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Potential Submarine Geologic Hazards at the Entrance of the Pearl River Estuary in the Northern South China Sea

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Abstract The potential submarine geologic hazards were distinguished and categorized at the entrance of the Pearl River Estuary in the northern South China Sea, based upon the analysis of side scan sonar and sub-bottom profiler surveying data of about 2500 km long, in an area about 2000 km^2 around the Wanshan Archipelago. The data obtained in the survey has the highest spatial resolution by far, which could reveal more detailed distributions and characteristics of the geologic hazards than before. In the study region, three paleo-channels that were buried about 10–30 m below the seabed were found; more than 10 shallow gas areas were discovered. The sand waves found in the region were generally small and located near the islands, and twenty pockmarks found on the seabed were mostly concentrated to north of Zhuzhou island. There are also many man-made obstacles in the region, such as wreckages, pipeline, *etc*. In this paper we provide a detailed distribution map of the submarine geologic hazards in this region for the first time, and discuss their formation and harmfulness, which will provide a scientific basis for marine engineering construction, marine geologic disaster prevention and mitigation.

Key words Wanshan Archipelago; submarine geologic hazards; sand waves; shallow gas; paleo-channel; bedrocks

1 Introduction

Marine hazard geology is a new emerging discipline that is originated from the marine oil exploitation and engineering constructions over the continental shelf of the ocean. The study of the marine hazard geology has been gradually extended from coastal shallow shelf to deep basin. There have been plentiful achievements on the marine geological hazardous survey and researches.

There are numerous potential marine geologic hazards in the South China Sea (Liu *et al.*, 2002; Chen and Yang, 1996; Liu *et al.*, 2000; Liu *et al.*, 2014a; Yang *et al.*, 2011). The Wanshan Archipelago and its adjacent region are located at the entrance of the Pearl River Estuary on the northern South China Sea shelf. The rapid development in the Pearl River Delta, accompanied by a large increase of human activities at sea, such as marine aquaculture, oil exploitation, submarine pipeline laying, *etc.*, results in an increase of the economic loss caused by the marine geologic disasters, which leads to a growing demand of survey and research on the potential marine geologic hazardous factors.

High resolution geophysical survey (such as sounding, side scan sonaor, sub-bottom profiler, seismic surveying and so on) is a primary way of geologic hazard study (Will, 2005; Liu *et al.*, 2005; Jin, 2007; Qiu *et al.*, 2012; Wang *et al.*, 2014; Liu *et al.*, 2014b). The research on the geologic hazard in the northern South China Sea started in the 1980's. Under the support from the United Nations Development Program (UNDP), the Guangzhou Marine Geological Survey Bureau completed the 1:200000 marine engineering geological survey of the Pearl River Mouth Oil Development region, covering 6.9×10^4 km^2 (Wu and Bao, 2000). In the project, a comprehensive marine engineering geological survey was conducted, the potential submarine geologic hazards types were identified and the stability of the seabed was assessed (Xia *et al.*, 1999; Feng *et al.*, 1996; Feng *et al.*, 1994a, b, c; Bao, 1995; Chen, 1996). After that, some more researches about potential submarine geologic hazards were also conducted around this region (Bao and Jiang, 1999). Wu and Bao (2000) analyzed the types, distribution characteristics, formation mechanisms and harmfulness of these potential submarine geologic hazards in the northeastern South China Sea; Wu and Chen (2008) studied the morphology, distribution and formation time of epicontinental seabed landslides in the northern South China Sea based on 2-D and 3-D seismic data.

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Although there were many historical researches on the geologic hazards in the northern South China Sea, the survey scales were not large enough and the resolutions were not high enough to reveal a complete view of the geologic hazards in more detail at the entrance of the Pearl River Estuary. In 2006, a cruise of the national project of comprehensive survey and assessment of the Chinese coastal seas was conducted with a large scale and high resolution survey by side scan sonar and sub-bottom profiler, that covered about 2000 km^2 in this area, at 1000 m interval spacing, traveling north to south, with a total length of 2500 km. The objective of this paper is to obtain more comprehensive characteristics of the potential submarine geologic hazards around the Wanshan Archipelago at the entrance of the Pearl River Estuary, which were not displayed and discussed in detail before, because of the coarse resolution of previous survey in this region. The result of such a research is expected to provide valuable information for more efficient and safer marine engineering activities in this area. The paper is organized as follows: the observation equipment and data analysis are briefly introduced in Section 2, the basic geological settings and the potential submarine geologic hazards are described in Sections 3 and 4 respectively, and a summary of this study is given in Section 5.

