International Journal of Civil Engineering (IJCE)
ISSN(P): 2278-9987; ISSN(E): 2278-9995
Vol. 6, Issue 4, Jun - Jul 2017; 47-56

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

THE APPLICATION OF SEQUENCE STRATIGRAPHY TO THE SAJAU (PLIOCENE) COAL DISTRIBUTION IN BERAU BASIN, NORTHEAST KALIMANTAN, INDONESIA

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ABSTRACT

The deposits in the Sajau coal measures of Berau Basin, northeastern Kalimantan were within a range of facies associations, which ranged a wide spectrum of settings from fluvial to marine. Siliciclastics were found to be more prominent in the transitional to terrestrial coal measures. However, these coal measures contained in addition three laterally extensive marine bands (mudstone). The function of these bands was to play the role of marker horizons, assisting in the correlation between fully marine and terrestrial facies. On investigating this range of facies and their sedimentology, a high-resolution sequence stratigraphic framework could be developed. The third-order Sajau transgression has been already established, and in its light, nine fourth-order sequences are recognized. The study reported peat accumulation principally correlating in transitional areas with early transgressive sequence sets (TSS) and high stand sequence set (HSS) in the composite sequences. In addition, in more landward areas, it correlated with the middle TSS to late high stand sequence sets (HSS). Peat accumulation regimes showed wide differences inside the sequence stratigraphic framework. These differences were considered to be because of deviations in subsidence and background siliciclastic input rates in depositional setting variants. A combination of differences and variations resulted in discrepancies in the rate of accommodation change. Nevertheless, the preservation of coal resources in the middle-to-late HSS in this area was probably due to the rise of the regional base level throughout Sajau.

KEYWORDS: High Resolution, Sequence Stratigraphy, Coal, Pliocene, Berau Basin

INTRODUCTION

The sedimentological characteristics of the flu-vio-deltaic coal measures from the Sajau (Pliocene) sedimentary succession in Berau Basin, northeastern Kalimantan are presented in this study. Furthermore, it recognizes a high-resolution sequence stratigraphic framework of the Sajau. The data obtained in the study helped to establish a proposal for a coal accumulation model. The results would most probably enable coal prediction. In addition, this economically important coal province of Kalimantan Island could be reviewed. Furthermore, a sedimentological and palaeoenvironmental framework was established for future investigations into the evolution of terrestrial to marine communities from this interval.

Sequence stratigraphy is the study of genetically related facies within a framework of chronostratigraphic significant surfaces [1]. The structure of these facies is a relatively conformable strata, which is layered at its top and base by sequence boundaries, unconformities or their correlative conformities [2, 3]. In accordance to this concept, the stratigraphic succession may be divided into genetically related facies of (depositional) sequences layered by sequence boundaries (SB) at their top and base contacts. The sequence may be further partitioned into systems tracts [4] in a complete unit. This study mainly considers the sequence stratigraphic interpretation on the basis of facies associations and development of laterally extensive marine bands, which are considered as marker horizons. The sedimentary observations and analyses provided in the study help to have a better understanding of the alterations occurring at base level and its identification during the development of the sedimentary sequences. It also allows evaluation of the lateral relationships of facies. The terminology of [1] is applied in this study. However, the concepts of "parasequence" and "parasequence set" are not eligible for the entirely terrestrial parts in the study area. This non-applicability is because of the tough task of identifying transgressive surfaces. Nevertheless, genetically related temporal units (i.e. system tracts or sequence sets) based on other well-developed key surfaces including unconformities and maximum flooding surfaces (MFSs) may also be identified. The sequence stratigraphic framework is constructed for regional correlation and mapping. The framework is built by applying a high-resolution sequence stratigraphic methodology [3]. A sequence is a genetically related succession of strata with no internal unconformities, which is bounded by unconformities and their correlative conformities [2]. Conversely, a composite sequence refers to a succession of related sequences in which the individual sequences stack into lowstand, transgressive, and highstand sequence sets [3]. In this area, long-term sequences (equivalent to third-order sequence) were found to have shorter term; therefore, the terminologies of composite sequence (CS) and associated sequence sets are applied in such scenarios.

