains are composed of highly abraded, undifferentiated bioclasts, foraminifera, and fine coral debris (Figure 3d). The combination of highly abraded grains within a mud-supported fabric suggests deposition via textural inversion, a process involving the transport of reworked material from a higher-energy zone into a low-energy depositional setting, typically by storms or sediment gravity flows (Flügel, 2010). This lithofacies corresponds well with Standard Microfacies Type 10 (SMF 10), which describes bioclastic wackestones with worn skeletal grains characteristic of toe-of-slope or deeper shelf environments (Flügel, 2010). The occurrence of such reworked wackestones is consistent with the broader understanding of the Minahaki platform carbonates (Hasanusi et al., 2012; Rahadian et al., 2018). This facies exhibits variable reservoir quality, with routine core analysis measuring porosity values of 16–29% and permeabilities ranging from 5 to 27 mD.

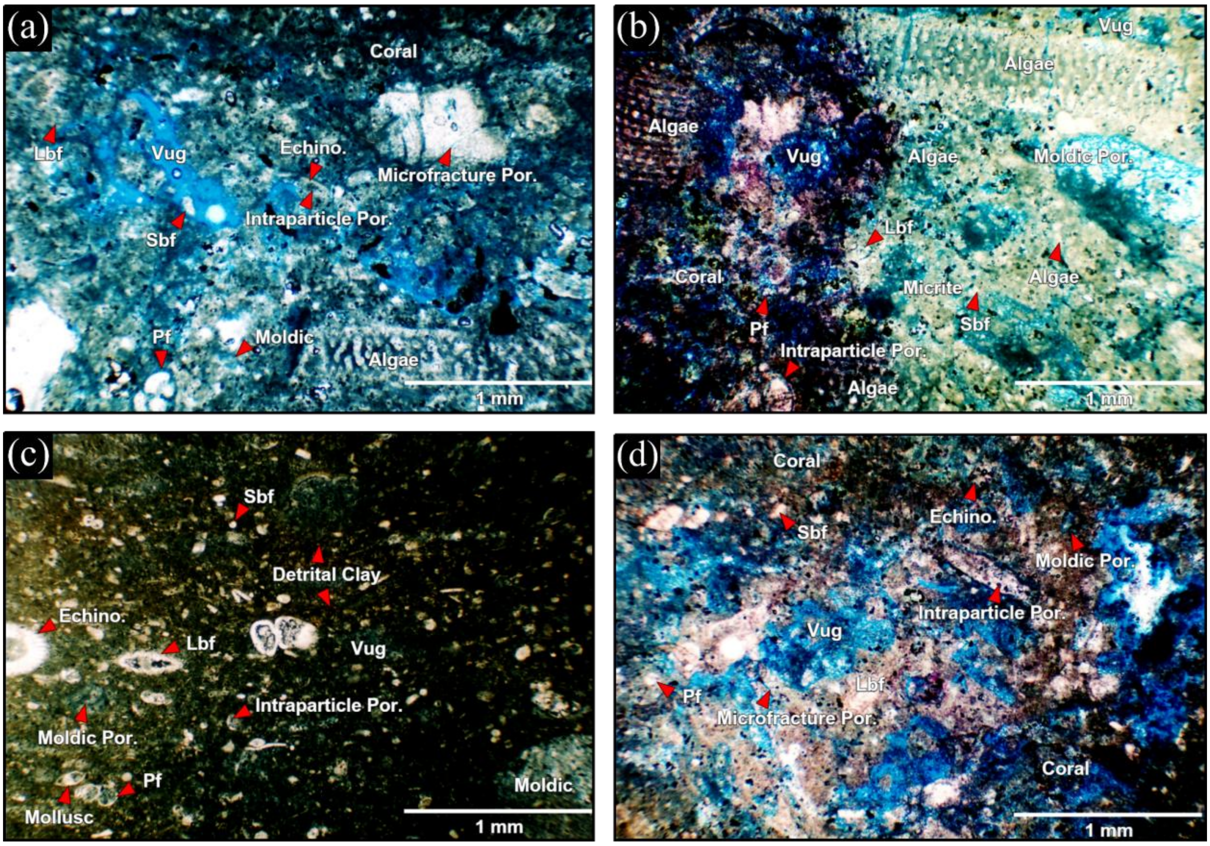


Figure 3. Photomicrographs of the four identified lithofacies from the Minahaki Formation in well IUS-1 (plane-polarized light). Samples were stained with Alizarin Red S to differentiate calcite and impregnated with blue-dyed epoxy to highlight porosity. (a) Bioclastic Coralline Floatstone (BCF). (b) Dolomitic Algae Bioclastic Packstone (DABP). (c) Argillaceous Dolomitic Foraminifers Bioclastic Wackestone (ADFW). (d) Bioclastic Wackestone (BW). Abbreviations are as follows: Lbf = Large Benthic Foraminifera; Sbf = Small Benthic Foraminifera; Pf = Planktonic Foraminifera; Echino = Echinoderm fragment; Vug = Vuggy Porosity.