2 Methods

A sub-bottom profiler and sidescan sonar combined system was used in the surveying in the study area (EdgeTech 2400, 2–16 kHz for sub-bottom profiler with 10 cm resolution and 20–50 m penetration; 120 kHz for sidescan sonar with 6.25 cm resolution). Positioning during the surveying was obtained by C-Nav 2050 GPS navigation systems. This study was carried out by interpreting sub-bottom profiles and side-scan sonar records collected in the study area. The geological phenomena information was first obtained by data interpreting through C-View (a software that can digitize and retrieve the location information of the geological phenomena in the images of the side scan sonar and sub-bottom profiler data), then the potential submarine geologic hazards information was distinguished and imported into the GIS system for further analysis.

3 Geological Setting

The study area is located at the center of the South China Fold System, in the depression section of several groups of large fractures named the Pearl River Delta Fault depression. The Binhai fault belt passes through the south section of study area and is also named as the Dangan-Jiapeng Southeast-East Fracture Belt (Liu, 1981). According to the historical data, the Binhai fault belt outside the Pearl River Estuary is an active earthquake zone (Zhan and Sun, 2001), where two earthquakes above 6.0 on the Richter Scale and an earthquake of 5.8 on the Richter Scale near the coastal region southeast to Hong Kong occurred before.

As for the geomorphology, the study area rea is located within the inner continental shelf plain of the northern South China Sea. It was formed by accumulation of large amounts of continental fine grained sediments on the continental shelf during the high sea level period after the last glaciation. The topography is slightly tilted from northwest to southeast, and the gradient changes evenly, with an average gradient typically between 0.5×10^{-3} and 0.7×10^{-3}. The water depth ranges from 10–40 m.

According to sub-bottom profile obtained by Guangzhou Marine Geological Survey Bureau, the subbottom sediments in the study area consist of shallow marine deposit after the high sea level of the Atlantic Stage, the continental alluvial plain and coastal marine deposit during the Late Pleistocene and the Early Holocene, and the alternate continental and marine deposits during the Late Wurm glacial stage, and other deposits. Analysis of the sediment cores shows that clay and silt are the major components of the upper layer sediments in this area. They unconformably cover the whole region, and the thickness decreases from northwest to the southeast part. The lower layer of the sediments mainly consists of sands, where buried paleo-channels, flood plain and riffle hollow could be observed.

4 The Types, Characteristics and Formation of Potential Submarine Geologic Hazards

Based on analyzing the data of side scan sonar and sub-bottom profiler in study area, we can identify various kinds of potential geologic hazards, including sandwaves, shallow gas, paleo-channel and so on (no faults found in the shallow stratum), and put the information into GIS (Geographic Information Systems) system, then a map is created to show the distribution of potential submarine geologic hazards (Fig.1).

There are various methods to distinguish the type of marine geologic hazards (Liu and Mo, 1997). They can be classified according to the spatial distribution, trigger mechanism, existing state, *etc.* Because there is no generally accepted method to categorize marine geologic hazards, in this paper we divided them into two types according to Feng *et al.* (1996): 1) those are active to cause damage; 2) and those are not active to cause damage.

4.1 Non-Active Geologic Hazards

4.1.1 Buried paleo-channels

Paleo-channel is the major type of geologic hazard in the study area (Fig.1). According to the sub-bottom profiles data, three large paleo-channels were discovered, ranging from 8–l0 m thick and buried about 10–30 m under the seabed (Fig.2).

The paleo-channel found in the western end of this region is obviously the largest among the three. Its maximum width in the study area is about 6000 m; however, the whole paleo-channel could not be fully displayed in Fig.1 due to the limited study area. The paleo-channel found in the eastern section of the study area, starts near the southwest of Henggang Island and extends southwestward to the shelf for about 40km in the southern section of the study area. Its width is smaller than that of the first channel, with a maximum width of 3500 m in the study area. The third paleo-channel is located in the southwest section of the study area, between the other two paleo-channels. It starts from the south of Dawanshan Island and extends southeastward to the continental shelf of the northern South China Sea. It is smaller than the other two paleo-channels in scale, with a maximum width of 3000 m, and the length of the channel found within the study area is about 30 km.

