Tertiary Sequence Stratigraphy
of Bird Head Area, Eastern Indonesia

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Abstract - A long depositional period of Papua limestone called Kais Formation, which is overlain by clastic sediments of Steenkool Formation, reflects an interesting stratigraphic architecture in the West Papua region. Using seismic stratigraphic method of five stacking patterns, forestepping, downstepping, upstepping, backstepping, and seismic facies (parallel, prograding clinoform, channel fill, mounded) have been observed. Chronostratigraphic reconstruction was completed to figure out the depositional units in space and time. This study reveals the lowstand deposit during Early to Middle Eocene (LST), transgressive-highstand carbonate deposit during Middle Eocene to Middle Oligocene, and transgressive-highstand silisiclastic (TST-HST) deposit during Middle Miocene - Late Pliocene.

Keywords: sequence stratigraphy, chronostratigraphy, Tertiary, West Papua, Kais Formation

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INTRODUCTION

There are a number of sedimentary basins around the Bird Head area of Papua Island, including Salawati and Bintuni Basins which are hydrocarbon-producing basins. Kasuri, Jamusura, Besiri River, and Monie are the dry wells that had been abandoned in West Papua (Tobing and Robinson, 1990).

Those wells are located around Bintuni Bay. The Bintuni Bay is an area that has some gas-producing wells. Although the Bintuni Bay has a structural trap, there is a possibility for exploring stratigraphic trap by discovering stratal clinoform geometry in the southern Bintuni Bay. In a seis-mic figure, this stratal clinoform is in association with drowning unconformity. In the eastern Bird Head region of West Papua, Indonesia, Middle Miocene strata record a drowning unconformity and their related strata are important records of key tectonic and environmental events throughout the earth history (Gold *et al*., 2017). Strata that may represent drowning successions have been described previously in the Bird Head, but were not recognized as such (Visser and Hermes, 1962; Pieters *et al*., 1983; Gibson and Soedirdja, 1986; Brash *et al*., 1991; McAdoo and Haebig, 2000).

The stratigraphic clinoform plays a significant role in the study of sequence stratigraphy as the key to some progradational and retrogradational

pattern. It is important to consider that clinoforms in seismic data are depositional forms with dimensions varying from few hundreds of meters to several kilometers (Berton and Fernando, 2016). This research aims to find answers to these problems, which is seeking the status of the clinoform through stratigraphic sequence analysis in the discovery of Tertiary play. Several issues remain to be addressed by clinoform involving the influence of paleotopography of the clinothem on deposition, as well as paleorelief between the clinoform inflection and paleodepth (Miller *et al.*, 2013).

Geological Setting

The geological setting of West Papua is tectonically complex, according to Pieters *et al.* (1983), Chevallier and Bordenave (1986), and Perkins and Livsey (1993). The eastern part of the West Papua region is bounded by Lengguru Fold-Thrust Belt (LFTB), the northern part is bounded by the oldest rock of Kemum Block, the western part is bounded by Misool-Onin-Kumawa (MOKA) Structural High, and the southern part is bounded by Tarera-Aiduna Fault, then also a strike-slip fault called Sorong Ransiki Yapen (Gold *et al.*, 2017; Fraser *et al.*, 1993). Pieters *et al.* (1983) has divided the Bird Head stratigraphy into Pre-Carboniferous Basement, Permian Sediments, Triassic-Jurrasic Sediments, Cretaceous Sediments, New Guinea Limestone Group, and Late Cenozoic Clastic Sediments.

