1 Introduction

Sedimentary waves are large-scale wavy bedforms, extend up to several kilometers in length and tens of meters in height, and are commonly found in modern deep-sea environments. (Wynn and Stow 2002a). Due to the abundant information about paleoceanography and deep-water depositional processes, the interests of sediment waves have been increasing since recent decades. Sediment waves, located inside the bend of the Taitung Canyon, were characterized by an upward migration and showed mass transport deposits (MTDs) at the bottom, while the inner curve of the bend was subdivided into lower and upper wavy transition units. The sediment waves on the outer curve of the bend were characterized by vertical accumulation, and there was no mass flow deposit at the bottom. According to the geometry of the sediment waves, the calculated flow thicknesses across the entire wave field ranged from 196 to 356 m, and the current velocity ranged from 15 to 21 cm/s. The morphological characteristics, the internal structure, and the distribution of sediment waves, as well as the numerical calculations, evidenced that these sediment waves had formed by turbidity currents. The development of the sediment wave field in eastern Taiwan was found to be similar to that in southwestern Taiwan. It was the sedimentary response of the tectonic movement between 3 and ~1 Ma which created the sedimentary systems where gravity flow processes predominated. Turbidity current sediments settled in the place of less topographical constraints or overflowed in the bend section of the Taitung Canyon, which resulted in the formation of sediment wave fields.

Abstract: Based on numerous high-resolution seismic profiles, sediment waves and their distribution, morphological characteristics, internal structure, and potential origins were revealed in the eastern waters of Taiwan. The sediment waves are located at the junction between the Taitung Canyon and other canyons in the slope. The wave length and the wave height of a single waveform ranged from 0.8 to 7.2 km and from 18 to 75 m, respectively (NE-SW direction). Sediment waves, located inside the bend of the Taitung Canyon, were characterized by an upward migration and showed mass transport deposits (MTDs) at the bottom, while the inner curve of the bend was subdivided into lower and upper wavy transition units. The sediment waves on the outer curve of the bend were characterized by vertical accumulation, and there was no mass flow deposit at the bottom. According to the geometry of the sediment waves, the calculated flow thicknesses across the entire wave field ranged from 196 to 356 m, and the current velocity ranged from 15 to 21 cm/s. The morphological characteristics, the internal structure, and the distribution of sediment waves, as well as the numerical calculations, evidenced that these sediment waves had formed by turbidity currents. The development of the sediment wave field in eastern Taiwan was found to be similar to that in southwestern Taiwan. It was the sedimentary response of the tectonic movement between 3 and ~1 Ma which created the sedimentary systems where gravity flow processes predominated. Turbidity current sediments settled in the place of less topographical constraints or overflowed in the bend section of the Taitung Canyon, which resulted in the formation of sediment wave fields.

Key words: Huatung Basin, Taitung Canyon, sediment wave, turbidity current, formation mechanism


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and evolution of sediment waves in the Huatung Basin located in the eastern waters of Taiwan.

In this study, the sediment wave fields in the Huatung Basin were identified based on multibeam bathymetry data, single-channel seismic reflection profiles, and multi-channel seismic profiles. Moreover, the distribution, geometry, and seismic features were described in detail. Combined with the geological setting of the Taiwan Island, the origin and formation processes of these sediment waves were discussed. Furthermore, the flow characteristics of turbidity currents in the sediment waves were calculated by simple numerical modeling. Considering the above information, we suggested that the sediment waves resulted from turbidity currents and that the arc-continent collision on the Taiwan Island could have had a strong influence on the formation and development of the sediment waves between 3 and ~1 Ma.

