Morpho-bathymetric features of the Southwest Celebes Sea

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ABSTRACT

The Southwest Celebes Sea lies within the region of Celebes Sea (also known locally as Sulawesi Sea)-Makassar Strait gateway which is controlled by active tectonic of North Sulawesi Trench and Palu-Koro Fault zone. In addition, this region is the major inter-ocean route of Indonesian Throughflow (ITF). Using the high-resolution multibeam bathymetry data supplemented with 2D seismic profiles, this study describes major morpho-bathymetric features that can be observed within the Southwest Celebes Sea. There are 4 types of morpho-bathymetric features: structural features, erosional features, gravitational features, and depositional features. The dominant structural related tectonic features and gravitational features mainly occur in the North Sulawesi Fold-Thrust Belt associated with the formation of the North Sulawesi Trench and Palu-Koro Fault zone. Whereas, to the northern part, the deeper area of the Celebes Sea and the region on the west are mainly controlled by erosional and depositional features. The identification of morpho-bathymetric features provides useful information for basin analysis study and present-day or future offshore activities such as infrastructure engineering related to geohazard potential caused.

Keywords: morpho-bathymetric; seabed morphology; multibeam bathymetry; Celebes Sea; Makassar Strait; Sulawesi

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INTRODUCTION

In 2017, the high-resolution multi beam bathymetry was made available by GeoData Ventures (GDV) covering an area of approximately 65,000 km^2 of the Celebes Sea-Makassar Strait gateway (note: the Celebes Sea is known locally as the Sulawesi Sea). The main purpose is to depict the basin architecture in the unexplored offshore area particularly the Southwest Celebes Sea and adjacent area. The Southwest Celebes Sea (Figure 1) is divided into 3 subareas. The North Sulawesi Fold-Thrust Belt (NSFTB) is separated from the other 2 subareas in the west by the Palu-Koro Fault. The southern basin is named here as the Muara Basin whereas the shallower part to the west of Celebes Sea is named the Deepwater Tarakan Basin. These 2 sub-areas are separated by a prominent structural high called the Maratua Ridge.

Several 2D seismic acquisitions have been acquired from 2005 to 2009 by PGS which mainly covers the Muara Sub-Basin, Deepwater Tarakan Basin, and a small part of NSFTB. The newly acquired multibeam dataset would not only aid the seismic interpretation of the sub-surface but also provide information on the seabed morphology. This also provides valuable information and understanding for the assessment for many present-day offshore activities related to infrastructures engineering, regional basin architecture study, and geohazard potential.

This paper presents an interpretation of morpho-bathymetric features related to the various geological processes that occurred in the region. The description and examples of the specific features are subdivided according to the main geological processes responsible for their development. The high-resolution bathymetry in the Southwest Celebes Sea provides exceptional details of the morpho-bathymetric features related to the different geological processes.

REGIONAL GEOLOGY & OCEANOGRAPHIC SETTING

Situated in the boundary of the Sunda margin and Celebes Sea Plate, the Celebes Sea has a complex deformation history, especially during the Pliocene-present day (Figure 1). This event formed the North Sulawesi Trench as a result of the southward subduction of the Celebes Sea and the formation of the Palu-Koro Fault. Important changes that happened during the past 45 Ma, including spreading of the Celebes Sea, associated with separation of West Sulawesi from Borneo (Hall, 2002, 2012), subsidence throughout the Oligocene-Early Miocene (25-20 Ma), and counter-clockwise rotation of Borneo followed by inversion during 20-10 Ma (Hall, 2002, 2012). A Pliocene tectonic event is critical to the formation of the North Sulawesi Trench and Palu-Koro Fault (Hall, 2002, 2012).

Early Pliocene (5 Ma) to the present, Celebes Sea Slab rollback (Hall, 2012; Rudyawan, 2016) caused a change of trend of the North Sulawesi Trench from a relatively NE-SW trending thrust to an ENE-WSW trending thrust (Advokaat, 2015). The Palu-Koro Fault formed during the Pliocene (5 Ma) based on the non-coaxial strain in the Palu metamorphic rocks (Watkinson, 2011). Furthermore, the northward rollback of the south-dipping Celebes Sea slab may have been linked to the Palu-Koro strike-slip fault as a subduction-transform edge propagator (STEP) fault (Govers and Wortel, 2005). The region of Southwest Celebes Sea effectively resulted from several complex tectonic phases from the Middle Eocene until the present day.

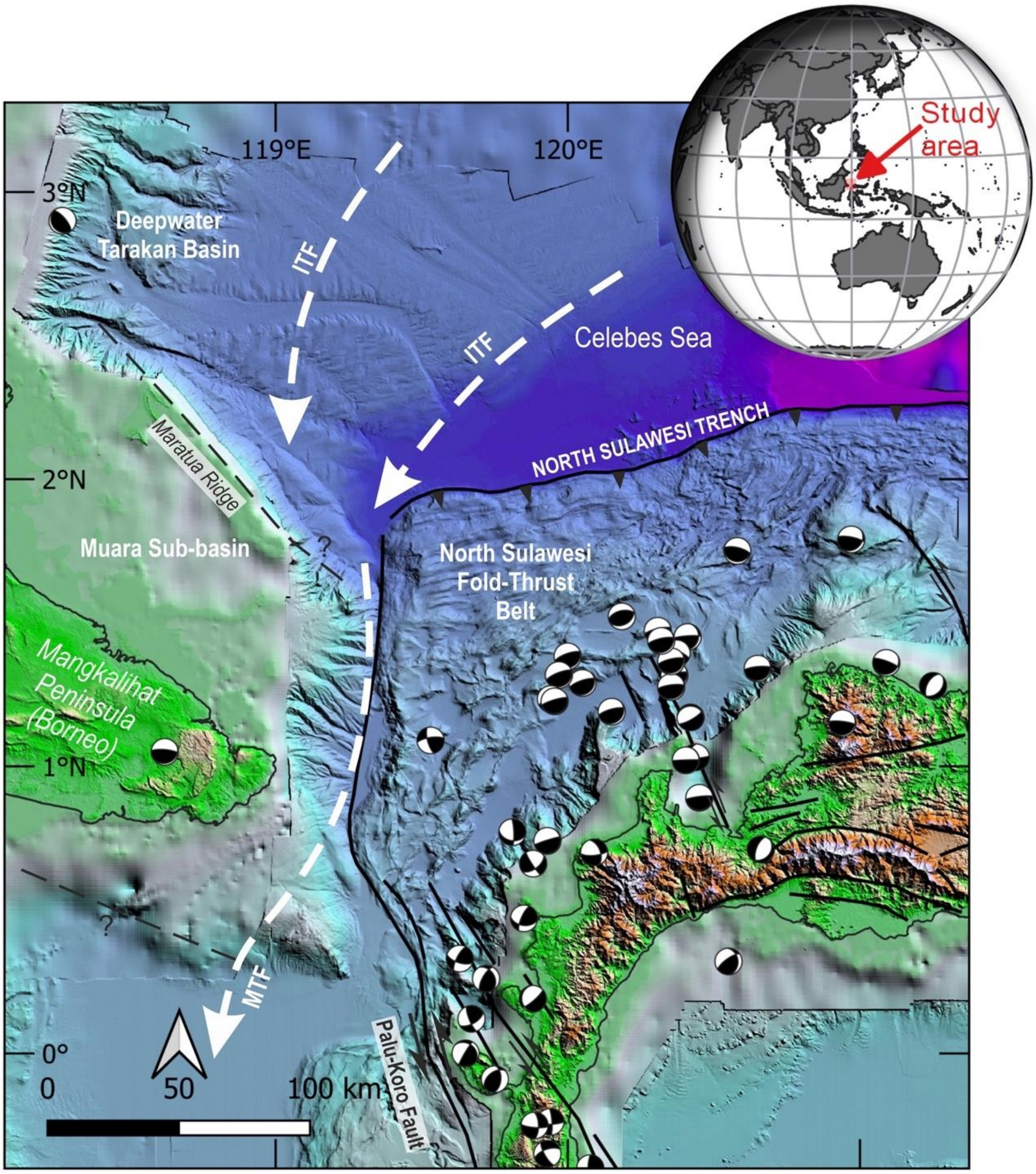

Figure 1. *ASTER DEM, bathymetry, and gravity image of study area showing topography, regions, basin or sub-basin, active seismicity, oceanography setting, and major tectonic provinces of the study area (Cloke et al., 1999; Camp et al., 2009; Advokaat, 2015; Hall, 2019; Tiranda and Hall, 2021, Preprint). Earthquake events are from 1976-to 2021 with focal depth <30 km from CMT focal mechanism based on Ekström et al. (2012). ITF and MTF's current orientation is from Gordon et al. (1999), Mayer and Damm (2012), Susanto et al. (2012), and Brackenridge et al. (2020).*

In terms of the oceanographic setting, the region of Southwest Celebes Sea has been identified as one of the major inter-ocean routes of Indonesian Through flow (ITF), with the Celebes Sea-Makassar Strait gateway is expected to transport high water mass (Wajsowicz, 1993, 1996; Gordon et al., 1999; Susanto et al., 2012) (Figure 1). The inter-ocean routes are part of the Pacific water inflow path, with the Makassar Strait as the primary inflow route known as the Makassar Strait Throughflow (MTF) (Mayer and Damm, 2012; Brackenridge et al., 2020). Based on the flow simulation conducted by Mayer and Damm (2012), the current enters the Makassar Strait from the north via the Celebes Sea as a surface current, deepens below the surface layer to become a strong and confined subsurface jet. The simulation results indicate high flow transport within the

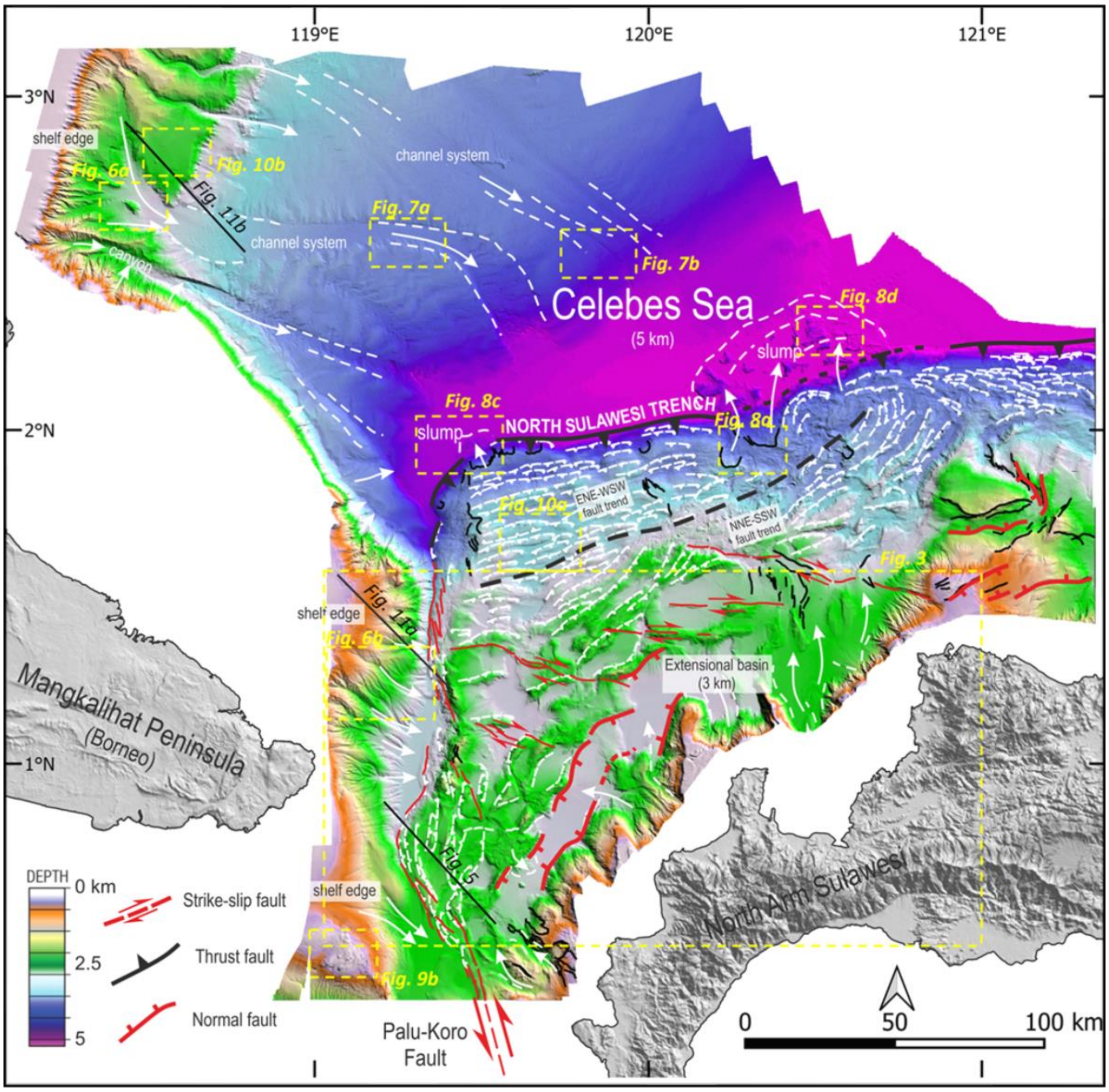

Figure 2. *Combined DEM from SRTM map with a shaded-relief map of multibeam bathymetry showing morpho-bathymetric interpretation with specific examples described in this paper. Illumination direction from NE.*

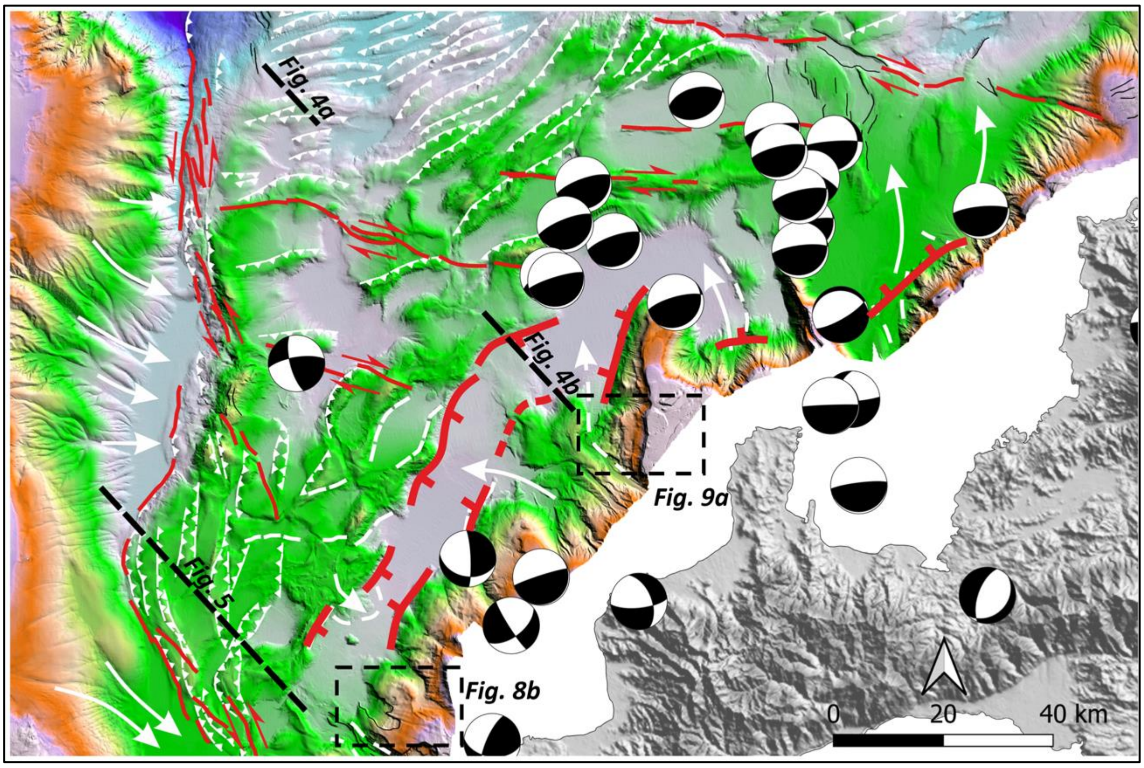

Figure 3. *Morpho-bathymetric interpretation of the NSFTB highlighting the complex structural features associated with the formation of NSFTB and the Palu-Koro Fault. Detailed structural features are shown in Figure 4, Figure 5, Figure 8, and Figure 9. Illumination direction from NE.*

range of about 50-300 m which contributes about 65-70% to the MTF and about 30% to the entire volume transport of the ITF (Mayer and Damm, 2012). This water mass flow in the region making it one of the most important factors of the oceanographic dynamics in the Indonesia region, especially in the Celebes Sea-Makassar Strait gateway.