Mesozoic series consist of terrigenous shaly material at the base. The Tertiary lithologies are dominated by thick Eocene to Miocene New Guinea Limestone, overlain by Middle Miocene to present, fine-grained turbidites, and Molasse deposits. However, Paleocene gravity flow sediments do not cropped out in the surface. Three major sequences from older to younger are:
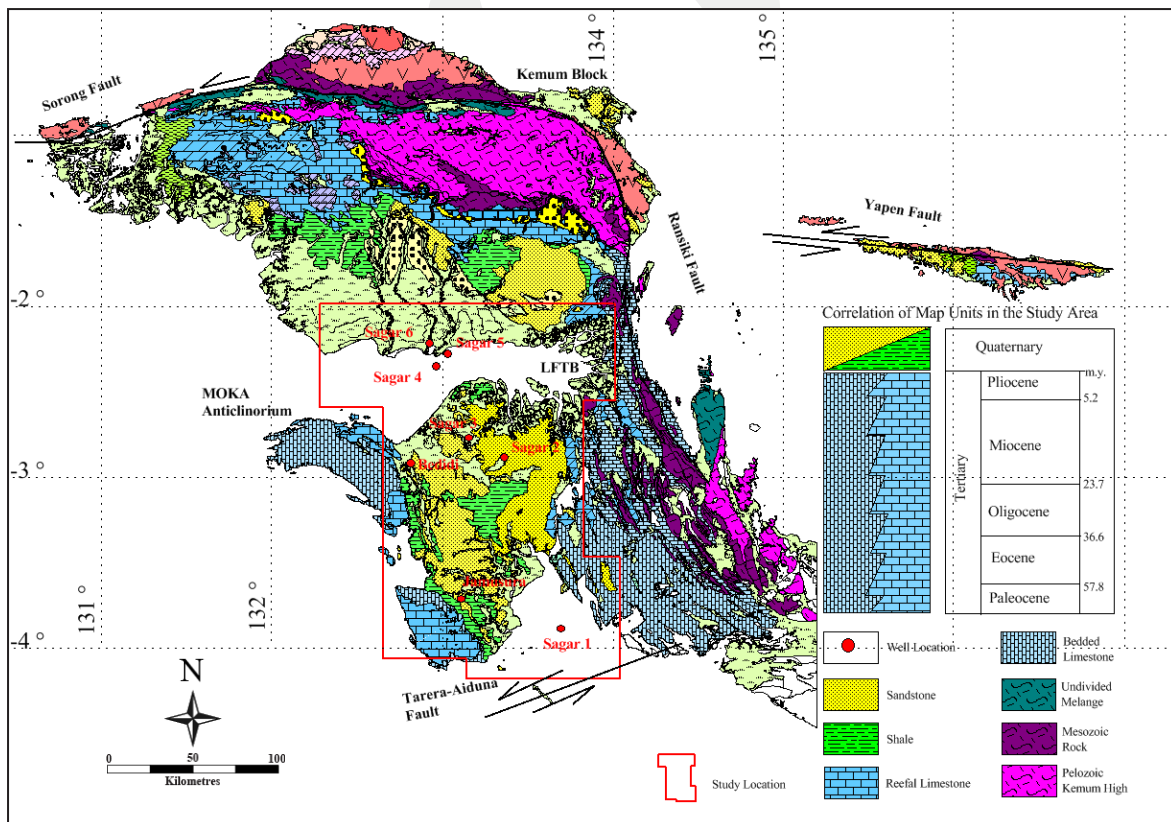

Figure 1. Geological map of West Papua region, modified from Atmawinata and Ratman, 1989; Atmawinata *et al.*, 1989; Hartono *et al.*, 1989; Sukanta and Pigram, 1989; Ratman *et al.*, 1989; Amri *et al.*, 1990; Supraman and Robinson, 1990; Tobing *et al.*, 19990; Tobing and Robinson, 1990).

- The Lower Tertiary group of New Guinea Limestone is as the main part of Lengguru Thrust Belt.
- Pliocene Steenkool Formation covers most of southern part of the Bird Head region (Bailly *et al*., 2009).
- The post sequence (11 Myr) shows two clastic formations which are synchronous to the LFTB.

Reef buildups were common in the Lower and Middle Miocene on paleohighs, including long-lived basement highs (Bailey *et al.*, 2015). There are several different published models of the origin of the Bird Head region. It is clear that deformation of the region varies from area to area indicating that the region experienced several translations and rotations during their history (Sapiie *et al*., 2012). Understanding the stratigraphy in the area is critical in solving Tertiary play of the Bird Head region, in addition to an understanding the complexity in structural trap and another trapping style. Figure 2 is a regional stratigraphy that in further explanation on stratigraphy (evaporitic to shaly carbonate) implies the presence of Paleocene to Middle Miocene rock and corresponds to lateral variation. The regional stratigraphy above is developed using lithostratigraphy that would be different emphasis from the concept of sequence stratigraphy, especially on the stratigraphic surface boundaries.

Older rock formation underlain the studied interval, Paleocene, is composed of sand-shale alternations overlain by evaporitic facies, changing laterally to shaly carbonates. Starting from Eocene to Early Miocene, Faumai, Sirga, and Sago Formations comprise of light brown, often dolomitic, limestone, and crystalline dolomite in a carbonate platform. An unconformity between Miocene limestones of Kais Formation with previous limestone formation is to be early formation of Bintuni Basin. The lithology of younger formations is composed of alternating shale and sandstone, with conglomeratic sandstones and claystones. Analysis and interpretation of this research integrate the seismic data and biostratigraphy that yield different conclusions from previous studies.

