[PS]The Sorong Fault Zone Kinematics: Implication for Structural Evolution on Salawati Basin, Seram and Misool, West Papua, Indonesia*

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Abstract

The Sorong Fault Zone (SFZ) is an active left lateral fault system that has been active since the Late Miocene. The SFZ is located in the northern margin of Papua, Indonesia, and extends thousand kilometers from the Eastern part of the island to the Bird's Head region. Our new model indicates that SFZ moved the Bird's Head area, including Salawati Basin to the west, relative-to the movement of the Pacific Plate. The movement of SFZ involves rotation and translation that separates Salawati Basin from the Bird's Head region with basement high as the boundary of the basin, and also gives an implication to the evolution of Seram Fold Thrust Belt (SFTB) and Misool Onin Kumawa Anticline (MOKA). More than 200 seismic lines have been interpreted along Seram, Misool, and Salawati offshore. These interpretations show the development of listric and planar normal faulting at the western part of Misool Island and flower structure at NW Bird's Head region. This faulting activity was interpreted as a result of SFZ activities, which cut Paleozoic through the Tertiary formations. The listric and planar normal fault in the Salawati Basin explains the block rotation mechanism that relates to the Bird's Head movement to the west. In addition, flower structures that observed at NW Bird's Head indicate the shortening effect of the SFZ activities. Seemingly, rotation and translation of SFZ to the west are associated with the evolution of SFTB indicated by NE-SW shortening perpendicular to the island. The deformation in the SFTB showed the development of fold-thrust belt structure at Seram Trough area, which repeated the Mesozoic-Miocene sequences, with the detachment surface located between Seram and Seram Trough. Reverse fault at Mesozoic through Miocene sequences in the north of the trough and at Misool area are reactivated normal faults formed during the NW shelf of Australia rifting since the Mesozoic. Therefore, SW directed shortening as a response of the Bird's Head region movement combined with additional westward movement of Tarera-Aiduna strike-slip system forms the SFTB. New seismic interpretations combined with palinspatic reconstruction suggest that there are rotation and translation phase in relation to SFZ mechanism that develops the Salawati Basin, MOKA, and SFTB. These deformations mechanism are active since the Late Miocene and related to the collision between Pacific island arc complexes and passive margin of the NW Australian plate.

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THE SORONG FAULT ZONE KINEMATICS: IMPLICATION FOR STRUCTURAL EVOLUTION ON SALAWATI BASIN, SERAM AND MISOOL, WEST PAPUA, INDONESIA

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ABSTRACT

The Sorong Fault Zone (SFZ) is an active left lateral fault system that active since the Late Miocene. The SFZ is located in the northern margin of Papua, Indonesia, extended thousand kilometers from the Eastern part of the island to the Bird's Head region. Our new model indicates that SFZ moved the Bird's Head area, including Salawati Basin to the west, related to the movement of the Pacific Plate. The movement of SFZ involves rotation and translation that separates Salawati Basin from the Bird's Head region with basement high as the boundary of the basin, and also give an implication to the evolution of Seram Fold Thrust Belt (SFTB) and Misool Onin Kumawa Anticline (MOKA).

More than 200 seismic lines have been interpreted along Seram, Misool, and Salawati offshores. These interpretations show the development of listric and planar normal faulting at Western part of Misool island and flower structure at NW Bird's Head region. This faulting activity was interpreted as a result of SFZ activities, which cut Paleozoic through the Tertiary formations. The listric and planar normal fault in the Salawati Basin explains the block rotation mechanism that related to the Bird's Head movement to the west. In addition, flower structures that observed at NW Bird's Head indicate the shortening effect of the SFZ activities. Seemingly, rotation and translation of SFZ to the west are associated with the evolution of SFTB that indicate by NE-SW shortening perpendicular to the island. The deformation in the SFTB showed the development of fold-thrust belt structure at Seram Trough area, which repeated the Mesozoic-Miocene sequences, with the detachment surface located between Seram and Seram Trough. Reverse fault at Mesozoic through Miocene sequences in the north of the trough and at Misool area are reactivated normal faults formed during the NW shelf of Australia rifting since the Mesozoic. Therefore, SW directed shortening as a response of the Bird's Head region movement combined with additional westward movement of Tarera-Aiduna strike-slip system forms the SFTB.

New seismic interpretations combined with palinspatic reconstruction suggest that there are rotation and translation phase in relation to SFZ mechanism that develops the Salawati Basin, MOKA, and SFTB. These deformations mechanism are active since the Late Miocene related to the collision between Pacific island arc complexes and passive margin of the NW Australian plate.

INTRODUCTION

Strike-slip fault movement is common to form wide deformation zone consisting of various scale of subsidiary fault system. In some case, large scale strike-slip fault such as transform fault system which acted as plate boundary can be associated with the formation and deformation of sedimentary basins including their depositional environment. The main purpose of this study is to evaluate effect of large continental boundary strike-slip fault movement in the basin formation and deformation of the Bird Head region, Papua, Indonesia.

The Yapen-Sorong Fault Zone is a major left-lateral strike-slip fault system located in northern Papua and extended for more than 1000 km from east to west. This strike-slip fault system is interpreted as transform fault bounded Pacific Plate in the north and Australia plate in south. In Bird Head region, this fault known as the SFZ and it changes its strike direction from NW-SE become NE-SW in the west corner. As a result, it formed very complex deformation pattern in the Bird Head region for example in the Salawati Basin, Misool, and Seram area. The Salawati Basin, Seram and Misool area has different sedimentary pattern and deformation style (Riadini et al., 2009) (Figure 1). There are thrust-fold belt structures in the Seram area, known as SFTB, while there is an anticline structure in Misool area (MOKA) as a result of reactivated structure from the activities of Bird's Head collision (Riadini et al., 2010). However, the relationship between different area was never been evaluated before due to lack of data. This study will present the result of integrated analysis of those areas using new acquired 2D seismic survey.