DATASET AND METHODOLOGY

The dataset used in this study includes the high-resolution multibeam bathymetry (kindly provided by GeoData Ventures) covering an area of approximately 65,000 km², mainly within the Celebes Sea, and it was supplemented by 2D seismic reflection data from PGS. The multibeam bathymetry or Multibeam Echo-sounder Systems (MBES) has a resolution of 25-15 m and has been processed to a shaded-relief map by mimicking the effect generated by illumination at a low angle using Geographic Information System (GIS) software ArcMap 10.3.1 and ER Mapper. The morpho-bathymetric features then were analyzed and interpreted using QGIS 3.16.13 software.

Additional information was compiled from public data services (e.g. global CMT catalog) and from published literature where data coverage was unavailable. Historical earthquake data from 1976 to 2021, with focal depth < 30 km from CMT focal mechanism based on Ekström et al.

(2012), were used to delineate shallow structures that possibly have surface expression. Information of the ITF (Indonesia Throughflow) and MTF (Makassar Strait Throughflow) current flow were gathered from Gordon et al. (1999); Mayer and Damm (2012); Susanto et al. (2012).

RESULTS AND DISCUSSION

Regional bathymetry

The seabed morphology within the study area has been controlled and shaped by tectonic and marine sedimentary features (Figure 2). This part presents the results of the description and interpretation of multibeam bathymetry data, including the structural interpretation and sedimentary features interpretation, followed by a description of the main features and exceptional examples of minor features that can be observed within the study area. The examples presented are sub-divided according to different geological features responsible for their development. Locations of the detailed figures in this paper (Figure 3 to Figure 11) are shown in Figure 2.

The water depth of the study area ranges from 0.5-5 km (Figure 2). Shallower areas are mainly close to the coastline of Borneo and the North Arm of Sulawesi. The study area is divided into two regions based on the multibeam bathymetry area coverage which are the Celebes Sea and the NSFTB (Figure 1). They are fault-bounded and separated by the Palu-Koro Fault and North Sulawesi Trench.

The Celebes Sea region includes the area of the Deepwater Tarakan Basin or Tarakan Deep Basin (Tiranda and Hall, 2021, Preprint) with a small portion of the Muara Basin. In the Celebes Sea region (Figure 2), shallower water is mainly located on

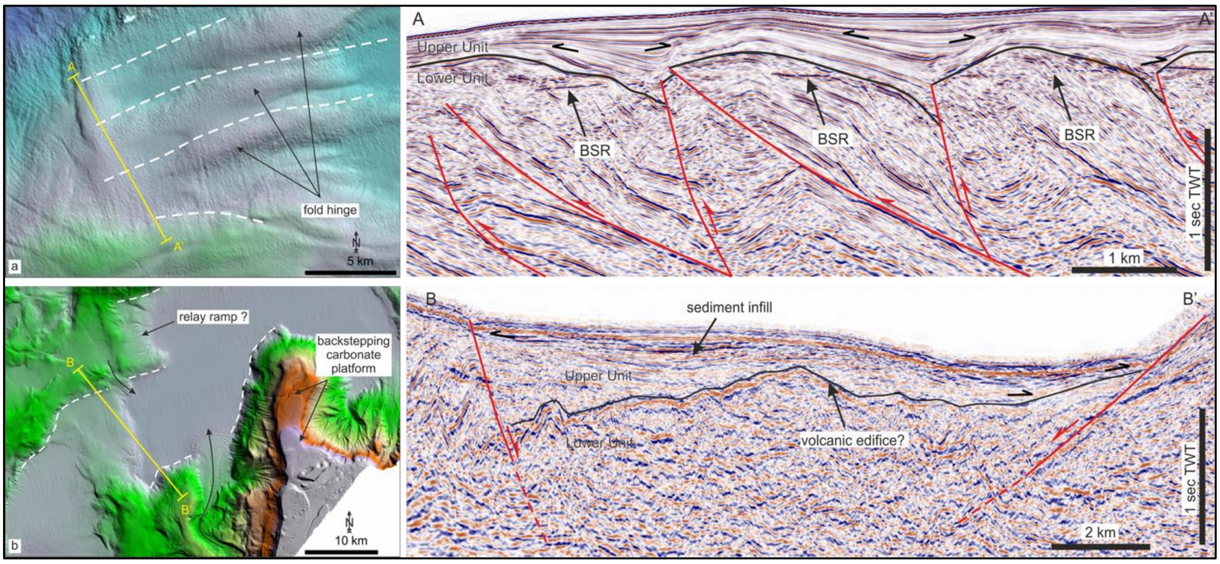

Figure 4. *Example of structural features as observed in the study area particularly the NSFTB. Illumination direction from NE. (a) Seabed morphology of the fold-thrust belt. (b) Extensional basin in the southern-most part of the NSFTB. The location is shown in Figure 2 and Figure 3.*

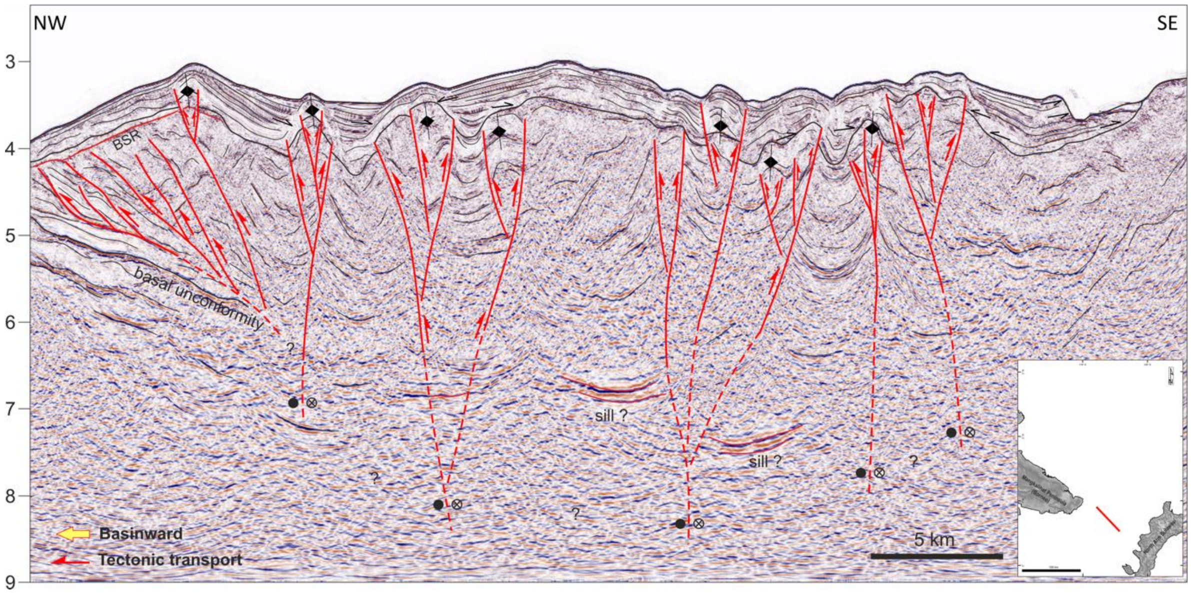

Figure 5. *The interpreted seismic section in the Celebes Sea-Makassar Strait gateway exhibits restraining stepover structure related to the Palu-Koro Fault system. The surface expression from bathymetry data shows typical rhomboidal shape geometry (Figure 3).*

the shelf margin of Borneo, where the average water depth is about 1000 m and the shallowest depths are about 500-600 m. The deeper waters are found in the eastern part of the Celebes Sea region which the main depocenter is approximately 5 km deep. A transition from shelf margin to the deeper part of the area in the east is marked by a submarine slope from the present-day shelf edge along the Borneo margin.

Within the NSFTB (Figure 2), the average water depth is approximately 2-3 km. This area is characterized by ENE-WSW and NE-SW lineaments in the northern part. NE-SW lineaments also dominate the southern part of this area with minor WNW-ESE lineaments. The westernmost part of this area was controlled by broadly N-S and NNW-SSE lineaments which might be strands of the Palu-Koro Fault. Several isolated mini-basins were developed within this area particularly in the south, associated with NE-SW trending lineaments.

Structural features

Various structural styles are observed within the study area, particularly in the NSFTB (Figure 3). For example, in the northern part of it adjacent to the North Sulawesi Trench, the fold-thrust belts are observed in seismic profiles (Figure 4). Unfortunately, the earthquake focal mechanism does not represent surface features as can be observed from bathymetry and seismic profile. The seismicity events are mainly associated with the subduction of the Celebes Sea Slab (Hall, 2019). Surface expressions mainly have shallow-rooted structures whilst the seismicity is much deeper around 25-30 km. Although at some parts, the faults are inherent to the seismicity zone below the subsurface (0-12 km depth), especially near the coastline of the North Arm of Sulawesi.

Several extensional faults seen on seismic lines are also observed in the southern-most part of the NSFTB (Figure 3 and Figure 4b). N-S trending thrust faults are observed along with the Palu-Koro Fault system which may extend and join at the edge of the North Sulawesi Trench (Figure 2). The N-S trend thrust fault observed along the northern offshore segment of the Palu-Koro Fault, is an east-dipping fault with a minor west-dipping back thrust system. In addition, from the multibeam bathymetry image, a rhomboidal-shaped structure is observed in this segment (Figure 3) and interpreted to have been formed by the left-lateral strike-slip fault forming restraining stepover structure (Figure 5).

Despite the complexity, there are a few features at the seabed that reveal the subsurface structural geology. For example, the fold-thrust belt structure in the NSFTB (Figure 4a). This fold-thrust belt is divided into two structural provinces based on the lineament trend which are the ENE-WSW trend and NNE-SSW trend (Figure 2). Moreover, the evolution of structural trends in the fold-thrust belt region may correspond to the development of extensional basins in this area associated with the subduction roll-back during Pliocene as proposed by Tiranda and Hall (2021, Preprint). There are few extensional faults developed onshore as reported by Advokaat (2015) and also supported by the seismic event onshore which is possibly associated with the development of the extensional basin offshore.

Erosional features

The region of the Celebes Sea includes well-developed canyons trending NW-

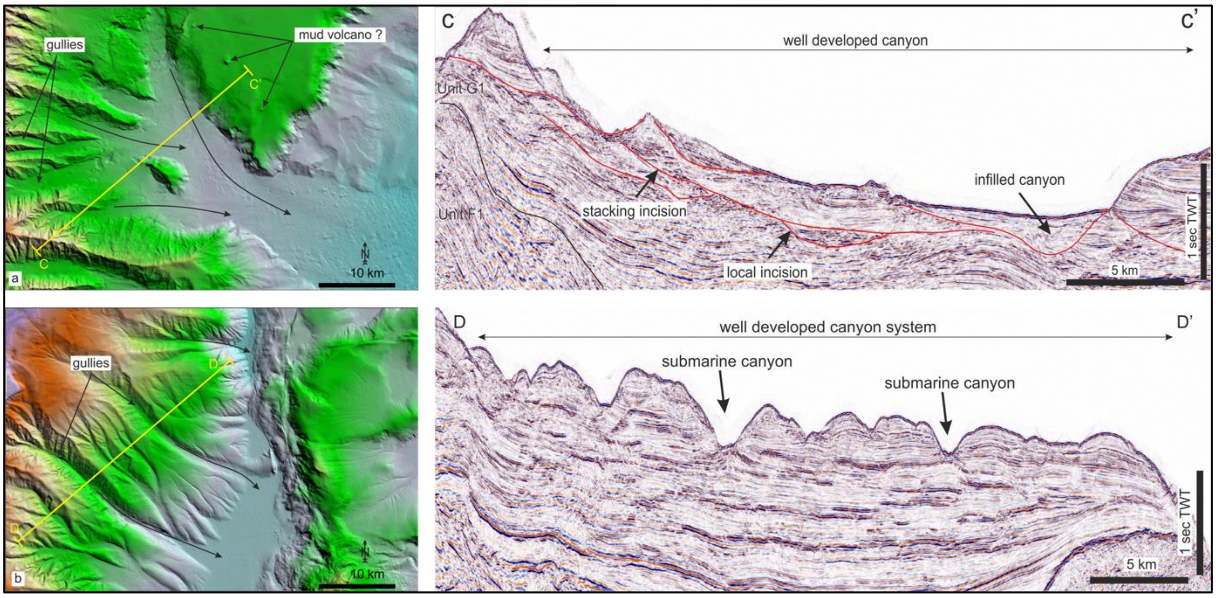

Figure 6. *Example of the erosional features showing canyon system/gullies based on multibeam bathymetry and seismic profiles. Illumination direction from NE. (a) Gullies in the Deepwater Tarakan Basin. (b) Gullies in the eastern edge of the Muara Sub-basin. The location is shown in Figure 3.*

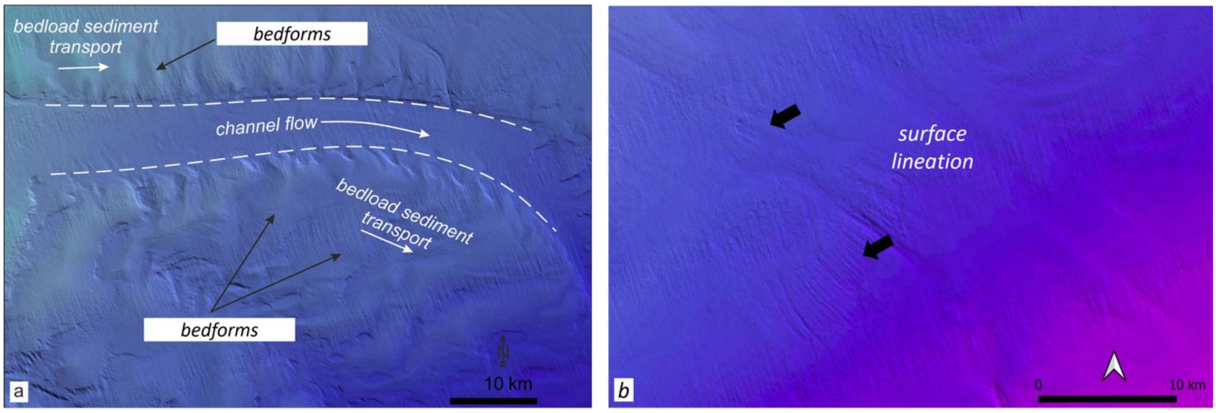

Figure 7. *Erosional features on the Celebes Sea seabed surface. Illumination direction from NE. (a) Bedforms with NE-SW trend of the crest. (b) Surface lineation indicates SE flow direction.*

SE with minor E-W and NE-SW trends (Figure 2). Present-day sedimentary deposits were transported through this canyon to the basin in the Celebes Sea and small basins close to the Palu-Koro Fault on the eastern edge of Borneo (Figure 6b). Several seismic lines also indicate vertical stacking channel systems that developed through time and were cut off by present-day submarine channel systems (Figure 6a). These features recorded in the subsurface might relate to the paleochannel system flowing broadly from west to east from the eastern part of Borneo.

