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Tracing the life history of a marginal sea—On “The South China Sea Deep” Research Program

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The Major Research Program “Deep Sea Processes and Evolution of the South China Sea”, or “The South China Sea Deep”, launched in January 2011 by the National Natural Science Foundation of China, is the first large-scale basic-research program in ocean science in the country aiming to reconstruct the life history of a marginal sea. The overall scientific objective of the program is to dissect this typical marginal sea by studying its history of evolution and its modern processes, including the following three major components: (1) Development of the deep basin: utilizing new techniques to re-measure magnetic anomaly lineations, to explore the deep tectonic features, to drill the oceanic crust, and to study volcanic seamount chains; (2) deep-water sediments: observing the modern processes to reveal the patterns of deep-water circulations and sedimentation, analyzing deep-sea sediments to recognize paleoceanographic response to basin evolution, and subsequently to bridge the modern and paleo-studies of the deep-sea processes; and (3) biogeochemical processes: using a variety of techniques including deploying submarine observation and deep-water diving device to investigate the distribution patterns and environmental impacts of deepwater seepages and sub-bottom circulation, and to reveal the role of microbes in deep-sea carbon cycling. As compared with the open ocean and other marginal seas, the South China Sea enjoys many more advantages as a marine basin for reconstructing the life history. Meanwhile, the South China Sea Deep Program provides unique opportunities in studying the evolution and variations of the sea-land interactions between the Pacific and Asia.

the South China Sea Deep, marginal sea, deep-sea process, life history, tectonic evolution, sedimentological response, biogeochemistry

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The deep-sea bottom is the last part of the Earth’s surface investigated by human, as seen from the fact that most of our knowledge on deep sea comes from the last half-century. The deep-sea processes comprise the research frontier of both the Earth and Life sciences. On the other hand, the perspectives of deep-water petroleum and gas hydrates have brought about fierce international maneuvering in to deep sea. The South China Sea (SCS) with its area of 3.5 million km^2 and maximal depth of 5500 m, is one of the largest marginal seas in the world, and the most important deep-sea basin off the Chinese coast. The major research program “Deep Sea Processes and Evolution of the South China Sea” or “The South China Sea Deep” for short, launched by the National Natural Science Foundation of China (NSFC) in January 2011, is the first large-scale basic research program in oceanography in China.

Initiation of a major basic research program on the SCS has been under discussion in China since 2000. Starting from 2007, a series of meetings were devoted to the program, including 5 workshops for rationale and 4 for designing of the project. Over a hundred of scientists from both sides across the Taiwan Strait and from overseas participated in discussion during these meetings. On the basis of their contributions and suggestions, the SCS Deep program was finalized and approved by the NSFC in 2010. Aiming to reconstruct the life history of the SCS as a typical marginal

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sea through studies of three major themes: deep basin evolution, deep-water sediments, and biogeochemistry, the program is scheduled to last for 8 years (2011–2018), with a preliminary budget of RMB 150 million yuan. The first theme projects will utilize new techniques to re-measure magnetic anomaly lineations, to drill the oceanic crust, and to systematically study volcanic seamount chains; the second theme projects will reveal the patterns of deep-water circulation and sedimentation through modern process observations, and extract information of basin evolution from analyses of deep-sea sediments; while the third theme projects will use a variety of techniques to investigate the distribution patterns and environmental impacts of deepwater seepages and fluid circulation below the sea floor, and to reveal the role of microbes in deep-sea carbon cycling.

The present paper is a brief introduction to the rationale and architecture of the program. Deep-sea studies in marginal seas over the years have shown a number of advantages in comparison with the open ocean. Compared to the Atlantic, the SCS is much smaller in size and much younger in age, offering more favorable conditions for reconstructing the evolution of its deep processes. Compared to the Pacific, the SCS enjoys much higher sedimentation rates and carbonate preservation, providing complementary records to the poorly preserved carbonates in the western Pacific Ocean. By a combination of modern processes and geological evolution within the marginal sea, the program is designed to dissect the particular case of the SCS in order to advance our understanding of its evolution and its effects on offshore resources and environmental changes, as well as to promote deep-sea studies in the country.

1 Formation and extinction of a marginal basin

The central deep basin of the SCS below 3500 m in depth has a rhomboid shape and overlies the basaltic oceanic crust. Although most offshore resources are explored in sedimentary basins in the continental shelf and slope, the key to understanding their formation lies in the deep basin. Over the past decades, researches have been carried out mainly in the northern margin of the SCS, but recently some European scientists are active in investigating the western part of the SCS off Vietnam. For all of the studies the most critical question is on the age and genesis of the oceanic crust.

1.1 Age of seafloor spreading

Unlike the Sea of Japan, the SCS can benefit very little for determining the age of its formation from either the surrounding land profiles or the oceanic crust because its thick sediment cover makes sampling difficult. Dating of seafloor spreading, therefore, relies almost completely on magnetic anomaly lineations left in the oceanic crust which were first measured on board a US research vessel about 30 years ago [1,2] and remain widely used today with little changes. The age estimations were given at the best scientific level at that time, but undoubtedly suffer from uncertainty in interpretation due to the lack of diurnal variation correction, to limitations in instrumental precision and positioning accuracy, and to the remarkable noise disturbance. Later, the original age model was revised and improved by French [3,4], Chinese [5,6] and German [7] authors, resulting in new versions of interpretation but meanwhile also in increased uncertainty (Table 1; Figure 1).

The deep basin of the SCS with oceanic crust falls into two parts, the Eastern and Southwestern Sub-Basins. The relationship between the two sub-basins inspires the first divergence of opinions on the seafloor spreading of the SCS. It is widely believed that the Eastern Sub-Basin formed first before propagating towards southwest with a jump of spreading ridge [4]. But an alternative view believes that the Southwestern Sub-Basin may have predated the Eastern one [5,8] (Table 1). Different opinions also exist on the age when seafloor spreading first started. Early studies ascribed the oldest anomaly to C12, corresponding to 32 Ma in the Early Oligocene according to the new geomagnetic timescale, but Hsu et al. (2004) [6] measured magnetic anomalies in the northeastern corner of the SCS and proposed that the spreading occurred much earlier, starting from ~37 Ma (Table 1), whereas magnetic measurements by the German "SONNE" cruise to the southwestern part of the SCS resulted in another age model of the seafloor spreading from 31 Ma to 20.5 Ma, with a ridge jump at 25 Ma [7]. All the interpretations are based on sparse sets of profiles with inherent ambiguity. A recent reinterpretation based on densely

Table 1 Comparison of different age estimations for the deep-basin formation of the South China Sea based on interpretation of magnetic anomaly lineations

Author (s)	Age (Ma)	Research area	Publication
Taylor and Hayes [1,2]	32–17	Eastern Sub-basin	1980, 1983
Briais et al. [4]	32–16	Eastern & SW Sub-basins	1993
Yao and Zeng [5]	42–35	SW Sub-basins	1994
Barckhausen and Roeser [7]	31–20.5	Eastern & SW Sub-basins	2004
Hsu et al. [6]	37–15	Eastern Sub-basin & NE part	2004
Li and Song [9]	32–16	Eastern & SW Sub-basins	2011

