PROCEEDINGS, INDONESIAN PETROLEUM ASSOCIATION
Forty-First Annual Convention & Exhibition, May 2017

"SOME NEW INSIGHTS TO TECTONIC AND STRATIGRAPHIC EVOLUTION OF THE TARAKAN SUB-BASIN, NORTH EAST KALIMANTAN, INDONESIA"

Sudarmono*
Angga Direza*
Hade Bakda Maulin*
Andika Wicaksono*

INTRODUCTION

This paper will discuss the tectonic and stratigraphic evolution of the Tarakan sub-basin, primarily the fluvio-deltaic deposition during the Neogene time. The Tarakan sub-basin is part of a sub-basin complex which includes the Tidung, Berau, and Muaras sub-basins located in Northeast Kalimantan. In this paper, the discussion about the Tarakan sub-basin also includes the Tidung sub-basin. The Tarakan sub-basin is located a few kilometers to the north of the famous Mahakam delta. To the north, the Tarakan sub-basin is bounded by the Sampoerna high and to the south it is bounded by the Mangkalihat high. The Neogene fluvio-deltaic sediment in the Tarakan sub-basin is thinning to the north to the Sampoerna high and to the south to the Mangkalihat high. The thickest sediment is in Bunyu, Tarakan and in the Ahus structure. The sub-basin is gently deeping to the east started from Kucing high in the west to the open sea of the Celebes sea in the east. The Kucing high is the hinterland and source provenance of the fluvio-deltaic sediment deposited eastwardly in the Tarakan sub-basin since the Early Miocene. To the east of the Tarakan sub-basin is the open sea of the Celebes sea. The Nunukan PSC, operated by Pertamina Hulu Nunukan Company (PHENC), is located in the eastern part of the sub-basin (see Figure 1). The available data in the Nunukan PSC including 2D seismic of 1970 to 1991 vintages and 3D seismic data of 2010 and well location is given in Figure 2.

It has been a long time since there were any publications to update the understanding of the Tarakan sub-basin. Little interest has been shown, probably due to the low exploration success of oil and gas in the area, although there are already oil and gas fields in the area which have been producing since the 1970's, namely the Bunyu Nibung and Tapa fields in Bunyu island, Pamusian in Tarakan island and Sembakung and Bangkudulis in onshore Northeast Kalimantan.

On the other side, although the depositional setting in the Tarakan sub-basin is deltaic which is located to the north of the Mahakam delta, people tend to use the Mahakam delta as a reference to discuss deltaic depositional systems. This means that the Mahakam delta is more understood than the delta systems in the Tarakan sub-basin. The Mahakam delta is single sourced by the Mahakam river which has been depositing a stacked deltaic sedimentary package in one focus area to the Makasar Strait probably since the Middle Miocene. The deltaic depositional setting is confined by the Makasar Strait which is in such a way protecting the sedimentary package not to disperse to an open sea. No major tectonic events disturbed the deltaic deposition in the Mahakam delta other than sea level changes and tidal influences. As a result, the Mahakam delta has developed very thick sedimentary packages to be dumped to the Makasar strait. On the other hand, deltaic sediments in the Tarakan sub-basin are sourced by several feeder rivers such as Sesayap, Sesanip and other smaller rivers. The mouth of the rivers faces the open sea of the Celebes sea which means that the deltaic sediment is subject to a high dilution by waves and tidal dispersing of the sediment to open sea. Consequently, the delta of the Tarakan sub-basin is not well developed with thickness varies across the sub-basin. Additionally, uplifting by some tectonic events and erosion have also contributed to make the deltaic deposition to be not focused in one area. The setting of the present day Bunyu and Tarakan islands is probably a good analog to the ancient setting. Bunyu and Tarakan islands indicate a unique feature which some geologists have used to interprete them, together with the Ahus structure as a three arches trending NW-SE. On a topography map, the Bunyu and Tarakan islands are positioned right in the mouth of the Sesayap river which is split into two rivers, as if

* Pertamina Hulu Energi Nunukan

Bunyu and Tarakan islands are sand bars deposited by the two river mouths. In fact, they act as bariers to split the current of the rivers into two main flows. Before reaching the Bunyu and Tarakan islands, the Sesayap river already splits into two rivers, which may be due to the same condition as in the Bunyu and Tarakan islands, i.e there is a structural high blocking the Sesayap river in the more upstream location (Figure 3).

This paper contributes insights and ideas about tectonic and stratigraphic evolution of the Tarakan sub-basin from the approach of the offshore data and although the discussion is focused on tectonic and stratigraphic evolution of the Mio-Pliocene to Recent delta of the Tarakan sub-basin, as a basin overview a small portion of the Paleogene setting will also be given. This paper will promote some evidence and insights based on some new well and 3D seismic data in addition to the existing well and 2D seismic data to have a better understanding of the tectonic and stratigraphy evolution of the Tarakan sub-basin.

Regional tectonic

The Tarakan sub-basin is controlled by a complex tectonic interaction such as oceanic spreading in the Celebes Sea and subduction and collision in the Kucing High by the South China Sea. Key tectonics affecting the Tarakan sub-basin is the uplift of the Rajang-Embaluh group during Late Oligocene to form the Kucing High which then becomes a sediment provenance of eastwardly deltaic deposition in the Tarakan sub-basin and westwardly to the Baram delta. The Kucing High complex was a meeting point interaction of eastwardly stress by subduction and collision of the South China sea to Luconia and Dangerous Ground and the westwardly docking of the Celebes Sea oceanic crust towards the northeastern margin of Sundaland. The interaction has been generating some stike slip movements afterwards which are still active until the present day, primarily the Sampoerna and Maratua-Mangkalihat strike slip faults, which are positioned in the north and south respectively bounding the Tarakan sub-basin. The two strike slip faults probably have been the main control of the tectonic events during Miocene to Pleistocene in the Tarakan sub-basin. The Sampoerna strike slip fault probably related to the oceanic spreading centre in the Celebes Sea while Maratua and Mangkalihat strike slip faults probably are a continuation of the Palukoro fault.

In the Tarakan sub-basin, the deltaic package during Mio-Pleistocene time used to be interpreted by some authors simply as a thin skinned induced gravity glidding, a couple of eastwardly normal-listric fault movements in the west associated with deltaic deposition and toe-thrusting in the far east of a deep water setting, both moving along a slippery decolement zone. A quite famous model illustrating W-E geological cross-section to desribe the Tarakan sub-basin in a regional context is the paper by Sri Hidayati (2007). In that model, the Bunyu and Tarakan islands are part of a thin skinned-induced gravity glidding up to the present day in the western part in a pair with toe-thrusting over a major decolment surface in the far eastern part (deep water setting). Interestingly, the gravity glidding (series of listric normal faults) starts from a major bounding fault to form the roll over structure of the Tarakan and Bunyu islands and the Paleogene presents beneath the decolment surface as rift-product described by a series of half grabens. This model has not been updated since it was published. Some interesting questions about the Tarakan sub-basin relate to the model include defining the contact boundary location between the oceanic crust underneath the Celebes sea over Kalimantan and in what way they are interacted. Other questions include defining what tectonic and stratigraphy is underneath the Neogene delta of the Tarakan sub-basin and what the decolement surface as a base of the gravity glidding is. This will be discussed in the Paleogene setting topic.

Of particular interest is the discussion related to the structure forming the Bunyu and Tarakan islands. Looking at a West-East offshore seismic section across the structure of the Bunyu island, it is easy to give a general impression that the Bunyu or Tarakan islands is a simple roll-over anticline structure resulted by prograding delta depositional setting. However, looking at the extensive erosion at the top of the Bunyu structure, it should have been a significant sea level drop to have such an erosional surface. Also, looking at the sesimic data, the listric normal faults are limited to certain level but the upper part of the section is a parallel bedded sedimentary package which was undisturbed during deposition and so the listric normal faults do not continue to cut the parallel bedded sedimentary package. This suggests that the prograding delta generating the listric normal faults stopped sometime before the parallel bedded sedimentary package was deposited. This also implies that the faults cutting the parallel bedded package in the upper part are a reactivation of the existing older faults which are the normal listric faults associated to the deltaic deposition.

Furthermore, an unconformity obviously appears on seismic data separating the deltaic package indicating a series of listric normal faults and the undisturbed parallel bedded sedimentary package above it (Figure 4a and 4b). The unconformity is in fact related to a regional tectonic event that occured during the Late Miocene which uplifted the majority of the western part of the Tarakan sub-basin. Similar to the Tarakan island and the Ahus structure, the Bunyu structure can likely be interpreted as an inversion structure resulted by a compressional stress. However, the inverted structure does not indicate any reverse faults in the upper section as during the relaxation stage, the older listric normal faults were reactivated to result in dragging down the "poped up" parallel bedded package. A very simplified cartoon model describes the structural evolution of the Bunyu, Tarakan and Ahus structures. First of all, a prograding deltaic sedimentary package was deposited eastwardly during the Middle-Late Miocene indicated by roll over anticline structures and listric normal faults over a regional decolment surface. The faults stopped during Late Miocene due to a major compressive tectonic event, then was followed up by a calm depositional of a deltaic sedimentary package which indicate fairly parallel structure and no listric or any normal faults are observed in the parallel bedded sedimentary package. This was probably due to the sedimentary source during the quiscent period was very limited which were reworked materials from the uplifted structures i.e. the rate of sedimentation is the same as the accommodation space. Then, by compression during Pleistocene, the whole sedimentary package was poped up. During relaxation, the existing listric faults were reactivated and the parallel sedimentary package above it were dragged down generating new faults right above the reactivated listric faults so that in overall the resulted structures are as if they are in one movement as a roll over structure. Some of the new faults and the reactivated listric faults may not be neccessarily connected and they can have different fault planes (Figure 5).

Tectono-Stratigraphic evolution

Neogene deltaic deposition in the Tarakan sub-basin

Stratigraphy in the Tarakan sub-basin is fluvio-deltaic deposition since Middle Miocene to the Present day. The nomenclature currently used by geoscientists is Meliat Fm as the oldest (Middle Miocene), followed up by Tabul Fm (Upper-Middle Miocene), Santul Fm (Middle to Late Miocene), Tarakan Fm. (Upper Late Miocene-Pliocene) and finally Bunyu Fm (Pleistocene to Recent). The boundary between formations is defined differently in different working areas. As an example, in the onshore area, the characteristic of the Tabul Fm is identified by coal-rich sedimentary package. Getting deeper, the coal is getting less and less and then changes to thick shale. The first sand identified after the shale will be depicted as the Meliat Fm.

