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The role of sediment gravity flows on the morphological development of a large submarine canyon (Taiwan Canyon), northeast South China Sea

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ABSTRACT

High-resolution multibeam bathymetric and multichannel seismic data are used to investigate the morphology of a submarine canyon (Taiwan Canyon), and surrounding strata, in the northeast South China Sea. This submarine canyon shows two main branches at its head, and changes its orientation from NW-SE to E-W due to the effect of a tectonically active seamount. The asymmetry of the submarine canyon's banks in its middle reach is due to the combined action of recurrent slope instability and turbidity currents. Two fields of sediment waves were also identified in the study area. Field 1 is located on the southwest levee of the canyon and is fed by turbidity currents from one of its branches, being also associated with marked hydraulic jumps. Field 2 is observed in the southern bank of the lower canyon reach and was formed by the overspill of turbidity currents within the

27 Taiwan Canyon due to the effect of inertial centrifugal forces. Turbidity currents sourced from
28 Dongsha Channel also contributed to forming Field 2. Importantly, trains of plunge pools have been
29 identified along the thalweg of the lower canyon reach, generated by turbidity currents deriving from
30 the submarine canyons in the north of the Taiwan Canyon. Our results not only provide a very detailed
31 account of submarine bedforms within and around a large submarine canyon, but also contribute to a
32 better understand of their origin and development. The high-resolution bathymetric and seismic data
33 in this work reveal how gravity flows can drive erosion and deposition in submarine canyons.

34

35 **Keywords:** South China Sea; Taiwan Canyon; slope failures; turbidity currents; sediment waves;
36 plunge pools.

37

38 INTRODUCTION

39 Sediment gravity flows, usually occurring as submarine landslides and turbidity currents, are
40 ubiquitous on both passive and active continental margins (Talling et al., 2012). Sub-
41 marine landslides can generate enormous turbidity currents and mass-transport deposits, or MTDs
42 (Nisbet and Piper, 1998). They both play significant roles in eroding continental shelves and slopes,
43 leading to the incision of submarine canyons while transporting large volumes of sediment into deep-
44 sea environments (Canals et al., 2006; Talling et al., 2012). In addition, sediment gravity flows can
45 generate widespread seafloor bedforms within and around submarine canyons, including vast fields
46 of sediment waves (Kostic, 2014; Symons et al., 2016; Normandeau et al., 2018), seafloor scours
47 (Lamb et al., 2008; Covault et al., 2014), troughs and plunge pools (Paull et al., 2011; Schnyder et al.,
48 2018).

49 Large submarine canyons have been documented on the northern South China Sea margin, where

50 sediment gravity flows play a vital role in their morphological development. Key examples are the
51 Central Canyon in the Qiongdongnan Basin (Gong et al., 2011; Li et al., 2013), the Pearl River
52 Canyon (Ding et al., 2013; Wang et al., 2017) and the multiple slope-confined canyons of the Pearl
53 River Mouth Basin (Gong et al., 2013) (Fig. 1). The Central Canyon was formed by the incision of
54 large-scale gravity flows (slumps, debris flows and turbidity currents), which started in the Late
55 Miocene (5.5 Ma) (Li et al., 2013). Two main phases of Quaternary mass-wasting have been
56 recognised in the middle segment of the Pearl River Canyon, indicating that MTDs play a significant
57 role in its development (Wang et al., 2017). There is also a clear asymmetry in the sub-linear, slope-
58 confined canyons in the Pearl River Mouth Basin, as shown by their steep eastern walls and stepped,
59 curved western walls sculpted by slumps and slides (Ding et al., 2013; He et al., 2014). Yin et al.
60 (2019) link the asymmetry of these submarine canyons to contour currents, as well as to turbidity
61 currents.

62 The Taiwan Canyon (also called South Taiwan Shoal Canyon or Taiwan Bank Canyon) is one of
63 the largest submarine canyons on the northeastern South China Sea margin, reaching a total length of
64 ~220 km (Ding et al., 2010; Xu et al., 2014; Zhong et al., 2015) (Fig. 1). Using two-dimensional
65 seismic and bathymetric data, Ding et al. (2010) revealed that the Taiwan Canyon was initiated in the
66 Middle Miocene, and tectonic structures (i.e. transform fault and seamount) have affected its
67 orientation since then. The origin and development of Taiwan Canyon were also investigated, and
68 high sediment supply, frequent gravity sliding (slumping) and faulting activities were considered as
69 the main controlling factors (Xu et al., 2014). Four fields of sediment waves are reported on the
70 northeast South China Sea and three of them are located around the Taiwan Canyon (Gong et al.,
71 2012; Kuang et al., 2014; Gong et al., 2015; Yin et al., 2015). Recent studies have documented the
72 complex morphology of scours along its thalweg, interpreting them as cyclic steps resulting from the

73 interaction of supercritical turbidity currents with the seafloor (Zhong et al., 2015).

