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Geological Framework and Rock Occurrence History of the Long Loreh Region, South Malinau District, North Kalimantan, Indonesia

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ABSTRACT

Northern Kalimantan preserves a complex record of tectono-sedimentary evolution from the Eocene to the Late Miocene. This study applies systematic surface geological mapping supported by detailed field observations of lithology, sedimentary structures, and measurements of bedding and fault orientations, complemented by regional geomorphic analysis. The Bilabekayuk Sandstone, Bilabekayuk Siltstone, and Gongsolok Argillite, assigned to the Malinau Formation of the Rajang–Embaluh Group, were deposited during a Middle–Late Eocene marine transgression in a shallow-marine to tidal-flat setting. Oligocene–Miocene subduction of the Palawan oceanic plate resulted in regional compression, thrust faulting, uplift of the Kuching High, and development of prominent W–E-trending lineaments with steeply tilted strata. Associated Miocene magmatism produced the Jelai volcanic rocks and Sengayan Tuff. Subsequent basin isolation led to Late Miocene lacustrine deposition of the Langap Formation, including the Sengayan Conglomerate and Sengayan Sandstone with local swamp influence. These results document a regional transition from marine sedimentation to tectonic inversion, volcanism, and continental basin development in northern Kalimantan.

1. INTRODUCTION

Kalimantan Island represents one of the most tectonically intricate regions in Southeast Asia, formed through prolonged interactions between the Eurasian, Indo-Australian, and Pacific plates since the Mesozoic [1,2]. The island records a complex history of terrane accretion, subduction, collision, and post-orogenic extension, resulting in a highly heterogeneous geological architecture characterized by metamorphic basement complexes, ophiolitic fragments, magmatic arcs, and thick sedimentary successions [2,3]. These tectonic processes not only controlled crustal growth in northern Sundaland but also governed the spatial and temporal distribution of lithological assemblages preserved across Kalimantan.

Northern Kalimantan, particularly the Malinau region, occupies a critical position along the southern margin of the Eurasian Plate and represents a transitional zone between stable continental crust and accreted Mesozoic–Cenozoic terranes. Previous regional studies have documented the presence of pre-Tertiary metamorphic rocks, Jurassic–Cretaceous mélanges, and Paleogene–Neogene sedimentary basins related to subduction rollback and subsequent foreland basin development [3-5]. However, despite its strategic tectonic setting, detailed geological investigations in the interior regions of North Kalimantan remain sparse due to limited accessibility and dense tropical vegetation.

The Long Loreh area, located in South Malinau District, constitutes an underexplored sector of northern Borneo where diverse lithological units are exposed along river cuts and structurally controlled valleys. Preliminary mapping suggests the coexistence of crystalline basement rocks, volcanic–volcaniclastic sequences, and clastic sedimentary units, reflecting multiple episodes of magmatism, deformation, erosion, and basin infill. These rock assemblages potentially record key geological events related to terrane amalgamation, arc evolution, and post-collisional sedimentation in northern Kalimantan. Nevertheless, the stratigraphic relationships, rock occurrence history, and tectono-sedimentary evolution of this area have not yet been systematically documented.

Understanding the geological framework and rock occurrence history of the Long Loreh region is essential for refining regional tectonic models of northern Borneo and for constraining the timing and mechanisms of crustal evolution in Southeast Asia. Moreover, such insights are fundamental for evaluating the region's resource potential, including metallic minerals, coal-bearing strata, and hydrocarbon-prone sedimentary units. Integrating detailed field-based lithological characterization with structural observations provides a robust approach to reconstructing the geological evolution of this complex region.

This study provides the first integrated, field-based geological framework and reconstruction of rock occurrence history for the Long Loreh region, offering new constraints on the tectono-stratigraphic evolution of northern Kalimantan within the East Borneo tectonic domain. The results bridge a critical gap between regional tectonic models and local-scale geological observations by documenting lithological assemblages, stratigraphic relationships, and structural features in an area that has remained largely unexplored. By integrating detailed field mapping with lithological analysis, this study refines the timing and genetic relationships between sedimentary and volcanic units and clarifies the role of inherited structures in controlling basin development and rock distribution. These new geological constraints contribute to a more robust understanding of the Mesozoic–Cenozoic evolution of northern Borneo and provide a valuable framework for future tectonic, stratigraphic, and resource-related studies in the region.

2. LITERATURE REVIEW

2.1 Regional Geological Setting

Kalimantan Island forms part of the Sundaland margin and records a complex geological evolution driven by prolonged Mesozoic–Cenozoic convergence, terrane accretion, and post-collisional basin development in Southeast Asia [3,6,7]. The island is composed of a mosaic of continental fragments, island arcs, ophiolitic complexes, and sedimentary basins that were progressively amalgamated through subduction and collision processes. These tectonic events resulted in the development of diverse lithological assemblages and complex structural architectures across Borneo [3,6,7].

Regionally, Borneo has been subdivided into several tectonic domains. Wang et al. [8] recognized five principal tectonic zones: the Southwest (SW) Zone, Kuching Zone, Sibu Zone, Miri Zone, and East Zone. The Long Loreh area located in South Malinau District, North Kalimantan, falls within the East Zone, which is structurally bounded by the Long Aran–Witti–Kinaya Fault system extending into the interior of Borneo (Fig.1). Pre-Tertiary basement rocks within this zone are sparsely exposed and are mainly confined to the Meratus Mountains and the Darvel Bay region, whereas the East Zone is predominantly characterized by thick Miocene to Quaternary sedimentary successions.

The East Zone preserves key geological records of Late Mesozoic subduction beneath southeastern Borneo, including Cretaceous-aged ophiolitic complexes and remnants of island arc volcanic rocks, particularly in the Meratus region [8]. To the west, the East Zone is bounded by the Kuching Zone, which represents a regional structural high that exerted significant control on basin development and sediment dispersal patterns. One of the oldest sedimentary units recognized in Borneo is the Rajang–Embaluh Group [9], which has traditionally been interpreted as an accretionary prism formed during the subduction of the proto–South China Sea in the Late Cretaceous to Early Paleogene. However, alternative interpretations suggest that this group represents deposits of a remnant ocean basin, highlighting ongoing debates regarding the tectono-sedimentary evolution of northern Borneo.

The broad spectrum of rock ages preserved across the East Zone reflects multiple tectonic phases associated with the subduction of the Luconia Block and the Danger Zone (Danger Ground) during the Cretaceous, followed by collisional tectonics [9,10]. These processes culminated in regional uplift during the Early Miocene, leading to the development of a mountain arc system across northern Borneo [7,10]. Continued subduction related to the opening of the South China Sea likely sustained this uplift and facilitated the subduction of the Palawan microplate beneath the region, positioned behind the Luconia Block and the Danger Zone [7,12]. Collectively, these tectonic events controlled the present-day geological framework of northern Kalimantan and provide the regional tectonic context for the geological evolution of the Long Loreh area [9, 13].