Facies Associations and Depositional Environment

The four lithofacies are grouped into two associations (Figure 4), each representing a specific depositional environment within a carbonate platform system.

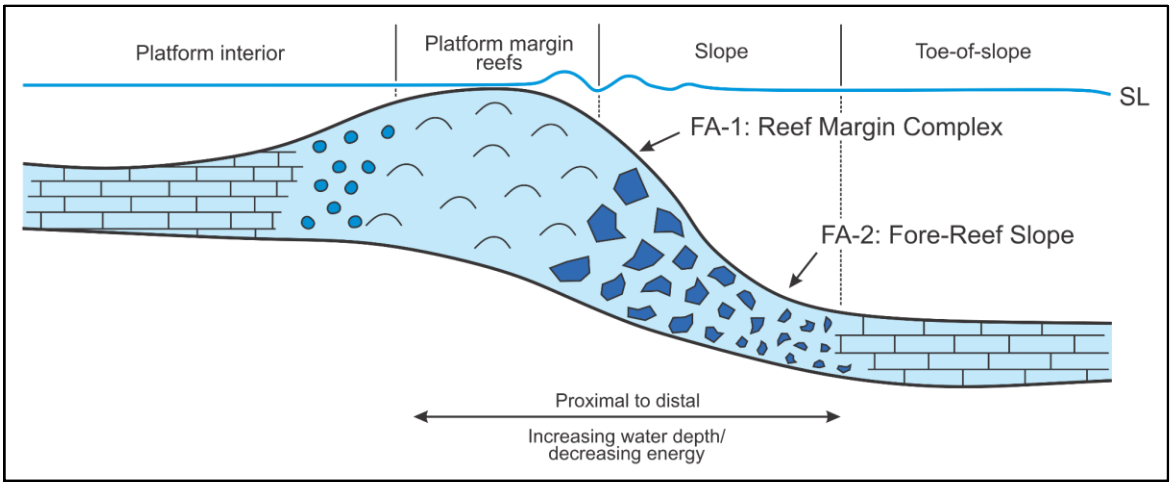


Figure 4. Schematic diagram showing the interpreted proximal position of Facies Association 1 (FA-1: Reef Margin Complex) near the platform margin (FZ 5) and upper slope, transitioning distally to Facies Association 2 (FA-2: Fore-Reef Slope) on the main slope (FZ 4) of a standard carbonate platform profile. (Model modified from the original of Wilson, as presented in Flügel, 2010).

- Facies Association 1 (FA-1): Reef Margin Complex

This association, comprising the Dolomitic Algae Bioclastic Packstone (DABP) and Bioclastic Coralline Floatstone (BCF) lithofacies, was interpreted as the high-energy reef margin complex that formed the pronounced outer edge of the platform. This interpretation is strongly supported by its characteristic low GR response, typically displaying a cylindrical (blocky) pattern with internal serrations (mean GR of ~39.4 ± 6.8 API, ranging from ~30 to 52 API based on 5-95 percentiles) (Figure 5). This low GR signature is consistent with the clean nature of carbonate debris accumulation, indicating minimal clay content. The DABP lithofacies and BCF lithofacies collectively represent the proximal fore-reef slope (talus) environment, with DABP likely forming coarser, more grain-supported accumulations closer to the reef crest. This environmental setting corresponds to the platform margin (FZ 5; Figure 8), typically found in shallow water depths of a few meters (e.g., 0-10 m), and the adjacent upper slope (FZ 4), which extends seaward below the margin (Flügel, 2010).

