SEDIMENTOLOGY OF THE UPPER MERAWU FORMATION, CIKADU AREA, NORTH SERAYU RANGE, CENTRAL JAVA: IMPLICATION FOR TECTONIC ACTIVITY AND HYDROCARBON EXPLORATION

Gentur Waluyo*, Akhmad Khahlil Gibran, Yogi Adi Prasetya, Ryan Dwi Wahyu Ardi, Muhammad Askar Sabiq Abdul Rosyid
Geological Engineering Department, Faculty of Engineering, Universitas Jenderal Soedirman, Purbalingga, Indonesia

*Email: gentur.waluyo@unsoed.ac.id

Abstract. The Upper Merawu Formation in the Cikadu area of the North Serayu Range, Central Java, presents a complex geological and sedimentological framework shaped by tectonic and sedimentary processes. This study aims to analyze the stratigraphy, lithofacies, and depositional environments of the Upper Merawu Formation through detailed geological mapping, lithofacies analysis, and micropaleontological examination. The Upper Merawu Formation is composed primarily of alternating sequences of shale, fine-grained sandstone, and tuffaceous sandstones, with distinct sedimentary structures including parallel laminations, cross-stratifications, and hummocky cross-stratification. These lithofacies indicate deposition in a marine setting ranging from distal shelf to shoreface environments. Thrust faults and folds dominate the region's structural geology, consistent with regional tectonic activity. This research provides new insights into the sedimentation and tectonic history of the North Serayu Range, suggesting significant tectonic influence during the Miocene to Pliocene period. These findings contribute to the broader understanding of the depositional systems within the Serayu Basin, with implications for hydrocarbon exploration in the region.

Keywords: upper merawu formation, sedimentology, tectonic activity, hydrocarbon exploration, north serayu range

A. Introduction

Merawu Formation is one of lithological formations in North Serayu Basin which could be classified further into two members, sandstone member and claystone member which consists of claystone, siltstone, and fine sandstone intercalation [1]. Previous studies suggested that Merawu Formation was deposited during the Early to Late Miocene through turbidite mechanism in deep marine fan environments [2–5]. In this case, some studies also suggested that Merawu Formation was formed in a tidal flat environment, particularly sand flat and mud flat with a north-originated sediment source [1,6,7]. Furthermore, the Merawu Formation was still deposited until the Pliocene hence the upper part of of Merawu Formation in the middle part of Serayu Basin may interfinger with the lower part of the Penyatan Formation which aged Middle–Late Miocene [7,8]. Merayu Formation is also known as Rambatan Formation according to older studies [9,10]. The unclear stratigraphic relation between this formation and other formations, including inconsistent naming of regional lithological formation, different opinions in depositional age and environment [1,3,11–13] (Figure 1).

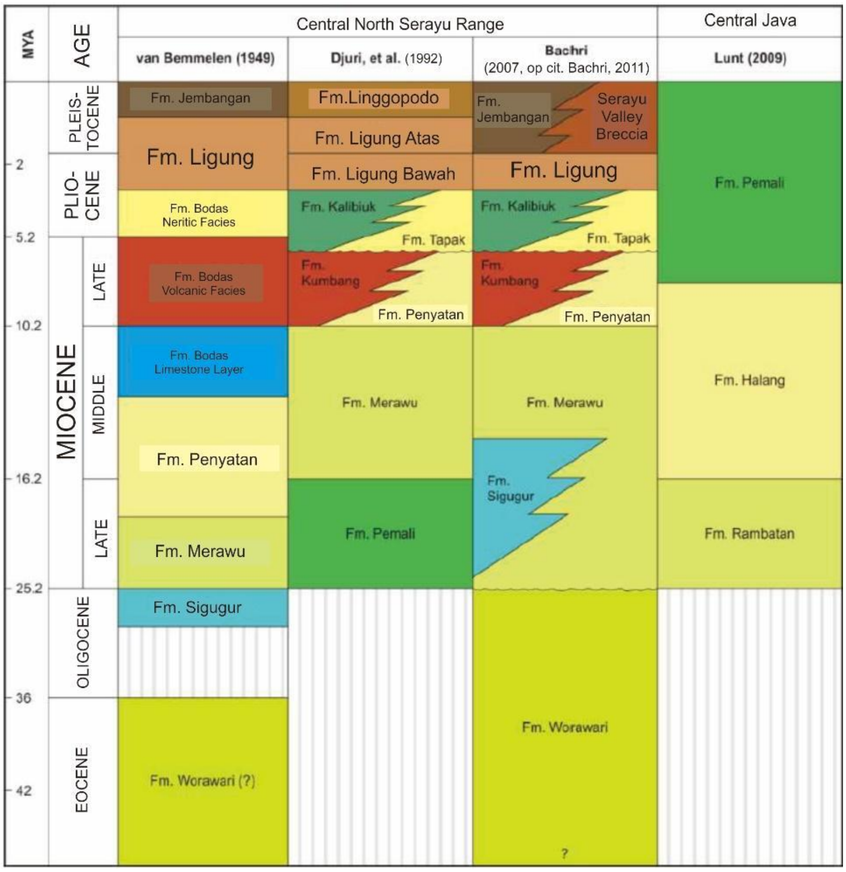

Figure 1. Regional stratigraphy of the North Serayu Mountains and its surroundings as studied by previous researchers [1,5,10,12].