Several wells in the Nunukan PSC indicate that change of the Santul to the Tarakan Fm is marked by a short transgressive event which then ended up with carbonate deposition as a maximum flooding surface (MFS). The carbonate is only limited to the distal area of the delta system. Towards proximal deltaic setting to the west, the carbonate is corellable to coal or shale belong to the MFS. Overlying the MFS of the Santul Fm. the deltaic depositional cycle starts again as a regressive system tract of the Tarakan Fm. Again, similar to what happened in the Santul Fm., the end of the Tarakan Fm is marked similarly by a short transgressive event which is ended up by carbonate deposition as the MFS. Based on this evidence, it is likely that Meliat and Tabul Fm have the same cycles like that. Hence, the Neogene fluvio-deltaic stratigraphy in the Tarakan sub-basin is a repeat cycle of a regressive system tract which ended up by a short transgression in each Formation, which is marked by the presence of carbonate.

As an illustration, particular discussion is given within the Tarakan Fm. The B-1 well in the Nunukan PSC indicates that the Tarakan Formation interval is identified by carbonate at the base and ended up by carbonate again in the upper part. Towards the west, in the W-1 well located 15 km to the West of the B-1, the two carbonates are much thinner than in the B-1 well. Towards Bunyu island, the carbonates diminish and change to marine shale or coal. The carbonate in the lower part of Tarakan Fm belongs to MSF of the Santul Fm located stratigraphically beneath the Tarakan Fm., while the carbonate in the upper part marked the MSF of the Tarakan Fm as the end of the regressive deltaic cycle of the Tarakan Fm. Overall, the B-1 and W-1 wells which are TD at the transition of Tarakan to Santul Fm. indicate dominantly coarsening upward sequences with occasionally present a short cycle of fining upward sequence. This means the position of B-1 and W-1 wells are in a delta front setting where occassionally the shore line shifted back and forth in a cycle in which the shifting back westward of soreline (transgressive) is much longer than the shifting forth of the shoreline eastwardly (regressive). The East-West well correlation illustrating the depositional environment across the Nunukan Psc. is given by Figure 6.

Tectonic and deposition are a pair of agents to form unique deltaic systems in the Tarakan Sub-basin. The Neogene startigraphic cycles coincidently is disturbed by several tectonic cycles. The most prominent tectonic events are compressive tectonics which occured twice, firstly during Late Miocene and secondly during Pleistocene. In this paper, the discussion of the sea level change and influence of wave or tidal is very limited to a certain level just to minimize complexity. An illustration of the effect of the compressional tectonics is as follows; In the Tarakan sub-basin, a tectonic event will uplift an area to create a new source sediment for the surrounding area whilst the river systems change in direction avoiding the uplifted area. A Formation which was uplifted during a tectonic event will be a part of source provenance of sediment for the respective younger Formation. Two sandstones separately located in a distance may lithologically appear the same but they are actually have different ages, one sandstone belongs to the uplifted older Formation and the other one belongs to the new Formation deposited along the flank of the uplited Formation. Hence, the erosional product of the older Formation partly will contribute to deposition of the younger Formation. Figure 7 illustrates a structural high resulted by a compressional tectonic which will act as a buffer to the deposition afterwards and the structural high will be a new source sediment provenance as well for the new Formation. The position of an uplifted structure appears to move sequentially eastward so that the position of the younger formation will be shifted eastward relatively to the older formation, and so the following tectonic event will uplift both formations and other younger formation will be deposited further to the east. The Neogene delta in the Tarakan sub-basin was developed in that way. It started with the uplifting of what in the present day is called Kucing High in the Late Oligocene, which then became a source provenance of the deltaic sediments not only to the east to the Tarakan sub-basin but also to the west to the Baram delta. During Middle to Late Miocene, the Tidung and Tarakan sub-basins were likely to be one basin with deltaic sedimentary package of Meliat, Tabul and Santul Formations which were deposited towards the east. Based on the available data, no tectonic event is identified during the deposition of Meliat, Tabul and Santul.

Where is the limit of the deltaic system of each Formation to the east? As the oldest, the Meliat delta predominantly may only reach Bunyu and Tarakan islands and this was probably already in the late stage, meaning that majority environment was already pro-delta to delta front. The prograding delta of the Tabul formation on the other hand, as an overall cycle of regressive system tract continuing from the Meliat Formation, was predominantly already as lower delta plain to delta front facies in the Bunyu island location. Therefore, in the Nunukan PSC. to the East of the Bunyu island, the depositional environment of the Tabul Formation probably graded from pro-delta in the lower part to delta front in the upper part. Finally, the Santul Fm, the delta front facies although already distal, was deposited further east up to the B-1 well location in the Nunukan PSC. A major tectonic event in the end of Late Miocene during the end of Santul Fm, uplifted some part of the area to the east of Kucing High where the Middle-Late Miocene delta (Meliat, Tabul and Santul Formations) was already deposited. The tectonic event is identified on seismic data offshore in the Nunukan PSC as an angular unconformity in the border of Santul to Tarakan Fm. and in the onshore area the angular unconformity is an erosion surface of uplifted structures. By erosion and denudation the uplifted area then became a new sedimentary provenance to surrounding area presumably to the east of the uplifted area as regionally the slope is dipping to the east started from the Kucing High to the Nunukan PSC. The existing river systems from the Kucing High may still be a source provenance but probably their direction already split due to the barrier by the presence of the uplifted area. Hence a new formation, which is called the Tarakan Formation, will be unconformably deposited to the east of the uplifted area and will have a mix sediment composition sourced from the Kucing High and the reworked of the uplifted area. No active faultings are obsereved during the deposition of the Tarakan Formation but only parallel bedded sedimentary package. This is probably due to limited sediment was deposited which was sourced from the reworked materials of the uplifted areas. On seismic data, the Tarakan Fm. onlaps to the uplifted Late Miocene structure. In the far eastern part of the Tarakan sub-basin, there is no surprise that the sandstone is of fine to very fine grain as it was a reworked material from the existing formation. As most of the Simenggaris area was uplifted due to the Late Miocene tectonic event, the Tarakan Fm was probably not deposited in the Simenggaris area which only has the Meliat, Tabul and eroded Santul Formations. Finally, the second major tectonic event occurred during Pleistocene where the western part of the Tarakan sub-basin (the uplifted structure during the Late Miocene tectonic event) was more uplifted and the eastern part where Nunukan PSC is located and the Tarakan Fm is dominantly deposited was “poped up” to form the present day Bunyu, Tarakan and Ahus structural features. Before the Pleistocene tectonic event, some pulse of tectonics probably already occured which is indicated by onlapping sedimentary package over a structural high below the Pleistocene unconformity, especially identified on seismic data offshore.

The erosion of the Tarakan Fm. in the Bunyu and Tarakan structural highs is then deposited as the Bunyu Fm. Hence, the Neogene deltaic deposition in the Tarakan and Tidung sub-basins is a product of sequential orogeny starting in the Late Oligocene up to the present day. By that combination of continuous eastwardly fluvio-deltaic depositional and some pulse of tectonic events causing every Formation to be deposited in a limited certain area and laterally each area has different facies of the Formation. For example, in the onshore Simenggaris area, only the Meliat and Tabul Fm. are present as most of Santul Fm. was eroded and the Tarakan Fm. was unlikely deposited in the area. The facies of Meliat and Tabul Fm. in the Simenggaris area is dominantly delta plain and in Bunyu island is lower delta plain and delta front facies. Hence, for Meliat and Tabul Formation, the question is what is left in the area further east as in the Nunukan PSC? By this fact, understanding the distribution of the deltaic facies is critical for oil/gas exploration in the Tarakan sub-basin.

In summary, the Neogene deltaic deposition in the Tarakan sub-basin was developed by sequential series of compressional uplift, erosion and deposition. Frequent tectonic pulses occured during the fluvio-deltaic deposition affected the fluvial systems to frequently shift laterally due to blocking by the compressional structural highs. By uplifting in the upstream area, some part of the area that used to be delta would become starved of clastic deposition and be dominated by carbonate deposition as in the Ahus location during the Late Miocene tectonic event. This is the key difference between the Mahakam delta and the Tarakan sub-basin delta. A stratigraphic model illustrating the tectono-stratigraphy of the Tarakan sub-basin is given in Figure 8.

Paleogene Setting

An interesting topic is what happens beneath the Neogene deltaic package in the Tarakan sub-basin, i.e. the presence of Paleogene sediment and what type. In the onshore Simenggaris area, the Paleogene includes shallow marine and coastal sediments of Sembakung Fm. in a grabenal area and Oligocene carbonates of Tabalar Fm. in basement highs. No well has penetrated up to the Paleogene in the Tarakan sub-basin offshore so that the presence of Paleogene is interpretative. Another big question is regarding the position of the contact of the Oceanic crust of the Celebes Sea to Kalimantan as part of the eastern margin of the Sundaland and in what way they are in interaction. Seismic data near the Bunyu island or across Ahus appears to indicate that Bunyu and Ahus are inverted structures as indicated by the previous seismic data. The inversion is interpreted due to a compressional force by Sampoerna strike slip faults in the north and Maratua/Mangkalihat strike slip fault in the south. The Neogene sedimentary package appears to be thicker in the center of the basin including the Tarakan, Bunyu and Ahus location and gradually thinning to the north and south. If only the Neogen sedimentary package is present, the compressional force by bounding Sampoerna and Maratuwa faults will likely result in one huge anticline structure. However, the N-S seismic section indicates that there are three inversion structures which are Tarakan, Bunyu and Ahus. This means there is a thick sedimentary package beneath the Neogene delta in each location as in Bunyu, Tarakan and Ahus presumably in a half graben setting with bounding normal fault in the west of the three structures. The half graben package is correlable with graben sedimentary package onshore which contains Paleogene sediments (Sembakung Fm) beneath the Neogene deltaic sediments (Meliat and Tabul Fm) and is also inverted. The Paleogene basin in onshore as well as the half graben beneath Bunyu, Tarakan and Ahus structure was probaby in a marine setting since they were directly exposed to the open marine of the Celebes sea to the east. Hence, the lowest sediment above the basement is probably flysch. Overlying the flysch should be marine equivalent of the carbonate Tabalar Fm. and then pro-delta shales of Meliat Fm. above the Tabalar equvalent shale.

