Indian Journal of Geo Marine Sciences
Vol. 50 (05), May 2021, pp. 366-373

Accumulation characteristics and geological hazard effects of gravity flow on northwestern lower continental slope in the South China Sea

W Gao, L J Liu, J Liu, Y Q Xu, P Li[†] & S Gao[$]

[a]Key Laboratory of Marine Geology and Metallogeny, First Institute of Oceanography, MNR, Qingdao – 266 061, China
[b]Laboratory for Marine Geology, Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao – 266 061, China

[E-mail: [†]liping@fio.org.cn; [$]gsyookio@fio.org.cn]

Received 02 December 2019; revised 30 November 2020

The northwestern lower continental slope margin in the South China Sea is the main fluid property conversion area of the debris flow and turbidity current, where accumulations of typical and special gravity flows are developed. In the upper strata of the research area, there are at least four stages of debris flow accumulations. Several 1-3 m high pressure ridges are developed on the seafloor surface and on the top of underlying accumulations. A large quantity of slide accumulations or extrusion deformation structures is developed on the slope and at the base of the slope. The slides accumulation surface can be clearly seen, and the accumulations are still moving downward slowly and extruding continuously, resulting in a series of geological hazard effects. The study shows that the sediments are mainly composed of silt and clayey silt on the northwestern lower continental slope in the South China Sea. The sediments are deposited at the foot of the slope where the energy of gravity flow begins to reduce rapidly. The cores and shallow seismic profiles of upper strata on the lower continental slope as described in this paper have proven that there are three different accumulation processes, and the geological hazard effects incurred are completely different so that we shall further enhance the research on the seafloor geological hazard effects.

[**Keywords**: Gravity flow, Geological hazards, Lower continental slope, South China Sea, Substance transport]

Introduction

The lower continental slope, as a significant place of sediment deposition and re-transport, acts as not only the “sink” where the sediments from continental shelf and upper continental slope accumulate, but also as the “source” guaranteeing the continuous transport of sediments towards the deep sea so the lower continental slope plays an important role in the “source- sink” research system of global continental margin. The existing massive sandy or gravelly depositional fans and deep-sea depositional plains far from the mainland by hundreds to thousands kilometers prove the importance of such substance transport system, and have become an important part of plate tectonics research. The transport and deposition of sediments under the effect of gravity have become one of the most important sediment transport mechanisms, which are usually classified to slide, slump, debris flow, turbidity current and other processes[1], and are also defined as a significant type of seafloor geological hazards, among which debris flow and turbidity current are widely developed on the lower continental slope. The northwest continental slope in the South China Sea is one of the typical areas where the sediments are transported and deposited under the effect of gravity. The high sediment supplying rate of the Red river, the uplift in Hainan, and the Indo-China Peninsula contributes to the big thickness of quaternary sediments on the northwestern continental slope in the South China Sea[2]. It promotes the development of deep-water sediment transfer and sedimentation system, and various sedimentation systems and complex form of sediment composition are developed in the deep water area[3]. Therefore, the northwestern lower continental slope margin in the South China Sea is a significant area where the fluid properties change from debris flow to turbidity current[4]. The very typical and special sedimentations are developed in this area, resulting in a series of geological hazards, and deeply changing the seafloor topography and strata structure. This area has become a key and focal area for research of geological hazard effect in the sediment transport and deposition process.

The study shows that the sediment transport and deposition of gravity flow plays an important role in the stability of upper seafloor strata on the continental slope[5], and the geological hazard effect accompanies the whole transport process. However, it has been also found that the research on the transport and deposition processes on the lower continental slope and other geological hazard effects develops slowly, in comparison with the outstanding research results of transport process of sediments on the continental slope in the South China Sea, especially the sedimentation features of sediments in the early period obtained by the use of plenty seismic data[6]. Therefore, the present work is focused on relevant research to deepen the theoretical research of the modern debris flow and turbidity current periods and the sedimentation characteristics of fluid conversion area, improve the understanding of functional mechanism of substance transport and deposition in the deep-water geological hazard, provide a modern deposition mark for the identification of deep-water gravity flow deposition in the early period, and to serve the safety of big science devices on the seafloor.

Materials and Methods

Sample source

In order to explore the accumulation characteristics of sediments in the property conversion area of gravity flow at the northwestern continental slope base in the South China Sea, we took one 4.3 m-long gravity core (Fig. 1) from the turbidity current sediments on the northwestern lower continental slope in the South China Sea by the "XIANGYANGHONG 01" research vessel for seal trial with the gravity sampler on the vessel in June 2017. At the same time, the sub-bottom profile survey in this area was carried out, and the stratigraphic information around the sample collection station was obtained.