74 This paper focuses on the sediment gravity flows of the northeast South China Sea and their roles
75 on the morphological development of the Taiwan Canyon. Sediment gravity flows occur frequently
76 within and around the Taiwan Canyon due to the frequent earthquakes that affect the Manila Trench
77 (Liu et al., 2013). Seasonal typhoons are also capable of triggering turbidity currents in this region
78 (Zhang et al., 2018). This study investigates the morphological features within and around the Taiwan
79 Canyon in a greater detail than previous publications (Figs. 1 and 2). Though sediment wave fields
80 around the Taiwan Canyon have been recognised in previous work (Gong et al., 2012; Kuang et al.,
81 2014), their origin and formation mechanisms are still poorly understood. This paper reveals for the
82 first time that levees in the middle reach of Taiwan Canyon are asymmetric and that a narrow (~1.6
83 km wide), elongated (~42 km long) trough with a W-E orientation occurs in the lower reach of Taiwan
84 Canyon. This latter trough has not been identified in the published literature. Hence, a comprehensive
85 analysis of submarine features and structures within and around the Taiwan Canyon is presented in
86 this work with the ultimate aim of:

87

- 88 1) Investigating the factors controlling the asymmetry of the middle reach of the Taiwan Canyon;
- 89 2) Determining the processes responsible for the formation of sediment waves around the Taiwan
90 Canyon;
- 91 3) Discussing how gravity flows can form erosional depressions in the lower reach of Taiwan Canyon.

92

93 **GEOLOGICAL SETTING**

94 The South China Sea (SCS) is a wedge-shaped marginal sea whose oceanic crust is wider in its
95 eastern part, narrowing down towards the southwest (Taylor and Hayes, 1983; Hsu et al., 2004).

96 Passive rifting in the SCS was initiated in the Late Cretaceous by N-S crustal extension (Wang et al.,
97 2006). A Late Oligocene to Middle Miocene phase of seafloor spreading followed the initial stages
98 of continental rifting, and was associated with progressive continental breakup along the SCS (Taylor
99 and Hayes, 1983; Zhao et al., 2016).

100 The study area is located to the northwest of the Taixinan Basin at a water depth of 200 m to
101 3500 m, in the northeast SCS (Figs. 1 and 2a). The Taiwan Canyon started to form in the Late Miocene
102 (Ding et al., 2010; Xu et al., 2014; Liao et al., 2016). During the Pliocene, the Taiwan Canyon served
103 as the main sediment conduit transporting terrestrial coarse-grained sediment onto deep-water
104 depocenters (Liao et al., 2016), shifted eastwards to converge with the Manila Trench during the late
105 Pleistocene (Liao et al., 2016). At this time, the ancient Hanjiang River flowed through the present-
106 day continental shelf to transport fluvial sediments directly to the Taiwan Canyon (Xu et al., 2014).

107 A left-lateral transform fault, called the Luzon-Ryukyu Transform Fault (LRTF), is located in the
108 southern part of the Taiwan Canyon (Fig. 2b). The LRTF is revealed by changes in the trend of
109 magnetic anomalies on the ocean floor, as well as changes in seafloor bathymetry and basement relief
110 (Sibuet et al., 2002; Hsu et al., 2004). The fault connects the former southeast-dipping Manila Trench
111 with the northwest-dipping Ryukyu Trench. In the Early Miocene, the LRTF became inactive due to
112 the formation of the Luzon Arc and onset of seafloor spreading in the eastern SCS between 20 and
113 18 Ma (Hsu et al., 2004). In addition to the LRTF, a seamount lies in the northwestern region of the
114 Taiwan Canyon (Fig. 2). This seamount was formed during the Early Miocene (21-22 Ma) as revealed
115 by the $^{40}\text{Ar}/^{39}\text{Ar}$ dating of its alkali basaltic rocks (Wang et al., 2012).

116

117 **DATA AND METHODS**

118 **Bathymetric and seismic data**

119 Multibeam bathymetric and multichannel seismic data are used as the primary datasets in this
120 work. These bathymetric data were acquired onboard the R/V SONNE during the joint Chinese-
121 German Cruise 177, June 2004, using a SIMRAD EM120 multi-beam echo-sounder system. The
122 horizontal and vertical resolutions of the bathymetric data are ~100 m and 3-6 m, respectively. The
123 multibeam bathymetric data were imported and analysed in Global Mapper®.

124 Multichannel seismic data are used to characterize near-seafloor bedforms around the Taiwan
125 Canyon. Two long seismic-reflection profiles (MGL0905-05 (~70 km) and MGL0905-10 (~41 km)),
126 acquired as part of the Taiwan Integrated Geodynamic Research (TAIGER) project, are also used in
127 this work together with an additional two-dimensional (2D) multichannel seismic profile acquired by
128 the South China Sea Institute of Oceanology, Chinese Academy of Sciences, in May 2019 (Fig. 2).
129 The frequency bandwidth of this latter seismic profile is 30-45 Hz, providing an average vertical
130 resolution of 11-17 m for shallow strata. The seismic profile was acquired by 1800 m-long streamer
131 with 144-channels and spaced 12.5 m (Fig. 2). The seismic profile was processed using RadExpro®
132 and interpreted on Geoframe®.

133

134 **Calculations of turbidity current properties**

135 The flow properties of turbidity currents flowing through the sediment wave fields were
136 calculated based on the morphological parameters of the sediment waves identified in seismic and
137 bathymetric data. These morphological parameters include the wavelength and the slope gradient of
138 the lee and stoss sides of sediment waves, which are used in several equations to calculate:

139 1) the internal Froude number (F_i) of turbidity currents using the slope gradient (α), drag

140 coefficient at the bed (C_f), and entrainment coefficient at the upper interface (e), as represented by
141 Equation (1);

142 2) the flow thickness (h) using the relationship between wavelength (L) and the internal Froude
143 number (F_i) in Equation (2);

144 3) the velocity of sediment waves in the stoss and lee sides using $\Delta\rho$ (grain density - density of
145 turbidity currents/seawater density), C (the volume concentration), g (gravitational acceleration),
146 internal Froude number (F_i) and flow thickness (h).

