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Chapter 4
Sedimentology

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Introduction

The South China Sea (SCS) receives approximately 700 million tons of deposits annually in modern times, including about 80% of terrigenous matters provided by surrounding rivers and 20% of biogenic carbonate and silicates and volcanic ash. A similar scenario has been identified also in the geological past. Since the early Oligocene, the sea has accumulated about 14.4 thousand trillion tons of deposits,

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which contain 63% terrigenous matters and 37% biogenic carbonate with negligible biogenic silicates and volcanic materials (Huang 2004). Most of these deposits accumulated on the SCS shelf (43% of total sediment mass) and slope (52%). Such a huge deposition cover makes the SCS an ideal place to study terrigenous input, paleoceanography, and regional and global climate evolution as well as sedimentary evolution of the SCS.

This chapter provides an overview of SCS sedimentology by synthesizing surface and geological deposition patterns in terms of terrigenous, biogenic, and volcanic deposits, and presents a systematic outline on sedimentation evolution since the SCS began to form in the early Oligocene.

4.1 Surface Deposition Patterns (Liu Z.)

Deposit Distribution Patterns

The SCS surface deposits have been intensively investigated over the past decades for both region-wide patterns (Chen P. 1978; Su and Wang 1994; Wang P. et al. 1995; Xu et al. 1997; Liu Z. et al. 2003a) and for deposit distribution in individual basin (Su et al. 1989; The Multidisciplinary Oceanographic Expedition Team of Academia Sinica to Nansha Islands 1993; Li X. 2005). In general, the surface deposit distribution is closely tied to water depth and topography, such as shallow shelf terrigenous clastic deposits, hemi-pelagic slope ooze, and abyssal basin clay (Su and Wang 1994) (Figs. 4.1 and 4.2).

(1) Shallow shelf terrigenous clastic sediments: mainly modern terrigenous clayey silt, silty clay, and bioclasts. The shelf sediments are mainly fluvial clasts with clay content higher than 80% and sand less than 15%. Bioclasts are mostly fragments of shell, gastropods, foraminifera, ostracods, and sponge spicules.

(2) Hemi-pelagic slope ooze: biogenic and terrigenous sediments above the carbonate compensation depth (CCD), including clayey silt, silty clay, and calcareous ooze. The ooze is grey or yellowish grey with planktonic foraminifera and other calcareous skeletons. The carbonate content is generally higher than 30% or even up to 62%. The carbonate content decreases with increasing water depth due to dissolution.

(3) Coral sediments: mainly biogenic sand and gravel, which are mainly restricted to shallow settings (0–400 m) of the Dongsha, Xisha, and Nansha islands. Fragments of coral and associating organisms such as bivalves, algae and foraminifera constitute the major components of coral sediments.

(4) Abyssal basin clay: mixed biogenic and terrigenous ooze below the CCD. Biogenic tests are much less than those in shelf and slope sediments, here mainly containing radiolarians and lesser amounts of diatoms and agglutinated foraminifera.

Among the terrigenous sediments in the surface SCS, clay minerals are most important components. The clay mineral distribution can be divided into six provinces
Fig. 4.1 Map shows genetic classification of surface sediments in the SCS (Su and Wang 1994). I Terrigenous type includes (1) nearshore modern terrigenous mud, (2) nearshore modern terrigenous sand and silt, and (3) neritic (paleo-littoral) relict sand. II Biogenic type includes (4) neritic coral sand and gravel, (5) hemi-pelagic and abyssal calcareous ooze, and (6) abyssal siliceous ooze. III Mixed type is represented by (7) abyssal clay. IV Volcanic-biogenic-terrigenous type includes (8) volcanic material (about 5% of the sediment).

(Fig. 4.3) (Chen P. 1978; Liu Z. et al. 2003a). Province A is dominated by illite and chlorite averaging 65% and 25%, respectively, and covers the northern shelf of the SCS, the Taiwan Strait, and the East China Sea, but not in the inner estuary of the Pearl River. Province B includes the central part of the SCS and extends...
Fig. 4.2 Map shows grain-size distribution in surface sediments of the SCS (Su and Wang 1994). Sediment types are: (1) clay, (2) silty clay, (3) clayey silt, (4) sand, (5) gravel-containing sand, and (6) coral sand and gravel.

northeastward through the Bashi (Luzon) Strait. Relative to province A, illite and chlorite in province B are reduced by 5–10%, whereas smectite and kaolinite increase by 6–8%. In province C, surrounding the Luzon islands, smectite increase to 23%, twice the amount in province B. Province D covers most of the Sunda
shelf and extends to the Gulf of Thailand and the Malacca Strait. Smectite becomes very prominent in this province, ranging from 20% to 50%, with an average of 30%. Coastal province E, including the bay and inner estuary of the Pearl River, is characterized by high kaolinite (50%) which rapidly decreases slope-ward. Province F, the Mekong River estuary, is relatively rich in illite and chlorite, 47% and 23% respectively. The kaolinite content in provinces C, D, and F averages about 20%, but reaches 50% in the Malacca Strait.

