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Deep Sea Sediment Gravity Flow Deposits in Gulf of Tomini, Sulawesi

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Abstract

Micro plate collision against the Eastern Arm of Sulawesi since Pliocene has resulted in a major supply of terigenous sediments into Late Miocene rift-basins in Gulf of Tomini. Studies on offshore multi-channel seismic reflection data complemented by published on-land geological data indicate a series of tectonic events that influenced the depositional system in the Gulf of Tomini. During the Late Neogene, alternating pulses of terigenous sediments were deposited in the basins in the form of deep-sea slump-turbidite-pelagic sediments. A sediment gravity flow deposit system at the slope and the base of the basins changed gradually into a deep-sea pelagic fill system toward the center of the basins.

Three tectono-stratigraphy sequences (A, B, and C) separated by unconformities indicating the Late Neogene history and the development of the basins were identified. These tectonic processes imply that the earlier sediments in the Gulf of Tomini are accomplished by a differential subsidence, which allows a thickening of basin infill. The Pliocene-Quaternary basin fill marks the onset of a predominant gravity flow depositional system

Keywords: Gulf of Tomini, basin, slump, turbidite, pelagic, seismic stratigraphy

Sari

Tumbukan benua mikro dengan Lengan Timur Sulawesi sejak zaman Pliosen telah mengakibatkan pasokan sedimen terigenus dalam jumlah besar ke dalam cekungan regangan berumur Miosen Akhir di Teluk Tomini. Studi data seismik pantul saluran ganda dilengkapi dengan data geologi, yang telah dipublikasikan, menunjukkan urutan peristiwa tektonik yang mempengaruhi sistem pengendapan di Teluk Tomini. Selama zaman Neogen Akhir, pengendapan sedimen terigenus yang berlangsung di dalam cekungan berupa endapan slump-turbidit-pelagos. Endapan aliran gaya berat pada lereng bagian atas dan bawah cekungan, berubah secara berangsur menjadi sistem sedimen pelagos laut-dalam pada daerah pusat cekungan.

Tiga runtunan tektono-stratigrafi (A, B, dan C) yang dipisahkan oleh bidang ketidakselarasan dan menunjukkan sejarah serta perkembangan cekungan tersebut dapat diidentifikasi. Proses tektonik ini menggambarkan bahwa sedimen yang diendapkan terdahulu di Teluk Tomini telah dibarengi oleh proses penurunan dasar cekungan secara perlahan, sehingga menyebabkan penebalan sedimen pengisi cekungan. Sedimen pengisi cekungan berumur Pliosen-Kuarter menandakan awal dominasi sistem pengendapan sedimen aliran gaya berat.

Kata kunci: *Teluk Tomini, cekungan, slump, turbidit, pelagos, stratigrafi seismik*

Introduction

Background and Aims of Study

The Indonesian archipelago (Figure 1) is a group of micro tectonic plates, which are united by the convergence of three main tectonic plates; those are Indian-Australian Plate from the southeast; Eurasian Continental Plate from the northwest, and Pacific Oceanic Plate from the northeast. The predominant convergent plate margin in Indonesia is the active deep-sea trench-island arc system that is called the Sunda-Banda Arc. The arc displays the classic morphology of the outer rise, trench, fore-arc ridge, fore-arc basin, volcanic inner arc and back-arc basin (Hamilton, 1988).