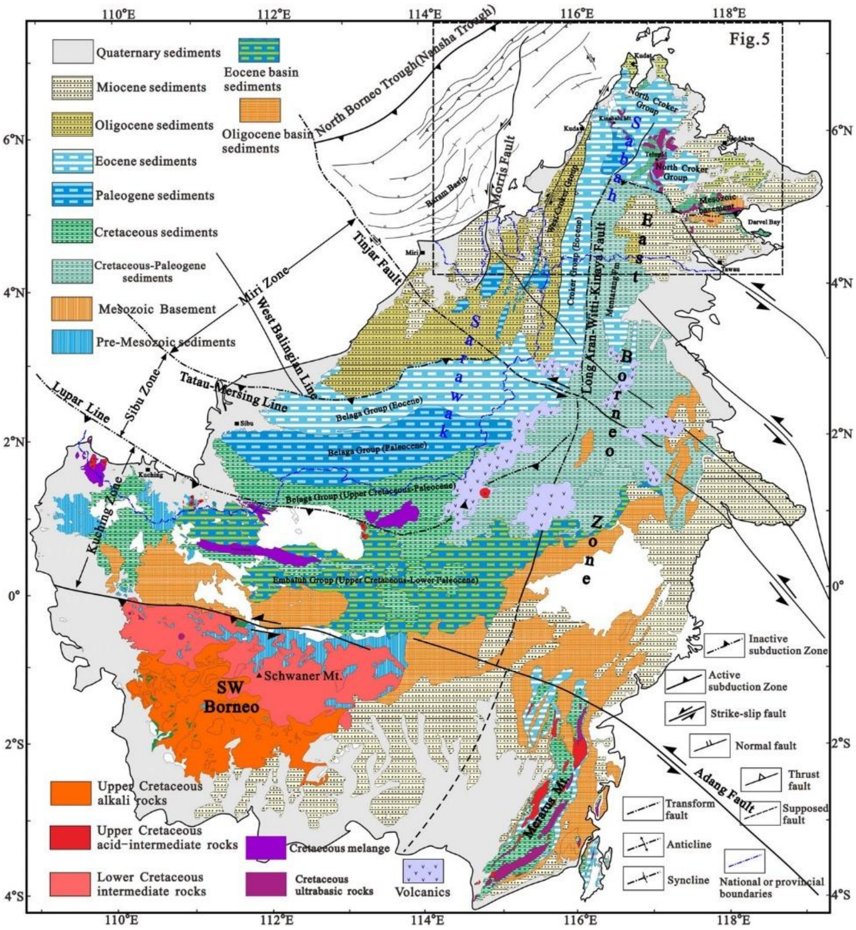


Figure 1. Physiographic–tectonic subdivision of Kalimantan Island based on Wang et al. [8].

2.2 Stratigraphic Framework of Research Area

The stratigraphic framework of the Long Loreh area, South Malinau District, North Kalimantan, is defined by the development of Neogene sedimentary and volcanic units that record the progressive infilling of the northern Tarakan Basin under an evolving tectonic regime [7, 15]. The study area encompasses three principal lithostratigraphic units, namely the Malinau Formation (Tema), the Langap Formation (Tml), and the Jelai Volcanic Rocks (Tomj) (Fig. 2), which collectively reflect a transition from marine to terrestrial depositional environments accompanied by contemporaneous volcanic activity [10]. These units document the response of sedimentation patterns to basin subsidence, hinterland uplift, and subduction-related magmatism during the Miocene, reflecting the complex interaction between regional tectonics and sediment supply along the northern margin of Borneo [15, 16].

The Malinau Formation (Tema) represents the dominant sedimentary unit within the study area and is generally assigned a Middle to Late Miocene age [14]. Lithologically, the formation is characterized by thick successions of sandstone, siltstone, mudstone, and locally developed carbonaceous shale and coal seams. Sedimentary facies associations indicate deposition in a fluvio-deltaic to coastal plain environment, where channelized sandstones alternate with overbank and floodplain deposits [10,11]. The presence of coal-bearing intervals suggests prolonged peat accumulation under humid tropical conditions, reflecting low-energy, poorly drained settings typical of delta plain to backswamp environments [17,18]. The Malinau Formation thus records an advanced stage of basin infill, during which terrestrial influence became dominant as sediment supply exceeded available accommodation space in response to continued uplift of the hinterland and diminishing marine influence in the northern Tarakan Basin [7,16].

Underlying and locally interfingering with the Malinau Formation, the Langap Formation (Tml) is interpreted as an Early to Middle Miocene unit deposited under more marine-influenced conditions [19]. The Langap Formation is composed mainly of fine- to medium-grained sandstones, siltstones, and mudstones, locally interbedded with calcareous layers, indicating deposition in shallow-marine to delta-front environments [19, 20]. The presence of marine sedimentary structures and finer-grained facies suggests a relatively higher accommodation space compared to the overlying Malinau Formation, reflecting active subsidence during the Early–Middle Miocene [12, 13]. Stratigraphically, the Langap Formation marks a transitional phase in the Long Loreh area, representing the shift from marine-dominated sedimentation toward increasingly terrestrial and deltaic systems driven by regional uplift and regression associated with tectonic reorganization along the northern margin of Borneo [12, 13].

The sedimentary succession in the Long Loreh area is locally influenced by the emplacement of the Jelai Volcanic Rocks (Tomj), which are generally dated to the Middle Miocene and consist predominantly of basaltic to andesitic lava flows, volcanic breccias, and associated volcaniclastic deposits [12, 21]. These volcanic rocks are interpreted to have formed in a subduction-related volcanic arc setting, reflecting active magmatism along the northern margin of Borneo during continued plate convergence and arc–continent interaction [22, 23]. Volcaniclastic material derived from the Jelai Volcanics was likely reworked into adjacent sedimentary environments, contributing tuffaceous components to the Langap and Malinau Formations and influencing their geochemical and mineralogical characteristics [13,22,23]. The close spatial and stratigraphic association between volcanic and sedimentary units indicates syn-depositional volcanism that played a significant role in controlling sediment supply, basin architecture, and facies distribution in the Long Loreh region.

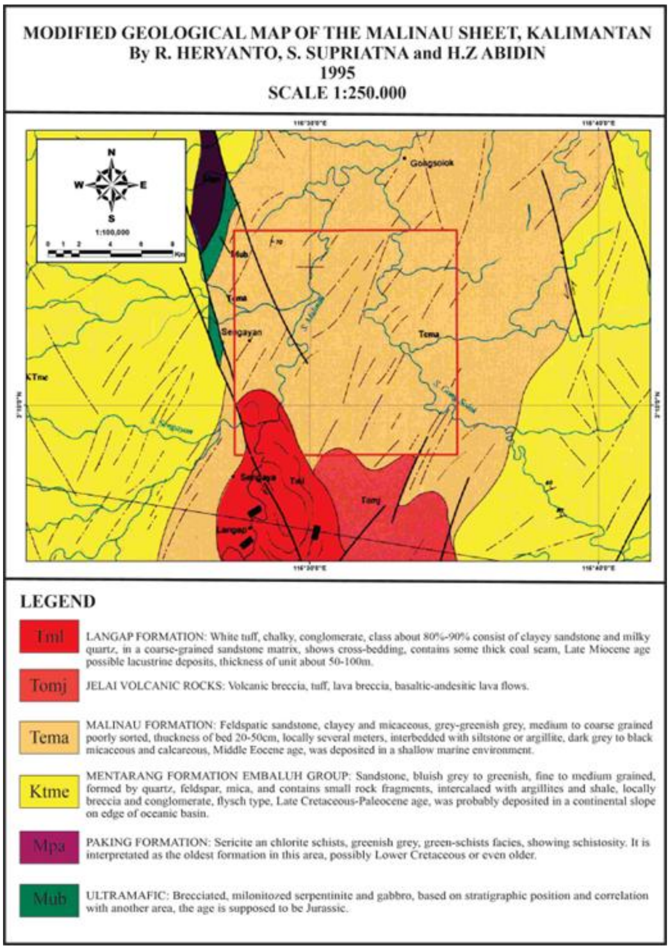


Figure 2. Location and geological setting of the Long Loreh research area, South Malinau District, North Kalimantan, Indonesia, showing the distribution of the Malinau Formation (Tema), Langap Formation (Tml), and Jelai Volcanic Rocks (Tomj) [13].

3. METHODOLOGY

This study was conducted through systematic surface geological mapping aimed at characterizing the geological framework of the study area. Primary data were obtained from detailed field observations, including lithological descriptions, identification of sedimentary structures, and documentation of geological structures at each observation station. Stratigraphic relationships and structural orientations were measured to support spatial and genetic interpretations.

The field-based dataset was integrated with secondary geospatial data, particularly the DEMNAS (National Digital Elevation Model), to analyze regional morphology and delineate structural features such as lineaments, faults, and other morphotectonic elements. DEM-derived geomorphic expressions were used to complement field observations and to refine structural interpretations in areas with limited outcrop exposure. The geological analysis was further constrained through critical comparison with previous regional and local studies, ensuring consistency with established stratigraphic and tectonic frameworks of North Kalimantan.