This interpretation of a distinct, high-energy reef margin complex is in strong agreement with several studies of the Miocene carbonates in the Banggai Basin. Rahadian et al. (2018) described a comparable "reefal build-up facies" in the Senoro field, characterized by grainstones and floatstones with abundant coral growth, which they distinguished from a separate, muddier platform facies. Similarly, Hasanusi et al. (2012) identified a "pinnacle reef build up type" as a key reservoir unit in the same area. The interpretation of the debris component (BCF) as a fore-reef talus deposit also aligns with the findings of Muhammad et al. (2020), who identified a distinct fore-reef system in their study of the Banggai Basin carbonates.

- Facies Association 2 (FA-2): Fore-Reef Slope

This association, consisting of the ADFW and BW lithofacies, was interpreted as the lower-energy, deeper-water fore-reef slope environment (corresponding to FZ 4), situated seaward of the reef margin complex (Figure 4). This association is characterized by a higher and more variable GR response compared to FA-1, typically exhibiting a bell-shaped log pattern (mean GR of ~49.8 ± 10.6 API, ranging from ~35 to 69 API based on 5-95 percentiles) (Figure 5). This higher GR signature reflects the greater proportion of carbonate mud and argillaceous material consistent with a lower-energy, more distal setting. The combination of these two mud-supported lithofacies represents a transition within the slope: the BW lithofacies, with its highly abraded bioclasts, suggests deposition on a middle slope environment receiving reworked skeletal debris, while the ADFW lithofacies indicates a more distal, lower-slope setting influenced by open-marine conditions. This distinction is supported by foraminiferal assemblages: the ADFW facies shows a significantly higher ratio of planktonic to large benthic foraminifera (1.5:1 to 3:1) compared to the BW facies (0.5:1 to 1.5:1), indicating increasing open-marine influence downslope. According to Flügel (2010), the slope environment (FZ 4) typically extends below the platform margin (FZ 5) and is characteristically composed of reworked platform material mixed with fine-grained pelagic components, consistent with the lithologies observed in this association.

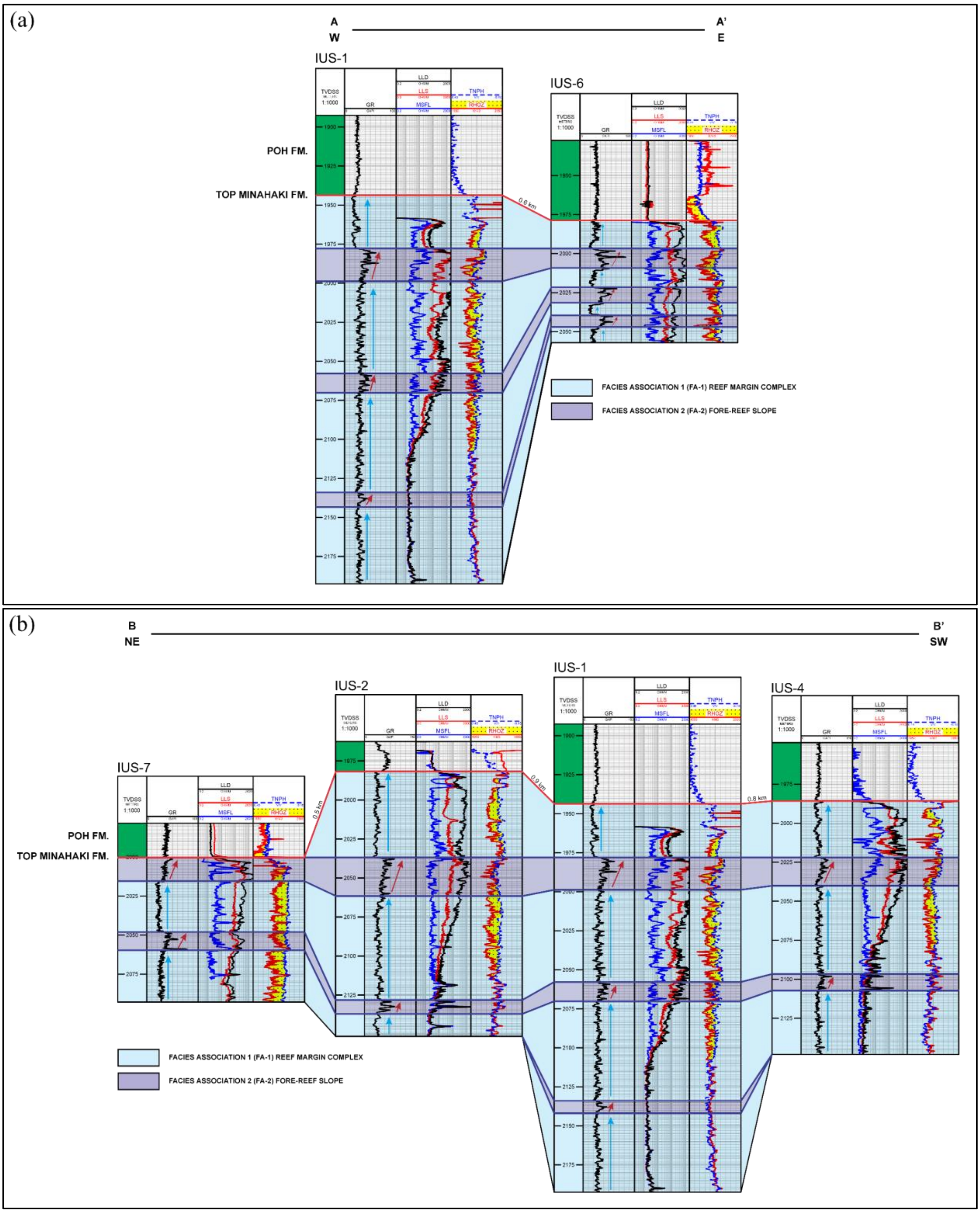
The interpretation of this association as a fore-reef slope environment is also well-supported by regional analogues. Pratama et al. (2020) specifically documented a slope environment in the Senoro Field that included "planktonic foraminifera wackestone and packstone", providing a direct lithological match for the ADFW facies. Furthermore, the overall muddy character of this association is consistent with the lower energy "platform facies" described by Rahadian et al. (2018) as being distinct from the high-energy reefal buildup in the Senoro Field.