MATERIAL AND METHOD

To accomplish these objectives, this study follows the procedure of seismic sequence, seismic facies, and chronostratigraphy analyses (Figure 3). Those procedures are made to be more objective. The data used in this study include
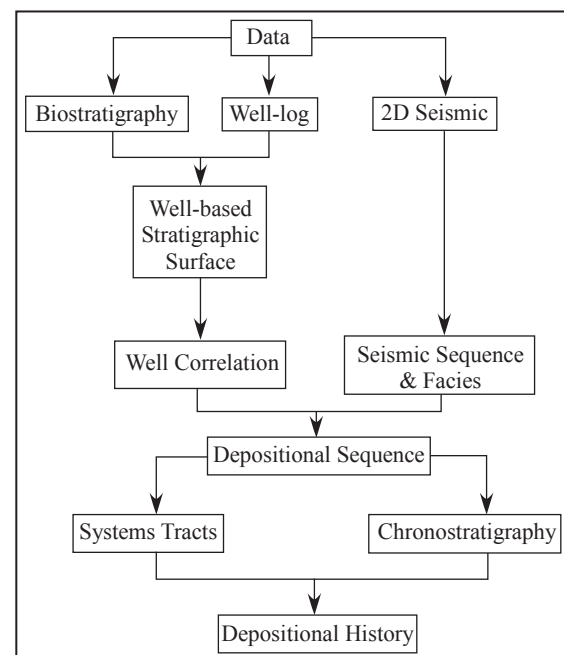

Figure 2. Stratigraphy of West Papua (Chevallier and Bordenave, 1986).

Figure 3. Research workflow.

moslty onshore seismic line, gamma-ray log, and biostratigraphy. The seismic data are used for analyzing seismic stratigraphy and facies geometry. The existing biostratigraphic analysis by Atlantic Richfield and Horizon is to obtain age rock formations and paleobathymetry.

The depositional sequences have two properties which make them ideal for interpretation on seismic data. First, they may be defined objectively using termination of reflections along surface of discontinuities, interpreted as stratal terminations along unconformable sequences boundaries. The second, deposition of most major sequences appears related to global changes of sea level (Mitchum and Vail, 1977).

Seismic sequence analysis aims to determine surface discontinuities of seismic termination as a result of gap time, due to erosion or nondeposition. Seismic facies analysis is a description of seismic strata configuration to interpret the depositional environmental and estimation of lithology. Chronostratigraphy analysis is a framework linking the depositional facies distribution over time.

Result and Analysis

The research result is divided into well-based and seismic-based analyses. All these types of analysis are to determine the stratigraphic surfaces. It is important to define its sequence architecture, including system tracts. Stratigraphic surfaces could be associated with the base-level fall or rise, also these can be explained by the interaction of sedimentation (Embry, 2009).

Biostratigraphy data in the south of the researched area assist in the determination of stratigraphic surface, especially with the changes of paleobathymetry and fossil abundance (Figure 4). Stratigraphic surfaces described sequence unit and their basic building blocks. Meanwhile, paleo-bathymetry changes related to the shift of shoreline trajectories at one point through time. The evolution of sedimentary environment marked by changes of lithofacies and benthic faunal assemblages in relation to sea level rise
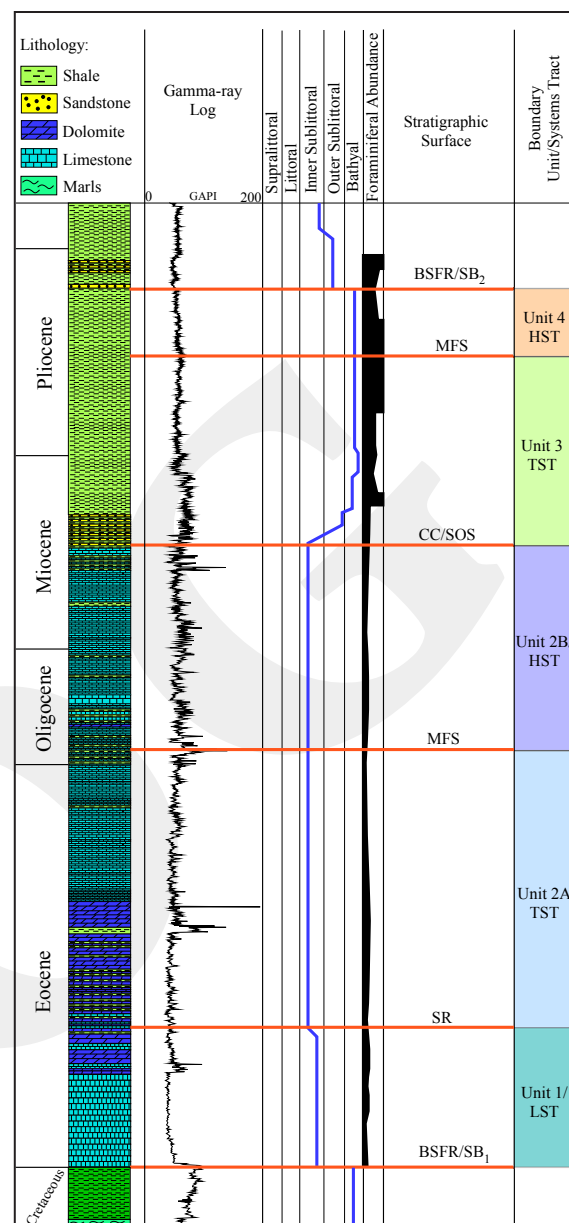