On the basis of the stratum and distributed characteristics of the buried paleo-channels discovered in the area, the three paleo-channels are inferred to be formed simultaneously and they are all rivers branches connecting to the Pearl River system before the start of Late Pleistocene transgression. The Pearl River Basin is the largest river system in South China, and as the sea level descended during the Late Pleistocene, most of continental shelf area was exposed. Meanwhile the river extended southward, and continued to carve the stratum to form the river valley. As the glacial period ended, global climate began to warm up and sea level continued to rise. Around 10000 years ago, the water flooded the area outside the present mouth of the Pearl River. During the period of sea level rise, the river valleys were flooded and covered with terrigenous materials, and gradually changed into the present buried paleo-channels.

The sediment in the buried paleo-channels is complex and changeable (Kou and Du, 1994). In the transverse distribution, the sediment in the paleo-channel is very different from that out of it: the grain-size, sorting, density, degree of consolidation, compressive resistance, shear force and many other physical and mechanical characteristics are different from the surrounding sediment. This can be very dangerous for an oil fixed platform construction. In the vertical distribution, the physical characteristics of the sediments filled in different geological periods might have great difference, and their inhomogeneous settling properties may lead to the inclining and collapsing of the building foundation caused by the unevenly distributed stress.

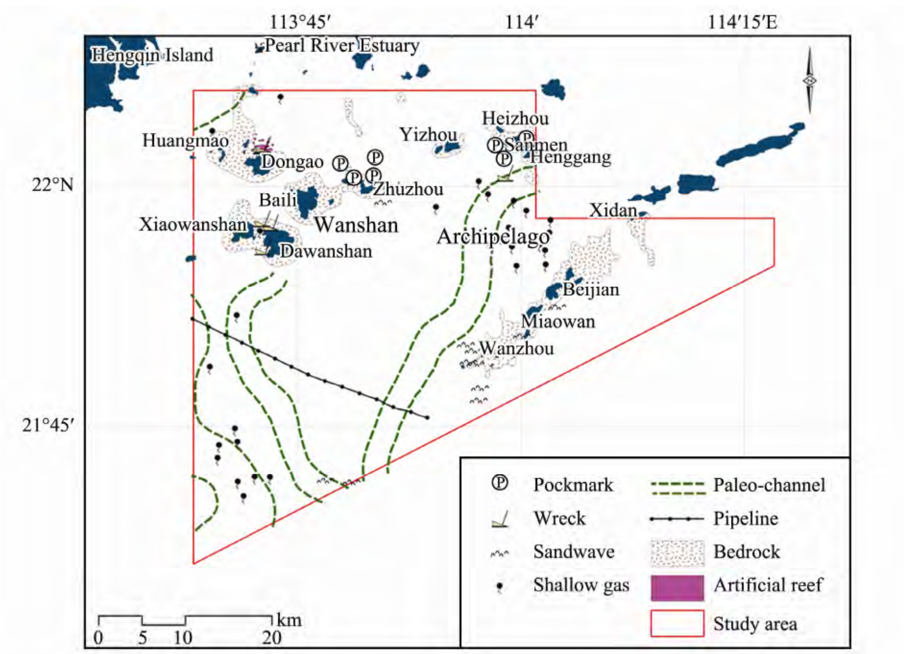

Fig.1 Potential submarine geologic hazards distribution map of the study area.

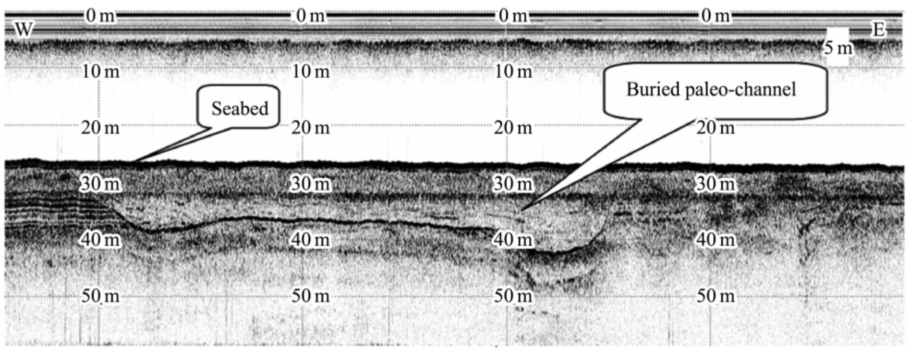

Fig.2 Buried paleo-channel identified on the acoustic image. A 3.5_kHz recording sample of the EdgeTech 2400 profiler.

