REGIONAL OVERVIEW OF OROGENIC BELTS IN INDONESIA: EMPHASIS ON THE OCCURRENCES OF THRUST WEDGE SYSTEMS

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ABSTRACT

Regional overview to the thrust wedge systems in Indonesia attempts to compile and review geologic settings related to the development of basement uplift and fold-thrust belts. Overview will be represented in orogenic belts of different geologic settings: Langsa Fold-Thrust Belt (North Sumatra Basin), Banyumas Fold-Thrust Belt (Western Central Java), Kutei Basin, West Sulawesi Fold-Thrust Belt (Lariang-Karama Basins and Makassar Straits), Offshore Northern Banggai-Sula, Misool-Onin-Kumawa Ridge, Berau-Bintuni Basins, and Lengguru Fuld-Thrust Belt. Key ideas and discussions encompass surface structural geology, geomorphology, and subsurface geology. Aiming to draw the big pictures, the integrated approaches will elaborate the relationship of thrust wedge system with strike-slip faulting as adjoining structural province. Geomorphology will be the basis to construct regional structural maps, while seismic images and regional cross-sections will contribute to subsurface reconstructions. Synthesis will highlight similarities on geomorphic features, associated structures to thrust wedge system, Pliocene – Recent as critical time to orogenic building in Indonesia, geodynamic significance of strike-slip faulting, and geodynamic settings related to thrust wedge system in Indonesia. Thrust wedge orogenic belts share curvilinear thrust faults traces and intensive folding near mountain front. On the other hand, associated structures to thrust wedge include synclinal feature in thrust front, detachment folds, and transpressive-transtensional fault reactivation. Strike-slip faults may act as separate or associated structures in thrust wedge orogeny. Separate strike-slip faults can be observed as Sumatran Fault, Palu-Koro Fault, Balantak Fault, and Tarera-Aiduna Fault that act in response to slip partitioning or shift in deformation. Reactivated faults and tear faults are considered as associated structures to thrust wedge system. Thrust wedge system develops in both subduction and collisional tectonics.

Keywords: *thrust wedge system, orogenic belts, geomorphology, subsurface geology, Indonesia*

INTRODUCTION

Regional tectonics of Indonesia has evolved within convergent settings until Recent. This overview attempts to compile and review geologic settings related to the development of thrust wedge. In order to construct comprehensive overview, six orogenic belts are selected to represent various geologic settings: Langsa Fold-Thrust Belt (North Sumatra Basin), Banyumas Fold-Thrust Belt (Western Central Java), Kutei Basin, West Sulawesi Fold-Thrust Belt (Lariang-Karama Basins and Makassar Straits), Offshore Northern Banggai-Sula, and Lengguru Fold-Thrust Belt and Berau-Bintuni Basins (extending from Onin Mountains, Misool Islands, and Obi Islands) as depicted in Figure 1.

Discussions on this overview range from surface structural geology, geomorphology, and subsurface geology. Integrated approaches are aimed to draw the big pictures and elaborate the relationship of thrust wedge system with strike-slip faulting as adjoining structural province.

Thrust wedge systems in this overview are entirely basement-involved structures. Similarities are related to geomorphic expressions, surface stratigraphic distributions, and structural association. Such similarities will be a guide to explore other possible thrust wedge systems in Indonesia. On the other hand, differences are captured in adjoining structural provinces and geologic settings. Otherwise, geodynamic significance of strike-slip faulting will also be addressed. Role of strike-slip faulting in restructuring and its position relative to thrust wedge systems will be outlined. Eventually, thrust wedge orogenic belts can develop in wide-ranging settings in Indonesia, precisely as a part of subduction or collisional tectonics.

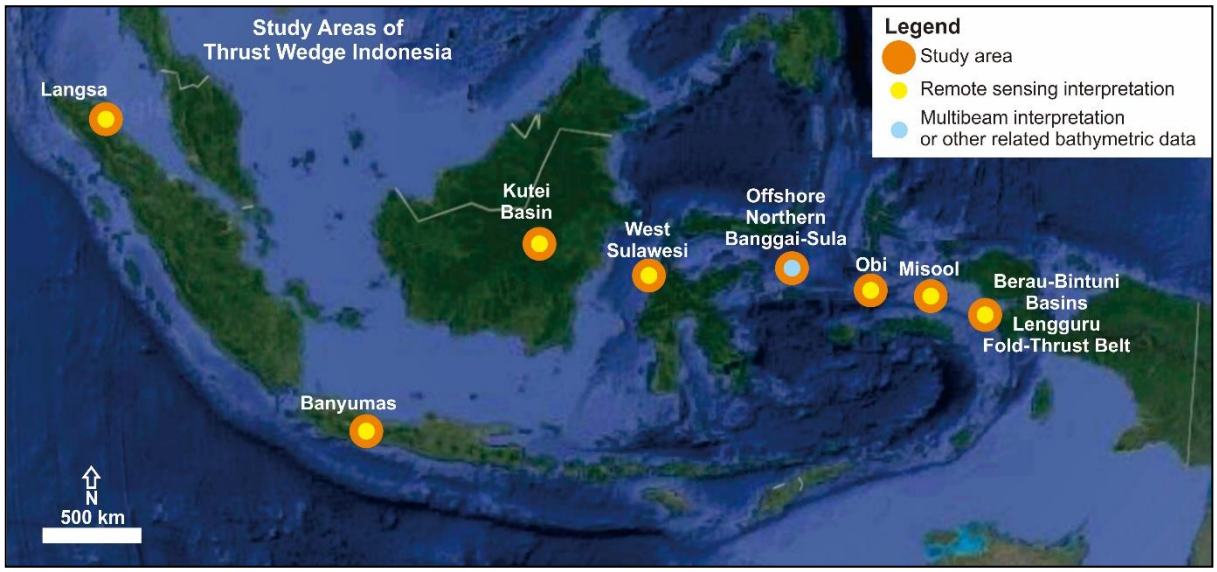


Figure 1: *Coverage of Study Areas*

DATA, METHODS AND TECTONIC CONCEPTS

Important tectonic concepts and interpretation techniques will be briefly outlined. Geomorphology and subsurface geology became the basis of structural frameworks on this overview. Data involved in the discussion include ASTER Global Digital Elevation Model (ASTER GDEM, 75-m spatial resolution) and published multi-beam data for geomorphology and published seismic images and cross-sections for subsurface geology. ASTER GDEM is a product of Japan Ministry of Economy, Trade, and Industry (METI) and NASA.

As expressed in Figure 2, geomorphology took role in defining regional structural maps, while seismic images and regional cross-sections produced subsurface reconstructions. Analyses on geomorphology and subsurface geology would be synthesized on the following five issues: similarities on geomorphic features, associated structures to thrust wedge system, Pliocene – Recent as critical time to orogenic belts emergence across Indonesia, geodynamic significance of strike-slip faulting, and geodynamic settings related to thrust wedge systems.

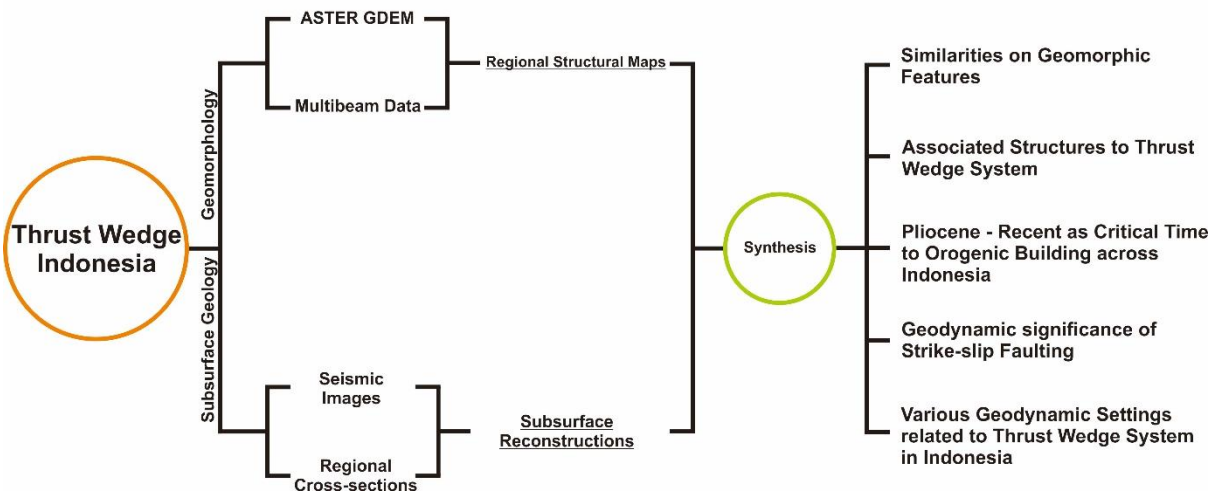


Figure 2: *Thrust Wedge Indonesia Research Workflow*

Important guidance on geomorphic interpretations for structural geology was brought from Burbank and Anderson (2012). Each fault type has distinctive geomorphic expressions. Thrust faults commonly cut the surface in low angle at about 30°. However, in reality, thrust faults can emerge at any angle. Concerning its low angle intersection to the surface, thrust faults generally have highly sinuous traces than normal faults (Burbank and Anderson, 2012). Thrust faults encounter strong influence from topography. In contrasts, normal faults cut the surface at high angles (~50 – 70°). Normal faulting is typified by down-dropped hanging wall blocks and uplifted horsts. Some cases also show unpaired normal faulting producing half-grabens or fault-angle depressions (Burbank and Anderson, 2012). Strike-slip faulting, meanwhile, produces varying geomorphic expressions. Various arrangement and anastomosing nature of strike-slip faulting contribute to varying, though distinctive, geomorphic expressions. Strike-slip faults commonly have straight segment, but, once in a while, relates to bending and curved fault segments (Burbank and Anderson, 2012). For example, releasing bend leads to depression and restraining bend generates compressive structures.

Thrust wedge can be based on a non-cohesive, frictional Coulomb wedge model (Nemcok et al., 2016). Critical taper, its basic physical parameter, will be achieved and attained by thrust wedging. A critically tapered wedge accretes no new material and is a thinnest possible thrust-belt (Nemcok et al., 2016). No further internal deformation as thrust wedge advances above detachment. Thickening of thrust wedge relates to four possible factors: contractional inversion of former basins; out-of-sequence thrusting along pre-existing thrusts; back-thrusting; and duplexing along detachment (Nemcok et al., 2016). On the contrary, excessive wedge taper leads to accretion of new materials and lengthening of deformation zone, or collapse near the top of wedge and gravitational instabilities (Nemcok et al., 2016).

In regional context, DeCelles and Giles (1996) proposed a conceptual framework. Flexural basins can be seen in two settings: peripheral and retro-arc settings. Peripheral setting involves topographic, sediment, and subduction loads. Subduction load refers to vertical shear force and bending moments at the end of subducting slab. On the other hand, retro-arc setting also incorporates dynamic slab loads caused by viscous coupling between the subducting slab, overlying mantle wedge material, and the base of overriding continental plate. Dynamic slab loads result in rapid, long-wavelength subsidence and uplift on the order of a kilometer (DeCelles and Giles, 1996, Figure 3a). An example of retro-arc setting can be seen in Sumatra-Java to Karimunjava Arch (Figure 3b). Mountain range along Sumatra-Java acts as orogenic wedge, while Karimun Java to Bangka-Belitung act as forebulge. Basins that located in-between the two provinces can be regarded as foredeep.

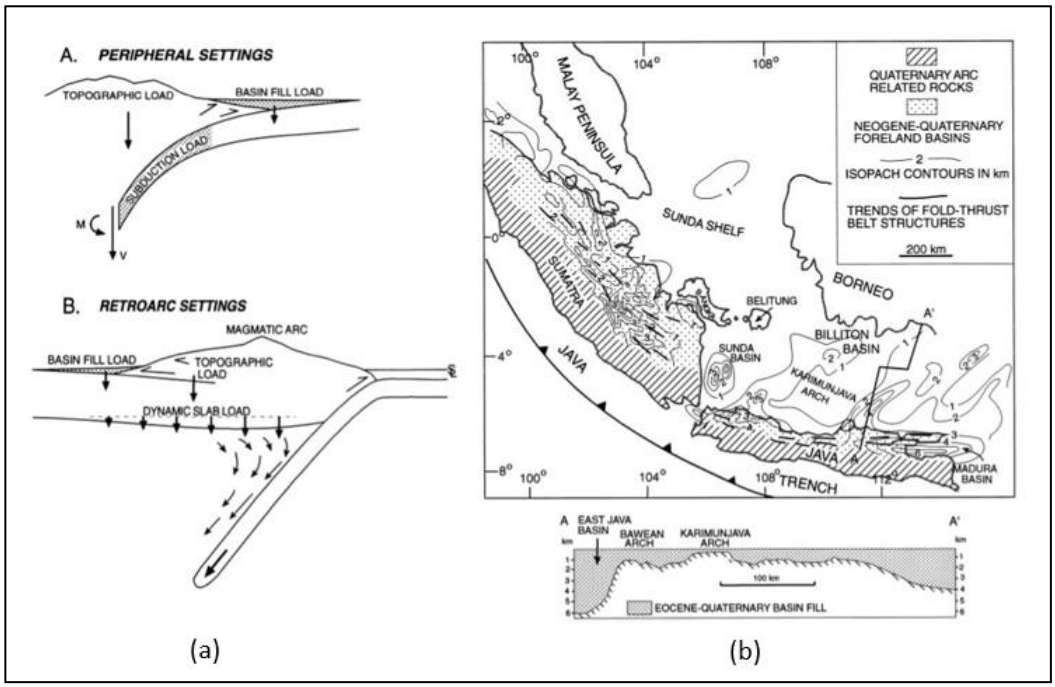


Figure 3: *Schemes of (a) settings of Foreland Basin; (b) Sumatra-Java and Karimunjava Arch Example (DeCelles and Giles, 1996)*

REGIONAL GEODYNAMICS

Indonesia is a region of complex plate interactions: the stationary SE-moving Eurasian Plate (*c.* 0.4 cm a^{-1}, NNE-moving Australian Plate (*c.* 8 cm a^{-1}), and NNW-moving Philippine Sea Plate (Simandjuntak and Barber, 1996). Complex plate tectonics gives Indonesia its archipelagoes geometry and various orogenic events. Looking more precisely, Indonesia possesses various geologic settings from west to east. For instance, Sumatra and Java are examples of subduction-related arcs, which the former belongs to oblique setting and the latter to orthogonal setting. In contrast, collided continents are exemplified by Sulawesi and Papua regions.