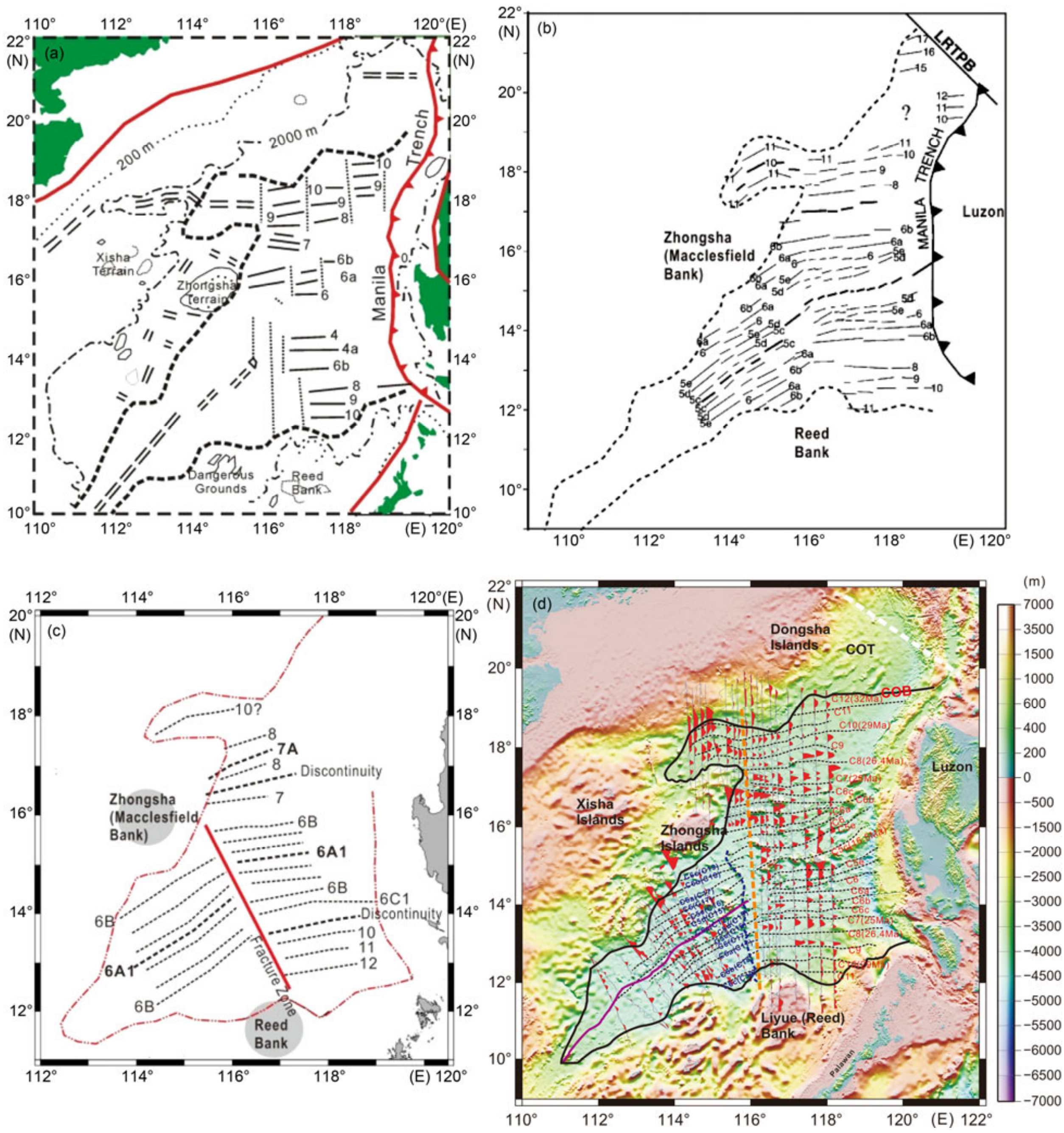

Figure 1 Different interpretations of the magnetic anomaly lineations in the SCS (see Table 1). (a) Hayes et al., 1995 [10]; (b) Hsu et al., 2004 [6]; (c) Barckhausen & Roeser, 2004 [7]; (d) Li & Song, 2012 [9].

distributed profiles from a large open magnetic data base of East Asia yielded a similar age of spreading as in early studies, but a different time for the ridge jump [9].

ODP Leg 184 to the SCS in 1999 has recovered sediment records over the past 33 Ma which was expected to cover all the sea-floor spreading history [11]. The Early Oligocene deposits, however, turned out to be of deep sea facies, and this was not expected as it was deposited at the beginning of spreading. Judging from the seismic profile, this marine sequence has not yet been penetrated, hence no signal of spreading onset can be found. By contrast, the most drastic change in sediment records occurs at the latest Oligocene. The Late Oligocene from 28.5 Ma to 23 Ma at ODP Site 1148 is represented by slump deposits, and multiple unconformities within this section indicate that as much as 3 Ma records have been erased. This layer is evident in seismic profiles as double reflectors and represents a stage of significant tectonic disturbance [12]. Drastically changes over this event are also found in almost all physical properties and geochemical indicators [13], as well as microfossil preservation. Microfossils below this layer have been diagenetically altered: foraminiferal tests recrystallized, radiolarian opal become cristobalite, and shark teeth by thermal alteration become brownish in color, in a sharp contrast to the well preserved fossils in the overlying Miocene [14].

Generally, this latest Oligocene event is tectonically ascribed to a "ridge jump" in the SCS. According to Briais et al. (1993) [4], the spreading ridge of the SCS jumped southwards and led to the initiation of seafloor spreading in the SW Sub-Basin during 7/6b about 25–23 Ma. On the basis of the abrupt changes in Nd isotopic and numerous other geochemical indices in sediments above this level, Li et al. (2002) [13] postulated that the sediment provenance changed from Indonesia and Borneo in the SW to the China continent in the North at ca. 26–23 Ma, lending a support to the hypothetical southeast extrusion of the Indochina subcontinent responsible for the opening of the SW Sub-Basin. Up to now it remains unclear when precisely the event occurred and how broad was its impact area. As discussed later, this tectonic event must have had a deep origin and a large regional scale, as it was associated with probably the most significant environmental reorganization in the Cenozoic for the region. The latest Oligocene event, therefore, is one of the major research topics of the SCS Deep program.

To reveal the age and process of the SCS spreading, the best approach is to re-measure the magnetic anomaly lineations and to carry out new scientific drilling to the oceanic crust with a high resolution. All the previous studies were based on ship borne magnetic measurements, but intensity of the magnetic field attenuates exponentially with increasing distance from the magnetic source. Near-bottom magnetic surveys using a deep-tow or ROV will improve the measurement resolution by two orders of magnitude. This new technology has been successfully applied to the eastern Pacific [15] and the Atlantic oceanic ridge [16], and in the recent years even to the hydrothermal fields of the mid-ocean ridge [17,18]. As shown by the successful records of the deep-tow measurements in other oceans, magnetice re-measuring is expected to generate high-resolution data which will allow us to precisely identify the anomaly lineations and to estimate the age and rate of the spreading process in the SCS.

Of course, the geophysical approaches cannot replace geological and geochemical studies because of the indirect nature of the obtained data. Petrology of the oceanic crust, petrophysical and geophysical analyses of rocks are a necessity for recognition of SCS spreading. The fundamental approach to unlock the opening process of the SCS and to settle up the related debate is to drill the deep bottom of the SCS, to core its oceanic crust for geochemical analyses and dating. Chinese scientists have already submitted the drilling proposal "Opening of the South China Sea and its implications for Southeast Asian tectonics, climates, and deep mantle processes" [19] to the Integrated Ocean Drilling Program (IODP), and the urgent task today is to promote its early implementation.

1.2 Dynamic mechanism of seafloor spreading

Although a number of hypothetical models have been proposed to explain seafloor spreading of the SCS, no consensus has been reached up to now [20]. Of particular importance are two contrasting end-member kinematic tectonic models: the tectonic extrusion model and the plate subduction model. The former was introduced by Tapponnier et al. (1982) [21] who show that opening of the SCS was driven by the SE extrusion of the Indochina Peninsula along the Red River fault zones owing to India's collision with Asia (Figure 2 (a)–(c)) [4,22]. The latter is based on the existence of a hypothetical Proto-South China Sea between Nansha (Spratly Islands and surround, also called "the Dangerous Ground") and Borneo, as suggested by Hall (1996) [23] that the SCS opened in response to slab pull during subduction of the proto-SCS oceanic crust beneath Borneo and Palawan (Figure 2(d)–(f)). Each of the two models has its own supporting and contradicting evidence from observations.