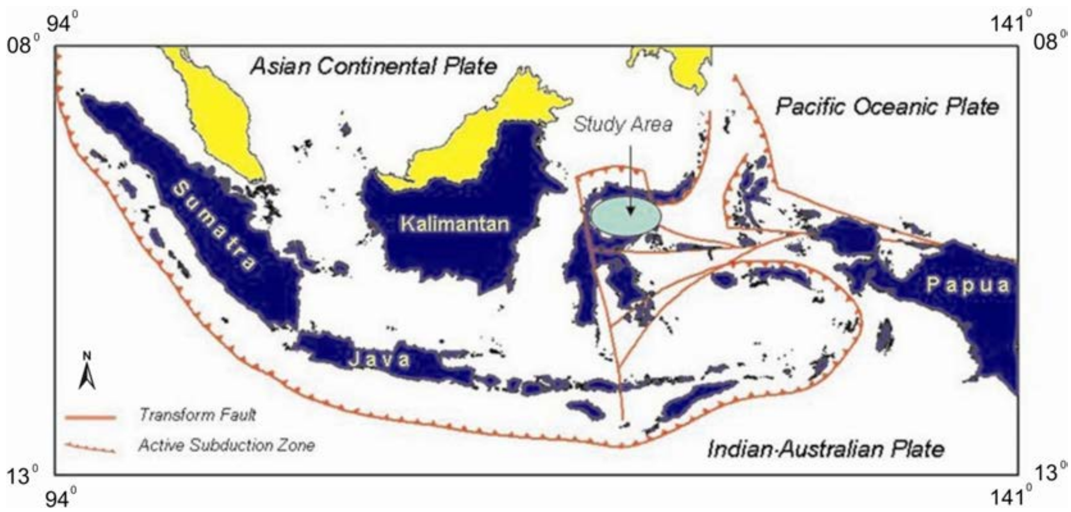

Figure 1. Major tectonic elements of Indonesian archipelago. Arrow pointed to the light blue area indicates the location of Figures 3 and 4.

Recently, Koesoemadinata (2006) proposed that the Indonesian archipelago tectonically could be divided into three plate tectonic regions, those are west, central and east Indonesia. West Indonesia, where the Sunda Platform acts as a continental core, is characterized by subduction tectonics between the Indian-Australian and the Eurasian Plates, with frontal subduction in the south of Java, and oblique subduction in the west of Sumatera. Central Indonesia which is ornamented by many micro continents and micro oceanic plates is separated from West Indonesia by Makassar Strait in the west, and trenches of Nusatenggara-Banda Arc in the south, Halmahera-Sangihe Islands in the east and Sulawesi Sea in the north. East Indonesia with Arafura Platform acting as a continental core and so called as the Banda Arc Complex is dominated by the collision between the Eurasian, Pacific and Indian-Australian Plates. The studied area (Figure 2) is situated in the poorly understood region, where it precisely lies in a transition zone separating the northern arm of Sulawesi Volcanic Arc to the north from the Banggai-Sula micro-continent collision, Maluku Sea Plate subduction systems to the east and Palu-Koro Transcurent Fault to the west.

According to Karig *et al.* (1980), the tectonic evolution of convergent plate margins makes the back- and fore-arc basins are very sensitive to be studied because of the complex interaction between tectonics and sedimentation processes. The basins form an important element of convergent plate boundaries. They represent large basins as major sites of a sediment accumulation with a volcanic/plutonic arc representing the major source of basin fill.

An offshore sedimentary basin situated around the western and southeastern regions of the Sunda Shelf has been explored and considerably well informed. An oil exploration and geological studies of the North Sumatera fore-arc Basin (Izart *et al.*, 1994), Central Sumatera Basin (Matson and Moore, 1992), West Sumatera Basin (Beaudry and Moore, 1985), East Java Basin (Letouzey *et al.*, 1990; Brensden *et al.*, 1992; Koesoemadinata *et al.*, 1999; Basden *et al.*, 2000; Sribudiyani *et al.*, 2003) and fore-arc basin off southwest Sumatera and southwest Java (Susilohadi *et al.*, 2005) give a valuable information on the geological evolution of this region. Studies of central Indonesian basins such as: Flores and Savu-Lombok fore-arc Basins (Silver *et al.*, 1986; Van Weering *et al.*, 1989; Van der Werff *et al.*, 1994) and Bali back-arc basin (Kusnida, 2001) provide a broad outline of the geometry and sedimentary sequences of this active margin system and portray the Cenozoic evolution of the basin.

