Provenance of a prominent sediment drift on the northern slope of the South China Sea

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Abstract The sedimentation rate of the sediment drift in the southeast of Dongsha Islands is as high as 49 cm/ka in the last 1.05 Ma. Although the sedimentation rate changes with time, the contents of rare elements of the sediments remain almost the same, indicating that the source area of the sediments has been constant with time. On the triangular diagrams of La-Th-Sc and Th-Sc-Zr/10, the samples from the southeast of Dongsha Islands fall within the continental island arc field, overlapping the samples from Taiwan, while the samples from the Pearl River, those from the west of the Philippines that contain volcanic material, are separated from them. This indicates that the sediments from the southeast of Dongsha Islands have a close relationship to those from Taiwan in terms of provenance. In fact, the sediments on the northern slope of the South China Sea were derived from northeast direction, as well as from Taiwan, most probably transported from Taiwan through Penghu channel into the South China Sea. The terrigenous part of the deep-sea sediments in the north of the South China Sea was provided by different sources.

Keywords: provenance, marine sediment, geochemistry, South China Sea, Ocean Drilling Program.

The area in the southeast of Dongsha Islands on the northern slope of the South China Sea is one of the most active sedimentary areas in the South China Sea. The highest sedimentation rate in the South China Sea was found in this area[1,2]. The core SO17940, which is 1315 cm long, was taken from a sediment drift in this area during the SONNE cruise 95 in 1994[1]. The sedimentation rate is about 33 cm/ka in the last 40000 a[2], based on $\delta^{18}O$ record and AMS^{14}C dating. According to the record from ODP Leg 184 Site 1144 on this sediment drift in 1999 (water depth of 2037 m and the core is 51900 cm long), the sedimentation rate reaches 49 cm/ka in the last 1.05 Ma[3], the highest record in the South China Sea. The sediment drift consists mostly of terrigenous material with some organic carbon (about 10%—20%), and siliceous biota (<5%), and is completely homogenized by bioturbation[3]. No slumping structure and mass transport have been found in the sediment core. Two seismic lines across this sediment drift show that there is no big sedimentary discontinuity and tectonic faults in the drift. In accordance with the seismic data, stratification undulated striking in NE-SW direction, dipping towards SSE, being monoclinal in NNW-SSE direction. The three-dimension bedform of the drift indicates that the drift was formed under a water current from the northeast[3] (fig. 1).

