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# Overview to the Regional Thrust Wedge Tectonics in Indonesia:

Similarities and Differences in Orogenic Belts

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## Abstract

Overview to the regional thrust wedge tectonics in Indonesia attempts to compile and review geologic settings related to the development of compressive structures. Comprehensive overview will be represented in six orogenic belts of 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 Strait), Offshore Northern Banggai-Sula, and Berau-Bintuni Basins (extending from Onin Mountains, Misool Islands, and Obi Islands). Thrust wedge systems in this context relate to orogenic belts development and basement-involved in its nature. Key ideas and discussions encompass surface structural geology, geomorphology, and subsurface geology. Aiming to draw the big pictures, the integrated approaches will elaborate incorporate the roles of significant adjoining structural provinces to thrust wedge developments. 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. Addressing geodynamic significance of strike-slip faulting, two groups can be defined: dependent and independent. Dependent strike-slip faults operate during thrust wedging and acts as tear faults or reactivated graben faults. Meanwhile, independent strike-slip faults run a role as a distinct geodynamic entity and coincide as adjoining structural provinces to thrust wedge system, as exemplified by Sumatran Fault in North Sumatra, Palu-Koro Transcurrent System in West Sulawesi, and Balantak Fault in East Sulawesi. As a conclusion, thrust wedge orogenic belts can develop in varying geologic settings in Indonesia, especially related to subduction and collisional tectonics.

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

## Introduction

Regional tectonics of Indonesia strongly correlate to compressive developments since Pliocene to Recent. Overview to the regional thrust wedge tectonics in Indonesia attempts to compile and review geologic settings related to the development of compressive structures. 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 Strait), Offshore Northern Banggai-Sula, 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 incorporate the roles of prominent adjoining structural provinces to thrust wedge developments.

Thrust wedge responsible in causing uplift in this overview are entirely basement-involved structures. Similarities are attached to geomorphic expressions, surface stratigraphic distributions, and structural association. Such similarities will be a guide to explore other possible thrust wedge developments in Indonesia and global examples. On the other hand, differences are captured in adjoining structural provinces and geologic settings. Adjoining structural provinces are critical to figure out their correlation to thrust wedge development. This intention builds upon an assumption that geologic structures operate in time and space, and are supposed to adjust with its adjoining environment. The goal of this approach is to draw comprehensive tectonic mechanisms in the areas. Otherwise, geodynamic significance of strike-slip faulting will also be addressed. Role of strike-slip faulting in restructuring thrust wedge and its position relative to regional tectonics 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.

## Data, Methods, and Tectonic Concepts

Overview to the regional thrust wedge tectonics in Indonesia presents reviews and discussions on compressive structures. Important tectonic concepts and interpretation techniques will be briefly outlined. Geomorphology and subsurface geology became the basis of structural frameworks on this review. 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 yielded regional structural map, 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 system.

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 $30^{o}$. 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 – $70^{o}$). 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).

## Recent Regional Geodynamics and Basin Evolution

### *Recent 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 frontal setting. In contrast, collided continents are exemplified by Papua region. Colliding Australian Plate with Sepik Mountains generated profound compressive structures across Papua.

Six orogenic belts were selected as thrust wedge system, each of which represents certain geologic settings. Regional Recent geodynamic settings of study areas are given in **Figure 3**. 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.

East Kalimantan Basins and West Sulawesi have a strong tectonic correlation. West Sulawesi was previously attached to East Kalimantan, drifting away during Paleocene-Eocene rifting (Hall, 1996). Owing to several episodes of subduction since Late Cretaceous, West Sulawesi derived its volcano-plutonic arc geology (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. 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 Graben and its subsidiary faults.

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 Transcurrent Faulting. In Eastern Indonesia, Berau-Bintuni Basins are examples of obliquely collided continent. Oblique northward movement of Australian Plate collided with Sepik Mountains in Eocene (Birt et al., 2017), triggering compressive deformation and uplift in the area. As a result, collisional event was diachronous along the tectonic margin. In Recent geodynamics, Berau-Bintuni Basins adjoin with Seram Trough in the south and Lengguru Fold-Thrust Belt in the east.

*Basin Evolution*

Overview to thrust wedge in Indonesia aims to organize geologic events from basin formation to orogenic belts building. Compilations on basin evolution intends to draw a big picture of major shift from extensional tectonics to flexural deformation. As suggested, a basin can undergo multiple history and goes through different settings. Since space and time are the basis of this overview, Basin Dynamics Time Frame Chart of the study areas are constructed from compilation of publications. Basin Dynamics Time Frame Chart highlights timing of rifting, thermal subsidence, and basin inversion of the study areas (**Figure 4**). For comparison, timing of adjoining tectonic events is also put in place. This compilation comes up with the pattern that early rifting occurred in Berau-Bintuni Basins, then moved to Banggai-Sula Microcontinent. Kutei Basin rifting initiated in Paleocene, while West Sulawesi in Eocene (Raharjo et al., 2012). North Sumatra Basin appeared to form the latest, being rifted in Late Oligocene to Early Miocene (Davies, 1984). Banyumas Fold-Thrust Belt went through flexural subsidence since Miocene to Pleistocene due to northward thrusting of West Java Southern Mountain. Consequentially, time spans of thermal subsidence got shorter towards Western Indonesia. Of basin dynamic phases, orogenic belts formation operated in similar timing across Indonesia. Intermittent uplifts are reported in Berau-Bintuni Basins since Triassic to Recent. Nevertheless, six orogenic belts entered major building phase in Pliocene to Recent. This time span proves major plate re-organization in Southeast Asia, witnessed as orogenic phases across the region. Even though some authors reported uplift initiation since Middle Miocene in Western and Central Indonesia, orogenic belts emerged to the surface since Pliocene. Evolution of each basin will be outlined below.

Basin formation in North Sumatra occurred in Late Oligocene (Davies, 1984), utilizing N-S lineaments both in present-day onshore and offshore area (Davies, 1984; Banukarso et al., 2013). Syn-rift deposition is represented by Bruksah and Bampo Formations (Davies, 1984; Wang et al., 1989). Rapid thermal subsidence in Early Miocene (Banukarso et al., 2013) followed the event successively. During thermal subsidence, depositional environments shifted from terrestrial-transition to shallow and deep marine. Shallow marine environments are marked by Peutu carbonate build-up, while deep marine represented as shale-dominated Baong Formation through Late Miocene (Wang et al., 1989). Depositional environment shifted to shallow marine and transitional in the overlying Keutapang Formation. However, subtle unconformity marked the transition. Davies (1984) speculated that North

Sumatra Basin was structurally continuous to West Sumatra Basin. Separation occurred during Plio-Pleistocene uplift. Davies (1984) has noted flexural deformation in North Sumatra Basin since pre-rift to inversion phase.

Sedimentation in Banyumas Fold-Thrust Belt has been reconstructed to Early Miocene, since older sequences do not reach the surface and drilled wells did not penetrate older age. Raharjo et al. (2002) constructed regional cross-section from Offshore Northwest Java Basin in the north to Southern Mountains of West Java in the south. Present-day Banyumas Fold-Thrust Belt is regarded as Bogor Trough in Raharjo et al. (2002). Early – Middle Miocene sedimentation in Banyumas Fold-Thrust Belt is indicated by Pemali Formation of turbiditic deposits, unconformably above Oligo-Miocene volcanics (Armandita et al., 2009). Late Miocene Halang Formation resumed deep marine sedimentation with provenance from north to northward direction and regarded as proto-Ciremai Volcanics (Armandita et al., 2009). Deep marine sedimentation in Banyumas Fold-Thrust Belt was preceeded by and contemporaneous with Oligo-Miocene volcanics in the south. Therefore, Banyumas Fold-Thrust Belt has experienced flexural subsidence since Miocene to Pleistocene.

Kutei Basin is the largest (165,000 $km^2$) and the deepest (12,000 – 14,000 meters) Tertiary sedimentary basin in Indonesia (Satyana et al., 1999). Rifting initiated in Paleocene by deposition of Kiham Haloq Formation and ended in Oligocene as indicated by Mangkupa Shale deposition in marginal to open marine environment (Satyana et al., 1999). Interruption by uplift to basin subsidence was recorded as coarse siliciclastics, such as Beriun Sands (Satyana et al., 1999). During basin rifting and thermal subsidence, neighboring paleo-highs were Mangkalihat Ridge in the north and Sunda Shield in the south (Ott, 1987). Present-day Kuching High was a basin deep at that time as the basin opened to the west. Subsequent stratigraphic depositions were contemporaneous to tectonic uplift and inversion. Uplift started in Early – Middle Miocene time and accompanied by alluvial to deltaic sedimentations in Kutei Basin.

West Sulawesi is tectonically-attached to Kalimantan prior to Eocene rifting. Previously attached to Kalimantan, West Sulawesi drifted to the east due to subduction roll-back of Pacific Plate. Such geodynamic setting enabled West Sulawesi to possess volcanic-plutonic emplacements during that phase. Raharjo et al. (2012) stated that Eocene rifting of West Sulawesi generating NE-SW graben structures, as observed in onshore Lariang-Karama Basins. Initial deposition is marked by Budung-budung Shales through Eocene – Middle Miocene. Fluvial clastics of West Sulawesi syn-rift deposit is represented by Eocene Kalumpang Formation. Clastic sedimentation of Budung-budung Shales was contemporaneous with Oligo-Miocene Lamasi-Talaya Volcanics in the present-day mountainous area (Sukido et al., 1993; Ratman and Atmawinata, 1993). Unconformity marked the top of Budung-budung Shales and was reported from KD-1 well (Raharjo et al., 2012). The overlying Lisu Formation has gravity-debris sediments with argilites, slates, volcanics, and others derived from Late Cretaceous basement (Raharjo et al., 2012), indicating initial uplift. Late Pliocene uplift was recorded as unconformity beneath Pasangkayu Formation in LG-1 well (Raharjo et al., 2012). Pasangkayu Formation has debris-related deposits and appears to be reworked materials carried from mountain front.