Figure 2 show 2D seismic surveys along Seram, Misool, and Salawati offshore conducting by TGS-NOPEC Geophysical Company on 1998, 1999, and 2007. The new data combined with the existing data will be used to generate new interpretation in the Bird Head Region particularly concentrated in evaluation the mechanism of SFZ.

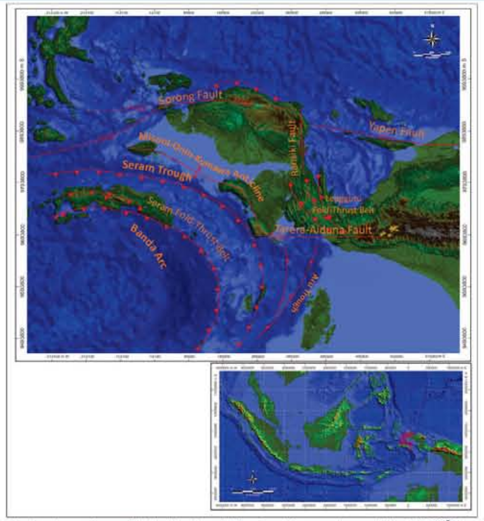


Figure 1. Tectonic elements on Bird's Head and Western Papua, showed the N 300°E and E-W lineament at Tarera Aiduna fault, Misool-Kumawa, and lineament on Sorong fault. The N-S lineaments as the result of the Northern Australia continental margin, showed at Lengguru fold-thrust belt (Riadini, 2009).

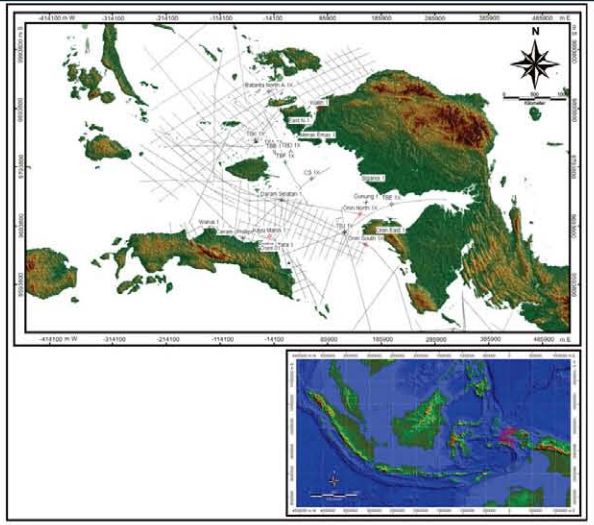


Figure 2. Location of seismic and well. The main concern area is bordered by Seram Island to the South, Misool Island to the NW and Onin High to the NE.

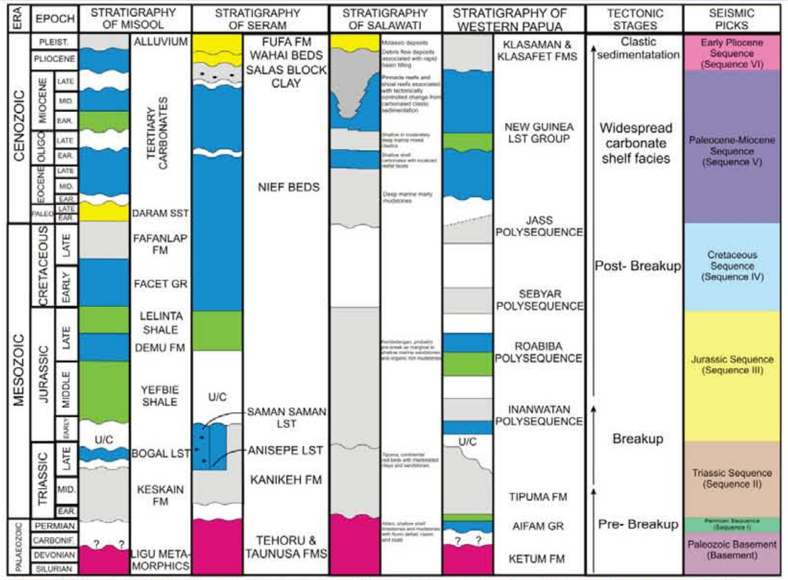


Figure 3. Seismic Picks based on stratigraphy column of Seram, Misool, Salawati, and Western Papua areas and also as a compilation with the wells data (modified from Fraser et al., 1993; Pairault, et al., 2003 and Satyana, 2003)

Table 1. Structural Event Compilation Between Bird's Head and Some Sub-Areas Around Bird's Head Areas (Riadini, 2009)