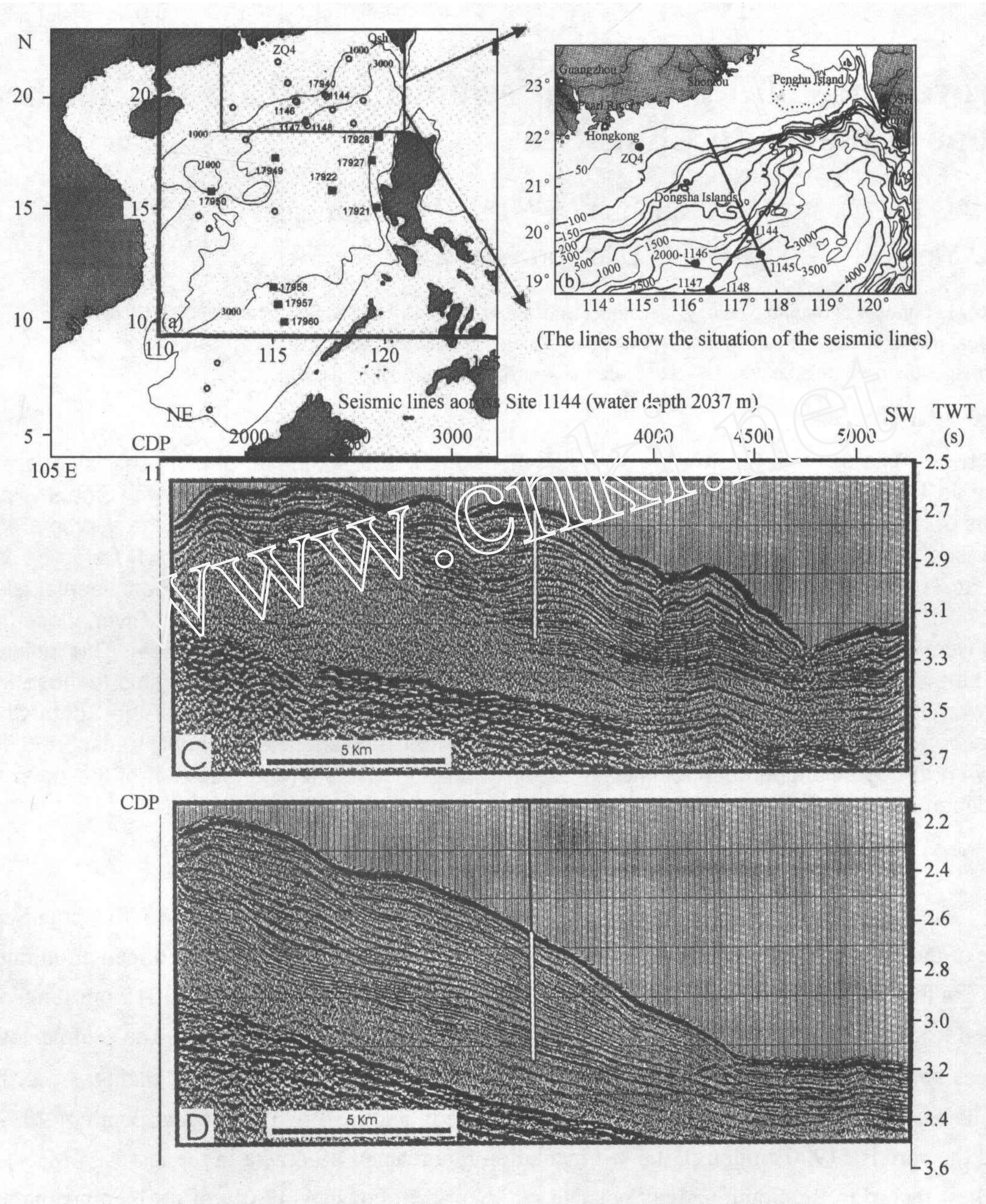

Fig. 1. Location map of the studied area in the South China Sea. (a) Locations of the analyzed samples; (b) detailed locations of the samples and seismic lines in the north of the South China Sea; (c) NE-SW seismic line; (d) NNW-SSE seismic line.

There are a variety of possible source areas for consideration, such as the Pearl River, Hanjiang River, Taiwan Island and the Luzon Island. The provenance of the sediment drift is one of the key issues for the sedimentology in the South China Sea. The terrigenous sediments mainly consist of clay. They are normally difficult to analyze with other methods than the geochemical analysis used in this paper to decipher the provenance.

1 Materials and methods

Site 1144 of ODP Leg 184 is located in the southeast of Dongsha Islands (20° 3.18′N, 117° 25.14′E), at a water depth of 2037 m. Most of the sediments are dull gray-green clay with quartz and calcite silt, as well as nannofossils and siliceous biota. Iron sulfides are abundant, and bioturbation is strong[3]. Forty-six samples were collected from top to bottom of the core for every 9.5 m. Nine deep-sea surface samples from the eastern part of the South China Sea, which contain some volcanic material[4], three post-glacial samples from the Pearl River (ZQ4) and fifteen local samples from the Quaternary of western Taiwan (QSH) are used for reference (fig. 1).

The sediment samples were firstly heated and dried at 350°C to remove the organic matter and the interlayer water of clay minerals. $CaCO_3$ was removed from the samples by 0.1MHCl in order to avoid the interference of authigenic components on the results of the analysis. Samples were then dissolved with $HF+HNO_3$ and analyzed by inductively coupled plasma emission mass spectrometry (ICP-MS). Each sample was analyzed for six times and calibrated with international rock standards (e.g., GSR-1, JSD-1), and checked with drift control samples, duplicate samples, and blank samples. Accuracy and precision could be estimated and monitored by the control of samples and duplicates. The samples were prepared in the Laboratory of Marine Geology, Tongji University and Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The analyses were accomplished in Guangzhou Institute of Geochemistry (samples from the South China Sea and the Pearl River), and China University of Geosciences (samples from Taiwan).

2 Results and discussion

The sedimentation rate of Site 1144 varied in the last 1.05 Ma, whereas the content of the terrigenous clast changed with time. The sequence can be subdivided into three parts in a descending order: (1) 0—210 m (0—0.21 Ma), the sedimentation rate is extremely high, about 100 cm/ka; (2) 210—405 m (0.21—0.9 Ma), the sedimentation rate is only 28.3 cm/ka; (3) 405—519 m (0.9—1.05 Ma), and the sedimentation rate increased again by about 76 cm/ka[3]. The average contents of the terrigenous material varied accordingly, showing that the input of the terrigenous material played a significant role in controlling the sedimentation rate.

