THE JURASSIC-CRETACEOUS PALEOGEOGRAPHY OF THE SULA AREA, NORTH MALUKU

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ABSTRACT

The study of paleogeography and hydrocarbon potentiality of the Sula area, North Maluku has been conducted by the Lemigas Exploration team. This paper specifically presents a paleogeography of the Jurassic-Cretaceous age of the Sula area as a part of the result of this study. In this paper, paleogeography means palaeoenvironment which is defined based on biostratigraphy. Data used in this paper are mostly secondary data obtained from National Data Center which is combined with primary data collected during field work campaign. The subsurface data analysis allows subdivision of 7 depositional sequences throughout Jurassic-Cretaceous succession. In fact, each sequence mostly consists of transgressive and highstand system tracts. Lowstand system tract only occurs in the earliest sequence. Sequences 1 (Bobong Formation), 2, 3 and 4 (Buya Formation) are assigned to the Jurassic age, whilst sequences 5, 6 and 7 (Buya Formation) are attributed to the Cretaceous age. Generally, the depositional environment of most sequences is getting deeper toward the North. The shallowest environment takes place in non-marine setting, whereas the deepest environment occurs in outer neritic (100m-200m). It is most likely that Jurassic-Cretaceous depocenter was situated in the northern part of the study area. However, it is required additional data to confirm this interpretation.

***Keywords**: Jurassic-Cretaceous, Paleogeography, Sula, North Maluku.*

I. INTRODUCTION

This paper is intended to disseminate the result of a research project called paleogeography and hydrocarbon potentiality of the Sula area, North Maluku which was hosted by LEMIGAS Stratigraphy Group. This project is funded by the Government (DIPA project) which was conducted in 2010. It is aimed to construct paleoenvironment of the sediment occurring in the Sula Basin and to evaluate hydrocarbon potentiality of this basin. The study area includes Sula Basin which is located in the North of the Banggai-Sula Island. This basin is about 12,580 square kilometers with elongated shape spanning from the West to the East and it is geographically situated in 123^{o}45'-126^{o}45' BT and 0^{o}45' - 2^{o} LS (Figure 1). Data used in this study are mostly secondary data provided by a certain service company. It consists of biostratigraphic data including foraminiferal, nannoplankton and palynological reports of two well sections called wells A and B.

The Sula area is believed to have hydrocarbon potentiality as indicated by several oil/ gas seepage (Garrard *et al*., 1988). However, its potentiality is poorly understood due to lack of investigation. This study evaluates most aspects that influence the occurrence of hydrocarbon within this area such as geology and geophysic and the existing petroleum system. In addition, paleogeography/paleoenvironment is helpful to define prospect area of the future exploration because it represents lateral succession of homo-chronological fenced space which shows lateral facies changes.

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Figure 1
The area of the study including approximate well location used in this study.

Stratigraphy is vertical succession of hetero-chronological events. In this case, events can be defined as biotic and non-biotic events. The biotic events may include base of datum, top of datum, peak abundance and discontinuity of abundance. Meanwhile, non biotic events may consist of seismic reflection events, well-log events, base and top of lithological events, anoxic events, tectonic events, trangressive surface, flooding surface, maximum flooding surface, marker beds, thin marine deposit, siderites bearing deposits, coal seam and climatic events (Soeka, 2007).

On the other hand, paleoenvironment represents lateral succession of homo-chronological fenced space. This means that in the same time, paleoenvironment may change laterally which results in the occurrence of lateral facies change (Soeka, 2007). In fact, this change will asociate with horizontal lithological distribution which contributes to the appearance of the petroleum system elements. It is well known that the coarse clastics of the deltaic sediment and shallow marine deposit are favourable for hydrocarbon accumulation. On the other hand, fine clastis of the deltaic succession and distal marine deposit yielding rich organic material may act as sourcerock if this is combined with sufficient gradient geothermal.

This paper is aimed to provide the paleoenvironments which occurred during Jurassic to Cretaceous age. The paleoenvironment interpretation includes the Sula Island and its surrounding area as shown in Figure 1.

II. MATERIAL AND METHOD

Data obtained from the area of study were generated from subsurface (wells) samples belonging to oil company. Therefore, the data are then considered to be confidential.

It needs to be emphasised that this research mostly relies on the existing biostratigraphic data obtained from two wells. Limited additional data generated from surface samples are also used in this study in order to support the existing well data.

The analysis of new samples is mostly intended to recognise pre-Tertiary taxa as LEMIGAS has inadequate experience of analyzing pre-Tertiary succession. Having this limitation, the paleoenvironmental study heavily relies on the secondary biostratigraphic data provided by a service company which are subsequently considered to be confidential. For the purpose of confidentiality, this paper hardly reveals detail information of the data such as well names, well location, operator, etc.

The sedimentary succession is separated into depositional sequences based on the combination of gamma log, the existing lithology (inferred from cutting) and biostratigraphic data. Each depositional sequence is then divided into packages referring to their system tracts. Subsequently, it is constructed well correlation to connect these packages which occur in the studied wells.

Paleoenvironment is interpreted on the basis of the following aspects:

- For marine environment refers to the composition of the benthonic foraminiferal assemblages which is supported by the occurrence of planktonic foraminifera, calcareous nannoplankton and other fossils such as coral and gastropod.
- For non-marine and transitional environments refer to palynological assemblages.
- Lithological data and the occurrence of selected minerals such as coal, siderite, pyrite, glauconitic, calcite and gypsum.
- The wireline log pattern and seismic facies.

The interpretation of paleoenvironment is based on the combined paleoenvironment classification of Tipsword *et al*. (1966) and Ingle (1980) as provided in Figure 2.

This study defines biostratigraphy of the pre-Tertiary sediments occurring in the provided wells. Detail biostratigraphy of the studied wells is presented on the project report (Lelono *et al*., 2010).

III. REGIONAL GEOLOGY

The study area is tectonically active due to interaction of three major plates including Asian, Australian and Pacific Plates as shown in Figure 3 (Kemp and Mogg, 1992). The Banggai-Sula Plate is interpreted as a micro-continent derived from Northwest Australia which was formed during Paleozoic and drifted to the West into its current position, so called Allochthonous Paleozoic Microcontinent. Its movement was controlled by sinistral strike-slip fault which is known as Sorong fault system. The Banggai-Sula micro-continent, also recognised as the Banggai-Sula platform is defined as a rock complex consisting of Carbonaceous metamorphic rocks, Permo-Triassic plutonic and volcanic rocks which are unconformably overlain by a series of Jurassic passive margin sediment, Cretaceous calcilutite sediment and Tertiary carbonate platform.

Based on regional tectonic analysis, there are three tectonic periods and two sedimentary basins. The tectonic events occurring in the study area includes rifting (Triassic-Jurassic age), drifting (Cretaceous-Early Tertiary) and collision (Tertiary). Meanwhile, the sedimentary basin appearing in the study area is historically separated into Mesozoic basin and Cenozoic basin.

IV. STRATIGRAPHY OF THE STUDY AREA

Referring to lithological association, fossil content and the age of successions, stratigraphy of the Banggai-Sula platform is generally divided into four major units including pre Jurassic basement complex, Mesozoic succession, Tertiary carbonate platform and Quaternary deposit (Surono and Sukarna, 1985). The stratigraphy of the study area is described as follows (Figure 4):

The pre Jurassic basement consists of metamorphic basement, Banggai granite and Mangole volcanic. The metamorphic basement is composed of slates, schist and gneiss that probably underwent deformation in the upper Paleozoic (Garrard *et al*., 1988). Banggai granites are mostly intrusive including red orthoclase rich granite, granodiorite, quartz diorite, microdiorite, syenite porphyry, aplite and pegmetite. This granite was assigned to late Permian to Triassic based on six K-Ar mica, two K-Ar hornblende and Rb-Sr feldspar (Pilgram *et al*., 1984). Meanwhile, the Mangole volcanic is mainly subaerial, well bedded, red/ brown to grey/ green in colour and frequently altered. It consists of rhyolite, dacite, ignimbrite, lithic tuff and breccias. The absolute dating