Banggai-Sula Microcontinent has a long basin history since Jurassic. Basement of this microcontinent refers to Carboniferous or greater age metamorphics and Permo-Triassic Granites. Rifting seemed to proceed in Jurassic as indicated by deposition of terrestrial conglomerates and sandstones of Bobong Formation. The overlying marine sediments belongs to Buya Formation of Lower Cretaceous. Carbonate deposition came later on as Late Cretaceous – Paleocene Tanamu Formation (Ferdian et al., 2010).

Berau-Bintuni Basins are part of obliquely colliding Australian Continent with Sepik Mountains. The two basins have long history since rifting in Permian-Triassic. Intermittent uplift occurred along the way. Middle Jurassic is marked by erosion as the basin widened and sediment got thicker towards south and east. Middle Eocene to Oligocene became the following uplift episodes. Karstification on Middle Eocene Faumai Formation became the basis to recognize the effect of Sepik Mountains docking to Australian Continent (Birt et al., 2017). Oligocene became important episode of folding and faulting in Bintuni Basin. Later on, Miocene Kais-Klasafet Formation was deposited on undulating paleo-topography. Continued oblique collision triggered Lengguru Fold-Thrust Belt uplift during 8 – 2 Ma (Late Pliocene).

## Key Ideas and Discussions

Key ideas and discussions will elaborate geomorphology, structural geology, tectonic phases, and adjoining structural provinces of study areas. Geomorphology became the basis to regional structural maps. Structural geology deals with regional structures, subsurface seismic images, structural associations, and role of stratigraphic variations to detached structures development. Sequence of events will be constructed within tectonic phases. As a comparison, structural development of thrust wedge system will be correlated to its adjoining structural provinces.

*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. As proposed in regional structures (**Figure 5**), Barisan Mountains have anastomosing fault arrays in NW-SE trend. 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. NE-SW schematic regional cross-section represents compressive system (modified after Wicaksono et al., 2009 in **Figure 6**), while geomorphic features also express similar and relatable thrusting and folding features. 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. Thrusting in eastern foothills brought Kluet, Bahorok, Serbajadi Batholith 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. 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; Wicaksono et al., 2009). 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. Further explanations on surface-subsurface structural geology of Langsa Fold-Thrust Belt will be presented in Putra et al., *in prep.*

Anastomosing fault arrays coupled with thrusting in eastern foothills uplifted Barisan Mountains in North Sumatra to significant elevation over wide areas. Another comparable feature could be Lubuksikaping Transtensional Duplex in Central Sumatra. Deformation zone of Sumatran Fault from Lake Singkarak to Lake Ranau and Semangko Bay in South Sumatra depicts narrower extension than in North Sumatra. In addition, western side of the study area also displays significant NW-SE fault trend. However, it is likely to involve greater strike-slip component.

Addressing the distribution of thrust wedge system in North Sumatra, synclinal features appear to be the termination of basement-involved thrust wedge. Structuring in the northeast extension involves transpressive reactivation and detachment folds. The neighboring areas to Langsa Fold-Thrust Belt show similar structural features (**Figure 7**). 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. 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) also noted prominent prograding seismic facies within Pliocene Seurula Formation. Thrust wedge system, therefore, developed in Early Pliocene to Recent and worked together with transpressive regime since Late Pliocene. Such regime change is constructed from geomorphic relationships: Lokop-Kutacane Fault truncating Langsa Thrusts and transpressive folds cutting compressive folds in foreland area.

Transcurrent faulting in Barisan Mountains and thrust wedging along its eastern foothills are implications to Sundaland counter-clockwise rotation. Hall (1996) proposed such reconstruction to explain prominent structural features. In other side, structural phenomenon in eastern Barisan Foothills is supplement to slip partitioning concept in Sumatra. Such partitioning is not as simply explaining the relationship between subduction trench and trench-parallel faulting. Compressive deformation could also develop in Recent backarc setting. Sumatran Fault, as the transcurrent phenomenon, is necessarily correlated with the Langsa Fold-Thrust Belt in the subsurface by applying slip partitioning concept.

*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 8**). Slamet Fault shows recent deformation since it involves Mt. Slamet Quaternary volcanic deposit.

Seismic image was published by Lunt et al. (2008) (**Figure 9**) 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) 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 ft as deepest penetration. No older age has been reported.

Three tectonic scenarios have been proposed regarding Banyumas Fold-Thrust Belt. Martodjojo (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 10**), 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 intervals (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 possible.

*Kutei Basin*

Thrust wedge system in Kutei Basin correlates to 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 11**). 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 12**). 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 Samarinda Anticlionorium. Isostatic rebound happened as a response to normal faulting. Nemcok et al. (2016) stated that gravitational instabilities above the wedge promoted continued uplift. Absence of normal fault scarps on geomorphology might be triggered by this rebound.

Ferguson and McClay (1997) provided a closer look in Samarinda Anticlinorium. The publication promoted inverted growth fault model to explain fold-thrust belt formation and evolution (**Figure 13**). Deltaic sedimentation since Miocene in Kutei Basin generated major growth faults, defined as depobelts in Ferguson and McClay (1997). 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 stable state. Tectonic scenarios explained by Ott (1987) and Ferguson and McClay (1997) could be arranged into composite. 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. Samarinda Anticliorium may utilize contacts between Pulubalang Sandstones and Karorang Shales.

Extensive thrust wedging 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 Samarinda Anticlinorium. Despite adjoining position and similar trend, structures of the two areas could not be easily correlated. Ott (1987) stated that Samarinda 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 overpressure 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 14**). 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).

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 transcurrent system 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 Faults. Palu-Koro Faults generated releasing bend geometry and induced graben formation.

Puspita et al. (2005) divided Offshore West Sulawesi in three structural provinces (**Figure 15**). 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.

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 Badung-badung 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 16**).

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 Transcurrent Faulting for the strike-slip kinematics. Meanwhile, West Sumatra 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 17**): 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 18**). 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.

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 collsion 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 19**).

*Berau-Bintuni Basins*

Geomorphic interpretation was performed in Onin Mountains, Zaag Mountains (Misool Island), and Obi Island (**Figure 20-22**). Onin Mountains experienced considerable uplift by thrusting and folding, manifested as outcropping of Oligo-Miocene Onin-Ogar Limestones (Suparman and Robinson, 1990). Progressive deformation triggered criss-crossing 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., 1990). 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 joining Onin Ridge-Misool Island terminates before Obi Island.

Perkins and Livsey (1993) and Birt et al. (2017) previously suggested high-angle E-W left-lateral faulting in Berau-Bintuni Basins. Re-interpretation on seismic came up with thrust wedge system trending E-W (**Figure 23**). Thrust wedge system in Berau-Bintuni Basins is supported by tight folding above thrust wedge and synclinal feature in the thrust front. Basal detachment of thrust wedge system occurs at its Paleozoic intervals. Detachment folding can also be observed within post-rift deposit away from thrust wedge.

Compressive regime in the formation of thrust wedge system in Berau-Bintuni Basins may relate to Seram Trough development. Patria and Hall (2017) highlighted Early Pliocene as the end of thrusting in Seram Trough development. Thus, this phenomenon is contemporaneous to Lengguru Fold-Thrust Belt uplift. As Lengguru Fold-Thrust Belt locked up and thrusting ceased in Seram Trough, flexural deformation shifted to Onin Mountains and Zaag Mountains. The final thrust wedge development shifted northward and occupied Berau-Bintuni Basins. Thrust wedge shifts is possible in Seram Trough-Onin-Misool-Berau-Bintuni System because of sequential deformation and situated in adjoining position. Comparison on regional structures of West Papua and Seram Trough is presented on **Figure 24**.

**Similarities and Differences in Orogenic Belts – A Synthesis**

Similarities and differences from six 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 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 tectonic response is transpressive and transtensional reactivations after thrust wedge development. On the context of regional view, thrust wedge development in Indonesia is related to rising mountains near the basinal areas to enable flexural deformation and to provide syn-inversion sediments.

Differences on thrust wedge developments in Indonesia primarily lie on Recent tectonic settings. During basin formation, the six study areas belonged to rift basin setting. 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 collided continent (or microcontinent) for Banggai-Sula and Berau-Bintuni Basins. In other words, this overview attempted to virtually represent possible settings in Indonesia.

*North Sumatra Basin* lies in the eastern side of Barisan Mountains. Thrust wedge development successfully outcrop basement rocks of the area. As thrust wedge developing in the eastern side, the core of Barisan Mountains is characterized by transtensional regime of Sumatran Fault. Blangkejeren and Kutacane Grabens are arranged from northwest to southeast. The former can be classified as overstep basin, while the latter as fault-bend basin. Further explanations on geology and structural evolution of Kutacane Graben have been discussed in Putra and Sidqi (2017). Possible geodynamic processes during orogenic building is counter-clockwise rotation. Thrust wedge accommodated NE transport as the eastern Barisan block moved to SE due to transcurrent faulting, resulted from counter-clockwise Sundaland rotation (Hall, 1996).

*Banyumas Fold-Thrust Belt* is a part of Western Central Java fold system. Compressive deformation developed from the south involving Oligo-Miocene Jampang Volcanics towards the north involving Neogene successions. Important aspect of Banyumas Fold-Thrust Belt is its position and, geomorphic and structural continuation from Karangsambung Anticline.

*Kutei Basin* has thick Tertiary sections in Indonesia (Satyana et al., 1999). Thrust wedge development is related to Kuching Uplift. Miocene to Pliocene uplift tilted the sedimentary sections, triggering major gravity gliding in the area. As a spatial compensation, compressive regime from Kuching High triggered inversion on delta growth faults in Samarinda Anticlinorium.

*West Sulawesi Fold-Thrust Belt* is separated from Kutei Basin by stable Makassar Strait. Compressive deformation is recorded as curvilinear thrust traces on the onshore and thrust wedging in the offshore. Neighboring structural provinces to West Sulawesi Fold-Thrust Belt are Kolaka-Matano-Lawanopo-Palu Fault Systems. Such transcurrent faulting accommodated tectonic forces during the collisions of Buton-Tukangbesi Microcontinent with Sulawesi SE Arm and of Banggai-Sula Microncontinent with East Sulawesi Ophiolite.