2.1 Distribution of rare earth elements

It has been proved that the contents of rare earth elements (REE) and their distribution pattern are provenance related. Sediments derived from different source rocks have quite distinct REE content and distribution pattern. Although the sedimentation rate varied with time in Site 1144, the REE contents and distribution pattern from different depths remain almost unchanged. The REE distribution patterns of the sediments show a clear LREE enrichment, an HREE flat and a negative Eu-anomaly (fig. 2). This pattern is generally similar to that of the upper continental crust, and means that the sediments are most probably derived from the same source area. The LREE enrichment indicates an overall enrichment in large ion lithophile elements. It means that

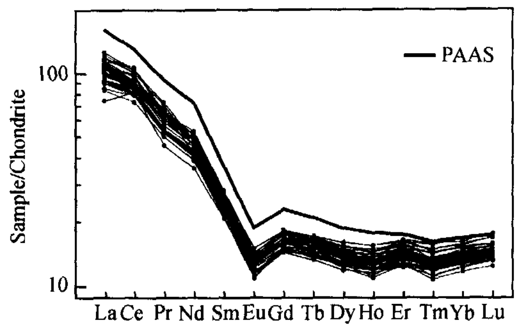

Fig. 2. Chondrite-normalized REE distribution for the samples of Site 1144, showing that the REE distribution of the 46 analyzed samples are parallel to those of PAAS, and the REE contents in different times are almost the same.

the sediments were from the upper crust other than the ultimate mantle sources. The flat HREE pattern suggests that there was no HREE fractionation when the source areas were formed in the upper crust. The presence of Eu-depletion follows the general pattern of Eu-depletion in the upper continental crust[5—7].

2.2 Provenance analysis

After weathering, transportation, and diagenesis, only stable minerals might be preserved in the sediments. It is difficult to detect the provenance from these detrital minerals, especially if the sediment consists mainly of clay. It is proved that the chemical composition of source rocks is the major factor in the chemistry of sediments[8], although some significant chemical changes may take place during sedimentation and cause the concentration of some trace elements and dilution of the others. Of great importance is the observation that Sc, Th, Co, La, Eu, etc. and critical elemental ratios (e.g. Th/Sc, Eu/Eu*, Th/U and La/Co) are not seriously affected by the processes of sedimentation and are the best index for provenance analysis[7,9].

Bhatia and Crook[10] distinguished four groups of provenances in accordance with the tectonic environments: oceanic island arc, continental island arc, active continental margin and passive margin by using triangular diagrams of La-Th-Sc and Th-Sc-Zr/10 trace elements. The samples from the eastern South China Sea, which contain volcanic material derived from Luzon Island Arc, fall within or near the oceanic island arc field. The samples from Site 1144 concentrate in continental island arc area, indicating the sediments coming from the same source area. Moreover, the samples from Taiwan overlap the samples from Site 1144, but show no

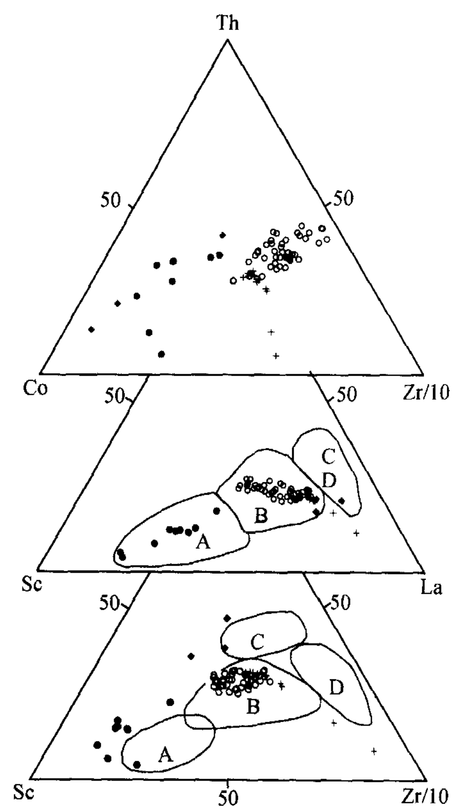

Fig. 3. Triangular diagrams of Th-Co-Zr/10 and La-Th-Sc, Th-Sc-Zr/10. A, Oceanic island arc; B, continental island arc; C, active continental margin; D, passive margin. ○, Samples from Site 1144; ◆, post-glacial samples from ZQ4; ●, deep-sea samples from the eastern South China Sea; +, Quaternary samples from southwest of Taiwan (QSH).

relation with the post-glacial samples of the Pearl River (fig. 3). This result is consistent with the conclusion deduced from the triangular diagram Th-Co-Zr/10 (fig. 3). Fig. 4 shows that the samples from Site 1144 superimpose upon those from Taiwan according to Eu/Eu* (Eu/Eu* = $Eu_N/[(Sm_N)(Gd_N)^{1/2}]$, subscript "N" represents a chondrite- normalized value) and their Th/U ratios are different from the samples from the eastern South China Sea and the Pearl River. Two of the fifteen samples from Taiwan are very different from the other samples. The contents of orthoclase, magnetite and dolomite are obviously high, while the contents of kaolinite, illite and montmorillonite are relatively low, indicating different source rocks. Therefore, it may be inferred that the provenance of the sediments from Site 1144 should be the same for Quaternary sediments of Taiwan. The sediments from the eastern South China Sea and the Pearl River are derived from other source areas.