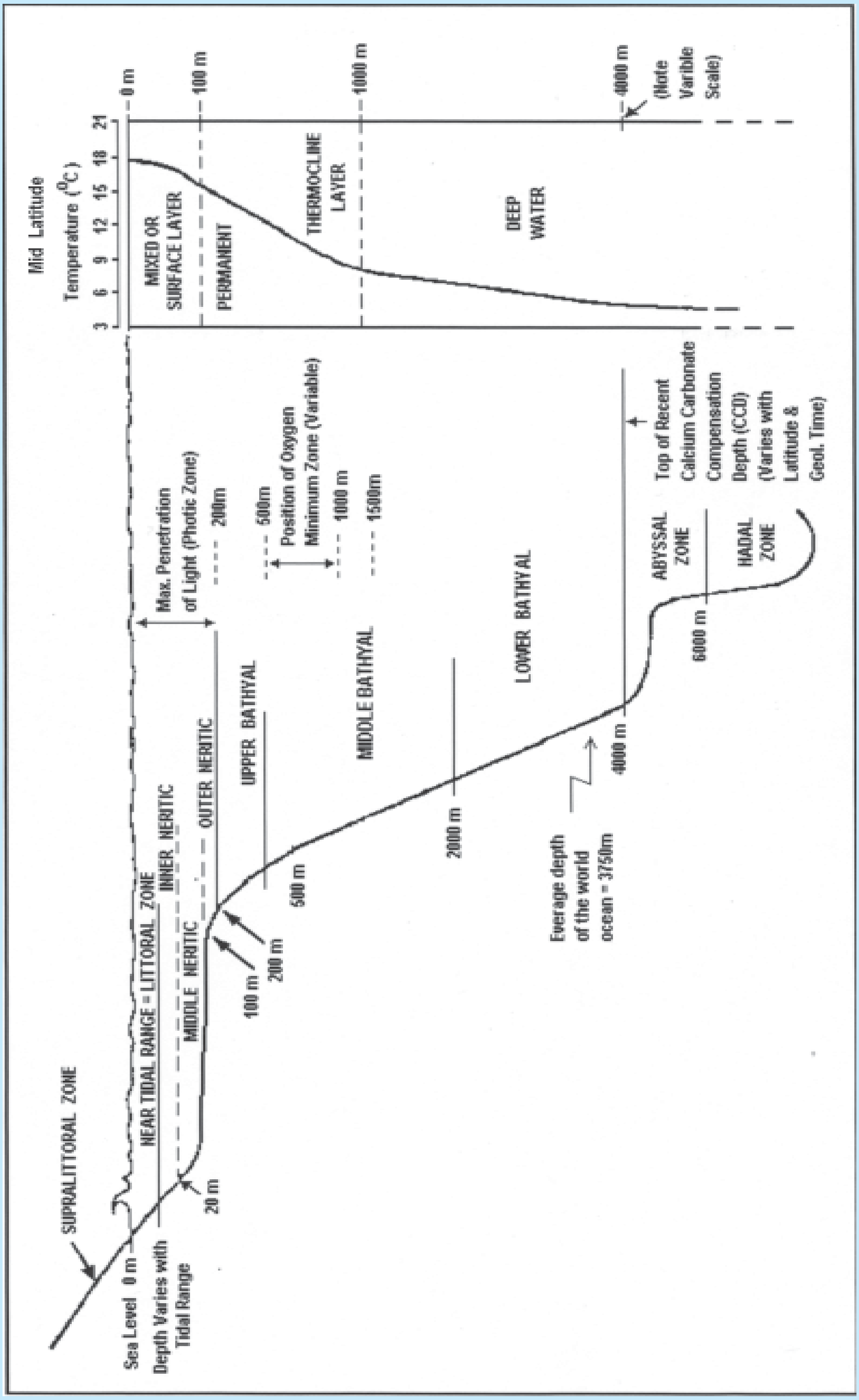

Figure 2
Classification of Benthonic Marine Environment based on the compilation of that by Tipsword *et at.* (1966) and Ingle (1980)

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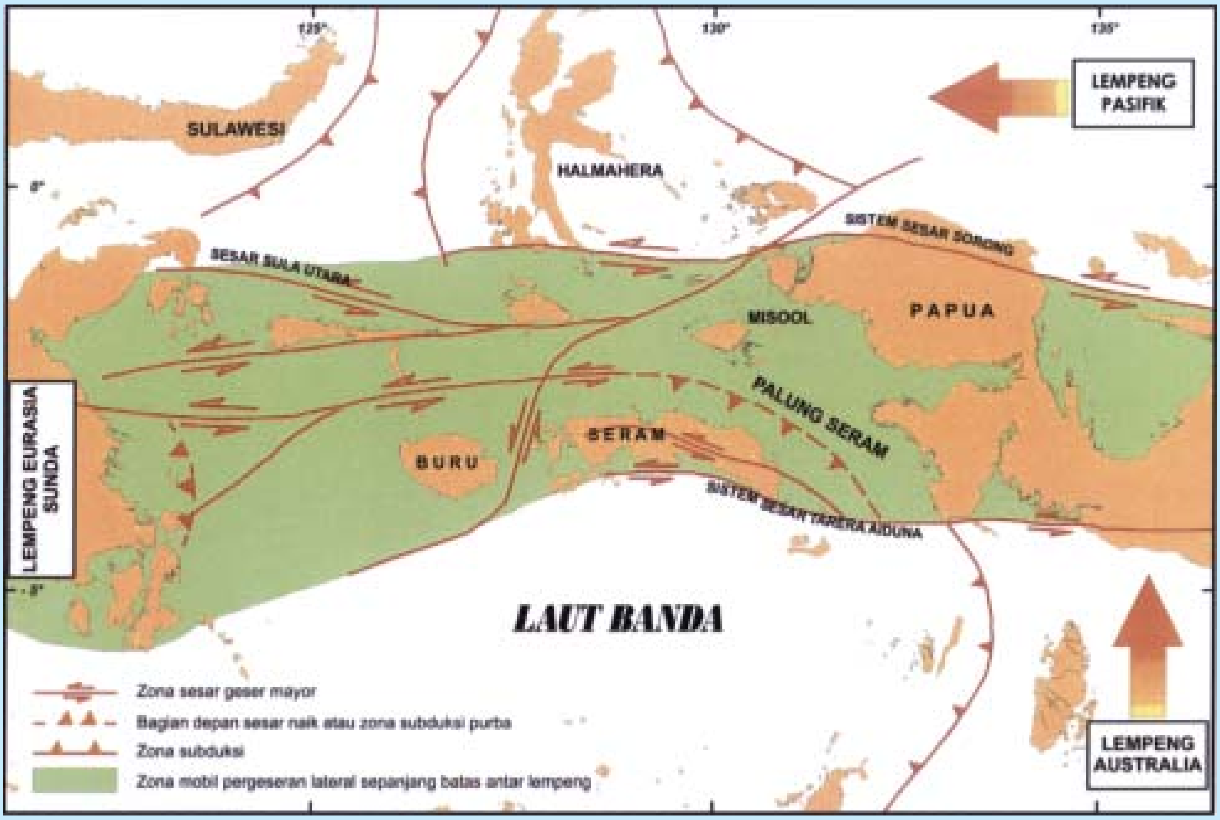

Figure 3
Tectonic element of the Banda arc and its surrounding
(Kemp and Mogg, 1992 with small modification)

on this volcanic indicates the age of 210+25 my 330+90 my (Sukamto, 1975).

The basement complex was block faulting during late Triassic and unconformably overlain by the Mesozoic formations which are composed of Menanga, Bobong, Buya and Tanamu Formations. The Menanga Formation consists of crystalline limestone, meta-sediment (skis and phylite) with quartzite intercalation. It is unconformably overlain by Early Jurassic, continental to shallow marine, coarse grained clastic of the Bobong Formation which is known as Kabau Formation in the eastern part of the study area. The Bobong Formation is interfingering with the younger succession of the Buya Formation which contains siltstone and shale with thin intercalation of limestones in the lower formation. In the Mangole and Taliabu Islands, the Buya Formation reaches 2000 meter thick which shows carbonaceous debris and glauconite suggesting shallow marine environment with condition of reduction. The youngest Mesozoic sediment is Tanamu Formation which rests conformably on the Buya Formation. The Tanamu Formation consists of calcilutite and marl which has a thickness of 500 meters. It was deposited in deep marine environment during Cretaceous.

The Tertiary carbonate platform unconformably overlies the older units. It consists of Salodik and Pancoran Formations. The Salodik Formation is composed of reef with calcarenite intercalation, marl and basal conglomerate in the lower formation. The microfaunal content indicates an Eocene to Middle Miocene age (Supandjono *et al*., 1986). This formation was formed in the shallow marine environment. Meanwhile, the Pancoran Formation is characterised by the occurrence of shallow water limestone with minor claystones and sandstone. It has an age of Early to Middle Miocene which is equivalent to the upper part of Salodik Formation. The Pancoran Formation is predicted to have thickness of 200m to 300m.

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Finally, the Quaternary sediment unconformably overlies the Tertiary carbonate platform. On the Peleng Island, this sediment is represented by reefal limestone, known as Peleng Formation. This formation is interpreted to form during Pliocene in shallow marine environment. On the other hand, recent deposits consisting of mud, silt, sand and gravel associated with swamps, rivers and beaches occur at various localities around the coasts and near river mouths. In the northern part of Peleng Island and along the north and the south coast of the Taliabu Island, these deposits are interfingering with reefal limestone of the Peleng Island (Garrard *et al*., 1988).