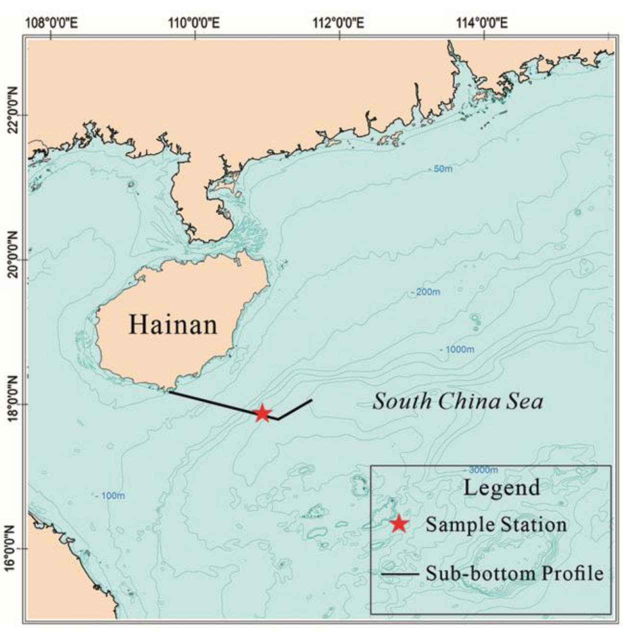

Fig. 1 — Position of sampling station and track line on the sub-bottom profile

Research method

Interpretation of acoustic survey data: the sub-bottom data were interpreted and processed by the man-machine method, *i.e.* the interpreter selected the wave impedance interface with obvious reflection characteristics for continuous tracking, divided the acoustic reflection interface by clicking on the screen, and deduced the strata characteristics of every unit and distinguishes the type of geological hazards in combination with the relevant survey results and regional environment data, and thus obtained the characteristics of sedimentary strata in the area of this station. The submarine topography and geomorphic characteristics were obtained by processing the multi beam survey data, and the interpretation of the sub-bottom data was based on the cores. At the same time, computer image processing and statistical analysis technology were used to extract and classify the key acoustic characteristics of sedimentary strata, to analyze the periodic activity of debris flow and the cycle characteristics of turbidity deposition in the study area, so as to establish the three-dimensional sedimentary framework of material accumulation on the lower continental slope and identify the scale and distribution range of geological hazards. The seismic interpretation was conducted by using Triton's Prespective software (Triton Imaging, INC, USA). The correlation between seismic and borehole data and different bandpass, stack, and other filtering methods was conducted to improve the interpretation accuracy[7].

Sample processing and analysis

After the gravity core was transported to the laboratory, the Siemens SOMATOM Definition Flash photon CT scanning equipment was used to do a non-destructive test on the core sample at every 0.5 mm (Setting parameters, Kv is 70, eff.mAs is 200, Tl is 1.0), and the 360° fine virtual data of sedimentary structure of core was obtained, so as to analyze the characteristics of its sedimentary structure. After the core was opened, a sample was taken at every 2 cm for the measurement of particle size. The measurement was conducted by using the Mastersizer

2000 laser particle analyzer (Malvern Inc, British) with a measure range of 0.02 to 2000 μm. The grain size was analyzed after pretreating the samples with 10 % H_2O_2 and 0.1 N HCl to remove organic matter and biogenic carbonate. To reduce systematic and artificial errors, the measure was repeated until such error is less than 3 %[ref. 8].

Results

Characteristics of sedimentary strata

There are many debris flow and turbidity current deposits in the lower continental slope, so an important work is how to identify debris flow and turbidity current deposits[9]. On the profile of shallow stratum, the debris flow accumulation body is often represented as a chaotic sedimentary lens in the stratum, and its sedimentary structure is obviously different from other adjacent sedimentary layers. For example, the bottom of turbidities is usually coarse-grained (gravel or mud gravel) eroded residual deposit, and the profile of shallow stratum is discontinuous coarse-grained reflector. The middle and upper parts are concave or nearly horizontal fine-grained reflector and the turbidity accumulation fans (deep sea fans) outside the outlet of the submarine canyon are obviously displayed on the three-dimensional topographic map and the bathymetric map.