Strong currents are indicated in the Celebes Sea canyon system that transported sediment to the depocenter. There are several types of erosional features produced by the bottom current observed in the Celebes Sea which is subdivided based on Stow et al. (2009) classification. Bottom currents produced bedform features characterized by asymmetrical (with an approximate size between 60 and 200 m high), bifurcating, and sinuous shapes which tend to be clustered in small areas with a coherent NE-SW trend of wave crests (Figure 7a). The asymmetrical wave shapes appear to indicate bottom traction towards the SE to the Celebes Sea. The surface lineations also indicate bottom current with SE direction formed in the much lower velocity with dominant fine-grained sediments (Figure 7b).

Gravitational features

In contrast, submarine canyons system in the NSFTB are less-developed compared to the Celebes Sea. The main sedimentary features in this area are dominated by subaqueous mass-flow features such as landslides and their secondary products like slump deposits (Figure 8). These features indicate an unstable slope which might be triggered by active tectonic activity within the area. For example, several landslides were observed along the North Sulawesi Trench, and some were associated with the subsidence in the extensional basin to the south of the NSFTB.

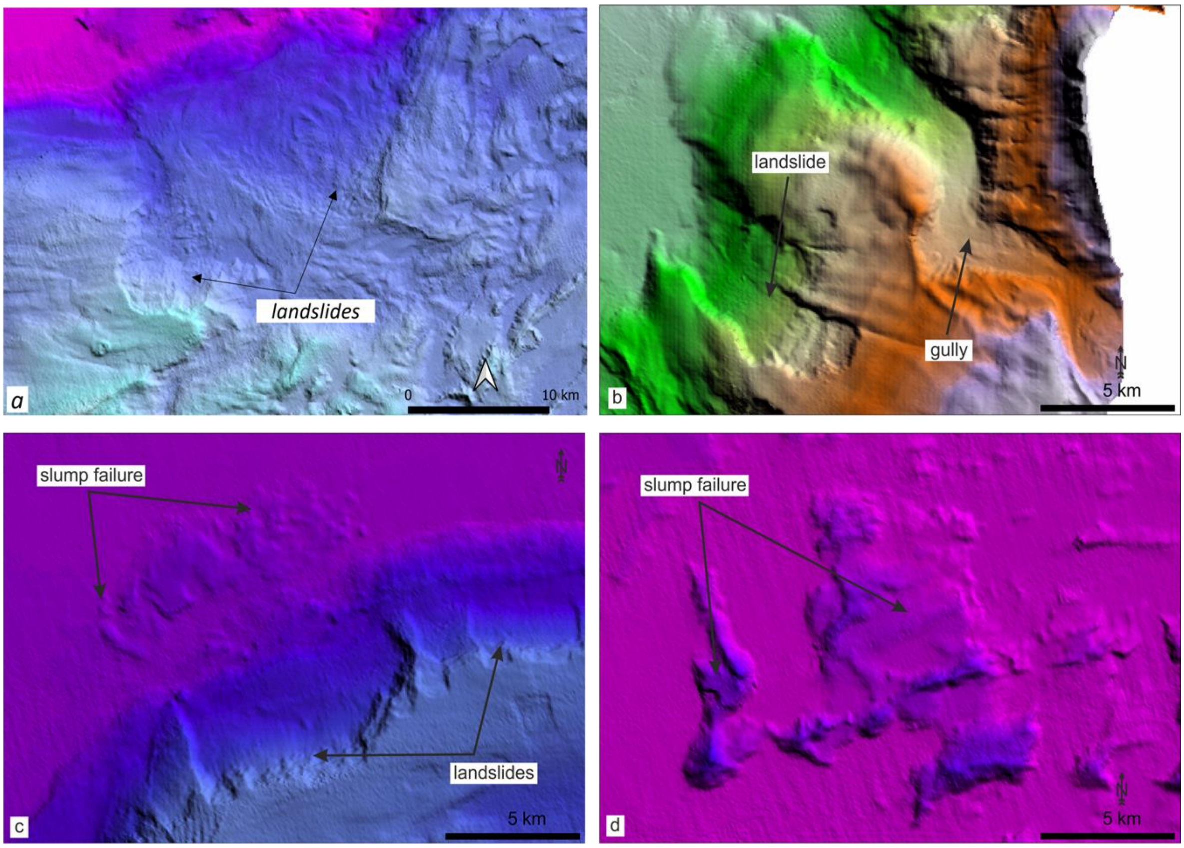

Figure 8. *Gravitational features were observed within the study area. Illumination direction from NE. (a) Sediment wave features in the Celebes Sea. (b), (c), and (d) Slope failures are characterized by landslides and slump failures. The location is shown in Figure 2 and Figure 3.*

Depositional features

Carbonate features are among the most obvious features that can be seen in this area. Relatively shallow water conditions close to the coastline along Borneo or the North Arm of Sulawesi with average water depths less than 100 m are ideal for carbonates to develop. Several stair-stepped marine terraces which are interpreted to be associated with submerged carbonate platform are observed in the southern-most of the NSFTB (Figure 9a). Their presence at depths that are now greater than 500 m indicates significant recent subsidence.

This possible carbonate platform mostly shows a typical backstepping character. Relative sea-level rise allows the carbonate to grow landward to create the morphology of backstepping carbonate. This could be due to either the sea level rise or tectonic subsidence; the latter is much more likely since recent eustatic sea-level changes of several hundred meters are impossible. Interestingly, the backstepping carbonates in this area are very close to the extensional fault system. The subsidence caused by extensional fault might be contributing to the development of this backstepping carbonate.

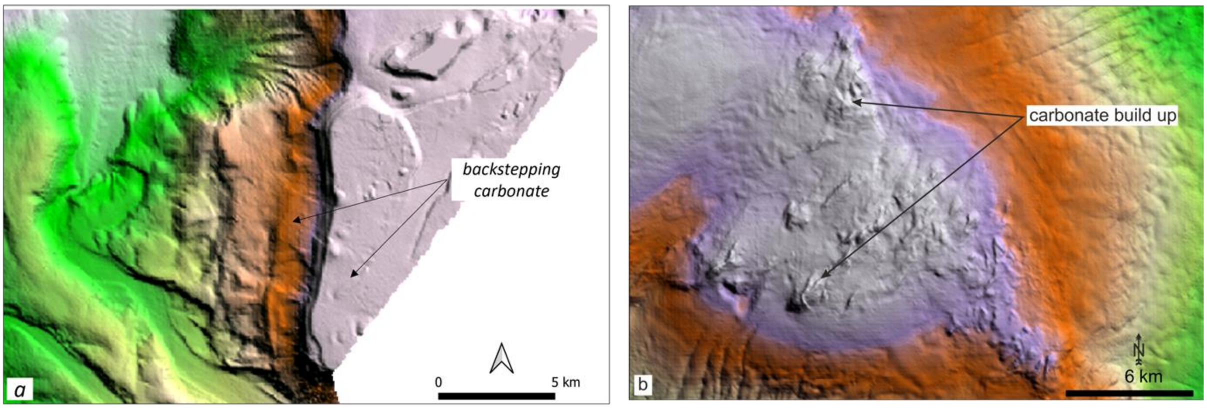

Figure 9. *Stair-stepped marine terraces which are interpreted as backstepping carbonate (a) and carbonate build up (b). Illumination direction from NE. The location is shown in Figure 2.*

Carbonate features are also observed in the eastern edge of the Mangkalihat Peninsula as a carbonate build-up (Figure 9b). The build-up morphology in this area mostly has a cone-shaped morphology and occurs in shallower water at approximately 600 m below sea level, again implying young tectonic subsidence.

Another feature observed is mud volcanoes. Several mud volcanoes lie on top of the anticline structures in the NSFTB (Figure 10a). However, there is little evidence of active mud diapirism in the seismic profiles. No seismic line crossing this feature makes it difficult to judge whether these features are mud-volcanoes-related features or not. The only evidence of active gas flow in the subsurface is the appearance of Bottom Simulating Reflector (BSR) as gas hydrates or biogenic gas-related features seen on several seismic lines as reported by Tiranda and Hall (2021, Preprint).

Similar features are observed in the Deepwater Tarakan Basin (Figure 10b). Their positions are almost in line with the fold crest of toe-thrust faults deep below the seabed observed from the seismic profile. This feature might appear as the manifestation of gas

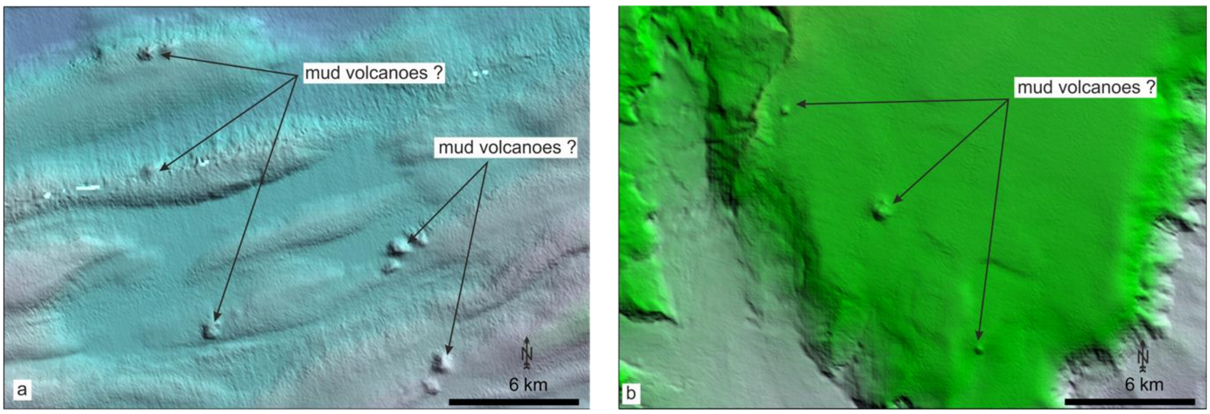

Figure 10. *Mud volcanoes-related features as observed in the study area. However, clear evidence of mud volcanoes in this area is very limited. Illumination direction from NE. The location is shown in Figure 2.*

leakage from the subsurface. Moreover, further observation of Direct Hydrocarbon Indicators (DHI) from the seismic profile indicates gas accumulation in the anticline structure from the specific interval of seismic reflection (Tiranda and Hall, 2021, Preprint).

Another obvious feature observed on the lower slope of the eastern most Muara Sub-basin and the Deepwater Tarakan Basin is the contourite feature. Their appearance shows possible contourite drift as observed from the seismic reflection. Based on Rebesco et al. (2014), the sediment drift types indicate possible mounded drift (with mounded elongate drift occurring occasionally) and plastered drift (Figure 11). Similar features have been reportedly found in the Makassar Strait, especially on the upper slope-middle slope on the western side close to the present-day Mahakam Delta shelf edge (Brackenridge et al., 2020) resulting from the bottom current of ITF (Gordon et al., 1999). According to Mayer and Damm (2012), on the ocean simulation flow of the ITF (Gordon et al., 1999; Susanto et al., 2012) or the MTF (Brackenridge et al., 2020), the strong current and volume transport within the upper 420 m has a high flow rate. This condition is sufficient for sediment to be redeposited along the slope environment in the deep-water.

CONCLUSIONS

This study describes morpho-bathymetric features of the Southwest Celebes Sea resulting from the interplay of tectonics, sedimentary, oceanography, and sea-level eustacy.

Types of morpho-bathymetric features of the Southwest Celebes Sea are structural-related tectonic features, erosional features, gravitational features, and depositional features.

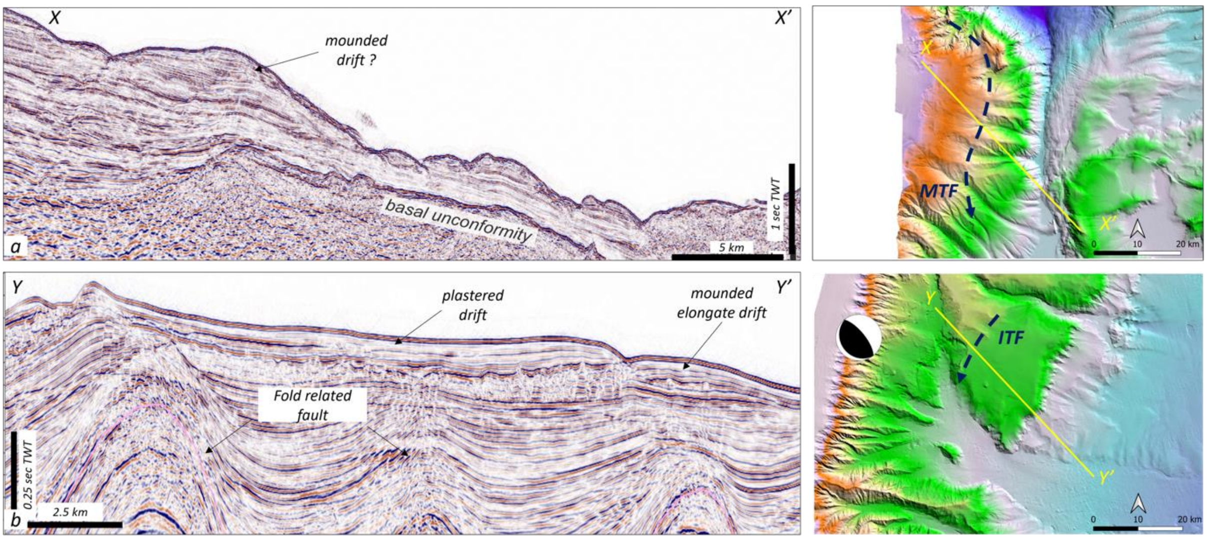

Figure 11. *Example of the contourite drift showing mounded drift and plastered drift observed from seismic reflection profiles. Multibeam bathymetry illumination direction from NE. (a) Possible mounded drift on the eastern edge of Muara Sub-basin. (b) Overlying plastered and mounded drift on top of buried fold related fault structures in the Deepwater Tarakan Basin. The location is shown in Figure 3.*

The NSFTB exhibits dominant structural related tectonic features associated with the deformation of NSFTB and Palu-Koro Fault zone with active seismicity.

In the region outside of the NSFTB (i.e., Deepwater Tarakan Basin, Muara Sub-basin), erosional and depositional features mainly occur along the slope and within the deep-marine environment.

The finding presented here carry implications for the geohazard potential and regional basin analysis.

ACKNOWLEDGEMENTS

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Kinematic analysis of Balantak Fault using fault-slip data in the Balantak area, Banggai Regency, Central Sulawesi

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ABSTRACT

Balantak is one of the sub-districts in Banggai Regency, Central Sulawesi Province. The research area is along the Balantak Strike-Slip Fault. This study presents geological mapping with focus on the deformation style that occurred within the area. The study provides an analogue of strike-slip structural trap types in convergent setting to support oil and gas field development. The research method was conducted using field observation and kinematic analysis of fault-slip data. Lithology in the study area that is part of the Banggai-Sula microplate has the characteristics of sedimentary rocks that are grainstone intercalating calcareous sandstone and rudstone consisting of limestone fragments. While part of the Sulawesi East Arm has crystalline rocks in the form of ultramafic-mafic rocks such as peridotite, serpentinite, gabbro and basalt. Structural analysis along the strike-slip fault indicates the collision of Banggai-Sula with Sulawesi East Arm on the side part of the micro-plate generates thrust fold belt along with well-developed uniform tearing faults present. The orientation and shape of the strain ellipsoid is pure shear transpression with the Balantak Fault as its plane of movement. The characteristic of the structure pattern complying with the model shows that the type of structures is en echelon thrusts and folds while the tearing faults are Riedel synthetics of the Balantak dextral Strike-Slip Fault that developed offset on the fold structures.