Onshore, the carbonate build up and platform of Oligocene of Tabalar Fm. was developed in the horst of grabens and other basement highs. Hence, the stratigraphy succession of the Tarakan sub-basin started with Paleogene graben or half graben fill followed by deposition of carbonates or their equivalent in line with regional transgression during Oligocene. In the Late Oligocene, a major tectonic event uplifted the present day Kucing High which then became a provenance for the Neogene fluvio-deltaic sediments over the Tarakan sub-basin until the present day. Based on that above evidence, it is likely that lineament beneath Tarakan, Bunyu and Ahus locations are a good candidate as the contact boundary of the oceanic crust to the margin of the Sundaland. The Bunyu or Tarakan or Ahus is the highest inverted structure as they have the thickest sedimentary package beneath them which may be related to the presence of a flexure created by contact of the oceanic crust and the margin of Sundaland. This contact is probably only suture but not subduction as the oceanic spreading centre in the Celebes sea pushed oceanic crust Northwest towards Sabah and southeast towards North Sulawesi. The bounding fault of Bunyu, Tarakan and Ahus is the westernmost normal fault dipping to the east and it may have root down to the suture. In summary, the Paleogene setting in the Tarakan sub-basin was Eocene graben and half graben filled by shallow marine sediments reworked from the local highs with occasionally vulcaniclastics and then followed by regional transgression during the stable condition which was dominated by carbonates during Oligocene. Finally, the collision of the Luconia micro-continent towards accretionary complex during the Late Oligocene resulted in the Rajang/Embaluh complex of the Kucing High. The collision was probably a coincidence with the docking of the Celebes oceanic crust. By then, the Neogene delta was set up with the Kucing High as the primary sedimentary provenance to sed off fluvio-deltaic sediments eastwardly. The fluvio-deltaic sediment was well developed from Meliat, Tabul to Santul Formations indicated by the prominent presence of listric normal faults. Only up to the Santul Fm, the deltaic setting in the Tarakan sub-basin is similar to the Mahakam delta. At the end of Santul Fm, a major tectonic event uplifted most of the Tarakan sub-basin particularly the present day onshore area. This stage is the distinct difference with the Mahakam delta, which present a new sedimentary provenance now involving the erosion of the uplifted structural highs during the Late Miocene tectonics. That is why the Tarakan Fm. is only well developed limited to the east of Bunyu, Tarakan and Ahus.

Another interesting question is regarding the slope position to provide turbiditic/deep water deposition in the far east of the Tarakan sub-basin, which also was responsible for triggering the toe-thrusting in the deep water depositional setting. A major fault called Main fault is the eastern boundary of a B structure located 20 km to the east of the Bunyu island (Figure 9). On the 3D seismic data, most of the lower section in the B structure obviously indicates features of carbonate build up developed along footwall of the Main fault trend, particularly in the level of Santul and older Formations. These carbonates developed along the footwall of the Main fault and are probably indicative of self edge position during Santul and older Formations. Coincidently, the outline of the present day self edge has a similar pattern with the Main Fault outline, which shifted eastward. Hence, although it is not located exactly at the same position, it is likely that the B structure position was a self edge during Meliat, Tabul to Santul Formations, which has provided slope to have the turbiditic deposition in the deep water setting further east. The Main fault was probably already active since the depostion of Tabul Fm. and was enhanced by deposition of the Tarakan Fm. On 3D seismic data, the Main fault appears to end up at a decolment surface as a listric fault which is then connected to the toe-thrusting in the deep water setting further east. During the Pleistocene tectonic event, in line with the “poped up” of the Bunyu, W and B structures, the hanging wall of the Main fault was gravitationally collapsed eastwardly along the fault plain of the Main fault whilst the half northern segment of the Main fault became dextral strike slip movement to create some horse tail faults (Figure 10).

A W-E geological cross-section model to describe the Tarakan sub-basin in a regional context modified from Sri Hidayati is given in Figure 11. In this modified model, the westernmost fault of Bunyu hyphothetically is a place of a suture of the Celebes oceanic crust against the margin of the Sundaland. Started at the Bunyu fault, the Neogene delta is thin-skin which was induced by gravity by the deltaic sediments to glide eastwardly through listric normal faults which end at a common decolment surface. Flysch overlying the Celebes oceanic crust and marine shale equivalent to Tabalar carbonate or Naintupo as well as the pro-delta shale of Meliat Fm. all together can provide an agent to transfer the energy of the normal listric faults towards east which ended up to toe-thrust faults in the deep marine setting. The Main fault during deltaic deposition of the Middle-Late Miocene was a shelf margin to provide a slope to the deep water deposition and so toe-thrusting. The Main fault during the deltaic deposition also triggered gravity glidding and so toe thrusting in the deep water setting further east.

Regional structural model - Riedle shears approach

The major structures in the study area are mainly folds and faults trending NE-SW. The large anticlines area probably represent positive flower structures in a transpressional system (uplift bounded by strike-slip faults) formed as 'push up' anticlines aligned sub-parallel to the strike-slip fault zones. An alternative approach is that strike-slip faults possibly present in between the well known Ahus Arch and Bunyu Arch and between Bunyu Arch and Tarakan

Arch which were active after ceasing the extensional faulting by deltaic deposition during Middle to Late Miocene and then was followed by an undisturbed deltaic depositional during Plio-Plesitocene (Figure 12). The strike-slip faults are located and aligned between the two major strike slip faulting of the Sampoerna Fault in the north and the Maratua Fault in the south.

The north-south anticline structure located in the southeastern portion of the Bunyu island can be interpreted to be a product of an east-west transpressional forces (shortening). Nevertheless, mapping the flower structure is not easy since most of the area is covered by only 2D seismic data. The anticline orientation and fault pattern in the Tarakan sub-basin correspond to the development of structural patterns of a sinistral strike-slip fault – see the Riedel shears or Strain Ellipsoid model (Figure 13). Even so, the old structure was reflected to strongly influenced its development and not all of the pattern (eg thrust faults) can be ideally established. The present day faults are believed to be a result of reactivation of the older extensional faults. The normal faulting obviously oriented northeast-southwest while the north-south faults more likely were activated by the strike slip faults.

It is likely that oil and gas fields in Bunyu and Tarakan generally have north-south trend and they are sub-parallel to the faults to form structural patterns which are well explained by the Riedel shears or Strain Ellipsoid model. Regionally, the area of Tarakan Basin alternatively can be divided into a complex arrangement of compressional duplex as manifested by the sinistral strike-slip system. The shape of each block within the complex is similar to the form of Ketupat so the complex is called as Ketupatzoid (Figure 14). In each complex, deformation by the compressional duplex overprinted to the existing structures to form the current geological structure.

Pitfall

Since not all of the fluvio-deltaic Formations are developed in the entirity of the Tarakan sub-basin, oil and gas exploration here is not simply just structural anticline trap but an accurate geological model is something that has to be done before deciding on any location to drill. A well will not penetrate all targets of all deltaic Formations and within one Formation it will not have the same facies as other wells encountered. On the other side, mature source rocks may not be present in all over the area at the same level. In a drilling well location, a well may penetrate many kind of deltaic facies up to the TD with hydrocarbon discovery only found in some particular levels.

The tectono-stratigraphy of the Tarakan sub-basin gives rise to petroleum systems complexity, not only as source rocks and reservoirs may have been deposited laterally in different places as the effect of uplift during several tectonic events but also in terms of maturation, hydrocarbon generation and expulsion and then migration may not be simple.

CONCLUSIONS

1. The overall stratigraphic cycle of fluvio-deltaic deposition in the Tarakan sub-basin is regressive with each Formation ended by short transgression marked by a Maximum Flooding Surface and carbonates in the self edge.

2. The Neogene fluvio-deltaic deposition in the Tarakan sub-basin was developed by sequential series of orogeny, erosion and deposition as the effect of compressional uplift started in the Late Oligocene with the uplifted Kucing High as the primary deltaic sediment provenance.

3. The Tarakan Formation may contain a mixture of sediment materials resulted from erosional products of the older Formation as well as from Kucing High.

4. The bounding Sampoerna and Maratuwa/Mangkalihat strike slip faults are the principle agents of the Neogene tectono-stratigraphy in the Tarakan sub-basin

ACKNOWLEDGEMENTS

The authors wishes to thank PHE Nunukan Company Top Management, Bapak Achmad Alfian Husein for encouragement to publish this paper and gratefully acknowledges the support of the Exploration Division – P.T Pertamina Hulu Energi, Bapak Rudy Ryacudu and Bapak Budi Tamtomo, especially during Regional Study of Tarakan Basin.

Thanks are also extended to PHENC Subsurface Team for technical discussions and great teamwork.

REFERENCES

Allagu Balaguru, 2003, Gary Nichols and Robert Hall, The origin of the 'circular basins' of Sabah, Malaysia:Geological Society of Malaysia, Sarawak.

Allagu Balaguru and Robert Hall, 2008, Tectonic Evolution and Sedimentation of Sabah, North Borneo, Malaysia: American Association of Petroleum Geology, Cape Town.

Sri Hidayati, 2007, Re-Visited Structural Framework of the Tarakan Sub-Basin Northeast Kalimantan – Indonesia: Indonesian Petroleum Association 31th Ann Conv, Jakarta.