Figure 4. Biostratigraphy summary of the southern part of the researched area.

and climate changes (Fanget *et al*., 2016). The fossil abundance is related to an adequate nutrition and accommodation space. Accommodation and sediment supply are factors from allogenic control (Catuneanu, 2006). Maximum flooding surfaces, as an indicative of peak transgression, are characterized by a peak in foraminiferal number (Olson and Leckie, 2003).

In this study, some significant paleo-bathymetric changes were present in Early Eocene (bathyal to inner sublittoral/shallowing), Middle

Miocene (inner sublittoral to bathyal/deepening), and Late Pliocene (bathyal to outer sublittoral/shallowing). The peak abundance of foraminifera is in the Pliocene interval within silisiclastic sediments (Klasafet/Steenkool Formations). Paleobathymetric change could be rapid or gradual change corresponding to the tectonic or sediment supply factors due to major erosion in Paleocene sediments. The rapid change of paleobathymetry in Early Eocene and Late Pliocene associated with Basal Surface of Forced Regression (BSFR) occurs as a sequence boundary. The gradual change in Middle Miocene accompanied by the deepening bathymetry, fossil abundance, and detached sandstone interval is also suggested as a correlative conformity in equal to slope onlap surface. Marginal collapse created carbonate scarps on slope and fed coarse sediment downdip. However, slope onlap surface is also equal to healing phase and correlative with shoreline ravinement (SR).

The following subsequent of low sedimentation/sediment supply reflects as a deeper facies of thick shale layer of Klasafet Formation. As mentioned by previous researches, the Klasafet Formation was deposited in a deep marine environment at the same time of convergence tectonics (Harahap, 2012). In another case, dolomitization remains the problem in Wata Formation, an example of mixed silisiclastic-carbonate sediments in the Middle East. Determination in system tracts within the Wata Formation is debatable owing to the action of dolomitization that has destroyed original component (Anan, 2014). However, in the area of Bird Head, paleobathymetry curves show no significant changes, this could not be interpreted any other stratigraphic surface as its consequence (Figure 5).

The rapid changes of paleo-bathymetry (Eocene and Late Pliocene) show the same thing to the biostratigraphy data located in the southern researched area. Tectonics change sedimentary environment from an open to restricted marine in the Early Eocene resulted in a marine erosion as a correlative conformity. Figure 6 shows the results of stratigraphic correlation based on stratigraphic
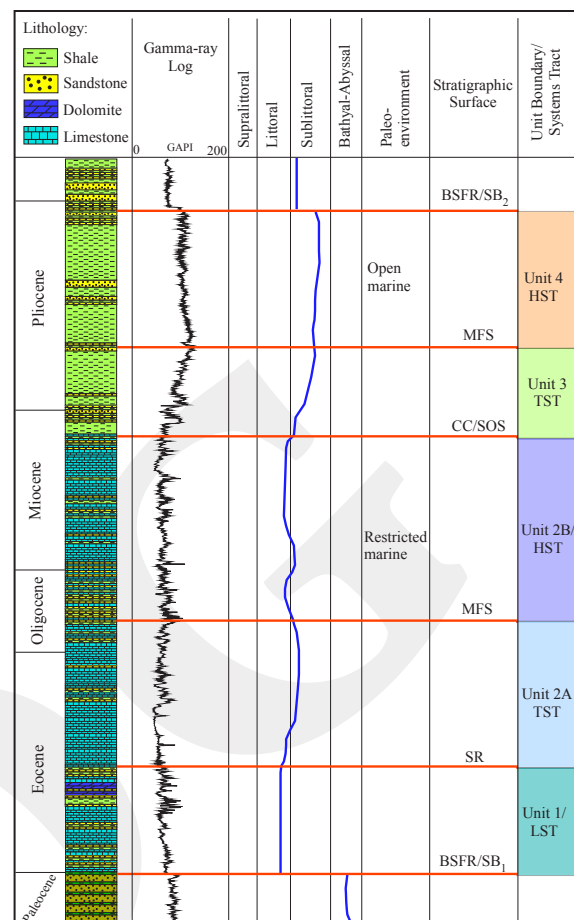