Orogenic belts related to thrust wedge system were selected, each of which represents certain geologic settings. Regional Recent geodynamic settings of study areas are given in Figure 4 and basin dynamics time chart is given in Figure 5. Starting from west, North Sumatra Basin is a present-day backarc basin. Its southern and southwestern boundaries are marked by Barisan Mountains. Separation between North and Central Sumatra Basins is Asahan High in its southeastern portion (Davies, 1984). Adjoining structural province to North Sumatra Basin is Sumatran Fault. Being a transcurrent phenomenon, Sumatran Fault is a result of slip partitioning in oblique subduction setting (McCaffrey, 2009).

Subduction of Java have generated volcanic arcs throughout Paleogene and Neogene. Such volcanism, particularly in West Java, developed well in the southern portion of the island. It is manifested as Oligo-Miocene Jampang Volcanics in Southern West Java (Simandjuntak and Surono, 1992) and Oligo-Miocene Gabon Volcanics in Karangbolong High of Southern Central Java (Asikin et al., 1992a). Quaternary volcanism of Java becomes backbone of the island. Plio-Pleistocene compression re-structured the island as indicated by emerging fold belts (Simandjuntak and Barber, 1996). Simandjuntak and Barber (1996) proposed major northward thrust system in South Java. It is supported by Martodjojo (1994) who outlines progradation of five major thrusts of West Java. Adjoining structural province to Banyumas Fold-Thrust Belt includes Karangsambung Anticline in the east, Quaternary Mt. Slamet in the north, Majalengka Fold-Thrust Belt, and thrusted Oligo-Miocene volcanics in the south. Karangsambung Anticline is previously Cretaceous accretion complex (Simandjuntak and Barber 1996). Asikin et al. (1992b) described Cretaceous stratigraphic unit in Karangsambung as Luk Ulo Complex. Cretaceous Luk Ulo Complex and younger intervals involved in Plio-Pleistocene deformation.

West Sulawesi was previously attached to East Kalimantan, drifting away during Paleocene-Eocene rifting (Hall, 1996). Magmatic arc in West Sulawesi-

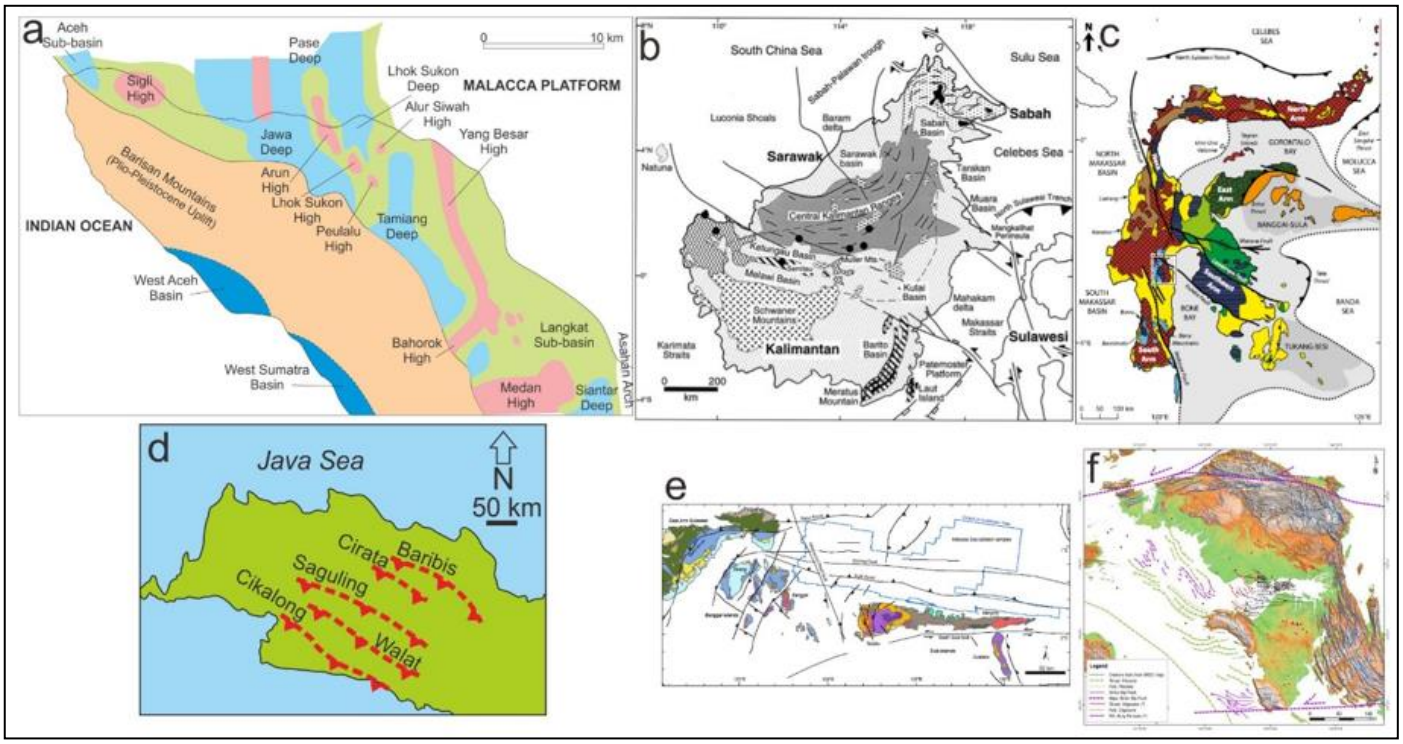


Figure 4: *Regional Recent Geodynamic Settings: (a) Oblique Subduction Backarc Basin – Modified after Davies, 1984; (b) Backarc Basin – Wilson and Moss, 1999; (c) Backarc Basin – White et al., 2017; (d) Intra-arc Setting – (modified after Martodjojo, 1994) (e) Collided Microcontinent – Ferdian et al., 2010; (f) Collided continent – Birt et al., 2017*

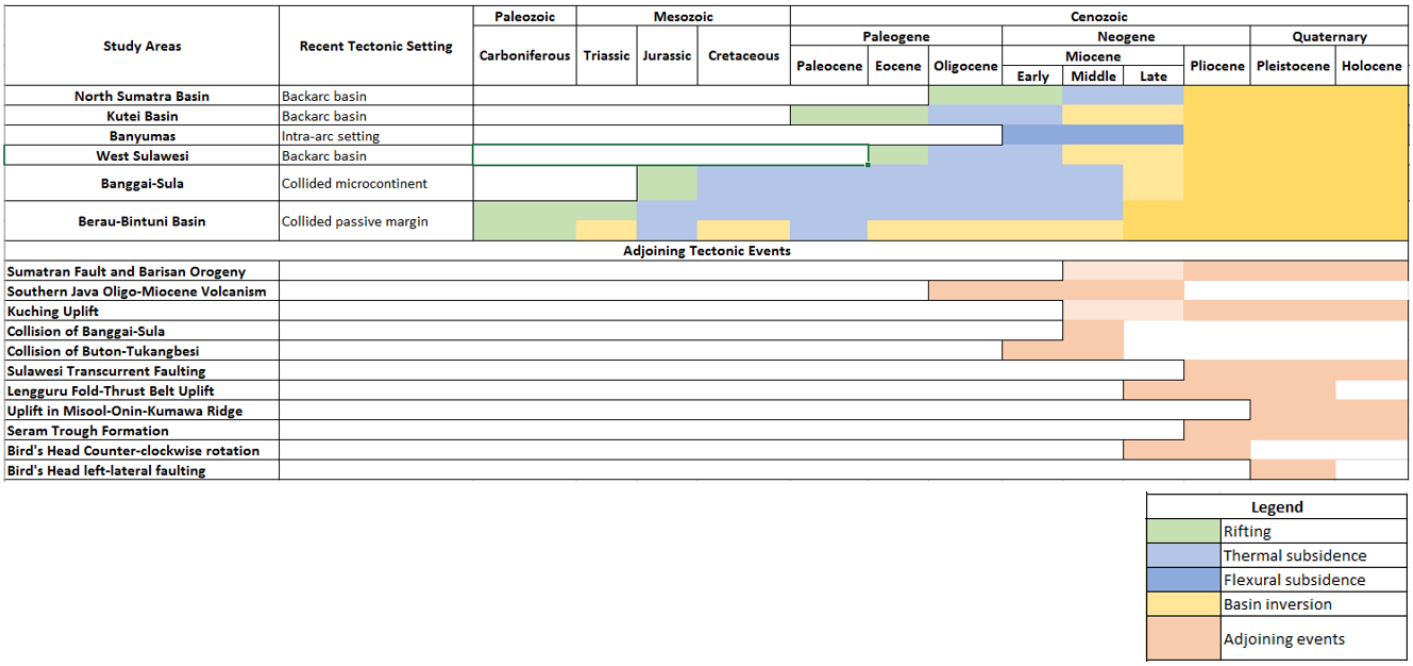


Figure 5: *Basin Dynamics Time Frame Chart (compiled from various sources cited in this manuscript)*

developed during several episodes of subduction since Late Cretaceous (Hall, 1996; Sukido et al., 1993; Ratman and Atmawinata. 1993). Several episodes of subduction in West Sulawesi also led to slab roll-back, implying to extensional tectonics between Kutei Basin and West Sulawesi. Considering this setting, West Sulawesi and Kutei Basin might develop as backarc basin before Sulawesi plate assembly. Adjoining structural provinces to Kutei Basin are Kuching High in the west, Mangkalihat High in the north, and Adang Flexure to the south – bordering Kutei Basin to Barito Basin. Kutei Basin is separated with West Sulawesi by Makassar Straits. On the other hand, adjoining structural provinces to West Sulawesi is Palu-Koro Fault.

Going to East Sulawesi, an important collisional event occurred during Middle – Late Miocene between Banggai-Sula Microcontinent with the ophiolite belt (Hall, 1996). Banggai-Sula Microcontinent was hypothesized to originate from Papua New Guinea (Hall, 1996), as it was brought by Sorong Fault. On the other hand, Berau-Bintuni Basins are the Australian part of oblique arc-contient collision. Oblique northward movement of Australian Plate collided with Sepik Mountains in Eocene (Birt et al., 2017), triggering deformation to get younger towards west. In Recent geodynamics, Berau-Bintuni Basins adjoin with Seram Trough in the south and Lengguru Fold-Thrust Belt in the east.

Geodynamics in Eastern Indonesia is closely related to the development of Banda Sea. Spoon-shaped geometry of the Banda Sea triggers questions - regarding its origin. Spakman and Hall (2010) argues that spoon-shaped geometry of the Banda Sea because of three aspects: rollback mechanism, mantle resistance to northward transport, and the external trough system enclosing the embayment. Rollback mechanism in Banda Sea was triggered by strong negative buoyancy of the Jurassic Banda Embayment. Such negative buoyancy is also contemporaneous with the northward transport of Australian Passive Margin. If subduction trench along Java remained stationary, the trench of Banda Sea was moving southwards. The evidence of rollback mechanism in Banda Sea are the opening of North (12.5 – 7.1 Ma) and South Banda Sea (6.5 – 3.5 Ma) (Spakman and Hall, 2010) and the exhumation of mantle peridotite and cordierite granite magmatism (ambonite) in Seram-Ambon Complexes (Pownall et al., 2013). Development of Banda Sea is contemporaneous to the uplift of Seram Trough and Lengguru Fold-Thrust Belt since Late Miocene. Seram Trough, Misool-Onin-Kumawa Ridge (MOKR), and Lengguru Fold-Thrust Belt exemplify convergent orogeny in Eastern Indonesia.

KEY IDEAS AND DISCUSSIONS

North Sumatra Basin – Langsa Fold-Thrust Belt

Geomorphic expressions suggest two different structural provinces in North Sumatra: Barisan Mountains and foreland area. Barisan Mountains are characterized by transtensional regime represented as Blangkejeren and Kutacane Grabens of Sumatran Fault. As proposed in regional structures (Figure 6), Barisan Mountains have anastomosing fault arrays in NW-SE trend.

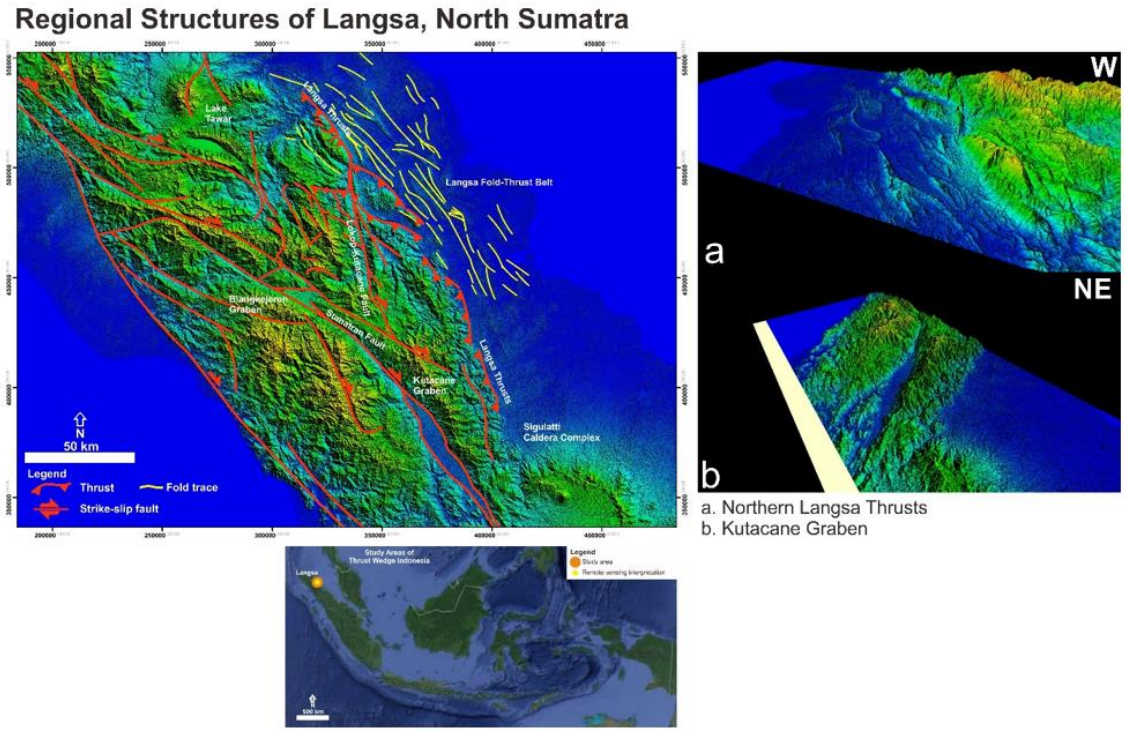


Figure 6: *Regional Structures of Langsa, North Sumatra: (a) Northern Langsa Thrusts scarp and fold traces; (b) Kutacane Graben*

Fault-bend basin, overstep basin, and horsetail structures are well-represented in the area. Thrust wedge system develops in Barisan Eastern Foothills as marked by Langsa Fold-Thrust Belt in NW-SE trend. Putra et al. (2018) outlined the development of thrust wedge system based on remote sensing and seismic images in North Sumatra Basin (Figure 7). Basal detachment of thrust wedge system may involve Kluet and Bahorok Formations. Thrust faults traces are indicated as triangular facets on 3D geomorphic model. Fold traces are represented as synclinal and monoclinal ridges. Prominent synclinal ridges next to mountain front related to intensive deformation. Besides, sinuous monoclinal ridges coincide with synclinal feature in the subsurface thrust front.