147

$$148 \quad F_i^2 = \frac{\sin(\alpha)}{C_f + e} \quad (1)$$

$$149 \quad h = \frac{L}{2\pi F_i^2} \quad (2)$$

$$150 \quad u^2 = \Delta\rho Cgh F_i^2 \quad (3)$$

151 where F_i is the internal Froude number of turbidity currents, and α is slope gradient of sediment waves.
152 Suggested values for the drag coefficient C_f of turbidity currents range from 3.5×10^{-3} to 4×10^{-3}
153 (Bowen et al., 1984). The lowest value of 3.5×10^{-3} is more applicable to unconfined flows (Wynn et
154 al., 2000). The entrainment coefficient e for most turbidity currents varies between 5×10^{-4} and 6×10^{-3} ,
155 while sediment concentration (C) is a dimensionless number ranging from 5×10^{-5} to 5×10^{-4} (Piper
156 and Savoye, 1993). The parameter g represents the gravitational acceleration, considered to be 9.81
157 m/s^2 .

158 This work calculated the Froude numbers of circular depressions within the Taiwan Canyon,
159 before and after hydraulic jumps, using Equations (4) and (5).

160

$$161 \quad Fr_1 = \frac{U}{\sqrt{\Delta\rho Cgh}} \quad (4)$$

$$F_{r_2} = \frac{2^{1.5} F_{r_1}}{(\sqrt{1+8F_{r_1}^2}-1)^{1.5}} \quad (5)$$

where the sediment concentration (C) is the volume sediment concentration, g is the gravitational acceleration (9.81 m/s²). The parameter h is the flow depth of turbidity currents and U represents the velocity of turbidity currents. Δρ (sediment density - density of turbidity currents/seawater density).

RESULTS

Morphological evolution of the Taiwan Canyon

The Taiwan Canyon is observed at a water depth ranging from 500 m to 3500 m (Fig. 2a). The Taiwan Canyon is approximately 220 km long and 6 to 12 km wide. In bathymetric data, Branch 1 is located in the northern part of the Taiwan Canyon at a water depth between 2000 m to 2500 m, while branch 2 is oriented NW-SE and occurs at a water depth of 2100 to 2500 m (Fig. 2). Branch 1 is 7 km wide and ~42 km long, while branch 2 is 6 km wide and 40 km long (Fig. 2a).

The middle reach of the Taiwan Canyon is ~80 km long and is observed at a water depth of 2500 m to 3125 m. Here, its banks are asymmetric in both their height and slope gradient (Figs. 3 and 4). The southwest bank of the Taiwan Canyon is steeper than its northeast counterpart; the slope gradient of the southwest bank ranges from 6.5° to 13°, whereas it ranges from 1° to 2° on the northeast bank (Figs. 3b and 4b). Moreover, the southwest bank of the Taiwan Canyon is higher than its northeast counterpart (~ 230 m and 300 m high, respectively) (Figs. 3b and 4b). Along the middle reach of the Taiwan Canyon, MTDs are presented on the seismic profiles, appearing as discontinuous, transparent reflections (Figs. 3c and 4c). These MTDs occur along the base of the continental slope in Pliocene and Pleistocene strata (Liao et al., 2016), indicating complex cut-and-fill processes during the development of Taiwan Canyon.

184 The lower reach of the Taiwan Canyon is ~60 km long and occurs at a water depth of 3125 m to
185 3500 m (Fig. 2a). The Taiwan Canyon changes its orientation from NW-SE to nearly E-W at a water
186 depth of 3070 m (Fig. 2). A seamount is located to the southwest part of the canyon at a water depth
187 of 2750 m. The seamount is 1200 m high and 6-8 km wide, spanning ~70 km² of the continental slope
188 (Fig. 2).

189

190 **Sediment waves fields around the Taiwan Canyon**

191 Two fields of sediment waves are observed around the Taiwan Canyon. Field 1 spans the
192 southwest levee in the middle reach of Taiwan Canyon at a water depth of 2250 m to 2840 m, with a
193 slope gradient of 0.5° on average (Figs. 2a and 5c). These sediment waves cover ~510 km² of the
194 levee and their dimensions (wavelengths and wave heights) become smaller with increasing water
195 depth (Figs. 2a, 5c and 6b). The wavelength of sediment waves in Field 1, from head to tail, ranges
196 from 1.2 km to 3.7 km and show wave heights of 30 m to 47 m. The slope gradient ranges from 0.43°
197 to 1.78° on the stoss sides of Field 1, and 1.09° to 2.49° on the observed lee sides (Table 1). The crests
198 of sediment waves are bifurcated and their orientation approaches NW-SE (Fig. 2). The seismic
199 reflections within the sediment waves are continuous and can be traced from one wave to another
200 (Fig. 5c). Discrete sediment waves show asymmetrical geometries with a long and thicker upslope
201 flank but a short and thinner downslope flank, and their crests display a trend of upslope migration
202 (Fig. 5c). This work estimates the velocities of turbidity currents flowing through Field 1 as
203 comprising V_{stoss} from 2.16 m/s to 3.31 m/s and V_{lee} between 2.17 m/s and 3.4 m/s, based on Equations
204 (1) - (3) (Table 1).