4. RESULTS AND DISCUSSION

4.1 Lithological Characteristics

The Bilabekayuk Sandstone is predominantly composed of greyish sandstone exposed in outcrop-scale blocks and channelized geometries (Fig. 3a). The sandstone is characterized by medium- to fine-grained sand, good sorting, and intense compaction, indicating significant burial diagenesis. Hand specimen observations suggest the unit is very well cemented, locally exhibiting calcareous cementation, as evidenced by lighter-colored, massive textures and reduced primary porosity (Fig. 3b).

The sandstone facies is locally interbedded with blackish shalestone layers (Fig. 3c), composed predominantly of clay- to silt-sized particles that form thin, laterally discontinuous beds. These finer-grained intercalations are also well compacted and well cemented, indicating early mechanical compaction followed by progressive chemical diagenesis. The close spatial association between sandstone and shalestone facies reflects fluctuating hydrodynamic energy conditions during deposition, likely driven by episodic suspension settling that intermittently interrupted traction-dominated sediment transport. Locally, the presence of calcareous components suggests post-depositional fluid circulation and carbonate precipitation within the pore network. Overall, the Bilabekayuk Sandstone records deposition in a moderate- to high-energy environment, where relatively stable sediment supply and sustained hydrodynamic reworking promoted good sorting and textural maturity, subsequently overprinted by intense diagenetic modification.

The Bilabekayuk Siltstone facies is composed of intercalated shalestone and siltstone, displaying well-developed lenticular and wavy lamination (Fig. 3d,e). The shalestone layers are typically dark grey, reflecting a higher clay content and possibly elevated organic matter. These laminated structures suggest deposition under variable energy conditions, where alternating traction and suspension processes were active. The siltstone intervals are locally associated with flaser sandstone structures (Fig. 3f), indicating intermittent sand influx during higher-energy episodes. The entire facies is highly compacted, with reduced visible porosity, and some layers exhibit calcareous attributes, implying carbonate cement precipitation during burial diagenesis.

The sedimentary structures, including lenticular, wavy, and flaser bedding, collectively point to a low- to moderate-energy depositional setting, such as a tidally influenced environment or distal deltaic system, where current strength fluctuated frequently. The alternation of mud-dominated and sand-influenced laminae records short-term changes in flow regime and sediment supply. The vertical and lateral association between the Bilabekayuk Sandstone and Siltstone suggests a transitional siliciclastic system, evolving between higher-energy sand-dominated conditions and lower-energy, mud-rich settings. Strong compaction and pervasive cementation across both lithologies indicate deep burial and advanced diagenetic modification, which significantly affected reservoir quality.

The Gongsolok Argilite is dominantly composed of shalestone, displaying a characteristic blackish to dark-grey coloration (Fig. 4a–d). The lithology consists of very fine-grained material, ranging from clay to silt size, and is intensely compacted, resulting in a hard, fissile to massive argillaceous rock that can be classified as argilite. A subtle yellowish tinge is locally observed, likely reflecting minor iron oxidation or diagenetic alteration processes. In the lower part of the succession, the argilite exhibits calcareous characteristics, manifested by calcite veinlets and patches of carbonate cement (Fig. 4c–d). These features indicate post-depositional fluid circulation and chemical diagenesis during burial. Locally developed oxide layers suggest episodic redox fluctuations, possibly linked to changes in pore-water chemistry or exposure to oxidizing fluids along fractures. The overall fabric, absence of primary sedimentary structures, and strong compaction imply deposition under low-energy conditions, most consistent with a distal marine, offshore, or deep lacustrine setting, followed by significant burial diagenesis.

Figure 3. Field photographs of the Bilabekayuk lithofacies. (A) Greyish Bilabekayuk Sandstone exposed as massive, well-compacted outcrops; (B) Medium- to fine-grained, well-sorted sandstone with strong cementation and local calcareous characteristics; (C) Interbedded blackish shalestone composed of clay–silt-sized grains, highly compacted and well cemented; (D) Dark-grey shalestone showing lenticular to wavy lamination; (E) Blocky sandstone exposure reflecting intense compaction; (F) Flaser sandstone intercalated with siltstone, indicating fluctuating energy conditions during deposition.

The Sengayan Tuff is characterized by white to greenish-colored volcanic ash deposits, composed of fine-grained tuff with a predominantly massive structure (Fig. 4e). The massive nature and lack of internal stratification suggest rapid deposition from volcanic fallout or ash-laden density currents. The greenish hue reflects secondary alteration, likely related to the transformation of volcanic glass into clay minerals (e.g., smectite or chlorite), indicating hydrothermal or burial-related alteration processes.

The Sengayan Tuff grades into tuffaceous sandstone (Fig. 4f), marked by a greyish color, coarse to very coarse sandsized grains, poor sorting, and poor cementation. This textural contrast indicates an increase in depositional energy and sediment supply, possibly due to reworking of volcanic material by traction currents. The presence of coarse, poorly sorted grains suggests short transport distances and rapid deposition, consistent with a volcaniclastic-dominated depositional system, such as a proximal volcanic apron or a volcanically influenced fluvial to shallow-marine environment.

The vertical association of Gongsolok Argilite and Sengayan Tuff records a transition from low-energy, fine-grained sedimentation to volcaniclastic-dominated deposition. This stratigraphic relationship suggests a significant change in sediment supply and depositional regime, likely driven by volcanic activity superimposed on a relatively quiescent argillaceous depositional environment. Subsequent compaction, carbonate cementation, and mineral alteration reflect advanced diagenetic overprinting, which has important implications for mechanical properties and fluid flow behavior within the succession.

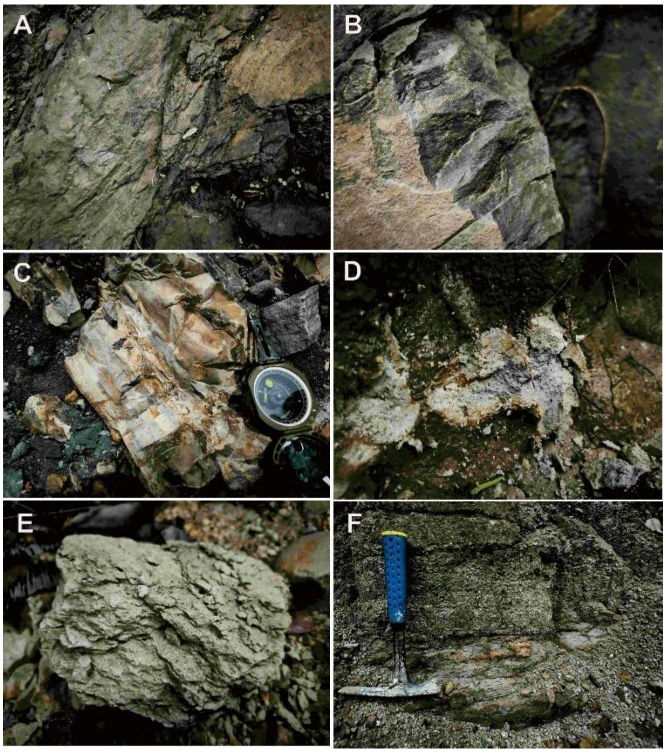


Figure 4. Field photographs of the Gongsolok Argilite and Sengayan Tuff. (A–D) Gongsolok Argilite showing blackish-grey shalestone, very fine-grained (clay–silt), highly compacted, with local calcareous features, oxide layers, and calcite veins; (E–F) Sengayan Tuff represented by massive, fine-grained altered tuff, overlain by greyish tuffaceous sandstone with coarse to very coarse grains, poor sorting, and weak cementation.

