Study of a Mass Transport Complex, South Makassar Strait Basin Indonesia

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Abstract

The South Makassar Strait Basin Mass Transport Complex (SMSB MTC) covers an area of at least 9000 km^2 and with a total volume of 2438 km^3. It is composed of a shale dominated sedimentary unit with high water content. The SMSB MTC differs from other very large MTC's in displaying relatively coherent internal sedimentary stratigraphy, and is probably the largest know coherent MTC or slump. It has a central region up to 1.7 kms thick which forms a bowl-shape confined by two NW-SE trending steep lateral ramps in the upper slope area and a NE-SW trending frontal ramp area. The MTC anatomy can be divided into an extension headwall, translational, toe, flank, lateral apron and frontal apron domains. It is interpreted to be triggered by SMSB accelerated subsidence in the Pliocene and slid along a weak basal detachment that lies at the interface between two sedimentary units of different lithologies which was probably overpressured due to fluid migration events. The internal fault patterns of the MTC show that its movement in the upper slope to the middle part of the bowl area is extensional which changes to compressional in the toe domain and apron. Later extensional collapse of parts of the compressional toe area occurred with negative inversion on some faults. The coherent internal stratigraphy suggests the MTC deformed at a slow strain rate, perhaps in the order of cms/yr over thousands of years. Hence this type of MTC does not have the potential to generate tsunamis but could affect deepwater facilities built on the active MTC.

Keywords: Mass transport complex

1. Introduction

Mass Transport Complex (MTC) is a general term used for slope deposits that flow or move in plastic or non-fluidized behavior in the main grain-support mechanism (Shanmugam, 1994) both in marine and freshwater environments. Terms for this kind of deposit are mass transport deposit, mass-movement complex or mass-gravity deposit which all define slope and basin floor deformation deposits (Posamentier et. al., 2011). In deepwater settings, MTC's often form the dominant deposit in stratigraphy successions and can be intercalated with turbidite deposits

(Dykstra et. al., 2011).

MTC's are also of particular interest to oil and gas exploration and development activities in deep water areas as submarine landslides can potentially induce serious damage to oil and gas production facilities, pipelines and seafloor communication cables (Gue, C.S., 2012). On a worldwide basis, 90% of MTC's are mud-prone (Meckel, 2011), but nevertheless a few MTC's do provide commercial reservoirs for hydrocarbons and as an example, the reservoir in the nearby Ruby Field in the Makassar Straits (Tanos et.al., 2012; Pireno and Darussalam, 2010) is an MTC deposit with a predominantly carbonate facies.

2. Location

This study focuses on a large relatively coherent MTC (slump) recognized on a regional seismic data set in the southern part of the Makassar Straits deepwater area, the South Makassar Strait Basin (SMSB) (Figures 1 NS 2). Water depth ranges from 100 – 2000 m. Morphologically, the research area covers the slope to basin floor area.

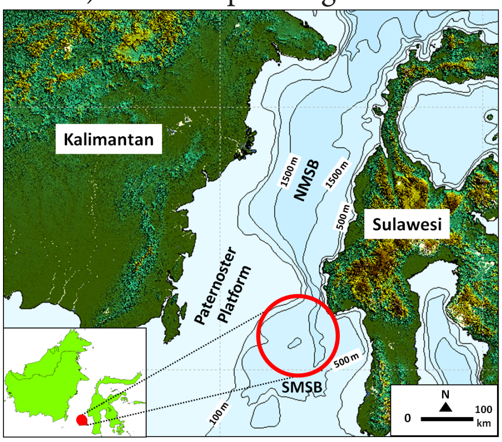

Figure 1. Regional map of Makassar Strait showing research area (red circle) NMSB = North Makassar Strait Basin, SMSB = South Makassar Strait Basin

The primary data set used for this study are 2185 km2 of 3D and 7054 km of 2D seismic data. All of this seismic data set covers +/- 11,000 km2 area in South Makassar Strait Basin. The dominant frequency in the MTC objective is approximately 45 Hz.