Figure 5. Biostratigraphy summary of the western part of the researched area.

surface previously defined by biostratigraphy, sequence boundary (SB), SOS and maximum flooding surface/MFS. Each sequence stratigraphic surface corresponds to the Early Eocene (lower sequence boundary), Middle Miocene (slope onlap surface), Late Miocene (MFS), and Late Pliocene (upper sequence boundary) ages.

The correlation results indicate the presence of four units based on depositional changes with varying thickness laterally. The oldest unit is prograding pattern of regression according to the shallowing facies and marked by dolomitization (Unit 1/LST). The overlying units consist of retrogradation (Unit 2A/TST) and aggradation (Unit 2B/HST) in normal regression, also possible prograding slope-fan complex, then continuosly covered by retrogradation (Unit 3/TST). However, MFS was well developed in the upper boundary of Unit 3 due to the occurrence of
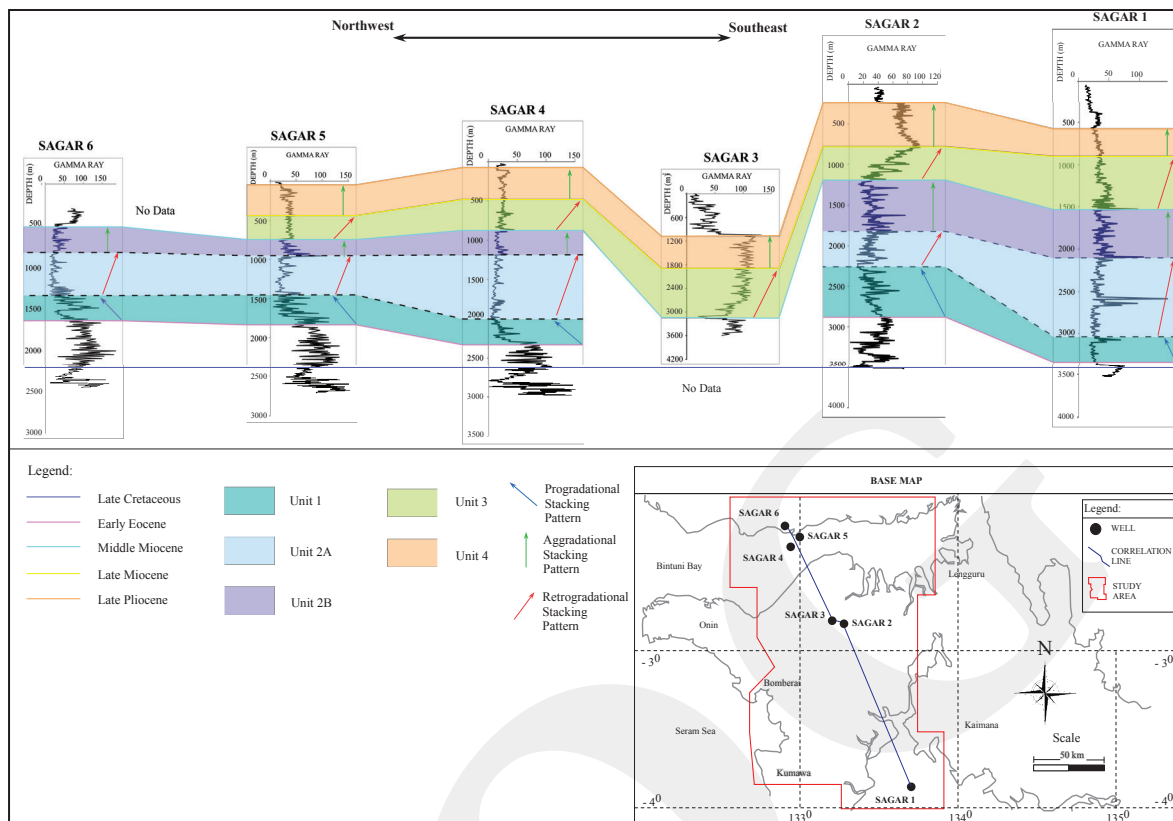
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Figure 6. Tertiary sequence stratigraphic surface correlation line of the researched area.

fossil abundance. MFS was also preserved in the boundary between Unit 2A and Unit 2B as well as set up by retrogradation followed by aggradation stacking pattern. The last unit is a prograding pattern in Unit 4 thickening to the centre of the studied area. The overlying shale facies made up the drowning previous carbonate in Unit 3.