The Sengayan Conglomerate comprises laterally continuous conglomeratic units with a dominant greyish coloration (Fig. 5 a–c). Two main textural associations are recognized. The upper interval is characterized by matrix-supported conglomerate with a sandy matrix, polymict composition, and clasts ranging from pebble to gravel size. Clast assemblages include sedimentary lithologies such as sandstone, claystone, and reworked conglomerate fragments, indicating multi-source provenance and limited transport reworking. Poor to moderate sorting and matrix dominance suggest deposition from high-concentration sediment gravity flows or debris-rich fluvial processes.

In contrast, the lower interval consists of grain-supported conglomerate, monomict in composition, dominated by silica clasts that are well rounded and range from gravel to cobble size (Fig. 5c). This unit displays normal grading and a distinct scoured basal contact, reflecting erosion into underlying strata. These features indicate deposition under higher-energy conditions, consistent with channelized traction-dominated flows, such as braided fluvial channels or proximal alluvial systems. The upward transition from grain-supported to matrix-supported conglomerate records a progressive decrease in flow competence and energy. The Sengayan Sandstone is dominated by cross-bedded sandstone with a greyish color and coarse- to medium-grained texture (Fig. 5d–e). The sandstone is generally poorly sorted and locally contains carbonaceous material and coal fragments, suggesting proximity to vegetated source areas. Sedimentary structures are well developed, with planar and trough cross-bedding indicative of migration of three-dimensional bedforms under unidirectional flow.

The association of Sengayan Conglomerate and Sengayan Sandstone indicates a high-energy siliciclastic system, evolving from proximal, erosion-dominated conglomeratic channels to sand-dominated fluvial deposits with localized swampy or floodplain conditions conducive to coal formation. Overall facies architecture supports deposition within a fluvial to alluvial setting, with fluctuating discharge and sediment supply controlling vertical grain-size trends.

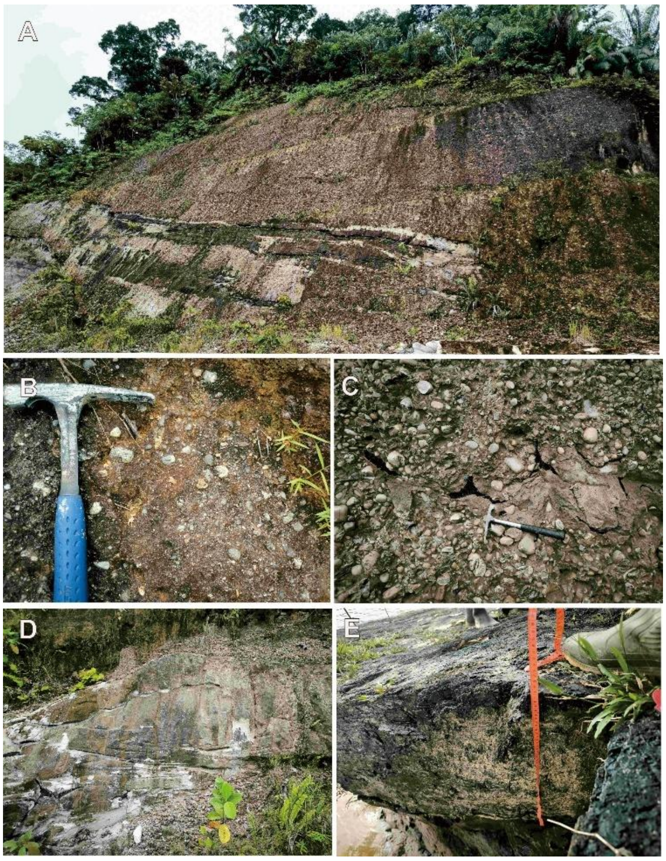


Figure 5. Field photographs of the Sengayan Conglomerate and Sengayan Sandstone. (A) Conglomerate Outcrop; (B) Matrix Supported Conglomerate; (C) Grain Supported Conglomerate; (D) Crossbedding Sandstone; (E) Coal Layer in Sengayan Sandstone Unit.

4.2 Structural Interpretation

The study area is structurally controlled by prominent NE–SW–trending lineaments expressed as ridge alignments, primarily affecting the Bilabekayuk Sandstone, Bilabekayuk Siltstone, and Gongsolok Argillite units (Fig. 6). These structures strongly govern bedding orientations across the area. In the western sector, strata strike N200°–215° with steep westward dips of 65°–80°, whereas the eastern sector shows strikes of N30°–45° with eastward dips of 31°–72°, indicating contrasting structural domains. Faulting is evident within the succession, dominated by NE–SW–trending thrust faults, marked by fault scarps. In addition, dextral strike-slip faults are recognized, including a W–E–trending fault cutting ridges in the Bilabekayuk Sandstone and northwestern Bilabekayuk Siltstone, and a N10°–trending dextral fault interpreted from fault-plane exposures at STA 27 (Fig. 6a-b).

Normal faults are widely developed across the study area, predominantly trending W–E to NW–SE, and are interpreted to reflect a regional extensional structural regime superimposed on earlier deformation. In the eastern sector, deformation is further expressed by a NE–SW–trending anticlinal ridge, indicating localized folding associated with compressional or transpressional stresses. At outcrop scale, microfaults are common and are interpreted as secondary structures related to major fault activity, particularly a dextral strike-slip fault trending N268°E (W–E) exposed at STA14 (Fig. 6c). Additionally, calcite veins occur within carbonate siltstone, with dominant orientations around N290°E (W–E), as observed at STA05 (Fig. 6d), suggesting fluid migration along structurally controlled fracture systems.

In contrast to the structurally deformed central and northeastern sectors, the southwestern part of the study area, encompassing the Sengayan Tuff, Sengayan Conglomerate, and Sengayan Sandstone units, is comparatively weakly deformed. Bedding attitudes define a gentle structural depression centered in this area, as indicated by consistent dip patterns. This geometry is further supported by lineament distributions observed on the geological map, suggesting limited tectonic overprinting and preservation of primary stratigraphic architecture.

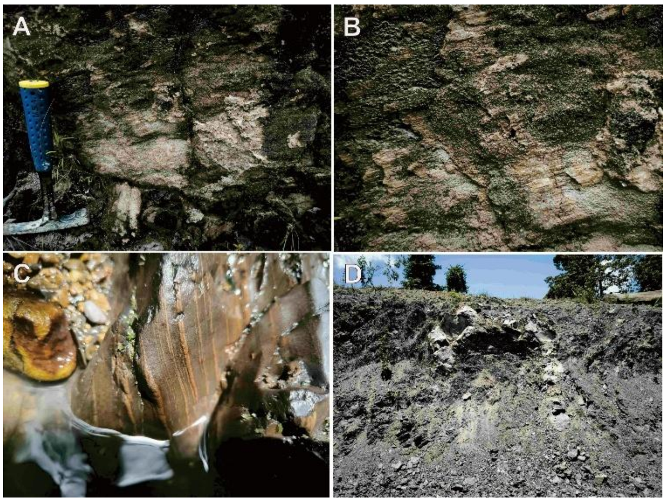


Figure 6. Structural features of the study area. (A-B) Result of dragging force on the fault plane; (B) Dextral strike-slip faults, including W–E–trending structures and the N10° fault plane exposed at STA 27; (C) Bilabekayuk Siltstone laminae layer cut by Faulting force; (D) Veined Outcrop Siltstone.

4.3 Stratigraphic Analysis

The Bilabekayuk Sandstone constitutes the oldest stratigraphic unit identified in the study area and forms the basal part of the exposed succession (Fig. 7a). Lithologically, the unit is dominated by fine- to medium-grained sandstone with subordinate interbeds of siltstone. The sandstone commonly displays massive bedding, locally forming thick and laterally continuous beds, which suggests deposition under relatively high-energy conditions where sediment was supplied continuously and reworked efficiently within the basin. Such massive textures are interpreted to reflect rapid sediment accumulation or intense bioturbation that obscured primary sedimentary structures (Fig. 7b).