While searching for the formation mechanism of the SCS, the role of magmatism cannot be neglected. Judging from the data available up to now, magmatic activities in the SCS occurred mostly after but only rarely before spreading. All the trawled basalt samples form the SCS postdate the oceanic crust and should represent the products of post-spreading magmatism [26–28]. The most prominent post-spreading magmatism includes the volcanic sea-mount chains in the deep basin, many of which are ranged along the relict spreading ridges and lacking a systematic investigation. A new research focus of magmatism in the SCS in the recent years is the mantle plume. Using the seismic tomography imaging technique, a low-velocity column called "Hainan Plume" was discovered under Hainan Island, extending downwards to the lower mantle [29]. As seen from high-resolution tomographic images, this is a tilting column with a diameter of about 80 km rising from the SCS in SE to Hainan in NW, presumably from the lower mantle [30]. The volcanic rocks in the SCS, including those of Quaternary on Hainan Island, have geochemical features of OIB (oceanic island basalt) and imply a deep mantle source [31], well in line with the "Hainan Plume" hypothesis. The presence of the Hainan Plume can easily give a hint at its relation to the opening of the SCS, and indeed there appeared some speculations ascribing the SCS formation to mantle plume [32]. However, the "Hainan Plume" has been active mainly since the middle Miocene, and the rifting processes in the SCS appear to have not been accompanied by active volcanic activities. The mismatch in timing and the non-volcanic rifting type, therefore, do not support the connection between mantle plume and the rifting and spreading processes in the SCS [33]. However, there is no doubt on the critical role of mantle plume and volcanism in tectonic evolution and hydrocarbon reservoir formation in the SCS [34], which requires

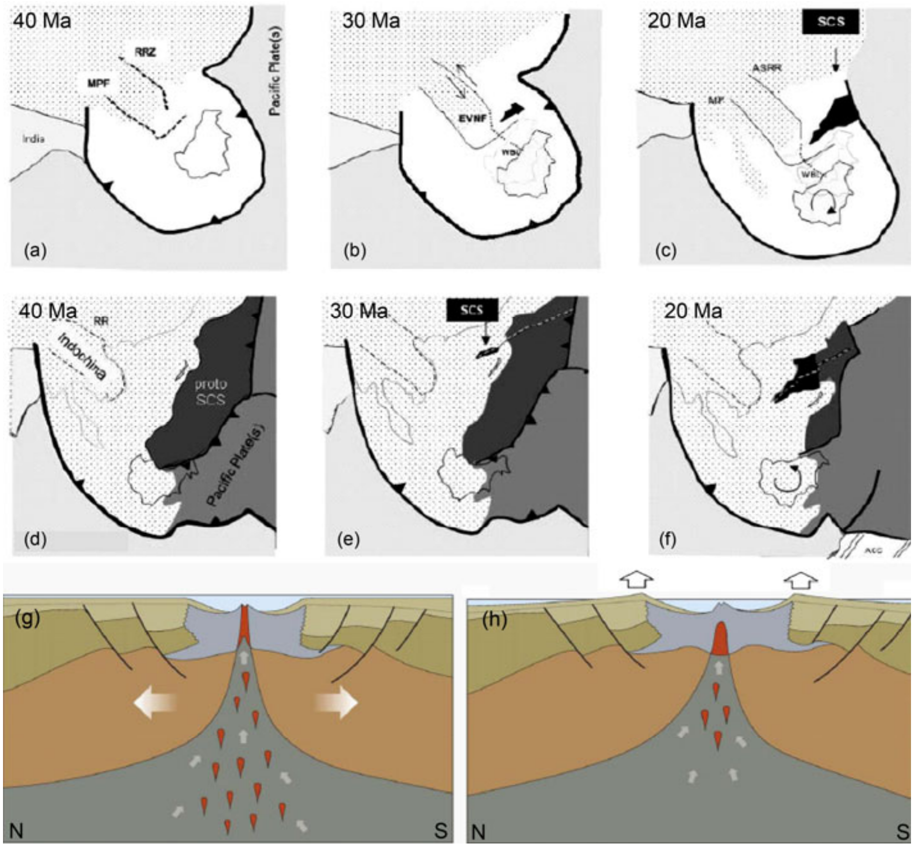

Figure 2 Tectonic models for the SCS formation: (a)–(c) Extrusion model; (d)–(f) Subduction model. From left to right: Eocene (40 Ma); Oligocene (30 Ma); and Miocene (20 Ma). (g), (h) Hypothesized cross sections showing magmatic activities. (g) Final rising melt in the Miocene resulted in thickening of the oceanic crust; (h) Post-spreading uplift and formation of volcanic chains [24,25].

urgent systematic investigations.

Recently, new data are emerging from the western part of the SCS off the Vietnam coast. Mainly based on offshore oil and gas exploration results, quite a number of papers on tectonics of the Mekong (Cuu Long), Wan'an (Nam Con Son), Zhongjiannan (Phu Khanh) and other basins have been published by European scientists in collaboration with their Vietnam counterparts, providing valuable information to our understanding of the opening processes of the SCS basin. For example, the new data dated the formation of the Wan'an Basin to 21–15 Ma with deep-water deposition only since the late Miocene. This geological evidence of timing [35] agrees with the conclusion of Chinese researchers [36] on the SW propagation of the spreading axis in the SW Sub-Basin. As to the tectonic hypotheses of the SCS formation, some authors support the subduction model and exclude the role of extrusion [35], while the majority of authors are positive to the collision-extrusion model, but differ in the relative importance of extrusion versus subduction as the driving mechanism [25]. The recent advance in land geology in Vietnam confirmed the importance of the Red River Fault, as revealed by a study in north Vietnam showing fault changes from transpression to transtension some 33 Ma ago, corresponding to the SCS opening in the earliest Oligocene [37]. However, some other authors suspect the SCS opening by a single driving force and, instead, propose a "hybrid tectonic model" [25], i.e. the Oligocene opening was related to extrusion, whereas the Miocene opening was driven by subduction towards Borneo. Thus in this hybrid model both extrusion and subduction are valid but for different times without any inclusion or exclusion to each other. The late Miocene magmatism was important not only as a driving force of spreading (Figure 2(g)), but also for its creation of volcanic chains along the ancient spreading ridge (Figure 2(h)) [26]. Post-spreading magmatism has been active since the middle Miocene to the Quaternary, its suspected relationship with the Hainan Plume is a crucial question worthy of further studies.

1.3 Closure and extinction of marginal basins

The fatal destination of all marginal seas is extinction. A marginal basin generated by seafloor spreading will eventually extinct by plate subduction. The modern SCS oceanic crust is subducting eastwards along the Manila Trench, and apparently the pace to extinction started already before the spreading process ended. According to magnetic anomalies, the seafloor spreading of the SCS ended at 16 Ma or 20.5

Ma. Currently, two hypotheses exist to explain the cessation of spreading: either by blockage in the course of the northward shift and pressure of the Australia-Indian Plate, or by obduction of the NW-moving Luzon island arc onto the SCS Plate. Because of fairly close timings, the cessation of spreading and the beginning of subduction under the Manila Trench may be genetically related to each other. The Manila Trench stretches almost meridianally form southern Taiwan to Mindoro Island and represents the subduction zone of the SCS oceanic crust beneath the Philippine Sea Plate. Opinions diverge on the time when subduction started. If subduction can be indicated by uplift of mountain ranges, it might have started at the latest Oligocene, as Zembales Range facing the subduction zone from the western side of Luzon uplifted at this time. If subduction can be signaled by magmatic activities, it might have begun at 17 Ma in the early Miocene, when volcanos along the Cordillera Central in Luzon Island first erupted. The latter estimation is close to the end of the seafloor spreading of the SCS [39], but postdates the former estimation by some ten million years.

The evolution of the Manila Trench, as a “guard” of the SCS eastern gate, is crucial to reconstruction of the life history of the basin. The modern SCS is connected with the open ocean through the Bashi Strait between Taiwan and Luzon with a sill depth over 2 km, as the only deep-water passageway (Figure 3) [40]. Also in the east, the Manila Trench determines the eastward extension of the SCS basin. With the NW shift of the Philippine Sea Plate, the Manila Trench has been approaching to the South China continent together with the accretionary prism and island arc resulted from the SCS subduction, subsequently reducing the size of the sea basin and restricting its connection to the open ocean. In brief, the SCS extinction started when its oceanic crust began to subduct eastward along the Manila Trench, and the history of extinction is believed to have been recorded in Luzon and Taiwan islands together with the Bashi Strait in between. For example, the copper-gold porphyry deposit in Luzon was most probably produced by subduction of the Scarborough (Huanyandao) Ridge in the SCS [41].