Different folding styles become distinguished features in thrust wedge system. Tight folds occupy above the thrust wedge, while significant synclinal feature observed in thrust wedge front (Putra et al., 2018). Thrusting in eastern foothills brought Kluet, Bahorok, and Serbajadi Batholiths and Sembuang Formations of Pre-Tertiary age and Tampur Formation of pre-rift phase to the surface. Syn-rift and early post-rift deposits has linear distribution parallel to thrusting features (Cameron et al., 1981; 1983). Detachment folds develop within Baong Interval, away from the basement-involved thrust wedge system (Putra et al., 2018). Fossen (2010) underlines three indications to detachment folding: undeformed substrates, overpressured shales or evaporites as detachment, and concentric fold geometry. Of other structural features, transpressive reactivation of faults also develops well in Langsa Fold-Thrust Belt with N-S trend (Davies 1984; Putra et al., 2018). Transpressive folds are aligned in NW-SE trend, but with right-stepping arrangement. As a comparison, N-S strike-slip fault is repeated in Barisan Mountains as Lokop-Kutacane Fault.

Addressing the distribution of thrust wedge system in North Sumatra, synclinal features appear to be the termination of basement-involved thrust wedge. Going to northeast of the area, deformation is represented as transpressive reactivation and detachment folds. The neighboring areas to Langsa Fold-Thrust Belt show similar structural features (Figure 8). In the southeast, Rantau Field possesses transpressive reactivation (Ryacudu et al., 1992), just as observed in Peusangan Block (Wang et al., 1989) in the northwest. Unique structural style was found in Peusangan Block as gravity gliding of upper stratigraphic section (Wang et al., 1989). For comparison, Banukarso et al. (2013) published structural styles in inverted syn-rift play in Offshore North Sumatra. Offshore area preserves N-S to NE-SW graben structures just as in the onshore. Western Offshore North Sumatra depicts greater inversion by having tighter folds than the eastern area. This phenomenon may coincide with the role of Western Offshore North Sumatra as major extensional fault in the area.

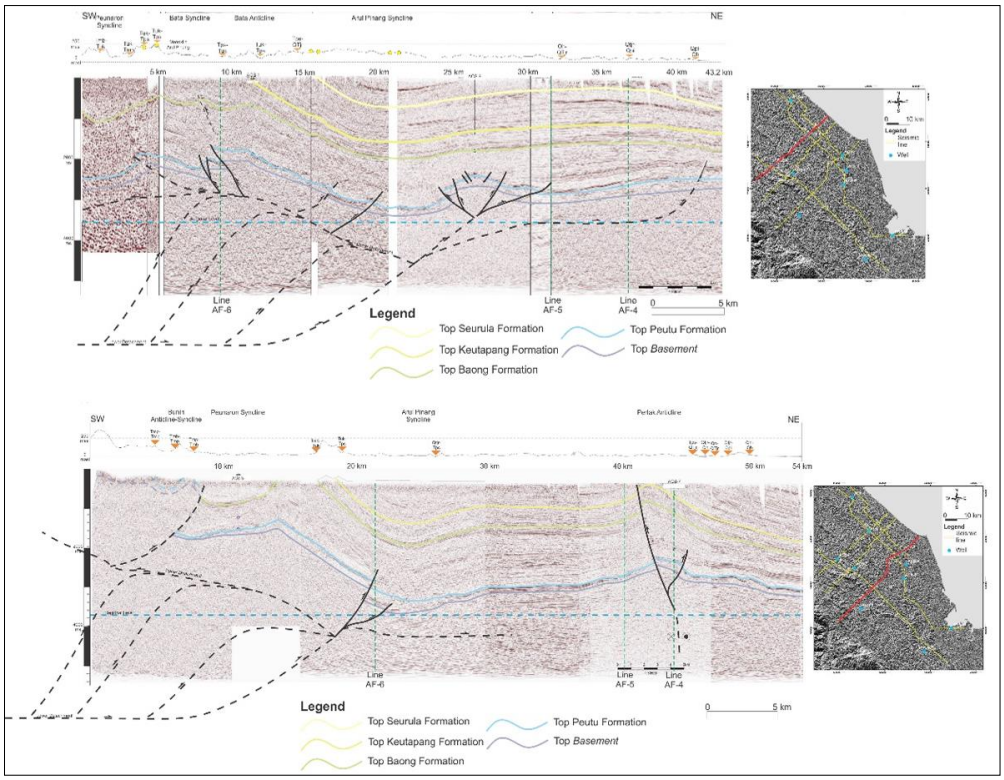


Figure 7: *Subsurface Interpretation in Langsa Fold-Thrust Belt (Putra et al., 2018)*

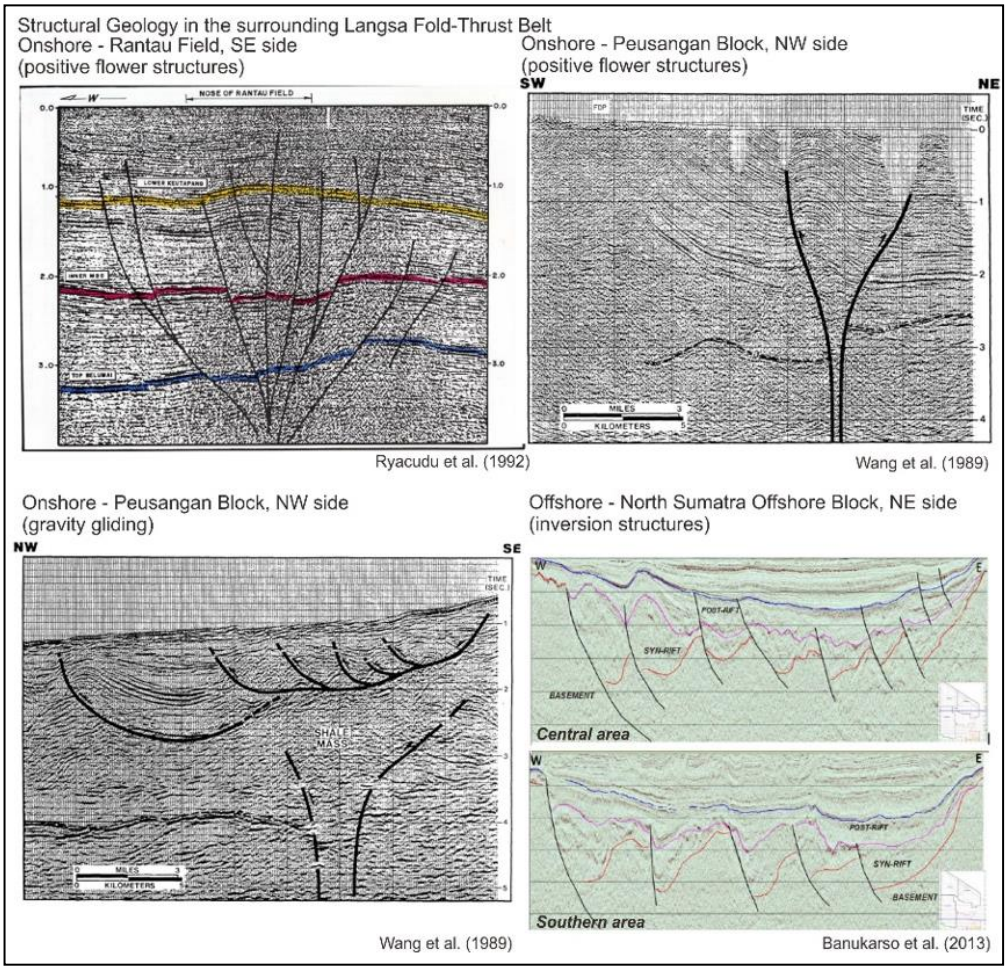


Figure 8: *Comparison on Structural Geology Surrounding Langsa Fold-Thrust Belt (Ryacudu et al., 1992; Wang et al., 1989; Banukarso et al., 2013)*

Lowell (1995) underlined that area having greater extension will experience greater inversion than the surrounding extensional structures.

Syn-inversion phase in North Sumatra Basin is assumed to start from Middle Miocene, reported as influx of volcaniclastics and regressive sediments by Simandjuntak and Barber (1996). Nevertheless, Wang et al. (1989) reported subtle unconformity beneath Keutapang Formation of Late Miocene – Pliocene age. Besides, Wang et al. (1989) and Putra et al. (2018) also noted prominent prograding seismic facies within Pliocene Seurula Formation. Putra et al. (2018) separated deformation sequence in two phases. Thrust wedge system operated through Early Pliocene to Recent, while transpressive reactivation initiatied in Late Pliocene to Recent. Separation of deformation sequence is interpreted based on geomorphic evidences: Lokop-Kutacane Fault truncating Langsa Thrusts and transpressive folds cutting compressive folds in foreland area.

Slip partitioning becomes the regional mechanism of Sumatran Fault and thrust wedge in Eastern Barisan Foothills. McCaffrey (2009) previously considered the implications of slip partitioning to explain deformation in accretionary prism and Sumatran Fault. However, with the evidence in North Sumatra, it is suggested to extend the implication of slip partitioning towards the backarc area.

Banyumas Fold-Thrust Belt

Banyumas Fold-Thrust Belt displays essentially E-W to NW-SE thrust and fold trends. Geomorphic features are characterized by curvilinear thrust traces along with anticlinal and synclinal ridges. Deformation in Banyumas Fold-Thrust Belt and Karangsambung Anticline involved Cretaceous Luk Ulo Complex, Eocene Karangsambung Formation, Miocene Waturanda, Penosogan, Pemali, Rambatan, and Halang Formations, Pliocene Kumbang Volcanics and Pliocene Tapak Formation (Asikin et al., 1992a, b; Kastowo, 1975). Oligo-Miocene Jampang Volcanics in the south (Simandjuntak and Surono, 1992) expressed similar thrust faulting towards northeast as observed in geomorphology. Banyumas Fold-Thrust Belt system follows regional structural pattern as depicted in Martodjojo (1994) (Figure 3). Imbricate thrusting in Banyumas is represented by Ciamis, Lumbir, and Banyumas Thrusts, while strike-slip faulting is depicted as Slamet Fault and Serayu Fault (Figure 9). Slamet Fault shows recent deformation since it involves Mt. Slamet Quaternary volcanic deposit.

Seismic image was published by Lunt et al. (2008) (Figure 10) and revealed subsurface thrusting in the north of Banyumas Fold-Thrust Belt mountain front. Seismic quality was poor due to cover of Recent volcanic deposits. Armandita et al. (2009) –

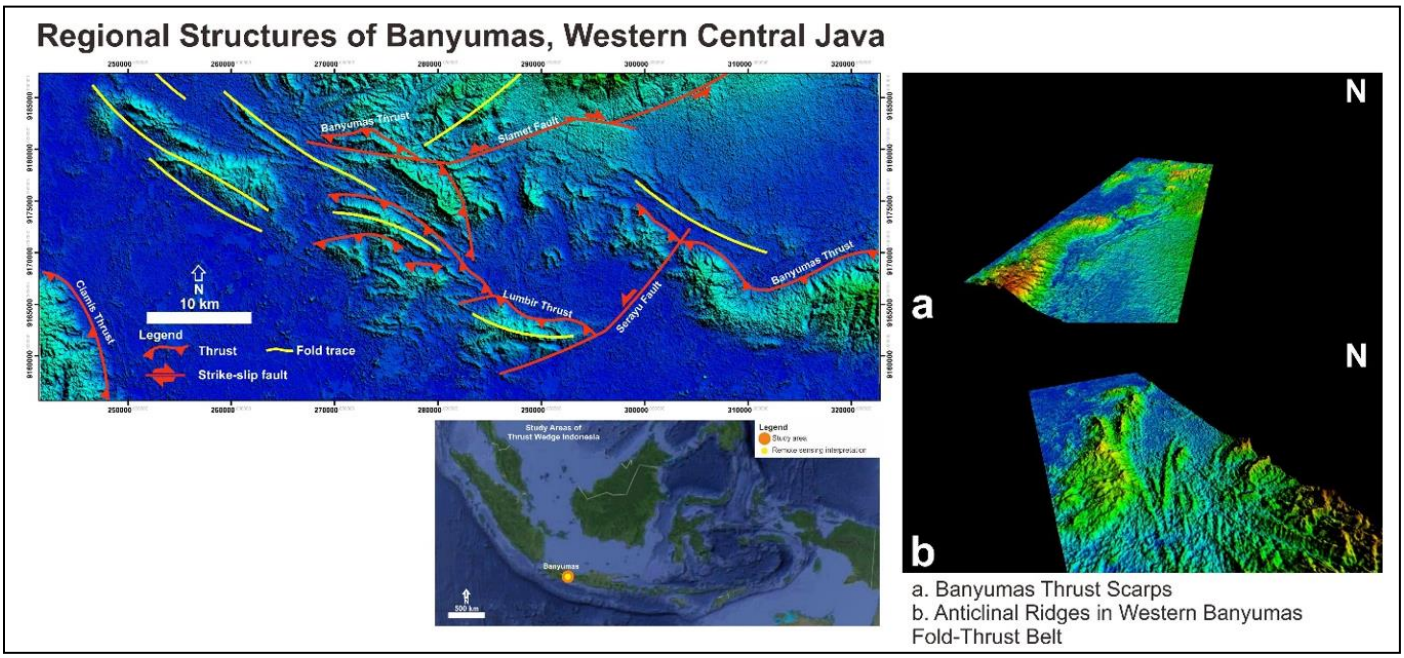


Figure 9: *Regional Structures of Banyumas, Western Central Java: (a) Banyumas Thrusts Scarps; (b) Anticlinal Ridges in Western Banyumas Fold-Thrust Belt*