3. Methods

Structural mapping over the area defined base and top of the main MTC body. On 3D data the base of MTC was picked for each 25 to 50 lines both inlines and crosslines, and the top MTC picked every 25 to 100 lines depending on the horizons complexity. Stratal slicing and rms windows were also used to define internal geometries.

4. Regional Geology

It is generally accepted that the Makassar Strait basins were formed as result of separation of Kalimantan to the west and Sulawesi to the east (Satyana, 2010). The onset of rifting is pre-45 ma in the North Makassar Straits, and possibly slightly younger in the South Makassar Basin (early Middle Eocene) (Bachtiar et al., 2013; Kupecz et al., 2013).

The basin deepened due to flexural subsidence since the Early Miocene (Satyana, 2010). A generalized cross-section of the basin is shown in Figure 3. The MTC observed in research area are deposited during Pliocene time and interpreted to be sourced from the Paternoster platform to the northwest.

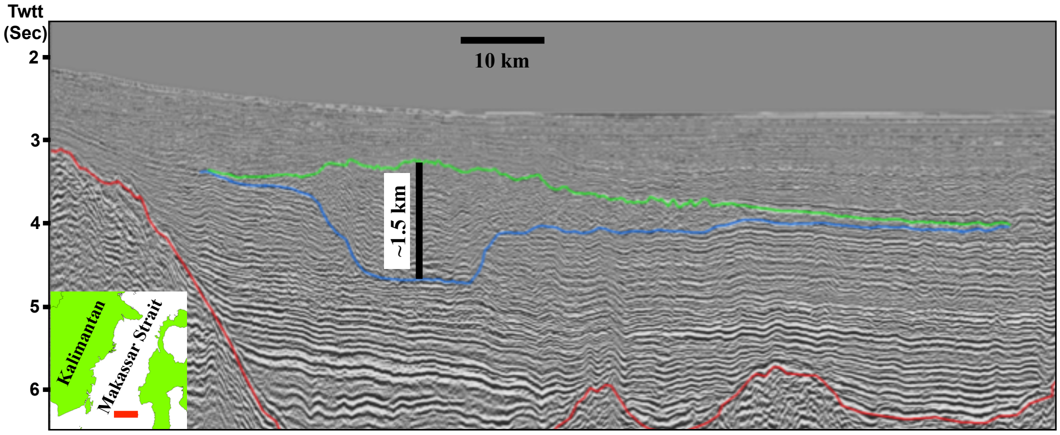

Figure 2. Regional seismic line shows the distinct thick relative coherent MTC (slump). Top and base MTC horizons were mapped throughout study area.

Well X penetrated the outer part (apron) of the MTC body (Figure 4). The average velocity from seabed to the top of the MTC, based on sonic log, is 1498 m/s and was used to generate depth maps. This is very slow velocity which indicates a high percentage of water present in shallow sub-surface deepwater sediments. Although well X did not penetrate the main MTC body, the mostly undeformed strata in well area can be clearly correlated on seismic reflection data to the main MTC (Figure 5).

Using a synthetic seismogram tie in well X, the velocity interval in the MTC main body can be calculated as approximately 2045 m/s. This interval velocity was used for thickness measurements in MTC body.

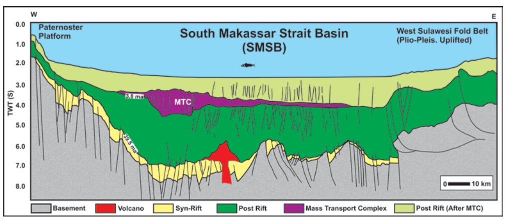

Figure 3. Regional geology cross section through South Makassar Strait Basin (Modified from Armandita, 2010).

5. Results

A NW-SE seismic line through the MTC shows its overall shape and the mapped top and base horizons (Figure 4). Based on map of the basal horizon in depth (Figure 5), the MTC covers an area of at least 9000 km2. Its overall dimensions are 120 km in NW-SE axial direction and +/- 100 km wide in the middle part. Its areal distribution extends beyond the data set especially to the southeast and southwest, but in these areas the MTC is very thin.