205 Field 2 is located in the southern side of the Taiwan Canyon at a water depth between 3150 m to
206 3500 m (Fig. 2a). Here, slope gradient reaches 0.57° on average, but only the northern part of the

207 Field 2 is fully imaged by our data set, covering a total area 870 km². These sediment waves are
208 oblique to the orientation of the Taiwan Canyon and reveal a NW–SE orientation (Figs. 2, 5b and 7b).
209 Sediment waves show asymmetrical profiles in cross-section and marked upslope-migrating, sinuous,
210 bifurcate crests (Fig. 7b). These waves crests develop parallel in two trains with a E-W direction.
211 Waves in Field 2 have relatively large dimensions, with wavelengths ranging from 1.5 km to 5.4 km
212 and have wave heights ranging from 50 m to 110 m.

213

214 **Trough along the Taiwan canyon thalweg**

215 Troughs are narrow, elongated depressions on the seafloor with flat bottoms and steep flanks
216 (Heap and Harris, 2008). In our study area, a new trough is identified in the lower reach of the Taiwan
217 Canyon at a water depth from 3300 m to 3500 m, where the slope gradient is 0.3° on average (Figs.
218 2a and 8). It extends for ~44 km with an E-W orientation, and has a width of ~1.6 km, covering about
219 72 km² of the continental slope (Fig. 8c). This trough is close to the north bank of the lower reach of
220 the Taiwan Canyon, and sediment waves are located further to the north (Figs. 8a, 8b and 9a). It has
221 an incision depth of ~100 m on average, and shows several undulations in cross-section view and
222 closed circular-shaped depressions in plan view (Figs. 8a and 8c). These depressions are 1.38 km to
223 3.86 km in diameter and 62 m to 119.1 m in height (Fig. 8c and Table 2). Moreover, marked
224 differences in slope gradient can be observed on the walls of the lower reach of the Taiwan Canyon
225 (Figs. 9b and 9d). The slope gradients of the northern canyon wall of these depressions range from
226 6.3° to 12.4°, while they vary from 3.2° to 14.3° on the southern canyon wall (Table 2).

227

228 **DISCUSSION**

229 **Controls on the asymmetry of the middle reach of Taiwan canyon**

230 Asymmetric submarine canyons have been widely observed when analyzing slope gradient and
231 the height of canyon banks on cross-sectional bathymetric profiles (Mountjoy et al., 2009; Micallef
232 et al., 2014). These asymmetric canyons have been suggested to result from regional tectonics (Dantec
233 et al., 2010; Micallef et al., 2012), the effect of the Coriolis force (Cossu et al., 2010; Cossu et al.,
234 2015), gravity flows (Keevil et al., 2007; Arzola et al., 2008) and contour currents acting on the
235 continental slope (Fonnesu et al., 2020; Miramontes et al., 2020). In the study area, a prominent
236 asymmetry in the Taiwan Canyon is documented not only by the recorded difference in its bank height,
237 but also by analyzing slope gradients in its middle reach (Figs. 3b and 4b). Several potential controls
238 on the asymmetry of the middle reach of Taiwan Canyon are discussed below.

239 Local tectonic structures such as folds and faults directly affect the location, alignment and
240 geometry of many a submarine canyon (Dantec et al., 2010; Micallef et al., 2014). Several researchers
241 have proposed the southwest levee of the middle reach of Taiwan Canyon to be part of a major
242 transform plate boundary, the Luzon-Ryukyu Transform Fault (LRTF) (Sibuet et al., 2002; Yeh et al.,
243 2004; Hsu et al., 2004). It appears that the orientation of the Taiwan Canyon is parallel to the Luzon-
244 Ryukyu Transform Fault (LRTF). However, the Luzon-Ryukyu Transform Fault cannot be clearly
245 identified on the seismic profiles across the Taiwan Canyon, and there is also no obvious fault close
246 to the southwest bank of this canyon (Figs. 3 and 4). A series of normal faults occur only in much
247 deeper strata (4.5 s-5.8 s TWTT), not influencing the asymmetry of the middle reach of Taiwan
248 canyon (Figs. 3a and 4a). Therefore, this study proposes that regional tectonics affected the
249 orientation of Taiwan Canyon but did not control the asymmetry observed in its middle reach.

250 In the Northern Hemisphere, the Coriolis force laterally deflects turbidity currents so that both

251 their density interface and downstream velocity maxima are deflected to the right-hand side of
252 submarine canyons in a downstream direction (Cossu et al., 2010). This shift in flow orientation can
253 change the loci of erosion and deposition on continental slopes, and consequently impose differences
254 in canyon bank height and slope gradient (Cossu and Wells, 2013; Cossu et al., 2015). The ratio
255 between the Coriolis force and the inertial force of gravity flows in submarine canyons is represented
256 by the Rossby number (Cossu et al., 2015).

257 Turbidity currents flowing southeast along the Taiwan Canyon are affected by the Coriolis force,
258 resulting in enhanced erosion and therefore larger slope gradients in the southwest side of its middle
259 reach. However, the Coriolis force may not impose great differences in canyon bank height due to the
260 large Rossby number ($|Ro| > 10$) recorded in low latitude areas (Cossu et al., 2010). In our study area,
261 at a latitude of 21°N, the Rossby number ranges from 10 to 20, suggesting that the Coriolis force is
262 not the main reason for the difference in canyon bank height recorded in the middle reach of the
263 Taiwan Canyon.