*Offshore Northern Banggai-Sula* is a collisional zone between Banggai-Sula Microcontinent with the overriding plate. Thrust wedge is well-observed in the collisional zone. Compared to its western counterpart, Salodik Anticlinorium (Luwuk) is suggested to be detached structures by recent field mapping (Husein et al., 2014). Therefore, it has no spatial tectonic connection to thrust wedging in Offshore Northern Banggai-Sula.

*Berau-Bintuni Basins* situated near the rising Lengguru Fold-Thrust Belt, Onin Mountains, Zaag Mountains (Misool Islands), and Obi Islands. Structural high trending E-W parallel to Onin Mountains is likely to form due to thrust wedging, rather than left-lateral strike-slip faulting as suggested by previous publications. Compressive regime in Berau-Bintuni Basins may develop from two tectonic forces: oblique collision and Seram Trough formation. Seram Trough is likely to contribute greater compressive push in Berau-Bintuni Basins.

Further studies on thrust wedge systems in Indonesia have two pathways: elaboration on other areas and comparison on global contexts. Other prospective areas for thrust wedge studies in Indonesia range from Ombilin Foreland System in Central Sumatra and Akimeugah Foredeep besides southern mountain front of Papua Central Range. Tectonically, Ombilin Foreland System lies besides Sumatran Fault graben structures, such as Lake Singkarak – overstep basin and Muaralaboh Graben – fault-bend basin (Putra and Husein, 2016). Unique setting of Ombilin Foreland System is its coexistence with Quaternary volcanism. Akimeugah Deep, as a comparison, represents oblique convergence. Contrasting feature of Akimeugah Deep from other areas, including those areas of this manuscript, is its relatively straight thrust traces. It may relate to deep elastic thickness (high flexural rigidity) of downgoing plate (Allen and Allen, 2013).

**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 dependent and independent. Dependent 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, independent 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 Transcurrent System in West Sulawesi, and Balantak Fault in Offshore Northern Banggai-Sula.

- 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 orogenic belts major structures.

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## Figures

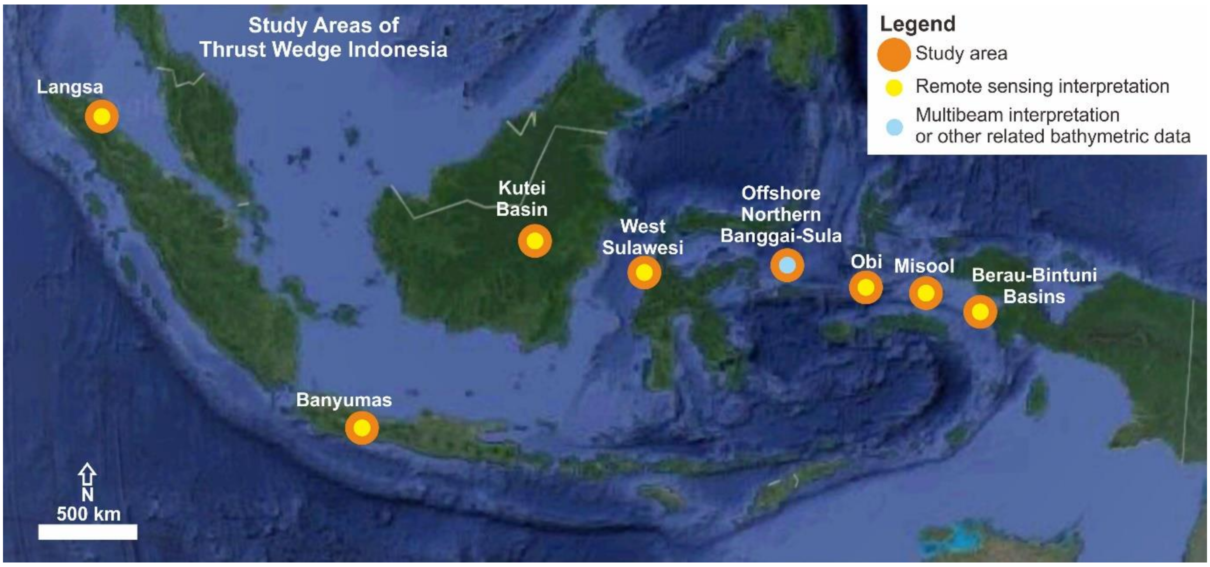



**Figure 1.** Coverage of Study Areas

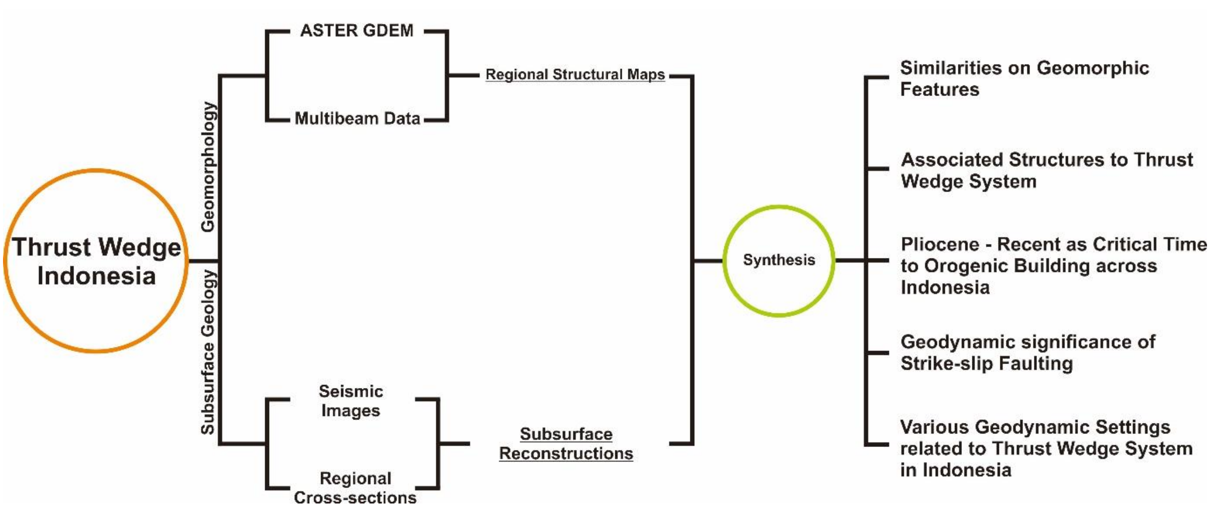



**Figure 2.** Thrust Wedge Indonesia Research Workflow

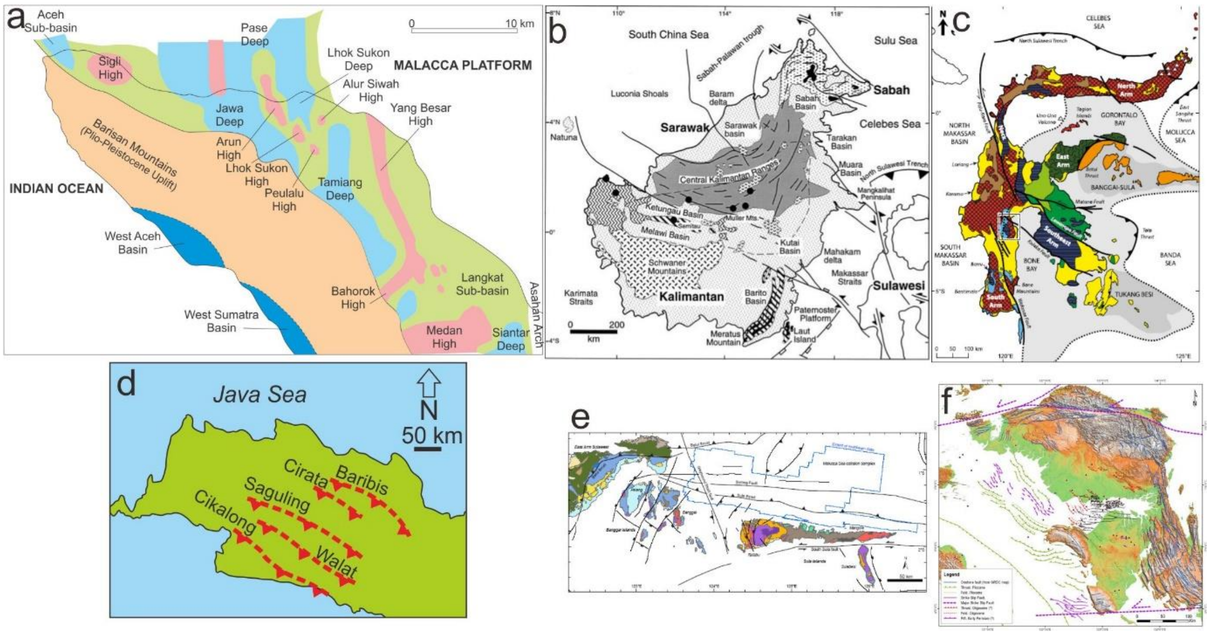



**Figure 3.** Regional Recent Geodynamic Settings: (a) Oblique Subduction Backarc Basin – Modified after Davies, 1984; (b) Backarc Basin – Wilson and Moss, 1999; (c) Backarc Basin – White et al., 2017; (d) Intra-arc Setting – (modified after Martodjojo, 1994) (e) Collided Microcontinent – Ferdian et al., 2010; (f) Collided continent – Birt et al., 2017