North Serayu Basin is one of the Tertiary sedimentary basins in Central Java which physiographically belongs to the North Serayu Range physiographic zone [5]. Hydrocarbon potential in North Serayu Basin is hinted by oil and gas seepages discovered on the surface, indicating the presence of mature source rocks and migrated hydrocarbons. Those hydrocarbon seepages are detected in multiple locations within North Serayu Basin, including Banjarnegara, Brebes, Pemalang, and Pekalongan area, all within the Neogene lithological formations [4,14–16]. Previous investigations of source rock potential in the North Serayu Basin have identified numerous Neogene lithological formations that have a high potential as source rocks in this basin, such as the Merawu Formation. [16–19].

The study area is situated in Cikadu Village and its surroundings, Watukumpul District, Pemalang Regency, ~68 km northeast of Purbalingga Regency and ~29 km south of Pekalongan City (Figure 2). This study aims to analyze the stratigraphy, lithofacies, and depositional environments of the Upper Merawu Formation, and their implications for tectonic activity and hydrocarbon exploration.

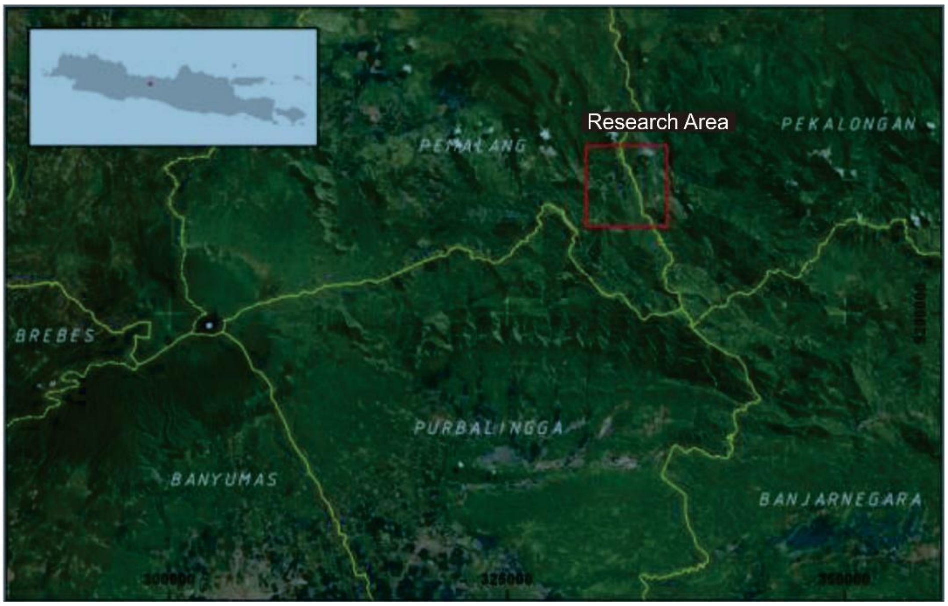

Figure 2. Research location, situated in the Watukumpul area, close to the border between Pemalang Regency and Pekalongan Regency.

B. Methods

This study was conducted through geological mapping, measuring section, and laboratory-studio analysis. Geological mapping was done by field observation and data collection including distribution and relationships of rock units (stratigraphy) and geological structure in the rock outcrops in the study area. Observations and descriptions of lithology, as well as measurements of the positions of geological structural elements at observation points where the presence of contacts between rock units and geological structural features were anticipated, were aided by the interpretation of topographic maps, regional geological maps, satellite imagery, and literature studies.

Measuring section is a method for determining the sequence of layering and the thickness of rocks along the observation path. The observation path is chosen based on the slope conditions of the outcrops and their vertical stratigraphic sequence (way-up stratigraphy) [20]. Measuring section was conducted to understand the lithology and stratigraphic sequence in detail, and to determine the thickness, geometry, texture, and structure of the rocks in the layers along the observation path.

Laboratory-studio analysis in this study consists of facies, structural geology, and micropaleontological analysis. Facies analysis was done by processing and analyzing the results of lithological analysis of outcrop observations into several lithofacies based on differences in physical characteristics (lithology, texture, and sediment structure). Structural geology analysis was conducted by combining the results of interpretations from satellite imagery and topographic maps with the results of structural geology elements measurement, which include planar structures (strike and dip, joints, slicken-sides, fault planes, minor folds) as well as linear features (lineations and striations) from field observation. Micropaleontological analysis was performed by determining foraminiferal species found on prepared rock samples using a binocular stereo microscope.