264 Gravity flows such as submarine landslides are ubiquitous in deep-sea environments, and are the
265 dominant processes eroding the continental slope and enlarging submarine canyons (Pratson and
266 Coakley, 1996). Recurrent MTDs are identified in the northeast overbank of the middle reach of
267 Taiwan Canyon (Figs. 3b and 4b); they are relatively younger than the Taiwan Canyon (Liao et al.,
268 2016). The presence of stacked MTDs indicates that the northeast bank of Taiwan Canyon was eroded
269 by slope failures originating from the area to the northeast (Fig. 8). This leads to the differences in
270 canyon bank height in the middle reach of the Taiwan Canyon.

271 The simultaneous interaction of contour and turbidity currents on continental slopes can result in
272 asymmetric canyon-levee systems (Gong et al., 2018; Fonnesu et al., 2020; Miramontes et al., 2020),
273 especially in the zones where the downslope turbidity currents have velocities of 2 m/s or less,

274 and where submarine channels are not deeply incised (Miramontes et al., 2020). The velocity of
275 turbidity currents in the middle reach of Taiwan Canyon range from 4-10 m/s (Zhong et al., 2015),
276 values that are 40-100 times larger than that of contour currents (~15 cm/s in average), as documented
277 by Zhao et al. (2016) in the same area. For one thing, contour currents may not have a marked effect
278 on the deflection of turbidity currents that flowing along the Taiwan Canyon towards southeast. In
279 addition, the differences in water depth between the thalweg and southwest levee in the middle reach
280 of Taiwan Canyon are ~300-400 m (Fig. 10), and such difference in levee height can prevent the
281 overspill of turbidity currents from Taiwan Canyon.

282 In summary, this study suggests that erosion by recurrent slope failures to the northeast of the
283 Taiwan Canyon is the main reason for the contrast in canyon bank heights (about 300 m on average).
284 However, it also suggests that the observed differences in slope gradient on both banks of the Taiwan
285 Canyon result mainly from the erosion of turbidity currents along the canyon which are heavily
286 influenced by inertial centrifugal forces.

287

288 **Mechanisms forming sediment waves around the Taiwan Canyon**

289 Based on the interpretation of the multibeam bathymetric map and two-dimensional seismic
290 profiles used in this study, two fields of sediment waves can be identified around the Taiwan Canyon
291 (Fig. 2). The sediment waves in the lower reach of Taiwan Canyon are not the focus in this work as
292 they have been proposed to be generated by unconfined turbidity currents flowing out of the West
293 Penghu Canyon (Gong et al., 2012; Kuang et al., 2014). The formation of deep-water sediment waves
294 has been attributed to multiple causes, including downslope turbidity currents (Wynn et al., 2002;
295 Covault et al., 2014), along-slope contour (bottom) currents (Masson et al., 2002; Betzler et al., 2014),
296 interactions between turbidity and contour currents (Normandeau et al., 2018) and submarine

297 landslides (Hampton et al., 1996; Pope et al., 2018; Casalbore et al., 2020). In the following sections,
298 the formation mechanisms of sediment waves in Fields 1 and 2 are analysed in detail.

299 Four key observations comprise key evidence to determine the formation mechanism of sediment
300 waves in Fields 1 and 2.

301 (a) The crests of sediment waves in Fields 1 and 2 are parallel to the bathymetric contours (Fig.
302 2). Wynn et al. (2002) have proposed that crests of sediment waves formed by bottom currents are
303 usually aligned at a low angle (typically 10° - 50°) to the regional contours, while the crests of sediment
304 waves generated by turbidity currents on slopes are normally slope-parallel. This indicates that the
305 sediment waves in Fields 1 and 2 cannot be solely be produced by bottom currents.

306 (b) The wave crests are sinuous and bifurcate in plan view and they oblique to the orientation of
307 Taiwan Canyon in its middle reach (Figs. 2a and 2b). In areas with good planform coverage most
308 turbidity current sediment waves appear as linear features with varying degrees of sinuosity and/or
309 bifurcation (Wynn et al., 2002; Symons et al., 2016), suggesting a turbidity current of origin for the
310 sediment waves of Fields 1 and 2.

311 (c) The dimensions (wavelengths and wave heights) of sediment waves in Fields 1 and 2 decrease
312 downslope in a gradual way (Figs. 5b, 5c and 6b). This is an important observation as sediment waves
313 formed by turbidity currents are usually smaller in a downslope direction due to decreasing sediment
314 supply and flow velocity downslope (Normark et al., 2002). In contrast, bottom current sediment
315 waves are irregular with no consistent change in wave dimensions (Wynn et al., 2002).

316 (d) Discrete seismic reflections within the sediment waves are continuous and can be traced
317 across the troughs from one wave to the next (Figs. 5b and 5c). Though seismic reflection patterns in
318 the wave troughs can mimic fault planes in some cases, sediment waves formed by turbidity currents
319 or bottom currents consist of continuous, parallel or sub-parallel reflections on both sides (Lee et al.,

2002). In comparison, submarine landslides or creep folds show clear displacement along fault planes, especially in their troughs (Hill et al., 1982; Lee and Chough, 2001). This suggests that submarine landslides may not result in the formation of sediment waves in Fields 1 and 2. As discussed above, the sediment waves in Fields 1 and 2 are most likely generated by turbidity currents.