The Hengchun Ridge on the western side of the Bashi Strait is an accretionary prism generated by the eastward subduction of the SCS oceanic crust, with a northern extension on-land as the Central Range in Taiwan. Across the Luzon Trough eastwards, the North Luzon volcanic arc extends along the eastern side of the Bashi Strait and northward onto the Coastal Range of Taiwan (Figure 3) [42,43]. By the end of Miocene, the oblique arc-continent collision between the North Luzon volcanic arc and the Eurasian continental margin led to the formation of proto-Taiwan and to further restriction of the connection between the SCS and

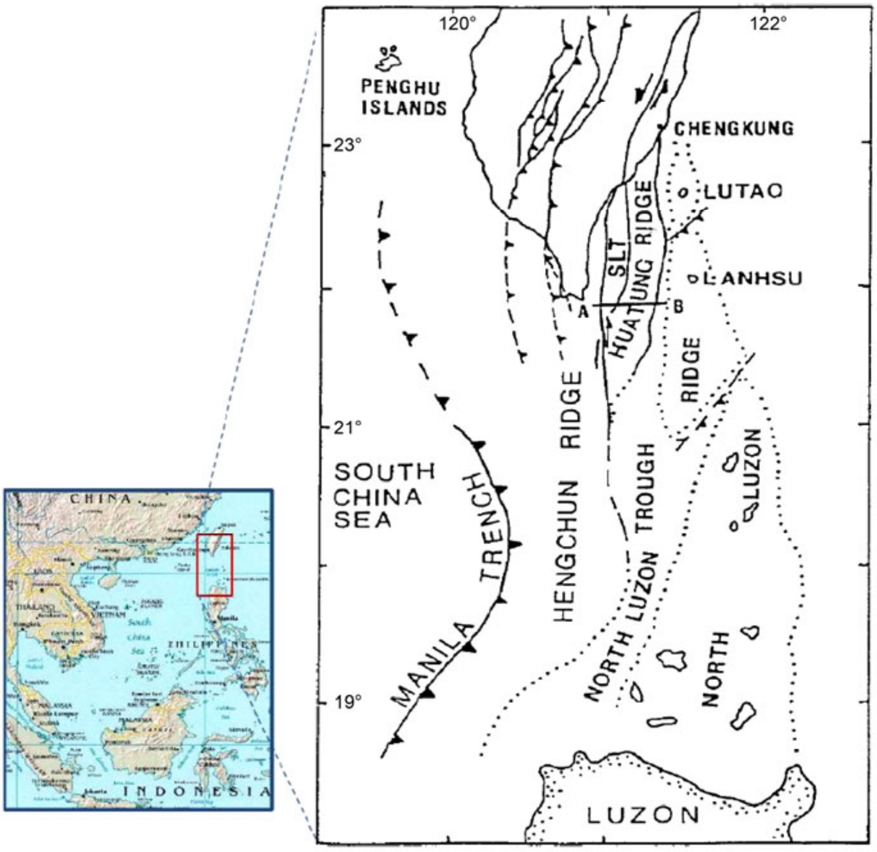

Figure 3 A sketch of geological structure of the Manila Trench and Bashi Strait (revised from [40]). SLT: South Longitudinal Trough.

open ocean, giving rise to the present semi-closed SCS basin. Therefore, the geological records onshore in Taiwan and offshore in the Bashi Strait provide valuable archives for reconstructing the extinction history of the SCS; and the rugged topography has been the key valve in controlling the evolution of deep waters in the SCS. Since the arc-continental collusion at 6.5 Ma, the submarine ridges in the Bashi Strait have blocked the free water exchanges of the SCS with the Pacific, and the processes should be observed on land in the mountain ranges of Taiwan as well [44]. This interesting topic will be explored further in section 2.3 below.

1.4 From active to passive margin

The above discussion on the opening and extinction of the marginal basin deals with a process restricted only to the late Cenozoic. If we broaden our scope from the SCS to the Pacific, a process of much larger scale involving the transfer of continental margin from active in the late Mesozoic to passive in the Cenozoic can be seen in operation. Why the major tectonic reorganizations such as the formation of the Pacific Plate, the breakup of the Gondwana, and the "Yanshan Movement" in China, all occurred in the same period of the Middle Jurassic, is an issue worthy of careful consideration. Ninety percent of the large magmatic provinces in SE China, with a 220000 km^2 outcrop area of granitoids and volcanic rocks, has been dated as belonging to the Yanshan Stage [45], and the 1300 km-wide intracontinental orogen [46] is believed to have resulted from a low-angle subduction of the Pacific Plate beneath Asia from the Late Jurassic to Late Cretaceous (180–80 Ma) [47]. The world's oldest oceanic crust located in the Western Pacific was dated to 170–165 Ma by the ODP [48], synchronous with breakup of the Gondwana, and this correlation has brought about a speculation that the Gondwana's breakup accounts for the Pacific Plate formation [49]. Since the Pacific Plate formed and the Gondwana supercontinent collapsed in result of divergence of the oceanic and continental lithospheres, respectively, it may not have been just a coincidence in the centers of the two processes which are antipodal in position, lying on the eastern and western equatorial "poles" of the Earth [50]. Presumably, this was a coupled global phenomenon with a deep-Earth origin. As seen from seismic tomographic images [51], the two centers have globally symmetric positions, corresponding to the Pacific and Anti-Pacific poles in the lower mantle [50]. If approved, this will be a typical example of inter-connection between the Earth's deep and surface systems.

Despite of the two ODP legs drilling to the oldest crust of the Pacific Plate, the Mesozoic history of the Pacific remains poorly constrained. Unlike in the Atlantic, the patterns of magnetic anomalies in the western Pacific are intricate, implying a complicated history of plate movement which is difficult to restore on the basis of the remaining fragments. It is clear, however, there was an active continental margin between Asia and Pacific during the Mesozoic when the Pacific Plate was subducting beneath the Asian Plate with a low angle. Apparently, the late Mesozoic western Pacific characterized by Andes-type mountainous coasts did not continue into the Cenozoic. In the early Cenozoic, numerous sedimentary basins with petroleum resources were generated in East Asia by rifting processes, and since the Oligocene a series of marginal seas appeared to separate the modern Asian continent from the Pacific [52], turning the East Asian offshore into a passive margin. It has been hypothesized that the late Mesozoic activation in East Asia resulted from low-angle west-dipping subduction of the newly formed Pacific Plate and/or its subsequent foundering, and related magmatism and uplift of South China has created the west-tilting topography in China [53].

The transition from the Mesozoic active to late Cenozoic passive margin was a period of the rifted basins formation, and also a period of the development of major petroleum basins in the northern SCS (Table 2) [54,55]. Although the zone of oceanic crust formed by seafloor spreading is significantly wider in the east than in the west, the total width of the rift zone in the west was greater than in the east. As both rifting and spreading broke up the continental crust, the total crustal extension including rifting and spreading to about 1100 km is consistent between the Eastern and SW Sub-Basins. The earlier initiation of seafloor spreading in the Eastern Sub-Basin has probably a deep origin. Since the Mesozoic Pacific Plate was subducting from the east, the eastern part of the SCS is relatively prone to spreading probably due to the residual effect of the lithospheric temperature perturbations associated with subduction [56].

However, it remains mysterious how the Meso/Cenozoic transition from subducting compression to breakup extension in the region took place. The mantle underlying the western Pacific has globally the largest amounts of subducting oceanic slabs and hence the highest water content [57]. It is an essential issue to explore whether the tectonic reorganization

Table 2 Four stages of the SCS basin Evolution

Stage	Age	Tectonic features
Active margin	Late Mesozoic (Middle Jurassic to Late Cretaceous)	Low-angle subduction of the Pacific Plate
Rifting	Latest Cretaceous to Eocene	Formation of rift basins
Seafloor spreading	Oligocene to Middle Miocene	Formation of oceanic crust and basin expansion
Closing and subduction	Since Middle Miocene	Basin closure and subduction beneath the Manila Trench

also has a global deep-Earth background. Unfortunately, the remnants of the Mesozoic oceanic crust and sediments are fragmentary, and the rift deposits in the northern SCS are mostly non-marine. A complete history of the transition could be reconstructed only by scientists who manage to integrate carefully the scattered fragments of the related data. From this view point, the discoveries of the Mesozoic marine deposits in the northern SCS and of the Cretaceous oceanic crust from the Huadong Basin east off Taiwan may provide valuable clues for further researches of the SCS Deep program.