The northwestern lower continental slope in the South China Sea has a gradient of about 0.4°, and is in the SE direction. Massive slide accumulations or extrusion deformation structures developed on the slope and at the slope base are seen obviously and the Core 01 is located at this slope base. According to the above identification standards, there are at least four periods (T0-T1, T1-T2, T2-T3, T3-T4) of debris flow accumulations in the upper strata in the detection scope of sub-bottom profile. The maximum thickness of accumulation is more than 20 m, and the accumulation surface of slide mass is seen clearly (T1, T2, T3, T4) (Fig. 2). Many 1-3 m high extrusion ridges are developed on the seafloor surface and the top of underlying accumulation, proving the continuous extrusion of slope base and the continuous download and slow slide of upper strata. It is obviously different from the structure characteristics of continuous strata in the normal sedimentation area, which the surface should be smooth and parallel among the strata. For example, the shallow profile has a large penetration depth in the normal deposition area, indicating that the layers there are mainly composed of fine particulate sediments. The stratigraphic continuity is good, the sedimentary layers are parallel, and the thickness of each layer is about 2-4 m (Fig. 3).

Characteristics of sedimentary structure

The columnar sample named Core 01, located at the slope base at the depth of 1,602 m in the southeastern sea area of Hainan, consists of upper strata samples of multi-phase debris flow accumulations. By CT scanning, it is found that the sedimentary structure is divided into three segments obviously. (1) 0-85 cm: mostly gray silt, with uniform sedimentation; several holes with diameter of 0.5-1.0 cm are developed; this segment is of normal sedimentation. (2) 85-370 cm: mostly clayey silt, with sedimentary structure and sedimentary lamina developed, contain a lot of relatively dense masses and biological shells, among which the sediment lump is uniform with the underlying sediment (segment three), reflecting the erosion of underlying strata