In addition to massive bedding, the Bilabekayuk Sandstone locally exhibits laminated sedimentary structures, including flaser bedding and cross-bedding, indicating short-term fluctuations in hydrodynamic energy (Fig. 7c). These structures record alternating phases of traction and suspension deposition, implying a dynamic depositional regime. The presence of calcareous cementation and carbonate-rich horizons suggests marine influence and early diagenetic modification, consistent with sedimentation in a shallow subtidal environment. In this setting, wave and current activity would have been sufficient to maintain sand-dominated facies while allowing intermittent mud deposition during lower-energy periods.

The Bilabekayuk Sandstone is conformably overlain by the Bilabekayuk Siltstone, which marks a clear upward transition to finer-grained sedimentation. This unit is characterized by the dominance of siltstone and shalestone, with well-developed wavy and lenticular laminations (Fig. 7d). These sedimentary structures consist of sand lenses encased within finer-grained mud, reflecting alternating current strengths and periodic slack-water conditions. Such features are widely regarded as diagnostic of tidally influenced depositional environments.

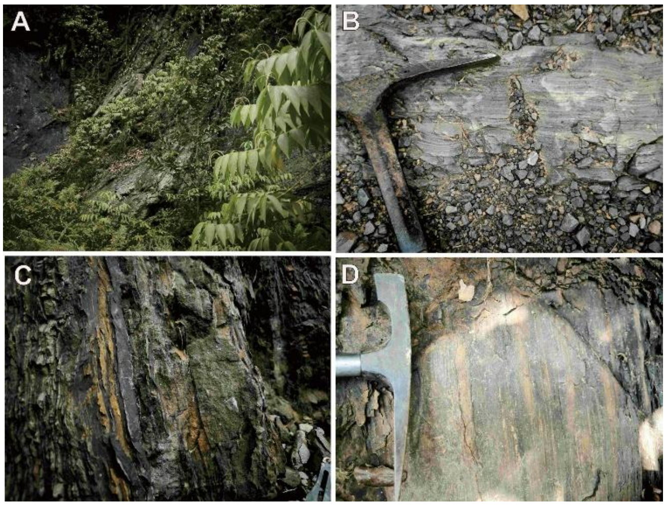


Figure 7. Field photographs of the Bilabekayuk fine-grained facies. (A) Exposure of steeply dipping, laminated shalestone–siltstone; (B) Thinly bedded siltstone with planar to wavy lamination; (C) Intensely compacted shalestone showing fissility and lamination; (D) Laminated siltstone with subtle color banding and minor sand laminae, reflecting tidally modulated deposition.

The prevalence of wavy and lenticular bedding in the Bilabekayuk Siltstone indicates deposition in a low- to moderate-energy intertidal setting, such as a tidal flat or the marginal zone of a tide-dominated delta. In this environment, sand is transported and deposited during peak tidal currents, whereas finer sediments settle from suspension during periods of reduced flow. The stratigraphic transition from sand-dominated subtidal deposits to mud-rich intertidal facies reflects a progressive shallowing trend, likely associated with relative sea-level fall or progradation of the depositional system.

The Gongsolok Argillite represents a fine-grained sedimentary unit deposited after the establishment of lower-energy depositional conditions. It is composed predominantly of siltstone and shale, exhibiting very hard, highly indurated characteristics and largely massive sedimentary structures, which suggest extensive post-depositional modification. The unit is consistently dark grey to blackish in color, indicating sedimentation under conditions enriched in organic matter, most likely from the accumulation of organic-rich mud in a restricted setting (Fig. 8a).

The presence of calcareous components, locally expressed as carbonate-rich horizons and cement, implies continued marine influence during deposition. These features are consistent with sedimentation in a supratidal to marginal-marine environment, where fine-grained sediments dominated and carbonate precipitation occurred intermittently under fluctuating chemical conditions. Limited evidence of primary sedimentary structures further supports deposition from suspension settling in a low-energy regime.

The development of argillitic textures reflects the overprinting effects of strong compressional stresses, leading to intense compaction and lithification (Fig. 8b-c). Such conditions indicate the unit has undergone low-grade metamorphism, likely within the anchizone, associated with regional tectonic deformation. This tectonic overprint not only enhanced rock induration but also obscured original depositional fabrics. Collectively, the lithological, textural, and diagenetic characteristics of the Gongsolok Argillite suggest deposition in a quiet marine setting followed by burial and tectonic compression linked to regional orogenic processes.

The Bilabekayuk Sandstone, Bilabekayuk Siltstone, and Gongsolok Argillite are assigned to the Malinau Formation [13], which is interpreted to be Middle to Late Eocene in age and deposited in a shallow-marine setting. This interpretation is supported by the dominance of fine- to medium-grained siliciclastic lithologies and the presence of sedimentary structures indicative of tidal-flat processes, including heterolithic bedding and rhythmic alternations of sand and mud, consistent with classic tidal-flat models [24].

Regionally, the Malinau Formation represents a local stratigraphic unit within the Embaluh (Rajang – Embaluh) Group. According to Moss [9], the Embaluh Group spans a broad age range from the Late Cretaceous to Early Miocene and is widely distributed across western and northern Kalimantan. The discovery of Middle Eocene large benthic foraminifera in the Boh River further corroborates the Eocene age of the Malinau Formation. Moss [9] also proposed that the Rajang – Embaluh Group may record the sedimentary infill of a remnant ocean basin, developed during progressive closure and tectonic reorganization of the region.

Overlying the Malinau Formation, the Sengayan Tuff unit marks a shift to volcaniclastic-dominated sedimentation. This unit is characterized by greenish-grey, massive tuff, with the greenish hue interpreted as the result of alteration processes and/or low-grade metamorphism (Fig. 8 d-e). Stratigraphically above, the succession grades into tuffaceous sandstone composed of coarse- to medium-grained particles, exhibiting poor sorting and weak cementation, reflecting rapid deposition from volcanically derived material (Fig. 8f). Such characteristics are consistent with pyroclastic fall deposits, where volcanic ash and lapilli settle directly from the eruption column [25].

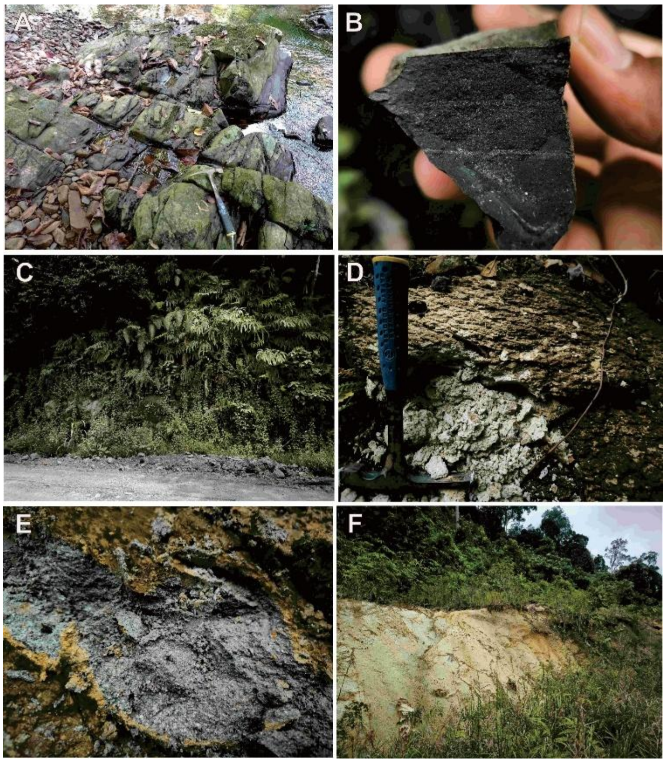


Figure 8. Field photographs of the Gongsolok Argillite and Sengayan Tuff units. (A) Outcrop-scale exposure of well-indurated, foliated argillite along a stream section; (B) Hand specimen of dark grey to blackish argillite with massive texture and very fine grain size; (C) Roadcut exposure of fine-grained argillite-dominated strata; (D) Argillite showing calcareous components and carbonate-rich layers; (E) Close-up of altered argillite with oxide staining and indurated fabric; (F) Sengayan Tuff exposure characterized by greenish-grey, massive tuff, reflecting alteration and volcaniclastic deposition.