2 Sediment filling of the South China Sea marginal basin

Aside from the tectonic and magmatic aspects, researches on the SCS basin evolution in the framework of the “SCS Deep” program have broader aspects to explore on how the hydrological, biological, chemical and sedimentological processes were responding to basin evolution, and eventually to unveil the life history of this marginal basin. From a mega-view of the planetary cycle in the Earth system, marine deposits are nothing except an intermediate halt for material transfer from the continental crust to the oceanic crust. The transferred material can be a product of physical weathering settling down after direct transport by river and sea water, or a product of chemical weathering deposited biochemically after being transported as solutes. Therefore, marine sediments have recorded both the physical and biochemical processes of the sea basin. A wealth of data on deep-sea sediments accumulated over thirty years of petroleum exploration and geological survey can be used to decipher the evolution of the SCS deep processes. Our following discussion will cover four aspects: basin filling, sediment response, deep-water circulation and carbonates.

2.1 Sediment filling at various stages

As mentioned above, the pre-spreading marine sediment records in the SCS, although sparse, can provide valuable clues to the history of the marginal basin from its origin. The question about the Tethys/Pacific connection in the late Mesozoic has since long attracted attention from the geological community, and the location of the present day SCS is the focal point to explore connection between the paleo-oceans. In the northern SCS, the Late Jurassic-Late Cretaceous marine deposits have been discovered in the SW Taiwan Basin and the Beigang Uplift [58]. According to the seismic data, mighty sequences of late Mesozoic marine deposits up to 7000 m thick are distributed in the eastern part of the Zhujiangkou (Pearl River Mouth) Basin, particularly in the Chaoshan Depression [59–61]. Radiolaria-bearing marine deposits of Jurassic-Cretaceous age were recovered from Well MZ-1-1 on the northern slope of the Chaoshan Depression in 2003 [62]. The presence of deep-water sediments in the sequence implies a Mesozoic scenario when East Asia was directly facing the Pacific subduction zone [63]. In the southern SCS, the Proto-SCS was believed to have developed between the modern Nansha Islands (the Dangerous Ground) and Borneo (Figure 2) [64], and Mesozoic marine deposits have been repeatedly encountered in dredge or borehole samples. All these may be considered as produced by and thus represent the relics of the same Mesozoic basin—the Proto-SCS, but torn apart to the present positions by the subsequent seafloor spreading [65]. Therefore, there are major scientific issues of primary significance for the region on the relation between the Proto-SCS deposits in the northern and southern parts of the modern SCS and the Tethys/ Pacific connection [66].

Numerous sedimentary basins developed from Late Cretaceous to Eocene when the SCS was experiencing its rifting stage. The basins were filled mainly with fluvio-lacustrine deposits in the northern part of the modern SCS. This was the critical stage when primary deposits of oil-generating deposits accumulated and, therefore, has been the main target of research efforts over the decades [55,67,68]. On the other side, marine environments of that stage can only be implied from reworked microfossils. Reworked calcareous nannofossils of Eocene and Paleocene age have been reported from industry wells in the northern shelf [69] and from ODP cores in the northern slope [11], but their source deposits remain unknown. As the Early Oligocene sediments recovered from ODP Site 1148 are of deep-water facies, and the deep-water sequence continues downward in the seismic profile, the possible existence of deep-water Eocene or even Paleocene in the northern slope is a key question requiring further investigations. As shown by available data, early Cenozoic sequences in many basins of the southern SCS are similarly of fluvio-lacustrine nature as in the northern part. However, shallow-marine deposits of Late Eocene-Oligocene age have been found from the Zengmu Basin in the SW part of the SCS, whereas the low-grade metamorphosed Paleocene-Middle Eocene deposits there [20,70] may belong to the “Proto-SCS”.

According to preliminary estimations, all continental shelf and slope basins of the SCS together has been filled with a total of 1.44×10^{16} t of sediments since its opening in the Early Oligocene, of which 63% belong to terrigenous clastic and 37% to biogenic carbonate components, with a minor amount of siliceous and volcanogenic material. These figures are results of rough estimations and calculated years ago using data from 40 boreholes, 121 sediment cores and 94 seismic profiles and represent incomplete statistic results [71]. Nevertheless it can be seen that the average accumulation rates were highest during the Oligocene, followed by the Quaternary, while lowest rates occurred in the Middle Miocene. Also noteworthy is that SCS sediments mostly accumulated on continental shelves and slopes, with no major deep-water fans developed [71]. These features distinguish the SCS from the open ocean, as well as from small back-arc marginal basins in the western Pacific. Estimations on the late Quaternary sediments are more reliable due to wider coverage and better core control, showing the annual average of the total deposit mass 1.5×10^8 t for the Holocene and up to 2.1×10^8 t for the LGM. The accumulation rate is the highest in the SW and NE areas, but the SW area has a much higher rate than the NE area during the Last Glaciation because of the well developed Paleo-Sunda river system [72].

There are two problems in sediment filling studies: calibration between geological records and modern process observation, and analysis of sediment provenances. Currently, the SCS annually receives 3.6×10^8 t of suspended sediments from the three major rivers of the Asian continent: the Pearl, Red and Mekong Rivers [73], but even more sediments may be discharged from the islands on the southern and eastern sides. Because of the intensive weathering process, the Taiwan island alone can contribute as much as 1.8×10^8 t/a of sediment to the SCS [74]. A calculation using the theoretical model of Milliman et al. (1999) [75] shows that the total sediment discharge from Borneo and Sumatra may reach 10×10^8 t/a. However, there is one order of magnitude in the difference between the modern sediment input and the sedimentation rate calculated from the Quaternary record. The mismatch between modern observation and paleo-record is not specific to the SCS, so a reasonable explanation for their calibration is needed. Another key issue is provenance analysis of the terrigenous mass. Evolution of sediment provenances in the SCS have been studied by a number of authors in recent years. A variety of approaches have been used such as sediment granulometry, element geochemistry, clay mineralogy and Neodymium isotopes, amongst others, in order to separate alluvial from eolian inputs, to identify the proportions of sediments from continent vs islands, and to trace back the changes in drainage system caused by uplift of Tibet [76–81]. Of particular interest is the quantitative analysis of clay mineral assemblages. As discovered, clay minerals are different from different provenances around the SCS: illite-chlorite assemblage from Taiwan, smectite-dominating assemblage from Luzon, and high kaolinite percentage (~50%) from the Pearl River source [82,83]. Sediments from different sources are being mixed in offshore environments of the SCS, but a combination of *in-situ* observation and quantitative clay-mineral analysis with Nd isotope and other analyses on sediments collected from traps and cores may help to decipher the combined results of source control and water current transport, and to provide a key to quantitative estimating sediment provenance in the SCS.

2.2 Sedimentological response to basin evolution

One of the research priorities of the SCS Deep program is to find out how the major tectonic events in the SCS were recorded by sedimentological processes. ODP Site 1148 from a modern water depth of 3300 m has yielded sediment records over 33 Ma, and discovered the most remarkable geological event at the end of Oligocene (Figure 4). The deposition rate reached its maximal values (>60 m/Ma) in the Early Oligocene, but dropped to minimal values (<5 m/Ma) in the Late Oligocene characterized by slumps and hiatuses. The tectonics-induced hiatuses are concentrated between 28.5 Ma in the mid-Oligocene and 23 Ma in the earliest Miocene, and the four hiatuses together have erased sediment records of 3 Ma at the least, with the main unconformity at the base of slump deposits dated at 25 Ma [12,84]. The northern SCS experienced tremendous environmental changes during the latest Oligocene. The succession of benthic faunas from ODP Site 1148 show a drastic deepening from the upper bathyal (<1500 m) in the Early Oligocene to lower bathyal (>2500 m) in the early Miocene [85]. A similar trend was observed in the sediment sequence from the Baiyun Depression on the modern upper slope, indicating a transition from shallow to deep water conditions [86]. Other concurring changes include abrupt reductions of opal and carbonate accumulation rates, and a sediment source shift from the southern to the northern provenance after the event [13]. The Latest Oligocene Event is not only the largest tectonic change recorded in SCS sediments, but also corresponds to an extensive reorganization of geological and climatological environments in SE Asia, as exemplified by the transition from a planetary to a monsoonal atmospheric circulation system [87]. Such a large-scale restructure in the Earth surface system must have its deep origin which is to be disclosed by further investigations.