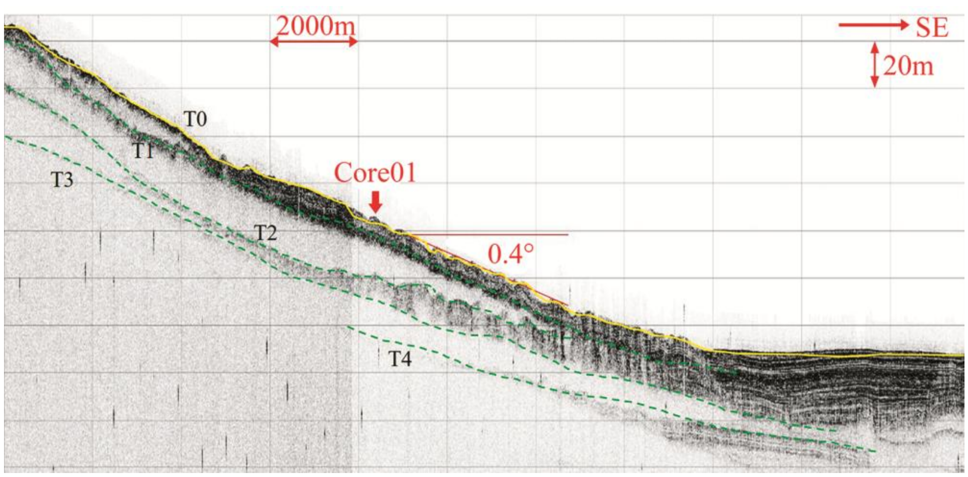

Fig. 2 — Sub-bottom profile near the sampling station

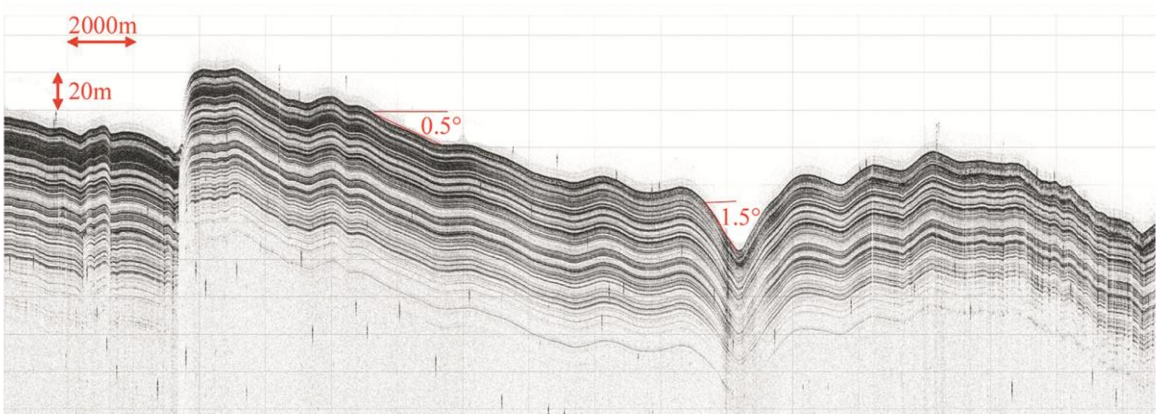

Fig. 3 — Sub-bottom profile of normal sedimentary area

caused by the gravity flow during transport; the whole segment shows the typical accumulation characteristics of debris flow. (3) 370-430 cm: mostly gray silt, with dense sediments and lower water content, the contact face with the second segment is unconformable; they are very different in the sedimentary structures and the physical and mechanical properties (Fig. 4).

Bauma sequence is an ideal sequence of turbidity current deposition and a kind of lithofacies combination in deep-water sedimentary environment, which not only includes turbidity current deposits, but also other types of gravity current and deep-water traction current deposits. Therefore, there may be uncertainty and multiplicity of solutions to judge whether it is turbidity deposition by this sequence. In order to set up a new criterion for judging turbidities, Shanmugam took the upward thinning grain sequence layer as a sign to distinguish the turbidity current deposition. With the strong erosion of turbidity current, the deposits are in unconformable contact with the accumulation body and underlying strata (for example, between segment two and segment three of Core 01). For the debris flows, the particularity is very obvious in the stratigraphic structure, sedimentary characteristics and grain size of sediments. Although the debris flow velocity is slow, the erosion to the underlying layer is strong, characterized by a large number of underlying formation sediment mass into the upper layer, and the Core 01 is the best explanation of this phenomenon. In conclusion, Core 01 shows the very typical accumulation characteristics of gravity flow.

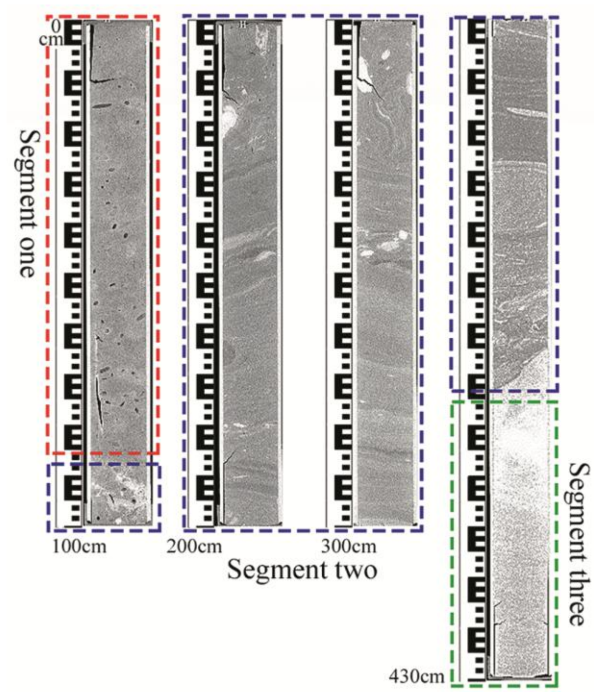

Fig. 4 — Sedimentary structure characteristics of columnar Core 01

Discussion

Hydrodynamic environment

The lower continental slope with normally developed debris flow and turbidity current process is the significant node of fluid property conversion in the course of deep-water gravity flow, and also the shift area of mass and turbidity transport of sediments, and thus the special and typical sedimentations occur. The typical characteristics of acoustic transparent layer are shown inside the sedimentary body on the sub-bottom profile, but in comparison with the shallow debris flow in the river mouth area, etc.[10], the trigger mechanism, sediment composition and destructiveness of deep-water debris flow have big differences, so does the turbidity current. The C-M map is drawn with the C and M values of every sample (Fig. 5), on which C indicates the particle size

