Transport and accumulation of plastic litter in submarine canyons – the role of gravity flows

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SUPPLEMENTARY BACKGROUND AND METHODS

Geological background

The northwestern continental margin of the South China Sea (SCS) between Hainan and the Xisha Islands (Fig. 1A) is ENE-orientated, and consists of a flat and wide continental shelf and a relatively steep and rugged continental slope from northwest to southeast. The Xisha Trough, a 430-km-long, roughly E-W-extending submarine canyon system, obliquely cuts across the continental slope. Numerous submarine canyons, named collectively “Xishabei Canyons” (GMGS, 2015), are developed in the relatively steep (3-15°) upper continental slope to the north and as the tributaries of the Xisha Trough (Fig. 1A).

The studied submarine canyon is located between longitudes of 111.86° and 112.10° and latitudes of 18.10° and 18.64° in the east of the Xishabei Canyons (Fig. 1A-B). The roughly N-S extending canyon is approximately 60 km long, 2.2-8.3 km wide and 50-880 m
deep. It commences at 350 m water depth in the outer shelf that is approximately 150 km away from the nearest coast, and extends southward to 2350 m deep in the continental slope, where it merges with the Xisha Trough (Fig. 1A). The shelf-indented and headless submarine canyon consists, from north to south, of a 20-km-long, wide and gently-sloping (average slope = 2°) upper reach, an 8-km-long, narrow, steep (average slope = 6°) and rugged middle reach, and a 32-km-long, wide and flat (average slope = 0.8°) lower reach (Figs. 1B, DR1).

Oceanographical background

It is generally suggested that the SCS contains three-layers of western boundary currents (WBC), which are the upper layer, the intermediate, and the deep WBCs, respectively (Su, 2004; Wang et al., 2011; Tian and Qu, 2012; Zhou et al., 2017; Wang et al., 2019; Zhu et al., 2019). On the northern SCS margin, the upper layer and deep WBCs are cyclonic and flow southwestward, while the intermediate WBC is anticyclonic and flows northeastward (Fig. 1A). The depth of the interface between the upper layer and intermediate WBCs is approximately 500-1000 m, and the depth of the interface between the intermediate and deep WBCs is about 2000 m (Qu et al. 2006; Lan et al., 2013; Zhao et al., 2014; Zhou et al., 2017). On the northern shelf of the SCS, there are year-round currents, including the seasonally reversed Guangdong Coastal Current (GCC, southwestward in winter and northeastward in summer) in the near-shore area and the northeastward SCS Warm Current mainly straddling between 200-400 m isobaths in the outer shelf to shelf-break region (Fig. 1A; Guan, 1978; Guan and Fang, 2006). In addition, the northern SCS margin is frequently attacked by typhoons (storms) and develops world-known strong internal waves, which facilitate cross-shelf transport and diapycnal mixing, respectively (Tian et al., 2009; Alford et al., 2015; Zhou et al., 2017; Xie et al., 2018).
Data and methods

Manned submersible dive observations and footage data, dive based bathymetric profiles, multibeam bathymetric data, and a piston core were available.

Seven dives—one on May 23, 2018 (Dive 78), three on July 5, 18, and 19, 2019 (Dives 159 and 172-173), and the remaining three on March 11-13, 2020 (Dives 227-229)—were conducted during three cruises using the manned submersible SHENHAIYONGSHI with R/V TANSUOYIHAO affiliated to the Institute of Deep-Sea Science and Engineering, Chinese Academy of Sciences (Figs. 1B, 2A-B). The 2018 dive covered a 7.8-km-long distance roughly along the canyon thalweg between 1896 m water depth on the downstream end of Scour 2 and 1435 m water depth in the upper reach of the long stepped chute (Figs. 1B and DR1). This dive provided general information on the geomorphology and litter distribution in the stepped chute and the end scours. In this dive, we unexpectedly encountered some litter piles in the scours (Fig. 1B, Peng et al. 2019). Thereafter, the 2019 and 2020 dives were successively made to specifically investigate the distribution of litter accumulations in the scours (Figs. 2-3).