GEOLOGY

The Berau Basin comprises the onshore areas of northeast Kalimantan passive continental margin. The Mesozoic and older rocks of the Sampurna High bound the basin in the north. To the west, it is bound by the strongly folded Mesozoic to Eocene mélange of the Kucing High. In the south, the basin is bound by the Mangkalihat High separating the Berau Basin in the north from the Muara Basin and Kutai Basin in the south. This high is considered to be associated with the Fault Zone along the north shore of the Mangkalihat Peninsula. In the east, the basin extends toward the Makasar Trough of the Celebes Sea (Figure 1).

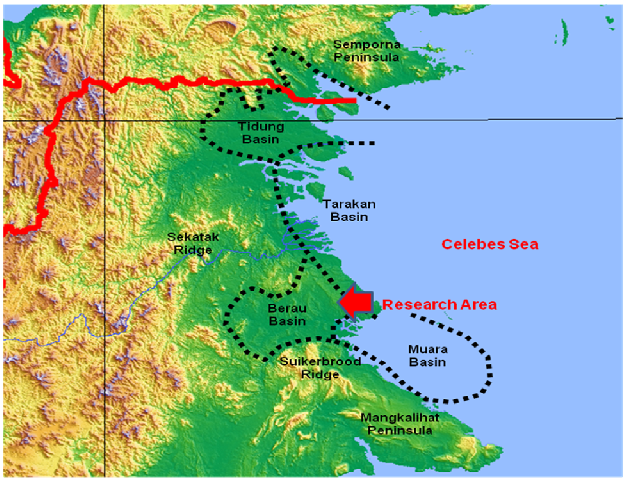

Figure 1: The Physiography Map of Berau Basin and other Basins in Northeastern Kalimantan. There are Basins around the Berau Basin that are Arranged distinctly as two Onshore and two Offshore

During the Upper Mesozoic era, the Kalimantan region was a comparatively more stable Sundaland. The subsiding sites were filled with thick flysch sediments formed because of erosion of basement highs to the southwest. In the Upper Cretaceous era, intensely folded and faulted sediments were shifted northwards by Eocene. This formed thick siliciclastic deposition in the Tidung Depocentre. In addition, thick mudstone associated with more stable platform occurred in Berau Basin. Tectonics in the northeast Kalimantan area occurred because of collision between Indian and

Eurasian Plates at 50 Ma. This collision resulted in the back arc extension, which was associated with subduction rollback in the west Pacific, and the opening of the Berau Basin by Rifting in the Eocene. [5], [6] The collision was comparatively less significant. The Tarakan basin is an aulacogen-like basin, and the rifting is related to the complex Eocene tectonic events and plate reorganization. This caused opening of the Makasar Strait to the south and the Celebes Sea to the east.

Orogenic uplift of the Sundaland had come to an end before the commencement of late Eocene. This process was also associated with slow continuous basinal subsidence, which highlighted the start of a marine transgression of the Berau Basin. The transgressive deposition continued during the Oligocene and early Miocene period, with continuous deposition of limestone and marl over most of the basin area. Renewed tectonic uplift was noticed in the western basin margin and highlands. Siliciclastic, coal and mudstone deposition was seen in the late Oligocene to early Miocene period in the northern basin, and limestone deposition was continuous in the stable shelf of the Mangkalihat area to the south. Two main structural trends noticed in the Berau Basin were NW to SE and NE to SSW. The initiation of these trends was in the Eocene. However, they were periodically reactivated during generally compressive phase from the Middle Miocene to present. The regional uplift and inversion in the Middle Miocene was correlated with the collision of continental fragments in the South China Sea. Nevertheless, an inversion arose that was associated with the collision of Australia with the Banda arc in the Pliocene. The Middle Miocene uplift caused the deposition of easterly prograding coarse siliciclastics in the northern Tarakan depocentres. The southern Mangkaliat Peninsula continued to be as a submerged limestone platform, with the possibility of reef build-ups.