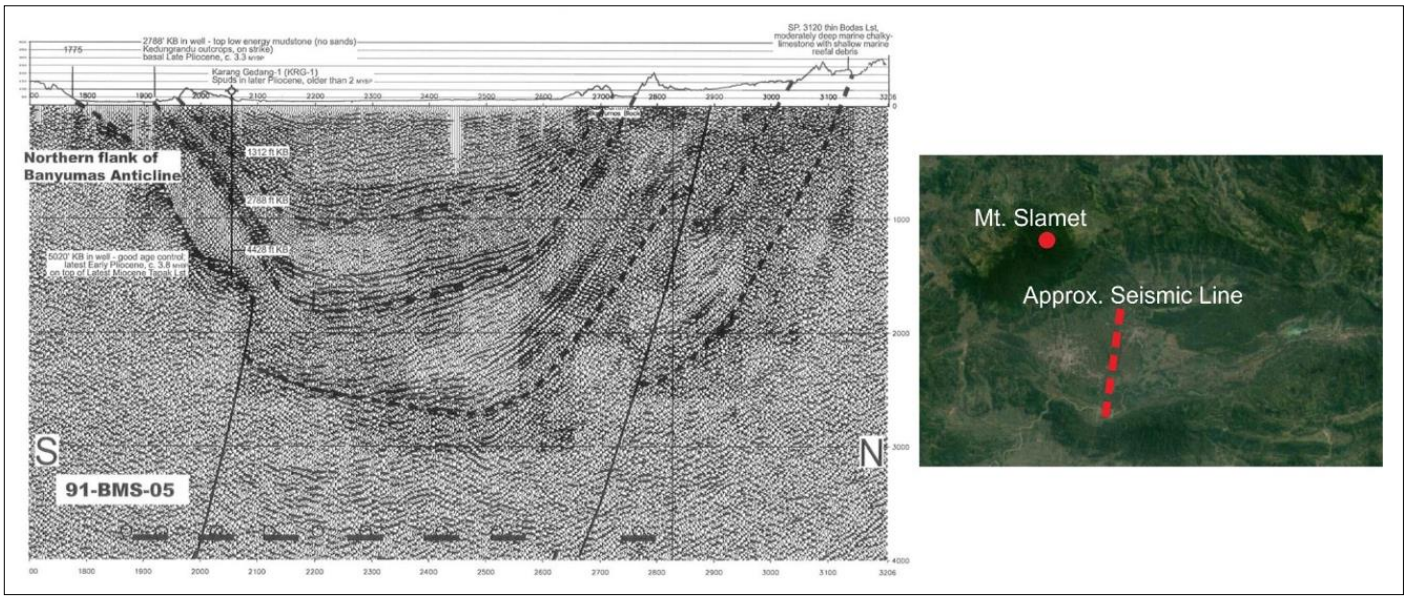


Figure 10: *Subsurface Image in the North of Banyumas Fold-Thrust Belt (modified after Lunt et al., 2008)*

observed major folds – particularly synclinal feature, large reverse faults, and angular truncation of Pemali Formation. On the other hand, Lunt et al. (2008) reported Early Pliocene age (3.8 Ma) on top of Late Miocene Tapak Limestone at 5020 feet as deepest penetration. No older age has been reported.

Three tectonic scenarios have been proposed regarding Banyumas Fold-Thrust Belt. Martodjodjo (1994) proposed northeastward thrusting in West Java, Noeradi et al. (2006) underlined transpressive zone of NE-SW left-lateral Cimandiri Fault in West Java and its counterpart in Central Java, and Armandita et al. (2009) elaborated compression along NW-SE Pamanukan-Cilacap Fault. By integrating geomorphic features and subsurface consideration, strike-slip faulting as primary deformation mechanism in Banyumas Fold-Thrust Belt is unlikely. Geomorphic features of Banyumas Fold-Thrust Belt suggest imbricate thrusting and development of compressive regime in the area. Raharjo et al. (2002) provided schematic regional cross-section from West Java Southern Mountains through Northwest Java Basin (Figure 11), -

suggesting thrusting of Oligo-Miocene volcanics and folding of Miocene and younger deposits. As mentioned earlier, thrust wedge system in Banyumas Fold-Thrust Belt involves wide stratigraphic interval, from Cretaceous Luk Ulo Complex to Pliocene Tapak Formation. Basal detachment of thrust wedge system may occur within Cretaceous or possibly older stratigraphy.

Basement involvement during formation of Banyumas Fold-Thrust Belt should be further attention. Possible basement involvement can be drawn from two aspects: thrusting of Oligo-Miocene Jampang Volcanics and its neighboring Karangsambung Anticline – Cretaceous accretion complexes (Simandjuntak and Barber, 1996). Thrusting of Oligo-Miocene Jampang Volcanics and similar structural styles in Karangsambung Anticline indicate that deformation involved wide stratigraphic intervals. Plio-Pleistocene deformation had involved Cretaceous Luk Ulo Complex and younger stratigraphy (Asikin et al., 1992b), indicating the role of basement during deformation. As Banyumas Fold-Thrust Belt is geomorphically continuous from Karangsambung Anticline, basement-involved thrust wedge system is proposed.

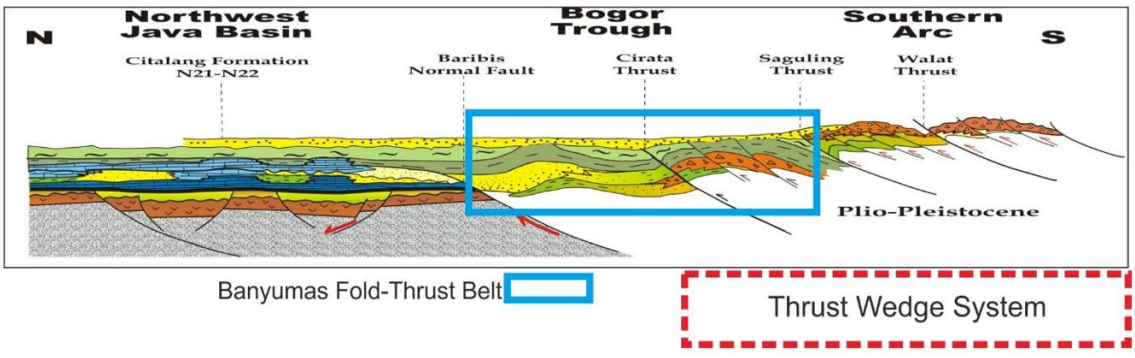


Figure 11: *Regional Schematic Cross-section from West Java Southern Mountains through Northwest Java Basin (modified after Raharjo et al., 2002)*

Kutei Basin

Thrust wedge system in Kutei Basin is a part of Kuching High. Uplift through Middle Miocene to Pliocene (Hall, 1996) resulted in significant geomorphic features of the area. Geomorphic observation and structural mapping took place in Mamahak area (Figure 12). Boundary between Kuching High and the lower relief area is ENE-WSW Mamahak Thrust. Thrusting phenomenon outcrops Cretaceous Embaluh Formation and syn-rift deposits. Thrust wedge generates imbricate arrangement, manifested as Long Pakaq and Mamahak Thrusts, with southeastward transport direction. Backthrusting is observed along the Naha Aruq and Tabang Backthrusts. Fold traces follow thrusting trend and synclinal feature exists in front of Mamahak Thrust. Uplift by thrust wedging was then followed by strike-slip faulting. NW-SE right-lateral strike-slip faults truncate thrust systems. Noticeable geomorphic feature is scarp of Long Bagun Fault truncating Mamahak Thrust in right-lateral sense. Anomalous NNW-SSE fold trace follows the lineament of Long Bagun Fault. Middle Miocene uplift in Kuching High has side-effect to intrusive emplacement. Abidin et al. (1993) reported Sintang Intrusives both in high and low relief zones in Mamahak area. Distribution of the intrusives roughly follows thrust trend. Coincidence in space and time of thrusting and intrusive emplacement should further be addressed.

Satyana et al. (1999) summarized four postulates in tectonics of Kutei Basin to explain folding in Samarinda Anticlinorium and the offshore area: grand-scale gravity gliding, strike-slip faulting, inverted growth fault, and collision of microcontinent. Ott (1987) acted as early publication in regional structures and promoted grand-scale gravity gliding. Ott (1987) combined structural features and stratigraphic variations. Generally, Ott (1987) defined Kutei Basin stratigraphy as Eocene-Oligocene shale-dominated intervals and Miocene alluvial-delta intervals. During Eocene-Oligocene deposition, Mangkalihat Ridge and Sunda Shelf acted as sediment source. Proto-Kuching High was structural low and Kutei Basin dip to the west.

Grand-scale gravity gliding scenario is supported by schematic regional cross-section in Ott (1987) (Figure 13). Basement-involved structures in uplifting Kuching High, later defined as thrust wedge, created significant relief. Oversteepening of thrust wedge system was responded by gravitational instabilities. Stratigraphic contacts between Eocene-Oligocene and Miocene deposits became detachment zone. Normal faulting developed near thrust wedge and compressive structures as toe thrusting happened to be present-day Mahakam Anticlionorium. Isostatic rebound happened as a response to normal faulting. Nemcok et al. (2016) stated that gravitational –

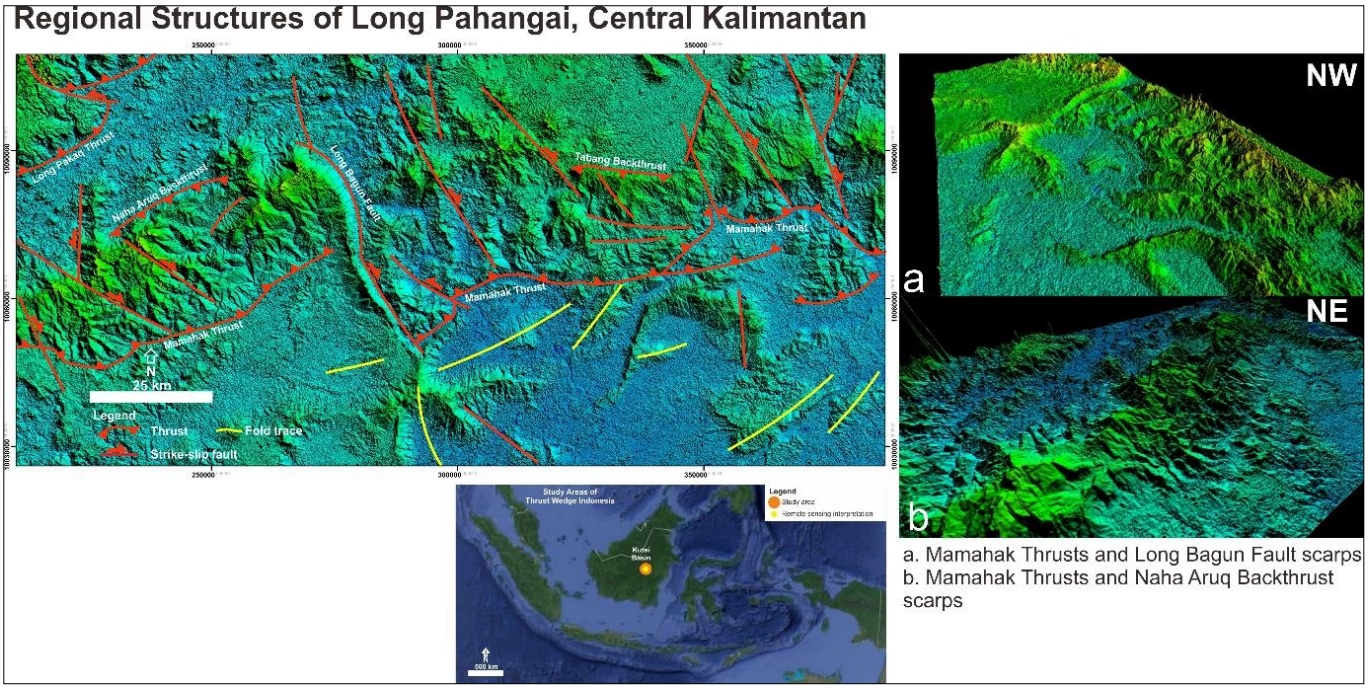


Figure 12: *Regional Structures of Long Pahangai, Central Kalimantan: (a) Mamahak Thrusts and Long Bagun Fault scarps; (b) Mamahak Thrusts and Naha Aruq Backthrust scarps*

instabilities above the wedge promoted continued uplift. Absence of normal fault scarps on geomorphology might be triggered by this rebound. McClay et al. (2000) provided a closer look in - Mahakam Anticlinorium. The publication promoted inverted growth fault model to explain fold-thrust belt formation and evolution (Figure 14).