ERA	EPOCH		STRUCTURAL EVENT OF BIRD'S HEAD	STRUCTURAL EVENT OF MISOOL	STRUCTURAL EVENT OF SERAM	STRUCTURAL EVENT OF SALAWATI
CENOZOIC	PLEIST., PLIOCENE	Post Break-up	wrench faulting activities	Early Pliocene unconformity	Seram fold-thrust belt	wrench faulting/SFZ activities
CENOZOIC	MIOCENE LATE	Post Break-up	wrench faulting	wrench faulting (reactivated the Triassic extensional fault)	wrench faulting (reactivated the Triassic extensional fault)	wrench faulting/SFZ
CENOZOIC	MIOCENE MID., EAR.; OLIGO LATE	Post Break-up	the end of extension arc-continent collision	starting of Misool-Onin anticline; Late Oligocene unconformity	Late Oligocene unconformity	Late Oligocene unconformity
CENOZOIC	OLIGO EAR.; EOCENE LATE, MID., EAR.; PALEO LATE, EAR.	Post Break-up		starting arc-continent collision	starting arc-continent collision	uplifted and eroded
MESOZOIC	CRETACEOUS LATE	Post Break-up	intracontinental extension	extensional phase (relative tectonic quiescence)	phases of continental rifting (E-W extension)	
MESOZOIC	CRETACEOUS EARLY; JURASSIC LATE	Post Break-up	phases of rifting on western margin of Australia			
MESOZOIC	JURASSIC MIDDLE	Post Break-up			distal passive continental margin	
MESOZOIC	JURASSIC EARLY	Break-up		minor angular unconformity		
MESOZOIC	TRIASSIC LATE	Break-up	extensional faulting		rift graben; block faulted structure; series of rotated normal fault blocks on north Berau	
MESOZOIC	TRIASSIC MID., EAR.		Pre-Breakup (rift system and a major phase of regional extension)	rift graben		rift graben
PALAEOZOIC	PERMIAN, CARBONIF., DEVONIAN, SILURIAN					

REGIONAL TECTONIC AND STRATIGRAPHY

The tectonic of Papua is considered to be one of the ideal examples where two major tectonic elements are contemporaneously active in one area. At the present time, the Pacific plate is moving west-southwest at 7.5 cm/y, while the Australian plate is moving northward at 10.5 cm/y. The collision of the two plates has been active ever since Eocene (Cloos et al. 2005; Hall, 1997). These tectonic episodes have imparted a complex structural setting to the Papua. Most of Papua is underlain by the continental crust belonging to the Australian continent. Neogene tectonics of Papua and New Guinea areas are marked by the collision of the northern Australian continental plate margin with the Pacific oceanic plate in the north (Hamilton, 1979), as well as collision with the Banda Sea oceanic plate in the northwest. The southwestward motion of the Pacific plate and N 25° E movement of Australian plate created a convergent strike-slip movement for the whole of Papua, resulting in wrench and thrust faulting across Papua and New Guinea. The N 300° E and E – W paleo faults, reactivated as sinistral wrench fault, and thrust faults, depending on their position to the Neogene stress field. The N – S paleo-fracture such as the Lengguru Fold Belt behaves as an accommodation zone for the westward moving of the northern block of Papua creating intensive network thrust faults and folds of the Lengguru zone (Sapiie and Closs, 2004). Generally, the major trend at Bird Head Region, Papua, is shown by the E-W to NW-SE lineation at Misool-Onin, N-S lineation in the Lengguru thrust-fold belt trend. The E-W to NE-S trend is associated with the presently active SFZ, and NNE-SSW to N-S trend related with Late Permian graben structures, which is shown at Vorwata and Wiriagar Deep area and likely to be more extensive around the region (Syafron et al., 2008).

Four major tectonics events have imparted a complex structural setting at Western Papua (Henage, 1993), which are: 1) Early Jurassic rifting along the Australian plate northern margin; 2) Early Jurassic rifting along the Australian NW Shelf; 3) Neogene collision of the Pacific and Australian plates with subduction on the New Guinea Trench drives the Papuan and Lengguru Fold Belt and 4) Neogene collision of the Banda Arc with the Australian plate has formed the Misool-Onin-Kumawa Arc. These tectonic events are related to the structural configuration and evolution on Bird's Head area. The main structural elements on Bird's Head area are the SFZ and the Kemum High, the Ayamaru Plateau in the north, the Ransiki Fault and the Lengguru Fold Thrust Belt in the east, the Misool-Onin-Kumawa in the south, Berau Basin in the southwest, and the Salawati Basin in the northwest. The SFZ and the Ransiki Fault bounded the exposed part of the Bird's Head basement known as Kemum High. It contains the Paleozoic (Siluro-Devonian) metamorphic sediments, to the south overlain by Carboniferous-Permian sediments of the Aifam Group. The Ayamaru Platform is overlain by a strong unconformity of Miocene Kais Fm and appears to be the source of sediments from the Late Paleozoic to recent. The structural configurations of Kemum High, Lengguru Fold Thrust Belt and Misool-Onin-Kumawa High bounded the low relief feature known as Bintuni Basin. It is separated from the Salawati Basin by the Ayamaru Platform. The Sorong fault also bounded the Salawati Basin on the north and on the southwest by the Misool-Onin-Kumawa High. The Salawati Basin is interpreted to be related to the trans-current movement of the SFZ. However, Bird's Head and Misool block controlled by the configuration of the Sorong Fault and the Ransiki Fault. The Bird's Head block was affected by an important phase of deformation during the Oligocene, most notably giving rise to the NW-SE trending Central Bird's Head (Vogelkop) Monocline (Visser and Hermes, 1962). A contemporaneous Oligocene structural event is also recognized in the Misool Island, where Late Oligocene-Early Miocene section unconformably overlies the gently deformed Eocene-Oligocene and the older strata (Pigram et al., 1982). The age of initial movement of the SFZ has been variously estimated between Oligocene and Middle Pliocene, with most possible placing the main phase of movement in the Middle Miocene-Pliocene (Charlton, 1996). Another structure related to the Tertiary deformation at the Bird's Head area is the Seram trough. The Seram trough is a foredeep area, which was developed by the fold-thrust belt system during the Early Pliocene (Pairault et al., 2003). All of these structural elements explain some hypotheses of Bird's Head relative movement; either a Late Tertiary clockwise rotation (Hamilton, 1979; Robinson and Ratman, 1978) or composite micro-continents with a separate drift history (Pigram and Pangabean, 1984). **Table 1** shows the regional structure compilation between some sub-areas around Bird's Head tectonics.