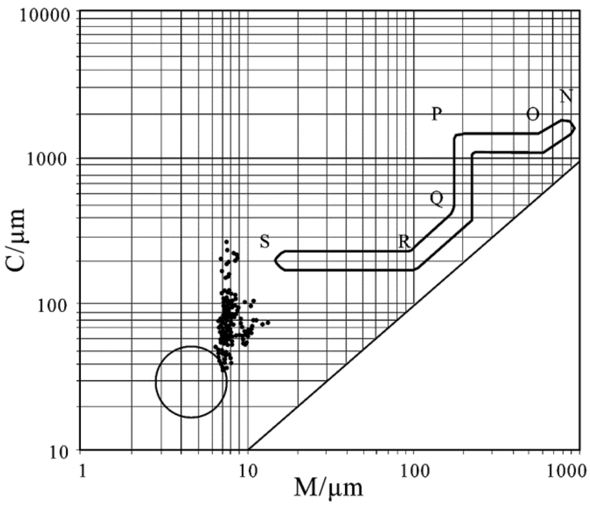

Fig. 5 — C-M chart of Core 01 sediments

corresponding to the 1 % particle content on the particle size analysis data cumulative curve, M indicates the particle size corresponding to 50% on the cumulative curve, namely the median particle size. C value is equivalent to the maximum particle size of samples, representing the maximum energy when the transport starts by hydrodynamic stirring, and M is a median value, representing the mean energy of hydrodynamic force. Every sedimentary environment has its own characteristic C-M map pattern. The research results show that: (1) 1.5~3° is the ideal gradient for the development of turbidity current; (2) The turbidity sedimentation deposit is fan-shaped, the thickest at the corner, and becomes thinner gradually towards the basin; (3) with other conditions unchanged, the larger the sediment particle size is and the thicker the sedimentation is, the smaller the expansion is; the larger the sediment particle size is and the thinner the sedimentation is, the wider the expansion is[11].

Grain size analysis shows that the content of each component sediment is relatively stable, and the composition of sediment is mainly silt in core 01. The content of silt is 65-80 %, the content of sand is less than 6.5 %, and the content of clay is 17-30 %. According to the sediment types, the columnar sample sediments can be divided into three segments, 0-50 cm is silt mainly; 50-370 cm is clayey silt mainly; 370-430 cm is silt mainly. The C-M map of Core 01 sediments shows that they are located near the static aqueous suspension (Fig. 5). Additionally, the water depth map and sub-bottom profile map show that it is located at the border of continental slope base, and the gradient is smaller, just 0.4°. Because the gravity flow on the continental slope arrives at the slope base after long transport, the energy loss is serious, and the sediment particle size is smaller, resulting that the sediments deposit here after they are transported in the state similar to static aqueous suspension.

Sediment transport characteristics

The 2D/3D seismic data obtained from the previous oil-gas exploration performed in the northwestern continental slope area in the South China Sea are very detailed, and contain rich geological information. The buried deep-water gravity flow sedimentary cycles and mass movement of many phases and their sedimentary records are found in the seismic data of northwest area in the South China Sea[12]. Therefore, the rich fundamental data and theoretical supports are provided for the oil-gas exploration. Among the large mass flow deposits, the slide deposits are mainly developed in the upper continental slope area; the slump deposits and debris flow deposits are mainly developed in the lower continental slope area. In the slide deposits, only slide exists without rotation of sedimentary strata, the original bedding and structure characteristics are retained, and the parallel beddings, lentoid beddings, wavy beddings and other shallow-water sedimentation structures are often developed inside, but generally accompanied with the different degrees of rotation[13,14]. In the slump deposits, the sediments inside rotate and have intense synsedimentary deformations which are typical plastic deformations[15] and represent the occurrence of rapid sedimentation. By means of high-resolution sub-bottom profile, geological core and other data, we have found that there are debris flow accumulations of many phases in the upper strata in the northwestern lower continental slope area in the South China Sea, and many 1-3 m-high extruded ridges on the seafloor surface and on the top of underlying accumulation, and their forms are quite similar to the deep-sea sediment wave formed by the internal wave and other deep flows[16,17], but very different in the water depth of development and the formation mechanism. The multi-phase turbidity sedimentary cycles are found in the core in the flat area with a smaller gradient so that the direct and visible information are provided for sediment transport and sedimentation on the lower continental slope.