4.1.2 Shallow buried bedrock and exposed bedrock

The islands in the study region are formed by the basement uplift due to the collision of the tectonic movements of the South China plate and the South China Sea plate. The bedrocks of the study area are extensions of the island's rock mass under the seabed. The shallow buried bedrock and exposed bedrock mainly exist around these islands in three regions (Fig.1), *i.e.*, the area around Dawanshan, Xiaowanshan, Dongao Island, Baili Island; the area around Yizhou, Sanmen Island; and the area around Wenweizhou, Beijian Island, Xidangan.

According to previous researches, all the bedrocks are granite, with large undulations along the interface, and their buried depths vary. Some bedrocks are above the seafloor, such as the bedrocks detected in the north part of Beijian Island which are about 10 m above seabed (Fig.3). Some bedrocks are shallowly buried under the seabed, such as the bedrocks detected in the north part of Xiaowanshan Island with a minimum burial depth of 3 m, while other parts of the bedrocks are buried deeper as their distances from the islands increase.

Bedrock is good solid foundation and bearing layer for marine engineering construction. However, if there are undulations on the surface of the bedrocks, the inhomogeneous lithological characters will result in the variation of the bearing capacity of the bedrock; in addition, large undulations of the shallowly buried bedrocks are probably accompanied by landslides, faults, *etc.*, which may lead to the occurrence of geologic hazards.

4.1.3 Artificial obstacles

According to the side scan sonar data, most of the artificial obstacles (Strictly, the artificial obstacles are not geohazards, but they may has a harmful effect on engineering) discovered in the study area are man-made reefs, wrecks, and pipelines, *etc.* (Fig.1). The man-made reefs are mainly distributed on the seabed of an area about 5 km^2 on the north of Dongao Island, but they are not evenly distributed. The area of each reef is about 6 m^2 and the height above the seabed is about 2–3 m. In the study region, 6 wrecks was discovered, *i.e.*, 3 wrecks near Dawanshan Island, 2 wrecks on the north of Dongao Island and 1 wreck on the southwest of Henggang Island. All the wrecks are common fishing boats, about 20–30 m in length and about 5 m in width. There is 1 pipeline across the southwest part of the study region which lies in the NW direction. The artificial obstacles discovered in the study area are normally on the surface of the seabed, thus they can be easily discovered.

4.2 Active Geologic Hazards

4.2.1 Shallow gas

According to the sub-bottom profile data, there are 12 places that contain shallow gas (Fig.1) within the seafloor sediment in the study area. Most of them are located in the southwest corner of the study region (Fig.4), and on the northwest of the Beijian Island; the rest of them are sporadically distributed in the northeast corner of the study region, and to the south of the Yizhou Island.

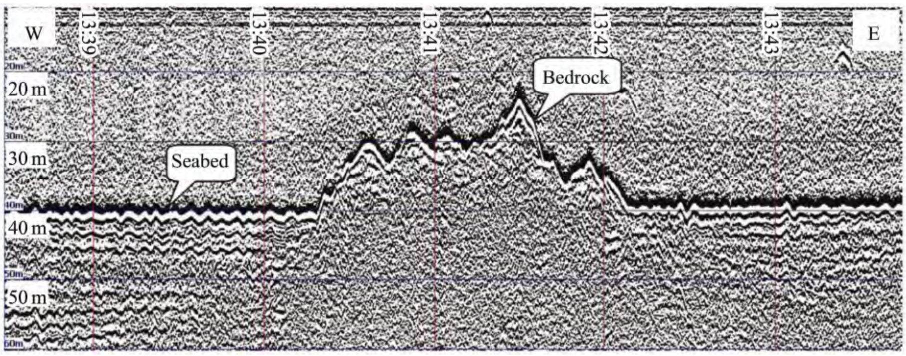

Fig.3 Exposed bedrock identified on the acoustic image. A 3.5_kHz recording sample of the EdgeTech 2400 profiler.