The stratigraphy of Western Papua and Bird's Head divide on seven sequences which associated with three main tectonics period on Eastern Indonesia (Fraser et al, 1993). Stratigraphic column showing Western Papua and Bird's Head lithologic strata is as shown in **Figure 3**.

METHOD AND RESULT OF STUDY

In this study, we integrated 2D seismic interpretation from Salawati, Misool and Seram areas connected through regional lines. The interpretation is conducted using guidance from Eastern Indonesia regional tectonic concept. Relationship between deformation and sedimentation is evaluated using several palinspatic regional cross-sections. This palinspatic cross-section is generated with balancing cross-section techniques using Midland Valley 2D/3D software package. Structural interpretation also confirmed with bathymetry and multibeams data provided by TGS-NOPEC.

The 2D seismic data set was provided by TGS-NOPEC Geophysical Company and tied to 22 wells around Seram, Misool, and Salawati areas. Seven horizons were interpreted and contoured. These horizons identified based on well data and Bird's Head stratigraphy (Fraser et al., 1993), those are: top Tipuma (Late Triassic), top Roabiba (Middle Jurassic), top Gamta (Early Cretaceous), top Ekmai (Late Cretaceous), top Faumai (Early Oligocene), and top Kais (Middle Miocene). A major unconformity on Early Pliocene identified as top sequence VII which separates the lower six horizons and the youngest sequence (**Figure 4**). There are four structural patterns around Seram, Misool, and Salawati (**Figure 5A**): The N-S trending normal faults that develops as horst and graben at Permian-Late Jurassic sequence; The NE-SW trending normal faults along West of Misool and Salawati area that associated with a large strike-slip zone; The E-W trending fold-thrust belt along Northern Seram area that deformed until the Early Pliocene sequence; The NE-SW trending reverse fault along NW Bird's Head area which associated with a large strike-slip zone. These structures pattern is show on the isochore map for each horizon (**Figure 5B**).

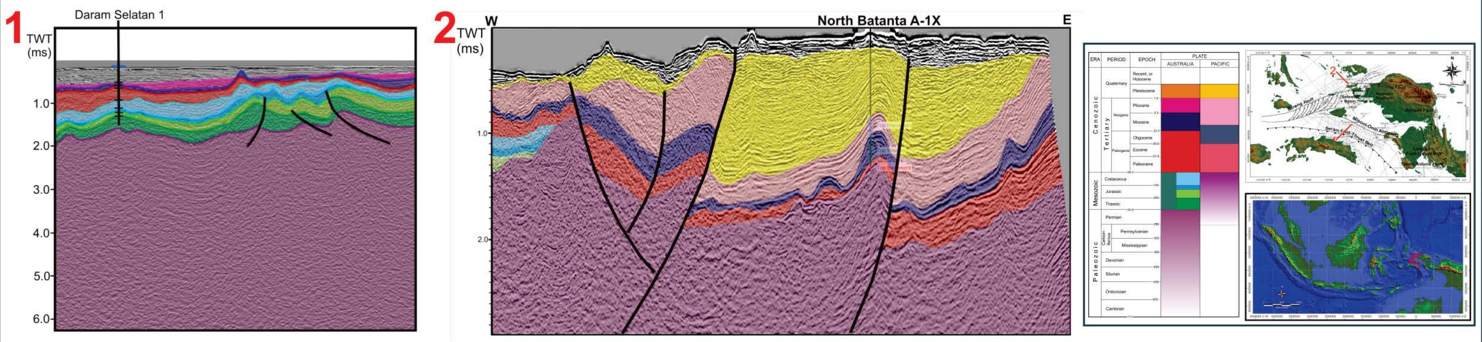
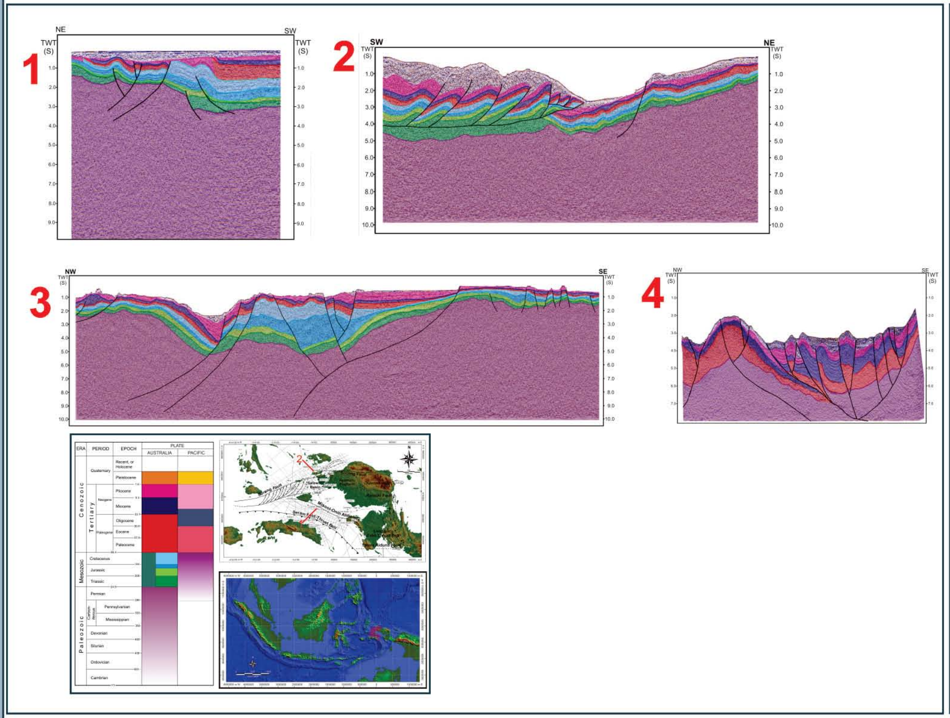