The MTC body can be divided into several domains which include the headwall, flank, translational, toe and lateral and frontal apron domains (Figure 6). The translational domain covers the area from the upper slope to the thick region of the bowl. The translational and toe domains in the thick region of the bowl are characterized by two major frontal ramps, and associated fault bend folds, that separate the well layered, largely undeformed/coherent regions (Figure 4). Thrusting and folding becomes more intense passing towards

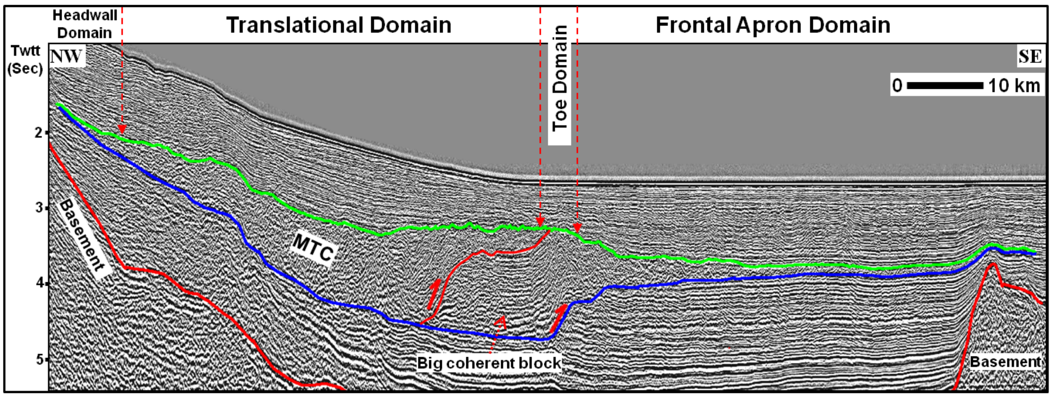

Figure 4. Seismic line across MTC with top and base horizons shown (Figure 5 for location).

the southeastern lateral and oblique ramps, and to a lesser degree towards the southwestern lateral ramp.

Internal structures of translational domain vary from coherent to chaotic patterns. Coherent sediment blocks are interpreted as blocks sliding down dip and some these blocks are large. One of the biggest coherent blocks is 1.20 km thick, 11.8 km long (Figure 7) and 10,7 km wide. The strata in this block shows relatively conformable bedding and correlates to the undeformed sediment beds to the west. This relatively correlatable strata indicates that the big coherent blocks did not moved a significant lateral distance.

Beyond the lateral and frontal ramps (bowl area) are relatively thin MTC which are interpreted as MTC flanks in the upper slope area and MTC spill-out in the down-dip area (Figure 7). These can be further divided into lateral apron and frontal apron domains. Flank, lateral and frontal apron domains are actually a continuous mass, and their boundaries gradational based on morphology and internal structural changes that are discussed in this section.

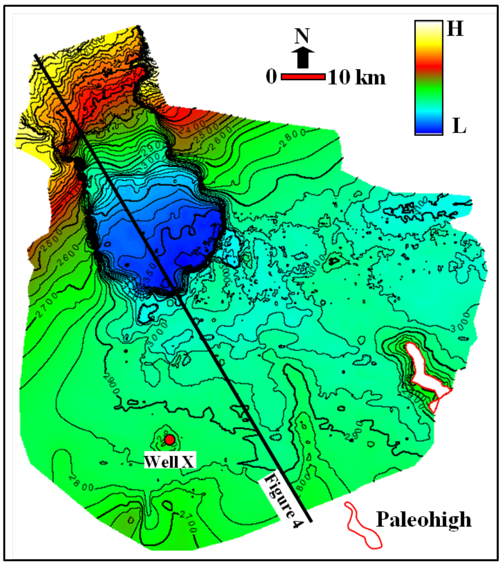

Figure 5. Depth map of Basal MTC in m TVDSS.