2 Geological Settings

The Huatung Basin is located off the eastern coast of the Taiwan Island. It is bordered by the Coastal Range of Taiwan and the North Luzon Arc to the west, the Gagua Ridge to the east, and the Ryukyu Trench to the north (Fig. 1). Three major submarine canyons are in the Huatung Basin, namely the Hualien Canyon, the Chimei Canyon, and the Taitung Canyon (from north to south). These canyons collect the sedimentary discharge from the Central and Coastal Ranges. However, there are numerous smaller submarine valleys and channels along the eastern coast (Fig. 1), many of them eventually merge into one of the three major canyons (Ramsey et al., 2006).

The Taitung Canyon is the most prominent and largest canyon in the Huatung Basin. The Taitung Canyon originated from the southern end of the Longitudinal Valley near Taitung and is connected to the Beinan River. The Beinan River is one of the main rivers in eastern Taiwan. It then extends southward along the axis of the Taitung Trough. Afterward, the Taitung Canyon turns sharply eastward through the Luzon Island Arc between the Lanyu and the Lutao Islands. The NE-trending canyon then almost crosses the whole Huatung Basin, of which the lower segment is characterized by several valleys and channels. Eventually, the Taitung Canyon ends near the intersection of the Gagua Ridge with the Ryukyu Trench (Schnürle et al., 1998; Sibuet et al., 2004).

The offshore slope of eastern Taiwan is driven by a variety of erosional processes, including mass wasting.
landslides or mass transport deposits (MTDs), are ubiquitous and affect the whole eastern coast of Taiwan. Moreover, energetic turbidity flows can erode and transport huge amounts of terrigenous materials from shelves to the deep sea through submarine canyons.

The Huatung Basin is a semi-enclosed and deep-water basin linked with the West Philippines Basin by the Ryukyu Trench. It is also connected with the South China Sea through the Bashi Strait. The semi-enclosed basin physiography confines the exchange and intrusion of bottom currents (Fig. 1). The Kuroshio Current (KC) is the most important current in the eastern waters of the Taiwan Island (Hsin et al., 2008; Luan et al., 2012; Liu et al., 2017). The KC originates from the northern branch of the North Equatorial Current and flows northward along the eastern coast of the Taiwan Island. The main stream of the KC traverses from the eastern coast of Taiwan to 100-150 km offshore and its depth reaches 800-1000 m. There are few studies describing bottom water circulation in the Huatung Basin. Therefore, the deep-water circulations in that basin are still poorly understood. The Northern Pacific Deep Water (NPDW) may be the predominant bottom current in this region, and flows in the NW-direction (Lüdmann et al., 2005).

3 Dataset and Methodology

The present study was effectuated by interpreting multibeam bathymetry data, single-channel seismic reflection profiles, and multi-channel seismic profiles. These data were collected by the Guangzhou Marine Geological Survey (GMGS) between 2013 and 2014. The two-way travel time (TWT) of the profiles was converted into depth using a velocity of 1.5 km/s for the water column and a shallow sediment velocity of 1.6 km/s.

The multibeam bathymetry data were acquired by GMGS in 2013, and by utilizing SeaBat 7150 deep water multibeam bathymetry system mounted on the vessel. The working depth ranged from 100 to 15,000 m, the maximum coverage angle was 150°, and the maximum simultaneously produced beams was 880. The bathymetric data were processed and mapped using MB-system and GMT software.

The single-channel seismic profiles were collected by a GI gun point source and are characterized by a 0.25 ms sampling rate, a 33 m offset, and an 1150 cubic inch volume. The multi-channel seismic profiles were collected by the seismic data acquisition system, which are characterized by a 6 km length, a 480-channel streamer with 2 ms sampling rate, a 12.5 m group spacing, and a 5080 cubic inch airgun array at a full-fold of 80. The dominant frequency of the near-surface seismic data is about 50 Hz.