The Plio-Pleistocene compression tectonics occurred because of fault reactivations and inversions, and a succession of NW-SE plunging oriented anticlines of Tarakan, Bunyu, Latih, and Sebatik anticlines, which were associated with Kantil and Mandul synclines. In the Pleistocene times, sedimentation of the Sajau formation mostly developed in balance with more rapid subsidence in the Berau Basin. The final result was thick deltaic progradational cycles associated with easterly shifted main depocenter from the Tarakan Island. In the Pliocene time, Mangkaliat area gradually formed into a positive land area with subsidence of the Muara dopocentres. Volcanic activity also occurred with igneous intrusives and extrusives in the Sekatak and Sadjau areas.

The basin-fill succession of the Berau Basin is categorized into 3 prime cycles of sedimentation. Each cycle represents varying lithological characteristics. The lithological characteristics are closely associated with tectonism and related relative sea-level changes, which progress to transgressive and regressive events. The oldest sedimentary cycle is a syn-rift volcanic bearing siliciclastic-rich unit of the Middle to Upper Eocene, which is called Sekatak Group. The Sekatak Group has the Sembakung Formation and the unconformably overlying Sujau and Malio Formations. The group unconformably overlies pre-rift, Triassic to Cretaceous Sundaland basement rocks, and also underlies the post-rift unconformity below the younger group sediments. The younger group sediments form the Sebuku Group and is represented by transgressive carbonate-bearing units, which progressed during Oligocene-Lower Miocene post-rift transgression. The units comprise Seilor Formation limestone and its lateral equivalent of the Mangkabua Formation. The unconformably overlying rocks constitute the Tempilan, Tabalar, Mesaloi and Naintupo Formations. Locally regressive sandstone of the uppermost part of Naintupo Formation forming coarsening and shallowing upward facies was noticed in various wells (e.g. Sembakung 6 well). This group is unconformably overlain by youngest group, which has coarser siliciclastic-rich units and lesser amounts of developed carbonate.

The youngest is called Simenggaris Group and has five lithostratigraphic units, that is Meliat/Latih (oldest), Tabul/Domaring, Tarakan/Sajau, and Bunyu (youngest) Formations. The deposition of sediments in this group occurred during major regression. Deposition was correlated with periods of regional tectonic uplift. Latih Formation is the oldest unit within the youngest group. In Kalmerah-1 well, the unit primarily comprised sandstone and shale in alternative formations, with coal. In this well, Domaring/Santul Formation conformably overlies Latih Formation and was formed of shale, sandstone, and coal. The coal-bearing shale and sandstone of Domaring Formation overlies Meliat Formation, and unconformably underlies Sajau Formation sediments. Both tectonic as well as eustatic controlled regression progressed. to the regression produced more proximal sediment deposition of the coarser grained and more developed coal-bearing lithologies, which were related with thinner shale of the Sajau Formation. The overlying Bunyu Formation depicted copious amounts of thick, medium to coarse grained, occasionally conglomeratic sandstone, which also had lignite interbeds and minor shale.

METHODOLOGY

Exploration of four wells (Kalmerah-1, Bu-nyut-1, Labak-1 and Galiadap-1) led to its stratigraphic description. In addition, eleven field-based measured sections were described along with facies analysis and correlation (Figure 2). These investigations helped to obtain the data required for the study.