Four sets of video footage were collected in each dive using high quality camera systems mounted respectively at the front, port, starboard, and bottom of the submersible. The data were used to investigate the occurrence of benthic litter, locate the litter piles and measure their sizes.

We used the video footage along selected longitudinal and transverse dive transects (Figs. 3, DR1) to count the number of scattered litter items (not including those in the litter piles) on each snapshot. The areas commonly covered by two consecutive snapshots were marked to avoid counting the litter items inside the common area twice. The counting results were expressed in terms of the number of litter items per snapshot (nlps, one snapshot covers around 10 m×7m area) disregarding particle size. In this counting exercise, litter
items larger than 10 cm were able to be identified in the footage, which represents the cutoff value for the size of the recognizable litter items. Areas of high litter density (≥ 4 nlps) were further delineated (Figs. 2A-B, 3).

The ranges of individual litter piles were determined by recording the locations of the submersible in crossing. Orientations of the litter piles were determined by their alignments relative to the tracks of the submersible. The apparent lengths and widths of the litter piles were measured by the amount of crossing displacement of the submersible. Laser marker points and specific litter items with known size were used as references to estimate the heights of the litter piles. All known litter piles were estimated for their length, average width, average height, and volume (Table DR1). These estimates have an error up to 20-30% as evaluated by repeat observations of certain litter piles. In addition, the time-lapse dive observations provide us a unique opportunity to investigate the temporal-spatial variations of the litter accumulations.

One 27-cm-long piston core was collected from Scour 1 in Dive 228, and was sampled at 1 cm interval for grain size analysis using a laser particle-size analyzer to understand the nature of bottom sediment (Fig. 4).

Multibeam bathymetric data covering the submarine canyon investigated were collected in the 2018 dive expedition using the EM122 multibeam acquisition system mounted on the R/V TANSUOYIHAO. The data were used for guiding the dives in the submarine canyon, and revealing the geomorphologic details of the canyon in a precision up to 6-12 m for the target range of 1000-2000 m water depth.

SUPPLEMENTAL REFERENCES
Alford, M.H., Peacock, T., MacKinnon, J.A., Nash, J.D., Buijsman, M.C., Centuroni, L.R., et al., 2015, The formation and fate of internal waves in the South China Sea: Nature, v. 521, p. 65-69.

GMGS (Guangzhou Marine Geological Survey), 2015, Atlas of geology and geophysics of the South China Sea: Beijing, China Navigation Publications Press, 116 p.

Guan, B., 1978, The warm current in the South China Sea — A current flowing against the wind in winter in the open sea off Guangdong Province: Oceanologia et Limnologia Sinica, v. 9, p. 117–127 (in Chinese with English abstract).

Guan, B., and Fang, G., 2006, Winter counter-wind currents off the southeastern China coast: A review: Journal of Oceanography, v. 62, p. 1-24.

Lan, J., Zhang, N., and Wang, Y., 2013, On the dynamics of the South China Sea deep circulation: Journal of Geophysical Research: Oceans, v. 118, p. 1206-1210.

Peng, X., Dasgupta, S., Zhong, G., Du, M., Xu, H., Chen, M., Chen, S., Ta, K., and Li, J., 2019, Large debris dumps in the northern South China Sea: Marine Pollution Bulletin, v. 142, p. 164-168.

Qu, T, Girton, J. B., and Whitehead, J. A., 2006, Deepwater overflow through Luzon Strait: Journal of Geophysical Research, v. 111, C01002.

Su, J., 2004, Overview of the South China Sea circulation and its influence on the coastal physical oceanography outside the Pearl River Estuary: Continental Shelf Research, v. 24, p. 1745-1760.