4 Results

4.1 Distribution and geometry of the sediment waves

Sediment wave field 1 lies near an unnamed canyon between the Chimei Canyon and the Taitung Canyon at a water depth of 4500-5300 m, and covers an area of approximately 2045 km². The multibeam topographic map shows that the wave crestslines are generally SW-NE oriented, which are roughly parallel to the regional bathymetric contours (Fig. 2a). The sediment waves in field 1 evidenced a variety of dimensions under the slope of 0.7°-1.6°. The wavelengths (WL) generally range from 1.2 to 7.2 km. The wave heights (WH) vary between 18 and 75 m. Furthermore, the WL:WH ratios range from 44 to 96 (Fig. 2b). The single-channel seismic reflection profiles show that most sediment waves usually display asymmetrical morphology with thicker, steeper, and shorter upslope flanks. This could be interpreted as being linked to turbidity currents (Fig 3a). In the downslope sense, the thickness, length, and height of the sediment waves become thinner and reduced. The downslope decrease in those parameters indicates that the source of the wavy sediments probably came from the upslope direction.

The course of the Taitung Canyon changes by a sharp 90° from the NE to the NW near the Gagua Ridge (Fig. 1b). A small sediment wave zone occurs at the high-sinuosity bend, which is named sediment wave field 2 and covers a ~820 km² area (Fig. 2a, Fig. 3, and Fig. 4). Due to centrifugal forces at the curves of the channel, the extent and dimension of the sediment waves indicate turbidity current overspill. Indeed, the outer bends are generally larger and have steeper curves than the inner bends of the meander loops or bends of the channel (Nakajima and Satoh, 2001). However, sediment supply and accommodation for sediment waves are constrained because of the barrier of the seamount in this area. Accordingly, sediment waves on the outer curve of the channel are characterized by vertical accretions and smaller scales (Fig. 4c and 4d). The characteristics of the wavy sediments were different on the inner (left-hand) and outer (right-hand) bends (Fig. 4). The WL and WH of the sediment waves on the outer bend are about 1.2 km and 37.5 m, respectively, and the WL:WH ratio is 32. Moreover, the sediment waves on the inner bend generally have WL, WH, and average slope values in the range of 2-4 km, 57-75 m, and 0.8°, respectively. The WL:WH ratios ranged from 35 to 57. The sediment wave migrating upslope has a distinct feature. That is, the stoss sides are generally shorter and thicker than the lee sides. The reflection events of the sediment waves are medium amplitude with high continuity. Additionally, the ridges of the sediment waves overlap and show regular migration in the upward sense. This is completely different from the occurrence of the rotating fault planes in the slump, which can eliminate similar topographic features, such as creeps (Chiang and Yu, 2011; Liang et al., 2018).

4.2 Seismic features and stratigraphy of the sediment waves

The sediment waves in field 1 form an undulating stratified unit up to 500 ms (TWT) thick, and this thickness decreases downslope to approximately 300 ms. The lower boundary of the sediment wave unit is a distinct unconformable surface, which will be termed S1, and presents across all the sediment wave zone. This surface is
irregular and displays the characteristics of down-cutting and erosion for the turbidity current channels (Fig. 4a and 4b). The unconformity S1 separates the continuous and wavy-reflective upper layer from the relatively chaotic lower layer. The wavy-stratified facies forming the sediment wave unit are overlying and infilling the lower chaotic seismic stratigraphic unit. Also, they exhibit strong-amplitude chaotic reflections which are partially alternating with weak-amplitude semitransparent reflections. This defines MTDs of which the bottom surface is named S2.

Based on the overall geometries, morphology, and internal seismic reflection configurations, the wavy stratified facies forming the sediment wave unit can be subdivided into two sets of seismic stratigraphic units. The top section of the sediment wave unit is composed of continuous reflections of long waves of medium amplitude. The stratified reflections within each sediment wave generally showed an unconformable configuration, with onlapping, downlapping and/or convergent reflections approaching the waves’ crests. The sediment wave thicknesses also varied within each wave. The sedimentary sequence on the upslope flank was thicker than that on the downslope flank. This indicates that the waves have migrated in the upslope direction. The continuity of the seismic reflections of the lower unit is worse than that of the upper unit. Some of the wavy geometries represent the early growth of the sediment waves (Fig. 4a and 4b).