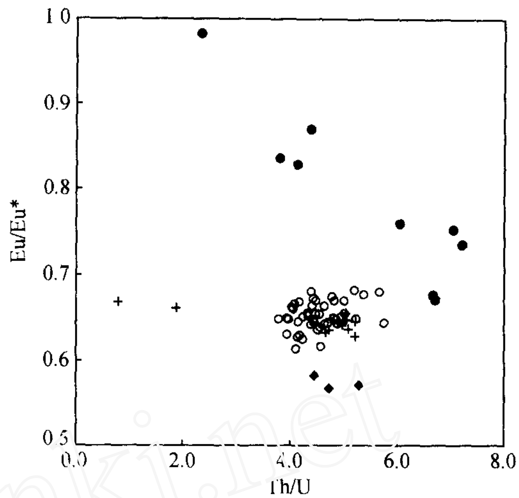

Fig. 4. Diagram of Eu/Eu* and Th/U ratios (for legend see fig. 3).

As mentioned above, the terrigenous sediments depositing on the northern slope of the South China Sea might come from different provenances, such as the Pearl River, Hanjiang River, Taiwan Island or from the Luzon Island via the Bashi Channel. Although the Pearl River is the largest river in the region, it transports only about 82.78×10^6 ton of sediments per year into the western part of the South China Sea. The Hanjiang River is similar to the Pearl River in terms of the concentration of sediment load. Its water volume is only one tenth of the Pearl River and the amount of transported sediments is just about 7×10^6 ton/a. However, the drainage area of the Gaoping and Zengwen rivulets of southwestern Taiwan is much smaller than that of the Pearl River, but their contributions of sediments come up to 67×10^6 ton/a, in the same range with the Pearl River[11,12]. Therefore, the sediments coming from Taiwan are very important to the deposition of terrigenous sediments on the northern margin of the South China Sea. Moreover, three cores (Sites 1146, 1147, 1148) have been drilled from the southwest of Dongsha Islands during the ODP Leg 184 cruise, these core sites are closer to the delta of the Pearl River than Site 1144 (fig. 1). They should receive a lot of deposits from the river. In fact, the sedimentation rate is much higher at Site 1144 than the other three cores (the average sedimentation rates of the three cores in Quaternary are 12 cm/ka at 1146, 4.1 cm/ka at 1147, and only 2 cm/ka at 1148). In this case, the sediment drift in the southeast of Dongsha Islands should receive sediment from another source. The NE-SW seismic line across this sediment drift disclosed undulating bedform, reflecting that the material of the sediment drift should be transported by the water current from the northeast. In addition to the results of geochemistry analyses, the seismic profiles provide evidence that the terrigenous material of the sediment drift is most probably derived from Taiwan. The tectonic line of Taiwan extends in north-south direction. The samples taken from the southwest of Taiwan (QSH) are typical for Quaternary deposits of western Taiwan. The Penghu Channel extends between Taiwan Island and Penghu Island[13]. The sediments from Taiwan should pass through this channel to approach the South China Sea. The results of pollen and foraminifer-δC^{13} analyses reflect that there are strong water currents via the Bashi Channel to the South China Sea[14,15]. Therefore, it is most likely that the sediments derived from Taiwan were transported through the Penghu Channel into the South China Sea, and affected by the water currents from the Bashi Channel.

3 Conclusions

Although the sedimentation rate of the sediment drift on the northern slope of the South China Sea varied with time, the REE contents and their distribution patterns are almost the same. The REE distribution pattern shows an LREE enrichment, a flat HREE pattern and a negative Eu-anomaly, which is generally similar to the feature of the upper continental crust. These demonstrate that the sediments are most probably derived from the same source area.

In the triangular diagrams of La-Th-Sc and Th-Sc-Zr/10, the samples from Site 1144 fall in a continental island arc range, overlapping the samples from Taiwan, and are away from the post-glacial samples from the Pearl River and those from the eastern South China Sea. This result is consistent with Th-Co-Zr/10 distribution and Eu/Eu* vs Th/U ratios. Therefore, the samples from Site 1144 and Taiwan should have a close relationship to each other. The sediments from the eastern South China Sea and the Pearl River should be derived from other source areas. Moreover, it is most likely that the sediments of the sediment drift on the northern slope of the South China Sea were derived from northeast direction, as well as from Taiwan, and were transported through the Penghu Channel into the South China Sea, and affected by the water currents from the Bashi Channel and finally deposited the sediment drift in the southeast of Dongsha Islands.

This indicates that the deep-sea sediments have a diverse and complex provenance, to which the tectonic active islands contributed substantially. The deep-sea sediments in the north South China Sea show little relationship to the Pearl River.

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