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 km² 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.

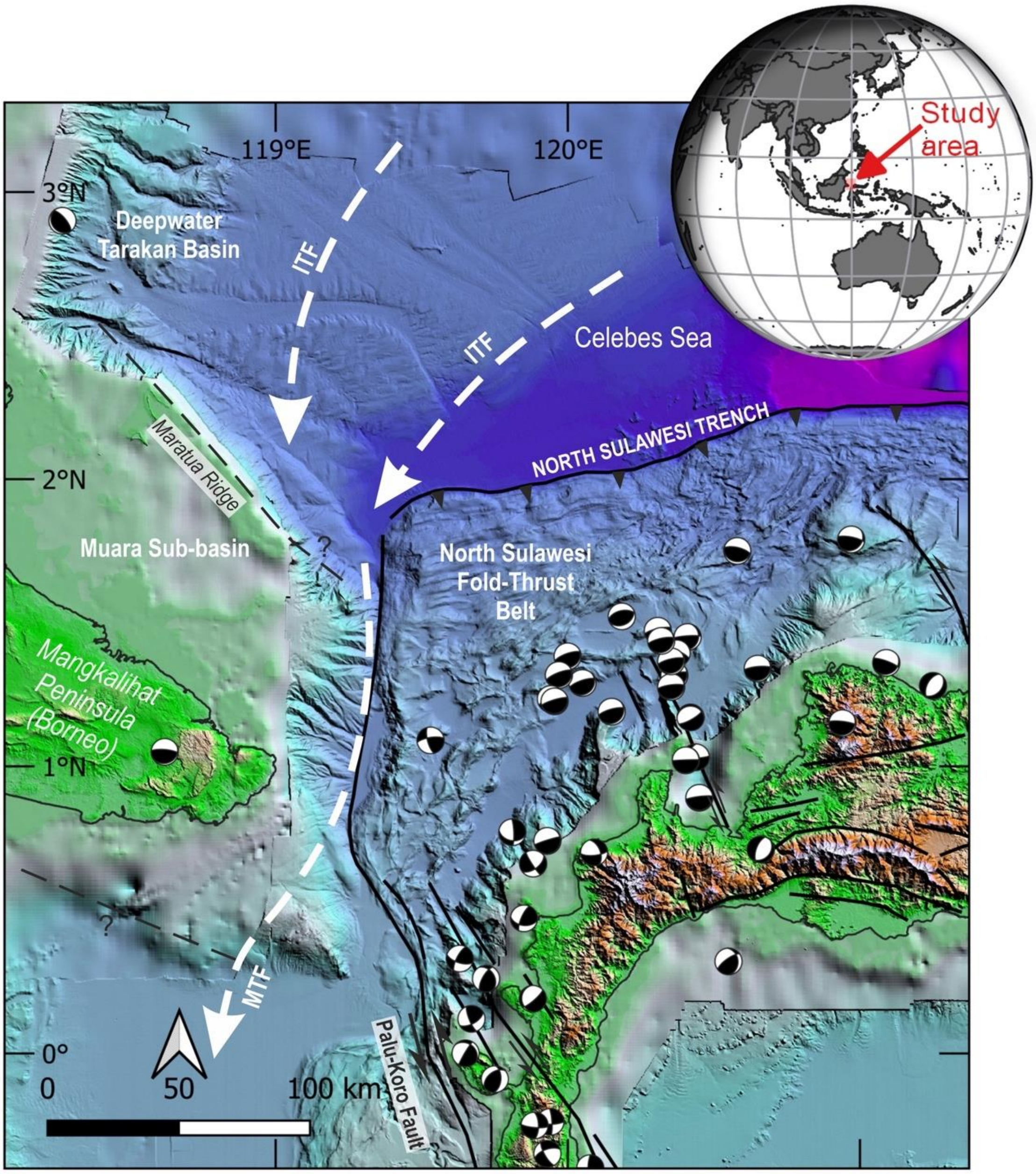


Figure 1. *ASTER DEM, bathymetry, and gravity image of study area showing topography, regions, basin or sub-basin, active seismicity, oceanography setting, and major tectonic provinces of the study area (Cloke et al., 1999; Camp et al., 2009; Advokaat, 2015; Hall, 2019; Tiranda and Hall, 2021, Preprint). 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