Figure 4. Well seismic tie on Seram-Misool and Salawati area that show the evidence of seven sequences from the Mesozoic until the Tertiary time.



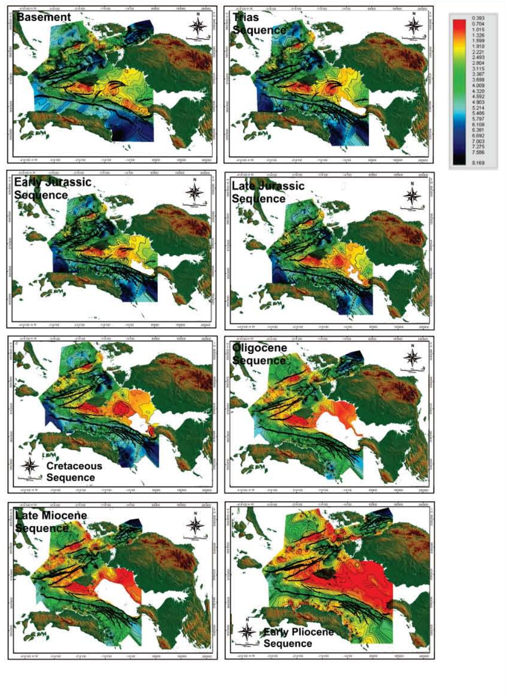


Figure 5A. Seismic interpretation along Seram, Misool, and Salawati show the development of three structure domain in the Tertiary time.

Figure 5B. Time structure map along Seram, Misool and Salawati area.

PALINSPATIC RECONSTRUCTION

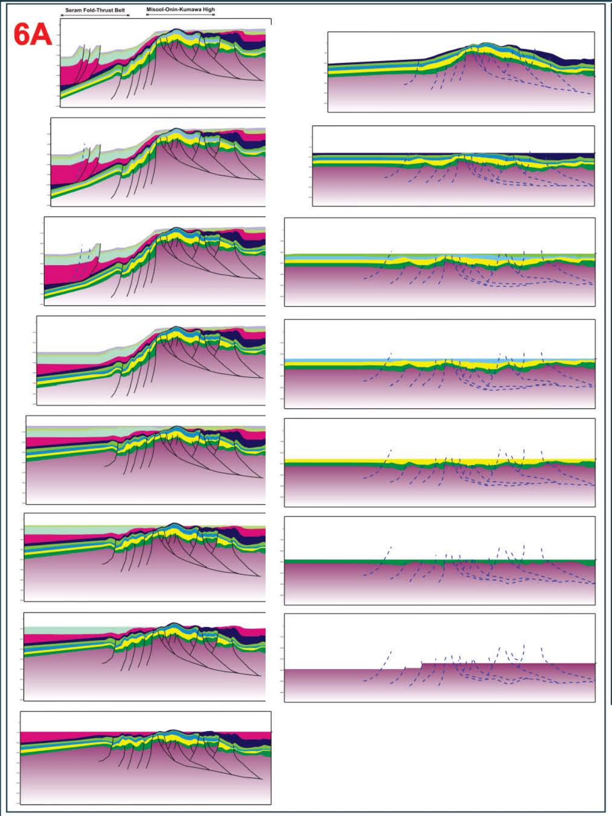
Palinspatic reconstruction was applied to reconstruct the structure deforming the research area. This method was used to estimate the timing and to define better generation of the structural events associated with the SFZ, SFTB and reactivation fault at the Misool-Onin high. The two dimensional configuration between surface and fault was seen by using 2D/3D Move Software (**Figure 6A, 6B, 6C, and 6D**).