C. Results And Discussion

1. Stratigraphy of Cikadu Area and its surroundings

The rock units in the Cikadu area and its surroundings consist of sedimentary rocks, including shale and sandstone, and igneous rocks categorized as basalt. Based on stratigraphic principles, the stratigraphic relationship between the sedimentary rocks and the igneous rocks in the study area is a nonconformity. Based on the Indonesian Stratigraphic Code, the stratigraphy in the study area is divided into two lithostratigraphic units, namely the Shale Unit and the Sandstone Unit, also one lithodemic unit, the Basalt Lava (Figure 3).

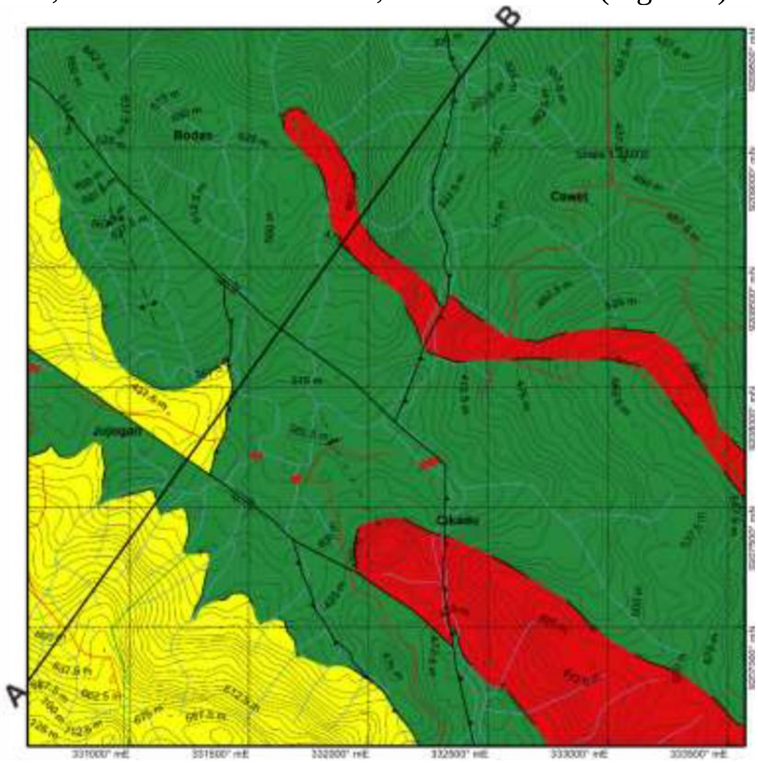

Figure 3. The geological map of the Cikadu area and its surroundings shows three lithological units: the Shale Unit (green), Basalt Lava (red), and Sandstone Unit (yellow).

Shale Unit consists of repetition of shale-siltstone, and carbonate sandstone with a coarsening-upward grain size pattern. The shale is dark gray, carbonaceous, with fissility structure and a thickness of 5-500 cm, interbedded with light gray siltstone laminations and thin layers with a thickness of 0.5–3 cm. The carbonate sandstone is light gray, with a grain size ranging from fine to coarse sand, featuring sub-rounded grains, good sorting, and tabular layer geometry with a thickness of 1–100 cm. In weathered conditions, reddish-brown oxide stains are present. The sedimentary structures present include parallel laminations, wavy cross-lamination, and hummocky cross-stratification, also deformation structures such as convolute lamination, slump, flame structure, and bioturbation (Figure 4). The stacking pattern in this unit is blocky, gradually transitioning to a coarsening-upward pattern, indicating a sedimentation trend that shifts from aggradation to progradation. Based on micropaleontological analysis using the presence of planktonic foraminifera taxa, this unit was deposited in the N11 N18 zone, equivalent to the Middle to Late Miocene [21]

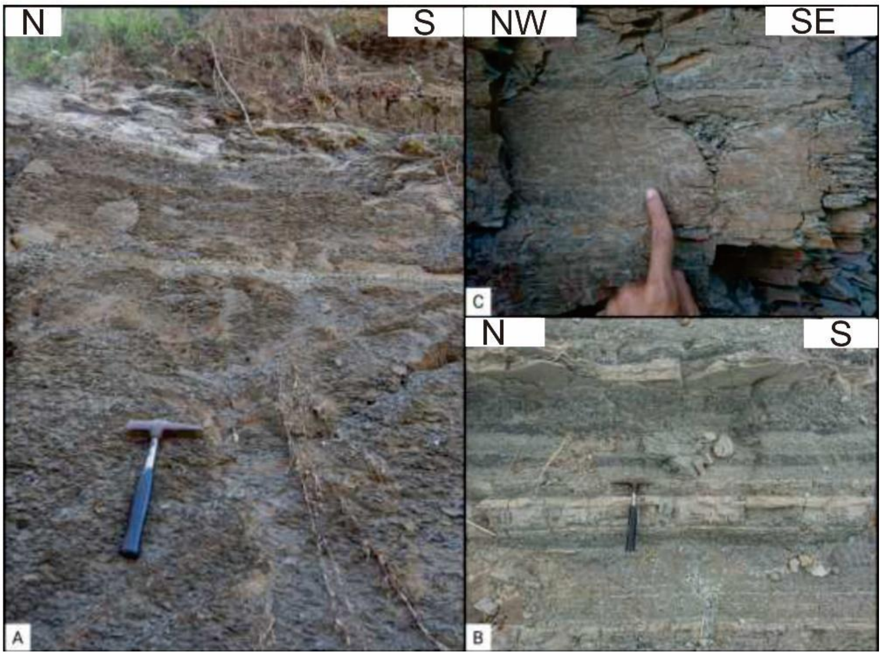

Figure 4. Outcrop features of the Shale Unit: (A) Fissility characteristics in the shale. (B) Lamination of mudstone in the shale. (C) Biogenic structures within the shale.