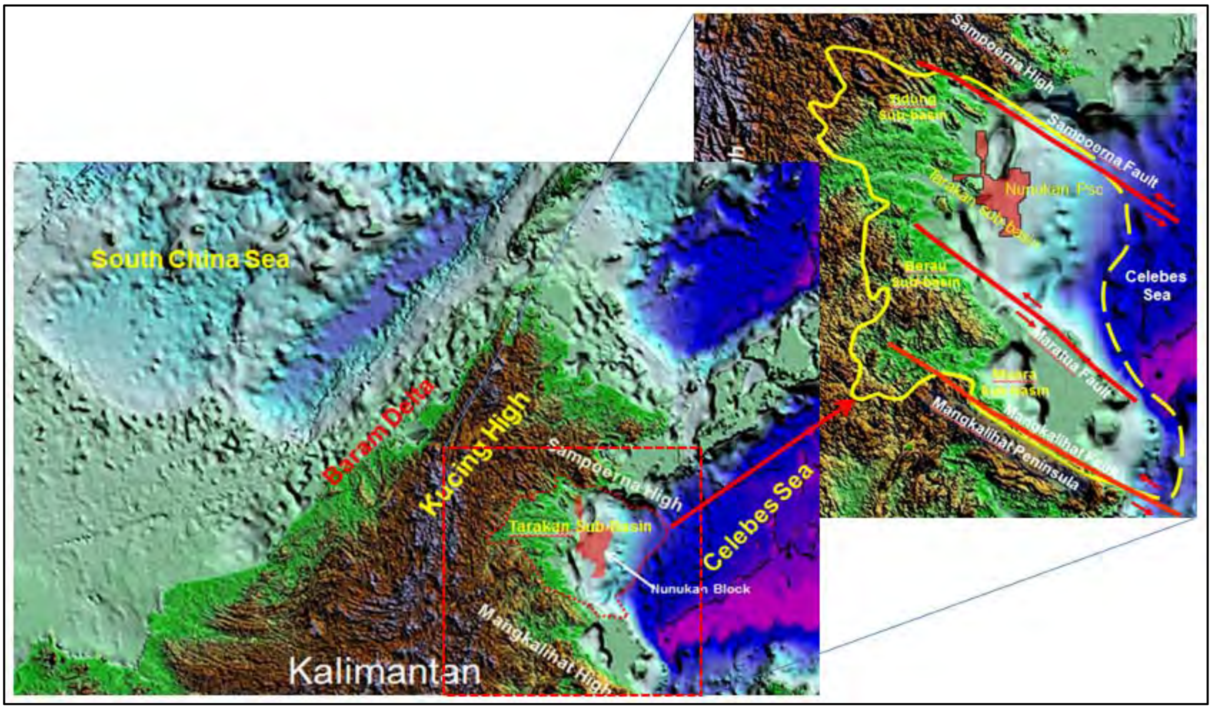

Figure 1 - Nunukan PSC and Tarakan sub-basin location. The Tarakan sub-basin, together with Tidung, Berau and Muara sub-basins, are bounded by strike slip faults which majorly include Sampoerna to the north and Maratua and Mangkalihat in the south. The Tarakan sub-basin faces to open marine the Celebes Sea.

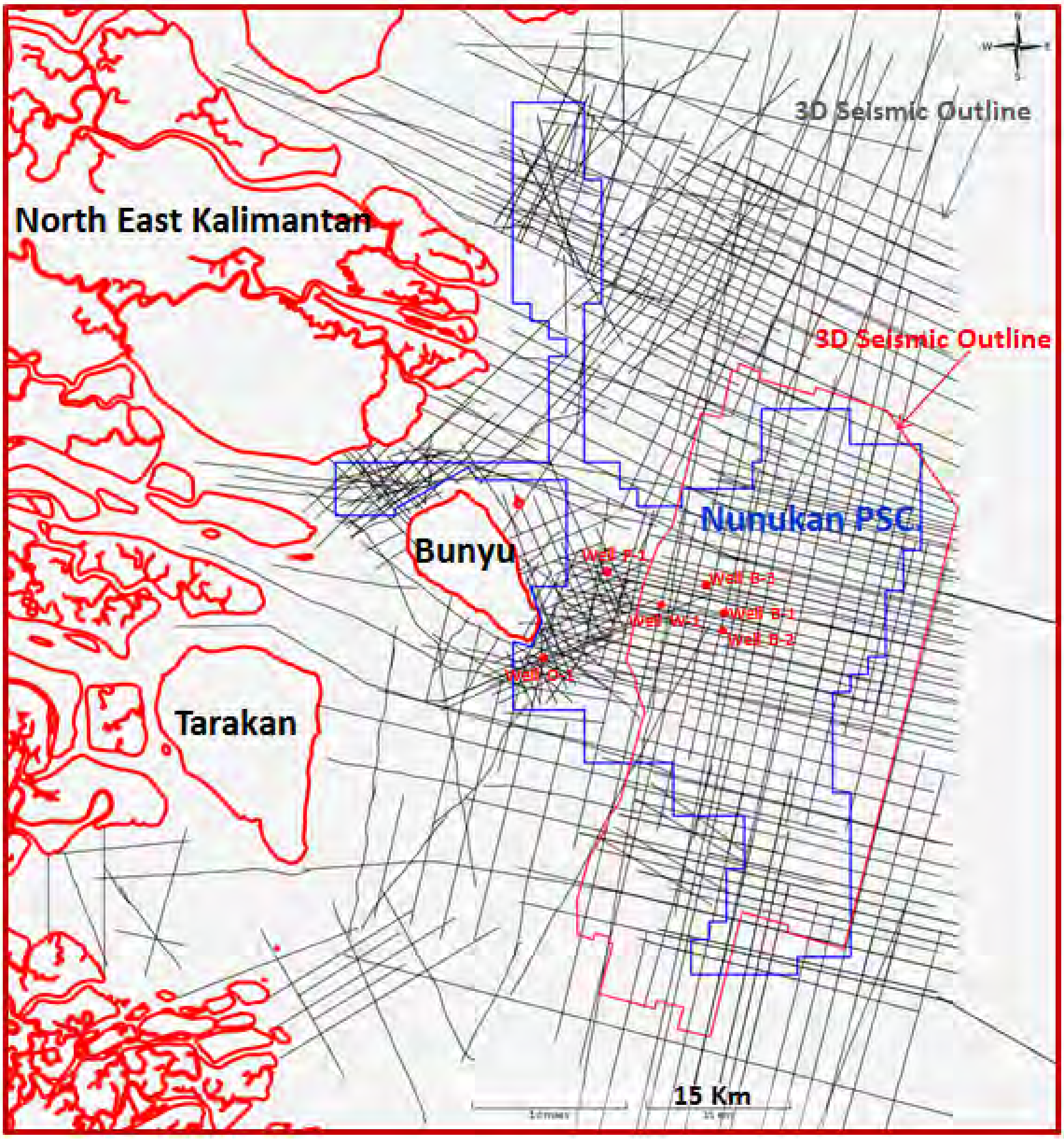

Figure 2 - Nunukan PSC and outline of 2D seismic (1970-1991), 3D seismic (2010) and well location.

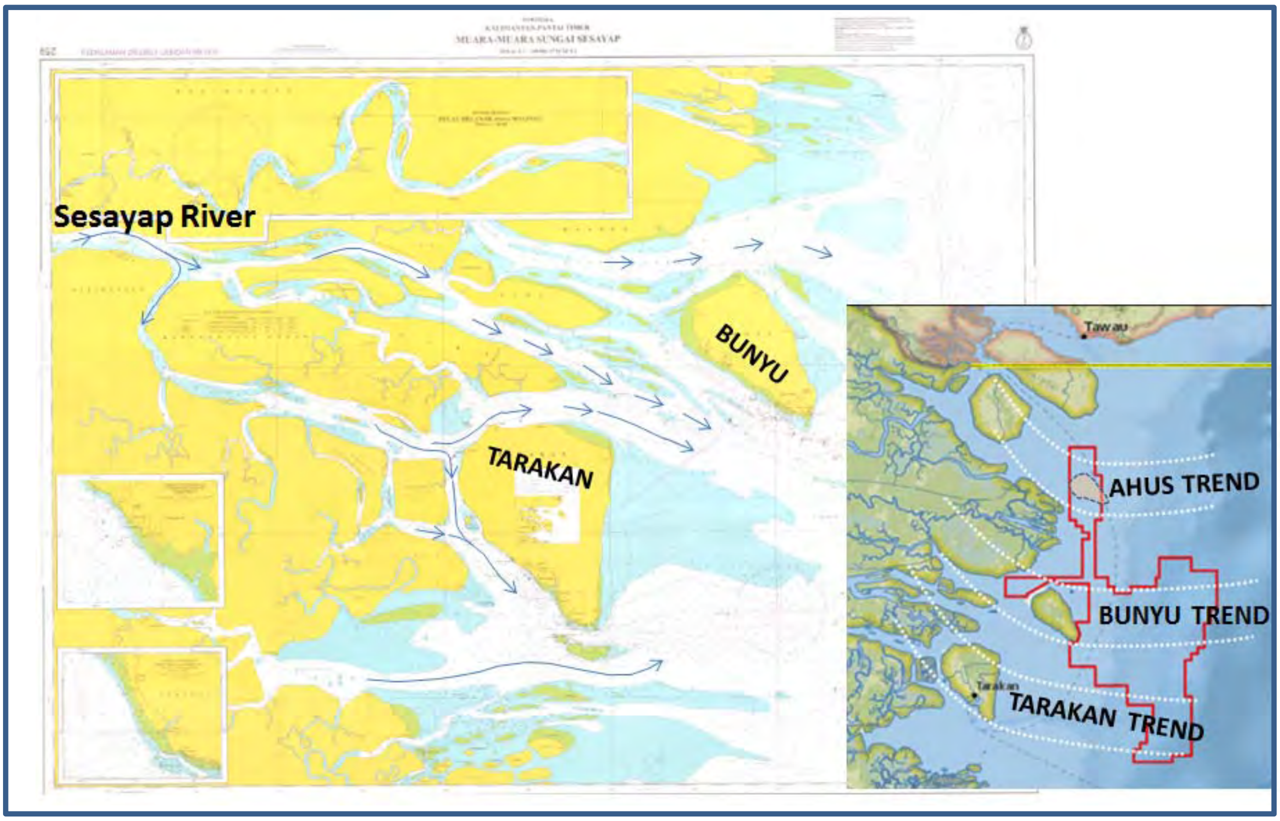

Figure 3 - Topographic map of Bunyu and Tarakan area. Note that the Sesayap river splits into two rivers as there is a structural high blocking the river, and then each of them splits again due to Bunyu and Tarakan islands blocking the two rivers as buffer to the current of the rivers into the open sea. Tarakan, Bunyu and Ahus are structural highs formed during the Pleistocene tectonic. A similar situation has likely been occuring since the Late Miocene.