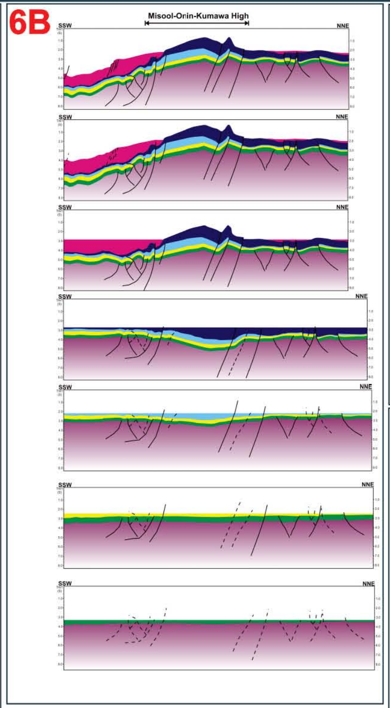
Figure 6A shows the palinspatic reconstruction of the Misool and Seram area. The reconstruction shows that there are at least two major tectonic events, which occurred in this area since the Permian-Triassic deposition. Normal faulting related to the Late Triassic-Early Jurassic rifting was developed after the deposition of the Permian-Triassic sequence. Some of the faults controlled the development of the Jurassic basin, especially those at the north of Misool and Onin area. The normal faulting during Jurassic controlled the thickness at some of the Jurassic sequence. The deformation continued and the deposition of carbonate sediments started in the Middle Miocene time. During this time, the area experienced a strike-slip event, and it reactivated the Late Triassic-Early Jurassic normal faults to reversed faults. The Middle-Miocene tectonic continued and the fault was active until the deposition of the Early Pliocene sequence. Some of the Middle Miocene faulting are still active and affected the Early Pliocene unconformity. In the Seram area, deformation continues and developed the fold-thrust belt system due the compression system. The fold-thrust belt systems were also found in the sequence above the unconformity. This suggests that the deformation was still active until the younger sequence in Seram to south of Misool-Onin area.

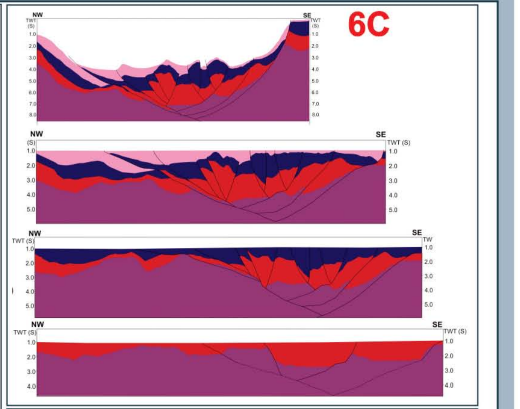
Figure 6B shows the other palinspatic reconstruction around the Onin high area. The section is crossing the South Onin-1 well and correlated to the surface cross section across the Onin East-1 well. The section shows the development of normal faulting due the Permian-Jurassic sequence deposition. The normal faulting is also related to the Late Triassic-Early Jurassic rifting. The development of the normal fault continued to the Cretaceous sequence deposition. The reactivation started after the Miocene sequence deposited and reactived most of the normal faulting in the Onin area to reverse faults. The reactivated fault is dominant in the Onin area and created significant uplifting of the Miocene sequence at the Onin high. The Early Pliocene sequence is deposited above the Miocene faulting and created the unconformity surface; the deformation continued to the Early Pliocene sequence as normal faults. This structure is still active up to the sequence above the unconformity. This suggests that the structure is related to the Tertiary deformation at Bird's Head area, which controlled by the strike-slip zone.

Figure 6C shows the palinspatic reconstruction around the West Salawati area. The reconstruction showed at least two events affected this area. The Early Oligocene sequence is overlain above the Paleozoic basement high. The evidence of Eocene to Oligocene graben started in this time showed by a normal fault as the bordered fault for the basin that created at this area. There is also evidence of rifting that interpreted as the Mesozoic rifting. The deformation continues and the deposition of carbonate sediments also started in the Middle Miocene time. In this Middle Miocene time the strike slip event that created the pop-up structure started, which showed as the first time of the growth structure. This strike slip system continued and the fault had been active until the deposition of Early Pliocene sequence. The growth up strike slip structure continued and deformed the youngest sequence. It is also interpreted that this deformation has been active until the present time. Starting from the Middle Miocene time, this fault has been developed as strike slip system and has created some antithetic fault. The pop-up structure that is developed in this area is interpreted as the antithetic fault from the big strike slip system known as the Sorong Fault. This palinspatic reconstruction confirms that the Sorong fault system has been active since the deposition of the Middle Miocene sequence until the present time. The palispatic reconstruction showed the trend of the compression that created the Sorong fault system was the NE-SW trend.

Figure 6D shows the palinspatic reconstruction around the West Misool area. The section show the development of Permian-Triassic normal faults that related with NW Australia rifting at passive margin event. The normal faults continous developed until the Early Jurassic sequence. The development of normal faulting followed by the subsidence event at Early Jurassic. The subsidence event created the significant thickness during the deposition of the Early Jurassic sequence. The development of normal faulting still continuos until the Cretaceous sequence developed. The collision event since the Early Eocene influenced to the structural development at West Misool area. In this phase the palinspatic reconstruction shows the changing of extensional phase to the shortening phase. Normal faults that developed since the Mesozoic at the Eastern part, reactivated as the reverse fault and also influenced to the reactivation at MOKA since the Late Oligocene. This normal faulting development are related with the SFZ activities, since the Late Miocene, with the NE-SW trend.