The volcanic and volcaniclastic succession identified in the study area is interpreted as part of the Jelai Volcanic Rocks, which are regionally dated to the Late Oligocene–Early Miocene. These volcanic deposits unconformably overlie the Malinau Formation, indicating a significant stratigraphic break marked by uplift, erosion, and subsequent volcanic activity. The presence of tuff as a dominant lithology reflects deposition from pyroclastic eruptions, demonstrating that volcanism exerted a major control on sedimentation during this period. Geochemical studies by Sulistyawan et al. [25] indicate that the Jelai volcanic rocks are dominated by calc-alkaline magma, with subordinate tholeiitic compositions. Calc-alkaline magmatism is typically associated with subduction-related tectonic environments, particularly volcanic arcs, and is uncommon in intraplate or extensional settings. This geochemical signature therefore strongly supports the interpretation that the onset of Miocene magmatism in Kalimantan was linked to active subduction processes. The preservation of altered tuff and volcaniclastic deposits further suggests interaction between volcanic products and surface or hydrothermal fluids during and after emplacement.

The Jelai Volcanic Rocks are thus interpreted to represent the initial phase of Miocene magmatism in eastern and central Kalimantan. Regionally, this magmatic episode is attributed to the subduction of the Palawan oceanic plate, and is comparable to other subduction-related volcanic sequences, such as the Nyaan Volcanic Rocks and Metulang Volcanic Rocks [27]. This tectonomagmatic event occurred following the cessation of South China Sea oceanic spreading, which was triggered by the collision of the Luconia Craton, an event that also promoted crustal melting and emplacement of intrusive bodies such as the Sintang intrusion.

In addition to the volcanic units, the Sengayan Conglomerate represents a coarse-grained clastic unit that records a shift to high-energy sedimentary conditions (Fig. 9a). The conglomerate is greyish in color and composed of diverse lithic fragments, including sandstone, mudstone, and reworked conglomerate clasts, indicating a mixed sediment source (Fig. 9a). The upper part of the unit is characterized by pebble- to gravel-sized clasts, whereas the lower part consists of grain-supported, monomict conglomerate dominated by siliceous lithic fragments (Fig. 9b). These clasts are generally well rounded, with sizes ranging from gravel to cobble, suggesting prolonged transport and reworking (Fig. 9c).

The presence of normal grading and a sharply defined erosional basal contact indicates deposition from high-energy flows, likely within a fluvial channel or proximal alluvial system, where rapid sediment influx and strong traction currents prevailed. Collectively, the Sengayan Conglomerate is interpreted to record tectonically driven uplift and erosion of older source areas, potentially linked to ongoing Miocene magmatism and regional deformation. Such conglomeratic deposits are consistent with syn-tectonic sedimentation.

The presence of coal fragments within the conglomerate matrix indicates incorporation of pre-existing organic-rich material during high-energy, rapid depositional events, likely related to channelized flows or debris-rich currents (Fig. 9d-e). Such processes enabled the transport, rapid burial, and preservation of organic matter, which subsequently underwent localized coalification under favorable burial and thermal conditions. The reworked nature of these coal fragments suggests erosion of nearby peat-forming environments and their redeposition within a coarse-grained clastic system.

This unit is deposited conformably above the Sengayan Sandstone, with a sharp but non-erosional contact, indicating a rapid shift in depositional energy rather than a major hiatus (Fig. 9f). The lower part of the Sengayan Sandstone is characterized by medium-grained, cross-bedded sandstone, reflecting deposition under moderate- to high-energy conditions, likely within fluvial to tidally influenced distributary channels. Upward, the sandstone shows a clear fining-upward trend, grading into fine-grained sandstone, which records progressive energy reduction.

The upper part of the succession is dominated by siltstone and carbonaceous mudstone, indicating deposition from suspension in a low-energy environment. The occurrence of coal seams, ranging from several centimeters to meter scale, reflects periods of prolonged organic accumulation in swampy or interdistributary settings, with limited clastic input. These vertical facies transition from conglomerate and cross-bedded sandstone to carbonaceous mudstone and coal suggests an overall depositional evolution from high-energy channelized systems to low-energy, swamp-dominated environments, consistent with delta-plain or coastal plain settings.

Figure 9. Sengayan Conglomerate field characteristics and stratigraphic relationship. (A) Polymict, greyish conglomerate with sandstone, mudstone, and reworked clasts; (B) Grain-supported, siliceous monomict conglomerate in the lower part; (C) Well-rounded gravel–cobble clasts indicating high-energy transport; (D–E) Reworked coal fragments within the matrix; (F) Sharp, conformable contact with the underlying Sengayan Sandstone, marking an abrupt increase in depositional energy.

The Sengayan Conglomerate and Sengayan Sandstone are assigned to the Langap Formation, which has been dated to the Late Miocene [13]. The Langap Formation is regionally interpreted as a succession deposited in a lacustrine to lacustrine-margin setting, an interpretation supported by its basin-like stratigraphic geometry and limited lateral continuity of individual beds. Such geometry is characteristic of sediment accumulation within an enclosed or semi-enclosed depocenter, where accommodation space was strongly controlled by syn-depositional subsidence.

From a facies perspective, these two units can be interpreted as components of a turbidite-dominated depositional system developed within a lake basin. The Sengayan Conglomerate represents high-density gravity-flow deposits, dominated by debris-flow processes. The presence of coarse-grained, poorly sorted clasts indicates rapid sediment emplacement under high-energy conditions, likely related to slope instability or sudden sediment input from basin margins. These conglomerates record traction-dominated transport with limited hydraulic sorting, consistent with proximal turbidite or debritic facies.

In contrast, the Sengayan Sandstone records deposition from relatively lower-energy turbidity currents. The vertical transition from conglomeratic facies to sandstone, and locally to finer-grained sediments, reflects waning flow energy and progressive sediment fallout. This facies association is consistent with elements of the Bouma sequence, where coarse basal units (Ta–Tb) pass upward into finer-grained laminated and massive beds (Tc–Td). The coexistence of debris-flow conglomerates and turbiditic sandstones suggests repeated sediment gravity-flow events within the lacustrine basin, likely triggered by tectonic activity or rapid sediment loading.

The measured stratigraphic section records (Fig. 10) a vertical transition from subtidal to supratidal tidal-flat systems, punctuated by pyroclastic fall and debris-flow events, and capped by lacustrine–swamp deposits. The lower part is dominated by well-compacted sandstones and shales with interbedded heterolithic facies, indicating fluctuating energy conditions in subtidal–intertidal settings. Upward, increased shale content, lamination, and calcareous intervals reflect reduced energy and episodic exposure in supratidal environments. Volcaniclastic tuff layers mark discrete pyroclastic input, while conglomerates represent short-lived high-energy debris-flow deposition. The upper succession comprises carbonaceous claystone, coal, and siltstone, indicating swampy to lacustrine conditions with persistent organic accumulation.