Keywords: *strike-slip, kinematic analysis, transpression.*

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INTRODUCTION

The tectonics of eastern Indonesia is influenced by the convergence of and interactions between Eurasia, Indian-Australia and the Pacific-Philippines plates. The tectonic record from these plates interactions can be found for example in the eastern flank of Sulawesi, where collision started from late Cenozoic. The eastern flank of Sulawesi also has petroleum potential as its petroleum system is proven and significant gas reserve has been produced in the Senoro area. The Balantak area (Figure 1) is located towards the east from Senoro gas field and is considered as the side part of Banggai-Sula micro-plate where strike-slip setting occurs. The study area is interesting for investigation because it provides potential structural trap analogues for future hydrocarbon exploration in the region. This paper presents geological structures observation along the Balantak Strike-Slip Fault Area including its kinematic analysis with fault-slip data.

GEOLOGICAL SETTING

Regional Geology

Sulawesi is located at the junction of three plates where the Pacific-Philippine and Indian-Australian plates are subducted under the Eurasian plate. As a result of this convergence, Sulawesi is composed of many fragments originating from these main plates. They include metamorphic complexes, volcanic arcs, ophiolite and micro-continental fragments and are all grouped generally into several major tectonic units (Katili, 1978; Hamilton, 1979; Taylor and van Leeuwen, 1980; Sukamto and Simandjuntak, 1983). The area of interest is the convergence between Banggai-Sula micro-continent and the East Arm of Sulawesi (Figure 2).

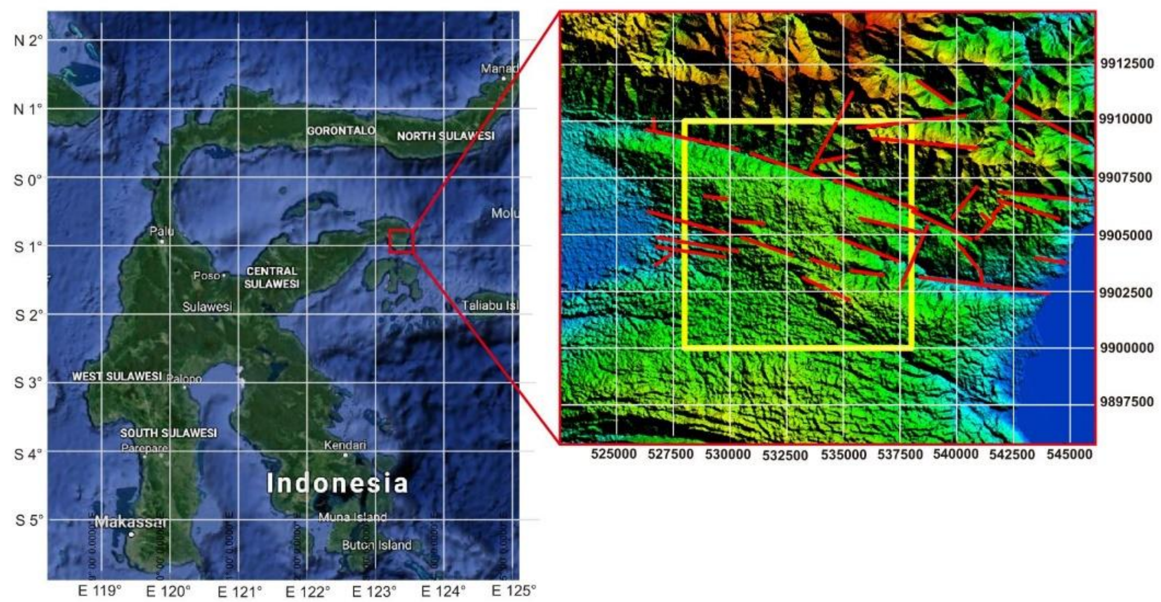

Figure 1: *Boloak Village administrative map and the study area, which is highlighted in yellow box.*

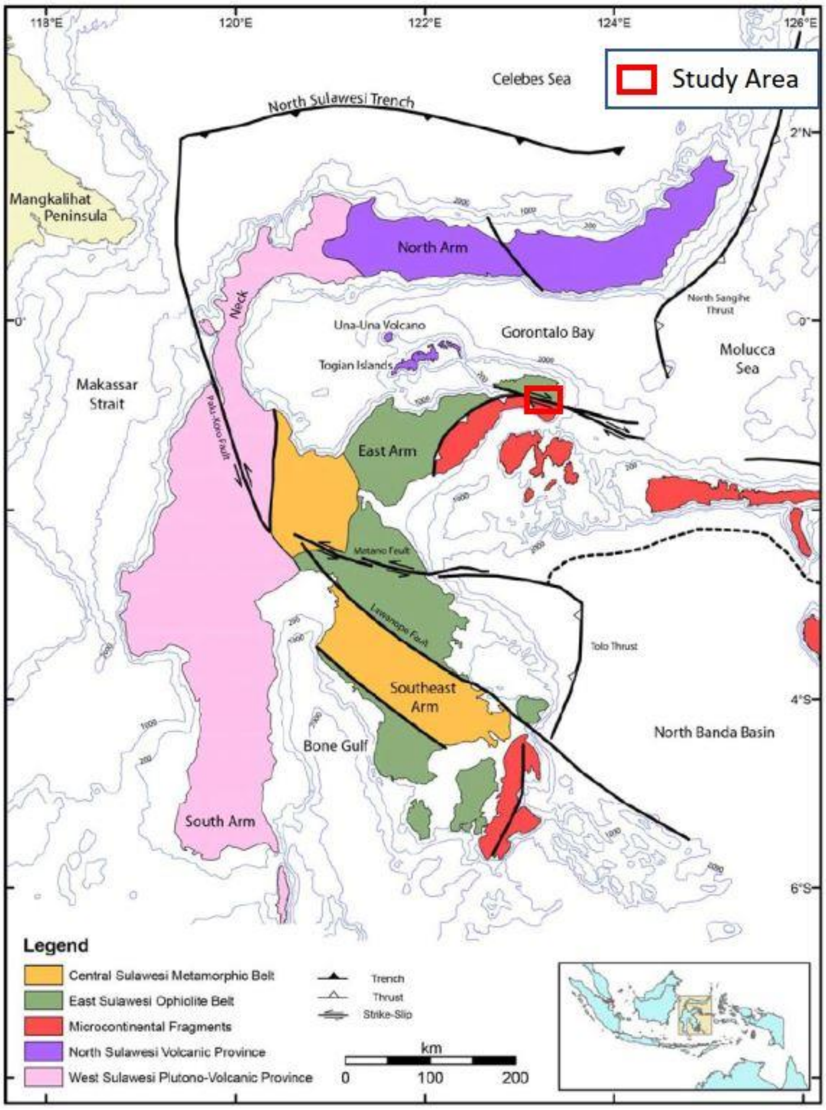

Figure 2: *Main Tectonic Groups of Sulawesi (Pholbud et al., 2012).*

According to Hall (2012) and Pholbud et al. (2012) the relationship between these different tectonic units and the tectonic development of Sulawesi is initiated by metamorphic complexes located in the west and center of Sulawesi formed by accretion of fragments of the Australian continental to Sundaland in the Middle Cretaceous. During the Early Eocene, the western part of Sulawesi separated away from Borneo to form the Makassar Strait, which coincides with the spreading of the oceanic plate in the Sulawesi Sea. In the Middle Eocene to Late Oligocene there was the formation of the Volcanic Arc in the north as a result of the subduction of the Indian Ocean into the North Arm. In the Early Miocene, the East Sulawesi Ophiolite was uplifted by north-west trending obduction during Sula's collision with the North Arm. The Central Sulawesi Metamorphic Belt includes metamorphic rocks associated with ophiolite, the Sundaland plate boundary, and the Banggai-Sula Block. Regional extension from Sulawesi to the east began in the Middle Miocene, associated with rollback subduction into the Banda. There has been magmatic activity in West Sulawesi, probably mostly related to the extensional regime, since the Middle Miocene produced high-K and calc-alkaline acid igneous rocks. To the south the subduction of the Celebes Sea under the North Arm is interpreted to have started around 5 Ma. Rollback subduction in the subduction zone of North Sulawesi started a new phase of extension in North Sulawesi which is active until now (Figure 3).

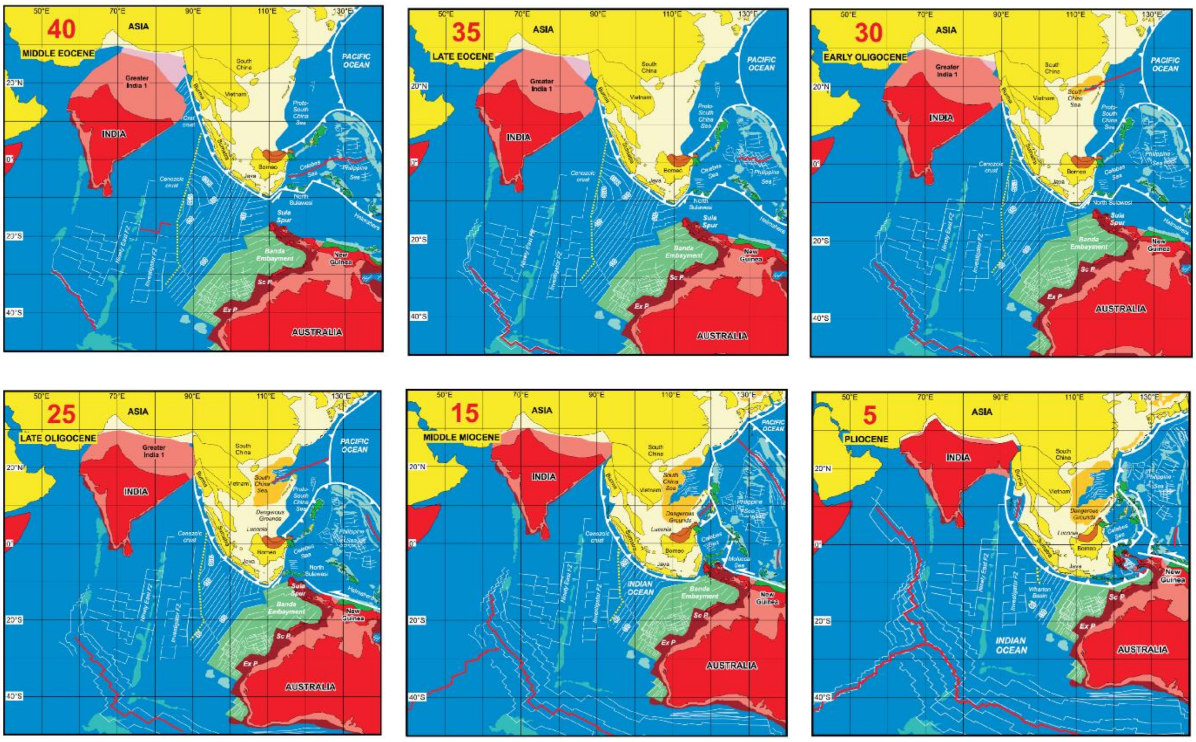

Figure 3: *Tectonic plates reconstruction of South East Asia (Hall, 2012)*

Other supporting studies shows that the Banggai-Sula microcontinent has been interpreted to have split up from Australia in the Mesozoic (Hamilton, 1979; Pigram et al., 1985; Garrard et al., 1988) which then collided with the East Arm of Sulawesi in Middle the Miocene (Simandjuntak, 1986), Middle Miocene to Pliocene (Garrard et al., 1988), Late Miocene (Hamilton, 1979), end of Miocene (Davies, 1990), and conclusively at the Neogene period from Early Miocene (Nugraha and Hall, 2018).

Batui Thrust Fault and the Poh Thrust Fault extends from the face of the thrust fault on the East Arm to the Balantak Fault continues offshore to the south then turns to north into the Moluccas Sea. The Batui Fault that stretches to the east considered to be the contact between the ophiolite and the microcontinent (Silver et al., 1983). Lots of previous research that considers the Sula Thrust Fault is considered a continuation of the Sorong Fault which is a fault stretching far to the east from New Guinea (Hamilton, 1979; Silver 1981; Silver et al., 1983; Garrard et al., 1988) (Figure 4). But after reinterpretation by Ferdian et al. (2010), Rudyawan and Hall (2012), the Sula Fault is the Banggai-Sula boundary with Maluku Sea and not the connection of the Sorong Fault because it has a different position and there is no evidence of continuity of the two faults. The Greyhound Strait Fault described by Silver, et al. (1983) as a steep fault with a northwest direction stretches about 350 km from Banggai and Taliabu Island, across the Gorontalo Bay, to the North Sulawesi arm where Katili

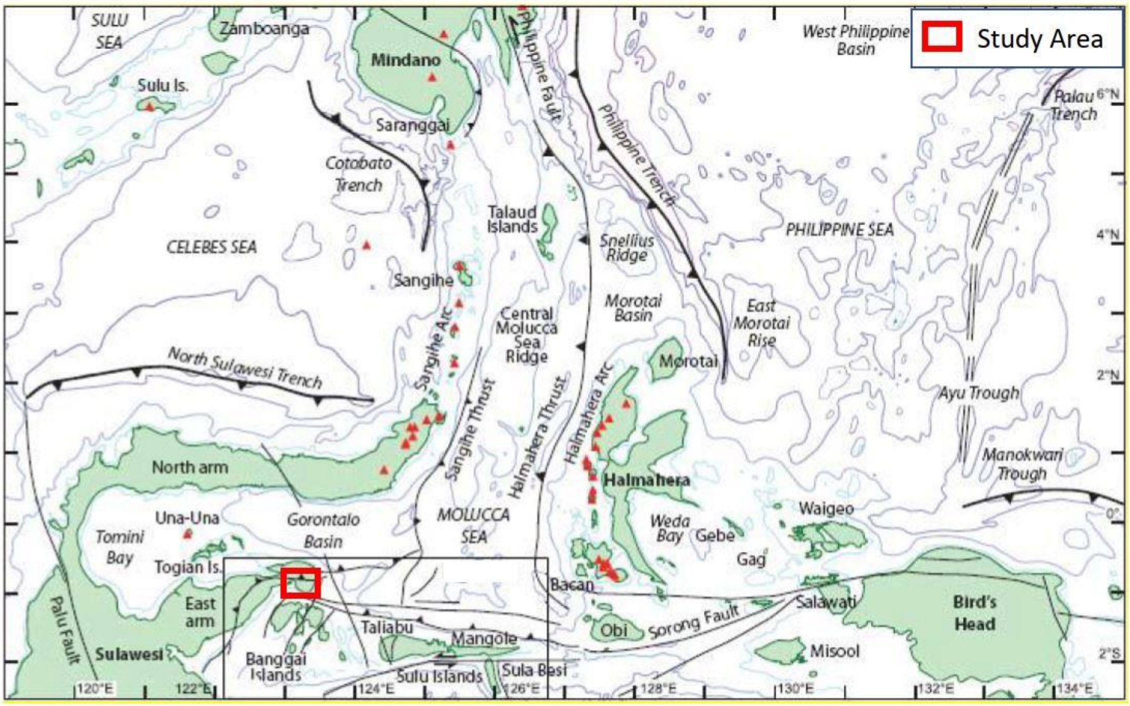

Figure 4: *Structural interpretation by Hamilton (1979) and Silver et al. (1983). Red triangles are active volcanoes and red square is Banggai-Sula Microcontinent.*

(1973) identified the Gorontalo Fault trending northwest (Figure 5).