The crests of sediment waves are considered to align perpendicularly to the flow direction of turbidity currents (Wynn et al., 2002). The wave crests in Field 1 are W-E oriented and this reveals that turbidity currents were sourced from branch 1 of the Taiwan Canyon. Thus, turbidity current stripping is considered to have occurred from the main flow in the Taiwan Canyon. The stripped turbidity current flowed over the southern levee in a series of hydraulic jumps, leading to the generation of sediment waves in Field 1 (Fig. 8). Overspilling turbidity currents have been documented in the Monterey East Channel (Fildani et al., 2006) and the Eel Canyon offshore California (Lamb et al., 2008), where sediment waves are widely distributed. Additionally, the observed overspilling turbidity currents in Eel canyon and Monterey East Channel show gradually decrease in their velocities, and consequently result in the decrease in sediment waves' dimensions.

The wave crests in Field 2 are observed to be sinuous and bifurcate on the bathymetric map, which are more complex compared to those in Field 1 (Figs. 2a and 10). The bifurcation and sinuosity of wave crests suggest an interaction of turbidity currents from different areas (e.g. Wynn et al., 2000). Moreover, these wave crests extend in a N-S or NE-SW direction, and they develop as two trains (Figs. 2b and 10). This phenomenon indicates that turbidity currents may be derived from north or northwest of Field 2. Hence, two possible sources of turbidity currents are proposed that may overspill into this field of sediment waves. The most likely case is the overspill of turbidity currents from the Taiwan Canyon due to inertial centrifugal forces. In addition, the Dongsha Channel is located to the west of sediment waves in Field 2, and there might be turbidity currents flowing through this channel.

343 These flows are initially constrained within a confined environment, but rapidly become unconfined
344 downslope and spread out over an extensive area.

345

346 **Origin and development of plunge pools within the lower reach of Taiwan Canyon**

347 Plunge pools are defined as a series of discrete depressions and occur at sharp changes in slope
348 gradient exceeding 4° (Lee et al., 2002). They are widely distributed within submarine canyons on
349 both active and passive continental margins (e.g. Betzler et al., 2014; Schnyder et al., 2018). In this
350 study, several discontinuous depressions are located close to the north flank in the lower reach of
351 Taiwan Canyon (Figs. 8b and 9a). The depth of these depressions is much larger than those
352 documented in other area (Table 3). They show circular-shaped closed depressions on the contour
353 map and are concave-shape in the cross section (Figs. 8a and c). Therefore, this study proposes that
354 these depressions observed in the lower reach of Taiwan Canyon are plunge pools.

355 The formation of plunge pools in deep-sea environments is chiefly caused by: a) sediment-laden
356 density flows (“impact pools”), b) erosion by contour currents or c) hydraulic jumps in turbidity
357 currents (“hydraulic jump pools”) (Lee et al., 2002). Plunge pools generated by sediment-laden
358 density flows often have larger slope gradients in their upslope bank ($> 20^{\circ}$) (Pratson et al., 2001; Lee
359 et al., 2002). However, the plunge pools in our study are characterised by slope gradients from 6.3°
360 to 12.4° on their northern flank, which is much smaller than the typical gradients of impact pools
361 (Table 2 and Table 3). Thus, sediment-laden density flows should not be responsible for the generation
362 of plunge pools in the study area. Depressions created by contour currents are generally wider than
363 plunge pools, forming an elongate trough instead of a series of discrete depressions (Stow et al., 1998;
364 Lee et al., 2002). In this study, the plunge pools are N-S orientated (Figs. 8b and 10), a direction
365 perpendicular to the bottom currents flowing along the lower reach of Taiwan Canyon (Gong et al.,

2012; Liu et al., 2016). This indicates that these plunge pools are unlikely to be formed by along-slope bottom currents.

The sharp change of calculated Froude numbers suggest that turbidity currents change their flow regime from supercritical to subcritical when passing over the bottom of plunge pools. Moreover, a sediment core collected on the southern edge of a Quaternary plunge pool indicates fine-to-medium grained sands and silts ranging in grain-size from 4Φ to 8Φ in the Krumbeinphi scale (Gong et al., 2012; Gong et al., 2015). These two lines of evidence suggest that plunge pools are most likely formed by hydraulic jumps of turbidity currents. There are two sources of turbidity currents that may flow through plunge pools, including the turbidity currents (towards east) within the Taiwan Canyon, and turbidity currents (towards south) from the northern bank of Taiwan Canyon. If the plunge pools were generated by turbidity currents within the Taiwan Canyon, they would overspill to the southeast due to the occurrence of the seamount (Fig. 2). They would be affected by the Coriolis force, resulting in enhanced erosion close to the south side of the lower reach of the Taiwan Canyon. These phenomena are inconsistent with the present of a series of plunge pools adjacently to the northern bank of Taiwan Canyon's lower reach. Thus, turbidity currents might be sourced from the northern bank (e.g. West Penghu Canyon) of the Taiwan Canyon.

IMPLICATIONS

Our results provide three main contributions towards a better understanding of sediment gravity flows (turbidity currents and submarine landslides) and their roles on the morphological development of submarine canyons.