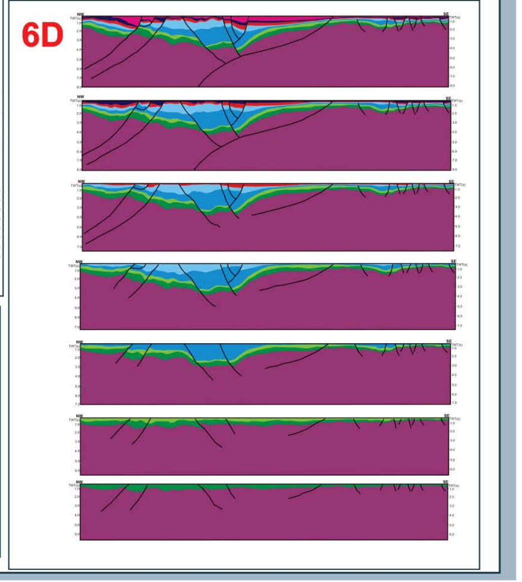
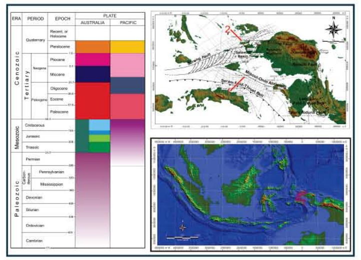


Figure 6. 2D palinspatic reconstruction on Seram, Misool, and Salawati area. This reconstruction show the development of strike-slip system and fold-thrust belt that developed since the Late Miocene and active until the present time.



STRUCTURAL MODEL AND DISCUSSION

The collision between the Pacific and NW Australia at Bird's Head area start since the Late Eocene (Closs et al, 2005). The collision event started after the end of the extensional phase related to the passive margin tectonic and Late Triassic-Early Jurassic rifting. The start of the reactivation structure around north of Misool-Onin and Berau-Bintuni area in the Late Oligocene are the first structure and deformation event that marked around the Bird's Head area. The development of thrust fault around this area continued with the deposition of the Late Oligocene sequence, which unconformably overlaid the previous Permian-Cretaceous sequence. The reactivation is significant at the some Jurassic basin area, and created a high area that will be known as Onin High. The reactivated reverse faults are also eroded some Createaceous-Late Oligocene sequence, especially around the old Jurassic basin. The deformation is continued after the deposition of Miocene sequence, and it still occurred by the collision activities. In the Miocene, some Mesozoic structure especially at Seram and south of Misool-Onin area are reactivated while the other area, such as Salawati, affected by the strike-slip system known as SFZ.

In the north of Misool-Onin and Bintuni area, the Miocene structure is developed above the Late Oligocene unconformity, and created folding at Oligocene-Miocene sequence as a result from structural reactivation at the Mesozoic faulting. The reactivation at the Miocene uplifted the Onin high. Some of the Miocene sequence is also eroded around the Onin High, especially at the old Jurassic basin. The structure is continues until the deposition of the Early Pliocene sequence that unconformable with the Permian-Miocene sequence.

Structure interpretation from the seismic and multibeams bathymetri show the SFZ mechanism is develop into two mechanisms, there are divergen strike-slip system on West Misool and Salawati area, and horsetail mechanism (releasing bend/fault) termination that related with reverse fault development on NW Salawati. The MOKA that active since the Late Oligocene related with the tilting process on South Misool until Seram. The compressional and shortening events on the Early Pliocene created the fold-thrust belt development that known as SFTB.

Structure and deformation still continued after the deposition of Early Pliocene sequence due to the collision event around the Bird's Head area. The fold-thrust belt at Seram area was developed after the Early Pliocene deposition and also affected the sequence above the Early Pliocene unconformity. The structural activities were related to the NE-SW shortening around the Bird's Head area and suggested as the accommodation from the SFZ activities to the northwest. The structure above the unconformity also explains that the structure is still active until present time. The normal faults during the Early Pliocene-youngest sequence explained the structural activities related to the E-W trending strike-slip deformation (**Figure 7 and 8**).

CONCLUSION

Deformation around Seram and Misool-Onin high start since the Late Triassic, known as the Late Triassic-Early Jurassic NNE-SSW normal fault. The development of the normal faults created some basin filled with the Jurassic sediments. During the Bird's Head collision, which has started in the Eocene, new structural event is developed at the north of Onin area (Berau-Bintuni area). The tectonic event reactivated the Mesozoic structures and created the unconformity surface known as the Late Oligocene-Miocene unconformity. This structural event was the first reactivation that caused the uplift around the Onin high area. Reactivation of the Mesozoic faults continued to the Miocene and amplified the uplift of the Misool-Onin high. The deformation in the Miocene developed normal faults related to the E-W trending strike-slip system, which also controlled structures that develop at the Miocene.

There are regional unconformity surfaces at the Early Pliocene time, which were truncated with sediments as old as Jurassic-Miocene sequence. This unconformity surface is also folded and deformed by the fold-thrust belt structure at the Seram area. This unconformity was also folded at the MOKA and it is assumed that the deformation occurred in the Late Oligocene and still active until the present time. Some normal faults also developed during the Early Pliocene. This suggests that the activities of the E-W strike-slip system since the Miocene are still active at the Seram and MOKA area.

Basinal areas are identified in the NW Bird's Head, which is bordered by a faulted basement high that created from the rifting event, associated with the Mesozoic rifting. Mesozoic sequence in the area was not deposited, due to the relatively stable basement high until the deposition of Early Oligocene sequence.

The strike slip system was started during the deposition of Middle Miocene sequence as a growth fault and remained active during the deposition of Early Pliocene time. The strike slip system created some antithetic fault which also known as the pop-up structure. This pop-up structure was created in extreme depth at the basin area and the deformation continued to the youngest sequence. The pop-up structure are the antithetic fault trending NE-SW from the left lateral couple Sorong fault system trending E-W and NNE-SSW.