V. RESULT AND DISCUSSION

Based on the integrated analysis of well log, biostratigraphy and the existing lithology, the sequence stratigraphic correlation of the studied wells can be constructed as shown in Figure 5. 7 depositional sequences are identified and correlated. The first 4 sequences (1, 2, 3 and 4) are assigned to Jurassic, whilst the last 3 sequences (5, 6 and 7) are attributed to

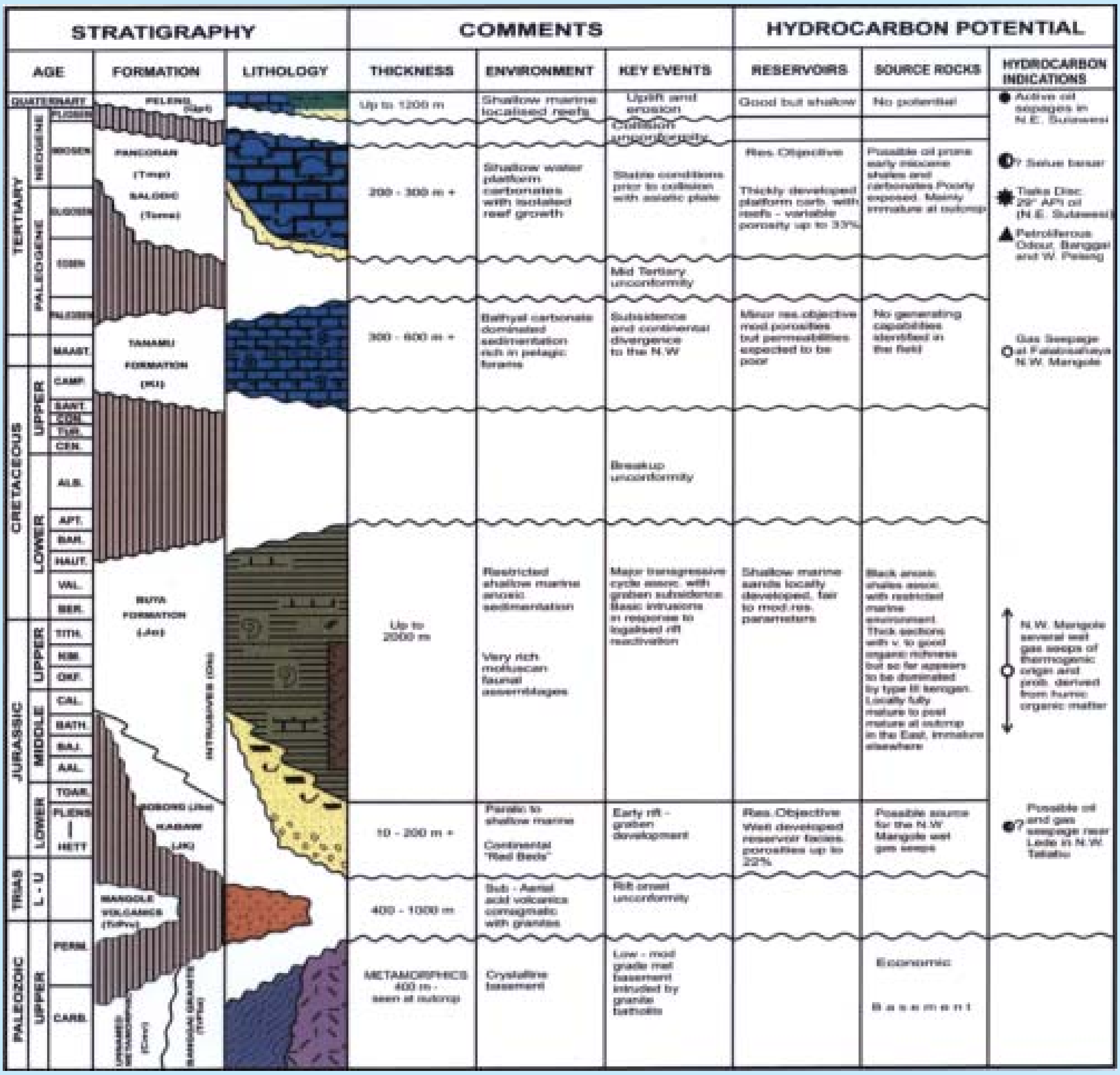

Figure 4
Regional stratigraphy of the Banggai-Sula (Garrard *et al*., 1988)