Tian, J., and Qu, T., 2012, Advances in research on the deep South China Sea circulation: Chinese Science Bulletin, v. 57, p. 1827-1832.

Tian, J., Yang, Q., and Zhao, W., 2009, Enhanced diapycnal mixing in the South China Sea: Journal of Physical Oceanography, v.39, p. 3191-3203.
Wang, D., Wang, Q., Cai, S., Shang, X., Peng, S., Shu, Y., Xiao, J., Xie, X., Zhang, Z., Liu, Z., Lan, J., Chen, D., Xue, H., Wang, G., Gan, J., Xie, X., Zhang, R., Chen, H., and Yang, Q., 2019, Advances in research of the mid-deep South China Sea circulation: Science China Earth Sciences, v. 62, p. 1992-2004.

Wang, G., Xie, S.-P., Qu, T., and Huang, R. X., 2011, Deep South China Sea circulation: Geophysical Research Letter, v. 38, L05601.

Xie, X., Liu, Q., Zhao, Z., Shang, X., Cai, S., Wang, D., and Chen, D., 2018, Deep sea currents driven by breaking internal tides on the continental slope: Geophysical Research Letters, v. 45, p. 6160-6166.

Zhao, W., Zhou, C., Tian, J., Yang, Q., Wang, B., Xie, L., and Qu, T., 2014, Deep water circulation in the Luzon Strait: Journal of Geophysical Research: Oceans, v.119, 790-804.

Zhou, C., Zhao, W., Tian, J., Yang, Q., and Qu, T., 2014, Variability of the Deep-Water Overflow in the Luzon Strait: Journal of Physical Oceanography, v. 44, p. 2972-2986.

Zhou, C., Zhao, W., Tian, J., Zhao, X., Zhu, Y., Yang, Q., and Qu, T., 2017, Deep Western Boundary Current in the South China Sea: Scientific Reports, v. 7, 9303.

Zhu, Y., Sun, J., Wang, Y., Li, S., Xu, T., Wei, Z., and Qu, T., 2019, Overview of the multi-layer circulation in the South China Sea: Progress in Oceanography, v. 175, p. 171-182.
**Supplementary Figure DR1:** Dive-based bathymetric and corresponding litter density profiles along the 2018 dive track. nlps, number of the scattered litter items per snapshot. See Fig. 2B for profile location.
Supplementary Table DR1: Summary of the locations, dimensions and orientations of the litter piles delineated.