The Balantak Fault is often represented as a continuation of the fault in the Poh Head area. Interpretation by Simandjuntak, (1989); Cottam, et al. (2011) suggest that the fault is precisely a right-lateral strike-slip fault, supported by field observations on land further to the west. The age of the fault is still unclear, but it occurred in the Pliocene to Recent because the fault probably

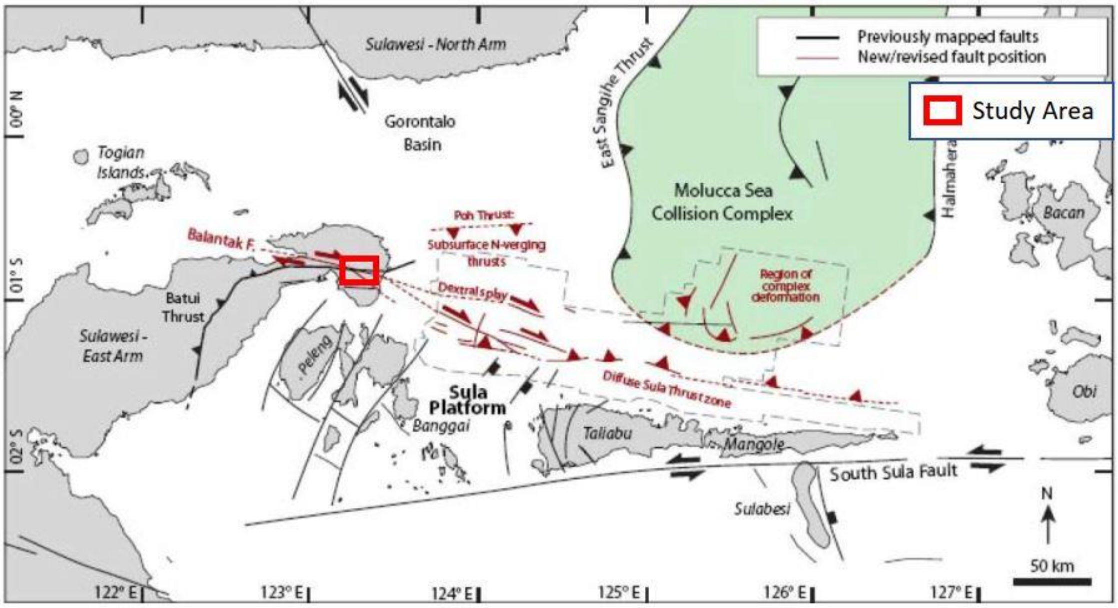

Figure 5: *Structural map and the study area (Ferdian et al., 2010).*

cut the Pliocene Volcanoclastic at Poh Head. Although the fault zone is very clearly visible on the seabed, it is not certain whether the fault is active or not. From the earthquake data under Poh Head from Global CMT (2009), it is considered to be a parallel fault surface with the Balantak Fault that shows a right-lateral strike-slip movement in the data within 14 km and a thrust fault movement with a right-lateral strike-slip component at a depth of 12 km which is almost continuous along the entire length of the 54 km from Balantak Sub-district to Teluk Poh in the West which is estimated to continue up to 30 km offshore (Figure 6).

Further studies also shows that Balantak Fault has been considered as part of the Batui Thrust Fault system (Silver et al., 1983), but the outcrop is very straight, from field observations (Simandjuntak, 1986) and changes in the direction of strike between uplift and local subsidence that indicates the fault has a steep plane with possible shear movement. Kinematic observation supports and is compatible with dextral shear sense. One of the zones in the quarter subsidence describes the termination system of the Balantak Fault off the coast to the east of Poh Head consisting of a left segment separated by folds and thrust faults. The contraction between the main left-stepping segment, which appears to be an antithetic sinistral fault with the orientation of the fold and the thrust fault is entirely kinematically compatible with the dextral strike-slip along the Balantak Fault (Watkinson et al., 2011).

REGIONAL STRATIGRAPHY

Stratigraphy that is used as reference by the author is geological map Luwuk sheet, Sulawesi by Rusmana et al. (1993), Hasanusi et al. (2012), and

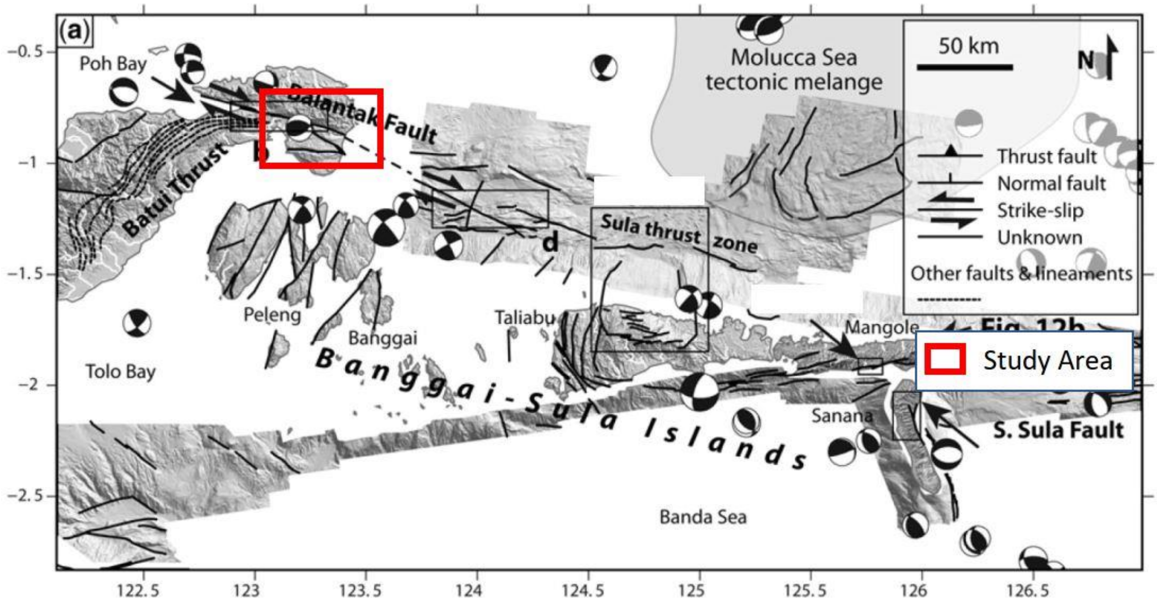

Figure 6: *DEM (SRTM) of East Arm of Sulawesi and bathymetry Banggai-Sula Island, earthquake data CMT with depth <35 km and structure that shows geomorphic proof Quarter tectonic activity (Watkinson and Hall, 2016).*

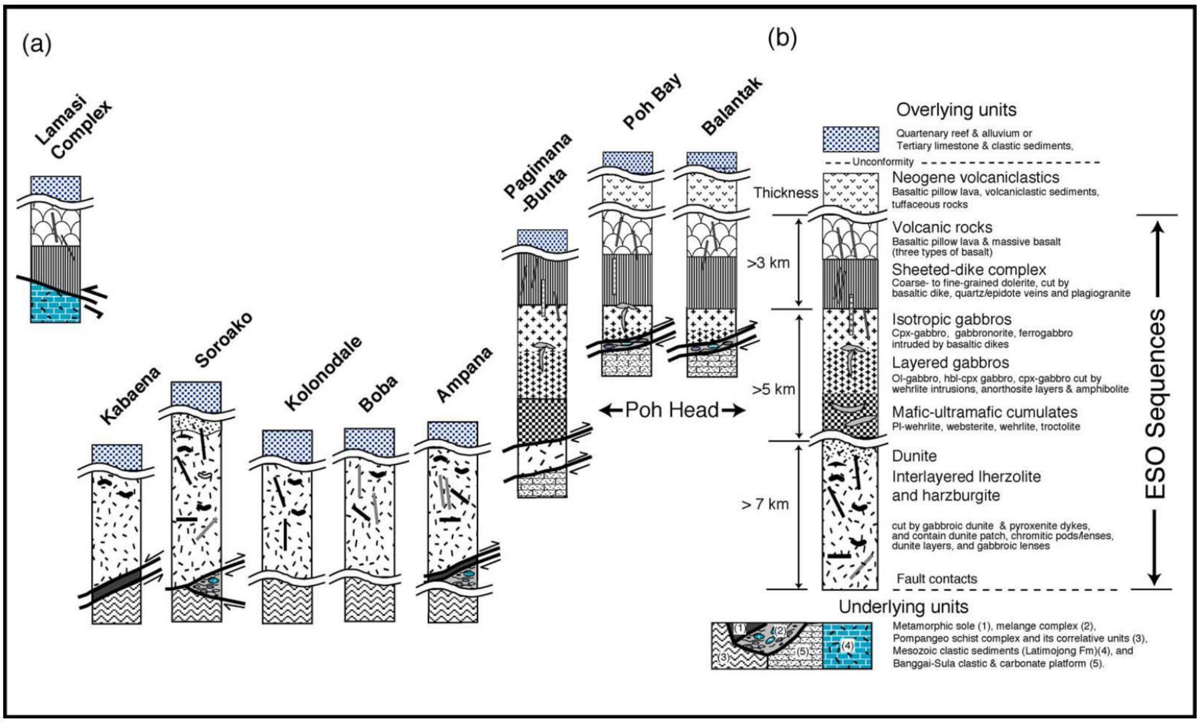

Figure 7: *(a) East Sulawesi Ophiolite column (ESO) in nine different location that is based on field investigation. (b) The reconstruction of the ophiolite series (Kadarusman et al., 2004).*

Garrard et al. (1998). Regionally, the Luwuk sheet at the study area has two main units that is Salodik Formation that consists of limestone with sandstones and Mafic Complex that consist of gabbro, basalt, serpentinite, phyllite, and schist.

Most of the Mafic Complex is found on the northern part of the study area, along the northern mountain range. The complex consists of harsburgit, dunite, pyroxenite, serpentinite, gabbro, diabase, basalt, and diorite. Schist, amphibolite, phyllite and metamorphozed gabbro are also present locally and suspected as part of an oceanic crust (Rusmana et al., 1993). According to Kadarusman et al. (2004), the Mafic Complex is a series of ophiolite rocks that compose the oceanic crust that is tectonically dismembered and spread from the centre and eastern part of Sulawesi. This ophiolite from bottom to the top consist of residual mantle peridotite and mafic-ultramafic accumulation from layered to isotropic gabbro, sheeted dolerites and volcanic basalt rocks (Figure 7). Ophiolite complex in Sulawesi indicates formation and displacement of various plate tectonics and considered very related with the triple junction plate phenomenon of Eurasia, Indo-Australian, and Pacific that is complex along the Late Mesozoic – Early Tertiary (Hutchison, 1975; Hamilton, 1979). The age of these rocks range between Middle Cretaceous until Late Oligocene, widely known as Balantak Ophiolite and considered to be part of the Eastern Sulawesi Ophiolite Belt that is far more extensive (Simandjuntak, 1986; Mubroto et al., 1994; Kadarusman et al., 2004).

Salodik Formation is widely spread on the Eastern Arm Sulawesi and locally in Banggai Island, Peleng Island, Mangole Island and a couple of surrounding small islands. Research is conducted by Sihombing et al., (2011) that divided this limestone unit into two parts: lower part that consist of grainstone-rudstone that is rich with Nummulites fossil, whereas the upper part consists of mudstone, wackestone, packstone and grainstone. The thickness of Salodik Formation is estimated to be around 1000 to 1200 meters.

According to Garrard et al. (1998), and Hasanusi, et al., (2007) the Salodik is a group that is divided into three parts that is Tomori Formation, Matindok Formation and Minahaki Formation. Tomori Formation is aged Eocene to Early Miocene, consist of reef that is underlain by clastic sediments gradually to the upper part of it and covered by limestone. Matindok Formation is aged Middle Miocene that consist of clastic sediments with lignite interbedding. Minahaki Formation is aged Late Miocene and consist of carbonate shelf deposition (Figure 8).

Husein et al. (2014) proposed on dividing the formation to three facies that is Nummulitic Grainstone-Rudstone that is deposited in Early Eocene to Late Eocene, grainstone with interbedding calcareous sandstone that contains smaller Nummulitic fossil, and rudstone with interbedding reefal limestone that is aged Early Eocene to Middle Miocene which these facies are characterized as framestone and a couple of bindstone that consists of coral, mudstone algae, and grainstone that has Nummulitic fossil.

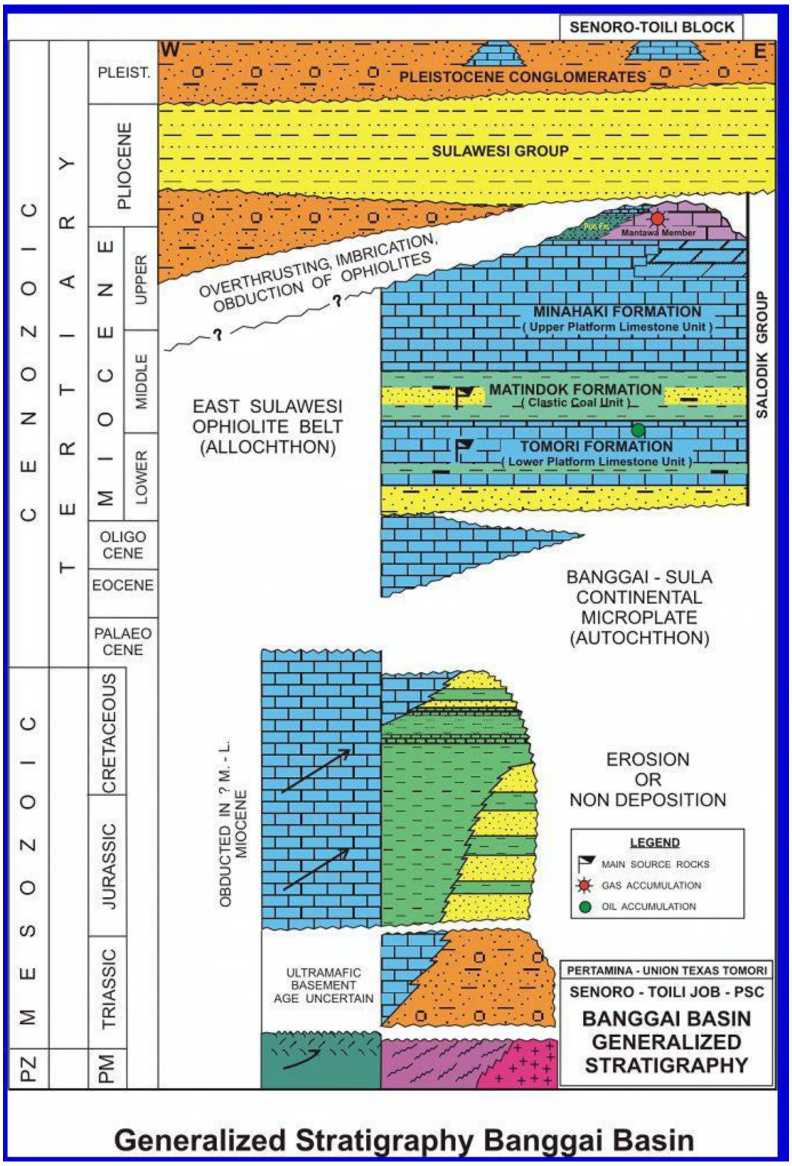

Figure 8: *Regional Stratigraphy Luwuk-Banggai Basin (Garrard et al., 1998; Hasanusi et al., 2007).*

Surono et al. (1994), Rusmana et al. (1994), and Husein et al. (2014) analyzed fossils in Salodik Formation that are *Proporocyclina*, *Numulites* sp., *Marginospora* sp., *Amphistegina* sp., *Operculina* sp., *Lepidocyclina* sp., *Fasciolites* sp., *Cycloclypeus* sp., *Alveolinella* sp., *Sorites* sp., *Rotalia* sp., *Flosculinella* sp., *Brizolina* sp., *Planulina* sp., *Heterostegina* sp., *Miogypsina* sp., *Globorotalia menardii*, and *Orbulina universa*. This indicates the depositional environment was shallow waters on the fore-reef shelf. Surono and Sukarna (1993) conducted biostratigraphy analysis and bring up the age of Salodik Formation to be Early Miocene to Middle Miocene. Rusmana et al. (1994) on the other hand proposed a different age that is Eocene to Late Miocene while Husein et al. (2014) conclude the age is Early Eocene to Middle Miocene.