The study shows that the high supply rate of the Red river, the uplift in Hainan, and the Indo-China Peninsula make contributions to the big thickness of quaternary sediments on the northwestern continental slope in the South China Sea which provides fundamental conditions for the development of deep-water sediment transport and sedimentation system. In the upper shallow water area on the continental slope, the continuously accumulated sediments are easy to become unstable, slide and even collapse under the effect of storm, wave, earthquake and tsunami. In the course of down slide, a lot of water enters the slide mass due to extrusion and disturbance, resulting that the slide mass is broken and changed into the debris flow with a higher fluidity than the slide[18]. Through the continuous movement, the debris flow is diluted continuously with the surrounding water, the sediment particles at the end of debris flow are eroded, and finally, the turbidity current is formed. With the decrease in gradient, the energy of turbidity current decreases, and the sediment particles contained in the turbidity current deposit in the low area of canyon, or are carried to the ocean basin, forming the seafloor canyon fan and deep-sea alluvial fan[19], and meanwhile the newly generated accumulations move and extrude downward continuously under the effect of gravity, forming a series of geological hazards and the special symptoms of sedimentology. The study area is located in the middle of southeastern continental slope and the sediment is mainly from the coastal rivers in the southeast of Hainan Island. Due to Songtao uplift, the transporting of sediments to the continental slope is restricted. The sedimentary action and the erosion action of bottom flow reach a balance and restrict each other. Both actions coexist in this section, and the local sedimentary action is strong, so the study area belongs to the transitional zone. The important reason for the limited extension of debris flow (Core 01) to the deep sea is also affected by the uplift.

Geological hazard effects

The deep-water geological hazard is one of most challenging aspect of current geoscience research. The whole course of substance transport and sedimentation on the continental slope is often accompanied with the geological hazards. The sediment activation implies the slide and stability losing, and the debris flow and turbidity current generated by the sediment transport generate the great destructive force. The form and occurring time of slide mass are determined through the seafloor landform and strata survey and analysis of seafloor slide, normally after occurring of slide, by dint of the geophysical survey data obtained by multiple beam, side scan sonar, sub-bottom profile and single/multi-channel earthquake, and in combination with the sedimentology knowledge obtained from cores and other sediment samples[20-22]. For example, for the famous Storegga slide in Norway, the seafloor slides of continental slopes in the South China Sea and the East China Sea, the detailed information about seafloor form, sediment distortion and strata structure were obtained by the marine geophysical survey technologies in order to identify the distribution and scale characteristics of slide mass[23]. At present, with the progress and development of oil-gas exploration and geophysical exploration technologies, the seafloor landform, strata distribution and sediment analysis data become more and more rich and accurate, the research on deep-water gravity flow sedimentation is improving, and the effective instruments are provided for the risk assessment of geological hazard[24]. Therefore, with the gradual progress of deep-water oil-gas development strategy, seafloor observation network and other seafloor big science devices, the theoretical and economic significances of geological hazard effect research on the seafloor sediment transport and sedimentation become more important. One purpose of Core 01 sampling position and sub-bottom track design is to consider and research the sedimentation characteristics of gravity flow accumulation area on the northwestern lower continental slope in the South China Sea. The study shows that the large-area multi-phase gravity flow accumulation areas are widely developed on the northwestern lower continental slope in the South China Sea, and the typical evidences proving the accumulation characteristics of end period of turbidity current and the slow downward motion and extrusion of debris flow are found on the top. Recently, we have obtained the approval for the next navigation for more acoustic survey data and core samples with one purpose of researching the active period of gravity flow accumulation and other geological hazard effects.

Since Shanmugam & Zimbrick[25] clearly proposed and established the concept of sandy debris flow[25], and separated the debris flow research from the high-density turbidity current research, the underwater debris flow research has rapidly become a topic of sedimentology research. However, due to the delay of debris flow, the attention to the destructive effect and geological hazard effect of debris flow is insufficient, and the research on the relation between the active cycle of debris flow and the formation and transfer of turbidity current needs further enhancement. The marine oil-gas exploration and development in the early period focused on the shallow water areas so the researches on the engineering geological conditions and geological hazards on the continental slope and in the deep water area with complex geological conditions are fewer[26]. Meanwhile, the survey and research in the early period focused on the identification and classification of hazards. Although the research on the occurring mechanism and simulation and forecast technologies of geological hazards is developing with the improvement of deep-water strategy and survey technology equipment of oil and gas resources in the later period, the researches on the sediment transport and sedimentation on the lower continental slope and the geological hazard effect are separated to some extent. There is still a long process to synchronize the source and sink process of sediments with the occurrence of geological hazards.