| Litter pile No. | Longitude (°E) | Latitude (°N) | Orientation | Length (m) | Avg. width (m) | Avg. height (m) | Volume (m³) | Dives |
|----------------|----------------|---------------|-------------|------------|----------------|----------------|-------------|-------|
| Small scour in the step chute |                |               |             |            |                |                |             |       |
| 1              | 111.90555      | 18.44897      | N56E        | 6          | 2.5            | 0.3            | 4.5         | 159   |
| 2              | 111.90555      | 18.44881      | N38W        | 8          | 3.5            | 0.5            | 14          | 159   |
| 3              | 111.90560      | 18.44869      | N60E        | 5          | 2              | 0.3            | 3           | 159   |
| Scour 1        |                |               |             |            |                |                |             |       |
| 1              | 111.90758      | 18.42253      | N13E        | 20         | 2              | 0.2            | 8           | 228   |
| 2              | 111.90768      | 18.42229      | N8E         | 5          | 0.5            | 0.1            | 0.3         | 228   |
| 3              | 111.90774      | 18.42218      | N6E         | 18         | 4              | 0.4            | 28.8        | 228   |
| 4              | 111.90791      | 18.42209      | N48W        | 9          | 6              | 0.8            | 43.2        | 228   |
| 5              | 111.90800      | 18.42200      | N58W        | 5          | 2              | 0.2            | 2           | 228   |
| 6              | 111.90870      | 18.42199      | N86W        | 2          | 1              | 0.1            | 0.2         | 179   |
| 7              | 111.90916      | 18.42192      | N-S         | 12         | 1              | 0.1            | 1.2         | 228   |
| 8              | 111.90804      | 18.42183      | N54W        | 4          | 1.5            | 0.2            | 1.2         | 228   |
| 9              | 111.90796      | 18.42181      | N3E         | 7          | 1.5            | 0.3            | 3.2         | 228   |
| 10             | 111.90766      | 18.42177      | N8E         | 10         | 2              | 0.1            | 2           | 228   |
| 11             | 111.90921      | 18.42176      | N26W        | 15         | 2              | 0.2            | 6           | 228   |
| 12             | 111.90904      | 18.42172      | N35E        | 12         | 2              | 0.2            | 4.8         | 78    |
| 13             | 111.90817      | 18.42166      | N79W        | 8          | 2.5            | 0.3            | 6           | 228   |
| 14             | 111.90890      | 18.42163      | N63E        | 5          | 1              | 0.2            | 1           | 179   |
| 15             | 111.90894      | 18.42160      | N66E        | 4.5        | 3              | 0.2            | 2.7         | 179   |
| 16             | 111.90820      | 18.42159      | N83E        | 12         | 3              | 0.2            | 7.2         | 228   |
| 17             | 111.90909      | 18.42146      | N40W        | 8          | 2              | 0.2            | 3.2         | 179   |
| 18             | 111.90962      | 18.42136      | N26W        | 6          | 1.2            | 0.3            | 2.2         | 179   |
| 19             | 111.90920      | 18.42134      | N22W        | 5          | 1              | 0.2            | 1           | 179   |
| 20-S1*         | 111.90896      | 18.42148      | N56E        | 22         | 3              | 0.5            | 33          | 179   |
| 20-S2          | 111.90907      | 18.42139      | N28E        | 6          | 3.5            | 0.4            | 8.4         | 179   |
| 20-S3          | 111.90907      | 18.42133      | N12W        | 14         | 1.5            | 0.2            | 4.2         | 179   |
| 20-S4          | 111.90914      | 18.42128      | N32W        | 7          | 3              | 0.5            | 10.5        | 179   |
| 21-S1          | 111.90897      | 18.42156      | N18W        | 29         | 2              | 0.2            | 11.6        | 179   |
| 21-S2          | 111.90891      | 18.42131      | N7E         | 18         | 2              | 0.3            | 10.8        | 179   |
| 22             | 111.90883      | 18.42125      | N24E        | 15         | 2.5            | 0.3            | 11.3        | 179   |