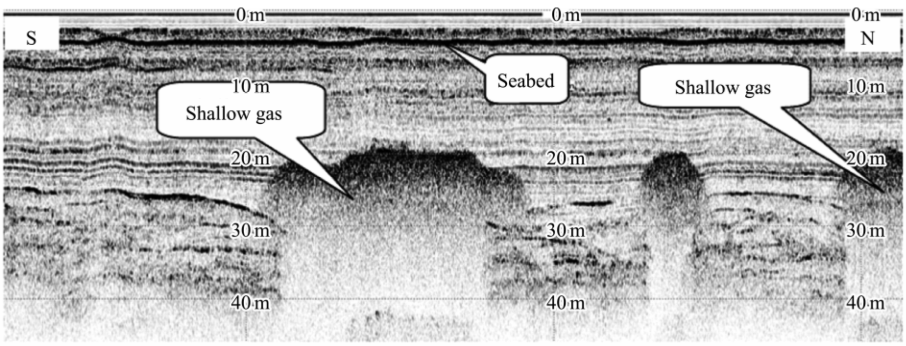

Fig.4 Shallow gas identified on the acoustic image. A 3.5_kHz recording sample of the EdgeTech 2400 profiler.

The shallow gases discovered in the study area are located within the same stratum, which indicate that they are formed at the same period. During the Late Pleistocene, when the sea level descended, rivers carrying large amount of terrigenous material flowed seaward to the study region. These terrigenous materials were rich in organic matters, they deposited in the study region, and then were slowly decomposed by the bacteria. Simultaneously a lot of gas was generated, and accumulated in the shallowly buried layer.

The presence of shallow gas within the seafloor sediments is considered as a potential hazard for two major reasons (Bouma *et al.*, 1981): (a) the presence of gas in the sediment pores may cause a reduction of the sediment strength and favor the occurrence of instability events; and (b) a sudden escape (blowout) of a large volume of gas through the sediment and into the water column may reduce the buoyancy of some artificial structures (*e.g.*, drilling platforms), or produce large sea-floor collapses.

4.2.2 Sand waves

The sand waves discovered in the study area are mainly distributed alongside the island, where the hydrodynamic processes are stronger. The sand waves are relatively small, with wavelengths of 1–2 m and heights of 0.3–0.5 m, mostly along the NNE direction. The two largest sand waves regions are on the west (south) of the Wanzhou Island, with an area of about 6 km^2 (2 km^2) (Fig.1), respectively. The rest of the sand waves regions are much smaller, and they are scattered around the west of the Mozhouwei Island, south of the Miaowan Island, southeast of the Zhuzhou and south of the Baili Island, *etc.*

The formation and development of sand waves are mainly controlled by the hydrodynamic conditions. Under the co-effects of the current, tide, and waves, the sand waves usually develop into different shapes, sizes and directions. The upper bodies of the sand waves in the coastal region are usually active, and they keep moving under the external forcing from ocean waves and currents, with more variable shapes. When the external force changes greatly, such as the typhoon passing by, the original sand waves might be flushed and razed, while new sand waves might be formed. The changes and movements of the sand waves might result in the breaking of the cables and pipelines, due to their suspension or displacement.

4.2.3 Pockmarks

More than twenty pockmarks were identified by side scan sonar in the study area (Fig.1) and they are mainly distributed around the islands. The majority of the pockmarks are concentrated on the north of Zhuzhou Island (Fig.5), while several others located to the north of Hengzhou Island and to the south of Heizhou Island. The size of these pockmarks varies, with a minimum diameter of 6 m and maximum of 40 m. The depths of the pockmarks are generally about 0.5–1 m, with a maximum depth of 2 m.

According to the locations of the pockmarks and the characteristics of the Pearl River Esutary, the formation of the pockmarks in the study area could be summarized as: the rapid deposition of the silt-rich sediment around the island carried by the Pearl River outflow made the pore-water and pore-air incapable of being discharged promptly, thus led to the formation of a solid-liquid-gas three-phase system. Under the vibration of the external load (waves are the main load around the island), the potential energy of the suspended solid particles (silt or the particles larger than silt) in the three-phase system was reduced, and the particles settled. This led to the increase of the pore-pressure, thus resulting in the discharge of the pore-air and pore-water with exhausting channels formed at the surface. Then the sediment had a tendency to be dense and collapsed around the channels, which led to the formation of pockmarks. The diameter of the pockmark is determined by the discharge volume of the pore-water and pore-air that are influenced by the intensity and duration of the waves. Similarly to the active sand waves, the existence of pockmarks results in undulations of the surface of the seabed, which is also potentially harmful to the cables and pipelines laid on it.