Another data set is from the southwestern SCS off Vietnam. As shown by recent exploration drilling in the Zhongjiannan (Phu Khanh), Mekong (Cuu Long), Wan'an (Nam Con Son) and other basins, the SW part of the SCS was inundated by marine transgression only since the Miocene (Figure 5(a)), and the earlier deposits are all of non-marine origin. Volcanism became active from the latest Early Miocene to Middle Miocene, when carbonate platforms also began to develop (Figure 5(b)). Significant subsidence started by the end of the Middle Miocene, which brought about the deep-water environment up to the present (Figure 5(c)). These records indicate a much later spreading in the SW than in the N part of the SCS, supporting the "hybrid tectonic model" which claims that spreading in the SE Sub-Basin in the Miocene was driven by subduction towards Borneo, when the spreading axis was propagating toward SW with accompanying active magmatism [24]. These new observations clearly show that different paces of evolution in the two Sub-Basins controlled the different histories of marine sedimentation in these areas.

2.3 Evolution of deep-water circulation in sediment Record

Opening and closure are two major processes of equal

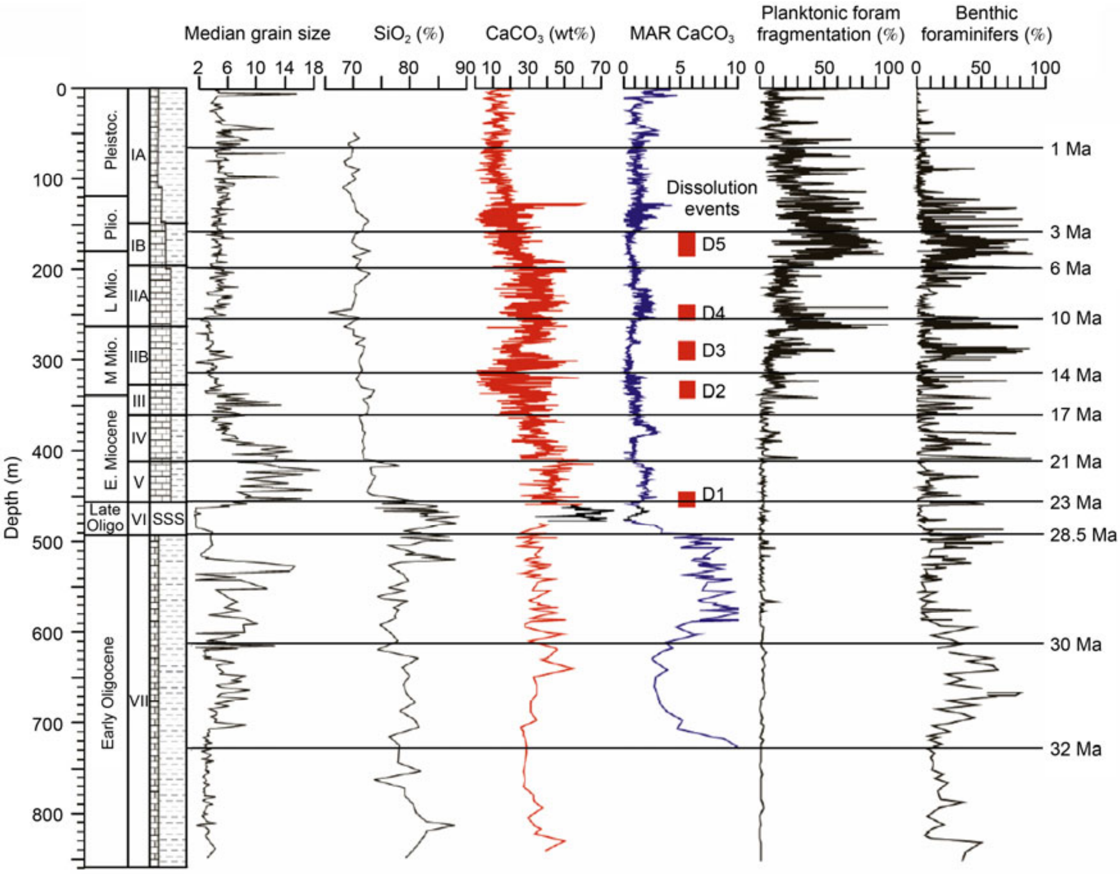

Figure 4 A 33 Ma sediment record from ODP Site 1148, northern slope of the SCS (water depth 3297 m): results of lithology, chemical and foraminiferal analyses. MAR $CaCO_3$ indicates mass accumulation rate of carbonate in g cm^{-1} ka^{-1}, D1–D5 denote deep-sea dissolution events [20].

importance in the evolution of a basin, but the deep-water circulation in the SCS seems to be sensitive to its closure more than opening. As discussed above, the northward migration of the Philippine Sea Plate and East-dipping subduction of the SCS oceanic crust along the Manila Trench might have triggered the closure and extinction of the SCS. The Bashi Strait between Luzon and Taiwan is the only deep-water passageway between the modern semi-enclosed SCS and the open ocean, and the subduction zone of the Manila Trench is the edge where the SCS material is being "engulfed". Accordingly, the SCS basin should have been much broader and more open in the Middle Miocene when the spreading process just came to completing, the Philippines and many islands along the eastern border of the modern SCS were far in the south or unborn, and the area of the SCS basin then could be twice as large as today (Figure 6) [88]. Therefore, the Manila Subduction Zone is a critical component in the SCS Deep research program. On the tectonic aspect, the Manila Subduction Zone is distinguished from those in the open ocean by its bilateral sudduction feature: Along with the Manila Trench where the SCS subducts eastward, there is the Philippine Trench where the Philippine Sea Plate subducts westward. How the two subducting plates meet under the Manila Trench? How the tectonic activities are operating under the double subduction zones? All are open questions of superior scientific significance. On the oceanographic aspect, the accretionary prism and volcanic arc generated by subduction are submarine sill which obstructs the free connection of waters and determines the depth interval of water exchange between the SCS and the Pacific. In result, the deep-water properties in the SCS are extremely sensitive to any changes in the Manila Trench subduction zone.

The Pacific is today the only deep-water source of the SCS. The incoming Pacific water enters the SCS through the Bashi Strait over the 2600 m deep sill, and the deep water overflow gradually gets mixed with ambient and then returns back to the Pacific in intermediate layers [89]. Consequently, the SCS deep waters below 2000 m are uniform and stable in terms of density and dissolved oxygen [90]. Here the key element in geography is the Bashi Strait which is not only the single passageway for deep-water exchange, but also the venue for energy exchange between the SCS and Pacific. Numerous internal waves are produced in the Bashi Strait and propagate into the SCS, enhancing deep-water mixing in the SCS by two orders of magnitude higher than in the Pacific. Diapycnal mixing drives the cyclonic circulation in the deep SCS and modulates the deep-