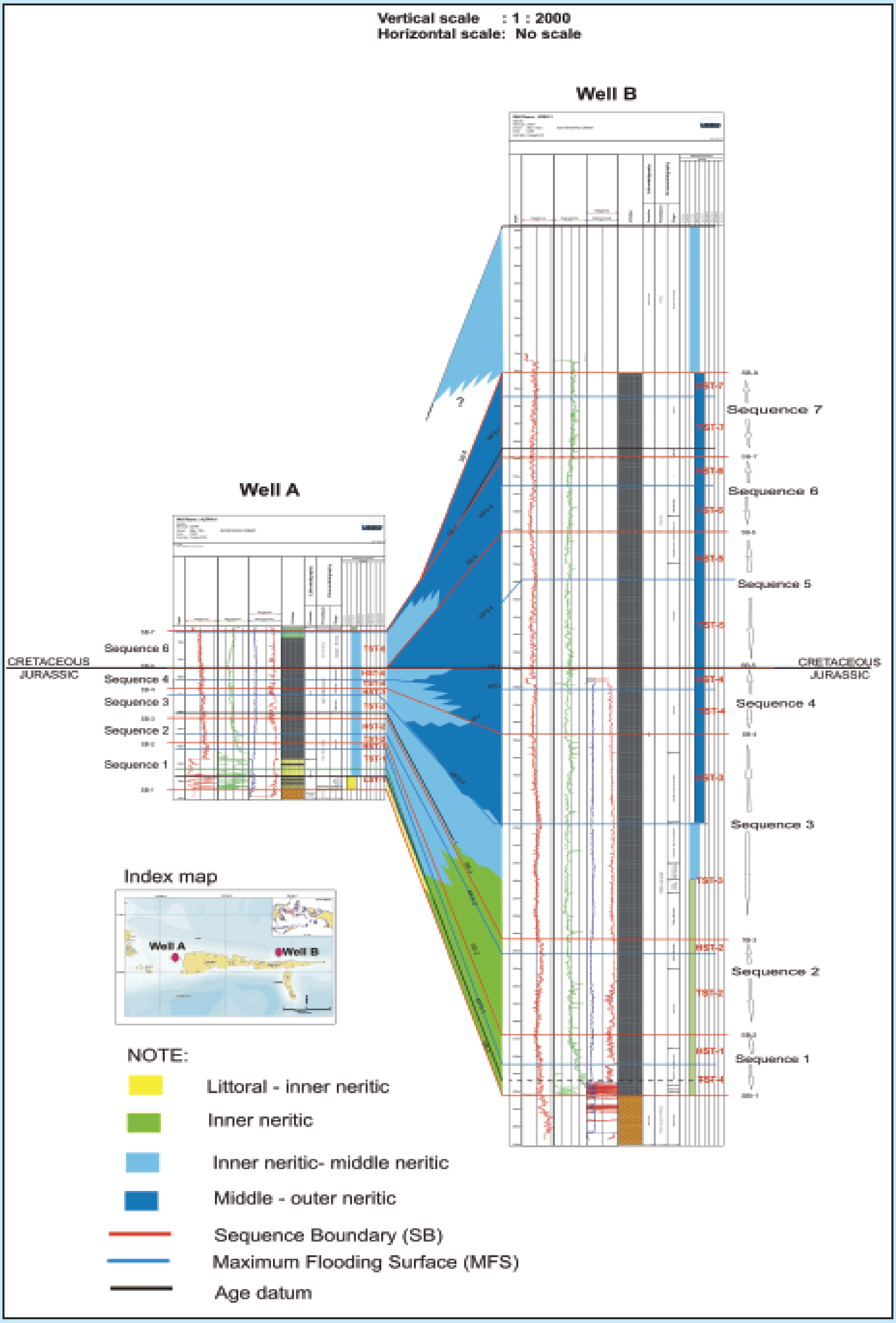

Figure 5
Correlation of depositional environments and sequences

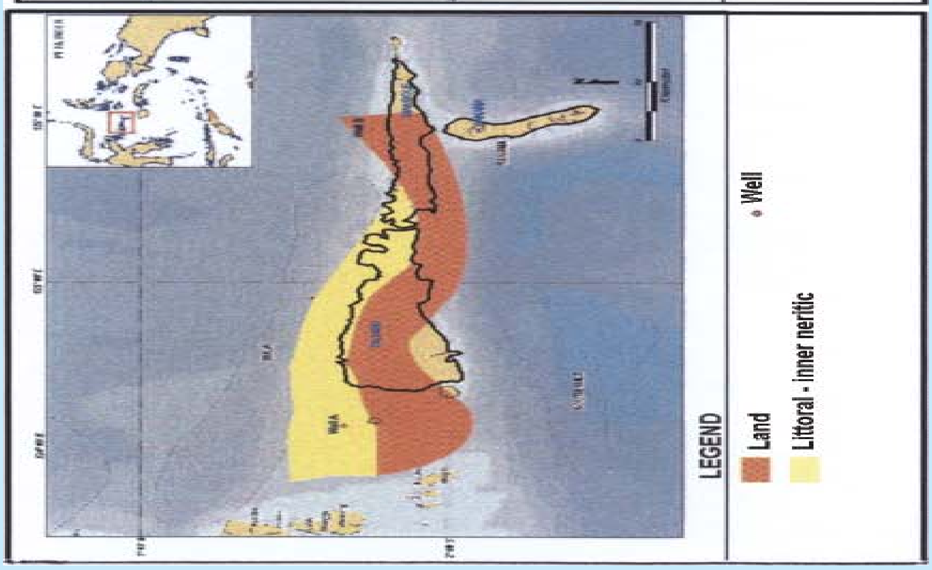

Figure 6a
Paleogeography of the LST-1
(Jurassic age)

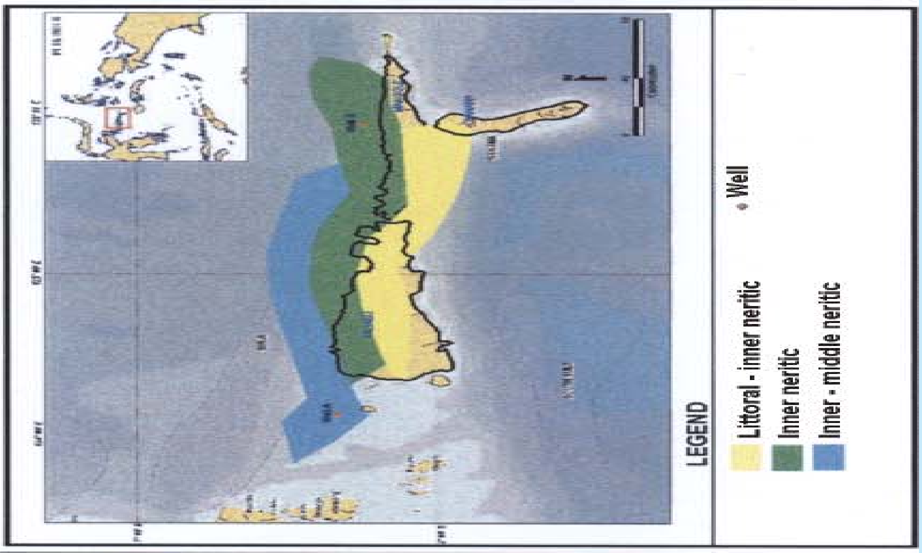

Figure 6b
Paleogeography of the TST-1
(Jurassic age)

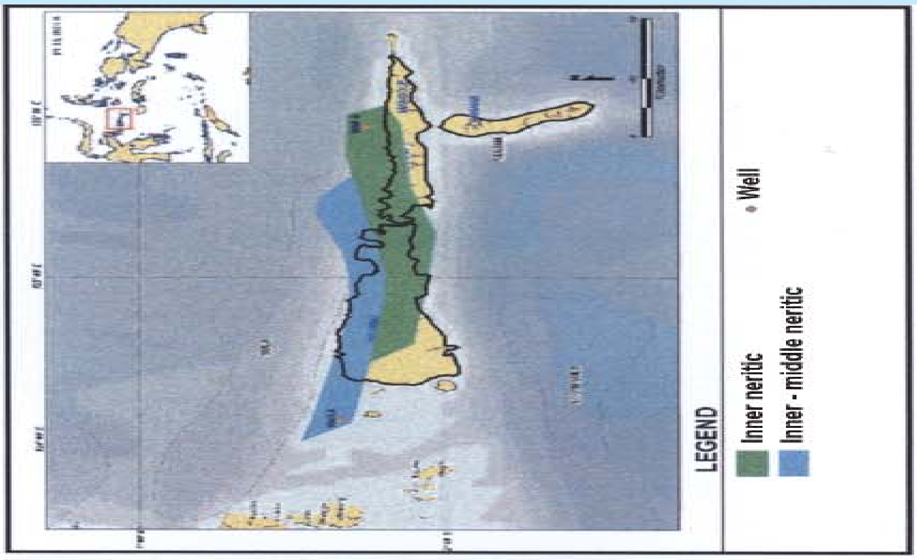

Figure 6c
Paleogeography of the HST-1
(Jurassic age)

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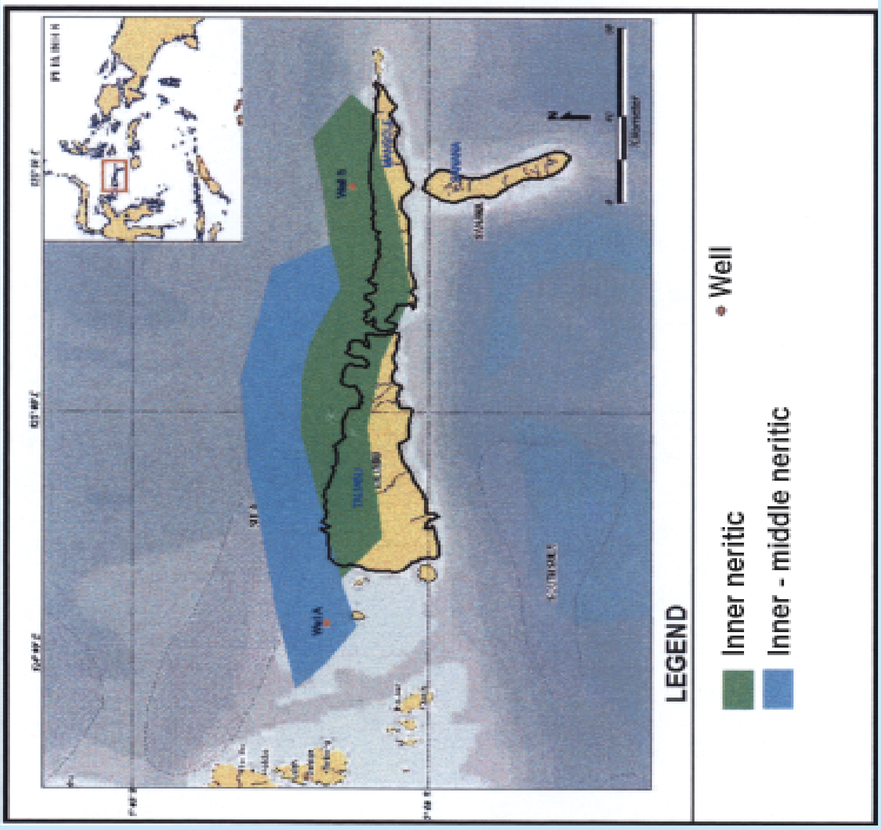

Figure 7a
Paleogeography of the TST-2
(Jurassic age)

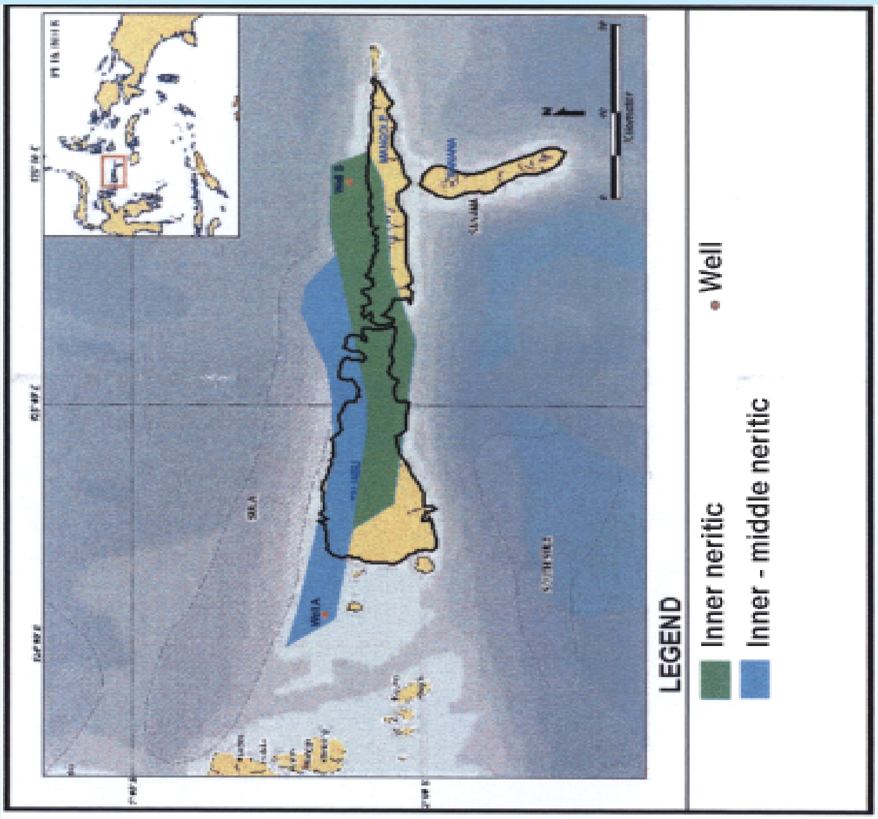

Figure 7b
Paleogeography of the HST-2
(Jurassic age)