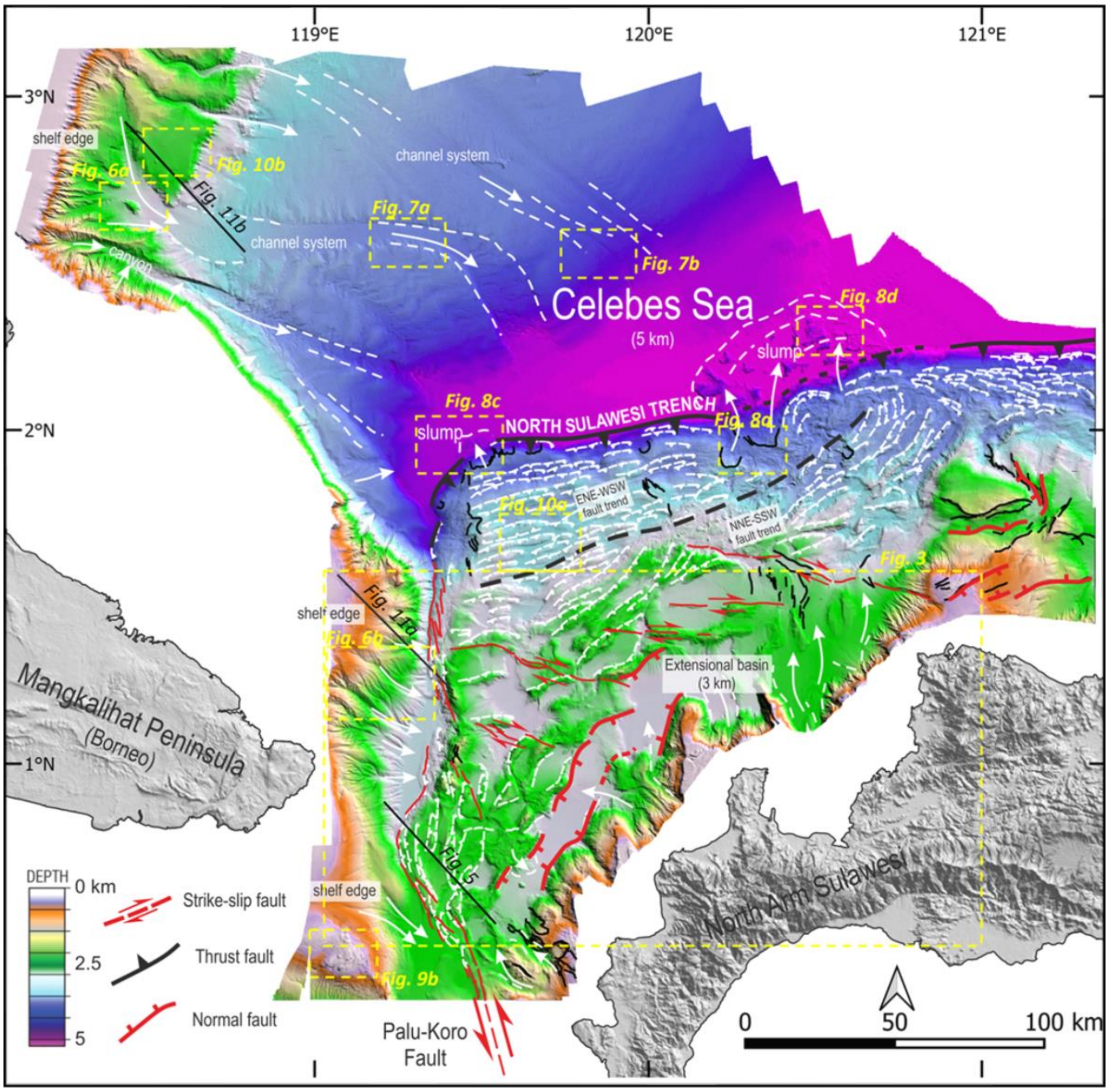


Figure 2. *Combined DEM from SRTM map with a shaded-relief map of multibeam bathymetry showing morpho-bathymetric interpretation with specific examples described in this paper. Illumination direction from NE.*