According to the Indonesian offshore basin status map (Dirjen Migas, 2003), the Gulf of Tomini where the Tomini and Gorontalo physiographic basins are situated is still unexplored, and so far has never been studied and discussed considerably in detail and it is still poorly understood. For this reason, it

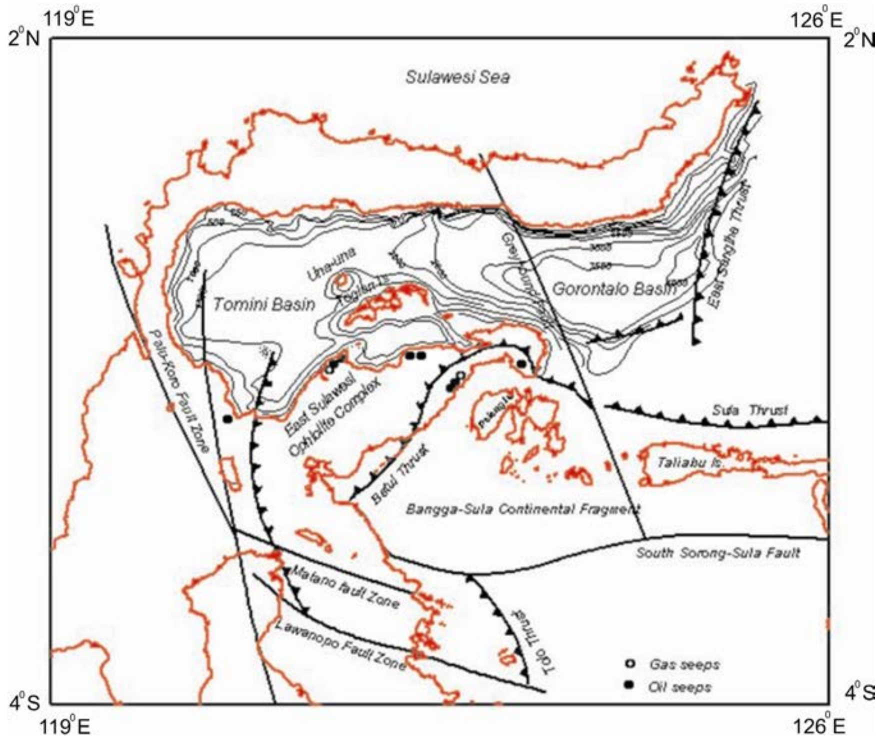

Figure 2. Tectonic elements of East Sulawesi where the Tomini and Gorontalo Basins are situated (modified from Silver *et al.,* 1983).

was decided to study the basins within the Gulf of Tomini to determine their stratigraphic successions, structures and depositional characteristics with a considerable interest for scientific purposes.

Setting of the Studied Area

The tectonic complexity is displayed in the central part of Indonesia as the results of a series of Neogene collisions between island arcs, continental fragments, and the Australian Continent. The Gulf of Tomini (Figure 2) is characterized by a bathymetric low of slightly below 1500 m in the Tomini Basin, and a bathymetric low of a slightly below 4000 m depth in the Gorontalo Basin to the east. The island group of Togian characterizing the NE-SW outer traversed highs together with the Una-Una Islands where the Colo Volcano is situated, separates the Tomini Basin in the west from the Gorontalo Basin in the east. The presence of dunite in Colo Volcanic products may indicate that the magma source had been through an oceanic material that possibly is part of East Sulawesi Ophiolite Complex (Silver *et al*., 1983).

On the basis of geophysical and geological expeditions in SW Maluku Sea, NW Banda Sea, and in the eastern arms of Sulawesi, Silver *et al*., (1983) indicate that the Gulf of Tomini is underlain by an oceanic crust, and its south edge is uplifted against the thrust. The Sulawesi ophiolites that can be traced offshore indicate their origins as the basement of the Gulf of Tomini. Permana *et al*., (2002) indicate that the Gulf of Tomini is dominated by an east-west direction of a steep graben-like structure. To the northern, the gulf is bordered by the north arm of Sulawesi and to the south is bordered by the East Sulawesi Ophiolite and Old Mélange Complexes. These may suggest that the gulf has been formed as the result of the opening and rotating of North Sulawesi in Neogene about 5 Ma (Walpersdorf *et al*., 1998).

Seismological data (Permana *et al*., 2002) show two different patterns beneath the Colo Volcano. The first pattern, at 100 to 200 km depth, is related to the southeast subduction of Sulawesi Sea Plate, and the second, directly beneath the Una Una Island at 70 to 100 km depth, is related with the northwest collision of Banggai-Sula micro-continent to the

Eastern Arm of Sulawesi to in some places is shows imbricated thrusts.