Cretaceous. The paleoenvironment of the area of study is separated referring to these sequences as follows:

A. Paleogeography of the sequence 1

Depositional sequence 1 is divided into 3 system tracts such as lowstand, transgressive and highstand. The lowstand system (LST-1) only occurs in well A showing gradual change from non-marine in the South to littoral-inner neritic in the North (Figure 6a). There was no deposition in well B during the appearance of LST-1. Subsequently, sea level rises to cause transgressive sequence (TST-1). This event occurs in both wells. Paleoenvironment is getting deeper than that of the previous system tract as shown by the occurrence of littoral in the South which shifts to middle neritic in the North (Figure 6b). During the highstand (HST-1), paleoenvironment takes place in inner neritic (South) which continues into deeper setting in middle neritic (North) as shown in Figure 6c.

Overall, it can be concluded that the paleoenvironment of the sequence 1 varies from non-marine (supra-littoral) to middle neritic. In addition, the paleoenvironment is getting deeper toward the North. The sequence 1 represents basal Buya Formation with Jurassic age.

B. Paleogeography of the sequence 2

The depositional sequence 2 conformably overlies the sequence 1. It consists of transgressive and high stand system tracts. The sequence 2 occurred in Jurassic age. This sequence can be observed in the studied wells (A and B).

In the transgressive system (TST-2), the depositional environment appears in inner neritic as proved by well A (Figure 7a). The depositional environment gradually moves into deeper setting in inner neritic to middle neritic toward the North as found in well A. Similar trend occurs to mark high stand system (HST-2), in which inner neritic environment (well B) shifts to deeper marine setting in inner neritic to middle neritic environment (well A) as shown in Figure 7b.

Afterall, it can be concluded that the sequence 2 paleoenvironment shows some changes from shallower environment in the South (inner neritic) into deeper environment in the North (inner neritic to middle neritic). This trend is consistent with the previous trend (sequence 1).

C. Paleogeography of the sequence 3

The sequence 3 appears conformably above the sequence 2. This sequence was formed during Jurassic in various marine environment starting from inner neritic (shallowest environment) to outer neritic (deepest environment). The sequence 3 consists of transgressive system tract (TST-3) and high stand system tract (HST-3). This sequence occurs in the studied wells (wells A and B).

The sequence 3 is initiated by the appearance of transgressive system (TST-3) in inner neritic environment as found in well B (South ward) which gradually shifts into deeper setting in inner neritic to middle neritic environment (North ward). In fact, the depositional environment gets deeper during the occurrence of high stand system tract (HST-3) as proved by the appearance of middle neritic to outer neritic environment. During HST-3, the inner neritic to middle neritic environment in well A (South ward) gradually changes into deeper marine in middle neritic to outer neritic environment in well B (North ward). Figures 8a and 8b show paleoenvironmental maps of the sequence 3.

Having the above discussion, it can be summarised that the paleoenvironmental trend of the sequence 3 resembles that of the sequence 2. The depositional environment seems to be deeper toward the North which means that the basin was possibly opened toward the North. However, paleoenvironment of the sequence 3 is somewhat deeper than that of the sequence 2.

D. Paleogeography of the sequence 4

The sequence 4 is the youngest sequence within the Jurassic age which is subdivided into transgressive (TST-4) and high stand (HST-4) system tracts. This sequence can be observed in all studied wells. Based on foraminiferal analysis, it is interpreted that the sequence 4 occurs inner neritic to outer neritic environment.

The TST-4 initially appears in inner neritic to middle neritic (well A) which then gradually changes into deeper environment in middle neritic to outer neritic (well B). The paleoenvironment of the TST-4 shows the trend where the basin gets deeper from the South toward the North (Figure 9a). This paleoenvironment trend is similar to that of the previous sequence (HST-3). Moreover, the

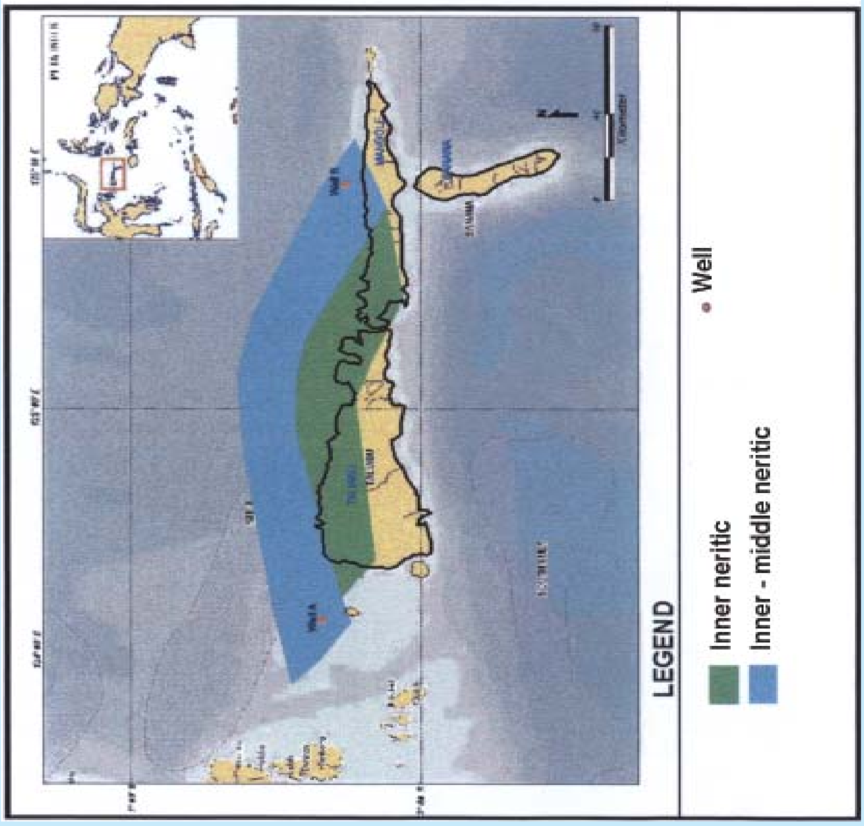

Figure 8a
Paleogeography of the TST-3
(Jurassic age)

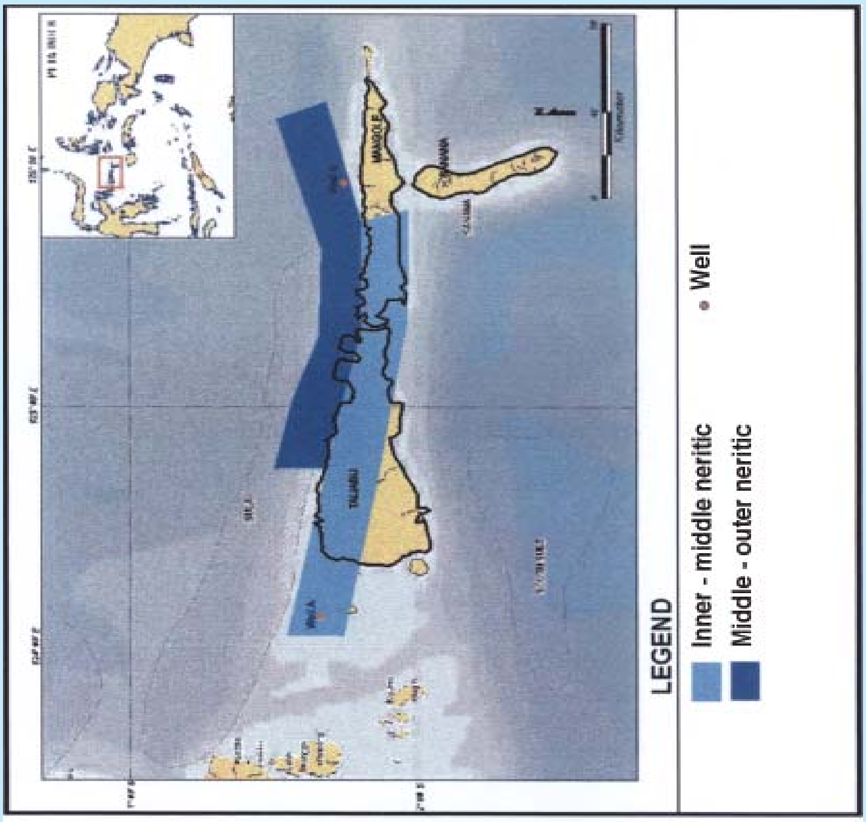

Figure 8b
Paleogeography of the HST-3
(Jurassic age)