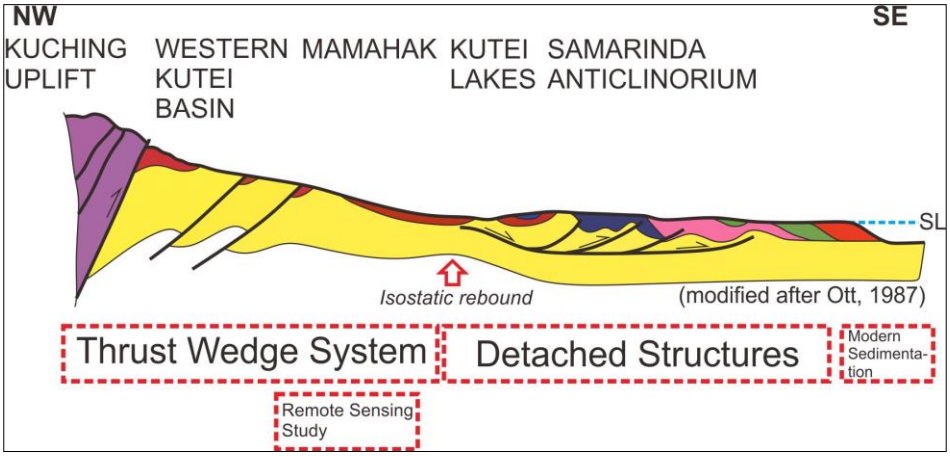


Figure 13: *Regional Cross-section from Kuching High to Coastline, East Kalimantan (modified after Ott, 1987)*

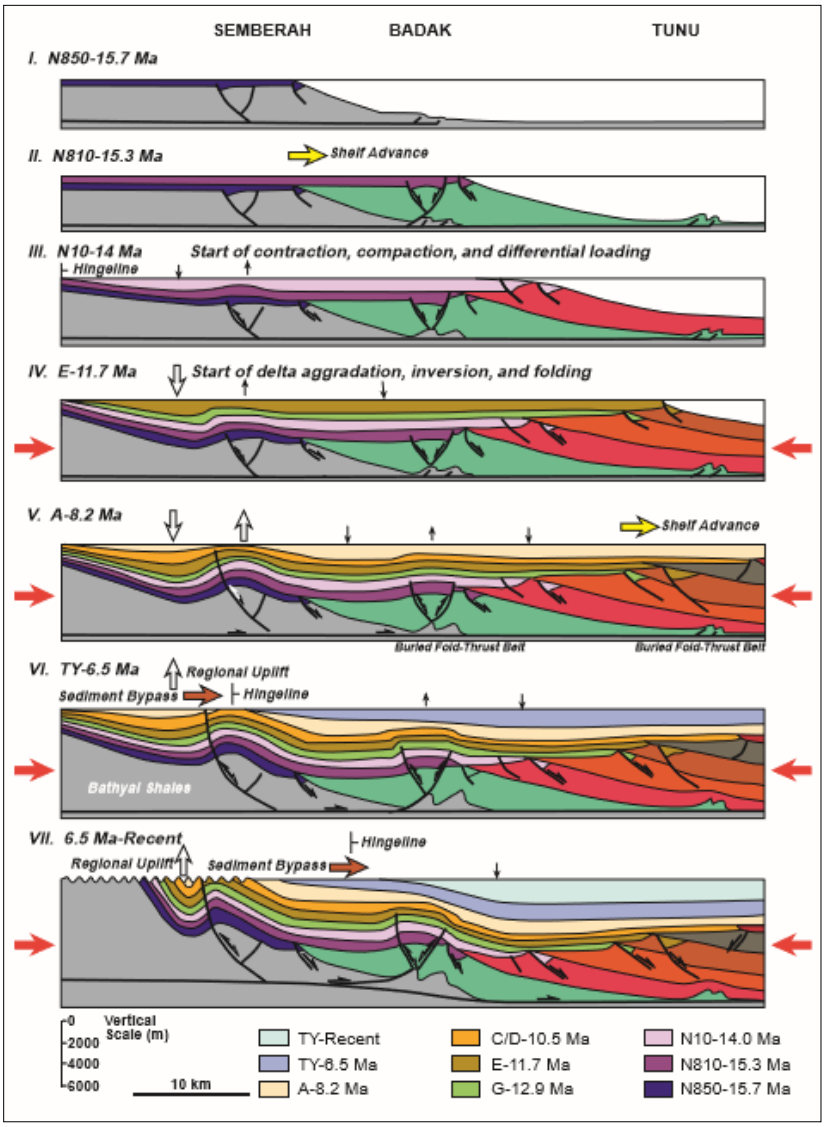


Figure 14: *Structural Evolution of Inverted Delta Growth Fault Model (McClay et al., 2000)*

Deltaic sedimentation since Miocene in Kutei Basin generated major growth faults, defined as depobelts in McClay et al. (2000). Growth faulting and inversion only operate in Miocene deposits and detach from the underlying overpressured shales. Regional compression regime for depobelts inversion is suggested to originate from Kuching High. Compression from West Sulawesi Fold-Thrust Belt and microcontinent collisions is unlikely, since seismic sections in Makassar Straits (Puspita et al., 2005) display undeformed strata. Tectonic scenarios explained by Ott (1987) and McClay et al. (2000) could be synthesized. Thrust wedge system gave significant relief to gravity gliding and induced compression to southeast. Growth faults in distant areas responded to the compression by inversion. Regarding basal detachment, Kutei Basin has two surfaces. Thrusting in Kuching High detaches at Pre-Tertiary basement. Mahakam Anticliorium may utilize contacts between Pulubalang Sandstones and Karorang Shales.

Extensive thrust wedge of Kuching High is supported by its previous role as Lupar Line, separating Mesozoic ophiolites with rigid fragment of South Borneo. Successive counter-clockwise of Borneo triggered re-structuring: Kuching Uplift, closing of South China Sea, and uplift of Meratus Mountains in Middle Miocene (Hall, 1996). Meratus Mountains have similar structural trend to Mahakam Anticlinorium. Despite adjoining position and similar trend, structures of the two areas could not be easily correlated. Ott (1987) stated that Mahakam Anticlinorium was separated from Meratus Mountains by South Kutei Boundary Fault (and Adang Flexure in the offshore). Furthermore, Meratus Mountains involved transpressive basement-involved structures, while Samarinda Anticlinorium exists above overpressured shales.

West Sulawesi Fold-Thrust Belt

Geomorphic interpretations suggest that uplift in West Sulawesi Fold-Thrust Belt is triggered by thrust wedging. NE-SW curvilinear thrust lineaments develop well from Donggala in the north to Mamuju-Tommo in the south (Figure 15). Fold traces appear to be parallel to thrust wedging trend. Thrust belt was then truncated by NW-SE left-lateral strike-slip faults. In West Sulawesi context, Donggala Thrust is likely to accommodate greater displacement than Mamuju and Tommo Thrusts since it has more intensive structuring and shorter distance to coastline. This phenomenon is confirmed in the Offshore West Sulawesi as published by Puspita et al. (2005). Thrust wedging in West Sulawesi Fold-Thrust Belt successfully brought Triassic Wana Metamorphics, Triassic-Jurassic Gumbasa Complex and Intrusives, and Cretaceous Latimojong Metamorphics to the surface (Sukido et al., 1993; Ratman and Atmawinata, 1993).

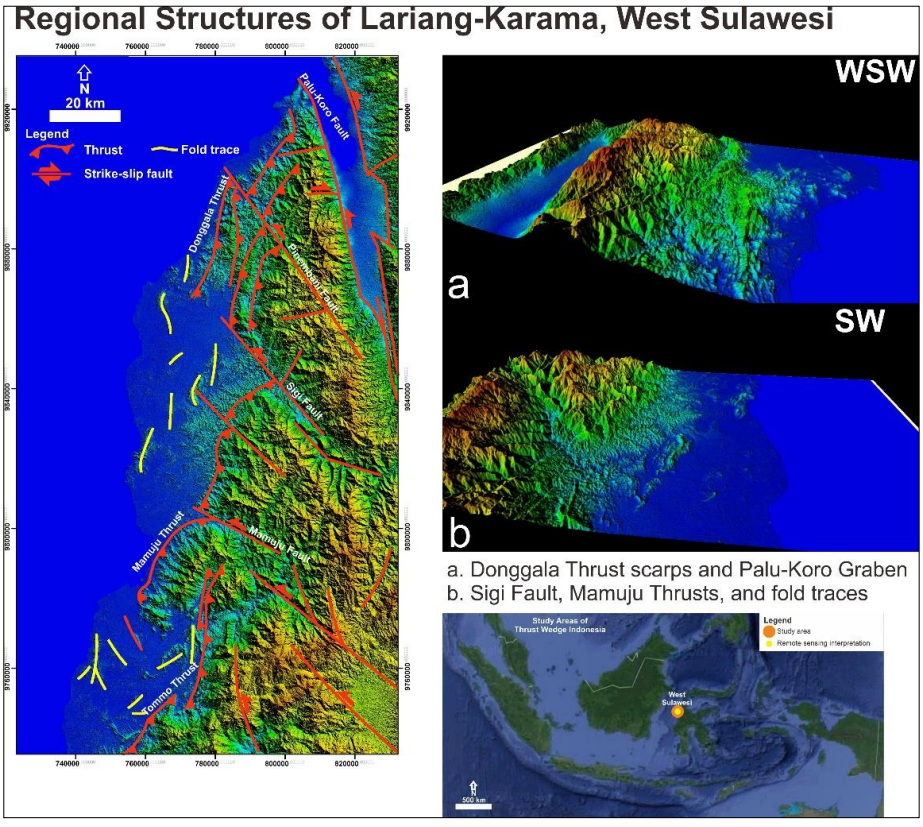


Figure 15. *Regional Structures of Lariang-Karama, West Sulawesi: (a) Palu-Koro Fault and Donggala Thrusts scarps; (b) Sigi Fault, Mamuju Thrusts scarps, and fold traces*

Strike-slip faulting in West Sulawesi employs left-lateral sense and arranged in right-stepping manner. Strike-slip fault arrangement in West Sulawesi may lead to popping-up of the area and may also contribute to the orogenic building. NW-SE strike-slip faulting in West Sulawesi is a part of Palu-Koro Fault induced by Early-Middle Miocene microcontinent collisions in Sulawesi. Collision of Buton-Tukangbesi Microcontinent to Southeast Sulawesi and Banggai-Sula Microcontinent to East Sulawesi contributed to compressive regime development. NW-SE strike-slip faults of West Sulawesi are splays from the adjoining Palu-Koro Fault. Palu-Koro Fault generated releasing bend geometry and induced graben formation.

Puspita et al. (2005) divided Offshore West Sulawesi in three structural provinces (Figure 16). Northern Structural Province (NSP) has steep scarp and thrust penetrating the surface along with complex deformation. NSP is separated from Central Structural Province (CSP) by NW-SE structural trend, strongly indicative as the offshore continuation of Sigi Fault. CSP displays less deformation even though preserves basement-involved structures. Synclinal feature can be observed at the thrust front of NSP and CSP. Southern structural province (SSP) has detachment folds as primary structural style. Otherwise, normal faulting and onlapping relationship can be defined in NW-SE southern seismic section.

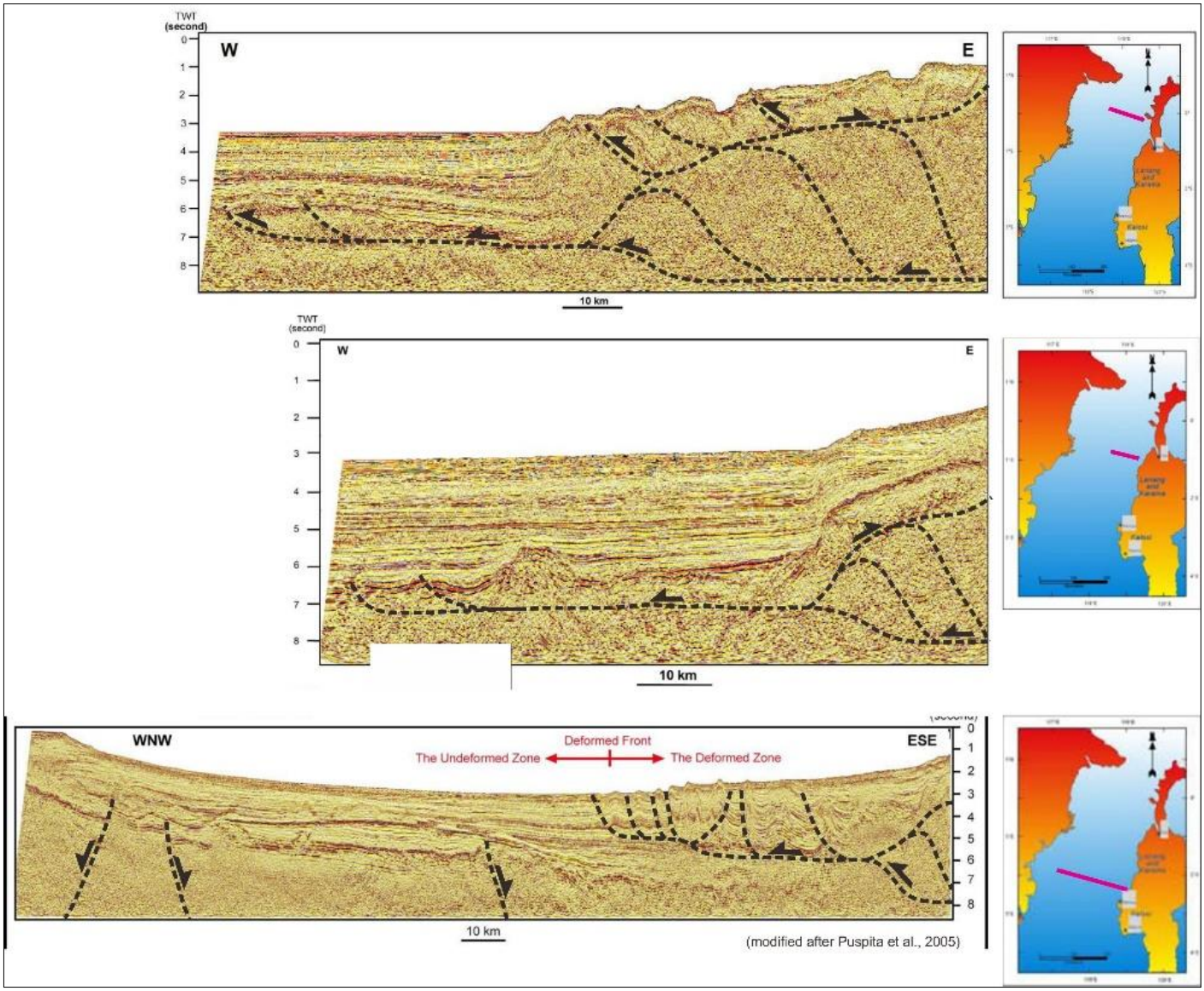


Figure 16: *Re-interpretation on Subsurface Offshore West Sulawesi and Deformation Front depicted from Bathymetry and Shuttle Radar Topographic Mission (SRTM) (modified after Puspita et al., 2005)*

Basal detachment of basement-involved thrust wedge may occur within West Sulawesi Mesozoic stratigraphy. Detachment folds of Offshore West Sulawesi utilized two detachment levels (Puspita et al., 2005). Lower detachment might use contacts between Budung-budung Formation with Lisu Formation. Ramp connected lower to upper detachment and followed with backthrusting. Upper detachment possibly utilized unconformity between Lisu and Pasangkayu Formations. On the other hand, seismic evidences show that strata involved in detachment folding shows strong onlapping relationship to previous deposits (Budung-budung Formation) and to pre-existing platform structures. Such extensional structures belong to Eocene rifting and not involve in Plio-Pleistocene compressive deformation. NNE-SSW seismic section provided by Satyana et al. (2012) confirms intensive detachment folding above Middle Miocene stratigraphy. Positive flower structures, as offshore continuation of Sigi Fault, are captured on the seismic section (Figure 17).