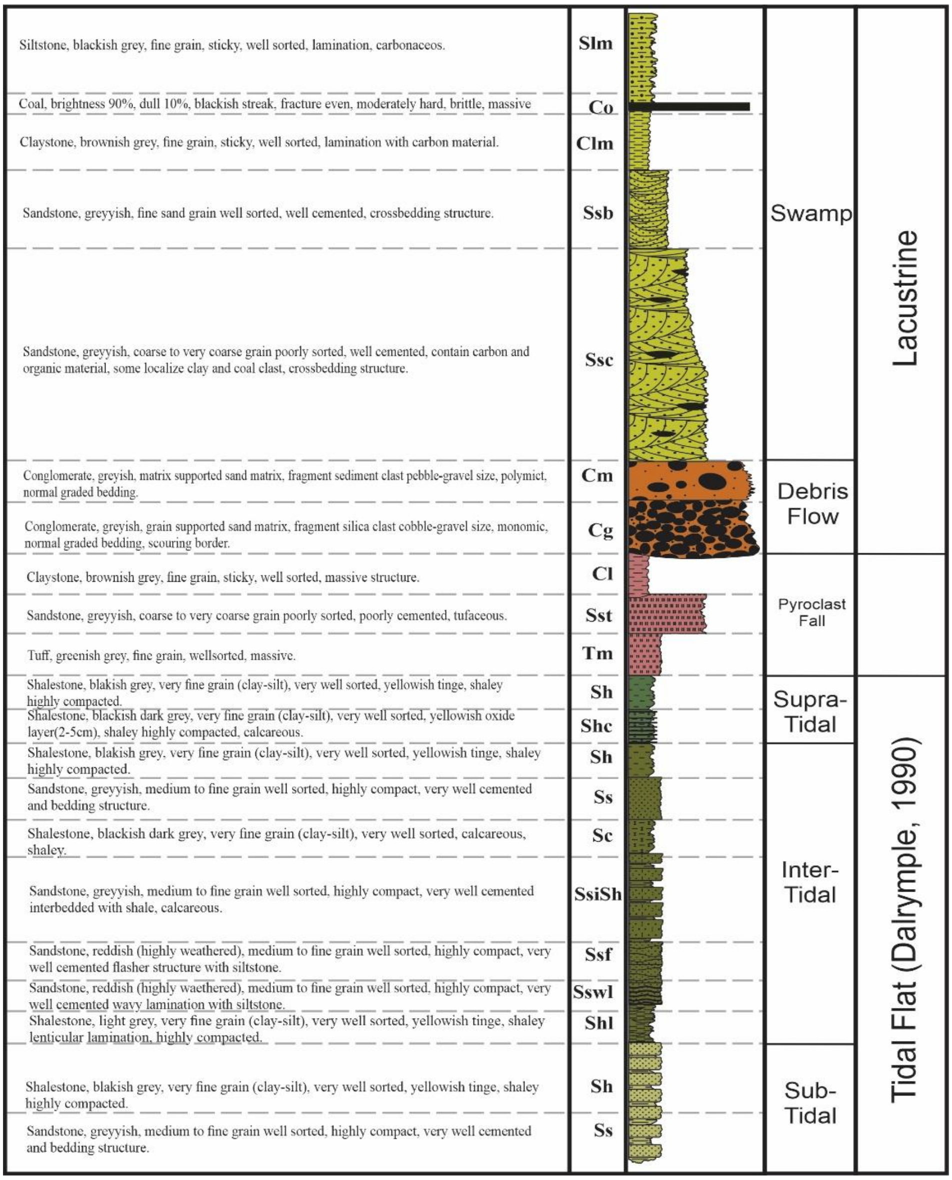
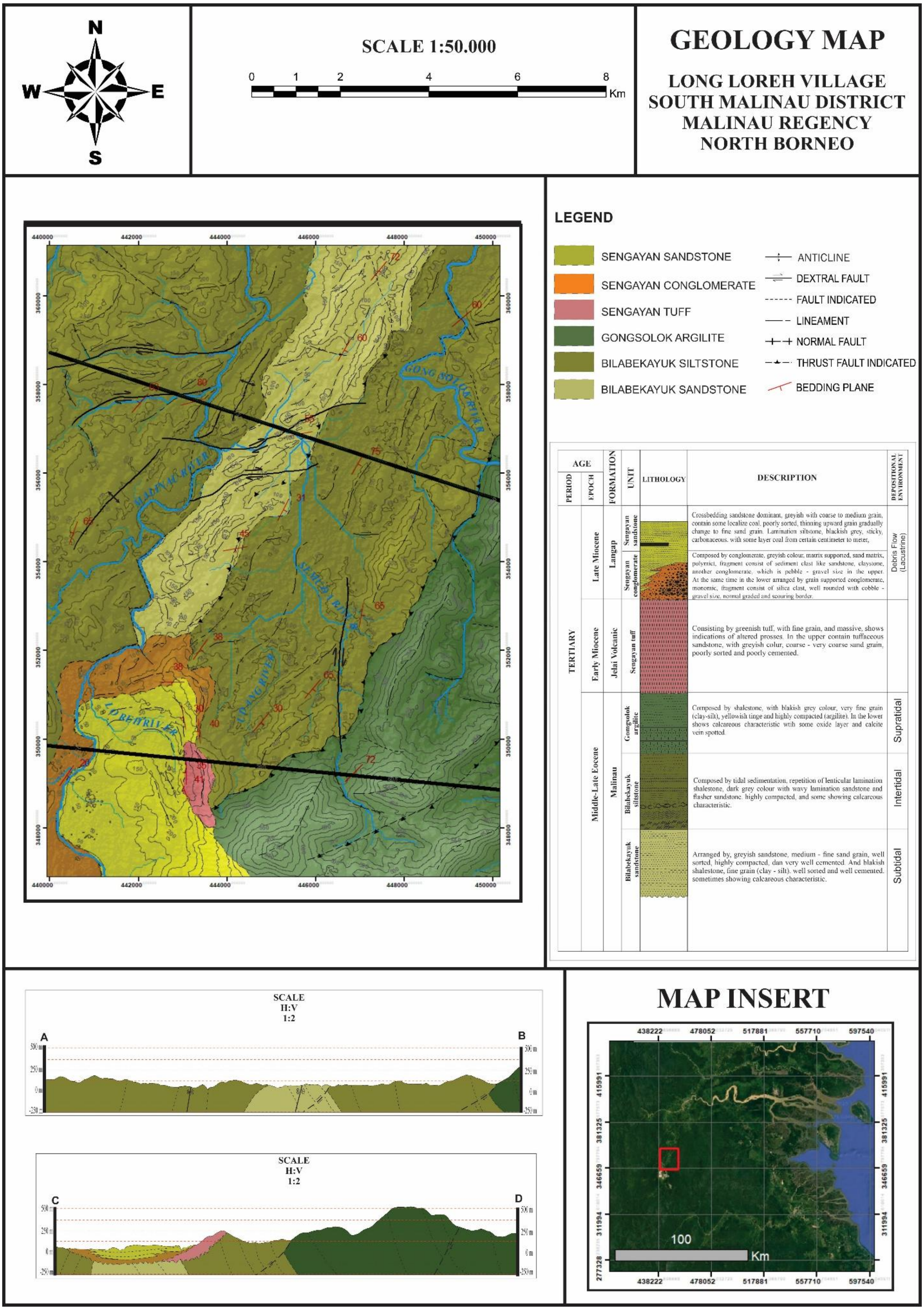


Figure 10. Measured stratigraphic section showing lithofacies distribution and interpreted depositional environments.

The geological map of Long Loreh Village, South Malinau District, Malinau Regency, North Borneo (Fig. 11) depicts the spatial relationships between lithostratigraphic units and structural elements, providing key insights into the tectono-sedimentary evolution of the area. The stratigraphy is dominated by the Sengayan Formation and the Bilabekayuk Formation, which together record a progressive transition from high-energy clastic deposition to lower-energy fine-grained sedimentation during the Cenozoic. The Sengayan Formation comprises conglomerate, sandstone, and tuff units. Sengayan Conglomerate is interpreted as a product of high-energy depositional processes, likely related to proximal fluvial or alluvial fan environments. The Sengayan Sandstone shows broader lateral continuity, suggesting deposition under moderate-energy conditions, such as braided river or deltaic channel systems. The presence of Sengayan Tuff indicates episodic volcanic activity contemporaneous with sedimentation, reflecting syn-depositional volcanism that contributed volcaniclastics to the basin and serves as an important marker for regional correlation.

The Bilabekayuk Formation consists predominantly of argillite, siltstone, and sandstone. The abundance of fine-grained facies reflects lower-energy depositional settings, interpreted as floodplain, lacustrine, or distal shallow-marine environments. Interbedded sandstone units indicate episodic increases in depositional energy, possibly related to channel migration or storm-induced processes. Facies relationships suggest an overall fining-upward trend, indicating a gradual reduction in sedimentary energy and increasing accommodation through time.