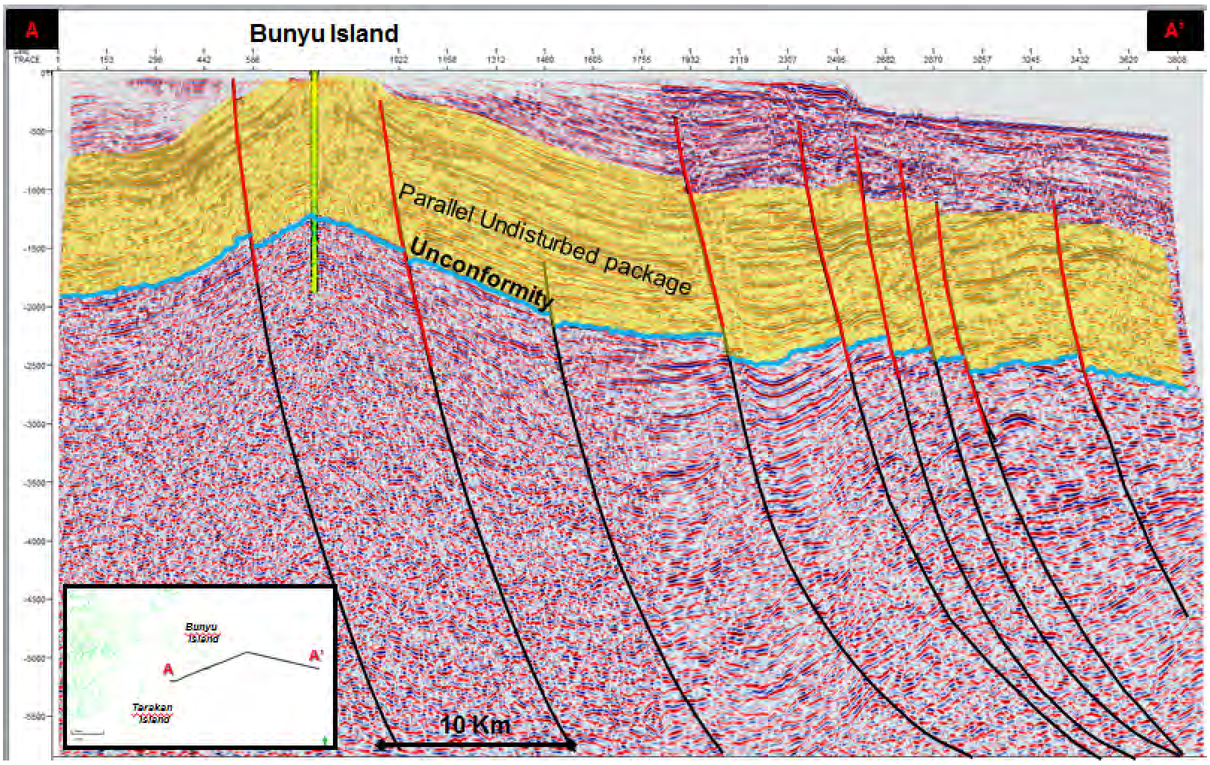

Figure 4a - Showing seismic section across the Bunyu structure. The parallel undisturbed package indicates that the red faults were generated due to the reactivation of the black faults. Beneath Bunyu island the sedimentary package is much thicker compared to surrounding, indicative that Bunyu structure is likely an inversion structure.

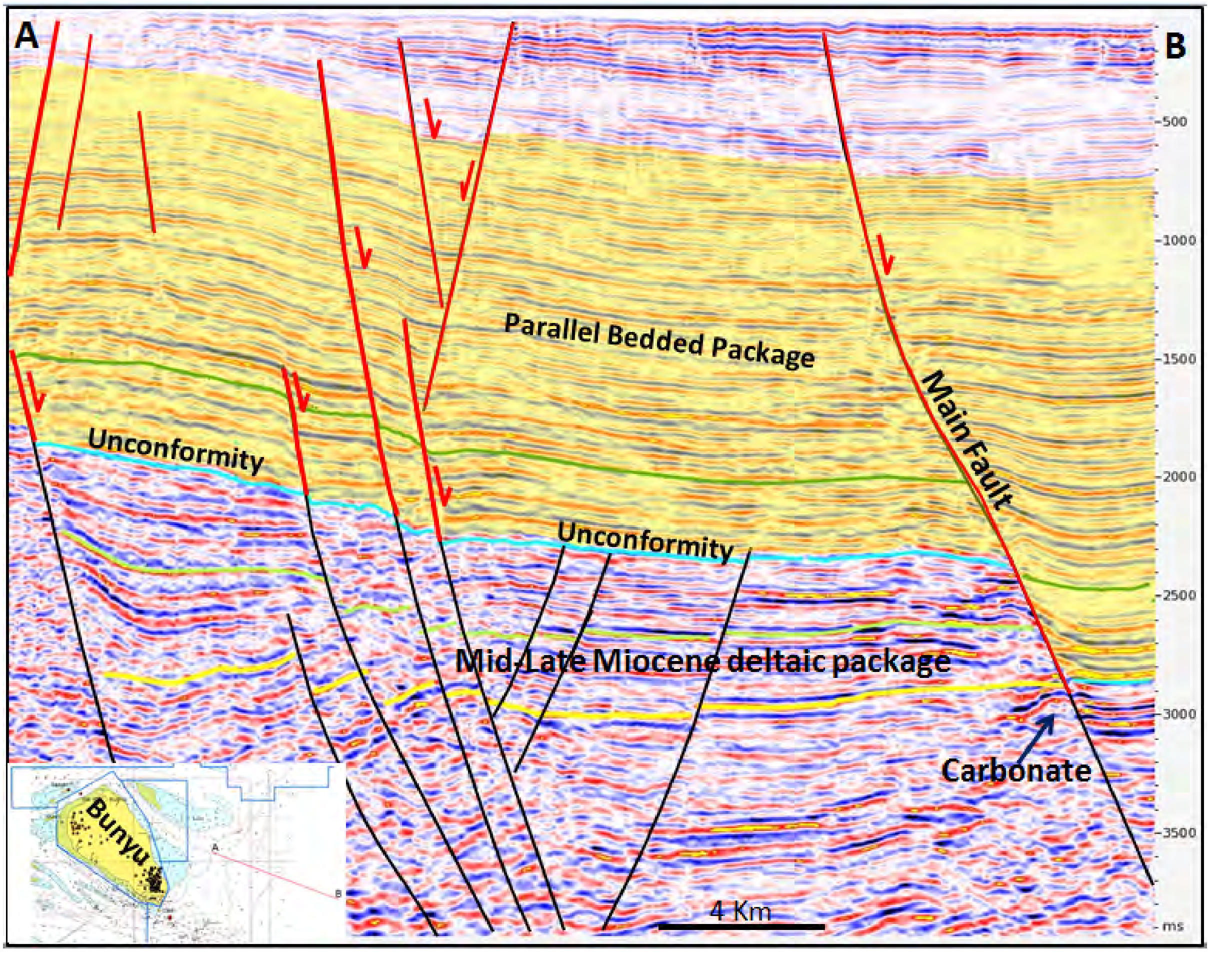

Figure 4b - E-W seismic section across the Nunukan PSC indicates 2 (two) distinct sedimentary packages separated by an unconformity due to the Late Miocene tectonic event. In the Main fault location, some carbonate features appear beneath the unconformity suggesting that during Middle to Late Miocene the Main fault position was probably a self edge of the westward deltaic deposition setting.

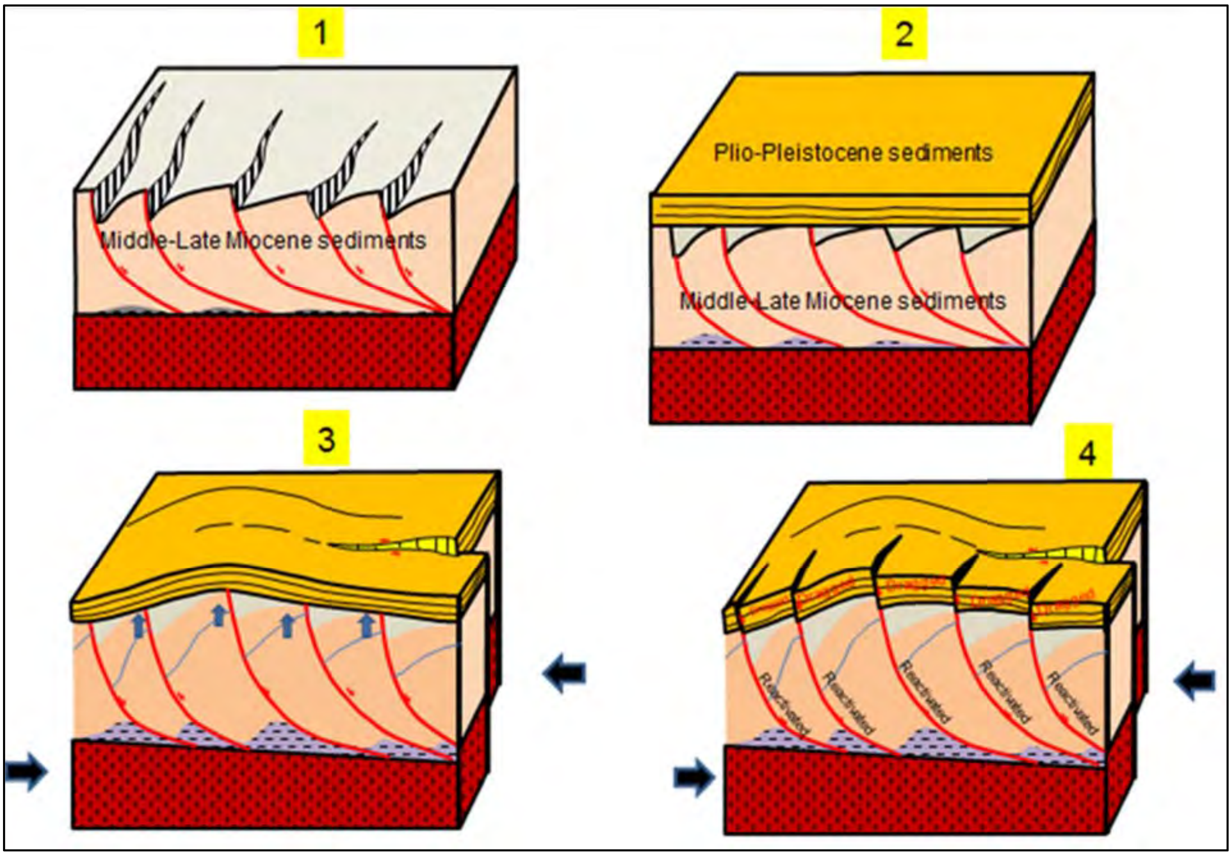

Figure 5 - A very simplified cartoon model describes the structural evolution of Bunyu, Tarakan and Ahus structures. The block model describes the structural evolution from normal listric faulting by deltaic deposition during Middle-Late Miocene to uplifting during Late Miocene (1) and then followed by Plio-Pleistocene parallel deltaic sediment deposition (2) until new compressional tectonic to uplift the whole block during Pleistocene (3) and finally reactivation of the existing listric faults to result in the present day features (4).