5 Discussion

5.1 Origins of the sediment waves

Multiple huge sediment wave fields were identified in the waters of southwestern Taiwan, which are mainly distributed at the flank, mouth or turns of the canyons/
channels. The WL and the WH of the sediment waves ranged between 1.5–7.2 km and 15–110 m, respectively, and were perpendicular or oblique to the axes of the canyons/channels. Regarding the genesis of the sedimentary waves in this region, several origins were identified, which are turbidity current, bottom (contour) current, upwelling current, and slope failure (Wang et al., 2008; Ding et al., 2010; Xu et al., 2012; Kuang et al., 2014; Xu et al., 2014; Gong et al., 2015; Yin et al., 2015). Some authors suggested that those sediment waves had developed by turbidity currents over spill from the flanks of the canyons or were unloaded in the mouth of the canyons (Wang et al., 2008; Ding et al., 2010; Kuang et al., 2014). Wang et al. (2008) and Ding et al. (2010) suggested that the development of the sediment waves is controlled by the Neogene Tectonic activities in the Taiwan Island and adjacent areas. The tectonic movement enhances the intensity and frequency of turbidity current activities, which could have favored the formation of the sediment waves roughly 1.2 Ma. The uplift and erosion of the Taiwan Island and the Dongsha uplift supplied sufficient terrigenous sediments for the formation and development of the sediment waves. Gong et al. (2012) suggested that the bottom currents, induced by the intrusion of the NPDW into the South China Sea, had an important influence on the formation of sediment waves in the area. The tectonic setting of the eastern Taiwan region and the southwestern Taiwan region are both affected by the oblique collision between the Philippine Sea Plate and the Eurasian continent. Furthermore, landslide, slump, and
turbidite sediments are widespread, which develop into canyons and/or gullies. The same regional geological conditions for developing large deep-sea sediment waves are found in the southwestern and eastern regions of Taiwan.

The Huatung Basin is a semi-enclosed and marginal deep-water basin. It is connected with the West Philippines Basin by the Ryukyu Trench, the latter limits the intrusion of oceanic bottom currents. There are few studies that describe the bottom water circulation in the Huatung Basin (Lüdmann et al., 2005). The NPDW flows in the NW-direction and can be considered as the predominant bottom current in this region. This bottom current direction is oblique to the alignment of the waves’ crestlines, which are roughly parallel to the bathymetric contours (Fig. 2a). This is not compatible with existing models of bottom current generated sediment waves developed on slopes. As a result, the alignment of the wave crests indicates that the sediment waves have unlikely been generated by bottom currents. In addition to main scarp, surface of rupture, and thrust fault, large-scale faults or diapirs, which would disturb and displace the stratified layers, are absent under the wavy stratified unit. The evidence indicates that the sediment wave unit is neither folded nor faulted, and its development, therefore, is not directly related to slope failure or gravitational mass movements. This leads to the conclusion that the waves have been generated by the action of turbidity currents.

The formation, evolution, and scale of the wavy sediments are closely related to sediment supply, topographic variation, accommodation, and sedimentation dynamics (such as turbidity current direction, and flow velocity). The accommodation provides the space for the development of wavy sediments, while the sediment supply and sedimentation dynamics determine the shape and scale of the sand waves (Wang et al., 2009; Bao et al., 2014; Tan et al., 2017). The sediment waves in field 2 are distributed at the high-sinuosity bend of the Taitung Canyon. The growth pattern migrating upslope, the well-bedded internal structure, and the development on the backslopes of levees signify that the sediment waves originated from turbidity currents. The channel depth of the canyon is defined as the vertical relief from the channel floor to the levee crest. The channel depth on the high-sinuosity bend is lower than the upper reaches of the canyon. The average channel depths on the high-sinuosity bend and at the upper reaches are about 370 and 500 m, respectively (with respect to the surrounding seafloor). Due to the effects of the centrifugal force and the weakening of the topographical constraint, it is very likely that the sediment waves in field 2 resulted from turbidity current overspill. On the contrary, downslope turbidity currents explain the formation of the sediment waves in field 1. Indeed, there are several indicators that strongly support that idea, which will be presented accordingly.