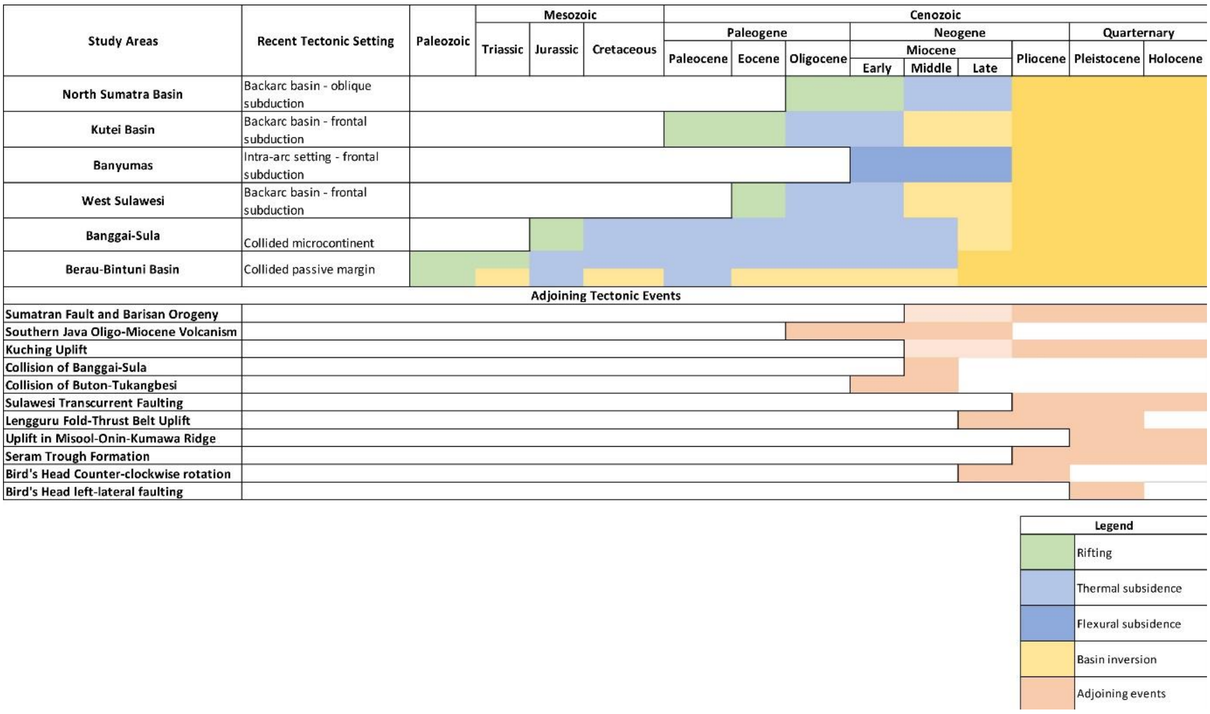



**Figure 4.** Basin Dynamics Time Frame Chart (compiled from various sources cited in this manuscript)

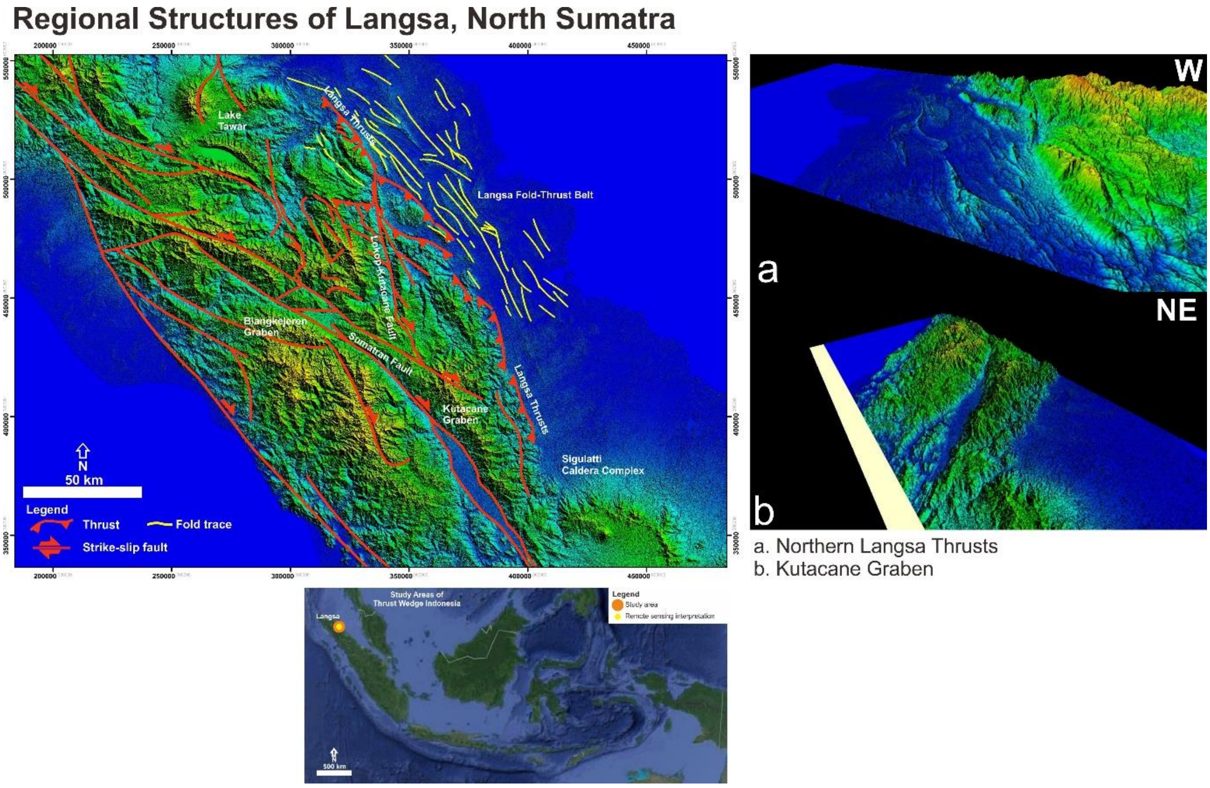



**Figure 5.** Regional Structures of Langsa, North Sumatra: (a) Northern Langsa Thrusts scarp and fold traces; (b) Kutacane Graben

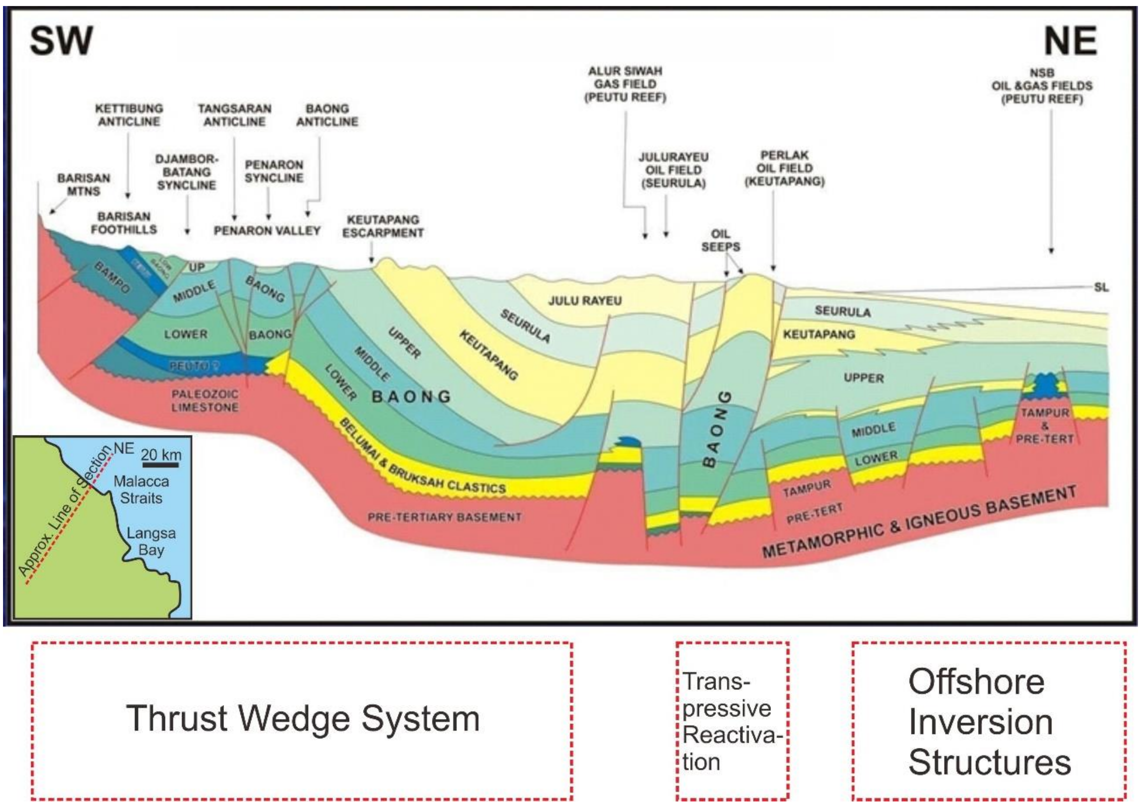



**Figure 6.** Schematic Regional Cross-section Transecting Langsa Fold-Thrust Belt (modified after Wicaksono et al., 2009)

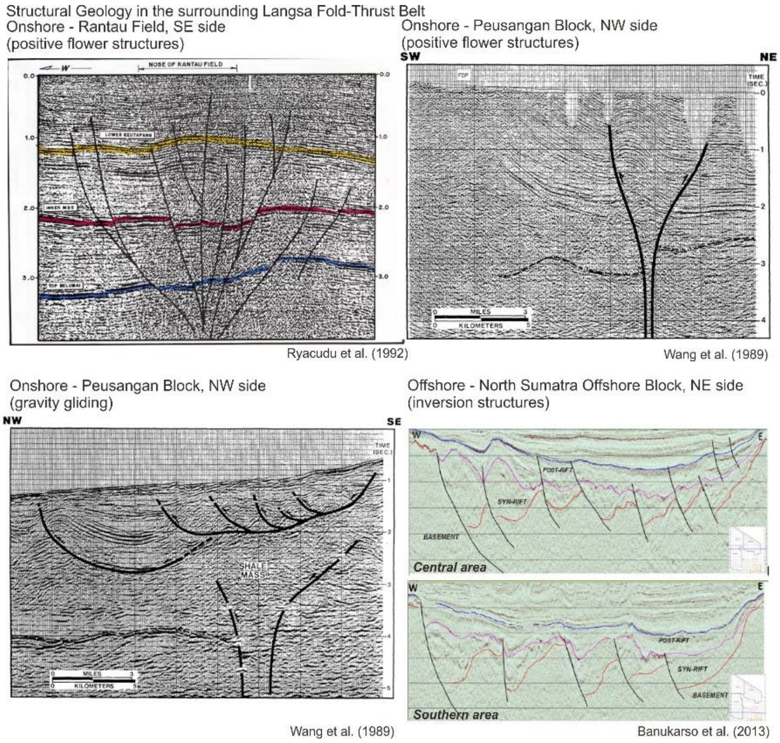



**Figure 7.** Comparison on Structural Geology Surrounding Langsa Fold-Thrust Belt (Ryacudu et al., 1992; Wang et al., 1989; Banukarso et al., 2013)