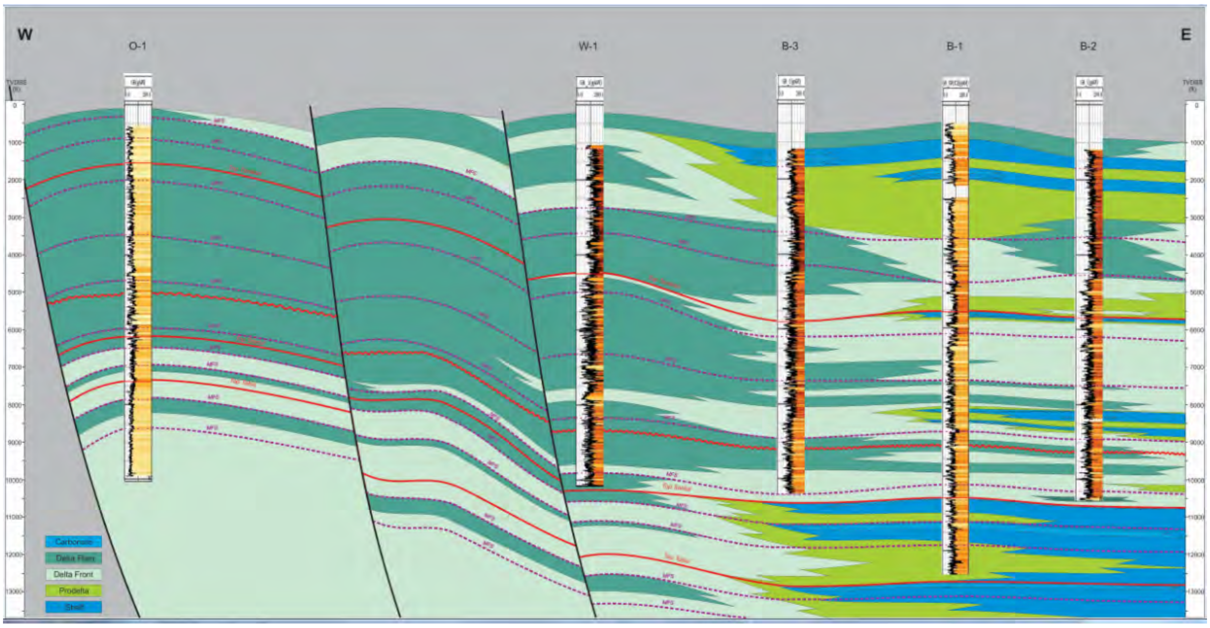

Figure 6 - Well geologic correlation to illustrate the depositional environment W-E across O-1, W-1, B-3, B-1, and B-2 wells. Note the presence of carbonates at the end of Santul and Tarakan Fm.

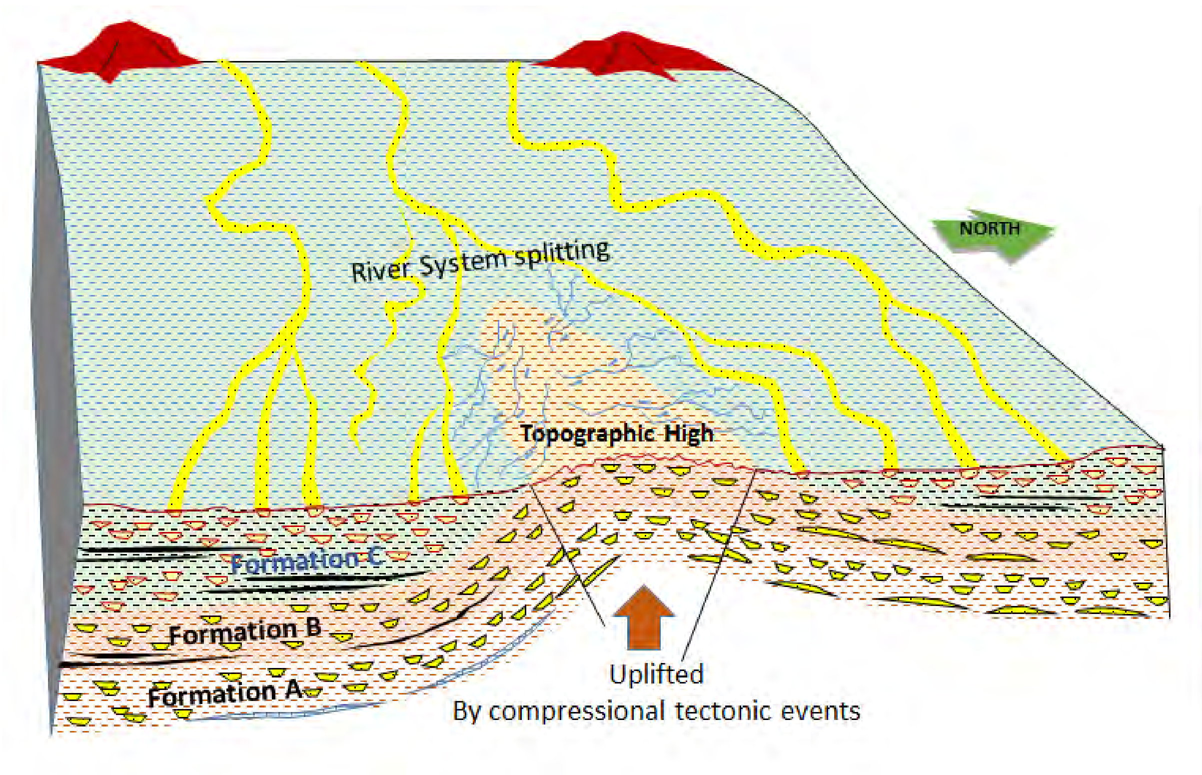

Figure 7 - A cartoon to illustrate the effect of the post-tectonic depositional setting in which a structural high resulted by a tectonic event will act as a buffer to the coming rivers and the new deposition of Formation B will have sediment materials mixtured coming from the existing provenance and from the erosional product of the uplifted existing Formation A & B.

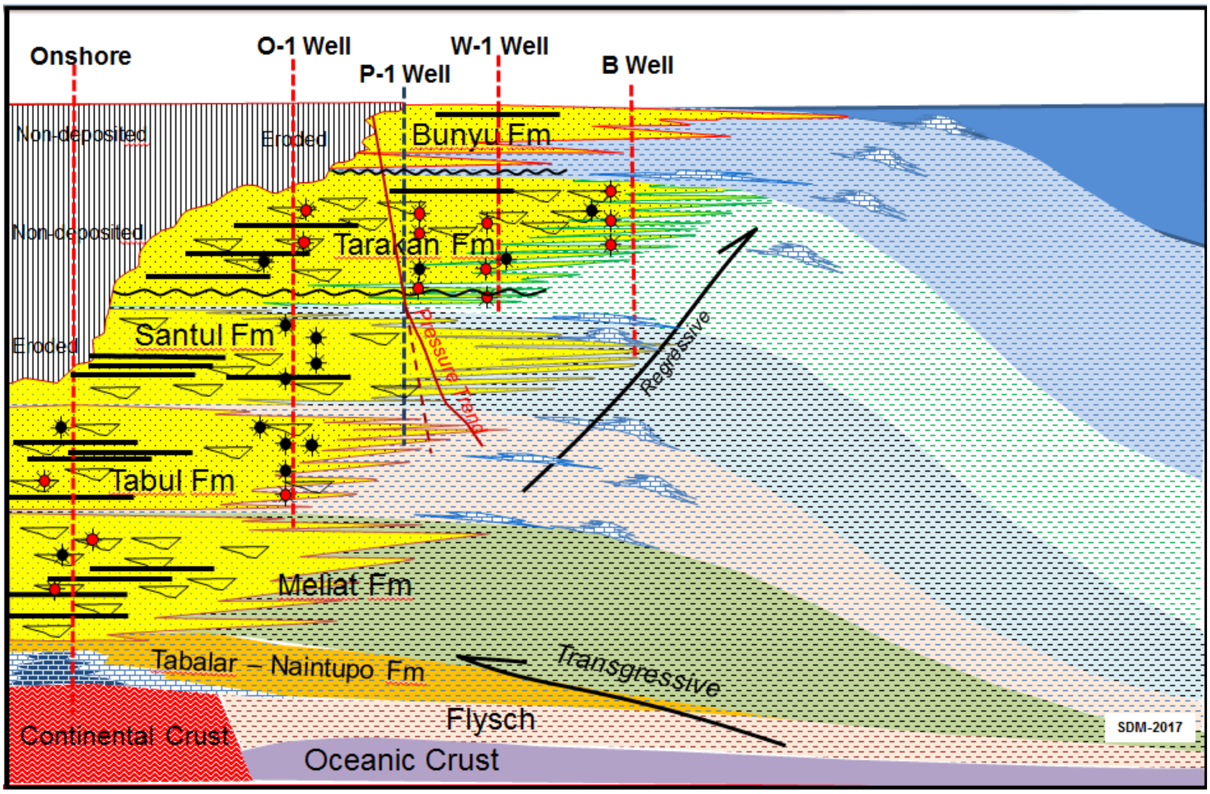

Figure 8 - Tectono-Stratigraphic evolution of Neogen fluvio-deltaic in the Tarakan sub-basin. Overall cycle, the fluvio-deltaic stratigraphy is regressive and a short transgression occured at the end of each Formation which is marked by carbonate as MFS. The dash vertical lines indicate the deepest penetration in the respective area and the penetrated Formations.