Firstly, the characteristics of the sediment waves in field 1 are similar to the turbidity current wave fields in southwestern Taiwan. The magnitude of recent sediment waves identified in the Huatung Basin is similar to that in southwestern Taiwan. The wave crestlines are roughly
parallel to the bathymetric contours, the sediment waves have an upslope wave migration, there is an asymmetry between the wave profile and the steeper and larger flank generally facing downslope, and there is a variation in sediment thickness across the wave, with the upslope flank being thicker than the downslope flank.

Secondly, the thickness, length, and height of the sediment waves became thinner and were reduced in the downslope direction. The downslope decrease of the sediment wave unit indicates that the wavy sediments are probably sourced from the upslope area. The slope’s parallel orientation of the wave crests, and their broad lateral extent, is appropriate for a setting where unconfined turbidity currents follow the maximum regional slope gradient (Normark et al., 2002; Wynn and Stow 2002a, b). As discussed previously, a slope with parallel wave crests restricts the occurrence of along-slope flowing bottom currents.

Lastly, the upslope migration of the waves suggests that they had formed in a manner similar to that reported from other turbidity current sediment wave fields (e.g. Normark et al., 2002; Wynn and Stow 2002a, b). Simple numerical modeling, based on the values of the slope gradient across the wave field, indicates that the waves are generated by turbidity currents with internal Froude numbers; the latter roughly agrees with the limits for antidune formation.

5.2 Turbidity current flow characteristics

The flow characteristics of turbidity currents in the field 1 sediment waves can be explained by simple numerical modeling. Firstly, the internal Froude number is calculated. This value is then combined with wavelength to estimate the flow thickness. Flow velocity is then calculated using an internal Froude number and sediment concentration as the key parameters.

The Froude number, which allows the characterization of the flows moving in the gravity field, may be calculated by the following formula (according to Bowen et al. (1984)):

\[ F_i^2 = 128.5 \tan \beta \] (1)

The relationship between the wavelength (L), the flow thickness (h), and the internal Froude number (Fi) is determined by the following formula (Normark et al. 1980):

\[ L = 2\pi h F_i^2 \] (2)

The flow velocity can be estimated using the following formula (Piper and Savoye, 1993):

\[ u^2 = C g h F_i^2 \left( \frac{\Delta \rho}{\rho} \right), \quad \frac{\Delta \rho}{\rho} = \frac{\Delta p - \rho}{\rho^0} \approx 1.5 \] (3)

In this formula, \( \rho \) is the average density of the sediment particles, \( \rho_0 \) is the density of water, \( g \approx 9.8 \text{ m/s}^2 \) is the acceleration due to gravity, and \( C \) is a dimensionless number that represents sediment concentration which is dependent on the type of flow involved. The volumetric content of a sediment in particulate matter (C) is taken to be between \( 5 \times 10^{-2} \) and \( 5 \times 10^{-2} \) by many authors (Piper and Savoye, 1993).

The average slope in the sediment waves of field 1 ranged from 0.8° to 1.45°. Consequently, the Froude number is estimated to be between 1.3 and 1.8. These figures are in agreement with previous findings on turbidity currents (Piper and Savoye, 1993; Ercilla et al., 2002) and are within the calculated limits of antidune existence (Normark et al., 1980). The average value of the sediments’ WL in field 1 is approximately 4 km. The results show that the flow thicknesses across the entire wave field range from 196 to 356 m, and the current velocity falls in the range of 15-21 cm/s.