- Depositional Model Synthesis

The spatial distribution of the previously defined facies associations was mapped through well-to-well correlation, integrating the petrographic data with calibrated electrofacies patterns from GR logs. The analysis revealed a predictable relationship between the facies associations and their log responses. Facies Association 1 (Reef Margin Complex) consistently showed a low GR response with a cylindrical (blocky) to serrated log pattern, characteristic of relatively clean, thick-bedded carbonate debris. In contrast, Facies Association 2 (Fore-Reef Slope) exhibited a higher and more variable GR response with a bell-shaped pattern, reflecting its greater content of carbonate mud and argillaceous material (Tiab & Donaldson, 2024).

The well-correlation cross-sections revealed a distinct and predictable depositional gradient across the “DM” field (Figure 5). The dip-oriented section (Figure 5a) illustrates a clear west-to-east transition: thick packages of the Reef Margin Complex (FA-1) with minor intercalations of FA-2 dominate the western wells, thinning eastward where they increasingly interfinger with and are ultimately replaced by the Fore-Reef Slope (FA-2) as the predominant facies association. The strike-oriented sections (Figure 5b; Figure 5c) confirm the lateral continuity of these depositional belts along the platform margin. The field's overall structure is presented in Figure 6. The interpreted spatial distribution of these facies associations across the structure is summarized in Figure 7, illustrating FA-1 forming the core of the structural high, transitioning eastward into FA-2.

This documented spatial relationship provides strong evidence for a rimmed carbonate platform architecture (Figure 8), consistent with the classic depositional model originally proposed by Wilson (as described in Flügel, 2010). Based on regional context and previous studies suggesting isolated platform growth in the area (e.g., Muhammad et al., 2020), this rimmed platform is interpreted as an unattached (isolated) build-up. This interpretation differs from the carbonate ramp model that has been proposed for the Minahaki Formation in other parts of the Banggai Basin (e.g., Laya et al., 2022). A ramp model is defined by a gently sloping profile lacking a distinct high-energy shelf-edge barrier. However, the data from the "DM" field, specifically the presence of a well-defined, high-energy Reef Margin Complex (FA-1) and its associated coarse talus deposits (BCF lithofacies), clearly indicates a significant topographic break, or shelf-margin break. This feature is the primary diagnostic criterion for a rimmed platform and is not characteristic of a ramp profile (Flügel, 2010). Therefore, while a ramp architecture may exist elsewhere, the depositional system in the "DM" field is more accurately represented by a rimmed platform model.