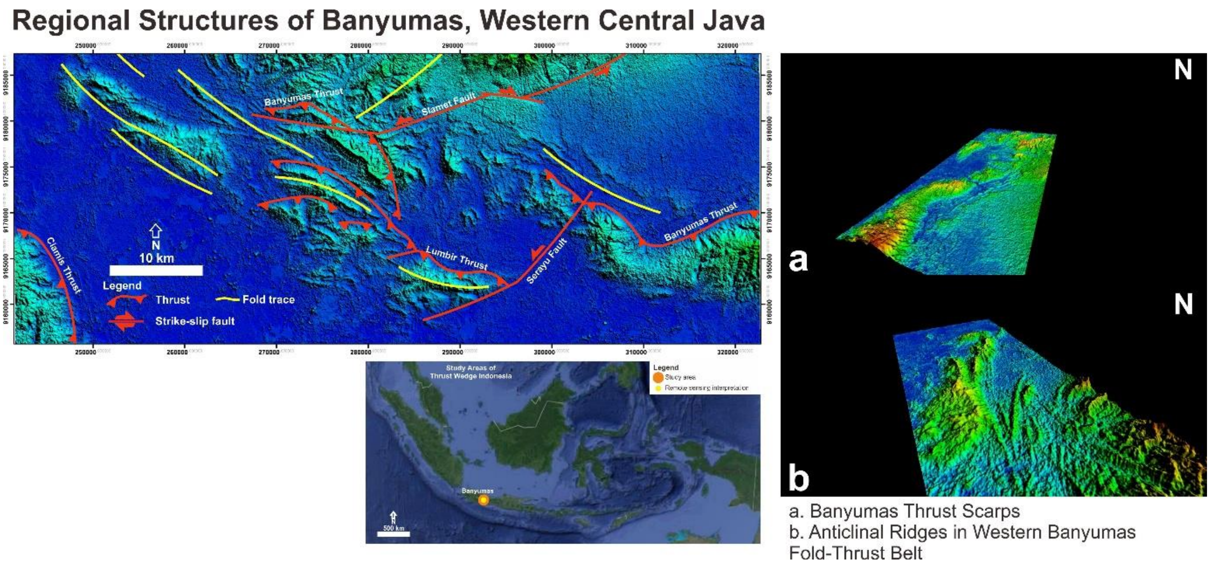



**Figure 8.** Regional Structures of Banyumas, Western Central Java: (a) Banyumas Thrusts Scarps; (b) Anticlinal Ridges in Western Banyumas Fold-Thrust Belt

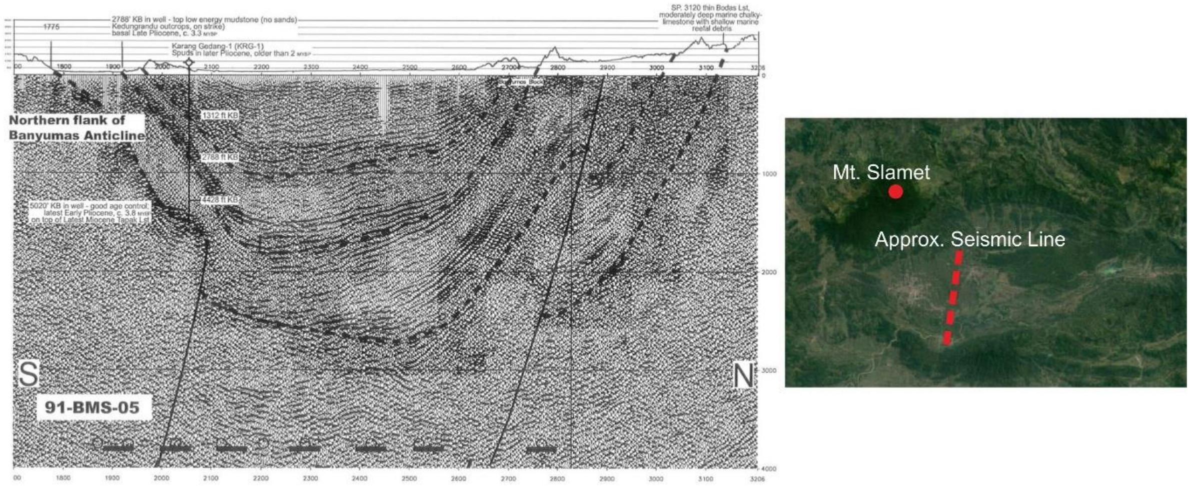



**Figure 9.** Subsurface Image in the North of Banyumas Fold-Thrust Belt (modified after Lunt et al., 2008)

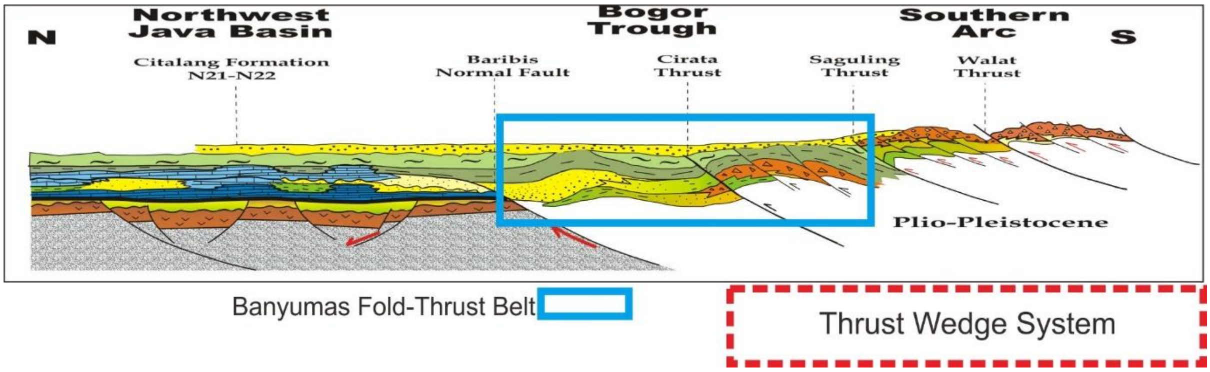



**Figure 10.** Regional Schematic Cross-section from West Java Southern Mountains through Northwest Java Basin (modified after Raharjo et al., 2002)

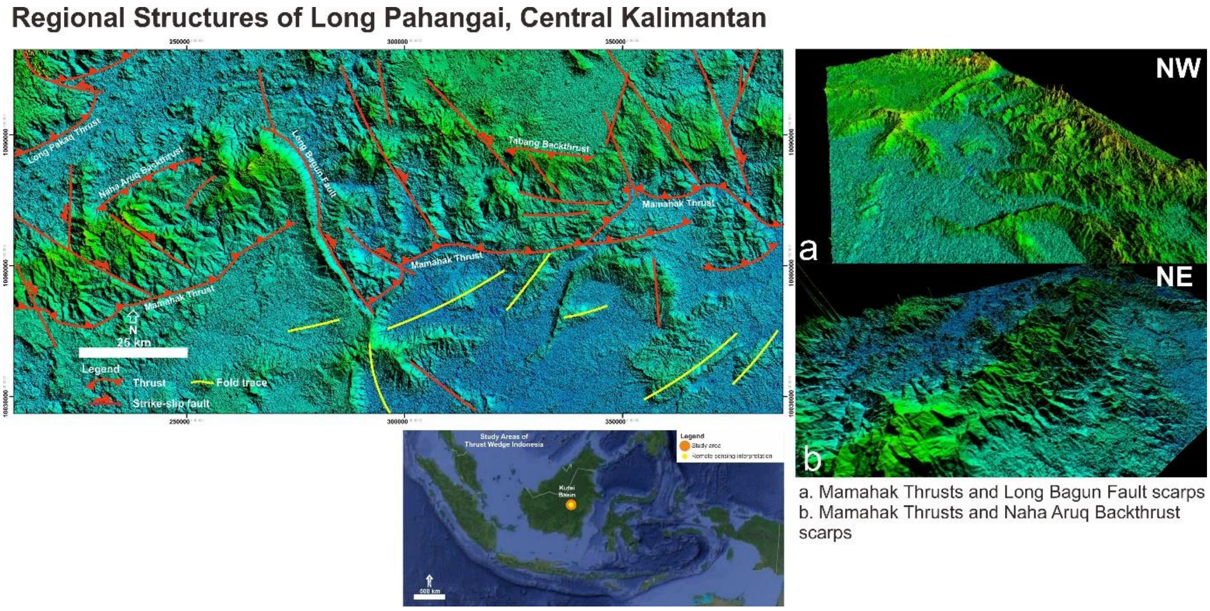



**Figure 11.** Regional Structures of Long Pahangai, Central Kalimantan: (a) Mamahak Thrusts and Long Bagun Fault scarps; (b) Mamahak Thrusts and Naha Aruq Backthrust scarps