The South China Sea is the sea area with the most complex hazardous geological conditions and the highest potential geological hazard risk[27], including various geological hazards such as shallow gas[28], natural gas hydrate, seafloor pits, escarpments, mud diapirs[29], slides and creeps, active faults, and deep-water seafloor debris flow. Most of geological hazard symptoms are directly related to the sediment transport and sedimentation. A lot of seafloor slides[30], debris flows and turbidity currents have been found on the continental slope in the South China Sea so the seafloor stability and structure safety are affected seriously. In China, the 3,000 m “Marine oil 981” and other top-grade oil equipment are booming, and the investments over 2 billion Yuan will be used to establish the national seafloor science observation networks in the South China Sea and the East China Sea, respectively. Additionally, the carrying of oil and gas resources, the construction of underwater transport node and the transmission of observation signal cannot be separated from the construction of seafloor cables; the cable rout and node selection cannot avoid the effect of geological hazard; the deep-water pipes and cables must pass through the continental slope area with frequent hazards. For the geological hazard research, we often highlight the turbidity current hazard that happens rapidly, but neglect the sluggish geological hazard effect of debris flow. In short, how to choose when both debris flow area and turbidity current area cannot be avoided? The research on the activity and erosion of debris flow becomes very important. The important role of substance transfers and sedimentation on the continental slope in the seafloor geological hazard effect needs further research in order to make the final judgment.

Conclusions

There are multi-phase debris flow accumulations in the upper strata on the northwestern lower continental slope in the South China Sea and a large quantity of slide accumulations or extrusion deformation structures developed on the slope and at the slope base are seen clearly, and the accumulation faces of slide masses are visible and distinct.

The characteristics of sediments on the northwestern lower continental slope of the South China Sea meet the accumulation features of debris flow. The sediments mostly consist of silt and clayey silt, and are in the stage from uniform suspension transport to static suspension transport. The sediments are located at the outer border of slope base so the long transport distance of sediments and the smaller gradient result in the relatively weak hydrodynamic environment here.

Acknowledgements

This study was jointly funded by the National Program on Global Change and Air-Sea Interaction (No. GASI-GEOGE-05), the National Natural Science Foundation of China (No. 41206054, No. 41706065 & No. 41506071). Data and samples were collected on board of R/V "XIANGYANGHONG 01" of First Institute of Oceanography, MNR, China.

Conflict of Interest

The authors declare that they do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Author Contributions

WG & PL designed experiments; JL & YQX carried out experiments; SG & LJL analyzed data and charted the illustrations; and WG wrote the manuscript.

References

1 Shipp R C, Weimer P & Posamentier H W, Mass-transport deposits in deepwater settings, *SEPM Special Publication*, 96 (2011) 1-4.

2 Liu Z F & Stattegger K, South China Sea fluvial sediments: An introduction, *J Asian Earth Sci*, 79 (2014) 507-508.

3 Chen H J, Zhan W H, Wen M M & Li L P, Characteristics of shelf break and sedimentation process at the Qiongdongnan basin, northwestern South China sea, *Mar-Geol Frontiers*, 31 (8) (2015) 1-9.

4 Li Y, Zhen R C, Zhu G J & Hu X Q, Reviews on sediment gravity flow, *Adv Earth Sci*, 26 (2) (2011) 157-165.

5 Wang D W, Wu S G, Dong D D, Yao G S & Cao Q B, Seismic characteristics of Quaternary mass transport deposits in Qiongdongnan basin, *Mar-Geol and Quat-Geol*, 29 (3) (2009) 69-74.

6 Xie X N, Chen Z H, Sun Z P, Jiang T & He Y L, Depositional architecture characteristics of deepwater depositional systems on the continental margins of northwestern South China Sea, *Earth Sci-J CUG*, 37 (4) (2012) 627-634.

7 Gao W, Liu S H, Liu J, Xu Y Q & Li P, The sedimentary facies and dynamic environment of the Diaokou lobe inthe modern Huanghe River Delta of China, *Acta Oceanol Sin*, 37 (11) (2018) 40-52.

8 Gao W, Li G X, Wang X D, Sun T & Liu Y, Sedimentary Characteristics of the Hyperpycnal Flow in the Modern Yellow River Delta, *Indian J Geo-Mar Sci*, 43 (8) (2014) 1438-1448.

9 Xu Y Q, Liu L J, Zhou H, Huang B Q, Li P, *et al.*, Submarine landslide identified in DLW3102 core of the northern Continental slope, South China Sea, *Acta Oceanol Sin*, 17 (1) (2018) 147-155.

10 Gao W, Li G X, Cao L H & Li P Y, Formation mechanism of seafloor instability in the modern Yellow River delta, *24th ISOPE*, 1 (2014) 289-293.