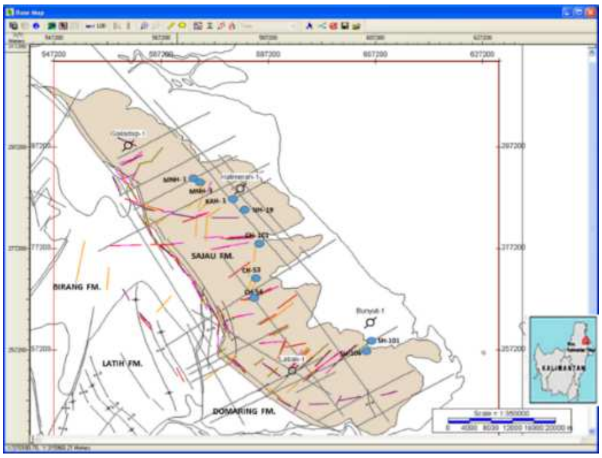

Figure 3: The Location of Well Exploration and Field Outcropped in Berau Basin, Northeast Kalimantan

The core was described using the following criteria: interval and bedding thickness, lithology, grain size, bioturbation index, sedimentary structures, identification, and nature of contacts. Fieldwork for the investigations was conducted during the period 2012-2013. A reconnaissance trip was arranged in the entire Sajau field area to select the outcrop locations. Selection was on the basis of the quality of exposure and proximity to core locations. Ten field-based measured sections were sampled and described in two areas (Tanah Kuning and Kasai). Facies, facies associations, and stacking patterns were allocated to the core samples and field observations.

Using the facies, facies associations, and stacking patterns allocated to the measured sections, flooding surfaces were identified. The identification of the flooding surfaces was based on their unique marine signatures. Marine flooding surfaces are actually isochronous surfaces separating the younger and older strata. Marine flooding surfaces indicate any abrupt increase in water depth. These surfaces are bound by a cycle of deposition in their upper and lower zones. The deposition forms the most effective and accurate correlation of genetically related strata within the Berau Basin.

RESULTS AND DISCUSSIONS

Sedimentary Facies and Facies Association

Litho logical and palaeontological criteria helped to recognize the field and well log based lithofacies. The identification of the lithofacies was assisted by the geometry and lateral relationships with other facies. The Sajau coal measures in Tanah Kuning, Mangkupadi, which is in northern part, and in Kasai, Batu-Batu Area, which is in southern part, mainly comprised siliciclastic rocks and coals, in addition to 13 (thirteen) distinct lithofacies (summarized in Table 1). A summary of the facies associations and the component facies as well as subfacies is elaborated in Table 2. The table highlights the most important characteristics of the facies associations, especially the corresponding peat-accumulation potentials.

Table 1: The Lithofacies of Sajau – Coal Bearing Formation

No	Lithofacies	Lithology	Sedimentary Structure	Fossils	Environment
1	Medium sized conglomerates	Clast supported conglomerates. Gravel: 1-2 cm, well rounded, medium to well-sorted, mainly siliceous rocks and quartz. Matrix: fine sands with siliceous, and glauconitic cements	Occasional graded and bidirectional bedding. Trough cross bedding. Scour and fill, erosional. More upward fining than coarsening upward.	Fossilized wood and coal parting.	Braided Channel and gravelly mouth bar
2	Fine sized conglomerates.	Conglomerates, gravel: <1 cm, well rounded, and poorly sorted. Matrix: fine sands with siliceous and glauconitic cements	Through and planar cross bedding, sometimes massive. More upward fining than coarsening upward.	Fossilized wood and coal parting	Crevasse splays or channel lags of meandering
3	Medium to coarse sized sandstone	Medium to coarse, moderately rounded, and moderately-sorted, with siliceous cement.	Erosional base. Trough and wedge cross bedding and graded bedding, with Fining upward sequence.	Fossilized wood	Braided Channel and overbank
4	Fine to medium sized sandstone	Fine to medium, well rounded, well-sorted, and occasional muddy gravels at their base, with siliceous cement	Mostly trough cross bedding.	Plant remains	Mouth Bar
5	Tabular Cross bedding sandstone	Fine to medium, moderately-sorted, and well rounded sandstones with siliceous cement	Mostly tabular cross bedding.	Plant remains	Meandering channel
6	Tidal bedded sandstone	Fine to medium, well-sorted, siliceous sandstones containing lag deposits of fine, often muddy gravels and coarse sands	Mostly found the tidal bedding, trough and tabular cross bedding	Plant remain and rootlets	Tidally influenced distributary channels
7	Bidirectional bedded Sandstones	Fine to medium , well-sorted and rounded, and siliceous sandstones that locally contain muddy gravel and glauconitic sandtone	Erosional base, bidirectional-bedding and tabular cross bedding, and erosional bases	Rootlets and plant fossils	Interdistributary bays.