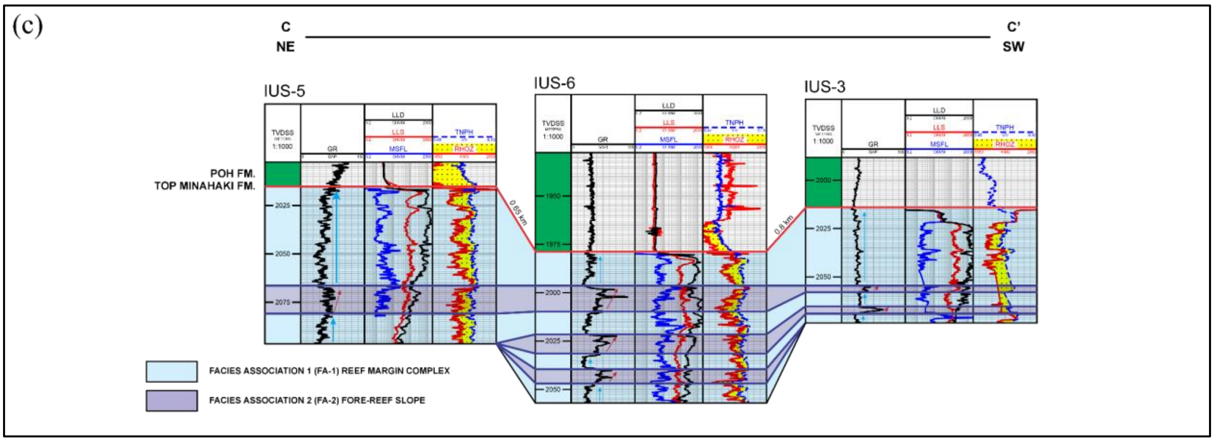


Figure 5. Well-to-Well Correlation Cross-Sections of the Minahaki Formation. The panels illustrate the spatial distribution of the primary facies associations across the "DM" field. The primary correlation datum corresponds to the top of the Fore-Reef Slope (FA-2) to visually emphasize the depositional relief of the reefal buildup. The legend defines the Reef Margin Complex (FA-1) and the Fore-Reef Slope (FA-2). Log trends are indicated by arrows on the Gamma Ray (GR) track. See Figure 6 for section locations. Vertical scale is indicated on well logs; horizontal distances between wells are shown numerically.

(a) Dip-oriented Section A-A' (W-E) illustrating the eastward transition from thick FA-1 successions with minor FA-2 intercalations in the west to thinner, interfingering FA-1 layers within the increasingly predominant FA-2 toward the east.
(b) Strike-oriented Section B-B' (NE-SW) illustrating the lateral continuity and correlation of both FA-1 and FA-2 in the western part of the field.
(c) Strike-oriented Section C-C' (NE-SW) illustrating the lateral continuity and correlation of both FA-1 and FA-2 in the eastern part of the field.