Methods and Techniques

The equipments used during the survey include a Multi-channel seismic reflection acquisition using a 700 m long of 28 high resolution channels group streamer, where the distance of each channel was 25 m. The Sleeve I/O air-gun array of 210 cu.inch, 150 cu.inch, 100 cu.inch and 70 cu.inch with power output of 1500 psi triggered by a Marine Controller Geometric Computer, was applied as a sound source for the seismic data acquisition. The geometry applied in this system was a streamer stretching as long as 700 m, which was hauled at 80 m behind the stern. The air-gun array was placed at 50 m from the stern resulting a distance between the air-gun and the first streamer channel as long as 30 m. The shooting was carried out every 25 m at the speed of 3-4 kts. This configuration resulted in 14 folds that obtained a 5 second penetration.

Seismic data processing was performed by using ProMax 2D software 2003.3.3 version. The following steps were applied to optimise the seismic data quality:

- Geometry that is a process of acquisition parameter input in seismic traces,
- Amplitude Correction, F-K Analisis/ Frequency Filter,
- CMP Sorting (seismic traces arrangement on the basis of Common Mid Point/CDP),
- Velocity Analysis, NMO Correction, Muting (omiting some recorded noises such as first break, spherical wave), Deconvolution, Stacking (summing of some corrected NMO of seismic) and Migration (reconstruction process of seismic profile to correct the reflection points to its true points).

The stratigraphic framework has been subdivided into several seismic intervals (depositional sequences) on the basis of sequence boundary and facies analysis (Vail *et al.*, 1977). The navigation in the surveyed area was carried out by means of the Global Positioning System (GPS) using EIVA A/S NAVIpac software. The marking of time and fixed point on recorder was plotted using an Annotator device. The database for this study is complemented by the on-and offshore geological data, which have been collected and published recently.

Results

Structures

The seismic reflection profiles indicate that the southeastern part of the Gulf of Tomini exhibits a prominent tectonic features of a series of buried faulted basement block that trends slightly NE-SW characterizing the submarine basement ridges which reached its depth greater than 4200 m and it is associated with Togian Islands Complex (Figures 3 and 4). The southern part of the Gulf of Tomini has been uplifted along the Togian Islands, which in turn is partially overthrust that has developed possibly since Pliocene. Seismic profiles also indicate that the largest part of these blocks divides the Gulf of Tomini into the Tomini Basin in the west and the Gorontalo Basin in the east.

The flat-lying, undeformed sediment filling in the centre of the basins within the gulf and lack of the faults underneath indicates that these normal faults have not been active prior to the opening of the Gulf of Tomini. The east-west widening of the gulf dimension and a smaller morphology can also be explained probably related to an east-west pull-apart basin formation. Based on the seismic profile interpretation, four general tectonic phases can be portrayed in the Gulf of Tomini:

a. Normal faults were active during the earliest phase of tectonism, forming a Late Miocene extensional basin that was filled continuously by Late Miocene sediment deposits.

b. The thrust structural style recognized in the Gulf of Tomini indicates the inversion tectonic related to the Pliocene collision of the Eastern Arm of Sulawesi with the Banggai-Sula micro continent, where the compression movement has modified the previously extensional tectonic environment within the gulf. It involved the basement differential subsidence of the basins and the formation of the Gulf of Tomini.

c. The back-arc thrust zone has been formed since Pliocene, indicated by the uplifted basement (see Figure 3).

d. The eastward widening of the gulf indicates a north-south increase in the total amount of shortening.

Seismic Stratigraphy

The seismic reflection profiles show the development of three seismic sequences A, B and C.