Based on data taken in the field and results from laboratory analysis, the stratigraphy of the study area consists of four unofficial rock units from the oldest to the youngest, starting with Cretaceous Ultramafic Units formed in the oceanic crust environment, Limestone Unit 1 that consist of grainstone intercalating calcareous sandstone which the age is around Middle Miocene with a backreef depositional environment and nearshore-inner neritic forereef shelf, Limestone Unit 2 that consist of rudstone with limestone fragments which the is Late Miocene age with a backreef depositional environment and outer neritic foreref shelf, and Alluvial Plains Unit of Recent age, which was deposited in a terrestrial environment.

DATA AND METHODS

Field Structural Geology

The geological structure of the study area consists of faults and folds. The fault structure found in the study area is the strike-slip fault, blind thrusts with repetition of sedimentary rock strata and tear faults that offsets the thrust fold belts. The folded structure found in the study area is in the form of synclines and anticlines from different directions of the bedding planes (Figure 9).

The formation of geological structures in the study area is influenced by the collision between the Banggai Sula microcontinent and the Eurasian continent in the Ophiolite section of the East Arm of Sulawesi in the Pliocene (Hall, 2012).

In the study area, the outcrops have a bedding with a NW-SE strike directions and there are also variations in the inclination of the bedding (Figure 10). The closer to the thrust, the steeper the inclination of the bedding on the hanging wall, while the inclination at the footwall and the crest of the anticline is gentle. This is interpreted as a fault propagation fold with blind thrusts which causes changes in the stance and inclination of rock strata in the study area.

The fold structures in the research area that can be mapped well are the anticline which is commonly found in the field and synclines. The syncline fold structure in the Rau area is interpreted based on the trellis river pattern on the Kiloma River and the Balantak River. This is supported by

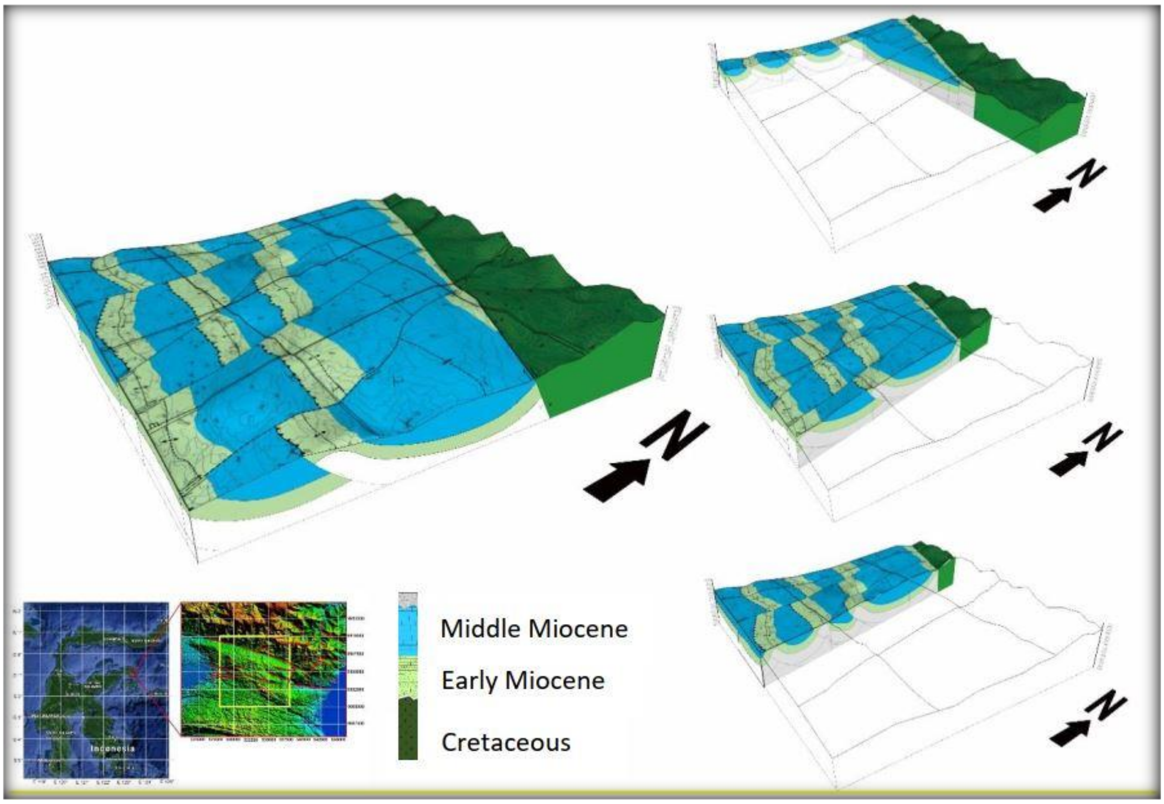

Figure 9: *Block Diagram of the study area showing the geological structures from field observation, the colours show the lithology units.*

the difference in the position of the rocks in the two rivers with opposite inclination direction. Limestone in the Balantak River has a bedding inclination towards the Southeast (Figure 11a). Meanwhile, the Kiloma River has a rock layer slope to the Northwest (Figure 11b).

Figure 10: *The inclination of the NE-SW strike bedding in Limestone Unit 1 caused by deformation. Yellow lines show the lithology units.*

The anticline fold structure in the Boloak area is interpreted based on the pattern of the trellis river and there is a lot of anticlinal repetition from north to south. This is

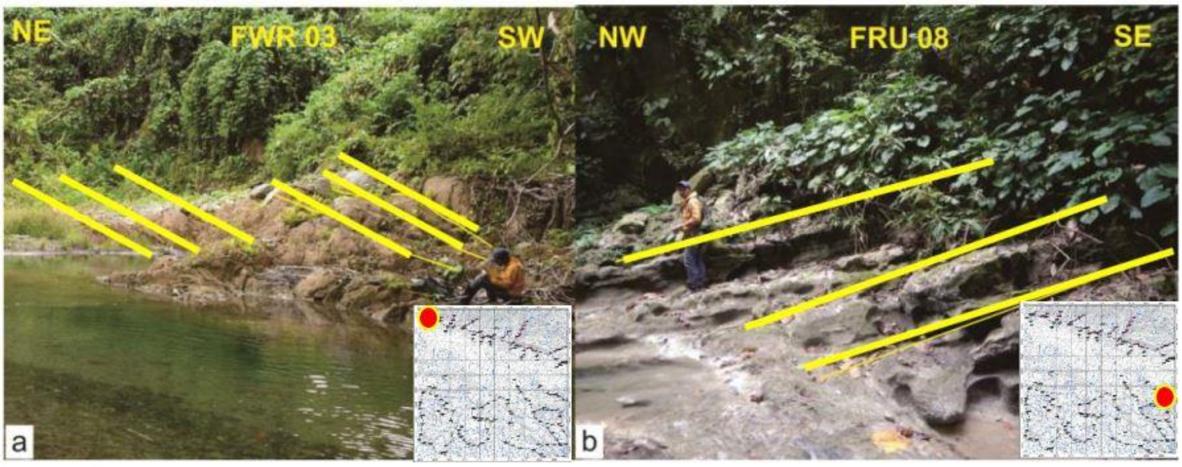

Figure 11: *Bedding inclination in Limestone Unit 1 a) Balantak River and b) Kiloma River*

supported by differences of the inclination direction of the rocks in the rivers of the Boloak area. The Limestone Unit 1 in the Boloak River on the left of the river has a northward bedding (Figure 12a). While the right side of the river has a slope of rock layers to the south (Figure 12b).

Structures found on the sedimentary rocks from field observations are considered as blind thrust faults (Figure 13) with tear faults, folds, and repetitions of rock layers which is commonly interpreted as thrust fold belts.

The fault structure in the study area is interpreted to occur in one deformation stage. The deformation that occurs is convergent, namely the collision between the Banggai Sula microcontinent and the Eurasian continent in the East Arm of Sulawesi in the Pliocene (Hall, 2012). The Balantak Fault which is a right-lateral strike-slip fault shown from slickenside observations in the field along the Balantak River is very suitable to be the main fault that develops other structures. The deformation is interpreted as still going on until Recent, which is supported by

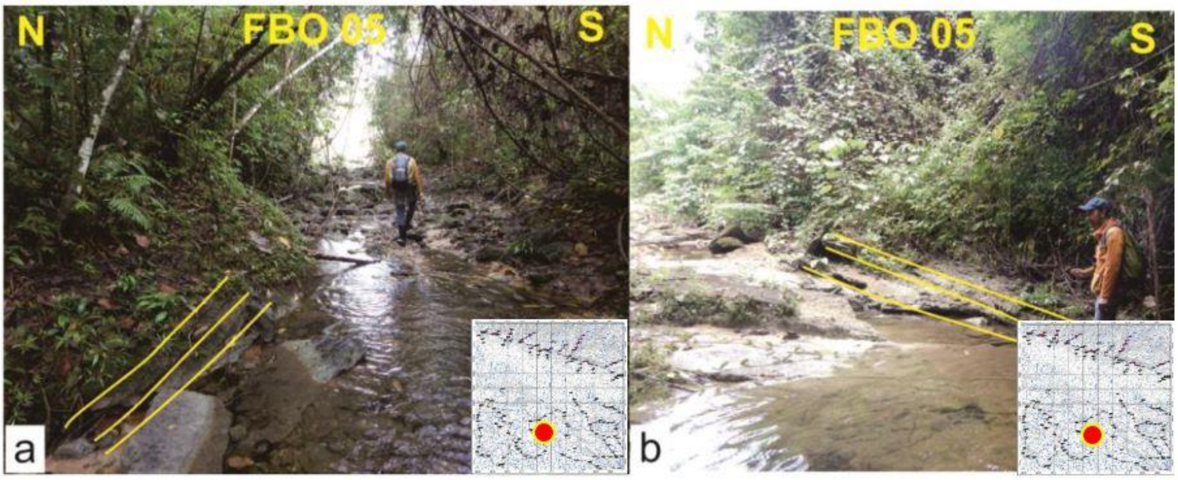

Figure 12: *Bedding inclination in Limestone Unit 1 a) Boloak River on the left and b) Boloak River on the right.*

two seismic data from Global CMT (2009) which show seismic activity on the Balantak Fault. This tectonic event is considered as forming a shear zone (Figure 14) along the Balantak River which shows structures including quartz boudinage from quartz veins and brecciation of ultramafic rocks.

Kinematic Analysis of Balantak Fault

The overall regional deformation can be explained by local deformation. At the point where geological structure data is taken, in addition to representation of geological structures in the research area, it will also be used as kinematics analysis that occurs in the research area. The collision between the Ultramafic Unit and other units in the study area originating from the Banggai-Sula microcontinent began in the Late Cenozoic. The geological structure of the study area is in the form of right-lateral strike-slips fault, thrust fold belts, and offset folds on limestone, as well as the Balantak Strike-Slip Fault as a boundary between the Ultramafic Unit and other structurally related rock units. The results of the n fault-slip kinematic analysis (n = total data) apply the Marrett and Allmendinger (1990) method (Sapiie, 2016). Each dominant structure and major fault zone are shown separately. FaultKin analysis was carried out on slickenside data taken along the Balantak Fault.

According to Marrett and Allmendinger (1990) (in Sapiie, 2016), finite strain estimation is required for deformation quantification. Theoretically, finite strain can be calculated using fault-slip data through tensor summation. However, this method requires information on the magnitude of the displacement to calculate the fault slip factors given the weighting of several factors. One approach is to measure the gouge width to estimate displacement, but this method is only applicable if the fault gouge width is fractal. No fault gouge was found in the field that can support this quantitative analysis, so it is necessary to assume that all faults in each segment have the same displacement and that the faults are fractalized through an infinite strain approach. If so, the P and T axes can be used as the basis for adding

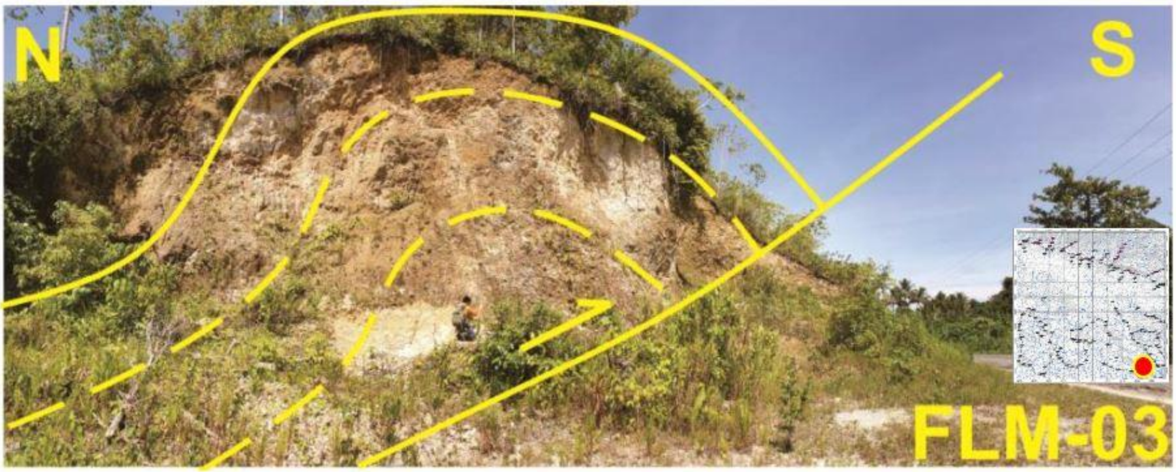

Figure 13: *Limestone Unit 1 outcrop showing a folded thrust fault structure.*

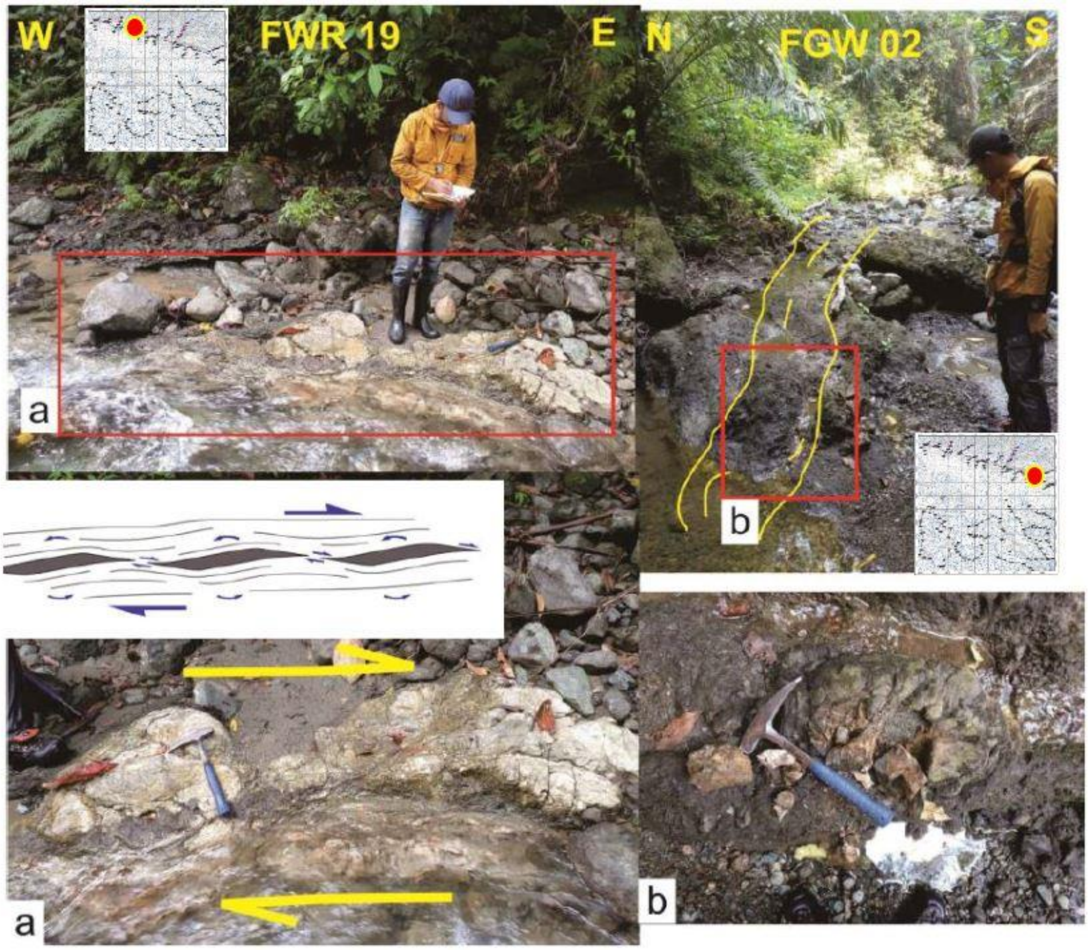

Figure 14: *The shear zone of the Ultramafic Unit shows a) boudinage with a right-lateral movement (Fossen, 2010) and b) brecciation.*

weightless tensors by using Bingham statistics that connect the P and T axes to each other (Marret and Allmendinger, 1990; in Sapiie, 2016).