Basalt lava is gray, with mineral sizes that are inequigranular, a porphyritic-aphanitic texture, and phenocrysts consisting of plagioclase and pyroxene. The groundmass consists of plagioclase, pyroxene, and volcanic glass. The geometry of the basalt lava follows the layering of the Shale Unit, featuring a pillow lava structure (Figure 5). Based on the lateral and vertical distribution, the basalt lava interfingers with the Shale Unit, so the relative age of the unit follows that of the Shale Unit, which is Middle to Late Miocene.

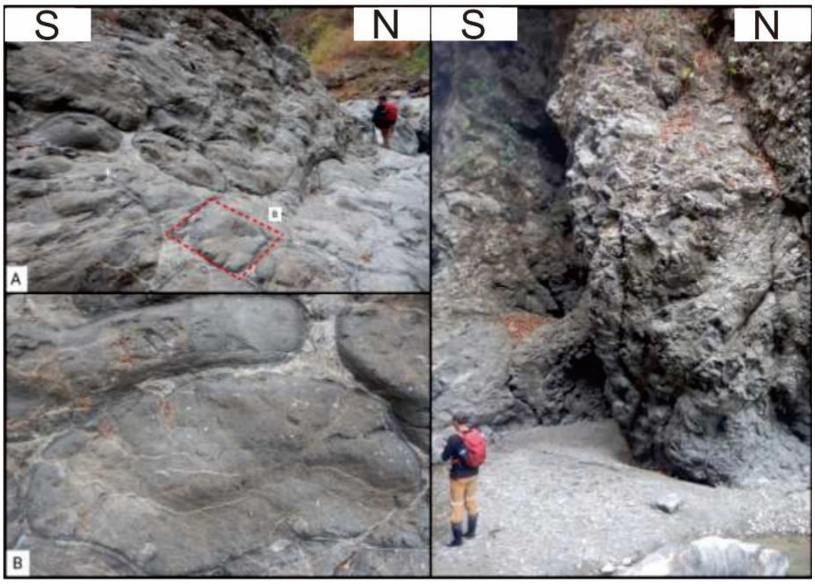

Figure 5. Outcrop features of the Basalt Unit: (A) and (B) are pillow lava structures, while (C) shows lava in a sheared condition.

The Sandstone Unit consists of medium to coarse sandstone with interbeds of breccia showing a coarsening-upward pattern at several locations. The sandstone is gray, with a grain size of medium to coarse sand, featuring sub-angular grains, fairly good sorting, and parallel laminations. Deformation structures such as convolute lamination, slump, and flame structures can be found in certain sections. At the base of this unit, there is a layer of monomictic breccia before the deposition of thick massive sandstone, exhibiting a thickening-upward stacking pattern and a coarsening-upward grain size pattern (Figure 6).

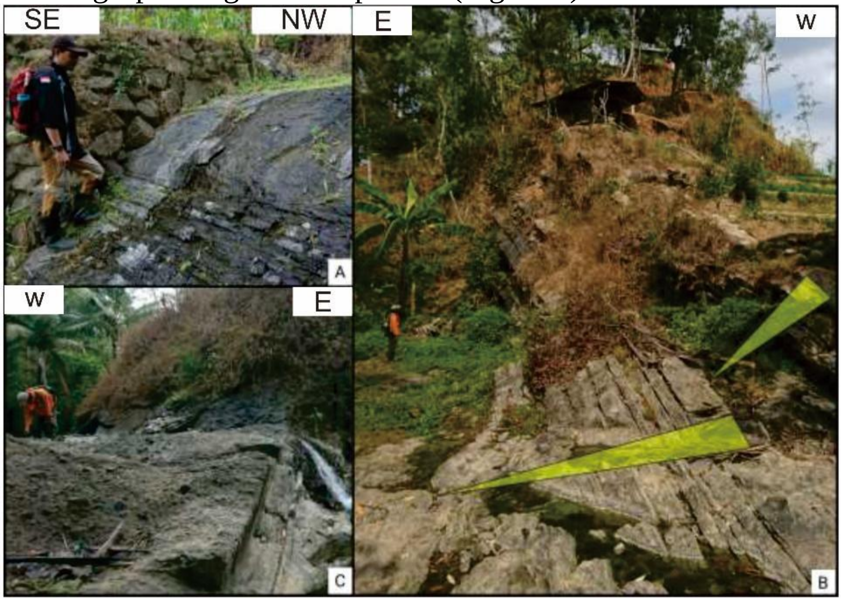

Figure 6. Outcrop features of the Sandstone Unit: (A) and (B) show sandstone layering with a coarsening-upward pattern, while (C) is a breccia layer at the lower part of the Sandstone Unit.