Table 1: Contd.,

No	Lithofacies	Lithology	Sedimentary Structure	Fossils	Environment
8	Alternating of fine sand, silt and mudstone with tidal bedding	Alternating of the fine, moderate to well-sorted and rounded sandstones, siltstones and mudstones,	Wavy interlaminations and flaser and lenticular-bedding.	Plant remains and rootlets	Tidal flats
9	Interlaminations of fine sand, silt and mudstone	Alternating of the fine, moderate to well-sorted and rounded sandstones, siltstones and mudstones and occasional coal streaks	Horizontal bedding, ripples and bioturbation.	Plant remains and rootlets	Flood plains or levees
10	Bidirectional inter-lamination sandstone, siltstone and mudstone	Alternation of fine sandstones with interbedded siltstones or mudstones	Erosional base, bidirectional tidal dominated structure and graded-bedding	Plant debris	Tidal channel
11	Mudstones	Interlamination mudstones, clays, and shales , containing pyrite and siderite.	Horizontal bedding, wavy and ripples, and occasionally bioturbated	Plant debris	Lagoonal
12	Carbonaceous Shale	Black colour carbonaceous shale	Massive.	Plant debris and rootlets	Mires, flood plains, and tidal flat
13	Coal	Brownish coal	Massive and banded	Plant debris Rootlets, and cytoclast	Mires with marine influences

Table 2: The Association between Main Facies and Facies/Subfacies of the Sajau Coal Formation

Main Facies Association	Facies	Subfacies	Lithofaies
Braided River and Braided Delta	Braided Delta Plain	Braided Channel Sandy channel Interfluvial Mire	1 4 9 12,13
	Delta Front	Gravelly Mouth Bar Sandy Mouth Bar	3 8
	Prodelta	Tidal Flat Lagoon Mire	9 12 13,14
Fluvial Plains	Meandering Fluvial	Crevasse Splay Flood plains Meandering Channel Mire	2 10 6 13,14
Delta	Upper Delta Tide Dominated Delta Plain	Levee Crevasse Splay Interdistributary bay Mire	5 10 2 8 13,14
	Lower Delta Tide-Dominated delta Plain	Tidal Channel Interdistributary bay Mire Tidal Flat	7 8 13,14 9

It could be inferred from the data that these lithofacies resulted in non-marine to transitional marine environments. Furthermore, field observations and geological mapping helped to construe the following facies associations: (1) braided river and braided delta, (2) fluvial plain, and (3) fluvial delta–tidal plain. The braided river and braided delta facies association have distinctive sedimentary features that help in differentiating it from the fluvial plain facies association (meandering river facies).