The flank domain is interpreted as an area with thin deposits on either side of the translational domain. The lateral apron domain is interpreted where the MTC material spills out from the translational domain. Further down-dip, the apron domain is the radially accumulation area of spill-out deposits pushed by the thrust complex in the toe domain. The translational and lateral apron domains are interpreted to be bordered by transpressional faults at the outer part of the bowl shape area which are orientated NW-SE or relatively parallel to the main transport direction (Figures 6 and 7). In the toe domain, the edges and inside of bowl shape area are confined and relatively perpendicular to the main NW-SE transport direction (Figure 6). This area is interpreted as the maximum compressional zone.

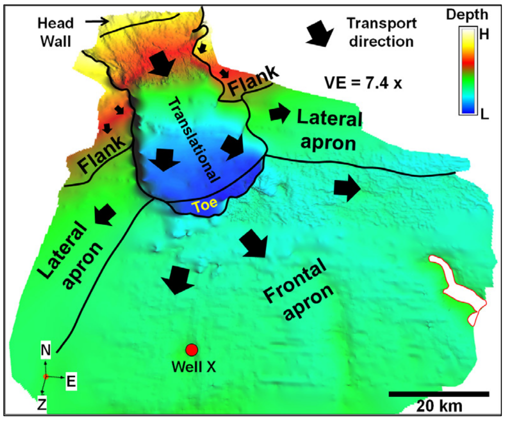

Figure 6. MTC anatomy based on basal depth map in 3D view. (X,Y,Z in meter)

The toe domain shows imbricate thrust systems. A unique feature in this area is negative inversion movement on the faults indicated by downthrown block movement along the hanging wall of the thrust planes (Figure 8). Movement sense is interpreted to change from thrust to normal fault system as the lateral stresses went from initial compression to later extension. Another possibility is that compaction of the thick MTC in the bowl area provided volume change that triggered extension.

The inversion in the toe domain is present in the proximal frontal apron domain which shows a characteristic change in geometry from thrusts to a series of normal faults dipping to the bowl shape area in the frontal apron domain (Figure 8).

In general the frontal apron domain can be divided into three main parts (Figure 9). The complex geometry of the basal detachment surface in this area indicates that the MTC movement mechanism plowed and deformed the sedimentary strata and generated gentle outward dipping wedge shape to this part of the MTC (Figure 9).

6. Discussion

The general NW to SE transport direction of the MTC is defined by the orientation of the lateral and frontal ramps, the headwall scarp, and the orientation of fold and imbrication structures (Figure 6). Along this transport direction, the stresses from change from extensional in the headwall and translational domain where the vertical stress is inferred to be σ1, to compressional in the toe domain where σ3 is vertical stress. Figure 10 is a generalized model of the stages in development of the MTC.

The condition before MTC formed (Figure 10-a) shows different dip angle of sediment unit below the future MTC which indicates that the basin underwent rotation to be due flexural subsidence that triggered instability in the slope area which was accentuated by fluid escape from within

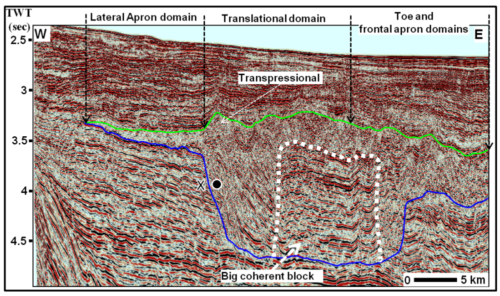

Figure 7. Big coherent block in translational domain.

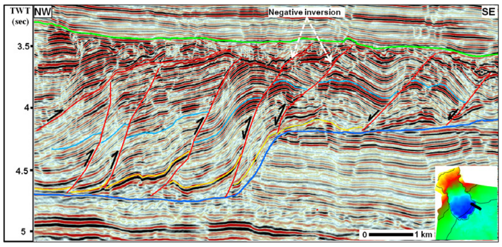

Figure 8. Negative inversion in the toe domain.