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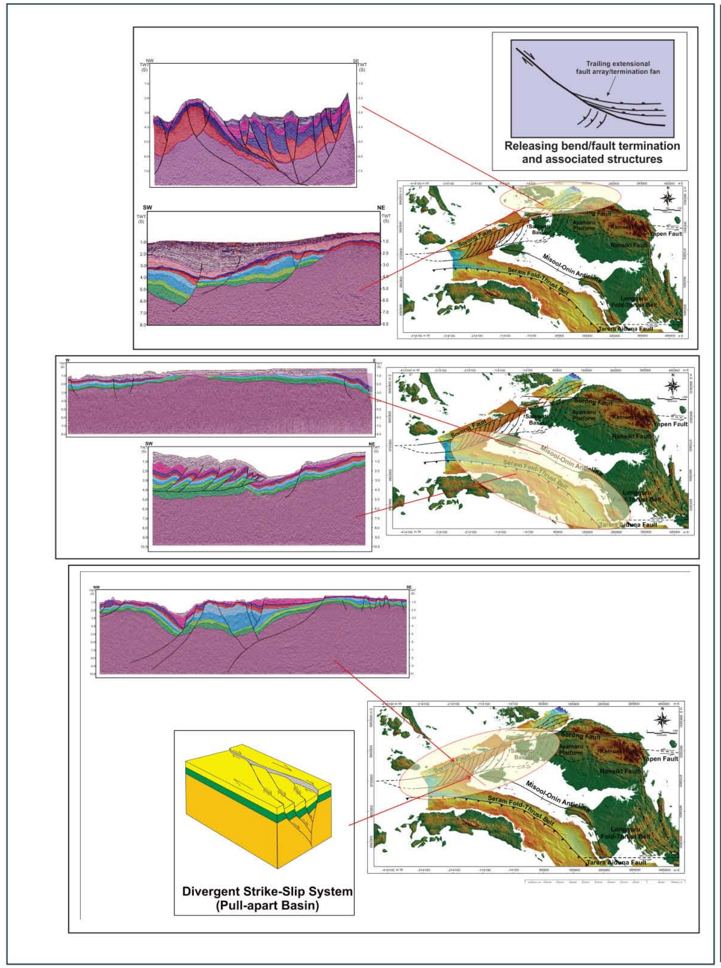

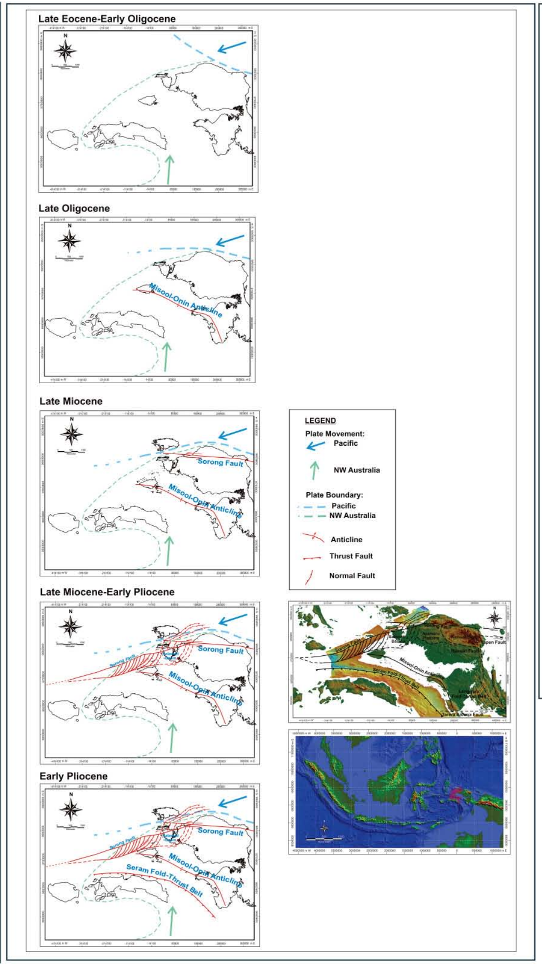

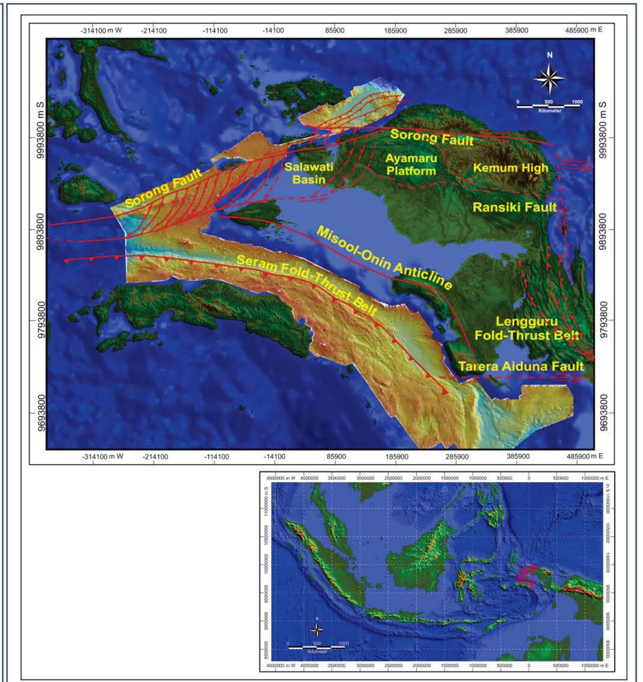

Figure 7. Structural model on Seram, Misool, and Salawati area that show three structural mechanism that active until the present time. The structural evolution on Seram, Misool, and Salawati area developed since the Late Oligocene as the collision effect on Bird's Head area.

Figure 8. Structural system configuration in the Bird's Head area.

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