The last unit (Unit 4) is interpreted as a normal regression in Highstand System Tracts/HST, because of the presence of aggradative pattern and the absence of rapid paleobathymetric change. Laterally, the thickness of transgressive sediment (Unit 3) is thickenning to the south. Instead, the regression of clastic sediment units (Unit 1 and 4) is thinning to the south. However, it must be noticed that the depth penetration of Kasuri well does not reach the carbonate target. At some depth interval, there are some of dolomitization. Carbonate systems of dolomite generated surface similar to a drowning unconformity, although no transgression occurred (Gattoling *et al*., 2015).

The integration of those stratigrpahic surfaces is critical in determining the depositional sequence. Seismic stratigraphy is closely related to changes in global sea level. The success and recognition of sequence stratigraphy from its applicability in hydrocarbon exploration basins, where data-driven and model-driven predictions of lateral and vertical facies changes, can be formulated (Amigun *et al*., 2014). Figure 7 is a seismic interpretation using sequence seismic surfaces that have previously been assigned of the well analysis. However, stratigraphic unit in seismic section does not have the same resolution to the higher resolution in well section. Seismic sequence was defined by the surface of discontinuity in terms of stratal termination from seismic reflection data (onlap, downlap, toplap, or truncation). Stratal downlap and onlap terminations are characterizing the lower boundary of stratigraphic unit. Meanwhile, upper boundary is determined by the toplap. Based on those stratal termination, three stratigraphic units have been
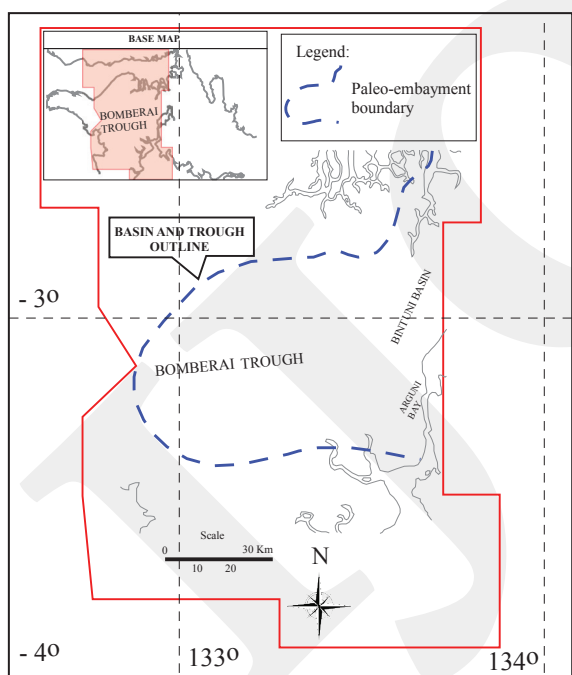
Figure 7. Line drawing of sequence seismic surface interpretation of the researched area, Bird Head, West Papua.

Figure 8. Tertiary basin configuration (Collins and Qureshi, 1977).

recognized. Stralal downlap-onlap is terminated on the Early Eocene, and Middle and Late Miocene Surfaces. All of downlap-onlap surfaces are assembled on the embayment in the Bird Head region.

Previous research of reef exploration in Bomberai Trough suggests a paleo-embayment formation in this studied area (Figure 8). The development of Bomberai Trough was complex and that several distinct margins were formed from Eocene through Miocene time (Collinson and Qureshi, 1977). By using the concept of seismic sequence, the surfaces of discontinuity were terminated to the embayment and clearly visible on the seismic sequence map. The oldest onlap-downlap are terminated on the Early Eocene sequence boundary due to forced regression based on seismic interpretation.

The overlying onlap surfaces are terminated to the end of thick carbonate unit, Middle Miocene, on the Slope Onlap Surface with carbonate scarpment system. The stratal below the slope onlap surface is a concordant unit, however the slope onlap surface is also correlable with shoreline ravinement. During base level fall, the slope can be onlapped by prograding siliscilastic, then being indicated by the detached sandstone interval above, as shown Figure 4, or can remain relatively starved (Embry, 2009). Starved basin is the basin which rate of subsidence exceeds rate of sedimentation, corresponding to sand-shale unit (Unit 3) above carbonate unit (Unit 2A and 2B). The youngest downlap surfaces are terminated to the MFS in the Late Miocene that formed Unit 4. Figure 9 is map of seismic sequence and

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facies. The period of age categorization (Eocene-Oligocene, Oligocene-Middle Miocene, Middle Miocene-Late Pliocene) is based on the onlap, downlap, and toplap terminated along those surfaces of discontinuity. The determination of seismic facies is done after determining the sequence boundary and other stratigraphic surfaces (MFS, ravinement surface, slope onlap surface). No well penetration around some existing basin fan and various clinoform, as shown in Figure 9, are still possible to be considered as clastic sediment derived from carbonate.