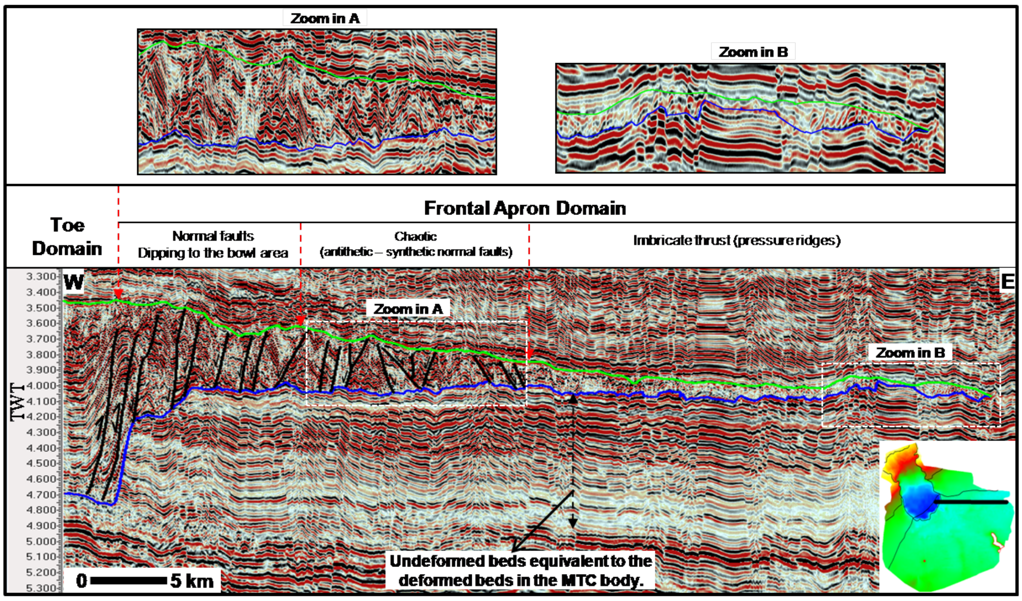

Figure 9. Toe to apron domain sections

Sedimentary Unit 2 which weakened the cohesion of the basal layer between two different sedimentary units. This became the potential sliding plane. Figure 10-b highlights the changes in stress during initial movement of the MTC. Note the change in orientation of both σ1 and σ3 along the body of the sedimentary mass. As the sliding mass moves down-dip, it becomes laterally constrained due to decreasing sliding energy.

The mass is forced in the vertical direction as minimum stress changes to be vertical and maximum stress becomes horizontal and generates compressional features. This thrust system became uplifted and transported the MTC material up the frontal and lateral ramps (Figure 10-b), and then continued to plow into and deform a much thinner sedimentary sequence which forms the frontal apron domain of the MTC.

The variation of internal structures developed in the frontal apron form three main sub-domains as discussed earlier. Much of the frontal apron domain is imbricated (Figure 9), and becomes progressively thinner passing away from the lateral and frontal ramps in the toe domain.

Negative inversion is observed in areas around the main lateral and frontal ramps in the toe and frontal apron domain, where extensional reactivation of the imbricate thrusts has occured (compare Figures 10-b and 10-c). The stress change is interpreted to be due to energy decrease or cessation of sliding movement from upper slope,