5.3 The formation and development of the sediment waves

The base of the wave field rests upon an irregular bounding surface (i.e. S1). This represents a regional unconformity that separates older turbidity current channel-fill and MTDs from the stratified sediment wave unit. The former shows chaotic seismic reflections with variable amplitudes and continuity. Therefore, the formation of the sediment wave field apparently occurred during a major change in the sedimentary regime in the Huatung Basin. The trigger for this change could be associated to the late Cenozoic tectonic activity in the Taiwan Island. Due to the inherent oblique arc collision of the Taiwan orogenic movement, the focus of collision consistently propagated southward.

The collision between the Luzon Arc and the underplating Eurasian continent has back-thrusted and uplifted the forearc sequence to develop the Huatung Ridge at 3.5 Mya. This plays a role of convergence and guidance for the source supply of the upper reach of the Taitung Canyon and the surrounding channels (Chang et al., 2001; Huang et al., 2012). Nowadays, sediments are transported southward to the Taitung Trough by the Beinan River and the submarine channels. Consequently, the sediments are hindered by the dam and transferred eastward along the Taitung Canyon and gullies or channels to the Huatung Basin (Huang et al., 2012). In response to the tectonic activities, the stratigraphic record in western and eastern Taiwan shows an increase in clastic sedimentation approximately 5 Mya, which was followed by a further increase approximately 3 Mya (Chang et al., 2001; Dadson et al., 2003; Huang et al., 2012). The outlet between the Guangchengao volcanic island and the Lutao volcanic island closed approximately 1 Mya. Indeed, this had happened when the supply of the unnamed canyon between the Chimei Canyon and the Taitung Canyon was interrupted or greatly weakened. Meanwhile, the outlet between the Lanyu volcanic island and the Lutao volcanic island is closed.

The tectonic movements between 3 and ~1 Ma created a sedimentary system where gravity flow processes predominated. The MTDs underlying the sediment waves were formed on slopes. The irregular top surface of the MTDs controls the succedent deposition to some extent. Moreover, the small-scale sag is an ideal place for turbidity currents to deposit (He et al., 2011). Besides the irregular surface at the base, sufficient supply provides the material basis for the formation of sediment waves. A two-fold subdivision of the sediment waves can be made into a basal wavy unit and an upper distinct asymmetric wavy unit. The difference between those two indicates the
gradual decrease of the turbidite energy. The basal wavy stratified unit represents the early growth of the sediment waves, with indistinct wavy geometries. The upper distinct asymmetric wavy unit consists of relatively more continuous, high-amplitude reflections, and show significant upslope migration. The change may be due to the increasing influence of the Huatung Ridge and the other gradual uplifting ridges as barriers to turbidity current.

Finally, the development of the sediment waves in eastern Taiwan is the same as that of southwestern Taiwan, which is the sedimentary response of the late Cenozoic tectonic activity of the Taiwan Island. The initiation of the studied sediment waves started between 3 and ~1 Ma when the arc-continent collision culminated on the Taiwan Island.

6 Conclusions

Firstly, this study identified two sediment wave fields in the Huatung Basin off the eastern Taiwan Island. Sediment wave field 1, with an area of approximately 2045 km$^2$, lies close to the unnamed canyons between the Chimei Canyon and the Taitung Canyon. Sediment wave field 2, with an area of about 820 km$^2$, is further basinward around the high-sinuosity bend of the Taitung Canyon. Secondly, the development of the sediment waves in field 1 was revealed to have originated from downslope turbidity currents. On the contrary, the development of the sediment waves in field 2 presumably resulted from turbidity current overspill caused by the sharp turn of the Taitung Canyon. Thirdly, two stages of sediment wave evolution have been identified. The waves display more regular geometries and internal reflection configuration throughout their evolution. The base of the sediment wave unit rests upon an irregular surface, a regional unconformity, across which there is a change in sedimentology from the MTDs below to the sediment waves above. These features are related to the increasing influence of the arc-continent collision between the Philippine Sea Plate and the Eurasian continent between 3 to ~1 Ma.

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