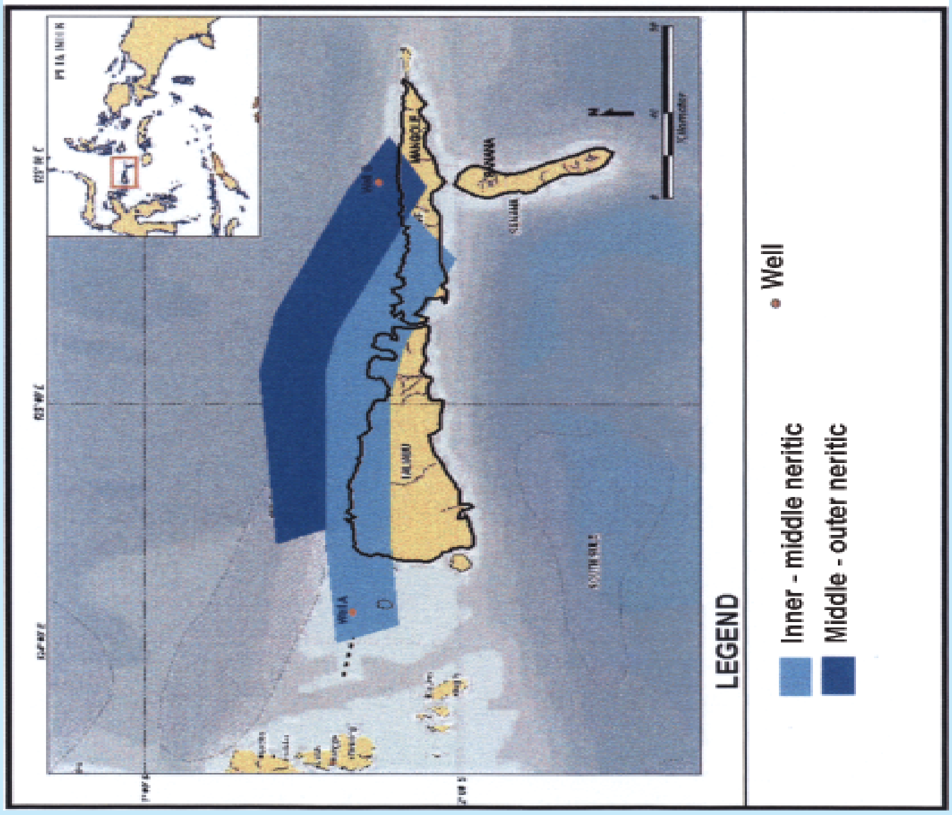

Figure 9a
Paleogeography of the TST-4
(Jurassic age)

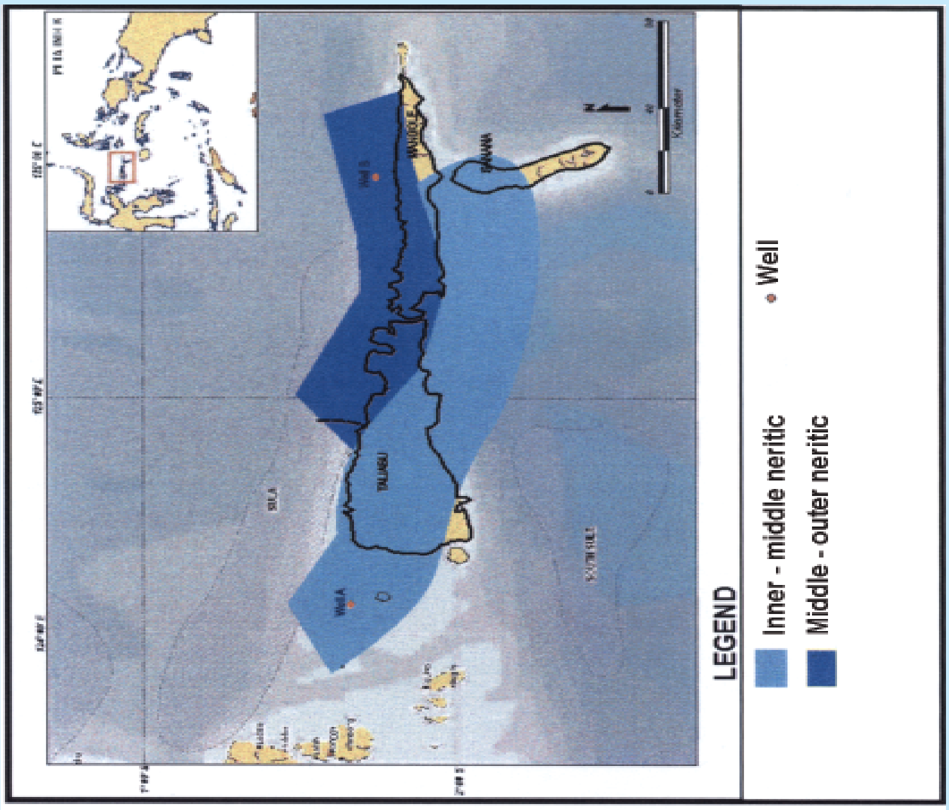

Figure 9b
Paleogeography of the HST-4
(Jurassic age)

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paleoenvironment of the HST-4 indicates similar pattern to that of TST-4, in which shallower marine in inner neritic to middle neritic environment (well A) gradually shifts into deeper marine in middle neritic to outer neritic environment (well B). During HST-4, the shallower environment in the South changes to deeper environment in the North (Figure 9b).

The above data suggest that the paleoenvironment of the sequence 4 gradually shifts from the shallower marine in the South into the deeper marine in the North.

E. Paleogeography of the sequence 5

This is the oldest sequence in the Cretaceous age. It consists of transgressive (TST-5) and high stand (HST-5) system tracts. The sequence 5 only appears in well B. The disappearance of this sequence in well A indicates non-deposition within the southern part of the studied area. This may relate to the up-lifting event to emerge the sedimentary successions above sea level. The sediment of the sequence 5 was possibly eroded after up-lifting.

The paleoenvironment of the TST-5 is middle neritic to outer neritic as indicated by benthonic foraminiferal assemblages which occurs in well B (Figure 10a). Similarly, the depositional environment of the HST-5 takes place in middle neritic to outer neritic (Figure 10b). The paleoenvironment pattern of the sequence 5 is hardly defined due to the disappearance of this sequence in the southern area.

Referring to the above discussion, it can be inferred that the sequence 5 is absent in well A due to erosion following local up-lifting in the southern part of the studied area. The disappearance of this sequence results in the difficulty in reconstructing paleoenvironmental map. The appearance of middle neritic to outer neritic environment in the northern part of the studied area may not be an indication of deeper marine toward the North.

F. Paleogeography of the sequence 6

The sequence 6 occurs conformably above the sequence 5 which consists of transgressive and high stand system tracts. Biostratigraphic analysis indicates that the sequence 6 is assigned to Cretaceous age. In fact, both sequences can be observed in the studied wells (A and B).

In the transgressive system (TST-2), the depositional environment of the southern part of the studied area occurs in inner neritic to middle neritic as proved by well A. The depositional environment gradually changes into deeper marine in middle neritic to outer neritic in the northern area of study as found in well B (Figure 11a). In addition, similar pattern is observed during high stand system (HST-6), in which inner neritic to middle neritic environment (well A) shifts into deeper setting in middle neritic to outer neritic environment (well B) as shown in Figure 11b.

Based on the above data, it can be inferred that the paleoenvironment of the sequence 6 indicates some changes from shallower environment in the South (inner neritic to middle neritic) into deeper environment in the North (middle neritic to outer neritic). In fact, this situation is similar to that of the previous sequence (5).

G. Paleogeography of the sequence 7

This is the youngest sequence along the studied section which only appears in well B. The sequence 7 disappears in well A indicating non-deposition event within the southern part of the studied area. This event is possibly caused by local up-lifting which emerges sedimentary successions above sea level. The sediment of the sequence 7 may be eroded following uplifting process. This sequence was formed during Cretaceous in middle to outer neritic environment. It consists of transgressive system tract (TST-7) and high stand system tract (HST-7).