Distributions of chemical elements in surface sediments of the SCS are closely correlated to the grain-size distribution. Here, we take two major chemical components of SiO$_2$ and CaCO$_3$ as examples (Figs. 4.4 and 4.5). SiO$_2$ is the major
Fig. 4.4 Map shows distribution of SiO₂ abundance in surface sediments of the SCS, based on data from Su et al. (1989) and The Multidisciplinary Oceanographic Expedition Team of Academia Sinica to Nansha Islands (1993)
Fig. 4.5 Map shows distribution of carbonate content in surface sediments of the SCS (Su et al. 1989; The Multidisciplinary Oceanographic Expedition Team of Academia Sinica to Nansha Islands 1993; Li and Yang 1997)

component of terrigenous sediments and therefore is distributed throughout the surface SCS. The shallow shelf contains most abundant SiO$_2$, such as the abyssal basin, with major terrigenous sediments for the former and clay and radiolarian and other silicate organisms for the latter. On the hemi-pelagic slope, calcareous ooze is abundant and therefore SiO$_2$ is relatively low. Variations of the CaCO$_3$ content are generally opposite to the SiO$_2$ content. When CaCO$_3$ content is high, SiO$_2$ content becomes low, and vice versa. The highest CaCO$_3$ content is in the coral
reef regions, e.g., the regions of the Dongsha, Xisha, and Nansha islands. On the slope of the northern and southern SCS, CaCO$_3$ contents generally exceed 30%. However, abyssal basin sediments contain less than 10% CaCO$_3$.

**Sediment Transport**

Sediment transport in the SCS is largely dependant on its circulation system (Chapter 2). It has been suggested that the surface circulation transported clay minerals throughout the SCS, by carrying more smectite to the north during interglacials and more illite and chlorite to the south during glacials (Liu Z. et al. 2003a). In addition, the surface circulation in the northern SCS is significantly affected by the flow of the Kuroshio Current through the Bashi Strait (Caruso et al. 2006). The current is one of the most important carriers accounting for smectite contribution to the northern SCS from the Luzon Arc and the western Philippine Sea (Wan et al. 2007; Liu Z. et al. 2008).

The pioneering work on bottom sedimentation processes in the SCS was based on “sonar mapping and piston-core studies”. Down-slope transporting processes, e.g., turbidity currents and mass wasting, were found to be predominant in the SCS basin (Damuth 1979, 1980). With technical progress in recent years, sediment transport caused by bottom currents are widely reported in the SCS, and one example is the high sedimentation-rate drifts on the slope southeast of the Dongsha Islands in the northern SCS (Fig. 4.6) (Lüdmann et al. 2001; Shao et al. 2001).

![Fig. 4.6 Sediment drift near the Dongsha Islands in the northern SCS was probably caused by the intrusion of the North Pacific Deep Water (NPDW) through the Bashi Channel (arrows), according to Lüdmann et al. (2005)]
Multi-channel reflection seismic data indicate a lenticular sediment drift with very thick deposition existing on the southeast slope of the Dongsha Islands (Fig. 4.7). The sediment decreases in thickness SE-wards and finally vanishes into normal deep ocean depositional environment (Shao et al. 2007). No slumping structure, turbidity deposition, and other gravity-flow transports have been found in sediment cores of SO17940, ODP Site 1144, and MD05-2905 (Wang L. et al. 1999; Wang P. et al. 2000; Laj et al. 2005). Sedimentation rates in the sediment drift are very high, from 33 cm/ka at core SO17940 (Wang L. et al. 1999), to 49 cm/ka at Site 1144 (Bühring et al. 2004), to 97 cm/ka at core MD05-2905 (Laj et al. 2005). Lüdmann et al. (2005) postulated that these drift deposits were generated by upward directed eddies near the Dongsha Islands of the North Pacific Deep Water (NPDW), which enters the SCS via the Bashi Channel (sill depth >2500 m) (Fig. 4.6). This flow results in deposition of slope sediments resuspended off East and South Taiwan on the slope southeast of the Dongsha Islands. However, newly-acquired high-resolution seismic data revealed that the sediment drift is actually composed of a series of sediment waves migrating upslope (Fig. 4.8) (Zhong et al. 2007).