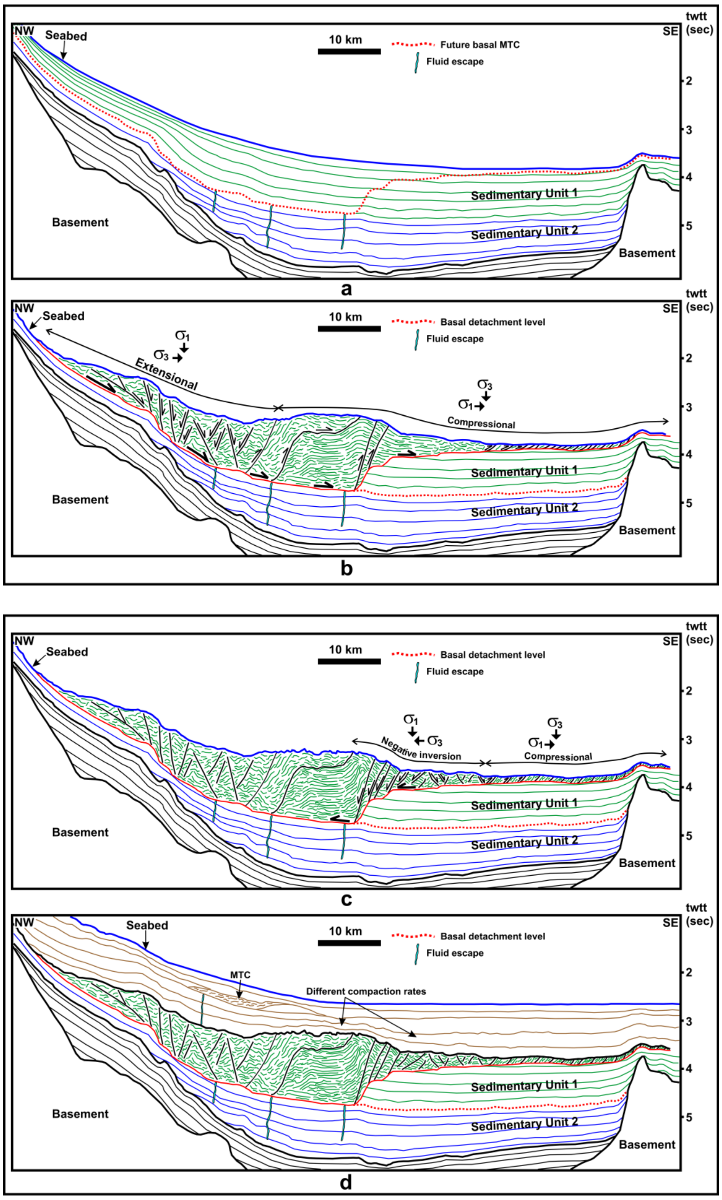

Figure 10. Sketch of the MTC formation model (seismic section in Figure 4).

so that compressional stresses ceased and the "overthickened" bulge of sediment collapsed back into the central bowl. The extensional faults mostly dip towards the centre of the MTC implying the mass released in this direction. The observations suggest that once the force driving at the back of the MTC diminished or ceased the wedge was too weak to maintain its taper in the compressional region, and it collapsed. Whether there was fluid loss and compaction driving the collapse is uncertain, but it is a likely mechanism.

The post-MTC sedimentary strata shows drape over and onlap onto the top MTC. (Figure 10-d). These sediments thin onto the thickest and highest morphology parts of the MTC. The rapid deposition of the MTC and subsequent burial caused the MTC to be overpressured as shown by fluid escape features and by the high pressure zone encountered in the MTC interval in Well X where they used 14 – 16 ppg of drilling mud.

The deformation rate was fast enough that syn-kinematic section is not present above the MTC. Assuming 1 mm/yr average sedimentation rate and seismic resolution of 20 m, then 20 m = 20,000 years which means that the MTC was emplaced faster than one seismic horizon. Based on the two main thrusts (Figure 4), the shortening of the MTC is estimated to be approximately 6.3 km and using the analogy to the Hawaiian coherent submarine volcaniclastic slumps strain rates of 6 to 60 cm/year (Morgan et.al., 2003). Based on these numbers, sedimentation rate assumption and seismic resolution, the emplacement time for the SMSB MTC is estimated to be about 10,000 years or faster since the SMSB MTCsedimentary strata is relatively weak compared to the volcaniclastic Hawaiian slump. Consequently this slow strain rate would not trigger a tsunami which is often associated with faster MTC movements such as the debris flows in the Storegga Slide Complex (Haflidason et.al., 2005).

A comparison of this MTC to others can be reviewed based on its size, internal characteristics and the processes that emplaced it. The volume of the SMSB MTC is 2438 km3 and it covers a total area of approximately 9000 km^2. With reference to Gee et.al., (2007) who compared the largest MTC's identified worldwide at that time, the SMSB MTC would rank as the second largest in terms of volume and the third largest in terms of areal extent.