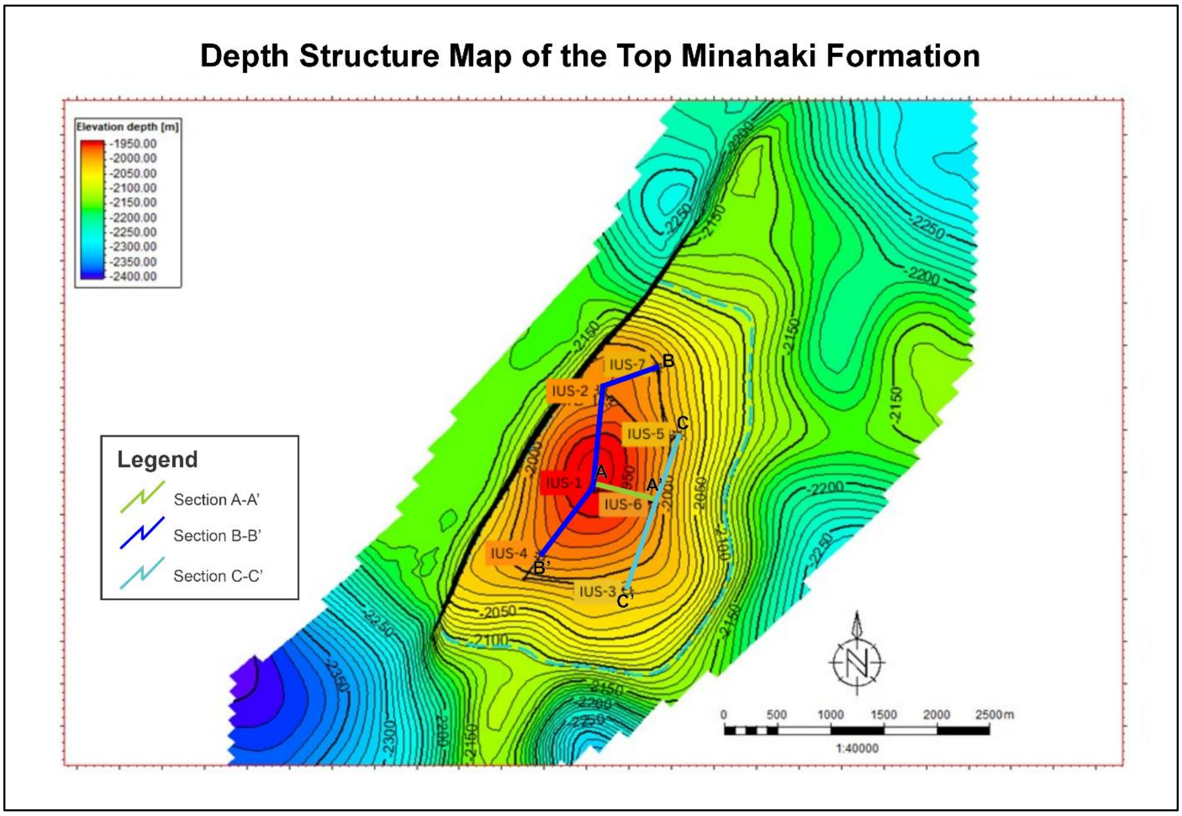


Figure 6. Depth Structure Map of the Top Minahaki Formation in the "DM" field showing well locations (IUS-1 to IUS-7) and structural contours (in meters subsea). This map serves as the base for the facies distribution interpretation in Figure 7.

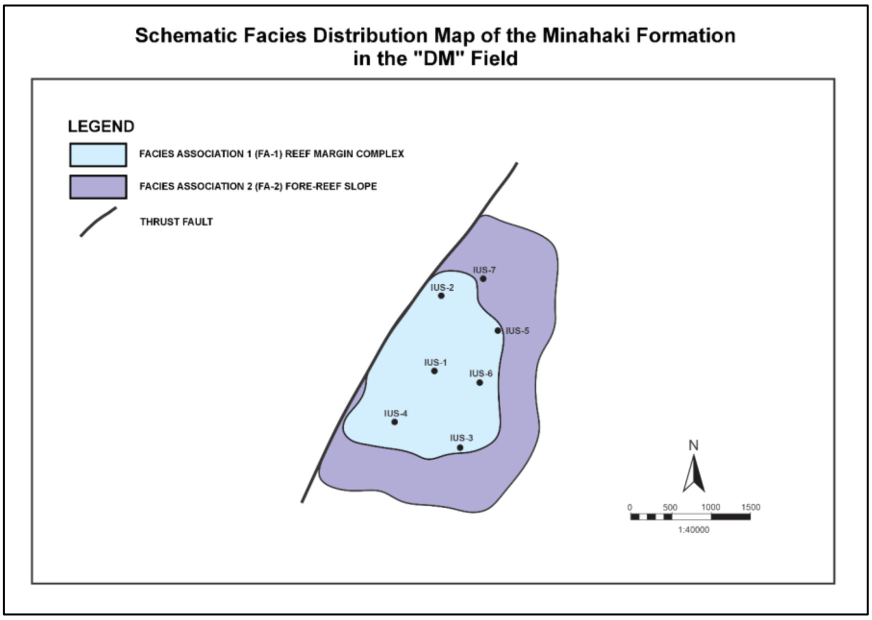


Figure 7. Schematic Facies Distribution Map of the Minahaki Formation in the "DM" Field, overlaid on the Top Minahaki depth-structure contours (from Figure 6). The map illustrates the interpreted distribution of Facies Association 1 (FA-1: Reef Margin Complex, blue) predominantly on the structural crest, transitioning to Facies Association 2 (FA-2: Fore-Reef Slope, purple) on the flanks and distal areas.

Despite the robust interpretation of a rimmed carbonate platform, it is important to acknowledge the inherent limitations of the well-based dataset in constraining the full extent of the depositional system. The stratigraphic penetrations in the "DM" field are predominantly concentrated within the platform margin (FA-1) and fore-reef slope (FA-2) environments. As a result, facies associated with the shallower platform interior (e.g., lagoonal or back-reef settings) were not intersected in the studied wells. This restricts direct observations of the depositional system to its outermost portions, thereby limiting a comprehensive characterization of the platform's areal extent and internal proximal facies variability.