2. Structural Geology of Cikadu Area and its surroundings

Based on the observation of contrast in hue and tone along the valley and hill alignment from the processing of the hillshade digital elevation model (DEM) in the study area, there are two dominant alignment directions: NNW-SSE and NW-SE. These alignments correspond to the kinematic analysis results of structural planes (joints, shear joints, and fault planes) as well as line structures (lineations) in the study area, indicating the presence of fault and fold structures with three main directions: NW-SE, N-S, and WNW-ESE (Figure 7). Geological structures in the study area are divided into several faults and folds, including the Jojogan Right-Lateral Fault, the Kalikadu Right-Lateral Fault, the Polaga Left-Lateral Fault, the Kalikadu Anticline, and the Cikadu Syncline (Figure 8).

3. Lithofacies of the Upper Merawu Formation

Lithofacies analysis was done through field observation on the AS-01 section and AS-06 section, located in Kadu River. Section AS-06 passes through the contact between two rock formations in the study area, the Merawu Formation and the Penyatan Formation. The contact between those formations is situated at the upper boundary between the fine sandstone amalgamation facies (Sm) which belongs to the Shale Unit and the normal-graded breccia facies (Gm) which belongs to the Sandstone Unit The facies in both sections are comprised of lithologies like shale, fine-to-coarse limestone sandstone, sandy limestone, and breccia. Based on the facies coding [20], those facies can be divided further into ten facies.

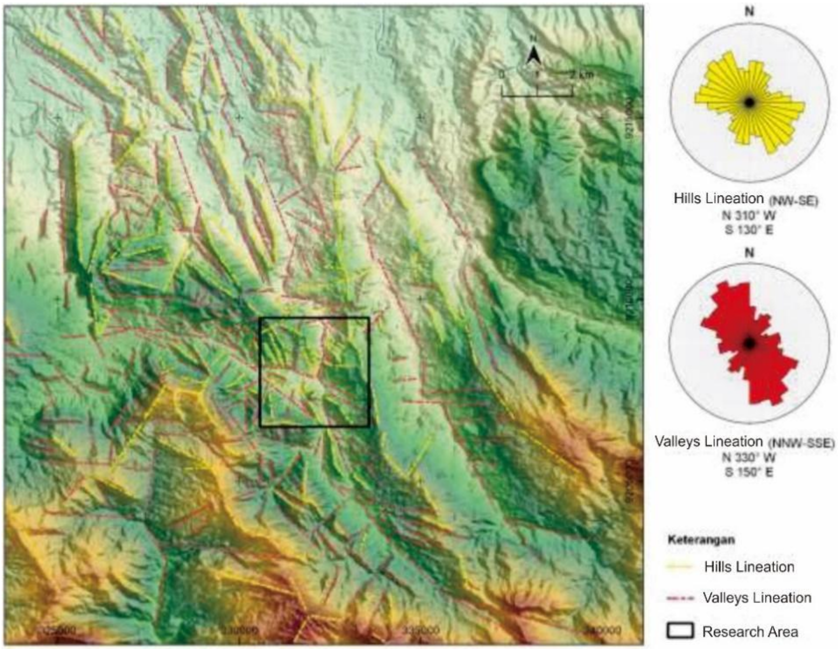

Figure 7. Lineament map of the study area. The inset map (black square) represents the Cikadu area and its surroundings.

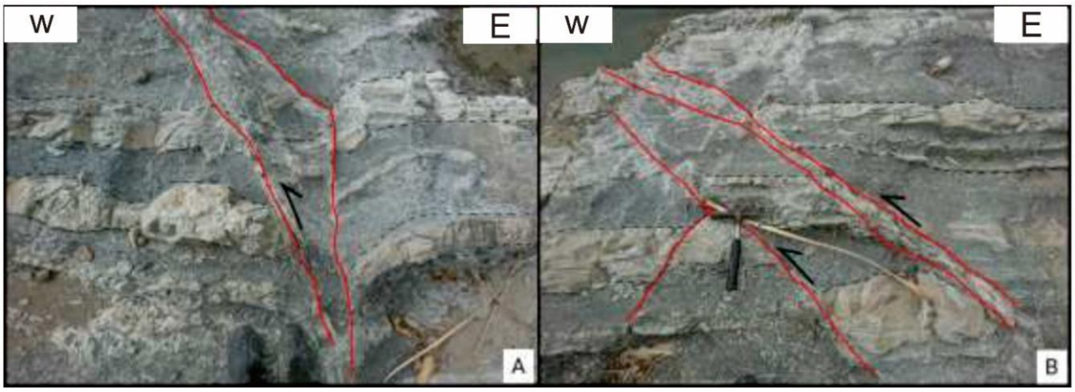

Figure 8. Fault offset on the Polaga Reverse Fault: (A) The presence of a reverse fault offset with an upward movement and a dip greater than 45° (reverse), and (B) a reverse fault offset with a Riedel shear pattern.