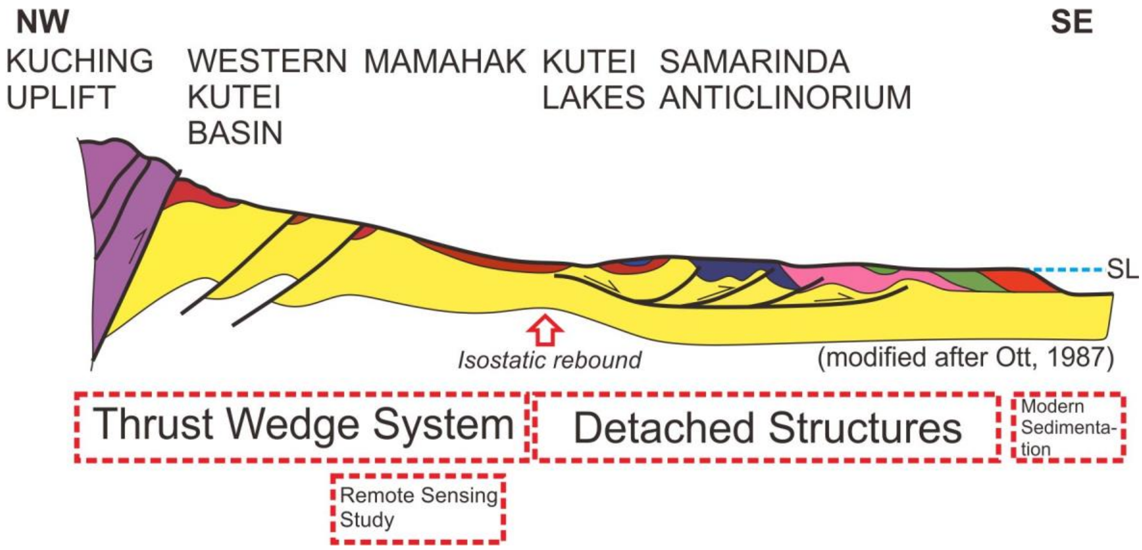



**Figure 12.** Regional Cross-section from Kuching High to Coastline, East Kalimantan (modified after Ott, 1987)

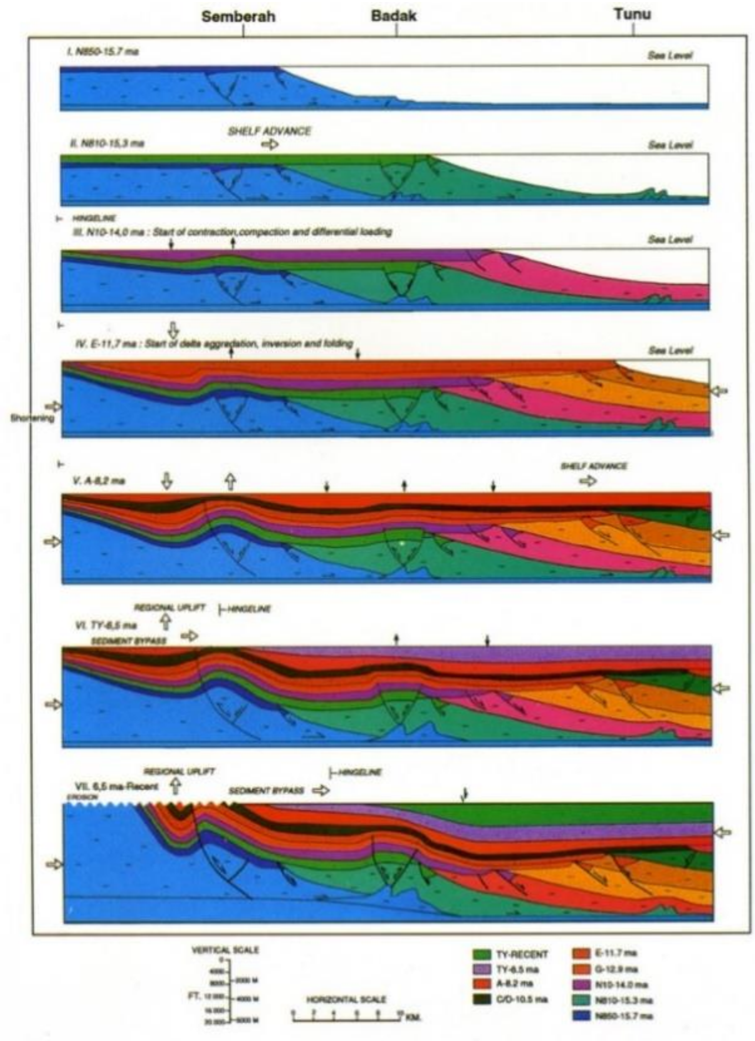


**Figure 13.** Structural Evolution of Inverted Delta Growth Fault Model (Ferguson and McClay, 1997)

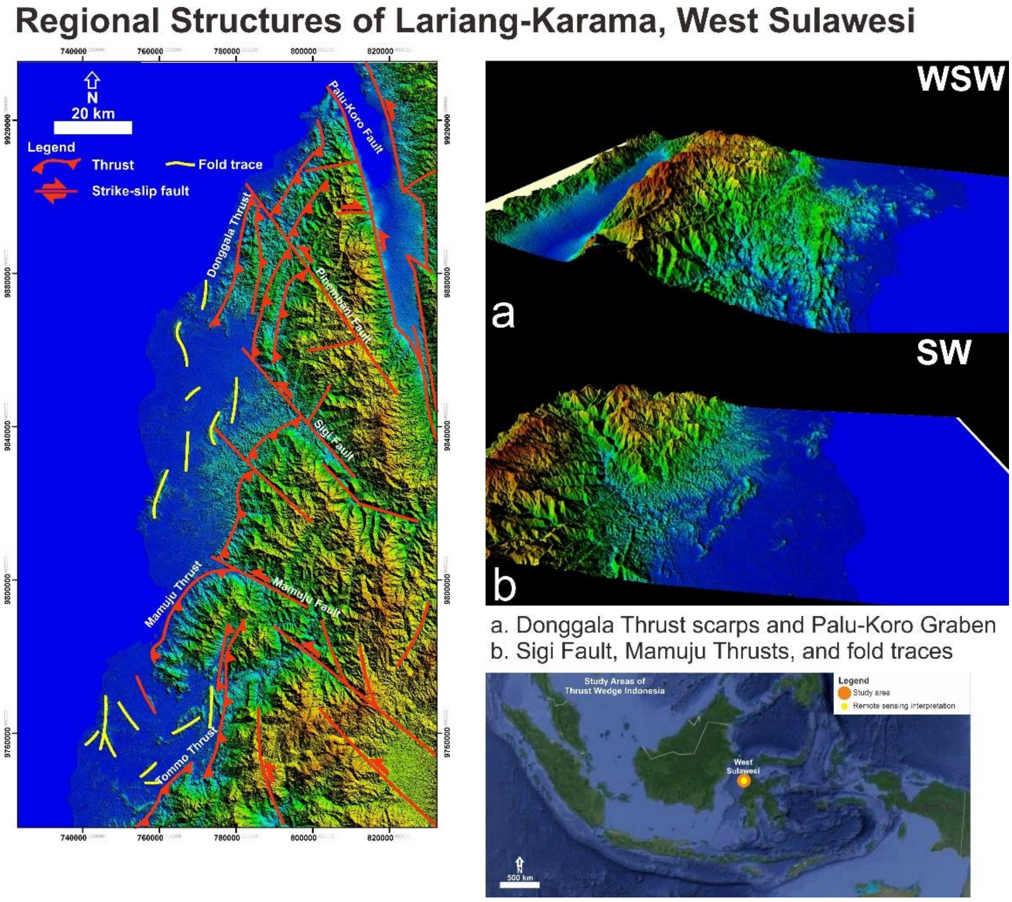



**Figure 14.** Regional Structures of Lariang-Karama, West Sulawesi: (a) Palu-Koro Graben and Donggala Thrusts scarps; (b) Sigi Fault, Mamuju Thrusts scarps, and fold traces

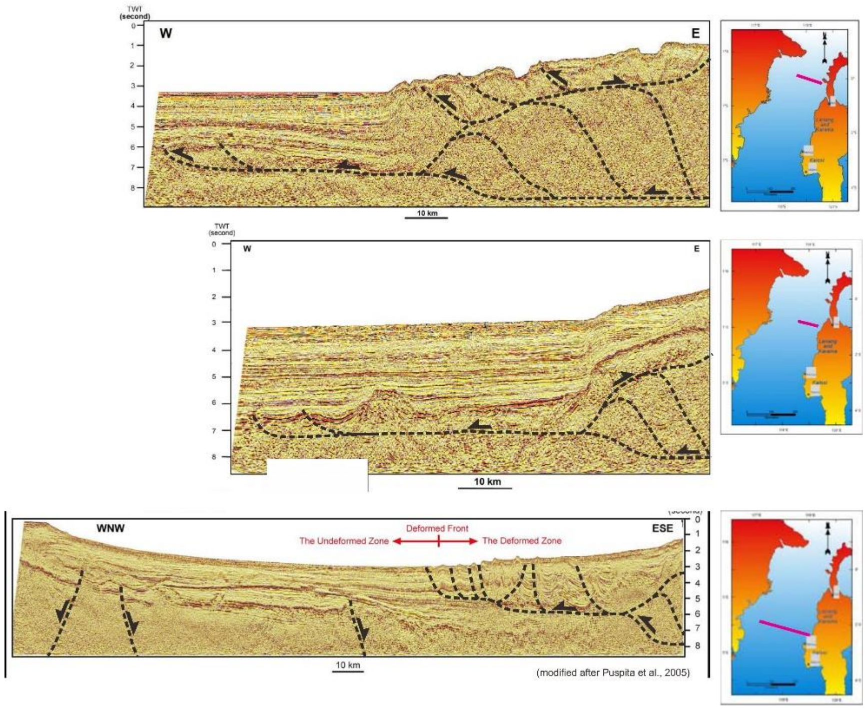



**Figure 15.** Re-interpretation on Subsurface Offshore West Sulawesi and Deformation Front depicted from Bathymetry and Shuttle Radar Topographic Mission (SRTM) (modified after Puspita et al., 2005)