AGE		FORMATION	UNIT	LITHOLOGY	DESCRIPTION	DEPOSITIONAL ENVIRONMENT
PERIOD	EPOCH					
TERTIARY	Late Miocene	Langap	Sengayan sandstone		Crossbedding sandstone dominant, greyish with coarse to medium grain, contain some localize coal, poorly sorted, thinning upward grain gradually change to fine sand grain. Lamination siltstone, blackish grey, sticky, carbonaceous, with some layer coal from certain centimeter to meter,	Debris Flow (Lacustrine)
			Sengayan conglomerate		Composed by conglomerate, greyish colour, matrix supported, sand matrix, polymict, fragment consist of sediment clast like sandstone, claystone, another conglomerate, which is pebble - gravel size in the upper. At the same time in the lower arranged by grain supported conglomerate, monomic, fragment consist of silica clast, well rounded with cobble - gravel size, normal graded and scouring border.	
	Early Miocene	Jelai Volcanic	Sengayan tuff		Consisting by greenish tuff, with fine grain, and massive, shows indications of altered prosses. In the upper contain tuffaceous sandstone, with greyish colur, coarse - very coarse sand grain, poorly sorted and poorly cemented.	
	Middle-Late Eocene	Malinau	Gomgsolok argilite		Composed by shalestone, with blakish grey colour, very fine grain (clay-silt), yellowish tinge and highly compacted (argilite). In the lower shows calcareous characteristic wtih some oxide layer and calcite vein spotted.	Supratidal
			Bilabekayuk siltstone		Composed by tidal sedimentation, repetition of lenticular lamination shalestone, dark grey colour with wavy lamination sandstone and flasher sandstone. highly compacted, and some showing calcareous characteristic.	Intertidal
			Bilabekayuk sandstone		Arranged by, greyish sandstone, medium - fine sand grain, well sorted, highly compacted, dan very well cemented. And blakish shalestone, fine grain (clay - silt). well sorted and well cemented. sometimes showing calcareous characteristic.	Subtidal

Figure 11. Geological map of Long Loreh Village, South Malinau District, North Borneo, showing the distribution of the Sengayan and Bilabekayuk formations.

4.4 Tectonic Setting

The tectonic evolution of the study area reflects a complex interaction between marine sedimentation, subduction-related deformation, magmatism, and subsequent basin isolation. During the Middle to Early Eocene, the region was submerged under shallow marine conditions as part of a regional marine transgression. This setting controlled the deposition of the Bilabekayuk Sandstone, Bilabekayuk Siltstone, and Gongsolok Argillite, which record tidal-flat sedimentation characterized by heterolithic facies, fine-grained dominance, and organic-rich mud accumulation. These units are assigned to the Malinau Formation, a local stratigraphic component of the Rajang–Embaluh Group, whose evolution was influenced by subduction-related processes linked to the Luconia Block along western Kalimantan.

A major tectonic reorganization occurred during the Oligocene–Miocene, associated with the subduction of the Palawan oceanic plate from the west. This compressional regime resulted in the development of thrust faults, regional shortening, and the progressive uplift of the Kuching High in western Kalimantan, effectively isolating the study area from open marine conditions. Structural deformation during this phase generated prominent W–E–oriented lineaments and induced significant tilting of the Malinau Formation strata, with bedding dips ranging from 40° to 80°, reflecting intense tectonic stress and basin inversion.

Contemporaneous with subduction, Miocene magmatic activity was initiated, supplying volcanic material that formed the Jelai volcanic rocks and associated tuffaceous units, including the Sengayan Tuff Member. These volcaniclastic deposits mark a transition from purely sedimentary processes to volcanically influenced sedimentation within the evolving basin (Fig. 11). Following tectonic uplift and basin isolation, a new phase of intrabasin sedimentation developed during the Late Miocene, leading to the deposition of the Langap Formation. This succession includes the Sengayan Conglomerate and Sengayan Sandstone, which were deposited in a lacustrine to fluvio-lacustrine environment. The presence of carbonaceous layers and coal seams indicates the development of swampy, low-energy conditions, reflecting a mature continental basin setting. Collectively, the stratigraphic and structural relationships document a tectonic transition from Eocene shallow-marine deposition to Miocene compressional deformation, volcanism, and Late Miocene continental basin development, consistent with regional tectonic models for northern Kalimantan.

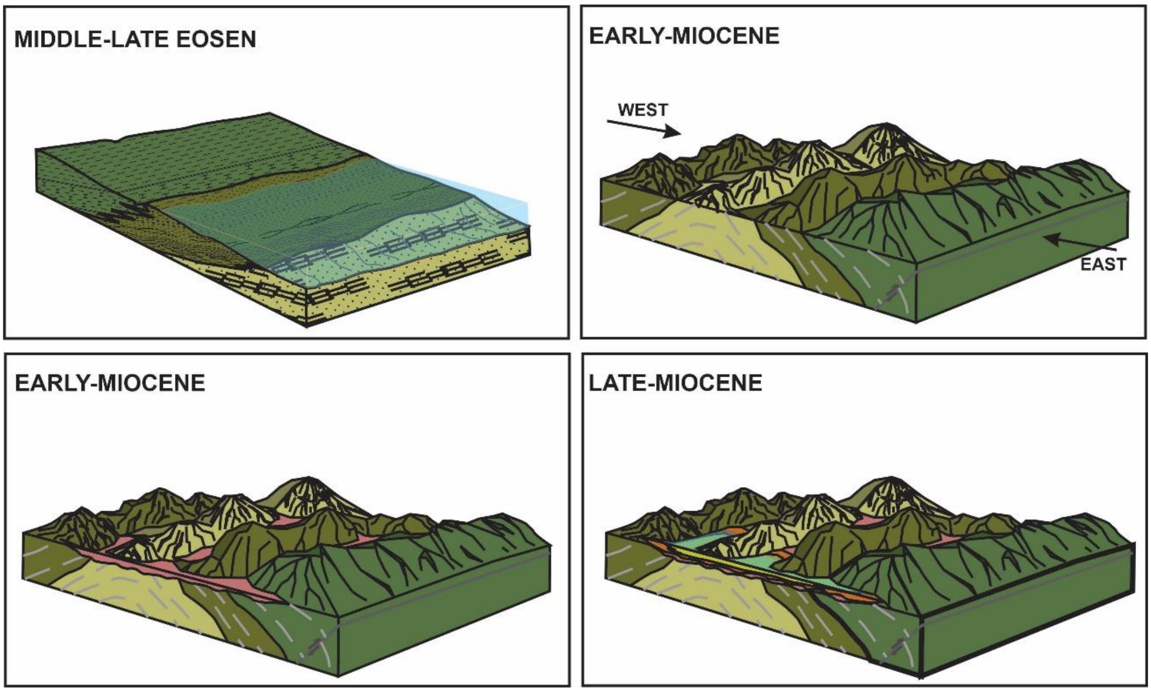


Figure 11. The block diagrams illustrate the tectono-sedimentary evolution from the Middle–Late Eocene to Late Miocene.

5. CONCLUSION

The study area in northern Kalimantan is strongly controlled by regional tectonic activity. The oldest units belong to the Malinau Formation of the Rajang–Embaluh Group, deposited during the Middle to Late Eocene in a tidal-flat, shallow-marine environment. From oldest to youngest, the stratigraphic succession comprises the Bilabekayuk Sandstone, Bilabekayuk Siltstone, and Gongsolok Argillite, all recording dynamic tidal processes. Subsequent deformation related to subduction of the Palawan oceanic plate from western Kalimantan resulted in uplift, faulting, and folding, and was accompanied by Oligocene–Early Miocene magmatism, producing volcanic units such as the Sengayan Tuff of the Jelai volcanic suite. Continued uplift led to basin isolation and the development of Late Miocene lacustrine environments, in which the Sengayan Conglomerate and Sengayan Sandstone of the Langap Formation were deposited.

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