The transgressive system (TST-7) indicates the occurrence of middle to outer neritic environment within the northern part of the study area as found in well B. The southern area of study appears as highland which is indicated by non-deposition. Similar situation occurs during HST-7, in which middle neritic to outer neritic appears in the northern area (well A), whilst highland spreadsout in over the southern area (well B). The paleoenvironmental maps of the sequence 7 is provided in Figures 12a and 12b.

Referring to the above data, it is interpreted that the paleoenvironmental trend of the sequence 7 seems to be deeper toward the North which means that the basin was possibly opened toward the North.

Having the above discussion, the depositional environments of sequences 1 to 7 show similar trend in which shallower setting in the South shifts gradually into deeper setting in the North. The disappearance of sequences 5 and 7 in the South (well A) indicates non-depositional period which may relate to local uplifting event.

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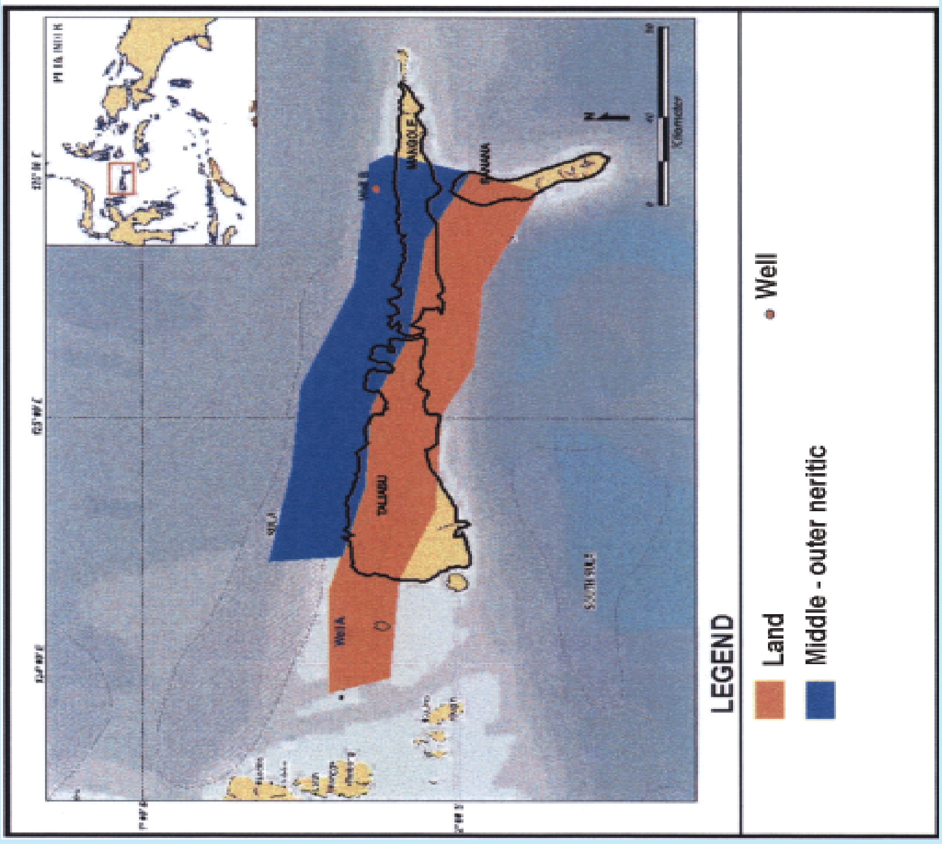

Figure 10a
Paleogeography of the TST-5
(Jurassic age)

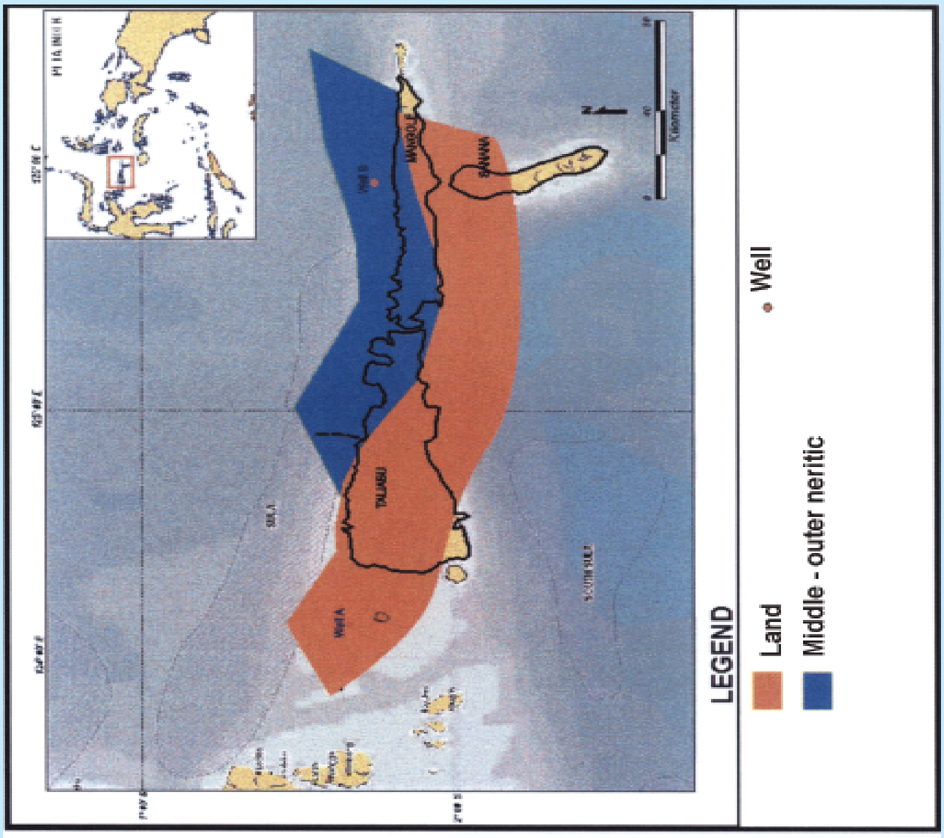

Figure 10b
Paleogeography of the HST-5
(Jurassic age)

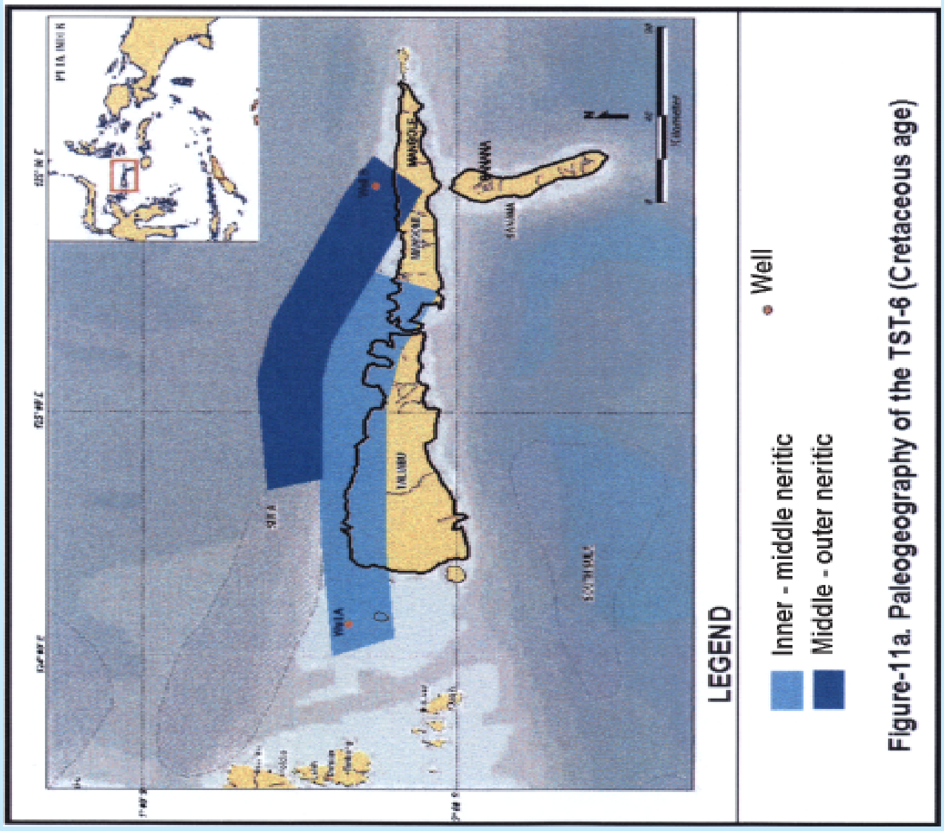

Figure 11a
Paleogeography of the TST-6
(Jurassic age)