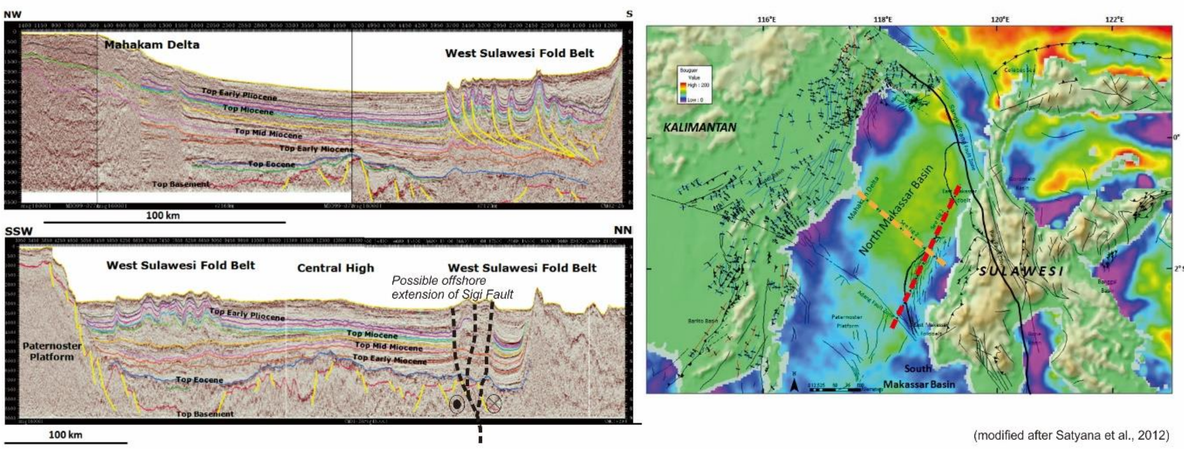



**Figure 16.** Subsurface Offshore West Sulawesi: Detachment Folds and Possible Offshore Extension of Sigi Fault (Orange dashed line refers to NW-SE section, Red dashed line to SSW-NNE section, modified after Satyana et al., 2012)

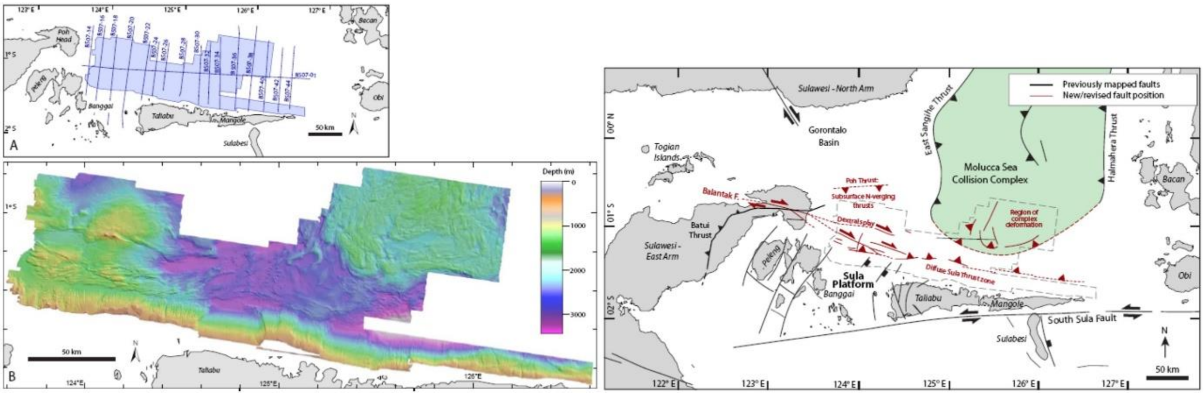



**Figure 17.** Multibeam Data and Structural Map of Offshore Northern Banggai-Sula (Ferdian et al., 2010)

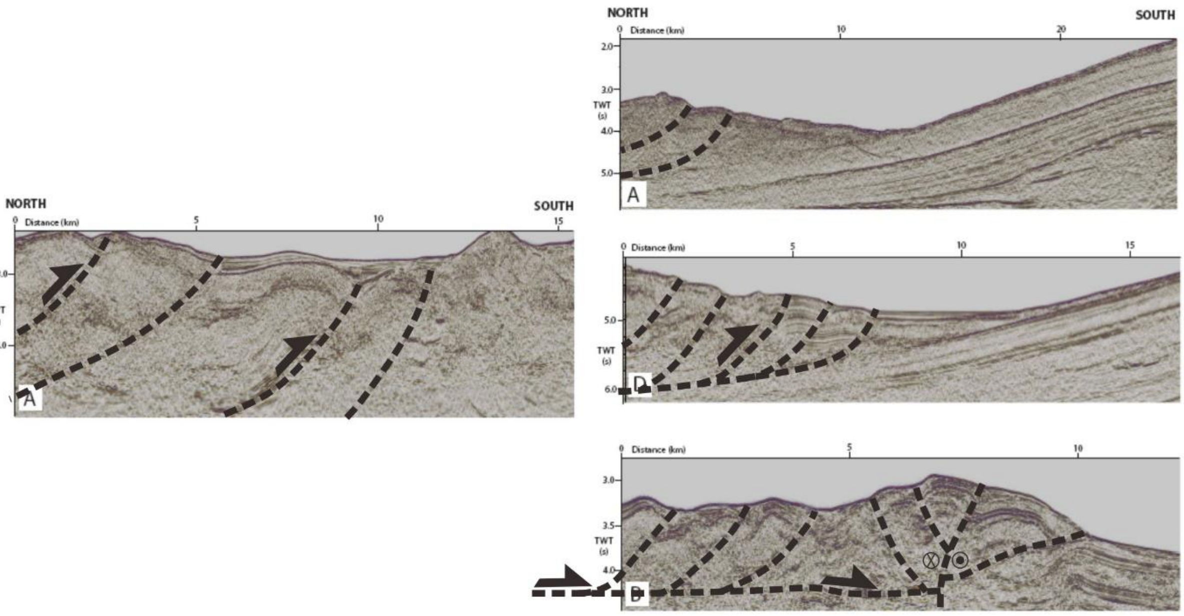



**Figure 18.** Subsurface Offshore Northern Banggai-Sula: Progressive Deformation towards West and Positive Flower Structure as Offshore Extension of Balantak Fault (modified after Ferdian et al., 2010)

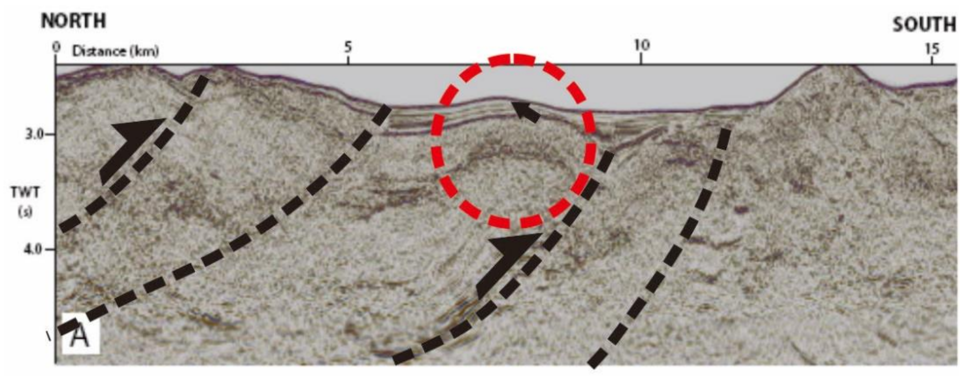



**Figure 19.** Seabed Deformation and Migrating Fold Hinge as a Sign to Recent Tectonics (modified after Ferdian et al., 2010)