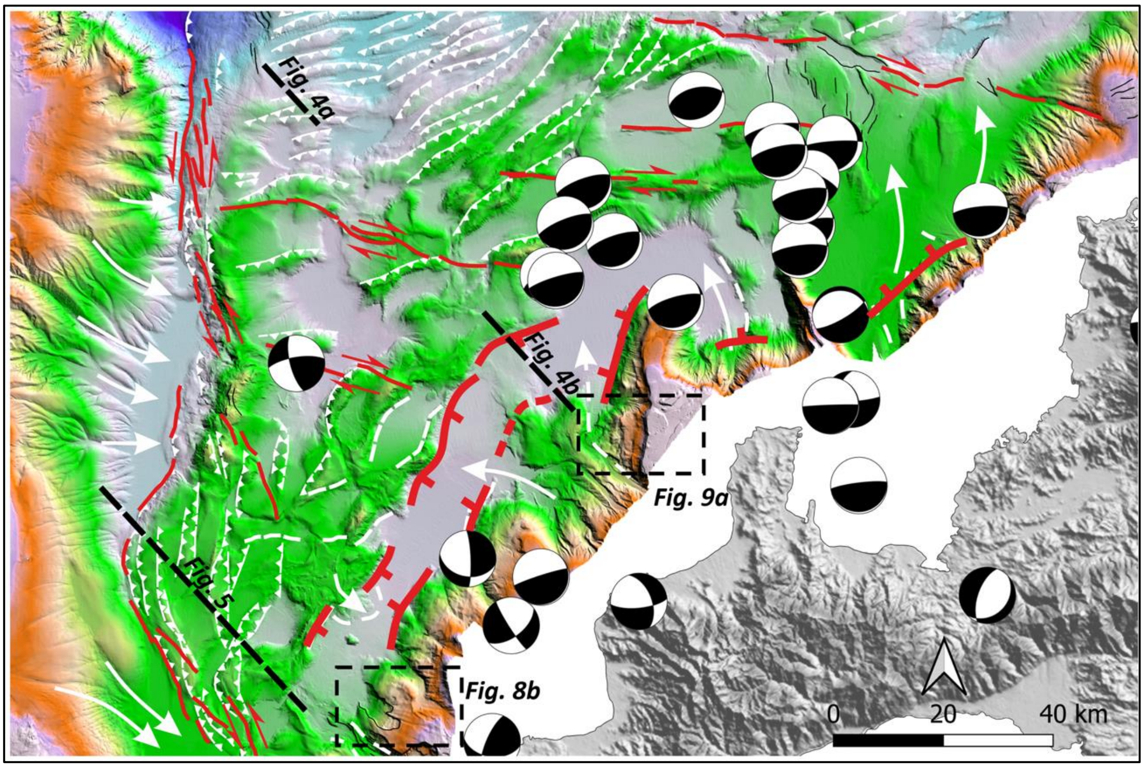


Figure 3. *Morpho-bathymetric interpretation of the NSFTB highlighting the complex structural features associated with the formation of NSFTB and the Palu-Koro Fault. Detailed structural features are shown in Figure 4, Figure 5, Figure 8, and Figure 9. Illumination direction from NE.*