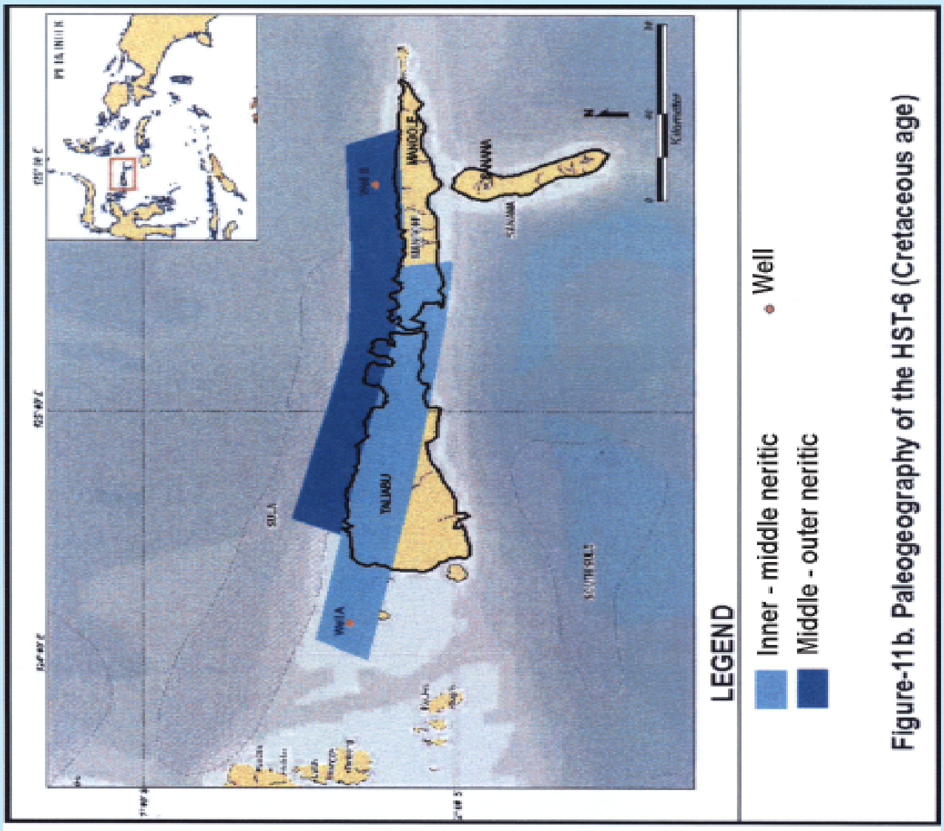

Figure 11b
Paleogeography of the HST-6
(Jurassic age)

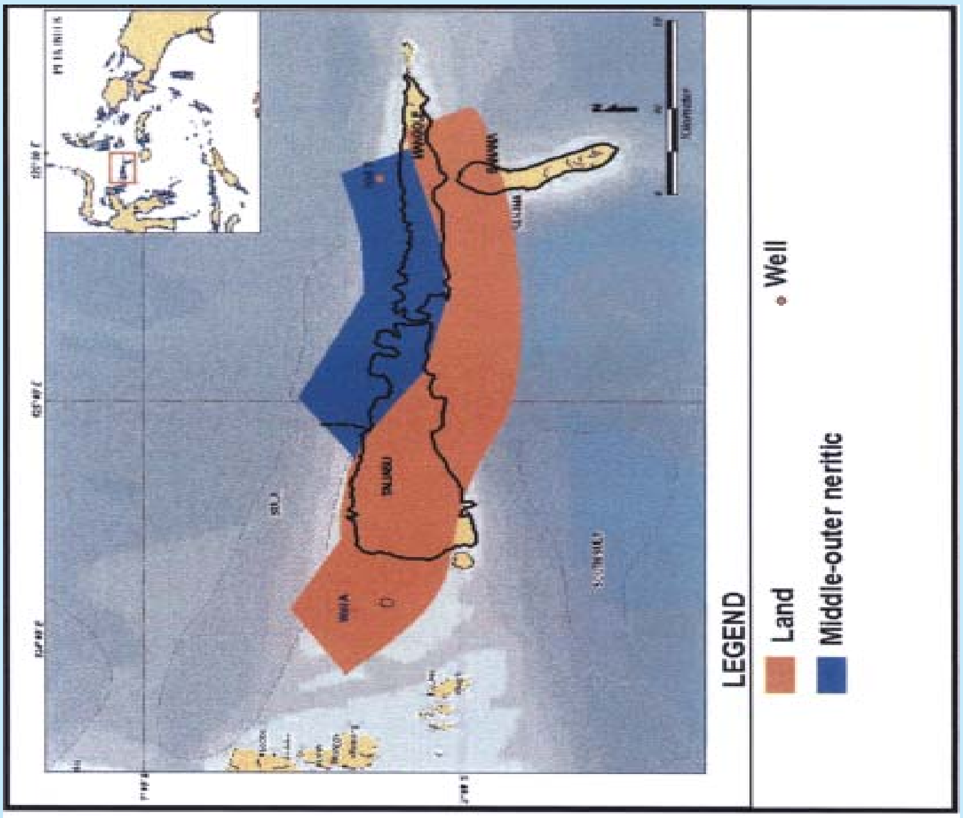

Figure 11b
Paleogeography of the HST-7
(Jurassic age)

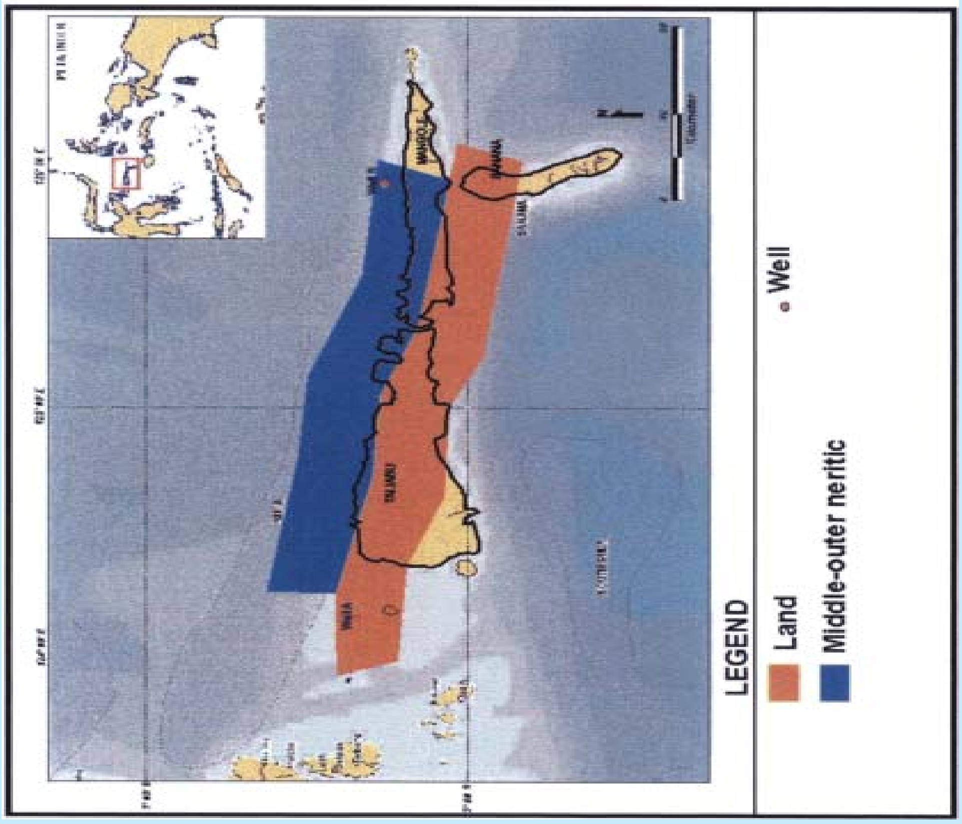

Figure 11a
Paleogeography of the TST-7
(Jurassic age)

VI. CONCLUSION

The Jurassic to Cretaceous depositional environment of the Sula area is interpreted based on the biostratigraphic analyses performed on the pre-Tertiary sediment which was collected from the selected well samples.

The sedimentary successions obtained from two studied wells consist of 7 depositional sequences which are subdivided into lowstand, transgressive and highstand system tracts. Sequences 1 to 4 belong to Jurassic age, whilst sequences 5 to 7 are assigned to Cretaceous age. Paleogeography is constructed following these sequences. This study shows that in general, the depositional environment is simply getting deeper toward the northern part of the study area. This trend can be observed throughout the existing sequences. However, due to the lack of data in the further North of the study area (interpreted to be deep area), it is immature to define that the central basin is pointing to the North. Therefore, for future works, it is important to obtain these data in order to construct comprehensive paleogeography of the studied area.

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