The Marret and Allmendinger method produces a shortening axis (P) and an elongation axis (T) from a population of faults that have the same displacement. The basis for calculating the kinematic axes is through the infinite strain approximation. The shortening (P) and extension (T) axes of heavily contoured data used the method of Kamb (1959) to obtain the distribution and orientation of the principal stresses. The kinematic axes P and T are made by dividing the two perpendicular planes to then obtain the solution of the fit fault plane along with the shear vector and the normal vector of the faults that form 45° angles to each other. (Figure 15).

In analysis, the P and T axes are equivalent to the eigenvectors and the eigenvalues can determine their magnitude (Marrett and Allmendinger, 1990). In the kinematic analysis plot diagram, P and T are equivalent to the eigenvectors and positional. The eigenvectors also define the magnitude of the vector (Marret and Allmendinger, 1990; in Sapiie, 2016). The finite strain

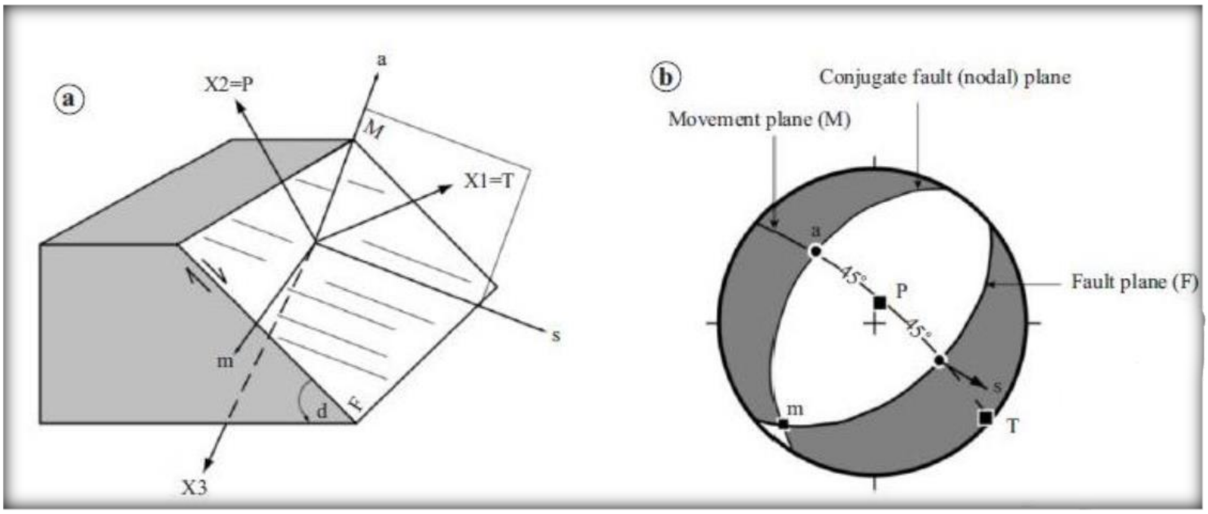

Figure 15: *a) The fault-slip geometry and kinematic coordinate system shows the relationship between the kinematic axes (X1, X2, X3), the fault plane (F), the slip direction (S), and the movement plane (M) where a = fault-pole, m = pole-plane of motion, d = fault. b) The same area projection depicts a graphical representation of the P and T axes where P and T are the main shortening and extension (modified from Marrett and Allmendinger (1990) in Sapiie, 2016).*

axes (e1, e2, e3) are plotted in a Flinn diagram to see variations in the ellipsoid strain formed in the study area. After obtaining the ellipsoid classification, it is possible to determine the type of deformation mechanism by the Balantak Fault.

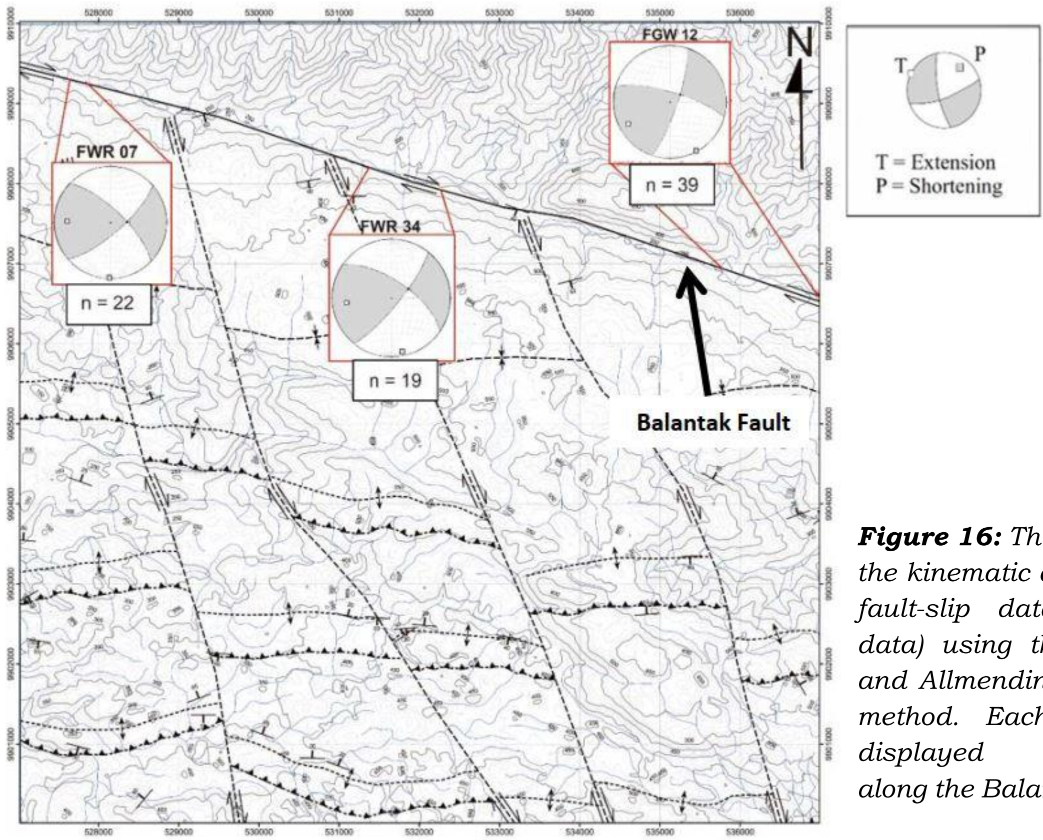

Figure 16: *The results of the kinematic analysis of fault-slip data (n=total data) using the Marrett and Allmendinger (1990) method. Each data is displayed separately along the Balantak Fault.*

Fault Slip Analysis of Balantak Fault

We can see that all fault plane solutions at three observation points along the Balantak Fault show a right-lateral movement (Figure 16). Using Fautkin's software, 80 fault slickensides have been shown to show a homogeneous kinetic axis in the direction of NW-SE shortening. The values of e1, e2, e3 are finite magnitudes and we can plot them onto a Flinn diagram to see the variation of strain formed at each measurement point (Figure 17).

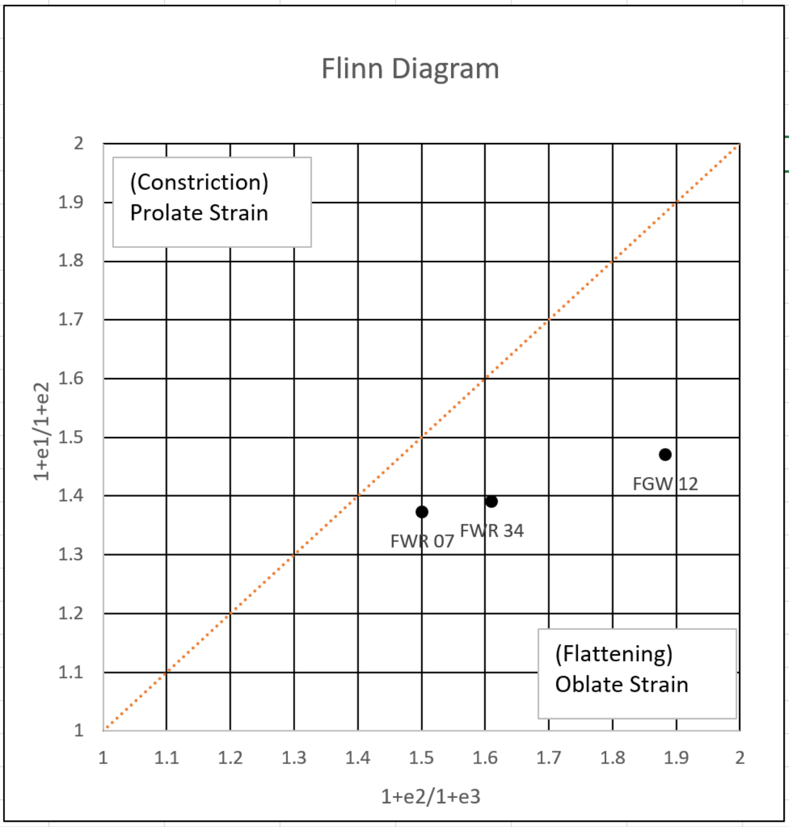

Figure 17: *Flinn diagram showing the three-dimensional shape of the strain ellipsoid determined from fault-slip data obtained from each area (Fossen, 2010).*

The calculated ellipsoid strain has the form of an oblate strain at each station. Oblate strains are considered to be in a convergent strike-slip system (Sanderson, 1984; Ratcschbacher, et al., 1993; Little, 1996 in Sapiie, 2016). Hall's (2012) tectonic setting considers the Banggai-Sula microplate to come from the southeast. We can calculate the general direction of arrival of the Banggai-Sula microcontinental plate by the average direction of the shortening axis (P) which is considered the greatest stress axis, namely 346.2° or 166.2°, NW-SE shortening (Table 1).

RESULTS AND INTERPRETATION

The angle between the maximum strain (T) and the shear zone can determine the class of the strain ellipsoid which is calculated in the illustration above (Figure 18). The observation of the results of the data

Table 1. *The method uses FaultKin which produces the relative value of the ellipsoid strain axis magnitude (e1, e2, e3) from the data for each point. pl = plunge, tr = trend.*

Structure Area	P axes (pl, tr)	T axes (pl, tr)	e1	e2	e3
FWR 07	1.5°, 177.2°	24.2°, 267.9°	0.3552	-0.0128	-0.3424
FWR 34	8.7°, 169.7°	25.2°, 263.8°	0.3852	-0.0038	-0.3814
FGW 12	2.4°, 151.7°	18°, 242.5°	0.468	-0.002	-0.47

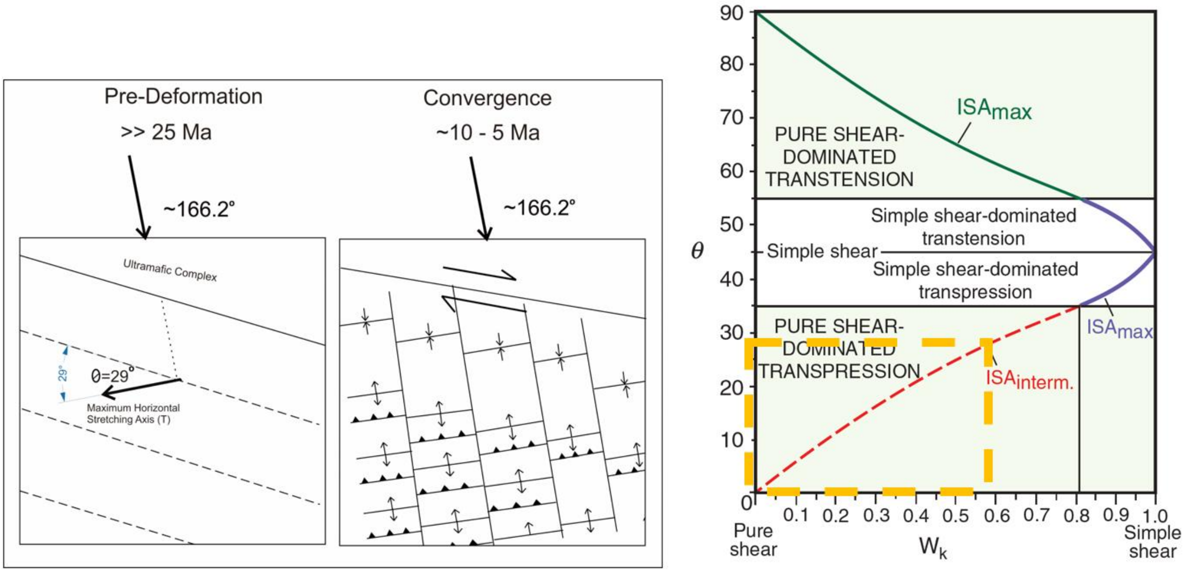

Figure 18: *The relationship and Wk where is the angle between the maximum horizontal strain (T) and the shearzone (Balantak Fault) based on Fossen and Tikoff (1993).*

analysed indicates that the pure shear component is more dominant than the simple shear with a W_k value of 0.6 which means that it is included in the transpression category (Figure 19).

This explains the formation of many folded thrust faults in almost the entire field because the vertical axis of the ellipsoid will be longer than the displacement distance. The classification of pure shear-dominated transpression is the most suitable ellipsoid strain to describe the deformation shape of the study area (Figure 20).