Compressive tectonics in West Sulawesi Fold-Thrust Belt is correlated to microcontinental collision in Banggai-Sula and Buton-Tukangbesi during Middle to Late Miocene (Hall, 1996). Compressive regime was then accommodated along Palu-Koro Fault for the strike-slip kinematics. Meanwhile, West Sulawesi Fold-Thrust Belt absorbed the dip-slip kineamtics. Implication of thrust wedge system in West Sulawesi is flexural subsidence of Makassar Straits. As appeared in Satyana et al. (2012), Makassar Straits are structurally stable and has no prominent faulting to date. Flexural deformation makes Makassar Straits to subside as isostatic response to uprising mountains in West Sulawesi and Samarinda Anticlinorium.

Offshore Northern Banggai-Sula

Offshore North Banggai-Sula is selected to represent thrust wedge system of colliding microcontinent. In this context, Ferdian et al. (2010) integrated seismic images and multibeam data to divide Offshore North Banggai-Sula into three structural provinces (Figure 18): western, central, and eastern areas. Based on seismic sections, Banggai-Sula Microcontinent dip to the north as it collides. Debris from erosion of tilted microcontinental margin become sediment source for the south-directed thrusting.

South-directed thrusting develop well in western area. However, since sediment sources are lacking in the eastern part of west area, thrusting is more prominent towards west. Important seismic feature in this area is flat-topped carbonate mound at 1000 meters water depth. This phenomenon indicates rapid subsidence following flexural deformation in the area. Central area has broad, deep basin. Water depth can reach more than 2500 meters and thrusted sediments are absent. Thrusting in east area belongs to Molucca Sea Collision Complex. Closing of Molucca Sea brings volcaniclastic sediments to be highly-deformed in east area. Extension of Balantak Fault in Onshore East Sulawesi generated prominent flower structure in Offshore North Banggai-Sula in NW-SE trend (Figure 19). Husein et al. (2014) stated that Balantak Fault has been active since Late Miocene and responsible for the clockwise rotation of Poh Head, East Sulawesi. Basal detachment of thrust wedge system of Offshore Northern Banggai-Sula develops at the base of accretion, where offscraping also operates.

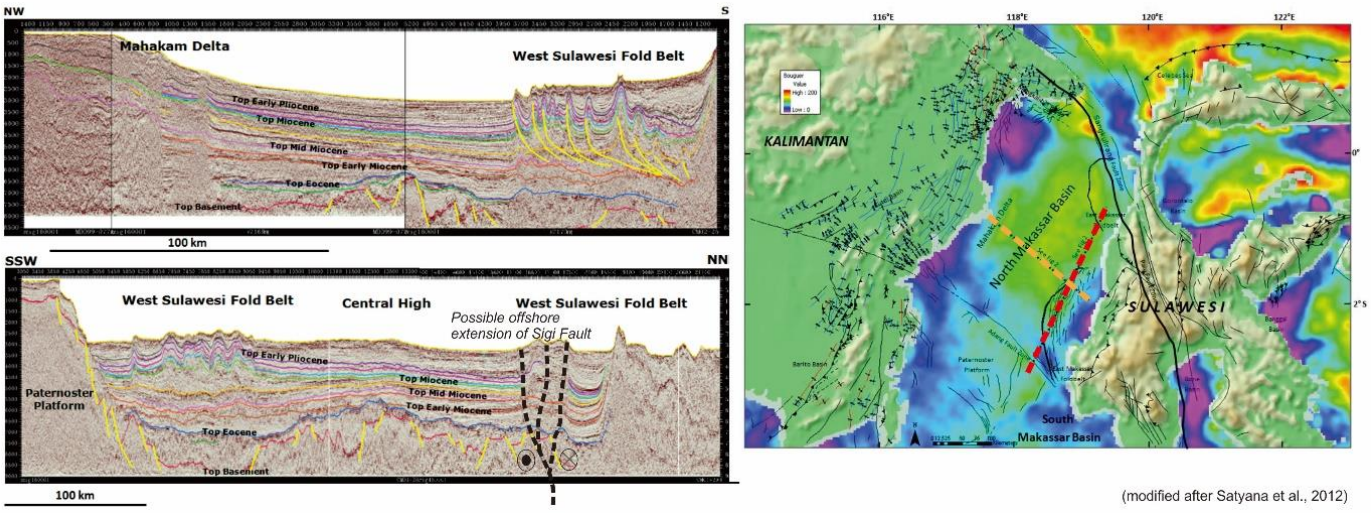


Figure 17: *Subsurface Offshore West Sulawesi: Detachment Folds and Possible Offshore Extension of Sigi Fault (Orange dashed line refers to NW-SE section, Red dashed line to SSW-NNE section, modified after Satyana et al., 2012)*

Tectonic driving force of Banggai-Sula Collision can be summed up into two possibilities: Sorong Transform Fault (Hall, 1996) and opening of North Banda Sea. Sorong Transform Fault played regional role in moving the microcontinent 1000 km from New Guinea (Hall, 1996). On Cenozoic tectonic reconstruction (Hall, 1996), North Banda Sea Opening played the role to cause oblique collision of Banggai-Sula. Davies (1990) surfaced thrust emplacement time to be between 5.2 – 3.8 Ma (Pliocene), while Hall (1996) suggested Middle Miocene as initial thrusting period. Seabed deformation with migrating fold hinge in Offshore North Banggai-Sula confirms thrusting still operating to date (Figure 20).

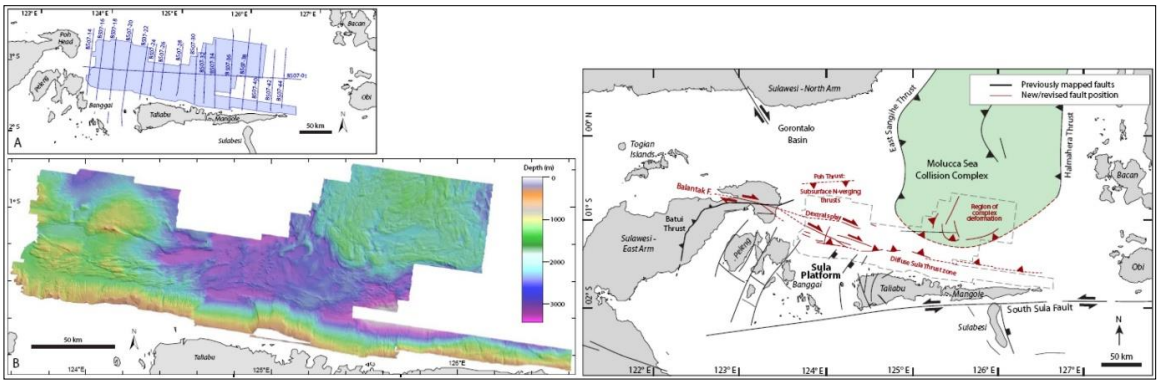


Figure 18: *Multibeam Data and Structural Map of Offshore Northern Banggai-Sula (Ferdian et al., 2010)*

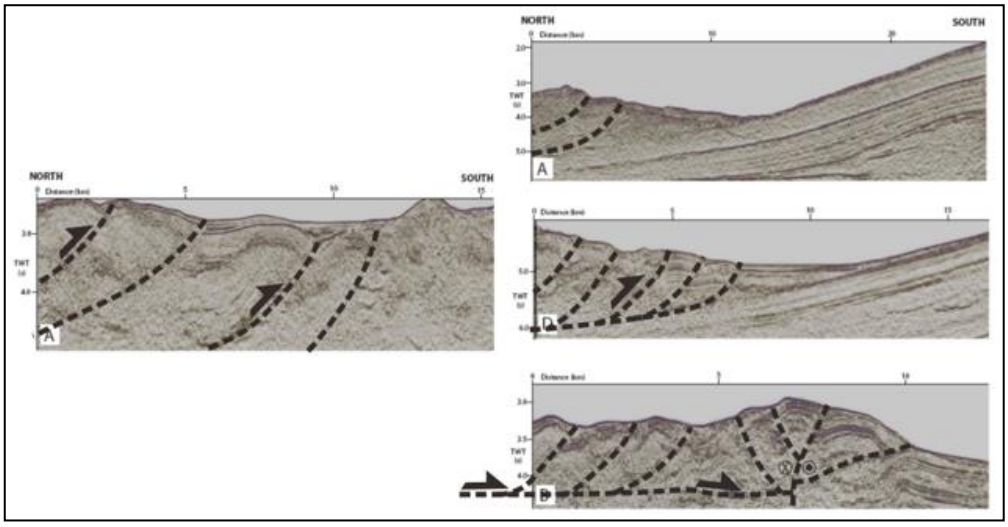


Figure 19: *Subsurface Offshore Northern Banggai-Sula: Progressive Deformation towards West and Positive Flower Structure as Offshore Extension of Balantak Fault (modified after Ferdian et al., 2010)*

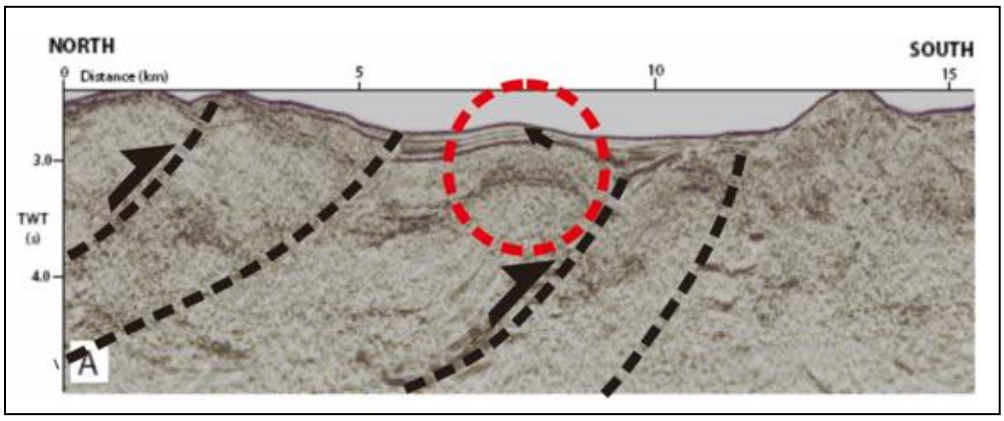


Figure 20: *Seabed Deformation and Migrating Fold Hinge as a Sign to Recent Tectonics (modified after Ferdian et al., 2010)*

Misool-Onin-Kumawa Ridge, Berau-Bintuni Basins, and Lengguru Fold-Thrust Belt

Banda Sea and the surrounding area possesses four zones of fold-thrusts belts: Seram Trough, Lengguru Fold-Thrust Belt, Misool-Onin-Kumawa Ridge (MOKR), and Berau-Bintuni Basins. Seram Trough displays compressive structures as the result of continental delamination due to rollback mechanism. Other than rollback mechanism, the three zones had accommodated continuous convergence between Australia and Pacific since Late Miocene (Bailly et al., 2009).

MOKR is a broad NW-SE anticlinorium located between two thrust wedges, the Seram Trough and Lengguru Fold-Thrust Belt (Figure 21). Seram Trough occupies the hinge zone between subduction of Bird's Head Microplate under the Banda Sea. In the other hand, Lengguru Fold-Thrust Belt is related to the previous subduction of Bird's Head Microplate under New Guinea Block (Sapin et al., 2009). Sapin et al. (2009) argues that MOKR is a triangle zone due to northeastward-moving crustal sheet carried over a detachment located at brittle-ductile transition (~12 km). MOKR are not part of Seram Trough or Lengguru Fold-Thrust Belt deformation because of its dimension. Sapin et al. (2009) noted that topographic features of MOKR exceeds 1000 meters at Kumawa Anticline, not in line with lithospheric flexure criteria to be the forebulge of the two adjoining orogens. Width of MOKR and distance of its axis to Seram Trough represent different tectonic processes than the surrounding orogens. During its development, MOKR displays has detachment at shallower structural levels. Considering its stratigraphic units, MOKR is composed of Permian-Paleocene Shales as incompetent layer, New Guinea Limestone as competent units, and Late Miocene – Plio-Pleistocene clastics as incompetent layer (Sapin et al., 2009). Therefore, the Permian-Paleocene Shales provide slippery surfaces for regional detachment.

Geomorphic features of the MOKR are typical of fold-thrust belts. Onin Mountains experienced considerable uplift by thrusting and folding, manifested as outcropping of Oligo-Miocene Onin-Ogar Limestones (Suparman and Robinson, 1990, Figure 22-24). Progressive deformation triggered intersecting fractures in NW-SE and NE-SW trends along major fold traces. Moving to the west, thrusting in Misool Island is indicated by curvilinear lineament and outcropping of Silurian Ligu Metamorphics, Triassic Keskain Shales, and Triassic Bogal Limestones (Rusmana et al., 1989). Zaag Thrusts are responsible for the northward-tilting Jurassic Fageo Group in front of Silurian Ligu Metamorphics. This structural feature is analogous to synclinal feature in subsurface cases. Other related structures are NW-SE and NE-SW strike-slip faults, developing in the east and northern portion of the island. Karstic morphology developed in the outcropping zone of Triassic Bogal Limestones (SE portion) and Miocene Openta Limestones (NE portion of the island). On the other hand, geomorphic interpretation in Obi Island suggested prominent NE-SW left-lateral strike-slip faulting in the eastern portion of the island, as it adjoins with Sorong Fault. NE-SW Obi Fault generated its subsidiary NW-SE antithetic faults in the western portion of the island. Thrust wedge system of MOKR terminates before Obi Island.