Turbidity currents are one the most important but also one of the least documented sediment transport processes on Earth (Talling et al., 2007; Paull et al., 2018). They can strongly modify the

389 seafloor morphology and generate various submarine bedforms (Talling et al., 2007; Meiburg and
390 Kneller, 2010). Frequent turbidity currents with high velocity (5-8 m/s) have been documented on the
391 northeastern South China Sea margin by in situ measurement (Zhang et al., 2018). In this study, the
392 velocity of turbidity currents is still 3-4 m/s after overspilling the southwest levee in middle reach of
393 Taiwan Canyon (~300-400 m), leading to the formation of sediment waves in Field 1 (Fig. 10).
394 Several plunge pools are discovered in the lower reach of Taiwan Canyon. The origin and
395 development of these plunge pools strongly suggests the powerful erosional ability of turbidity
396 currents when entering the Taiwan Canyon. In contrast to the previous literature (Xu et al., 2014;
397 Kuang et al., 2014; Yin et al., 2015), this study succeeds in reporting numerous morphological
398 features (sediment waves and plunge pools) within and around the Taiwan Canyon to reveal the role
399 of turbidity currents on their development.

400 The dimensions (wavelengths and wave heights) of sediment waves are mainly controlled by the
401 hydraulic characteristics of turbidity currents (e.g. velocity, discharge and energy loss) (Wynn et al.,
402 2002; Symons et al., 2016). Though sediment waves have been reported on the southwest levee of
403 middle reach of Taiwan Canyon in pervious literature (e.g. Kuang et al., 2014; Zhong et al., 2015;
404 Yin et al., 2015), this study conducts a quantitative analysis of their formation mechanism and
405 proposes a schematic model for their development. This work contributes to a more complete
406 understanding of flow dynamics in turbidity currents occurring around submarine canyons.

407 Submarine landslides can transport large volume of sediment from the continental slope to the
408 deep ocean (Hampton et al., 1996; Nisbet and Piper, 1998; Pope et al., 2015) and they can largely
409 affect the seafloor morphology by producing slide scars (Williams, 2016). The asymmetry of
410 submarine canyons (i.e. the difference of height and slope gradient of canyon flank) have been
411 suggested to be caused by regional tectonics (Micallef et al., 2012), the deflection of turbidity currents

412 (Cossu et al., 2015) and the interaction of turbidity currents and contour currents (Miramontes et al.,
413 2020). In this work, the marked asymmetry in the middle reach of the Taiwan Canyon is first reported,
414 and the huge difference recorded here in terms of canyon levee height (up to 400 m), differences
415 rarely documented in other regions. The repeated submarine landslides have eroded the northeastern
416 levee in the middle reach of Taiwan Canyon, resulting in the asymmetrical geometry of Taiwan
417 Canyon in its middle reach. Our results provide a new case study and explanation related to the
418 controlling factors on the asymmetry of submarine canyons.

419

420 **CONCLUSIONS**

421 High-resolution multibeam bathymetric and multichannel seismic data are used in this study to
422 investigate the development and geomorphology of the Taiwan Canyon. The main conclusions are as
423 follows:

424 (1) Seafloor bedforms include two fields of sediment waves (Fields 1 and 2) and a series of
425 plunge pools identified within and around the Taiwan Canyon. A seamount is located in the southwest
426 part of the Taiwan Canyon, resulting in changes in the orientation of this latter, from NW-SE to nearly
427 W-E.

428 (2) Marked asymmetry is observed in the middle reach of the Taiwan Canyon. The southwest
429 bank of the canyon is much higher than its northeast counterpart, showing an average height
430 difference of up to 400 m. The southwest bank of the canyon reveals more erosion than the opposite
431 bank.

432 (3) Recurrent slope failures sourced from the northeast side of the middle reach of the Taiwan
433 Canyon are considered as the main reason for obvious difference in canyon bank heights. Variations
434 in the erosion power of landslides and turbidity currents are due to the effect of the inertial centrifugal

435 forces.

436 (4) Sediment waves in Field 1 are related to turbidity currents sourced from branch 1 of the
437 Taiwan Canyon. They are also associated with marked hydraulic jumps of ~300 m. The velocity of
438 turbidity currents flowing through the stoss and lee sides of sediment waves ranges from 2.16 m/s to
439 3.31 m/s, and 2.17 m/s to 3.4 m/s, respectively.

440 (5) Three sources of turbidity currents are proposed to be responsible for the formation of
441 sediment waves in Field 2. The most likely scenario is that the turbidity currents overspill the Taiwan
442 Canyon due to inertial centrifugal forces. Turbidity currents from Dongsha Channel and submarine
443 canyons in the north of Taiwan Canyon might also contribute to the generation of sediment waves in
444 Field 2.

445 (6) Plunge pools are observed close to the northern bank of the Taiwan Canyon, and their
446 formation is related to erosion imposed by turbidity currents sourcing from the submarine canyons in
447 the north of Taiwan Canyon. The northern banks of plunge pools reveal steeper slope gradients than
448 their opposite sides.