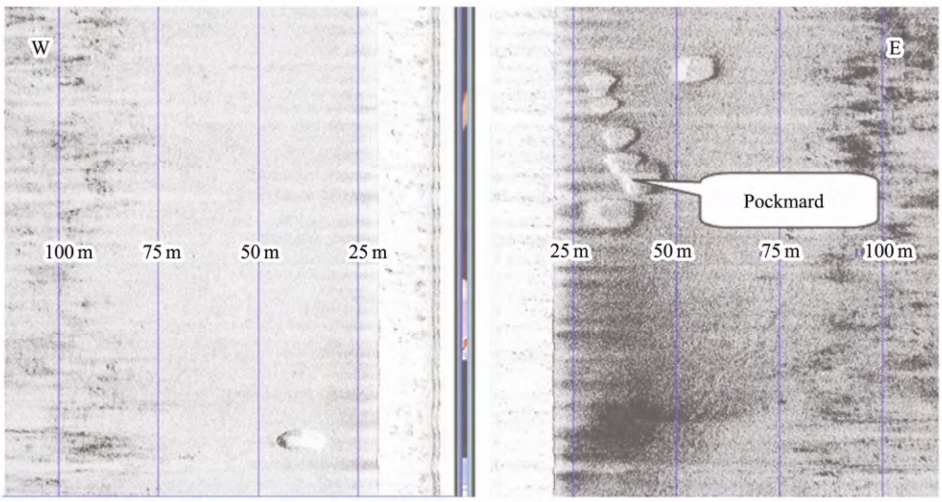

Fig.5 Pockmarks identified on acoustic image. A 100/400_kHz recording sample of the EdgeTech 4200 side scan sonar.

4.3 Relationship Between the Sea Level Variation and Geologic Hazards

In the study region, the potential submarine geologic hazards are mainly related to the sea level variations from Late Pleistocene, except for the bedrock formed from Yanshan Epoch. From Late Pleistocene to Holocene, the sea level around the Pearl River Estuary has gone through a 'regression- transgression-high sea level' process (Huang *et al.*, 1985). During the Wurm glacical stage in Late Pleistocene (about 8000–24000 years ago), there was large scale regression, the sea level descended about 120–150 m, and the present continental shelf emerged from the sea water, with a lot of rivers being developed that formed the ancient channels. After entering Holocene, it became warmer, and the marine transgression reached its maximum about 6000–7000 years ago. The ancient channels were submerged into the sea, and were deposited with the sediments mainly consisting of Littoral facies clay silt. From Late Holocene, the sea level around the Pearl River Estuary region was relatively high, sediments rich in organic matters deposited fast, and some organic matters were decomposed by bacteria and converted into shallow gas. At the same time, the effects from tidal current were enhanced too, thus formed sand waves, sand ridges, pits, *etc.* (Sun *et al.*, 2010).

5 Conclusions

1) Based upon the interpreting of the high resolution observation data obtained by side scan sonar and sub-bottom profiler, around the entrance of the Pearl River Estuary in the northern South China Sea, a variety of potential submarine geologic hazards on the seabed surface and in the subsurface stratum within 50 m below the seabed were revealed in detail. The result shows active geologic hazards, including shallow gas, sand waves, pockmarks, *etc.*; the hazards without activity include buried paleo-channels, shallow buried bedrock & exposed bedrock, artificial obstacles, *etc.*

2) The types and distributions of the potential geologic hazards in the study region are mainly determined by the tectonic movement and the 'regression- transgression-high sea level' process of the sea surface since Late Pleistocene.

3) This paper delineates the distribution of submarine geologic hazards in the study area and for the first time provides a high resolution distribution map of potential geologic hazards at the entrance of the Pearl River Estuary, which will provide a theoretical basis for future engineering construction and disaster prevention and mitigation.

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