| 23             | 111.91052      | 18.42094      | N30W        | 10         | 3              | 0.5            | 15          | 228   |
|    | Latitude | Longitude | Bearing | Distance | Elevation | Reference |
|----|----------|-----------|---------|----------|-----------|-----------|
| 1  | 111.91468| 18.40932  | NS      | 6        | 2         | 2.4       |
| 2  | 111.91337| 18.40906  | N47W    | 9        | 2.5       | 0.4       |
| 3  | 111.91340| 18.40879  | N72W    | 9        | 2         | 0.2       |
| 4  | 111.91340| 18.40832  | N54W    | 6        | 1.2       | 0.2       |
| 5  | 111.91340| 18.40823  | N56W    | 8        | 2.5       | 0.3       |
| 6  | 111.91367| 18.40822  | N52W    | 21       | 3         | 0.2       |
| 7  | 111.91329| 18.40803  | N45W    | 35       | 2.5       | 0.1       |
| 8  | 111.91308| 18.40791  | N35W    | 20       | 2         | 0.1       |
| 9  | 111.91324| 18.40785  | N38W    | 18       | 2.5       | 0.1       |
|10  | 111.91421| 18.40782  | N27W    | 3.5      | 1         | 0.1       |
|11  | 111.91354| 18.40770  | N59E    | 3.5      | 1         | 0.1       |
|12  | 111.91382| 18.40769  | N32W    | 10       | 3         | 0.3       |
|13  | 111.91405| 18.40766  | N60E    | 5        | 1.2       | 0.2       |
|14  | 111.91355| 18.40765  | N10W    | 7        | 2         | 0.2       |
|15  | 111.91435| 18.40765  | N72W    | 12       | 6         | 0.8       |
|16  | 111.91376| 18.40760  | N23W    | 8        | 3         | 0.2       |
|17-S1| 111.91346| 18.40768  | N45W    | 23       | 8         | 0.2       |
|17-S2| 111.91354| 18.40753  | N56W    | 20       | 6.5       | 1.2       |
|17-S3| 111.91365| 18.40739  | N37W    | 18       | 4.5       | 0.6       |
|18  | 111.91405| 18.40749  | N81W    | 5        | 2         | 0.3       |
|19  | 111.91383| 18.40748  | N46E    | 4        | 3         | 0.3       |
|20  | 111.91342| 18.40747  | N55W    | 6        | 2         | 0.1       |
|21  | 111.91386| 18.40745  | N30W    | 4        | 1.5       | 0.2       |
|22  | 111.91392| 18.40741  | N46W    | 11       | 2.5       | 0.1       |
|23  | 111.91387| 18.40729  | N43W    | 9        | 1.5       | 0.1       |
|24  | 111.91494| 18.40722  | N80W    | 2        | 1         | 0.2       |
|25  | 111.91359| 18.40698  | N48W    | 14       | 1.5       | 0.1       |
|26  | 111.91324| 18.40679  | N70W    | 7.5      | 2.5       | 0.3       |
| Litter Pile | Coordinates | Orientation | Size | Segment Size | Distance | Status |
|------------|-------------|-------------|------|--------------|----------|--------|
| 27         | 111.91347   | 18.40664    | N25E | 2.5          | 1.2      | 0.3    | 0.9    | 173    |
| 28         | 111.91321   | 18.40643    | N83W | 4            | 1.5      | 0.2    | 1.2    | 227    |
| 29         | 111.91321   | 18.40636    | N53E | 2            | 1.5      | 0.2    | 0.6    | 227    |
| 30         | 111.91351   | 18.40628    | N56E | 3.5          | 2        | 0.2    | 1.4    | 173    |
| 31         | 111.91350   | 18.40620    | N85E | 4.5          | 2        | 0.3    | 2.7    | 173    |
| 32         | 111.91380   | 18.40614    | N74W | 3            | 2        | 0.1    | 0.6    | 226    |
| 33         | 111.91375   | 18.40612    | NS   | 3            | 0.8      | 0.1    | 0.2    | 226    |
| 34         | 111.91341   | 18.40612    | N23W | 3.5          | 1        | 0.3    | 1.1    | 173    |
| 35         | 111.91348   | 18.40611    | N45W | 4            | 1.2      | 0.3    | 1.4    | 173    |
| 36         | 111.91348   | 18.40597    | N73W | 8            | 1        | 0.2    | 1.6    | 173    |
| 37         | 111.91377   | 18.40597    | N63W | 6            | 1.2      | 0.2    | 1.4    | 78, 173, 226 |
| 38         | 111.91245   | 18.40526    | N62E | 2.5          | 0.8      | 0.1    | 0.2    | 227    |
| 39         | 111.91250   | 18.40525    | N41E | 4            | 3        | 0.3    | 3.6    | 227    |
| 40         | 111.91260   | 18.40523    | N73E | 7            | 2.5      | 0.3    | 5.3    | 227    |
| 41         | 111.91398   | 18.40376    | N72W | 7.5          | 3        | 0.8    | 18     | 172, 173, 226, 227 |
| 42         | 111.91419   | 18.40370    | N39W | 2            | 1        | 0.4    | 0.8    | 226, 227 |

* The suffixes S1-S4 after litter pile numbers represent the serial numbers of the segments comprising the litter piles.