11 Jiang T, Xie X N & Tang S L, Hydrodynamic simulation of turbidity and its application for reservoir prediction, *Geol Sci and Tech Info*, 24 (2) (2005) 1-6.

12 Yuan S Q, Wu S G & Zhao Z J, Deepwater sediment transportation models for northern South China sea slopes, *Mar-Geol and Quat-Geol*, 30 (4) (2010) 39-48.

13 Pan S X, Zheng C R & Wei P S, Deposition characteristics, recognition mark and form mechanism of mass transport deposits in terrestrial lake Basin, *Lithologic Reservoirs*, 25 (2) (2013) 9-18.

14 Posamentier H W & Martinsen O J, The character and genesis of submarine mass-transport deposits: Insights from outcrop and 3D seismic data, *SEPM Special Publication 96*, (2011) 7-38.

15 Moscardelli L, Wood L & Mann P, Mass-transport complexes and associated processes in the offshore area of Trinidad and Venezuela, *AAPG Bulletin*, 90 (7) (2006) 1059-1088.

16 Ding W W, Li J B, Han X Q, Li M B & Erwin S, Geomorphology, grain-size charicteristics, matter source and forming mechanism of sediment waves on the ocean bottom of the northeast South China Sea, *Acta Oceanol Sin*, 32 (2) (2010) 96-105.

17 Gao P & He Y B, Status and prospect of study on deep-sea large-scale sediment waves, *Mar Sci*, 33 (5) (2009) 92-97.

18 Khripounoff A, Vangriesheim A, Crassous P & Etoubleau J, High frequency of sediment gravity flow events in the Var submarine canyon (Mediterranean Sea), *Mar Geol*, 263 (2009) 1-6.

19 Parsons J D, Whipple K X & Simoni A, Experimental study of the grain-flow, fluid-mud transition in debris flows, *J Geol*, 109 (2001) 427-447.

20 Martinez F J, 3D Seismic interpretation of mass transport deposits: implications for basin analysis and geo-hazard evaluation, In: *Advances in Natural and Technological Hazards Research*, edited by Mosher D C (Springer, Dordrecht), 2010, pp. 553-568.

21 Xu Y Q, Li P, Li P Y, Du J, Liu L J, *et al.*, The microstructure characteristic of cohesive soil in inner shelf of the East China Sea and its engineering implication, *Indian J Geo-Mar Sci*, 48 (3) (2019) 389-396.

22 Zhai J S, Zou B, Xu J & Gao S P, A new algorithm for high-precision submarine topography imaging, *Indian J Geo-Mar Sci*, 48 (5) (2019) 730-738.

23 Lecomte I, Bano M & Hamran S E, Submarine slides at Finneidfjord (Norway): geophysical investigations, *JEEG*, (2008) 376-388.

24 Chen Y L, Liu L J, Liu X Y & Li X S, Seabed Topographic Survey Technology in Deep-sea Oil and Gas Exploration, *Hydrographic Surveying and Charting*, 35 (2) (2015) 18-22.

25 Shanmugam G & Zimbrick G, Core-based evidence for sandy slump and sandy debris flow facies in the Pliocene and Pleistocene of the Gulf of Mexico: Implications for submarine fan models, *AAPG Bulletin*, 5 (1996) 128-129.

26 Yang W D, Zhang Y B & Li B, Types and characteristics of deepwater geologic hazard in Qiongdongnan of the South China Sea, *Offshore Oil*, 31 (1) (2011) 1-7.

27 Liu S Q, Liu X Q, Wang S J & Guo Y G, Kinds of hazardous geology and division in South China Sea, *Chinese J Geol Hazard Control*, 11 (4) (2000) 39-44.

28 Zhu C Q & Jia Y G, Submarine slope stability analysis during natural gas hydrate dissociation: Discussion, *Mar Georesour Geotec*, 38 (6) (2020) 753-754.

29 Wan Z F, Yao Y J, Chen K W, Zhong S L & Sun Y F, Characterization of mud volcanoes in the northern Zhongjiannan Basin, western South China Sea, *Geol J*, 54 (7) (2019) 177-189.

30 He Y, Zhong G F, Wang L L & Kuang Z G, Characteristics and occurrence of submarine canyon-associated landslides in the middle of the northern continental slope, South China Sea, *Mar Petrol Geol*, 57 (2) (2014) 546-560.