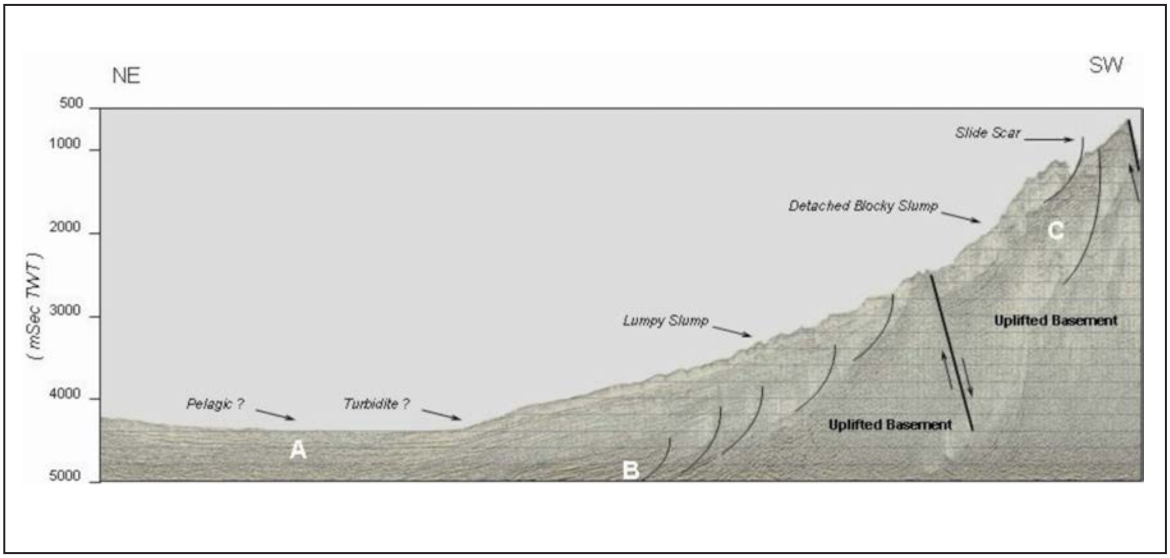

Figure 3. Seismic profile across the Gorontalo Basin indicating sediment gravity flow deposits on the centre of the basin derived from both the NE and SW directions. For location see Figures 1 and 2.

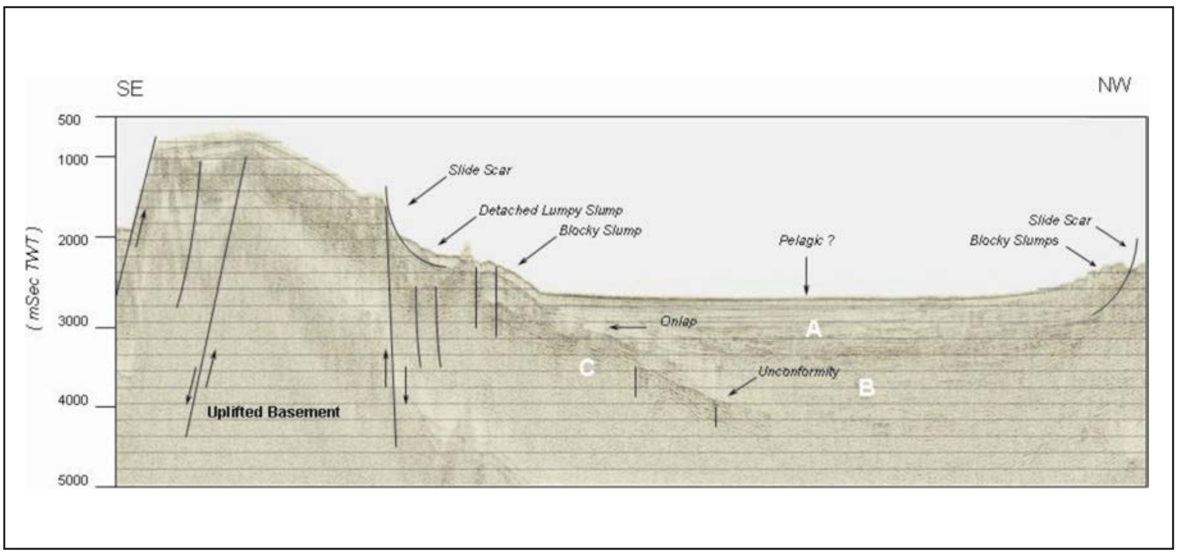

Figure 4. Seismic profile across the Tomini Basin indicating sediment gravity flow deposits on the centre of the basin derived from both the SE and NW directions. For location see Figures 1 and 2.