The shale facies (Fl) consist of shale interbedded with siltstone laminations, have a thickness of 1 200 cm, and alternate with all sandstone facies. The fine sandstone facies with parallel laminations (Sh) consist of very fine to fine-grained sandstone layers with a thickness of 1 50 cm and alternates with shale facies (Fl), exhibiting a sheet-like layer geometry. Fine sandstone facies with cross-lamination (Sl) are composed of very fine to fine sandstone layers, 1 70 cm thick, alternating with shale facies (Fl), and having a lenticular geometry characterized by the presence of erosional boundaries on the upper and lower parts of the layers. Wave ripple cross-laminated fine sandstone facies (Sr) consist of very fine to fine sandstone layers, 1 15 cm thick, alternating with shale facies (Fl), lenticular geometry was observed from the presence of erosional boundaries at the upper and lower parts of the layers. The fine-grained sandstone facies with hummocky cross-stratification (Sr2) consist of very fine to fine sandstone layers, 5 25 cm thick, alternating with shale facies (Fl) tabular and sheet-like layer geometry, and the presence of gentle erosion marks (undulation) in each sandstone set.

The amalgamated fine sandstone facies (Sm) consist of fine to medium sandstone layers with a thickness of 50 cm, interbedded with shale facies (Fl), serve as a marker for the initial change in the stacking pattern of subsequent layers, amalgamated layer geometry characterized by stacked sandstone layers not separated by claystone/mud drape laminations, and erosion marks in the form of gutter casts are present at the bottom of the layers. The convolute laminated fine sandstone facies (Sh2) consist of very fine to fine sandstone layers with a thickness of 1 70 cm, alternating with shale facies (Fl), lenticular layer geometry, characterized by the presence of erosional boundaries at the top and bottom of the layers. The fine sandstone slump facies consist of very fine to fine sandstone layers with a thickness of 1 70 cm, alternating with shale facies (Fl), tabular layer geometry, and deformation structures in the form of slumps (some of them have a S fold-like shape) are present. The wackestone facies consist of fine to very fine-grained clastic limestone layers with a thickness of 1 50 cm, alternating with shale facies (Fl), tabular layer geometry with an erosional boundary at the base, and the presence of *Glossifungites* trace fossils and vertical bioturbation. The normal-graded breccia facies (Gm) consist of dark gray breccia with a thickness of 2 meters, eroding alternating shale and sandstone facies, channel-shaped geometry marked by an erosional boundary at the base of the layers, and is only found in the AS-06 section. The massive medium sandstone facies (Sm2) consist of medium to coarse sandstone layers with a thickness of 30 100 cm, sheet-like and amalgamated geometry layer, characterized by stacked sandstone layers that are not interrupted by claystone/mud drape layers and lack erosion marks in each sandstone layer set, and the presence of *Planolites* trace fossils at the bottom of the layers.

4. Depositional environments of the Upper Merawu Formation

The depositional environment analysis is based on the relationships between lithofacies, which eventually form lithofacies associations. These lithofacies associations represent interconnected sedimentological processes formed in sub-depositional environments, divided into distal shelf facies association, lower shoreface, ravinement surface, slump scar, and channel infill (Figure 9).

The distal shelf facies association (FA1) is composed of alternating shale facies (Fl) with wave-rippled cross-laminated sandstone facies (Sr) and parallel-laminated sandstone facies (Sh). This collection of facies characterizes the distal shelf environment, the outermost part of the shelf which is close to the slope (shelf edge). The shelf edge serves as the location for the deposit of thick clay facies [22]. Sediments eroded and transported from land to the shelf edge undergo grain smoothing and abrasion, leading to the deposition of thick clay in this environment. Meanwhile, the presence of sandstone layers within the thick clay sequence represents episodic deposition occurring at the shelf edge.

The lower shoreface facies association (FA2) consists of an amalgamation of amalgamated sandstone facies (Sm), parallel laminated sandstone facies (Sh), and wave ripple laminated sandstone facies (Sr). The lower shoreface is part of the shelf located within the storm-weather base water column, situated between the normal sea level and the deep marine zone. Deposition in this part of the shelf is influenced by storm winds that rework the sediments. This reworking forms hummocky cross-stratification.