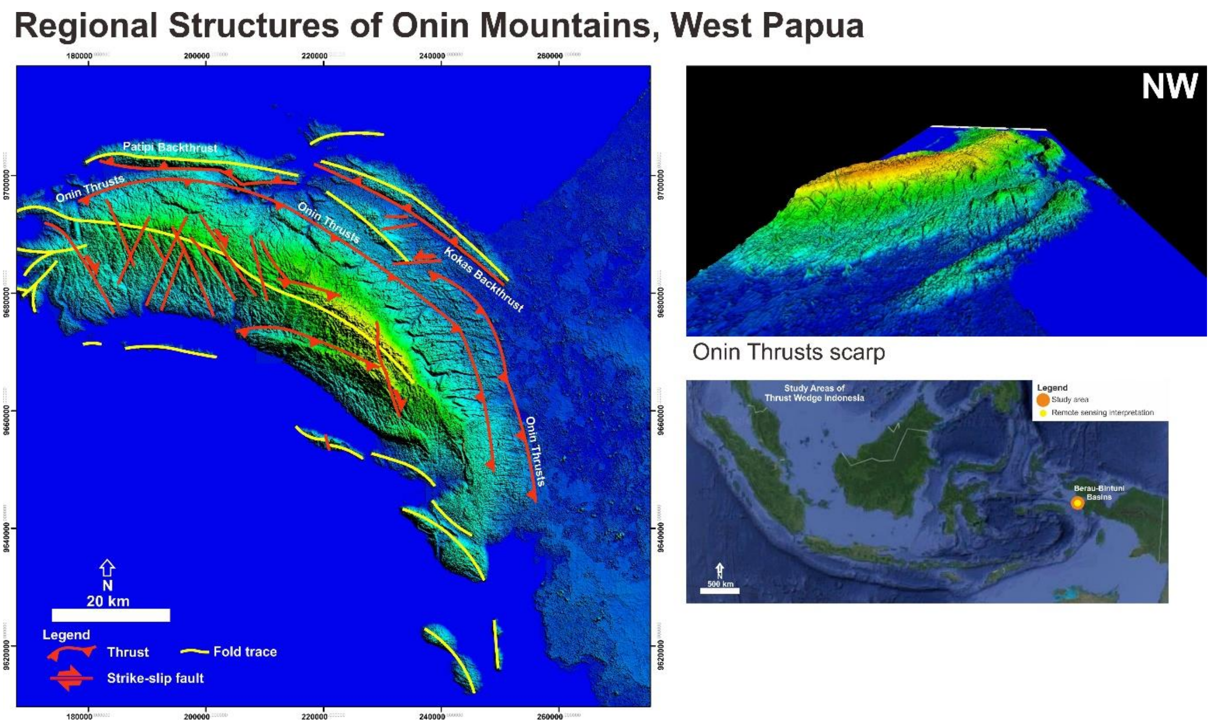



**Figure 20.** Regional Structres of Onin Ridge, West Papua: Onin Thrusts scarps and Fold Traces

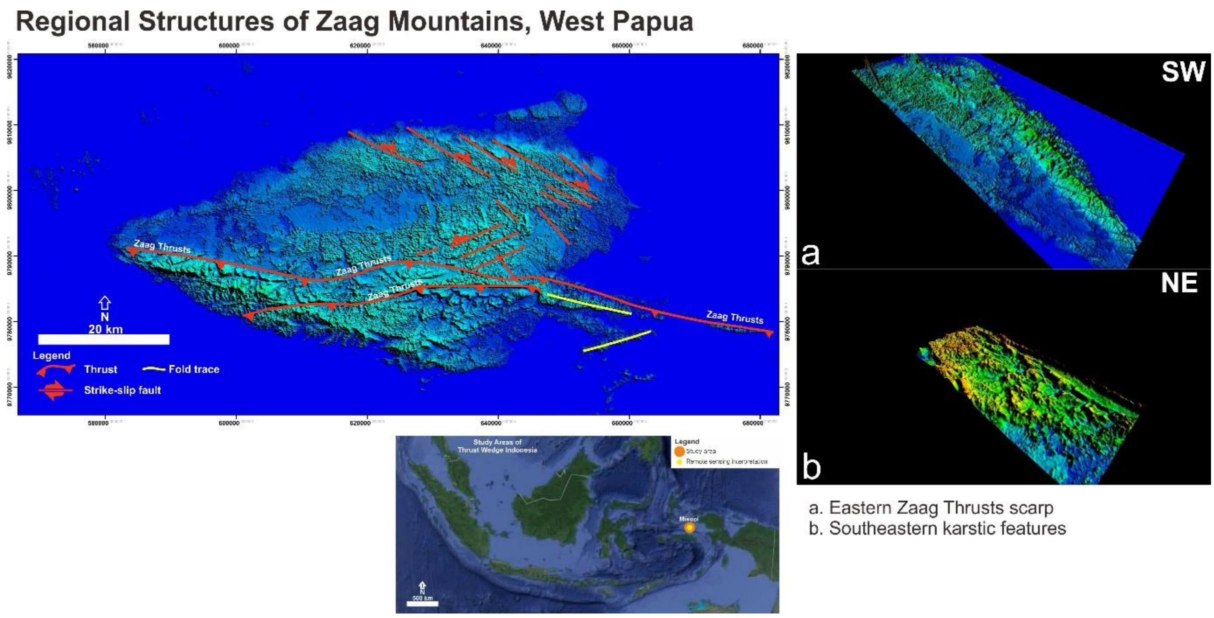



**Figure 21.** Regional Structures of Zaag Mountains, West Papua: (a) Eastern Zaag Thrusts Scarp; (b) Southeastern Karstic Features of Triassic Bogal Limestones

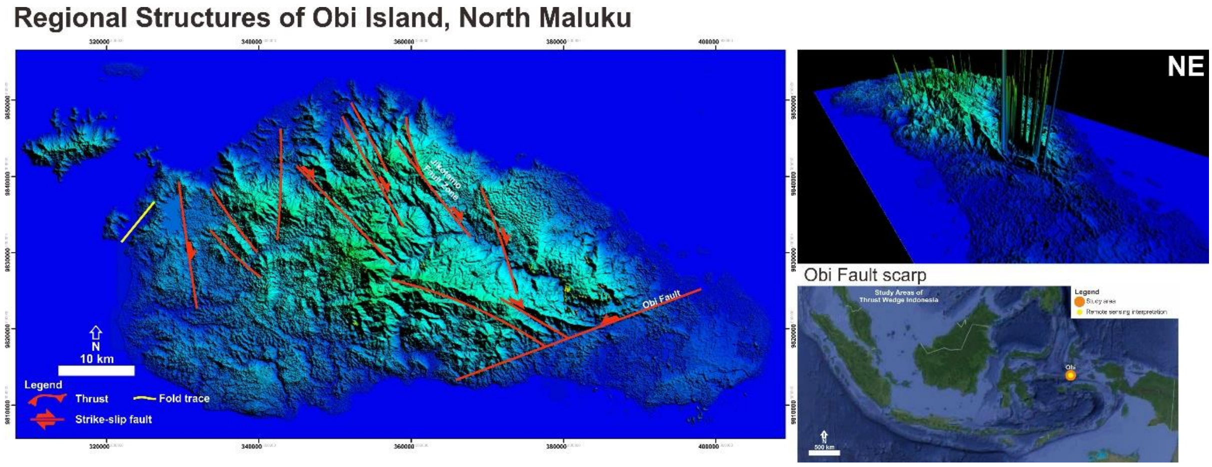
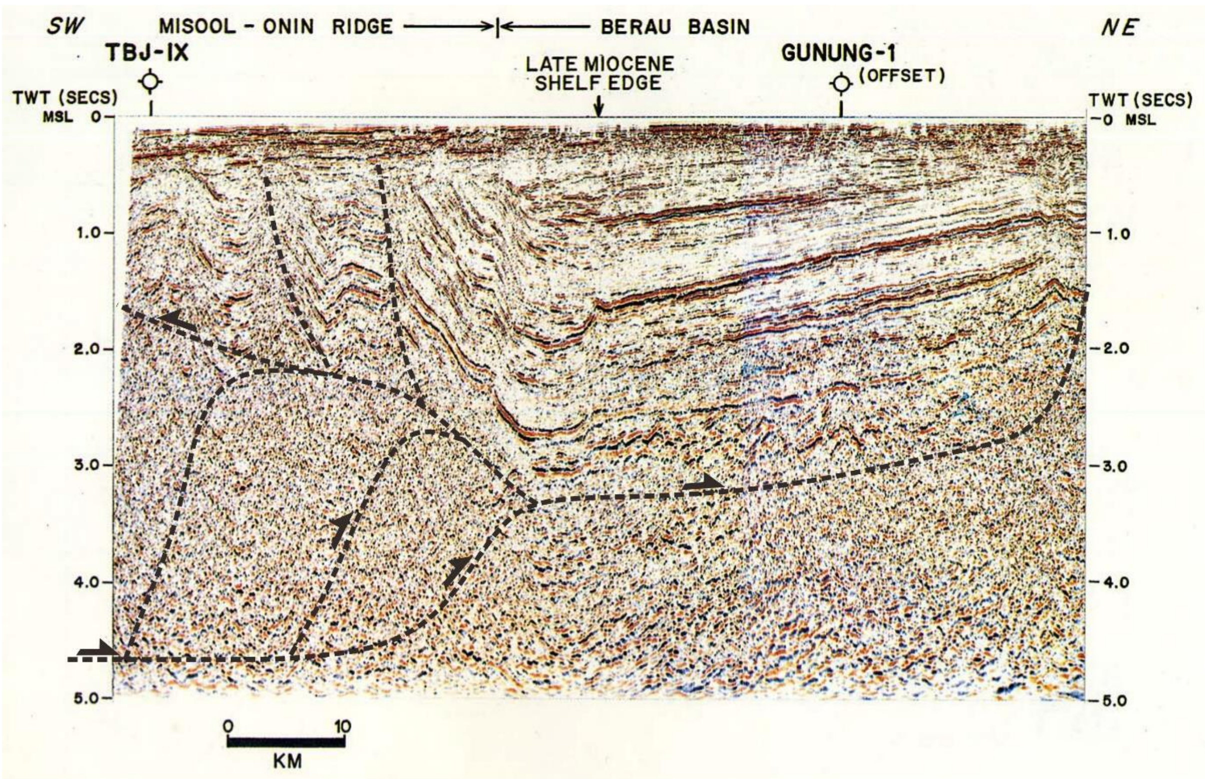



**Figure 22.** Regional Structures of Obi Island, North Maluku




(modified after Livsey and Perkins, 1993)

**Figure 23.** Subsurface Offshore Berau Basin: E-W trending Thrust Wedge System (modified after Livsey and Perkins, 1993)

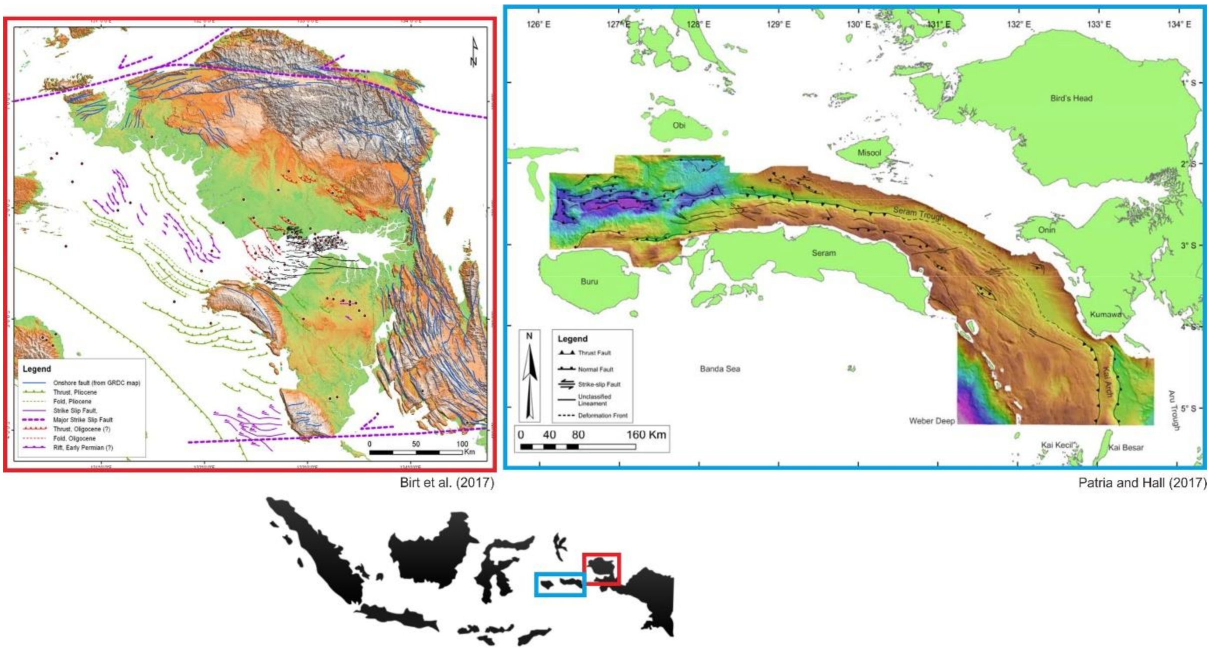



**Figure 24.** Comparison on West Papua and Seram Trough Regional Structures: Progressive Compressive Regime from South to North (modified after Birt et al., (2017) and Patria and Hall (2017))