Mesozoic and Tertiary tectonics have developed the basin embayment. Some of them are Late Tertiary clockwise rotation, counterclockwise rotation, or no significant rotation of Bird Head due to the continuity of rift and collision related structural trends across Irian Jaya since Jurassic (Henage, 1993). To be objectives, a seismic sequence analysis reached out without any other information except seismic data. Each sequence unit on the basis of seismic sequence represents stratal thickness, geometry, and stacking pattern. Stratal stacking pattern is a powerful descriptive analysis in determining shelf, slope, and basin.

The specific types of shoreline trajectory are forced regression (forestepping and downstepping), normal regression (forestepping and up-stepping), and transgression (backstepping) in combinations of depositional trends (Catuneanu *et al*., 2011). In Cycle 1, Eocene to Oligocene, forestepping, and downstepping stacking patterns in oblique clinoform indicate forced regression phase in view of rapid paleo-bathymetric change (open marine to restricted marine/shallowing facies). Mounded reef and retrograding pattern set up the Cycles 2 and 3. The younger onlap have moved towards the south in those cycles. The northern carbonate enscarpment yield an avalanche of sediment in the embayment. In the last cycle (Cycle 4), upper boundary sequence unit is marked by toplap to the Late Pliocene surfaces. This cycle is characterized by forestepping and upstepping stacking pattern. Cycle 4 is interpreted as a normal regression and terminated by overlying channel incision. Figure 10 is a Wheeler Diagram as the representative of chronostratigraphy of the basin. From the figure above, the distribution of depositional sequence is related to their age and their characteristic of discontinuity (onlap, downlap, toplap) reflecting shoreline trajectories. The periodicity of this time axis curve is predictable through comparison with global sea level curve.

Marine erosion in Early Eocene (time axis 0) yields slope fan and wedge deposition. The base level started to rise and the coastal onlap continued to create an appropriate accomodation
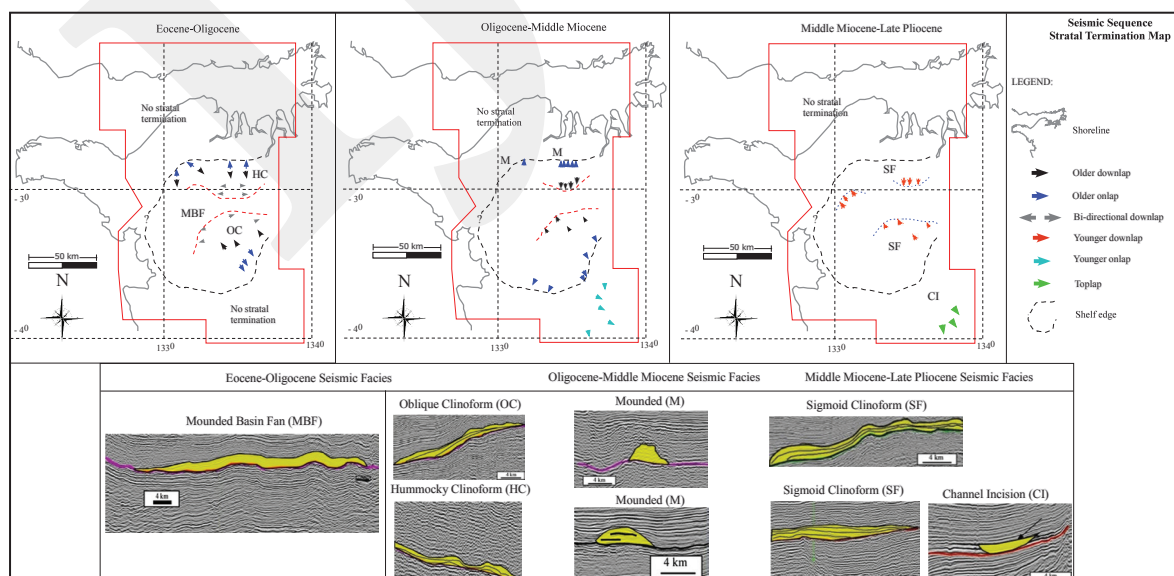