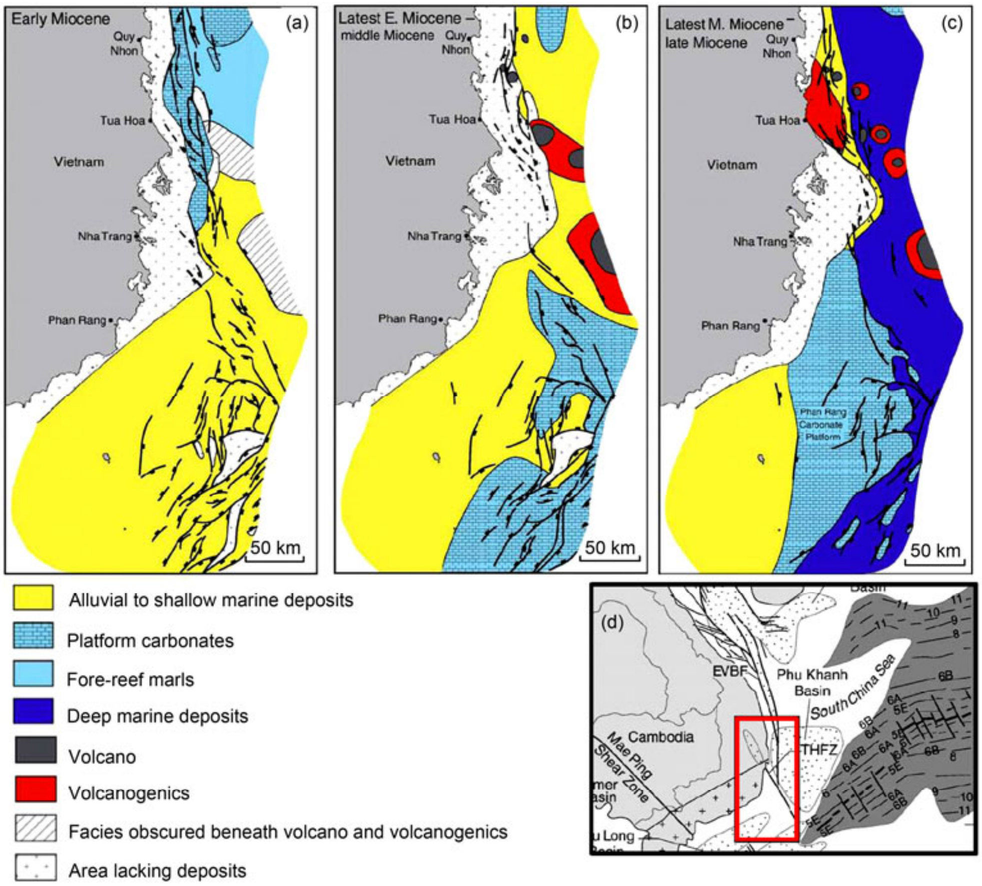

Figure 5 Evolution of Miocene sediment facies in the SW part of the SCS. (a) Early Miocene; (b) latest Early Miocene–Middle Miocene; (c) Middle Miocene to Late Miocene; (d) geographic position of the area under discussion (red square) (modified from [24]).

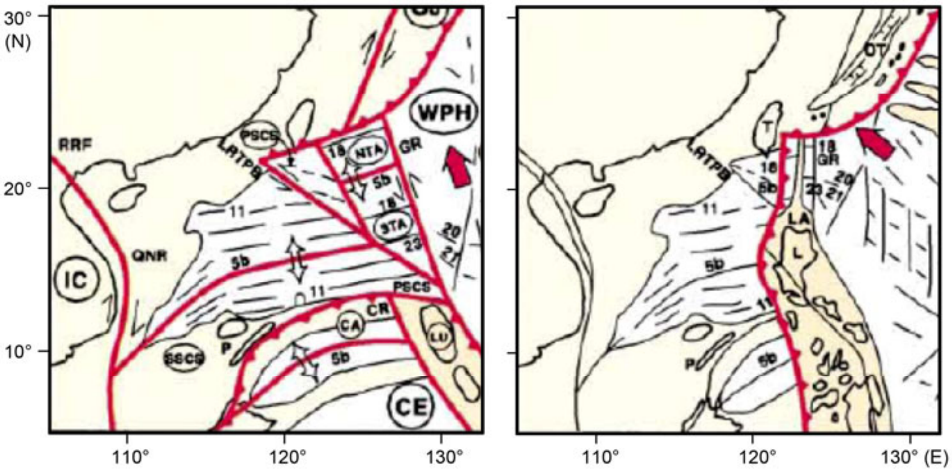

Figure 6 Patterns of plate movements around the South China Sea in the Miocene (15 Ma; left) and the present (0 Ma; right) (after [24]). Plates: IC, Indochina; PSCS, Proto-South China Sea; CA, Cagayan; CE, Celebes; NTA, North Taiwan Sea; STA, South Taiwan Sea; LU, Luzon; WPH, West Philippine Sea; QNR, Qui Nhon Ridge; LATPB, Luzon-Ryukyu transform plate boundary; CR, Cagayan Ridge; GA, Gagua Ridge. Numbers denote magnetic anomalies.

water renewal there [91]. This explains the extraordinary deep-water ventilation in the modern SCS, with a fast flushing time of 40–50 years [92] or even 30 years [93]. Unlike the Sea of Japan, the SCS deep waters below 2000 m are all from the Pacific, and no deep water is locally produced. This particular feature enables us to use the SCS sediment records to monitor the evolution of water masses in the western Pacific over time.

The above described are only the modern patterns. In the geological past, the newly formed SCS was completely open to the East with free water exchanges with the Pacific. No “deep water overflow” was then needed, nor was the deep circulation necessarily cyclonic. Together with the northern migration of the Luzon Arc and closure of the SCS basin, the submarine sill restricted water exchanges and enhanced deep-water ventilation, giving rise to extremely young and well oxygenized deep-waters in the SCS. Specifically, the accretionary prism of the Manila Trench and the Luzon Volcanic Arc are the two sills obstructing water exchanges. Fortunately both sills extend northwards, respectively as Hengchun Peninsula and the Coastal Range in Taiwan (Figure 3), so that the history of submarine sill can be learned from outcrops on the island. As shown by geological records in Taiwan, the accretionary prism and the volcanic arc were formed some 15–16 Ma ago in the early Middle Miocene, and subaerially emerged by the end of Miocene about 6.5 Ma [42,43]. Interestingly, these are exactly the two time intervals when deep-water oxygen concentration and negative excursion of carbon isotope remarkably increased in deep-sea drilling records. As seen from Figure 7, the faunal succession of benthic foraminifera from ODP Site 1148 displays a two-step increase in the high-oxygen group, and the carbon isotopes show significant lighter values at the corresponding stratigraphic levels in comparison to the global average [20]. Another critical event in the formation of the submarine sill in the Bashi Strait occurred around 3.5–3.7 Ma, as marked by the Lichi mélange in the northern extension of the Huadong Ridge in Taiwan. At about the same time, the Rb/Zr record of ODP Site 1148 drastically changed its general trend from decreasing to uprising (Lianwen Liu, personnel communication, 2008). This event is also shown in the benthic δ^{13}C curve as a significant negative excursion. However, whether these observations are associated with the sill formation and reorganization of the bottom circulations needs urgent studies. The Cenozoic strata in Taiwan are essentially the SCS sediment sequences outcropped on land. If the offshore studies of the Bashi Strait and on land research in Taiwan are integrated and further compared with geological records of the deep-water evolution, we may be able to unlock the presumable coupling between the evolution of the Manila subduction zone and deep-water changes in the SCS. Once successful, this will be a typical example to demonstrate the tectonic control of deep-water paleoceanography in a marginal basin [44].

Certainly, the deep-water evolution in the SCS is controlled not only by the Bashi Strait, but also by the Pacific. The incoming water through the Bashi Strait has its source

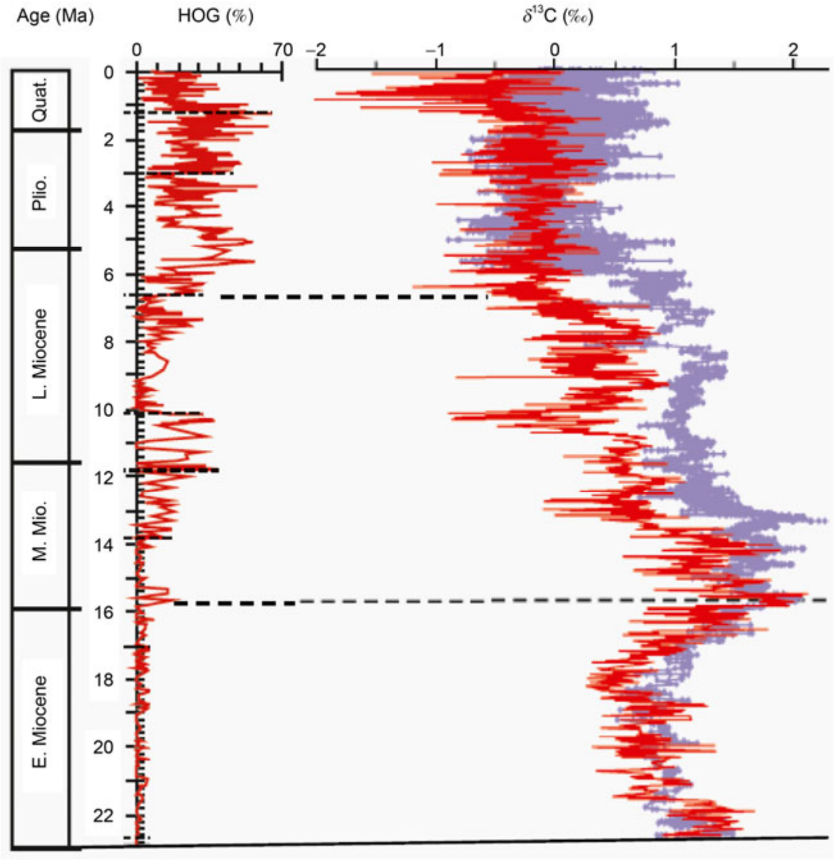

Figure 7 Downhole variations of (left) high oxygen group (HOG) of benthic foraminifera and (right) benthic δ^{13}C (red) at ODP Site 1148, as compared to the global ocean average (purple). Dotted lines show development stages of the submarine sill in the Bashi Strait (redrawn from [20]).

in the Philippine Sea, hence the basin evolution of the Philippine Sea must have its impact on the SCS deep water. Moreover, changes in the deep water structure of the entire western Pacific also exert their influence on the SCS [91]. As determined largely by the current topography of the basin, the cyclonic deep water circulation must have experienced reorganizations during the long history of SCS opening and closing. Therefore, the δ^{13}C signals from ODP Site 1148 discussed above (Figure 7) may be indicative of the history of circulation changes in the Pacific and in the SCS, which is again expected to be clarified by future researches.