Sequence Stratigraphy of Sajau Formation

In the high-resolution sequence stratigraphic framework, fourth order sequences stack upon each other forming composite sequences. Low stand sequence sets (LSS), transgressive sequence sets (TSS), and high stand sequence sets (HSS) are recognized in the composite sequences by the stacking patterns of fourth order sequences and the surfaces bounding them. In the LSS, individual sequences are arranged in a prograding to aggrading pattern. Due to the low rate of accommodation increase during the low stand stage of the composite sequence, most of the fourth-order sequences included in the LSS are comparatively more multistoried and multi-lateral, with incised valley fills. However, some fourth order sequences without basal scours may be formed because of short-term base-level highs. TSS is has a back-stepping or retrograding stacking pattern of individual sequences in the set. In the investigation site, primarily in coastal settings with high sedimentary cyclicity, each fourth-order sequence was characterized with distal facies having thicker equivalent marine bands until the MFS, which is highlighted by the presence of most widespread marine bands. In fact, two extensive marine bands (MB1, and MB2, MB3), which vary from landward areas to shallow marine environments, could easily limit the position of the TSS approximately in each third-order sequence set. Besides, basal erosion could occur in the fourth-order sequences in TSSs; however, similar events are not as pronounced as those in the LSS. Meanwhile, sand bodies in the TSS are further isolated with high sinuosity and single-storeyed channel deposits, whereas the LSS has multi-storeyed fluvial sand. Similarly, considerable increase of overbank and flooding plain deposit in the TSS is representative of an increase in accommodation rate in a third-order cycle.

The prograding stacking pattern of individual sequences in the set distinguish the HSS from the others. The top and bottom surfaces of the HSS signify the sequence boundary of the next composite sequence and the MFS, respectively. The fourth-order sequence with HSS in the paralic setting has significant amplified portions of marine sediments, both in extent and thickness. This feature is most apparent immediately after the MFS. In the terrestrial area, fluvial sandstones of the HSS are more amalgamated than those of the TSS. This implies a reduction in the creating rate of accommodation space. Figure 3 provides a summary of sequence stratigraphy of Sajau Formation.

Coal Distribution Pattern within the Sequence Stratigraphic Framework in Berau Basin

In the earliest Sa-jau, a third-order transgression originated after the extensive late Miocene unconformity (SB1) [7], 2008). In this phase, coal-forming environs expanded on a vast, newly exposed, palaeoweathering base. This feature has been illustrated in the sequence sections of Figs. 3. On quantitatively studying the major coals within sequence sets of the composite sequences from this study, the idea that peat usually developed from the late LSS to HSS [8] - [12] could be endorsed. However, obvious variances are noticed among the landward, transitional and seaward areas. Regionally extensive coal seams are considered important in sequence stratigraphic correlation, especially as indicators of MFS [13].