A recent study discovered a Pearl River deep-water fan system, located in the deep water slope area of Baiyun Sag in the Zhujiangkou (Pearl River Mouth) Basin (Fig. 4.9). With the rich sediments supplied by the Pearl River, bottom currents are suggested to have accounted for the sediment transport and formation of the paleo-fan system (Pang et al. 2006). Bottom currents in the SCS can also drive deep-water turbidity deposition. In the southern SCS, a highly graded foraminifera-rich turbidite in core MD05-2894 (07°02'N, 111°33'E, water depth 1982 m) originates from the Sunda slope (Fig. 4.10). The turbidite layer has an abrupt contact with the underlying clay and calcareous ooze, with grain sizes fining upwards.
Fig. 4.8 The sediment drift on the slope near ODP Site 1144 was generated likely by sediment waves with sediments coming from Taiwan (Zhong et al. 2007)

Fig. 4.9 Interpretation profile of sequence stratigraphy of the Zhujiangkou (Pear River Mouth) Basin reveals a deep-water fan system (Pang et al. 2006)

4.2 Terrigenous Deposition (Liu Z.)

*Clay Mineralogy and Geochemistry of Source Areas*

The primary control on mineralogical and geochemical variations of sediments in the modern and past SCS is exerted by different sediment provenances (Chen P. 1978; Liu Z. et al. 2004). Two main source areas with markedly different geological characteristics contribute terrigenous sediments to the SCS. The northern and western source is mainly the Asian continent and Taiwan, while the southern and eastern source consists of islands or volcanic arcs lying along the eastern margin of the SCS.
A graded foraminifera-rich turbidite layer in core MD05-2894 shows a sharp lower boundary and fining upward grain sizes (Laj et al. 2005) (Fig. 4.11). Weathering products from these land-source areas are transported to the SCS chiefly by larger rivers, mainly the Mekong River, Pearl River, and Red River, and small mountainous rivers especially those in southwestern Taiwan (Table 4.1). Here we characterize clay mineralogy and geochemistry of these source areas.

**Clay Minerals**

Detrital sediments in the northern SCS are mainly derived from the Pearl River and the Red River, as well as rivers in southern Taiwan and in Luzon (Philippines). In the Pearl River drainage basin, kaolinite (30–67%) is the most dominant clay mineral with an average of 46%, while chlorite (15–37%) and illite (6–40%) have lesser abundance with a similar average content of about 25%. Smectite (0–11%) is very scarce with an average content of about 3% (Table 4.2, Fig. 4.12) (Boulay et al. 2005; Liu Z. et al. 2007a,b). For the Red River sediments, illite (31–57%) is the dominant clay mineral, with an average content of 43%; kaolinite (17–38%) and chlorite (6–29%) are less abundant, with a similar average content of about 25%; smectite (1–14%) remains as a minor component, but its average 7% content is higher than in the Pearl River basin (Liu Z. et al. 2007a). In southwestern Taiwan, river and lake sediments contain high percentages of illite (44–66%) and chlorite (33–48%), with very rare kaolinite (0–4%) and smectite (0–8%). The average percentage is 55% for illite, 42% for chlorite, 2% for kaolinite, and 1% for smectite (Fig. 4.12) (Liu Z. et al. 2008). For Luzon rivers, the clay is predominantly smectite (83–92%, average 88%), with minor kaolinite (average 9%) and scarce chlorite and illite (Fig. 4.12).
In the southern SCS, the Mekong River, northern Borneo, and Indonesian volcanic arcs are the major suppliers of terrigenous sediments. Samples from the Mekong River delta have similar clay mineral assemblages between various locations: kaolinite (24–41%), illite (21–38%), and chlorite (21–30%) making up the dominant clay minerals with an average content of 28%, 35%, and 26%, respectively (Liu Z. et al. 2007a). Smectite (6–18%) is a minor clay mineral with an average percentage of 11%, a value considerably higher than the Pearl and Red records. In northern Borneo, Baram and Trusan rivers provide high contents of illite (63%), lesser abundant chlorite (24%) and kaolinite (12%), but no smectite (Liu Z. et al. 2007c). Surface sediments from the northern Sunda Shelf show a high content of smectite (average 40%) and moderate contents of kaolinite, illite, and chlorite (average ~20%, respectively) (recalculated from Jagodziński 2005). The Indonesian islands are characteristic in having abundant smectite (41–76%, average