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

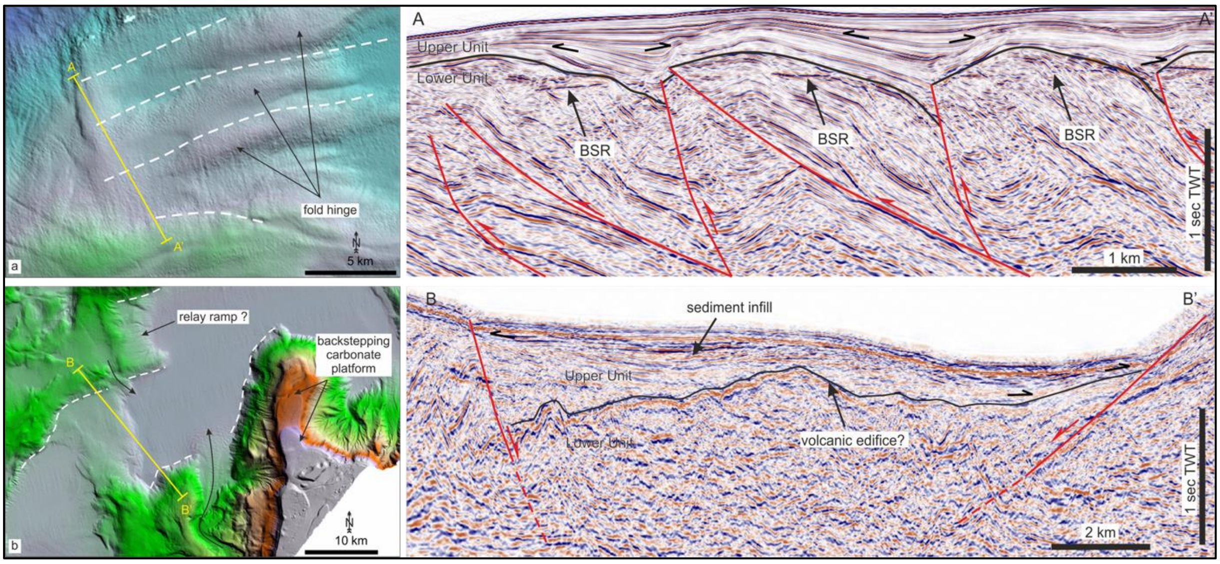


Figure 4. *Example of structural features as observed in the study area particularly the NSFTB. Illumination direction from NE. (a) Seabed morphology of the fold-thrust belt. (b) Extensional basin in the southern-most part of the NSFTB. The location is shown in Figure 2 and Figure 3.*