Previous work in the Berau-Bintuni Basins stated that E-W high-angle left-lateral faulting deformed the basins (Perkins and Livsey (1993); Birt et al., (2017)). On the contrary, thrust wedge orogeny in MOKR continues to Berau-Bintuni Basins. This consideration comes up with the idea of northeastward-moving crustal sheet of MOKR and the proximity of the basins with the orogen. Thrust wedge system in Berau-Bintuni Basins is supported by tight folding above thrust wedge and synclinal feature in the thrust front (Figure 25). Basal detachment of thrust wedge system occurs at its Permian – Paleocene intervals. Detachment folding can also be observed within post-rift deposit away from thrust wedge.

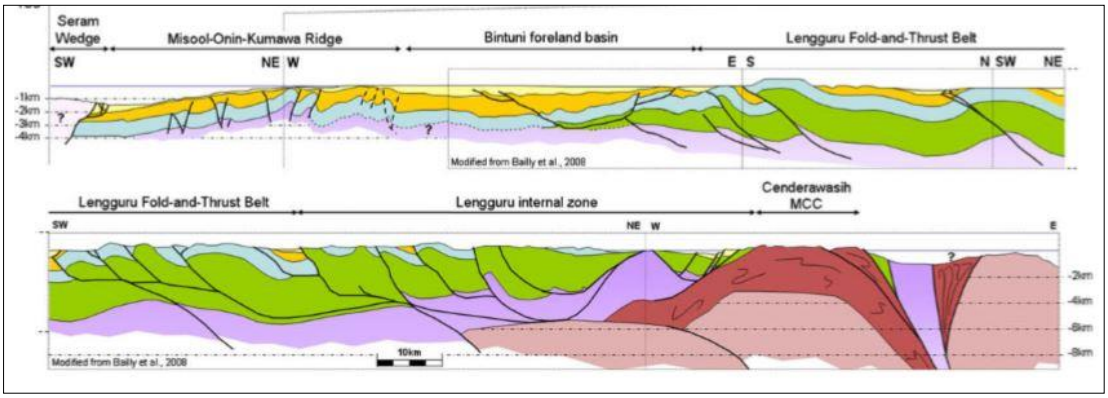


Figure 21: *Regional Cross-section from Seram Trough to Lengguru Fold-Thrust Belt (Sapin et al., 2009)*

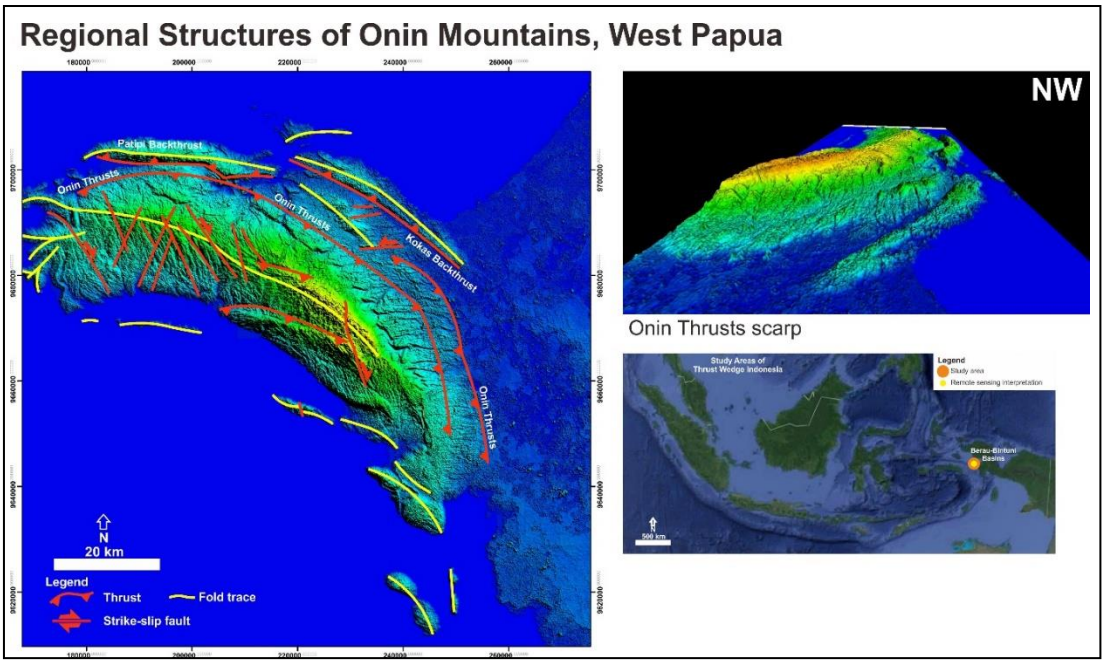


Figure 22: *Regional Structres of Onin Ridge, West Papua: Onin Thrusts scarps and Fold Traces*

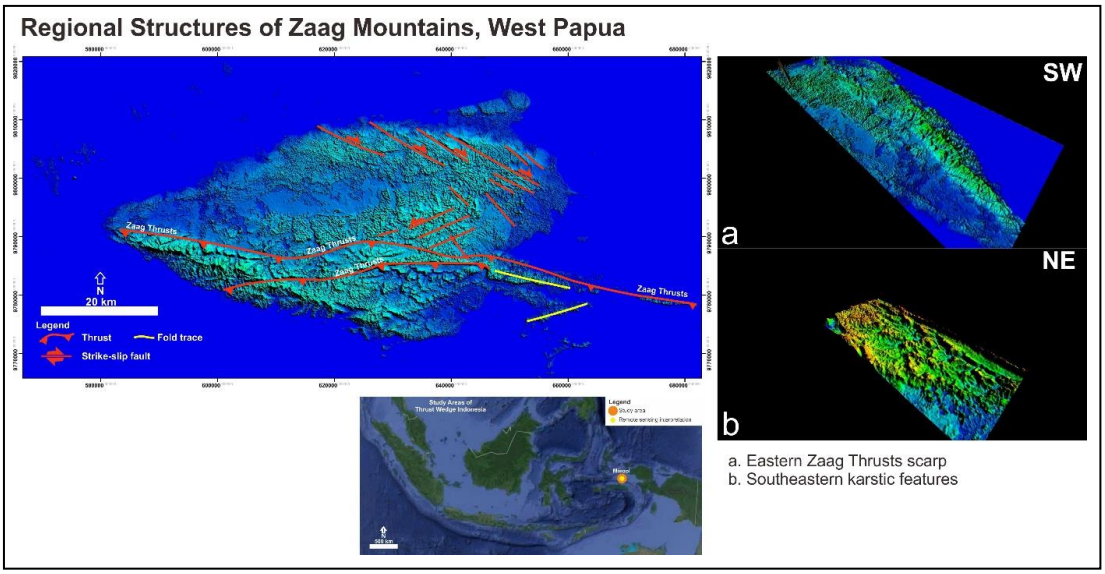


Figure 23: *Regional Structures of Zaag Mountains (Misool Island), West Papua: (a) Eastern Zaag Thrusts Scarp; (b) Southeastern Karstic Features of Triassic Bogal Limestones*

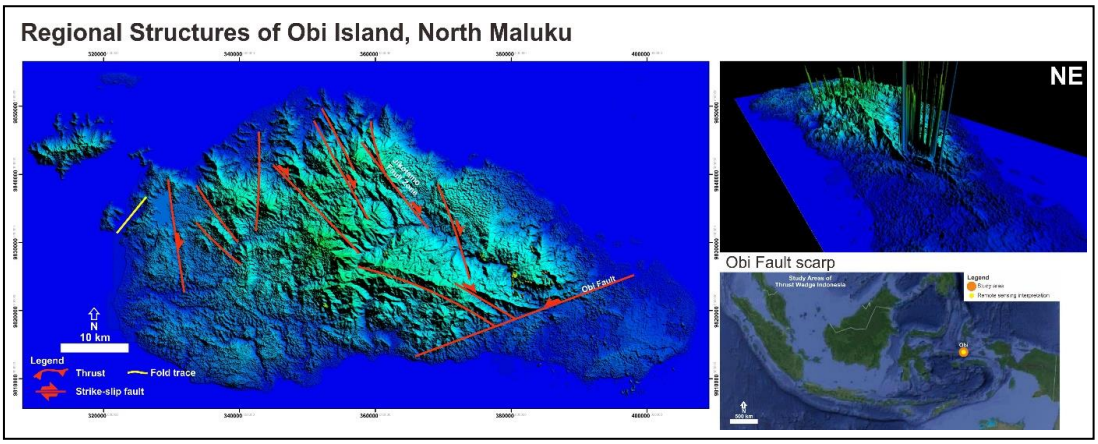


Figure 24: *Regional Structures of Obi Island, North Maluku*

Lengguru Fold-Thrust Belts represent a good example of thrust wedge orogeny. Lengguru Fold-Thrust Belts has complete components of thrust wedge orogeny: crustal backstop, thick-skinned deformation, and thin-skinned deformation. Bailly et al. (2009) divides Lengguru Fold-Thrust Belt into two areas: external and internal zones (Figure 26). External zone encompasses the deformation of sedimentary successions and the basement, while internal zone represents the exhumed subduction - zone. With this configuration, external zone deformation is controlled by stratigraphic units and rheological properties. As previously discussed in MOKR, Lengguru Fold-Thrust Belt exhibits similar stratigraphy. Permian – Paleocene succession acts as main detachment, while the Tertiary New Guinea Limestone as the competent layer. Internal Zone is composed of meta-sediments and high-grade metamorphic units (Bailly et al., 2009).

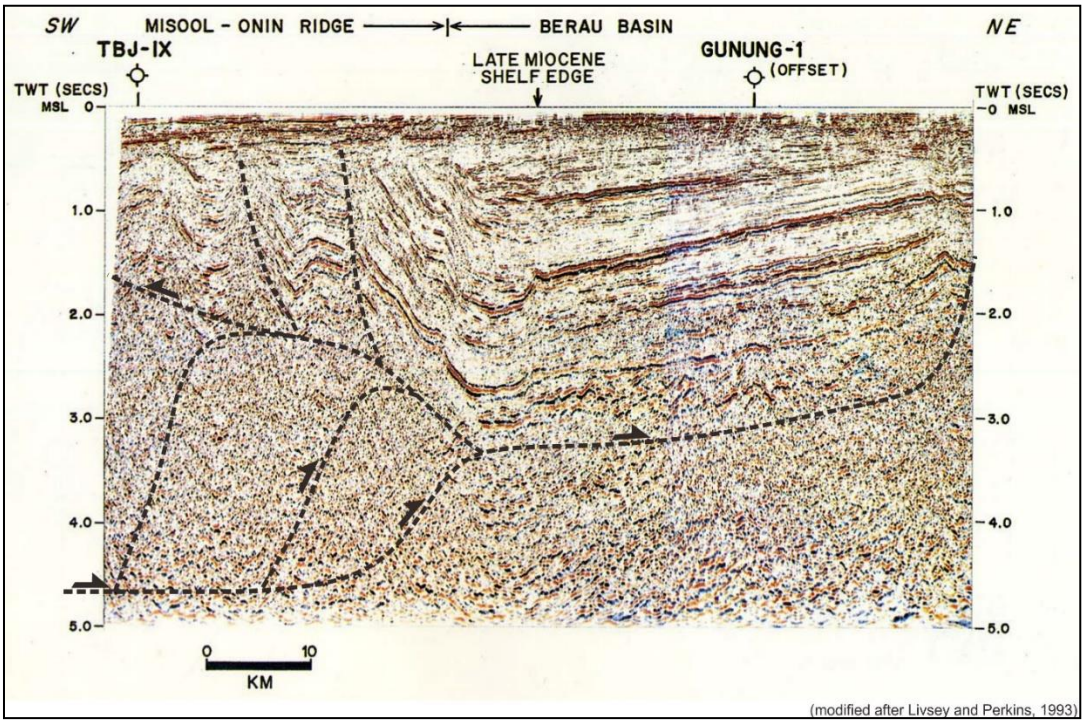


Figure 25: *Subsurface Offshore Berau Basin: E-W trending Thrust Wedge System (modified after Livsey and Perkins, 1993)*

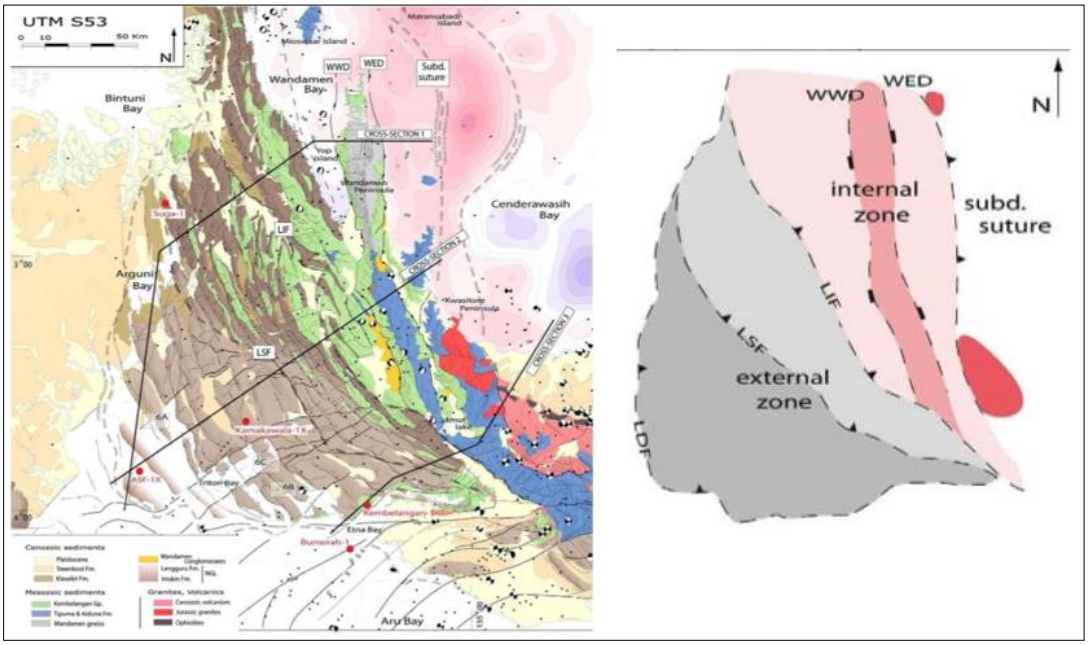


Figure 26: *Geologic Map and Structural Zones of Lengguru Fold-Thrust Belt (Bailly et al., 2009)*

Deformation of the external zones is characterized by two superimposed wedges (Bailly et al., 2009, Figure 27). The first wedge is represented as NE-SW trending folds with detachment at 4 – 5 km depth. Arcuate shape of the orogen originated from this wedge. The second wedge detached to 7 – 8 km deep in Aiduna Formation. Addressing its deep detachment, the second wedge is responsible to construct prominent topography (up to 800 meters) of the orogen. The second wedge has NW-SE trending fold-thrusts, representing the general trend of the orogen. Several factors may cause differences in trend of the two wedges, including friction or structural inheritance. The first wedge acted as passive roof to the second wedge during deformation. The last stage of deformation in the external zone of Lengguru Fold-Thrust Belt is block-faulting tectonics (Bailly et al., 2009). Collapse structures occurred along NE-SW trend, possibly using the pre-existing structures. Shortening in Lengguru Fold-Thrust Belt has been accommodated by Tarera-Aiduna Fault since at least 3 Ma. This shift in deformation may result from increasing friction and immense load of the wedge (Bailly et al., 2009).