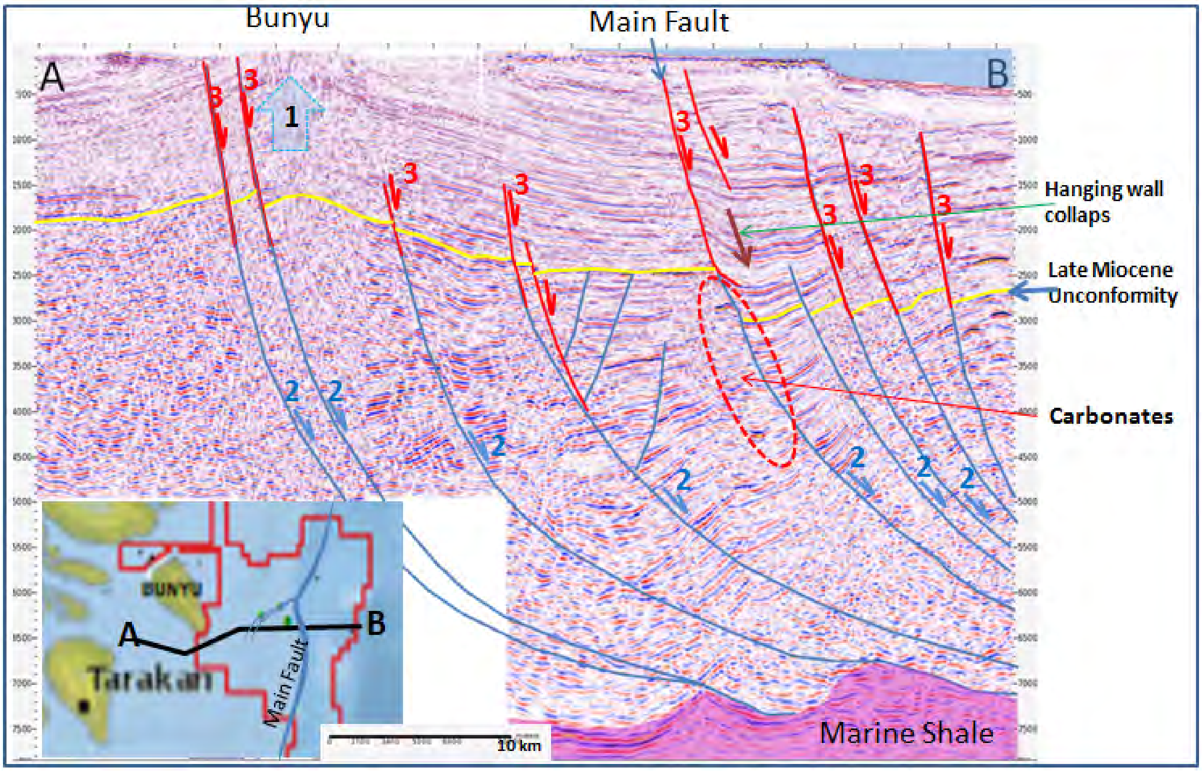

Figure 9 - Seismic section across Bunyu to Main Fault. From Bunyu to Main, normal faults appear listric to a decolment surface of thick marine shale. The blue fault segments are listric normal faults during the delatic deposition from Middle to Late Miocene whilst the red fault segments are faults resulted by reactivation (2) of older listric normal faults during Pleistocene tectonics, which Bunyu was "poped up (1)" and the upper part of the section was dragged down (3).

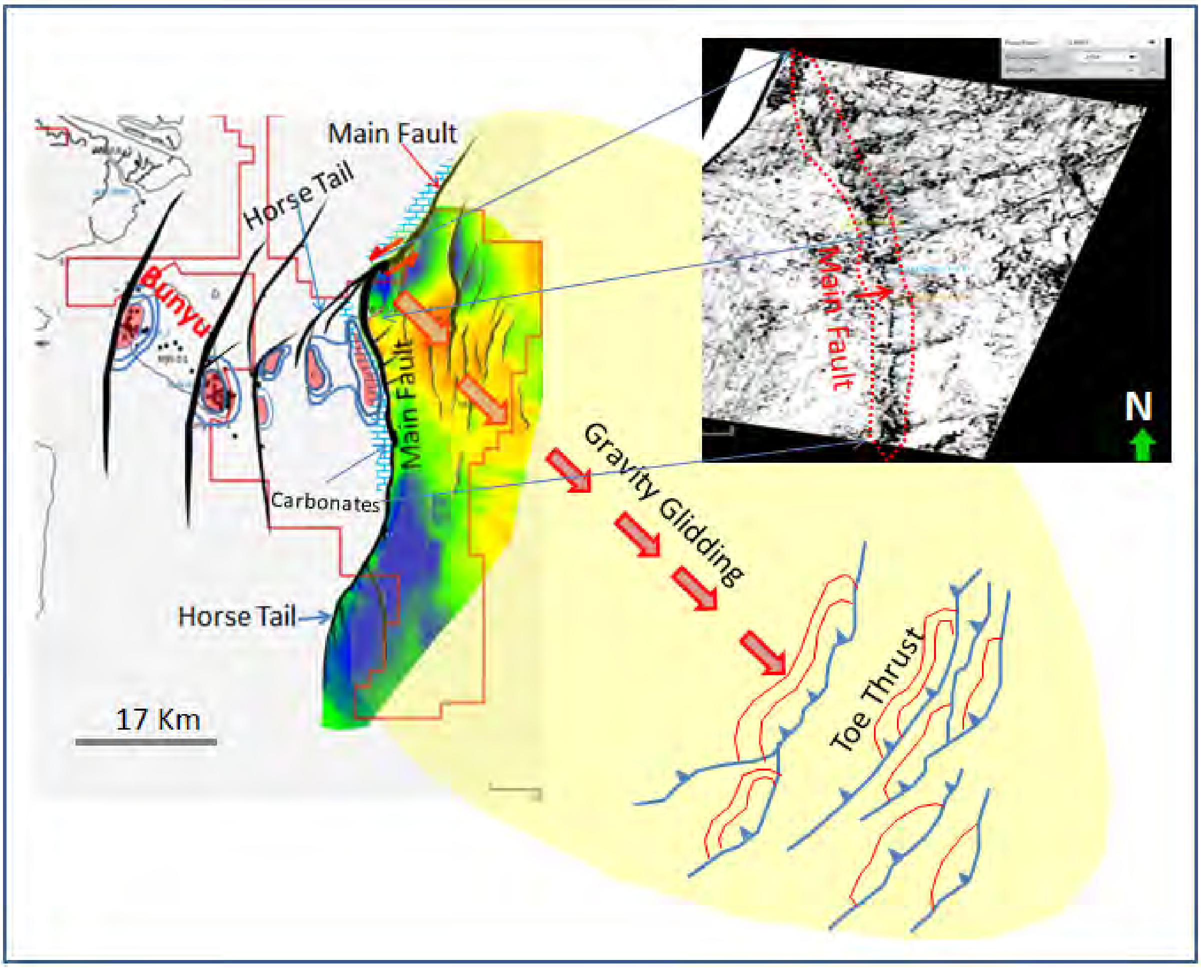

Figure 10 - Proto-Main fault position probably was as self edge during Meliat, Tabul and Santul deposition marked by presence of carbonates. The self edge provided a slope for deep marine turbiditic sediments toward east. The Main fault were re-activated during Pleistocene tectonic event, which poped up Bunyu and it's trend up to the Badik structure causing the hanging wall of Main fault collaps eastward along the Main fault plane.

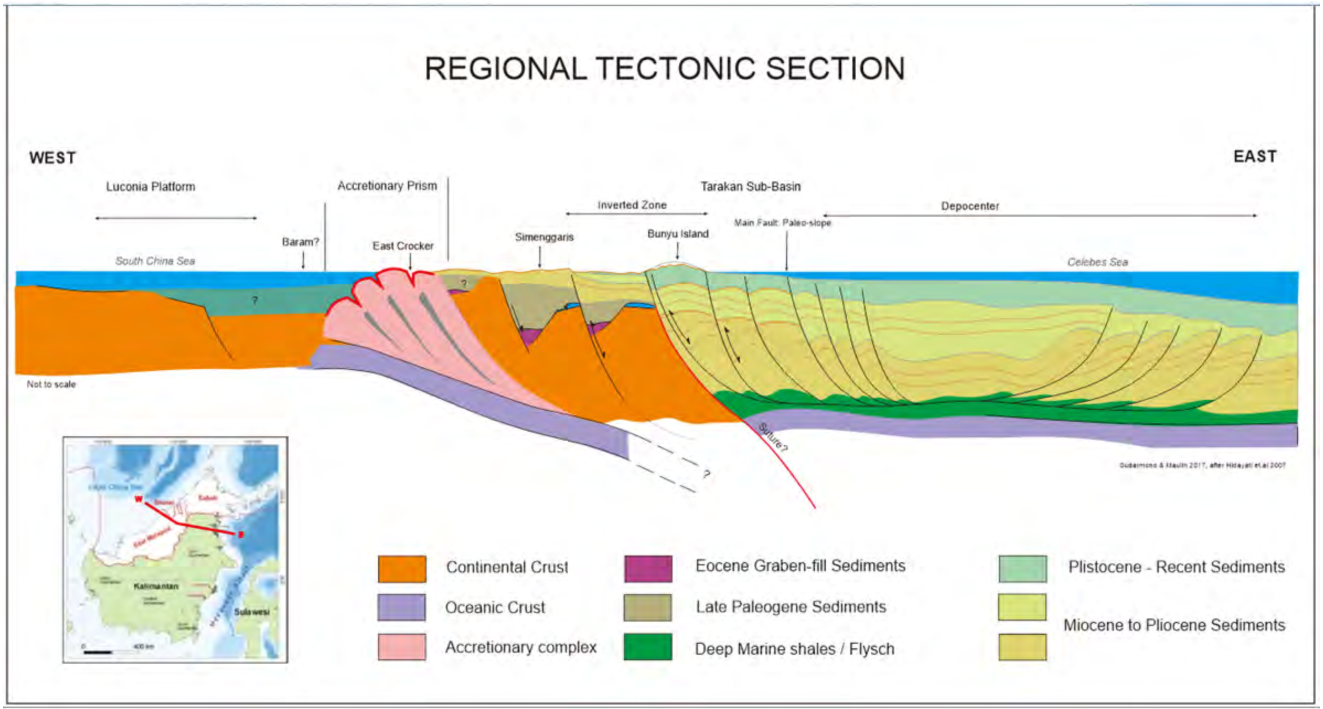

Figure 11 - W-E geological cross-section model to desribe the Tarakan sub-basin in a regional context modified from *Sri Hidayati*. In this modified model, Bunyu hyphothetically is a place of a suture of oceanic crust against the margin of Sundaland. The suture also provide a slope to the prograding delta deposition during Middle to Late Miocene to result in listric normal faults.