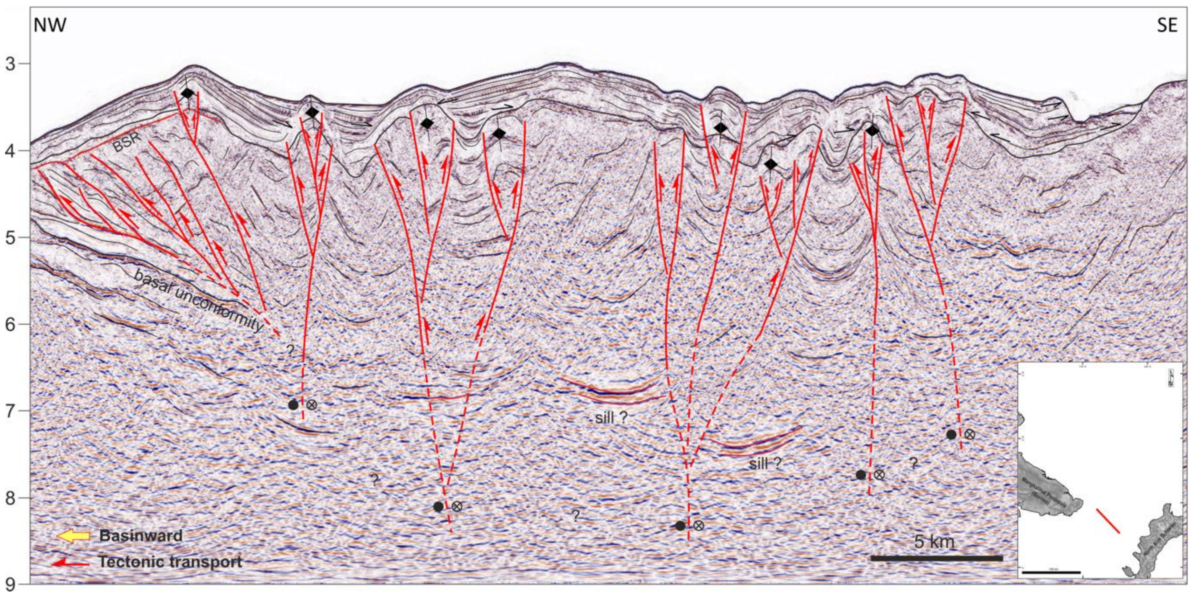


Figure 5. *The interpreted seismic section in the Celebes Sea-Makassar Strait gateway exhibits restraining stepover structure related to the Palu-Koro Fault system. The surface expression from bathymetry data shows typical rhomboidal shape geometry (Figure 3).*

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-

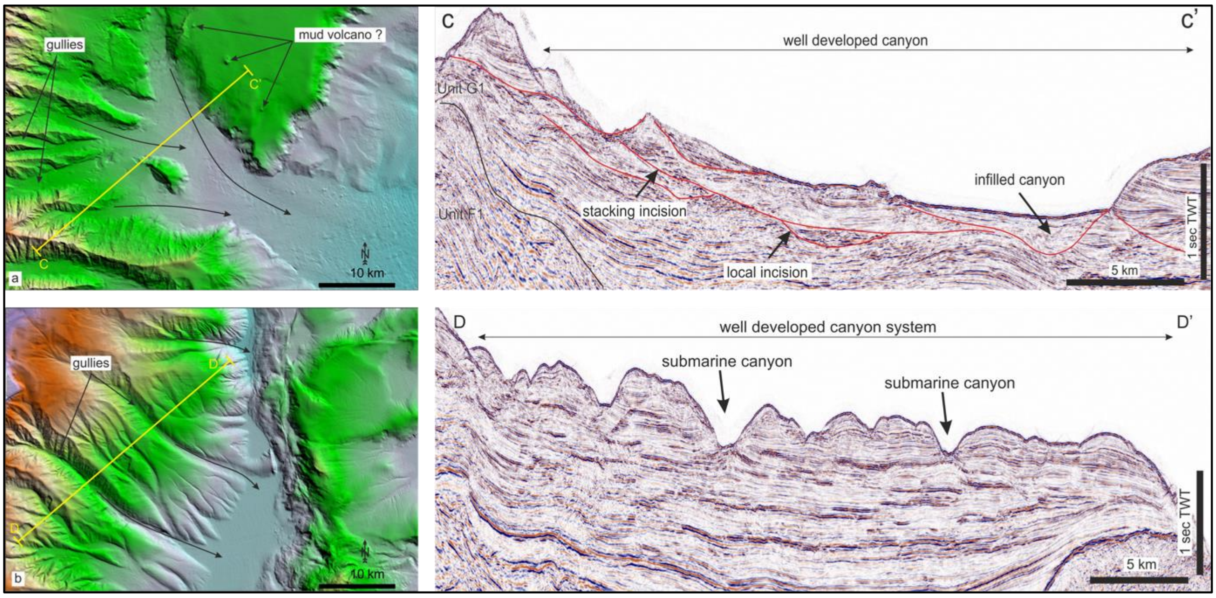
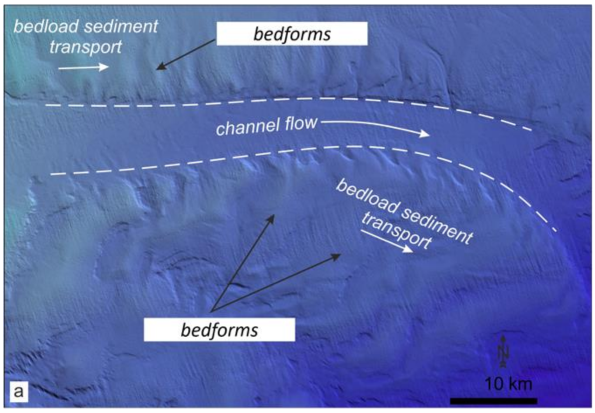