449

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458

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FIGURES

Fig. 1 Detailed location of the study area in the South China Sea. The red lines represent the Central Canyon, Pearl River Canyon, slope-confined canyons and Taiwan Canyon from southwest to northeast. The black box indicates the location of Fig. 2. The dashed black lines represent the boundaries of the Qiongdongnan Basin (QDNB), Pearl River Mouth Basin (PRMB) and Taixinan Basin (TXNB). Major topographical features such as the Xisha Islands, Dongsha Islands and Manila Trench, are highlighted in the figure.

Fig. 2 (a) High-resolution multibeam bathymetric map of the study area showing several submarine canyons with large gullies in their heads. The white box represents the location of Figure 9a. The yellow solid line in the middle reach of Taiwan Canyon marks the location of the seismic profile in Figure 5. Two shorter yellow solid lines highlight the levee asymmetry of the Taiwan Canyon shown in Figures 3a and 4a. Three blue solid lines in the upper and middle reach of Taiwan Canyon represent seismic profiles shown in Figure 6a, b and c. (b) Slope gradient map of the study area. The black dotted line represents the potential location of Luzon-Ryukyu Transform Fault (LRTF). The red dotted lines indicate the rims of Taiwan Canyon. B1: Branch 1; B2: Branch 2; SW: sediment waves; TC: Taiwan Canyon; JLC: Jiulong Canyon; WPC: West Penghu Canyon.

Fig. 3 (a) Two-dimensional (2D) seismic profile of the Taiwan Canyon highlighting the morphological differences in canyon banks shown in Figure 2. The black box indicates the location of the MTDs shown in Figure 3b. Note that slope gradient and the height of the southwest levee are larger than to the northeast. (b) The MTDs are characterized by chaotic amplitude reflections. The black arrows represent canyon rims. (c) Line-drawn interpretation of Fig. 3b illustrating the presence of widespread MTDs in the northeast of Taiwan Canyon. Note that the northeastern flank of Taiwan Canyon was eroded by these MTDs.

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Fig. 4 (a) Two-dimensional (2D) seismic profile of the Taiwan Canyon showing the morphological differences in canyon banks imaged in Figure 2. The black box indicates the position of the MTDs shown in Figure 4b. (b) The MTDs are characterized by chaotic amplitude reflections. Note that slope gradient and the height of the southwest levee is larger than to the northeast. The black arrows point at canyon rims and sediment waves. (c) Line-drawn interpretation of Fig. 4b shows the internal architecture of the middle reach of Taiwan Canyon and numerous MTDs can be observed.

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 681 Fig. 5 (a) Two-dimensional (2D) multichannel seismic profile across an area with sediment waves in Fields 1
 682 and 2 (see Figure 2 for location). The black box indicates the location of Fields 1 and 2 as shown in Figures
 683 5c and 5b. (b) Upslope migration in sediment waves comprising Field 2. Downslope decrease is shown in the
 684 dimension of sediment waves in Field 2. (c) Upslope migration and downslope decrease of dimension in
 685 sediment waves comprising Field 1.

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 687 Fig. 6 (a) Bathymetric profile illustrating two branches (B1 and B2) in the upper reach of Taiwan Canyon. (b)
 688 Bathymetric profile showing the sediment waves in Field 1 and their dimensions (wavelengths and wave
 689 heights) decrease downslope.

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692 Fig. 7 (a) Two-dimensional (2D) multi-channel seismic profile of the seismic line modified from Gong et al.
 693 (2012). See Figure 2 for location. The red box indicates the trough (elongated depression) shown in Figure 9a.
 694 (b) 2D multi-channel seismic profile of the seismic line modified from Gong et al. (2012) in Figure 2. The red
 695 box indicates the trough shown in Figure 9c.

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 697 Fig. 8 (a) Contour map in the lower reach of Taiwan Canyon showing trains of plunge pools. The blue line
 698 indicates the cross-section profile of plunge pools shown in Figure 8c. (b) Slope gradient map illustrates the
 699 presence of numerous plunge pools within the trough. The blue box shows the distribution of plunge pools. (c)
 700 Cross-sectional bathymetric profile of the plunge pools shown in Figure 8a. Eight plunge pools are observed
 701 from the east to west at water depth from 3300 to 3500 m.
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 704 Fig. 9 (a) Two-dimensional (2D) multi-channel seismic profile of the trough in Figure 7a. Truncation
 705 reflections are observed on the seismic profile. Truncations can be observed on both sides of the trough. (b)
 706 Line-drawn interpretation of Fig. 9a outlining the internal architecture of trough and MTDs. (c) Two-
 707 dimensional (2D) multi-channel seismic profile of the trough shown in Figure 7b. Erosional truncation
 708 (truncated reflections) is observed on the seismic profile. (d) Line-drawn interpretation of Fig. 9c showing the
 709 internal character of trough at the bottom of Taiwan Canyon. The grey blocks indicate the recurrent MTDs.

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711 Fig. 10 Three-dimensional view of the morphological features within and around the Taiwan Canyon,
 712 including the sediment waves in Fields 1 and 2, and plunge pools in the lower reach of Taiwan Canyon.
 713 Schematic diagrams summarize the formation mechanisms of sediment waves in Field 1 and plunge pools in
 714 the lower reach of Taiwan Canyon. The dark grey lines indicate the position of the canyon rim, while the blue
 715 lines indicate the crests of sediment waves. The red arrows illustrate the direction of turbidity currents. B1:
 716 branch 1; B2: branch 2; SWs: sediment waves; JLC: Jiulong Canyon; WPC: West Penghu Canyon.