Seismic Sequence A

This sequence extends into the center of the basins, and gradually thins to a few reflectors above the flanks of the basins with the thickness of less than 100 msec. The sequence pinches out against the top of the basement high, especially in the southern flank of the basins. As recognized in the Bali back-arc basin (Kusnida, 2001), the seismic facies in the Tomini and Gorontalo Basins can also be subdivided into two sub-sequences with different reflection characters. In the Tomini Basin (Figure 4), the lower part of sequence A has a thickness of 600 msec TWT in average and it is composed of alternating transparent to weakly reflective beds of a limited continuity. At the base, a minor base of slope mound deposits is found and lap onto the seismic sequence C at both flanks of the basin. The upper part is 400 msec TWT thick and consists of a band of continuous reflectors alternated by a chaotic, low amplitude and low frequency. The geometry and seismic facies of both sub-sequences indicate an active lower slope progradation similar to the seismic sequence B underneath. Both the weak reflectivity and the low seismic coherence of the lower seismic facies unit indicate slump deposits. The high amplitude reflections of the upper sub-sequence suggest an alternation of turbidites and pelagic sediments. Following Mc. Caffrey and Silver (1981), this sequence possibly indicates an alternating Quaternary turbidite-pelagic deposits.

Seismic Sequence B

This sequence is characterized by a semi transparent amplitude mostly chaotic and medium at the base-of-slope of the basins, and stratified, divergence with parallel reflectors toward the central part of the basin. This difference presumably reflects a differentiation of the sedimentary facies of the basin fill. This sequence has slightly been deformed, especially along the margins of the basin, and laps onto the sequence C underneath. In the center of the basins, the sequence has a maximum thickness of 400-600 msec TWT and is faulted. Toward the flanks of the basins, it rapidly thins to a few hundred meters, and extends northward across graben and basement high in the center of the basin, as a parallel bedded depositional unit. The seismic sequence B laps onto the seismic sequence C at both flanks of the basins beneath the seismic sequence A. The seismic facies is composed of relatively steep north-dipping oblique progradational reflectors, which downlap the seismic sequence C and has an interval velocity of 2000 m/s. The reflection pattern is characterized by a semitransparent to chaotic, even bedded, high amplitude, low frequency reflectors. The upper boundary is erosive and characterized by a high amplitude reflector. The depositional setting and seismic facies are typical of an active slope mass-flow progradation of submarine fan complex (Vail *et al*., 1977). The same reflector is also recognized in the entire Lombok forearc basin (Van der Werff *et al*., 1994) and Bali back-arc basin (Kusnida, 2001). This reflection character and configuration suggest the presence an alternation of turbidite and thin bedded pelagic sediments possibly of Lower Pliocene.

Seismic Sequence C

At the base-of-slope of the basins, this seismic sequence acts as the basin floor for the seismic sequence A and B, which fills the depressions between its basement highs underneath. The lower sequence boundary is formed by seismic reflection terminations which lap on the basement. In the center of the basin, the sequence boundary is slightly erosional to paraconformable and is covered in the south by the downlapping reflectors of sequence B. The seismic facies is characterized by continuous, even bedded, high amplitude, low frequency reflectors and has an interval velocity of 2600 m/s. On the basis of its depositional setting and reflection configuration (Vail *et al*., 1977), the lithofacies is interpreted as a siliclastic sequence, which was deposited in a deep water environment. Following Mc. Caffrey and Silver (1981), it is assumed that the age for the unconformity on the top of the block faulted, is Late Miocene, thus assigning that this sequence is considered as having a Miocene age. The unconformity on top may mark the regional important of Late Miocene tectonic phase.

Basin Slope Sediments

At the base of the basin slope, the seismic sequence C is overlain by sediments with an age that overlaps the seismic sequence B, but have characteristics similar to the seismic sequence A. Seismically, the sequence C from this zone is relatively lithified and faulted, reflecting the exposure of an acoustic basement for the seismic sequences A and B.

In the Gorontalo Basin (Figure 3), the seismic sequence B is a thick deposit. The lithologic unit corresponding to the seismic sequence B is distinguished from the seismic sequence A by an increase in lumpy block elements and a decrease in the pelagic material. It is also characterized by a rapid deposition and high frequency of locally derived turbidites generated by rapid changes in the seafloor topography, which resulted in the slope instability. Blocky and lumpy slumps deposits characterize this zone.