Figure 6. *Example of the erosional features showing canyon system/gullies based on multibeam bathymetry and seismic profiles. Illumination direction from NE. (a) Gullies in the Deepwater Tarakan Basin. (b) Gullies in the eastern edge of the Muara Sub-basin. The location is shown in Figure 3.*



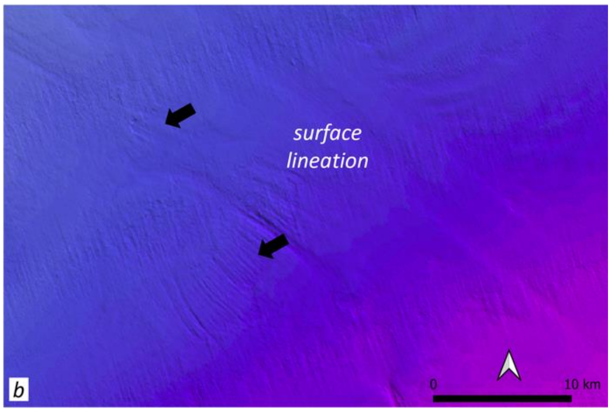


Figure 7. *Erosional features on the Celebes Sea seabed surface. Illumination direction from NE. (a) Bedforms with NE-SW trend of the crest. (b) Surface lineation indicates SE flow direction.*

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.