The internal zone of Lengguru Fold-Thrust Belt exposed weakly metamorphosed rocks and metamorphic rocks. Exposure in the Wandamen Peninsula includes gneiss, eclogite, amphibolite, metasediments, metabasalts, paragneiss, and granite. Paragenesis shows that high temperature assemblage of biotite-sillimanite-garnet overprints high pressure assemblage of kyanite-garner-muscovite. Other evidences of high temperature metamorphism are migmatites and antectic leucosomes. On the other hand, Triassic – Early Jurassic unmetamorphosed granite exposure in Kwasitore Peninsula is considered to be the backstop of the orogen.

Lengguru Fold-Thrust Belt has Cendrawasih Bay to the north as the neighbor. The neighboring basin has peculiar triangular shape. Sapiie et al. (2010) regarded Cendrawasih Bay as the result of coupling movement of two left-lateral strike-slip systems: Yapen-Sorong and Tarera-Aiduna Faults. Considering the relation between the two areas, Cendrawasih Bay may form after Lengguru Fold-Thrust Belt orogeny since it was part of Tarera-

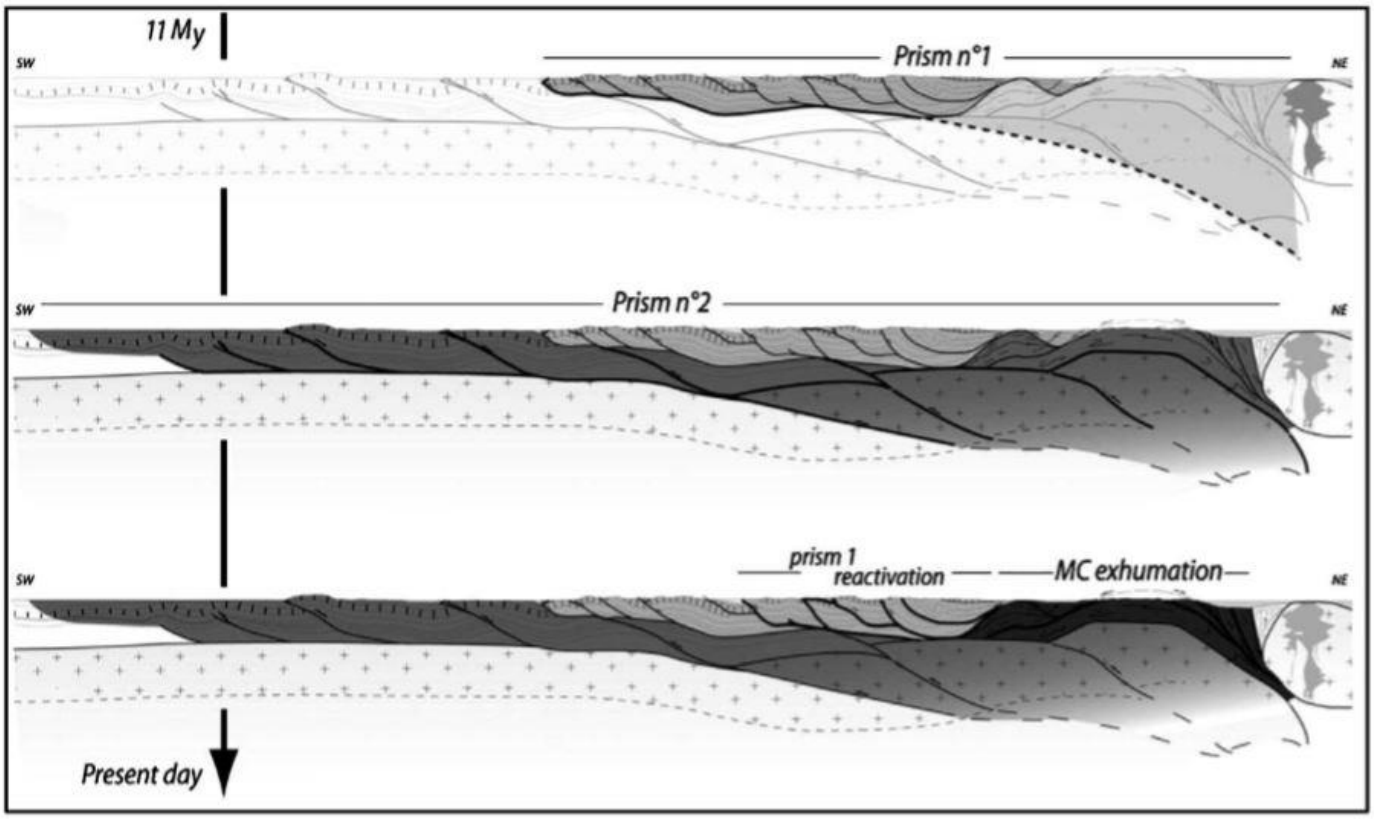


Figure 27: *Schematic Tectonic Evolution of Lengguru Fold-Thrust Belt (Bailly et al., 2009)*

Aiduna Fault activity. Sapiie et al. (2010) also suspected small rotation in the Bird's Head area due to strike-slip movement during Cendrawasih Bay formation.

Thrust wedge orogeny in Seram Trough, MOKR, Lengguru Fold-Thrust Belt, and Berau-Bintuni Basins occurs contemporaneously in Late Miocene to Pliocene. Compressive regime came from convergence between Australia and the Pacific as well as rollback mechanism in the Banda Sea. Schematic tectonic evolution in Seram Trough, MOKR, and Lengguru Fold-Thrust Belt from Bailly et al. (2009) is provided in Figure 28.

trace on the surface, tight folds near mountain front, formation of asymmetric syncline at thrust front, and detachment folds away from the thrust wedge. Termination of basement-involved thrust wedge system coincides with major synclinal feature. Detachment folds develop well in post-rift shale-dominated interval. Associated structure is transpressive and transtensional reactivations during and after thrust wedge development.

Primary difference on thrust wedge systems in Indonesia is Recent tectonic settings. During basin formation, study areas belonged to rift basin setting, except Banyumas Fold-Thrust Belt as

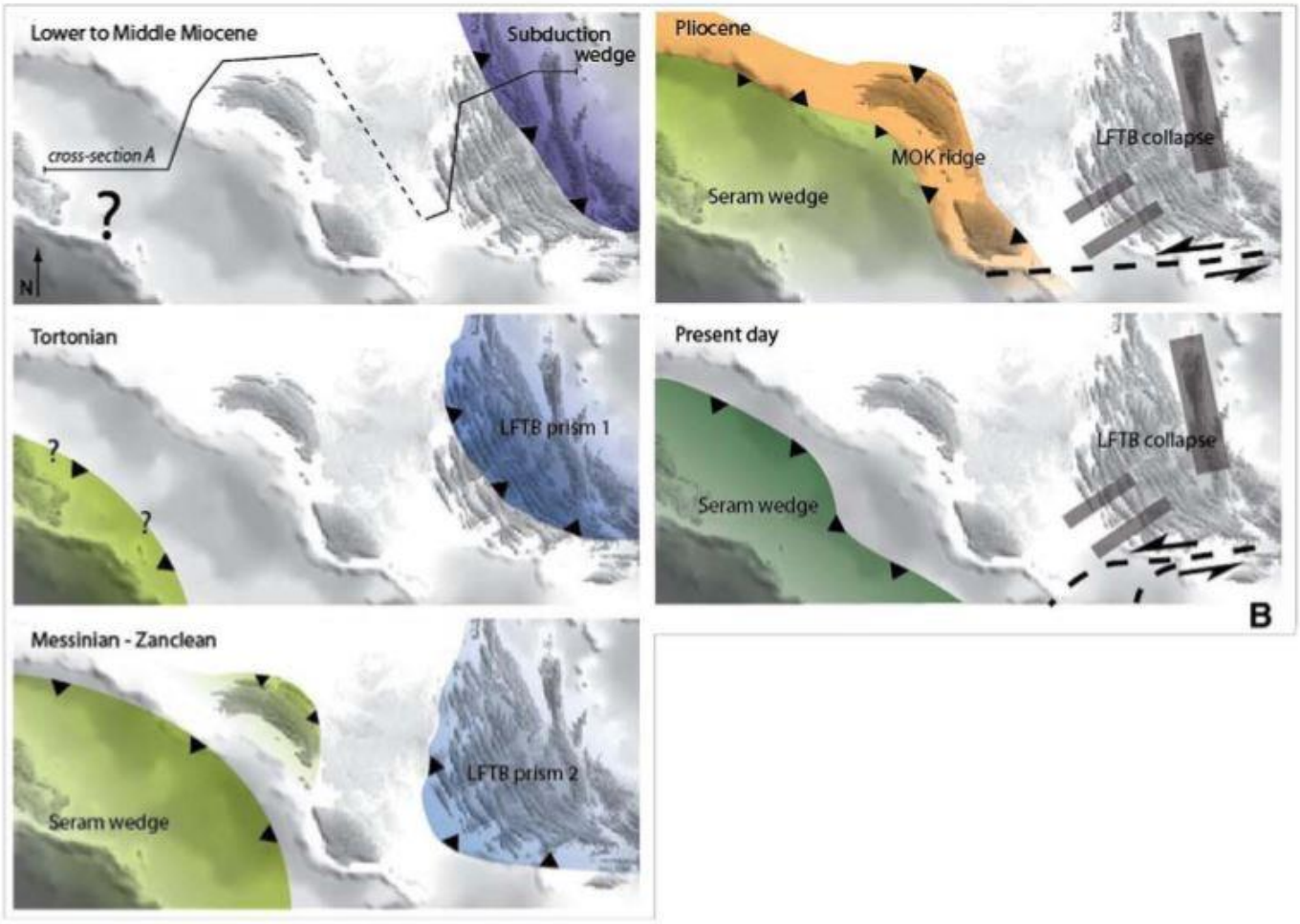


Figure 28: *Schematic Tectonic Evolution of Seram Trough, MOKR, and Lengguru Fold-Thrust Belt (Bailly et al., 2009)*

SIMILARITIES AND DIFFERENCES IN OROGENIC BELTS – A SYNTHESIS

Similarities and differences from orogenic belts of thrust wedge system can be drawn from discussions above. In terms of geomorphic expressions and structural associations, thrust wedge system relates to curvilinear thrust faults

flexural basin. However, succeeding geodynamics transformed the basins into backarc settings for North Sumatra Basin, Kutei Basin, and West Sulawesi Fold-Thrust Belt, intra-arc for Banyumas Fold-Thrust Belt, and colliding continents (or microcontinent) for Banggai-Sula and Berau-Bintuni Basins. In other words, this overview attempted to virtually represent possible settings in Indonesia.

Geodynamic significance of strike-slip faults in thrust wedge system is manifested in two occurrences. Strike-slip faults occur as a separate geodynamic features or as associated structures to the thrust wedge system. Cases in North Sumatra, West Sulawesi, and Lengguru Fold-Thrust Belt display strike-slip faults as different entity. Whether transcurrent or transform in nature, separate strike-slip features in study areas have been evidences of slip partitioning in regional scale. Sumatran Fault operates the strike-slip kinematics due to oblique subduction, Palu-Koro Fault, Balantak Fault, and Tarera-Aiduna Fault develop in response to collision. Associated structures may act as reactivated faults and tear faults.

Further study on thrust wedge systems in Indonesia should focus on exploration in varying areas. Exploration is crucial since fold-thrust belts develop in various areas in Indonesia. Other areas may include Meratus Mountains and the Barito Basin, Akimeugah Foredeep of Papua, and the Lesser Sunda Islands. Regional understanding of thrust wedge system in Indonesia helps improving our knowledge on the Plio-Pleistocene orogeny of Southeast Asia.

CONCLUSIONS

From the discussions above, five points can be concluded:

- Geomorphic similarities lie on curvilinear thrust faults trace and tight, parallel fold traces to mountain front.
- Thrust wedge system associates with tight folding above the system, synclinal feature at thrust wedge, and detachment folds away from thrust wedge but within shale-dominated post-rift interval. Thrust wedge development is also followed by fault reactivation, both in transpressive and transtensional regimes.
- Pliocene – Recent is a critical time to orogenic building in Indonesia, especially in the developments of thrust wedge orogenic belts.
- Geodynamic significance of strike-slip faulting can be regarded as separate and associated structures. Associated strike-slip faulting operates during thrust wedging and acts as tear faults or reactivated graben faults, as exemplified in Banyumas Fold-Thrust Belt, Kutei Basin, Berau-Bintuni Basins. On the contrary, separate strike-slip faulting runs a role as a distinct geodynamic entity and coincides as adjoining structural province to thrust wedge system. This system is represented by Sumatran Fault in North Sumatra, Palu-Koro Fault in West Sulawesi, Balantak Fault in Offshore Northern Banggai-Sula, and Tarera-Aiduna Fault in Lengguru Fold-Thrust Belt.
- Synthesis on similarities and differences of thrust wedge in Indonesia shows that thrust wedge is a common phenomenon and occurs in varying dimensions and geodynamic settings. Both subduction and continental collision contribute to thrust wedge system as major structures in orogenic belts.

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