The results of this analysis match the regional tectonics which is a convergence area. After being analyzed it also shows that the research area is an oblique convergence in the Balantak area because the Banggai-Sula microcontinent is not head on colliding with the East Arm of Sulawesi as in the Batui area. The

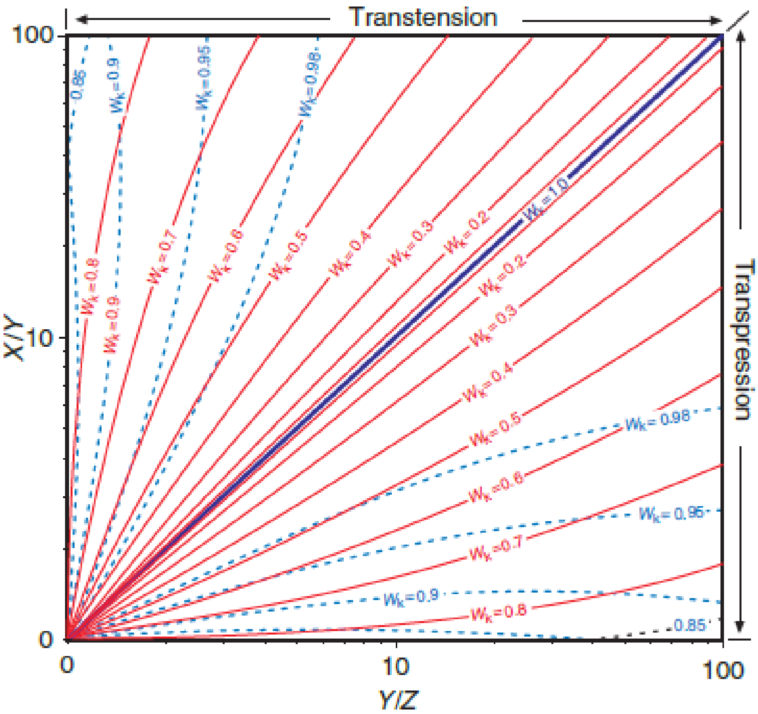

Figure 19: *Calculations show that the third point strain has an oblate strain ellipsoid that undergoes transpression with Wk = 0.6 based on Fossen and Tikoff (1993).*

eastern part of Sulawesi has been described by Hall (2012) Banggai-Sula microcontinent coming from the Australian Plate and colliding with the Ultramafic Complex of the East Arm of Sulawesi from the direction southeast in the Pliocene. The structure formed as a result of this collision is the dextral strike-slip of the Balantak Fault by including evolutionary structures such as thrust faults and tearing faults. The similarity of the structural pattern with the model indicates that the research area is interpreted as a wrench tectonic setting (Figure 21).

The research area whose structure is formed by dextral strike slip causes the type of trap formed to be different from the trap type due to ordinary pure shear at the Poh Area. The structure of the study area forms an en echelon thrust and fold trap type. Meanwhile, tear faults, which are synthetic Riedel from the Balantak Fault, form an offset fold trap type (Figure 22).

The Late Miocene to Pliocene collision between the Banggai-Sula microcontinent and the East Arm of Sulawesi deformed the rock intensively. This collision occurred due to the docking process of the microcontinental plate. The docking occurred because the microcontinent oceanic plate that was subducted into the East Arm of Sulawesi has run out. In the study area, the collision occurred in oblique convergence and the Balantak Fault is the boundary between the two plates.

The strike-slip fault movement occurred between Banggai-Sula crystalline rock and Sulawesi East Arm crystalline rock (Ultramafic Unit) and affected the sediments above Banggai-Sula (Limestone Unit 1 and Limestone Unit 2) during the collision period between the Sulawesi East Arm plate

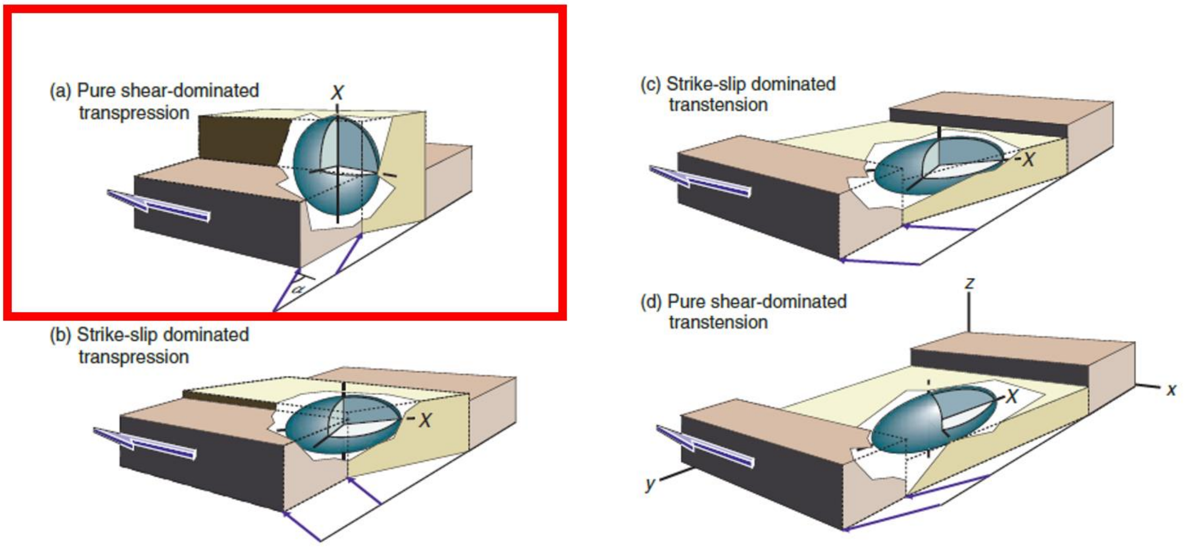

Figure 20: *The orientation and shape of the finite strain ellipsoid in the four classes of transpression/transtension. Balantak is in the form of an ellipsoid strain of pure shear dominated transpression (Fossen, 2010).*

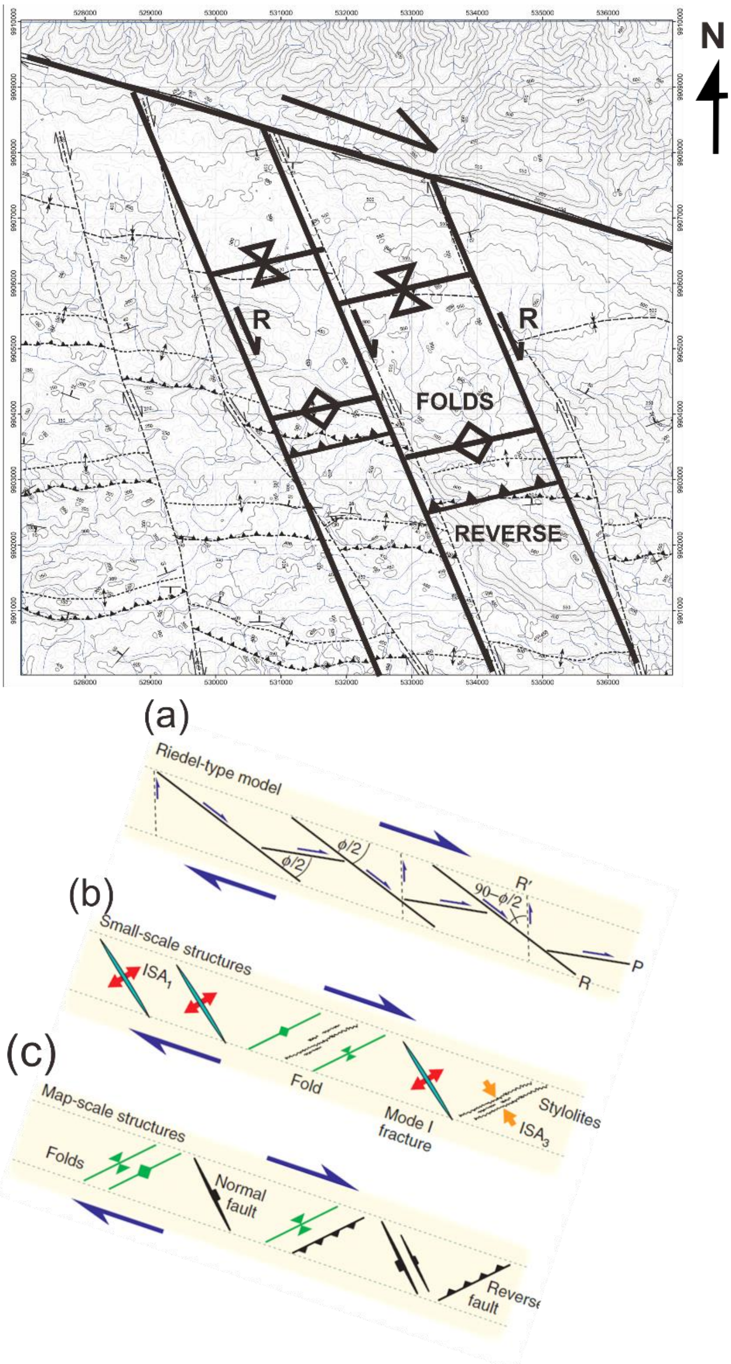

Figure 21: *The geological structure of the study area is juxtaposed with the ideal model of the strain pattern by dextral shear fault movements. (a) Riedel-model where R = synthetic Riedel and R' = antithetic. P-shears are secondary structures associated with the R and R' surfaces. is the internal shear angle. (b) Small-scale structures that can form in shear fault zones. (c) Large-scale structure. (Fossen, 2010).*

and the Banggai-Sula microcontinent which shows the current geological conditions (Figure 23).

CONCLUSION

The pattern of the tear fault close to the main fault of the Balantak Fault resembles the pattern of the minor fault in the classical experiment. The tear fault is interpreted as R (synthetic Riedel fracture). Anticlines, synclines and thrust faults perpendicular to these tear faults are interpreted as concurrent structural features. The main fault is the Balantak Fault on the surface parallel to the primary shift zone in the bedrock. Kinematics analysis revealed that the study area near the Balantak Fault has a structurally uniform domain in character.

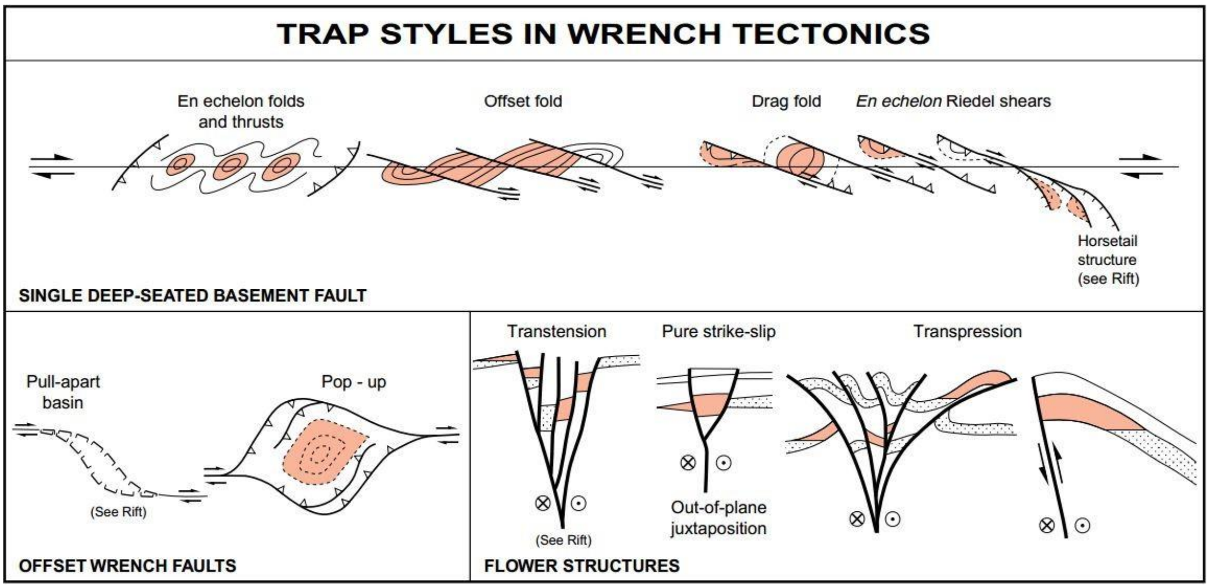

Figure 22: *Trap types within the wrench tectonic setting (E&P Geology Forum, 2009).*

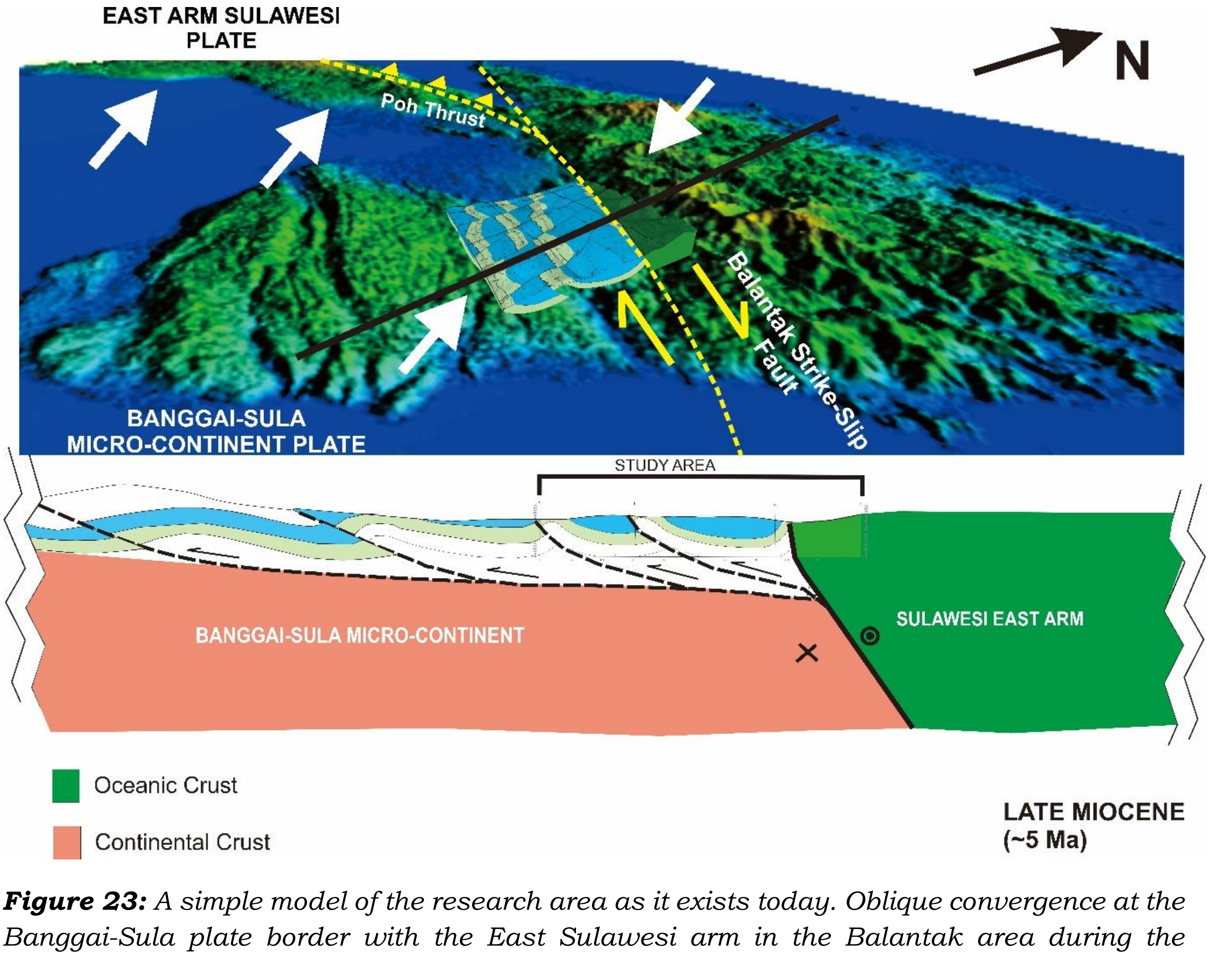

Figure 23: *A simple model of the research area as it exists today. Oblique convergence at the Banggai-Sula plate border with the East Sulawesi arm in the Balantak area during the docking process due to the depletion of oceanic crust belonging to the microcontinent.*

The discovery of anticline, syncline, and thrust fault structures in the dextral strike slip system of the Balantak Fault is the background for the kinematics analysis. The results of the study stated that the ellipsoid strain found in the field was a pure shear dominated ellipsoid. This explains that the greatest strain actually occurs vertically so that even in the shear system, folds and thrust faults can be found as in the study area. The type of trap structure due to this arrangement will be slightly different from the usual, namely en echelon thrust fault folds and offset folds.

Further study is needed such as integration with subsurface data to confirm if the structures on the surface is similar with the structures in the subsurface.

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