Its internal characteristics show mostly coherent sedimentary strata with slump and slide structures inside the MTC. It is unique when compared to the other large MTC's as shown in Table 1. The largest MTC's in the world mostly consist of debris flows (Gee et.al., 2007 ; Canals et.al., 2004). Purely rotational slides or slumps which show preservation of the original internal structure of the MTC are rare and particularly of such a large size like the SMSB MTC. It ranks as the largest MTC of its kind in the world. Its coherent characteristics are interpreted to be due to its higher internal strength relative to the basal detachment layer and a relatively slow strain rate.

The relative efficiency of a MTC flow can be understood by comparing the ratio between area and volume. Using the parameter A/V2/3 (from Dade and Huppert, 1998) where A is area and V is volume, the SMSB MTC appears relatively inefficient with a value of 50, similar to the Brunei slide (Table 1 and Figure 11). The SMSB MTC and Brunei slide have relatively small areal distributions and have a similar bowl shape of the MTC body. However the Brunei slide volume is smaller compared to the SMSB MTC.

7. Conclusions

- The MTC is composed of a shale dominated sedimentary unit with high water content.
- It is a big slump which shows very clear coherent internal sedimentary layering. The MTC covers an area of at least 9000 km^2 with the total volume as 2438 km^3.

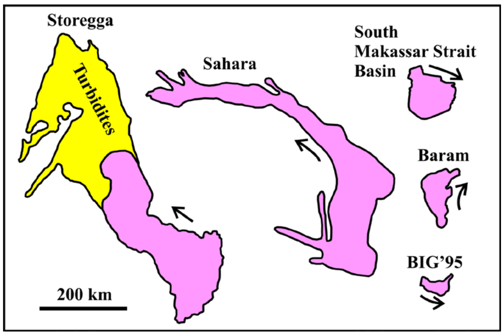

Figure 11. Area comparison of five giant MTCs. SMSB MTC shows relatively small area but it has second largest volume.

- The main transport direction is from high platform margin area in the northwest to the southeast as indicated by the orientation of lateral and frontal ramps to the bowl area.
- The deformed sedimentary strata in the main body of the MTC are correlated with the undeformed shale dominant strata of Sedimentary Unit 1 above basal detachment in Well X.
- The general fault patterns of the MTC indicates the MTC movement in the upper slope to the middle part of the bowl area is an extensional regime driven by gravitational force, which becomes compressional in the toe domain. Late negative inversion affected the toe domain, which in part maybe related to fluid loss and compaction in the bowl area.

Table 1. Comparison of five giant MTCs (modified from Gee et. al., 2007).

Storegga (Canals et.al., 2004)	Passive margin	3000	44000	212	Mostly debris flow with not completely imaged of outrunner	Earthquake activity associated with postglacial isostatic rebound. Presence of gas and gas hydrates.
Sahara (Embley, 1976 ; Masson et.al., 1993 in Gee et.al., 2007)	Active convergent margin	1100	30000	282	Mostly debris flow	Unknown
South Makassar Strait Basin (this study)	**Post rift sag basin/late foredeep basin with uplift process in the main land/platform.**	**2438**	**8985**	**50**	**Landslide blocks (Slide) and Slump**	**Sediment loading from Paternoster and overpresure of sediment deposits. Possibly to be due to inside and below the MTC formation overpressure, upward moving fluids from bellow MTC sediment stratal and basin rotation due to Paternoster uplift.**
Brunei (Gee et.al., 2007)	Active convergent margin	1200	5300	47	Internal Deformation	Sediment loading from Baram river and canyon. Sediment column weakened by upward moving fluids, possible anticline collapse. Presence of gas and gas hydrates. Earthquake activity likely.
Big 95 (Canals et.al., 2004)	Passive margin	26	2000	228	Landslide blocks and debris flow.	

• Trigger mechanisms are a combination of basin rotation, fluid overpressure and a weak basal layer in between two different sedimentary units.

• The strain rate of the MTC is interpreted to be relatively slow hence this type of MTC does not have the potential to generate tsunamis but could affect deepwater facilities built on the active MTC.

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