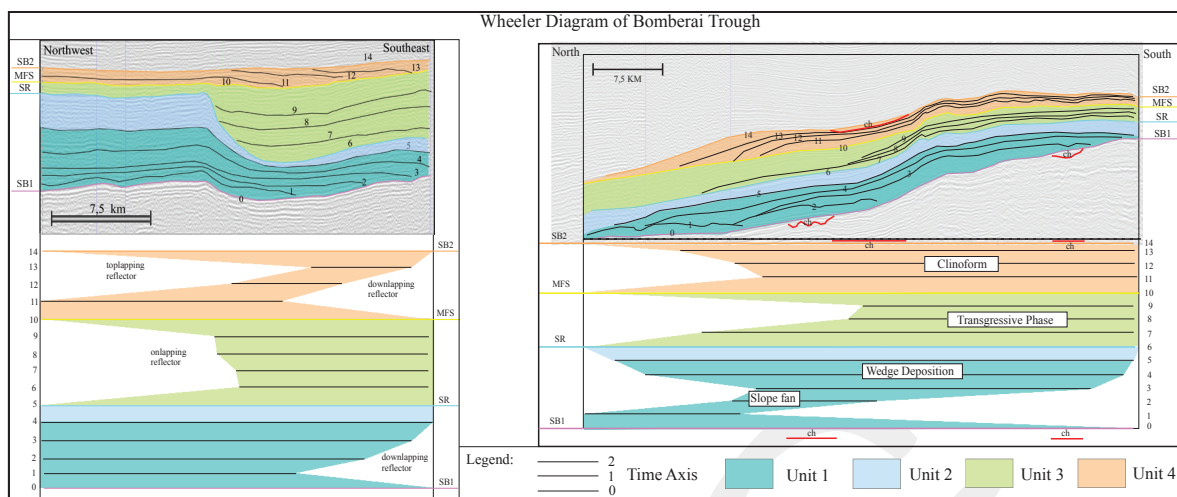Figure 9. Seismic sequence map and seismic facies of the researched area, West Papua.

Figure 10. Wheeler Diagram (Chronostratigraphy) of northwest−southeast section in Bird Head area, West Papua.

space that accompanied by the Middle Miocene carbonate growth (time axis 6). This transgressive carbonate cycle experienced drowning and terminated by MFS (time axis 10). The normal regression occurred in the presence of downlapping reflector to the embayment (time axis10-14).

DISCUSSIONS

One of the problems in sequence stratigraphy is sequence order (hierarchy). Notably, two very different methodologies for developing such a hierarchy of sequence boundaries have been proposed, model-driven and data-driven (Embry *et al*., 2007).

In model-driven, such an approach postulates a priori that sequence stratigraphic surfaces are generated by eustacy-driven, the very large amplitude changes driven by tectono-eustacy. The six orders and characteristics scheme are:

- 1st order: 50 Ma
- 2nd order: 5 - 50 Ma
- 3rd order: 3-5 Ma
- 4th order: 0.8-3 Ma
- 5th order: 0.3-0.8 Ma
- 6th order: 0.1-0.8 Ma

In the data-driven, such an approach is based on objectives scientific criteria rather than on a priori assumptions (Embry *et al*., 2007). In this research, the methodology used is data-driven that is more realistic. The rules of data-driven states "A sequence cannot contain within it a sequence boundary that has an equal or greater magnitude (equal or lower order) than of its lowest magnitude (highest order) boundary.

Sequence stratigraphy predicts subaerial exposure in marine carbonate at any peritidally-capped parasequence and at any sequence boundary (Railsback *et al*., 2012). In Figure 10, subaerial exposured exposed at time axis 6-10 by the presence of marine coastal onlapped to the carbonate slope onlap surface. In Figure 11, the time spanned of sequence boundary (Eocene 52 Ma, Pliocene-4 Ma) is 48 Ma. In model-driven, this is 2nd order called mega-sequence. Since there is a minor unconformity observed by the coastal onlap, another sequence unit must be considered (32 Ma of time spanned) and cannot be in equal order. In data-driven, this is still 3rd sequence order.

Figure 11. The age and stratigraphic surfaces.

Conclusions

Major erosion in the Early Eocene started the depositional sequence. Early Eocene erosion yielded the sediment accumulation to the basin embayment within lowstand system tracts, resulted in basin fan, slope fan, lowstand wedge units, and subsequently overlain by the thick transgressive system tracts (Kais Formation). Coastal onlap led the carbonate drowned by shale unit (Klasafet Formation). The normal regression occurred in highstand system tracts (Steenkool Formation) after maximum flooding. Late Pliocene erosion terminated the sequence unit of Bird Head, West Papua.

Acknowledgement

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