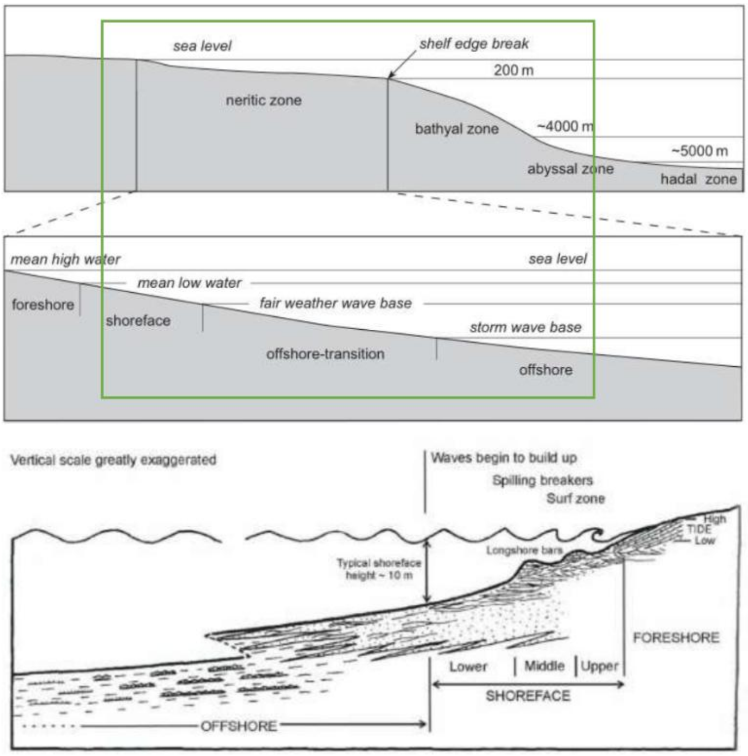

Figure 9. Morphological sketch of the shelf along with its sub-environmental divisions [23].

The lower-middle shoreface facies association (FA3) consists of amalgamated sandstone facies (Sm) and fine carbonaceous sandstone facies with hummocky cross-stratification (Sr2), interbedded with shale facies (Fl). A distinctive feature of these facies is the presence of a ravinement surface or the erosion of the shelf caused by sedimentation during the transition from a progradational to a retrogradational deposition pattern due to shelf erosion during sea-level rise [23]. At the lower boundary of this facies association, there are signs of a coarsening-upward deposition pattern, marked by an erosional boundary characterized by the presence of gutter cast structures that erode the shale facies. The resulting deep scours are then quickly filled with sand when sea level reaches its peak (scour and fill) [23].

The slump scar facies association (FA4) consists of slump sandstone facies and convolute laminated sandstone facies (Sh2). This facies association is interpreted to have formed due to episodic slumping on the edge of the shelf. These facies fill depressions present on the slope at the shelf edge. Sediment deposition on the slope is influenced by gravity, leading to the deposition of facies characterized by coarse grains and poor sorting, with a grain-size gradation as the deposition energy decreases [23].

The channel infill facies association (FA5) consists of amalgamated medium sandstone facies (Sm) and normally-graded breccia facies (Gm). Gravity-driven processes from slumping deposit coarse sediment fractions, with decreasing energy during deposition, forming a fining-upward grain pattern. Deposition occurs rapidly, leading to the amalgamation of sandstone layers.

5. Implication for Tectonic Activity and Hydrocarbon Exploration

The shale facies (Fl) in the study area, which is part of the Upper Merawu Formation, are likely to act as a source rock in the petroleum system, as supported by previous studies [16,17,19]. In this case, the kerogen in the shape of the Upper Merawu Formation consists of Type III kerogen (organic material from terrestrial sources) and Type II kerogen (organic material from a combination of terrestrial and marine sources), making it capable of generating both gas and oil [16]. The normally graded breccia facies (Gm) and massive medium sandstone facies (Sm2) which are part of the Lower Penyatan Formation, could serve as hydrocarbon reservoirs, according to previous study [24].

Compressional tectonics during the Early Pliocene might have formed folds and oblique faults that could create structural traps if a lithological formation capable of acting as a cap rock was deposited above the Penyatan Formation. In the North Serayu Basin, the Tapak Formation that has marl lithology, and the Kalibiuk Formation, consisting of claystone and marl [1], could serve as potential cap rocks. In this context, hydrocarbon exploration would be more promising in areas with indications of structural traps containing the stratigraphic sequence of the Merawu Formation, Penyatan Formation, and Tapak/Kalibiuk Formation. Additionally, shale gas exploration in areas where the Merawu Formation is not exposed could also be pursued.

D. Conclusion

Stratigraphy in the study area is divided into two lithostratigraphic units, namely the Shale Unit and the Sandstone Unit, and one lithodemic unit, the Basalt Lava. The lithofacies of the Upper Merawu Formation consist of shale lithofacies, fine sandstone with parallel laminations, fine sandstone facies with cross-lamination, fine sandstone with wave ripple laminations, fine sandstone with hummocky cross-stratification, amalgamated fine sandstone, fine sandstone with convolute laminations, fine sandstone with slump, and wackestone facies. Meanwhile, the lithofacies of the Lower Penyatan Formation consists of breccia facies and massive medium sandstone facies.

The analysis of lithofacies associations indicates that the lithological facies in the study area were deposited in a distal shelf to middle shoreface environment. The shale in the upper Merawu Formation might act as a source rock in the petroleum system of the North Serayu Basin.

E. Acknowledgement

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F. References

[1]. Bachri S. Basin Development and History of Neogene Deposition in the Bobotsari Low Area, Purbalingga Regency, Central Java. Geo-Resources 2011;21:285–307.

[2]. Armandita C, Satyana AH, Ma'ruf Mukti M, Yuliandri I. Trace of the Translated Subduction in Central Java and its Role on the Paleogene Basins and Petroleum System Development. The 36th HAGI and 40th IAGI Annual Convention and Exhibition Makassar, 2011, p. 26–7.