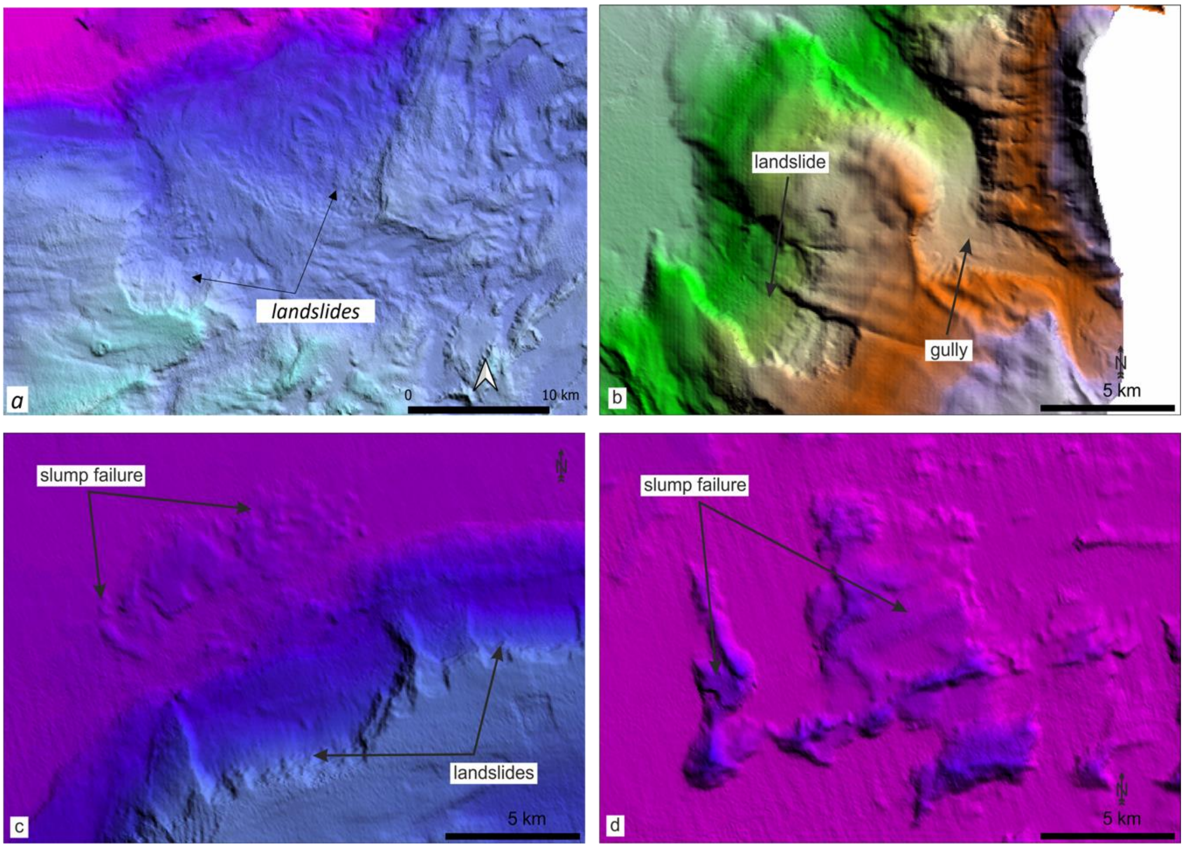


Figure 8. *Gravitational features were observed within the study area. Illumination direction from NE. (a) Sediment wave features in the Celebes Sea. (b), (c), and (d) Slope failures are characterized by landslides and slump failures. The location is shown in Figure 2 and Figure 3.*

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.

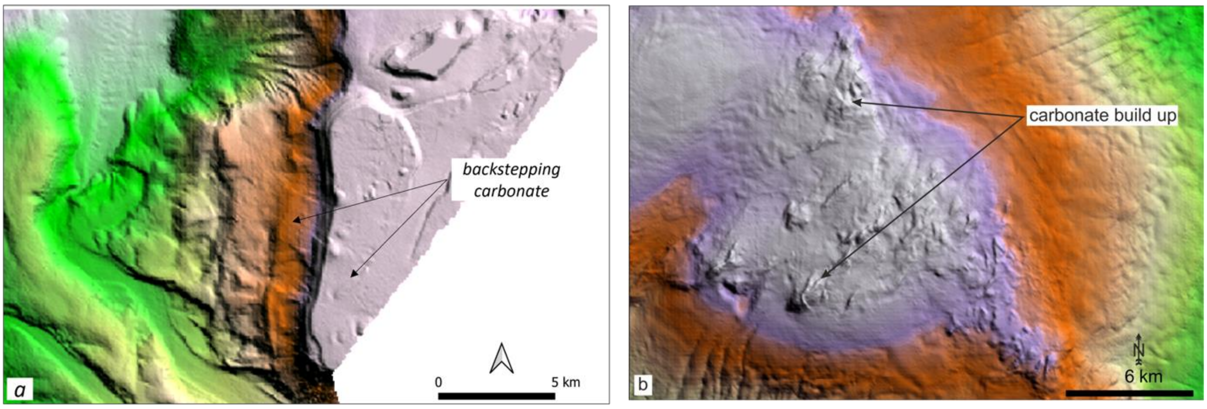


Figure 9. *Stair-stepped marine terraces which are interpreted as backstepping carbonate (a) and carbonate build up (b). Illumination direction from NE. The location is shown in Figure 2.*