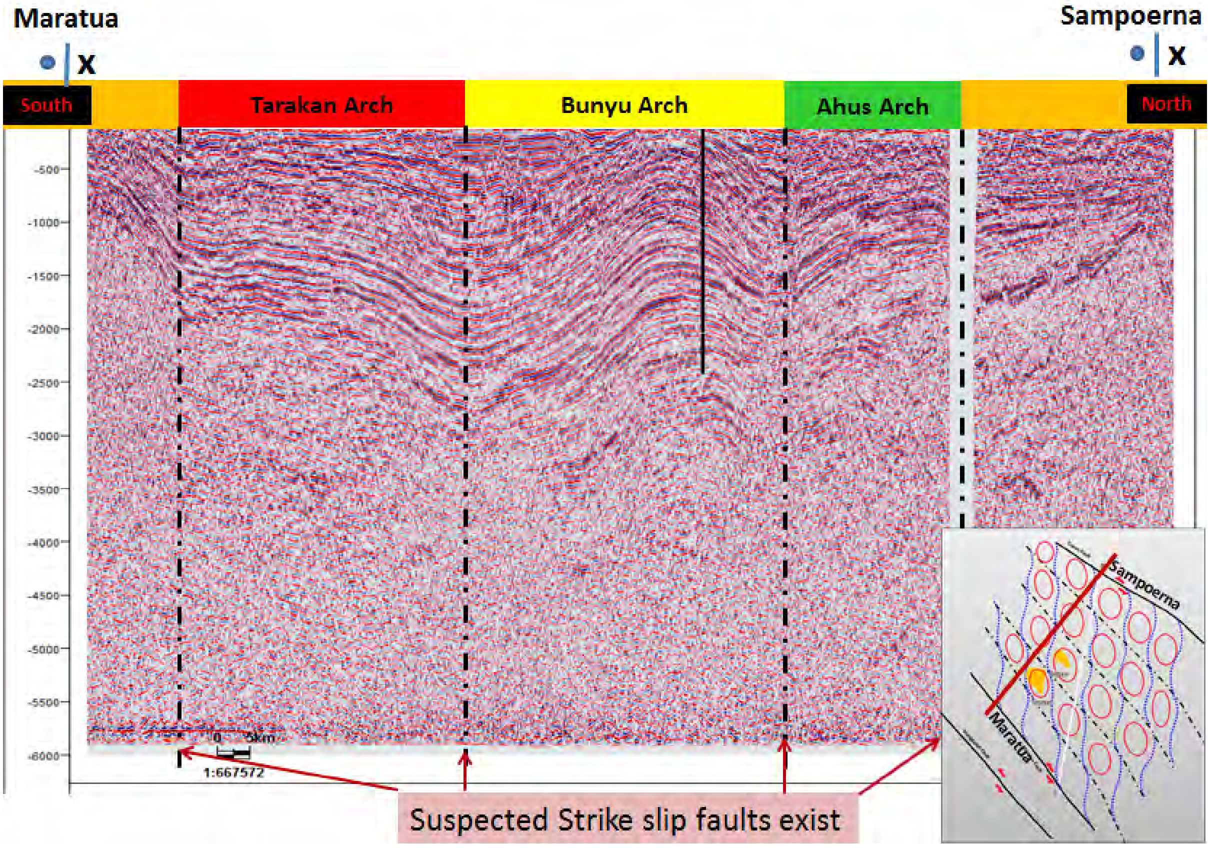

Figure 12 - SW-NE seismic section across Tarakan, Bunyu and Ahus Arch. Interpretative Stike slip faults as synthetic or far field stress of the Maratua/Mangkalihat and Sampoerna major faults probably present between the arches to generate the Tarakan, Bunyu and Ahus structures.

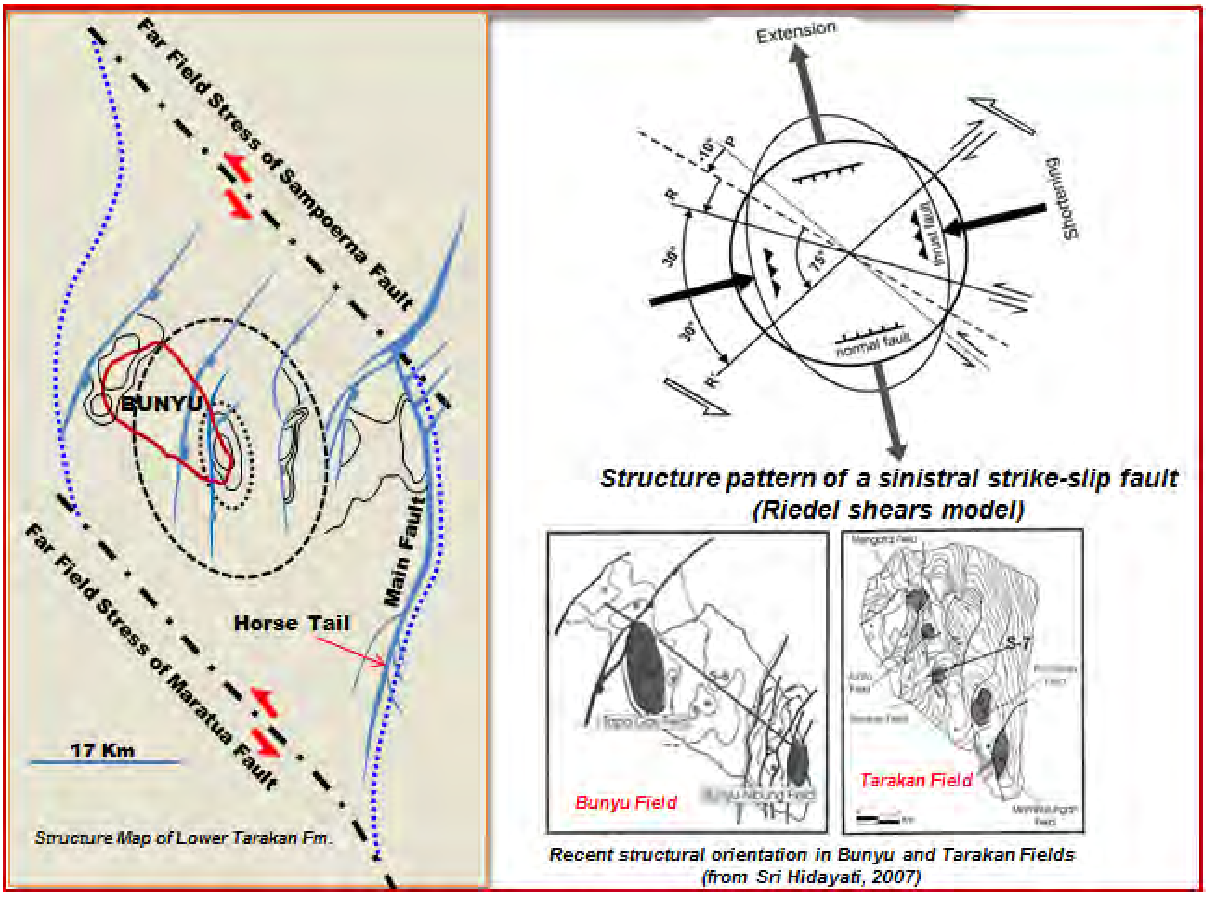

Figure 13 - Sinistral strike-slip fault - Riedel shears or Strain Ellipsoid model explain very well the anticline orientation and fault patterns in the Tarakan sub-basin as in Bunyu and Tarakan island.

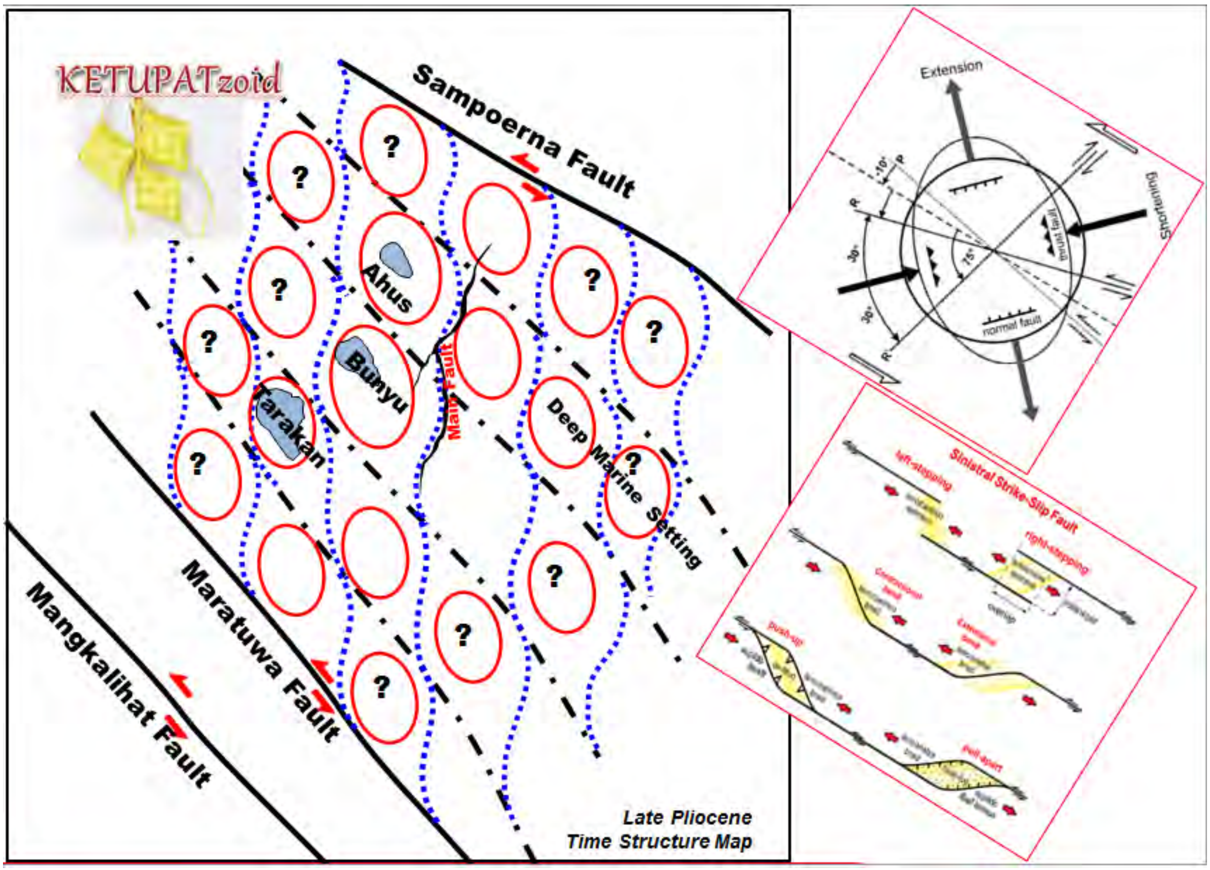

Figure 14 - By Riedel shears or Strain Ellipsoid model, the sinistral Maratua and Sampoerna strike slip faults generated far field stress to form compartment structural pattern called "Ketupatzoid" in the Tarakan sub-basin. Some structural highs fit and fall within the the compartment like Tarakan, Bunyu and Ahus.