[3]. Astuti BS. Stratigrafi dan Sedimentasi Batuan Neogen di Cekungan Serayu Utara, Daerah Kuningan, Jawa Barat–Larangan, Brebes, Jawa Tengah. Universitas Gadjah Mada, 2012.

[4]. Nursecha MAQ, Jyalita J, Husein S. Tectonic Control on Hydrocarbon Seepages of Sijenggung, North Serayu Basin, Central Java. Proceedings, Indonesian Petroleum Association, 38th Annual Convention & Exhibition 2014. https://doi.org/10.13140/RG.2.1.2413.6407.

[5]. van Bemmelen RW. The Geology of Indonesia: General Geology of Indonesia and Adjacent Archipelagoes. vol. IA. Government Printing Office; 1949.

[6]. Bachri S, Panggabean H. Sedimentologi Formasi Worawari Paleogen di Pegunungan Serayu Utara. Geosciences (Basel) 2010;20:25–32.

[7]. [7] Martosuwito S, Fakhruddin R. Tidal Sedimentary Rocks at the Keruh Creek, Lor Agung Village, Pekalongan Residents. Geo-Resources 2014;15:41–53.

[8]. [8] Gibran AK, Waluyo G. Lower–Middle Miocene Biostratigraphy of the Silisiclastic Rambatan Formation, North Serayu Basin. Proceeding ICMA-SURE-2024 The 6th International Conference on Multidisciplinary Approaches for Sustainable Rural Development, 2024.

[9]. Condon WH, Pardyanto L, Ketner KB, Amin TC, Gafoer S, Samodra H. Geological Map, Scale 1:100,000, Banjarnegara-Pekalongan Sheet, Java. 1996.

[10]. Djuri M, Samodra H, Amin TC, Gafoer S. Geological Map, Scale 1:100,000, Purwokerto-Tegal Sheet, Java. 1992.

[11]. Clements B, Hall R. Cretaceous to Late Miocene stratigraphic and tectonic evolution of West Java. Proceedings, Indonesian Petroleum Association, 31st Annual Convention & Exhibition, 2007.

[12]. Lunt P, Burgon G, Baky A. The Pemali Formation of Central Java and equivalents: Indicators of sedimentation on an active plate margin. J Asian Earth Sci 2009;34:100–13. https://doi.org/10.1016/j.jseaes.2008.03.006.

[13]. Martosuwito S, Bachri S, Kamal ZA. Stratigraphical and Sedimentological Review of the Merawu Formation, Serayu Basin, Central Jawa, Indonesia. Indonesian Journal on Geoscience 2018;5:117–28. https://doi.org/10.17014/ijog.5.2.117-128.

[14]. Satyana AH. Hydrocarbon Prospectivity of Java: Opportunities and Challenges. Proceedings, Indonesian Petroleum Association, 41st Annual Convention & Exhibition, 2016.

[15]. Satyana AH. New Insight on Tectonics of Central Java, Indonesia and Its Petroleum Implications. AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS (AAPG) International Conference and Exhibition Perth, Australia, November 5-8, 2006, 2006.

[16]. Slameto E, Panggabean H, Bachri S. Kandungan Material Organik dan Sifat Geokimia Batulempung Paleogen dan Neogen di Cekungan Serayu: Suatu Analisis Potensi Batuan Induk Hidrokarbon. Geo-Resources 2010;20:189–97.

[17]. Iswahyudi S, Widagdo A. The Source Rock Potential of Shale And Claystone of Watukumpul Area Pemalang Central Java. Dinamika Rekayasa 2009;5:9–13.

[18]. Praptisih. Biomarker characteristics of source rock and oil seepage correlation in Central Java. IOP Conf Ser Earth Environ Sci, vol. 118, Institute of Physics Publishing; 2018. https://doi.org/10.1088/1755-1315/118/1/012008.

[19]. Praptisih, Kamtono, Siregar MS, Subroto EA. Studi Batuan Induk Pada Sub Cekungan Serayu Utara, Banjarnegara dan Sekitarnya, Jawa Tengah. Prosiding Seminar Geoteknologi Kontribusi Ilmu Kebumian Dalam Pembangunan Berkelanjutan, 2007, p. 1–6.

[20]. Miall. A. D. Stratigraphy: A Modern Synthesis. Springer; 2015.

[21]. Blow WH. Late Middle Eocene to Recent planktonic foraminiferal Biostratigraphy. In: Bronniman R, Renz HH, editors. Proceedings of the First International Conference on Planktonic Microfossils 1, Geneva: 1969, p. 199–421.

[22]. Reading HG. Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Publishing; 1996.

[23]. James NP, Robert DW. Facies Models. 4th ed. Geological Association of Canada; 2010.

[24]. Purwasatriya EB, Gibran AK, Aditama MR, Waluyo G. Sedimentology and Tectonostratigaphy of Halang Formation in Banyumas Basin and Its Potential as Hydrocarbon Reservoir. Geo-Resources 2021;22:153–63. https://doi.org/10.33332/jgsm.geologi.22.3.153-163p.