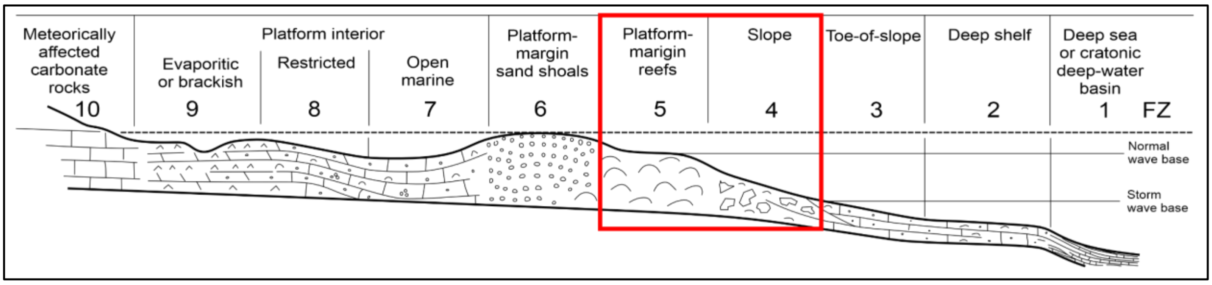


Figure 8. Conceptual depositional model of a rimmed carbonate platform, illustrating the distribution of standard facies zones (FZ). The model shows the typical environmental belts from the shallow platform interior to the deep basin. The facies associations identified in this study correspond directly to this profile: the Reef Margin Complex (FA-1) represents the platform margin (FZ 5), while the Fore-Reef Slope (FA-2) represents the adjacent slope environment (FZ 4). The red box highlights these key environments that define the depositional system in the "DM" field. (Model modified from the original of Wilson, as presented in Flügel, 2010).

This depositional model directly explains the observed reservoir heterogeneity across the field. The highest-quality reservoir properties are predicted to be concentrated within the Reef Margin Complex (FA-1) in the western part of the field (average porosity ≈ 24%, average permeability ≈ 33 mD). In contrast, the muddier, fine-grained lithologies of the Fore-Reef Slope (FA-2) exhibit lower overall permeability (average porosity ≈ 20%, average permeability ≈ 11 mD).

Conclusion

This study characterized the carbonate facies of the Miocene Minahaki Formation in the "DM" field and reconstructed its depositional architecture. Four main lithofacies were identified (DABP, BCF, ADFW, BW) and grouped into two distinct associations: a high-energy Reef Margin Complex (FA-1) and a lower-energy, deeper-water Fore-Reef Slope (FA-2). The spatial correlation of these associations revealed a clear proximal-to-distal environmental gradient from west to east. The depositional architecture of the Minahaki Formation in the study area was interpreted as a rimmed carbonate platform, supported by the observed high-energy, blocky GR responses of FA-1 at the structural high, transitioning to bell-shaped GR responses of FA-2 on the flanks. This model explained the observed reservoir heterogeneity, concluding that higher-quality reservoir bodies are concentrated within the single reefal buildup in the western part of the field, which is composed of the coarse-grained Reef Margin Complex (FA-1) (average porosity ≈ 24%, average permeability ≈ 33 mD). In contrast, the muddier, fine-grained Fore-Reef Slope (FA-2) exhibits lower reservoir quality (average porosity ≈ 20%, average permeability ≈ 11 mD). This finding provides a direct, geology-based predictive tool for optimizing future drilling activities within the "DM" field and offers valuable insights for exploration and development of similar carbonate plays in the Banggai Basin and broader Southeast Asian region. This research highlights the value of integrated facies analysis in building predictive depositional models for complex carbonate reservoirs and provides a specific, field-scale refinement to the regional understanding of the Banggai Basin.

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Author Contribution

Ival Umar Sayaf was responsible for the study's conceptualization, methodology, formal analysis, and investigation. He also carried out data curation, prepared the visualizations, and wrote the original draft of the manuscript. Vijaya Isnaniawardhani and Budi Muljana provided supervision, validated the results, and contributed to the review and editing of the manuscript. Wingky Suganda supplied essential resources for the project and assisted with supervision and validation.

Conflict of Interest

The authors declare that they have no conflicts of interest relevant to the content of this publication.

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