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

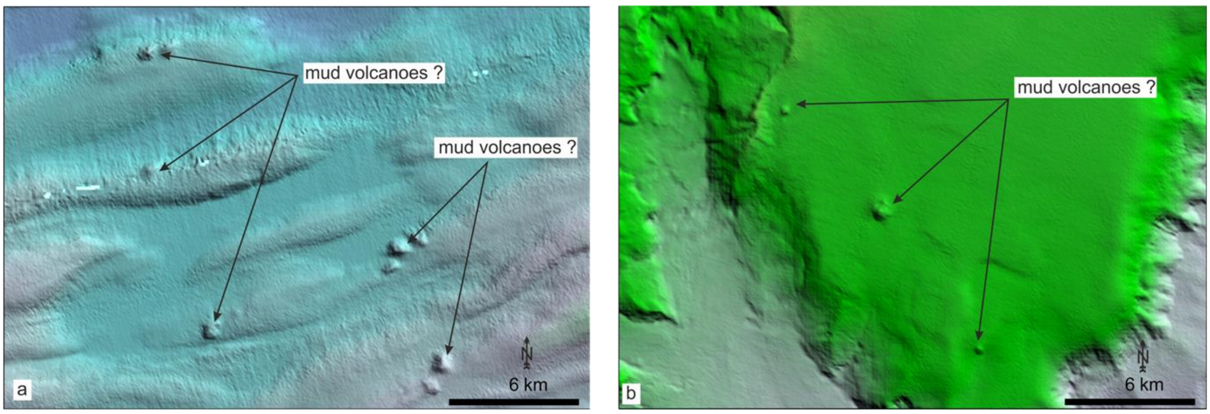


Figure 10. *Mud volcanoes-related features as observed in the study area. However, clear evidence of mud volcanoes in this area is very limited. Illumination direction from NE. The location is shown in Figure 2.*

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.

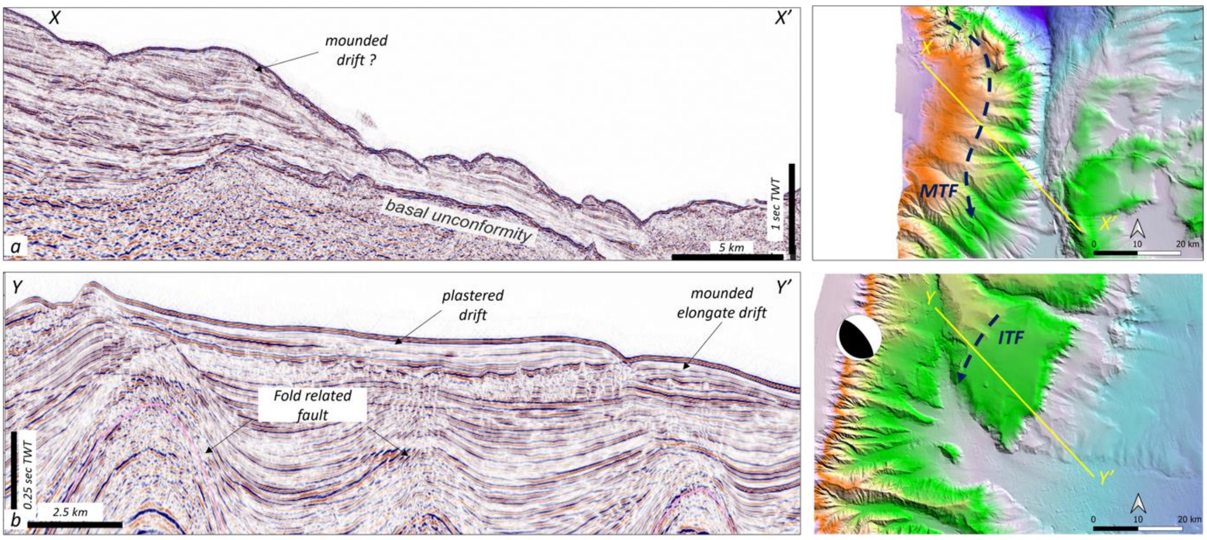


Figure 11. *Example of the contourite drift showing mounded drift and plastered drift observed from seismic reflection profiles. Multibeam bathymetry illumination direction from NE. (a) Possible mounded drift on the eastern edge of Muara Sub-basin. (b) Overlying plastered and mounded drift on top of 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.

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