Basin Plain Sediments

Two main seismic sequences (seismic sequence A and B) occur above the acoustic basement (seismic sequence C), which is well imaged on Figure 3 and 4. In the ascending order, these seismic sequences consist of sediments with short, irregular reflectors that passes up into sediments with strong, irregular, and laterally discontinuous reflectors (seismic sequence C). The seismic sequence B comprises ± 600 msec TWT of irregularly reflecting sediments, with stronger, chaotic reflections that are concentrated at the base-of-slope. The seismic sequence A comprises an upper unit of acoustically intercalated sediments with markedly weakly semi parallel reflectors in longer segments and an upper unit of stronger, more continuous reflectors, many displaying diffraction hyperbolae, especially at the base-of-slope of the Gorontalo Basin (Figure 3).

At the base-of-slope of the basins, the seismic sequence A represents younger deep-sea fan sediments, and sequence B represents older deep-sea fan sediments. At the base-of-slope of the basins, the seismic sequence B is characterized by a high degree of deformation and fracturing, consistent with its long history of movement, burial and deformation. Internal structures in these units are poorly preserved. The seismic sequence A is also composed of pelagic interspersed with thick turbidites. The zones of harder reflectors in the upper parts of the seismic sequences A and B are made up of large numbers of short, concave-downward segments, some of which represent refractions from hard zones lying within the sediments, possibly thin slumps-turbidite intercalated with pelagic sediments.

Discussion

Analysis of multi-channel seismic reflection profiles has revealed that the Tomini Basin in the west and the Gorontalo Basin in the east comprise the western and eastern depocenters containing thick (over 1500 and 2500 m, respectively) Late Neogene–Quaternary sediments. Basin infill that began in the Late Miocene caused a regional extension along the western and eastern basin margins, bringing large volumes of sediments into the basin. Most of these sediments was deposited directly onto the base of the slope and basin floor, resulted in widespread sediment gravity flow deposits, especially in the Gorontalo Basin (Figure 3). Since the Late Miocene, sediment gravity flow deposits have retreated rapidly in an updip direction as the tectonic activity along the basin margins waned significantly. The apparent dominance of sediment gravity flow deposits in the Gorontalo Basin indicates that the sedimentation pattern in this basin is quite different from those in the Tomini Basin in the west where basinal turbidite and hemipelagic sedimentation had prevailed throughout the Pliocene and Quaternary. The maximum two-way travel-time sediment thickness in the Tomini Basin, about half of that of the Gorontalo Basin, further suggests more massive sedimentation in the Tomini Basin.

Sediment gravity flow deposits are an important processes controlling the sedimentary structure and growth patterns of the Tomini and Gorontalo Basins during at least Pliocene. The overall development of sediment gravity flow deposit features on the Gulf of Tomini slopes has been favoured by a local tectonism and high sedimentation rates on the upper slope sediments, which correspond to differential basement subsidence of the basin. Geometrical relationships between sediment gravity flow deposits and the deformed basin-plain sediments (pelagic) indicate that the deformation occurred mainly during the deposition of slumps and turbidites. Slope failure induced by the rapid sedimentation and the frequent earthquakes are proposed as the driving mechanism for this deformation.

Conclusion

Three tectono-stratigraphy sequences separated by unconformities in the Gulf of Tomini indicate the Late Neogene history and the development of the basins. During the Late Miocene, the basins within the Gulf of Tomini seem to have been stable. However, here the emplacement of a large sediment gravity flow deposits, resulted from the Late Neogene collision between the East Sulawesi Ophiolite Belt and the micro continent Banggai-Sula platform were examined. The collision system between the Eastern Arm of Sulawesi and Banggai-Sula micro continent since Pliocene forms the Gulf of Tomini and the two basins. Submarine sediment gravity flow is the major mechanism of sediment transportation from the slope to deep-sea environments in the Tomini and Gorontalo Basins.

In the Gulf of Tomini, most slides appear and are related to a rapid progradation of turbiditic fan sediment units beyond the base of slope of the basins. Prior to the collision, the pelagic sedimentation dominated the slope processes in the basins, with focused deposition in deep scars. Earthquakes seem to be the main triggers of submarine sediment gravity flow deposits in the Gulf of Tomini.

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