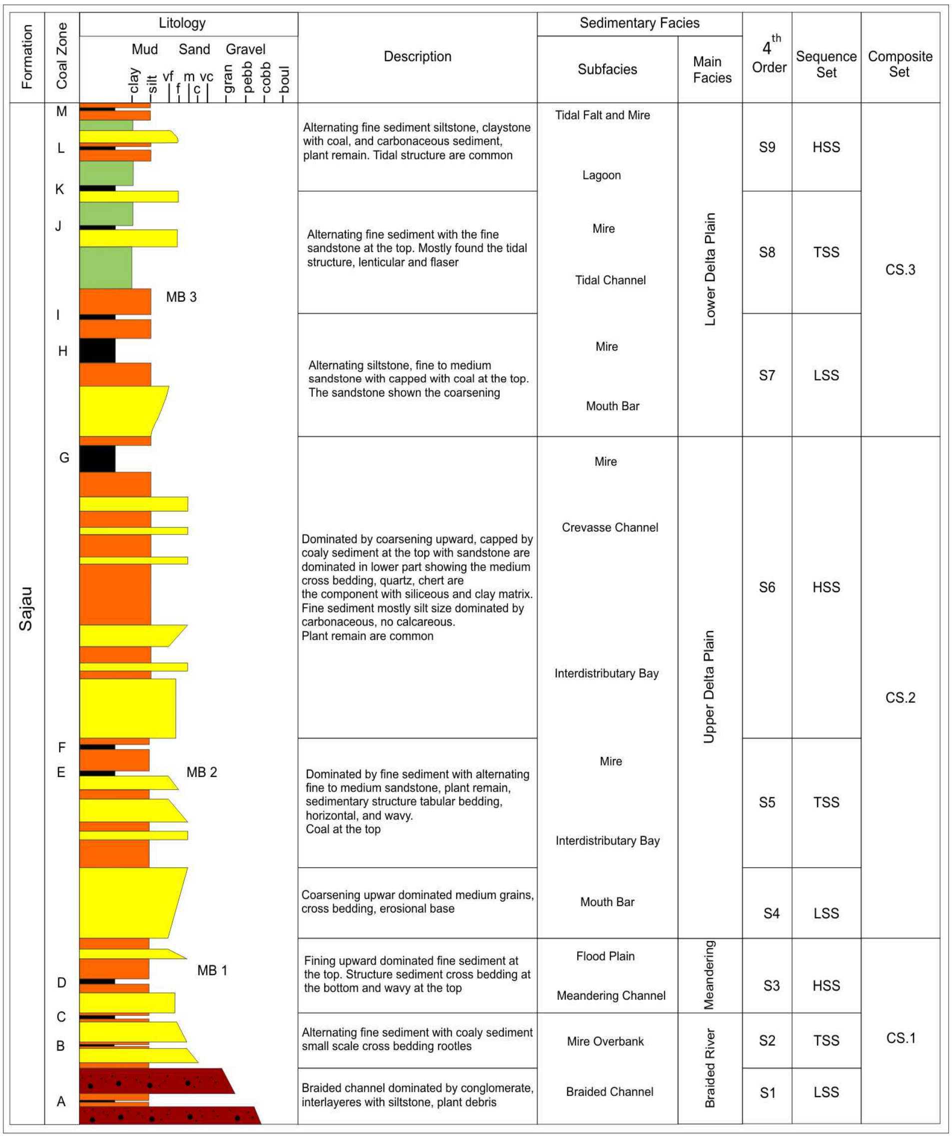

Figure 3: Columnar Section Indicating the Sequence Stratigraphic Delineation of the Sajau Formation from the Berau Basin. CS — Composite Sequences (Third-Order); S1— Sequence Sets; HSS — Highstand Se-Quence Set; TSS — Transgressive Sequence Set; LSS — Lowstand Sequence Set; 4th Order – Fourth-Order Sequences; MB — Marine Bands; A – M – Coal Seam...

CONCLUSIONS

In the investigation site, the sedimentary infill and peat formation developed on a paleoweathering surface. This surface was established during the late Miocene to Pliocene Age. The development was mainly controlled by a third-order transgression in the Sajau. In the early stages in the Sajau, the eastern part of the basin had alluvial systems. Gradually, during the newly initiated transgression, the accumulation of peat was initiated on the lagoon–tidal plain in western and southern areas. By the middle of the Sajau, fluvial plain were more prominent in the eastern basin. Meanwhile, further east, a fluvial delta–flat plain system occurred because of a greater marine influence. Continued and extensive transgression in the later stages of the Sajau resulted in less clastic input from the west of the research area; however, peat continued to pile up in a range of settings. Although peat accumulation was predominant in all settings, it was extensive in fluvial delta–tidal plain settings.

A comprehensive sedimentary analysis and subsequently high-resolution sequence stratigraphy could be conducted by employing laterally extensive and correlatable marine bands. Furthermore, three composite sequences (third-order) and thirteen fourth-order sequences within the Sajau strata of Berau Basin are identified. Base-level changes are responsible for the accumulation of these sequences and their associated peats/coals. On the basis of the composite sequence framework, peat development is indicated to be favorable from late LSS to HSS. However, deviations are noticed in the marine and terrestrial regimes. Usually, it is more probable that peat developed in marine areas during the late LSS via TSS to late HSS, and in terrestrial areas during the late TSS to HSS. Variance in subsidence and background clastic input rates in different settings cause disparities in coal accumulation regimes. The variations result in discrepancies in rates of accommodation change. Moreover, in the investigation area, the preservation of coal resources in the middle to late HSS was most probably because of the rise of the regional base level through the Sajau.

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