Sedimentary structures provide another group of geological records of deep-water evolution. Abundant turbidite deposits fill the deep water basin of the SCS, and sediment waves and sediment drifts are extensively distributed on the continental slopes, but their systematical researches are lacking. Because of the absence of on-site observation of deep-water currents, the direction of deep water circulation is speculated on the basis of the patterns of water density and oxygen concentration, while sedimentary structures on seismic profiles. The SCS as a marginal sea is characterized by high sedimentation rate of hemi-pelagic deposits, which can be illustrated by the sediment drift body to the southeast of Dongsha Island on the northern slope where several boreholes at ODP Site 1144 were drilled. This sediment body has very high depositional rates up to 97 cm/ka [95], yet its origin remains a matter of debate. Some authors postulate that the inflowing North Pacific Deep Water transports fine terrigenous sediments of Taiwan origin to the northern slope, and shed off its load there while pushing upslope [96]; others ascribed it to contourite [97]; still others claim it comprising a series of sediment waves migrated upslope [98]. The divergence of opinions is rooted in the lack of observation. In order to understand the deep-water currents and their role in sediment transport, systematical researches involving *in-situ* observations into “source to sink” type in sediment dynamics are required [99]. Up to now, the study of hyperpycnal flows off the Gaoping River mouth, Taiwan, is the most successful example of seafloor observation of the modern sedimentation process in the SCS. The Gaoping catchment basin in southern Taiwan has a topography range of 3000 m and annual precipitation of over 3000 mm. With the annual sediment discharge of 35 million tons in average, the Gaoping River runoff turns to hyperpycnal flows into the SCS, cutting the continental slope to form the Gaoping submarine canyon down to ~400 m water depth outside the shelf break. The canyon is an effective conduit transporting sediments from the Gaoping River’s drainage basin to the deep sea bottom [100,101]. We invite research projects to integrate observations and numerical simulations across spatio-temporal scales, combining results from *in-situ* observations of sediment grains transportation and from sediment structure analyses of seismic profiles. This new approach to sedimentology will build up a bridge between physical oceanography and sedimentary geology, just like writing on a Rosetta Stone that bridges the ancient Egyptian and ancient Greek scripts [102].

2.4 Deep-water carbonates and carbonate platform in the South China Sea

Thanks to its low-latitude position and intensive ventilation of deep waters, the SCS has the best deep-water carbonate preservation in the western Pacific region. Aside from the deep part below 3500 m, the rest of the SCS contains no less than 10% carbonate in bottom sediments and thus has preserved excellent geological records of the deepwater processes in the basin. Carbonate deposits in the SCS are composed of two groups: deep-water carbonates and reef carbonates. Through analyses of a large number of sediment cores, two different models of late Quaternary carbonate cycles have been found respectively from below and above the lysocline in the modern SCS [103]. The ocean drilling has revealed remarkable variations in carbonate accumulation over the last 33 Ma, including changes common to the low-latitude Pacific: the carbonate dissolution events (D1–D5 in Figure 4), the “carbonate crash” after 11 Ma, and the “biogenic bloom” after 8 Ma (Figure 4) [20]. Together with the terrestrial sediment records discussed above, deposition and dissolution of deep-water carbonates yield a substantial basis for reconstruction of the life history of the marginal basin.

As a specific feature, the SCS basin is studded with numerous coral reefs, with an estimated total modern reef area of ca. 8000 km^2. The reefs are mostly distributed on carbonate platforms, and the largest platform is the Nansha Islands, or “Dangerous Grounds”, with a total sea area of 820000 km^2, nearly 60 times the size of the Bahamas. The total annual reef carbonate production in the SCS is in the order of 2.1×10^7 t, which is about 1.6%–3.3% of global reefal carbonate production [104]. Certainly, coral reef by itself does not belong to deep-sea sediments, but the produced carbonate only partially make up the reef framework, while the major part is being destroyed by waves and storms or eroded during the lowered sea-level stand, and subsequently transported to the deep basin. Eventually, the reef carbonate contributes to the deep-sea deposits and together with planktonic and other skeletons they form the carbonate biogenic components in deep-sea sediments. Several deep boreholes were drilled in the 1970s on Xisha (Paracel) and Nansha Islands each with a few hundred meters of penetration or more. The deepest hole on Yongxing Island of Xisha reaches 1279 m of penetration and uncovers a carbonate sequence since the Miocene lying on the Pre-Cambrian Basement [105]. Apart from the present reef islands and platforms, there are older reef carbonates buried under the northern and southwestern margins of the SCS. Coral reefs in the SCS have produced a thousand or more meters of carbonate deposits and make up an important part of the global carbonate platforms. In terms of time length and carbonate thickness, however, SCS reefs are inferior to the Bahamas which has a reef sequence of several thousands of meters thick dated back to the Mesozoic.

The Bahamas has become the global standard in carbonate studies since 1950s, or even the "holy ground" after two ODP legs. All researches of carbonate geology follow the Bahamas model, ranging from carbonate structure and diagenesis to carbonate sequence stratigraphy. By contrast, the Nansha Islands remain a "dangerous ground" for the international scientific community, despite of decadal investigations and numerous publications in China. During recent years, coral reef studies in the region have achieved encouraging results in high-resolution paleoclimatology, but research activities devoting to sediment response to the basin evolution from a broader view are lacking. On a regional aspect, coral reefs should be studied as a part of the carbonate platform rather than individual reef bodies isolated from the surrounding sea areas. Carbonate platforms in the SCS are not only of theoretical importance but also have primary practical values. We should answer such questions as, for example, why did the development of most carbonate oil reservoirs in the SCS started only since the Middle Miocene (Figure 5(b),(c)), and what role has the coral reef played in the SCS carbon cycling? All these are questions to be addressed by the SCS Deep program.

3 Energy and material flows in the South China Sea Deep

A great discovery in the ocean science over the past 3–4 decades is the bidirectional nature of the marine energy and material fluxes. As the discovery of deep-sea hydrothermal system and fauna near the end of 1970s shows, a bottom-up flux driven by heat energy from the Earth's interior is working along with the familiar top-down flux driven by solar radiation. The deep-sea bottom is the venue proximal to the Earth's interior and hence provides a window for interactions between the Earth's surface and interior. From the mid-ocean ridge to the subduction zone, and from the continental margin to the abyssal basin, a large amount of fluids are circulating under the sea floor comparable to "the sub-seafloor ocean" [106]. The interstitial liquid contained in pores and fissures of sediments or rocks disperses or migrates under the control of topographic, tectonic or thermal pressures, and exerts influence on the deep-sea processes especially on the evolving chemical composition of the sea water, whereby participating in the Earth surface system cycle. Since the ancient spreading ridge and active subduction zone co-exist in the SCS, changes in past and modern energy and material flows comprise a substantial part of the basin evolution history. This is a totally new research area, and no research results can be reviewed as the foregoing. Instead, the following discussion will focus on relevant research directions.

3.1 Hydrothermal and cold seep, serpentinization, gas hydrates

Hydrothermal activities at the mid-ocean ridge are the most sensational discovery from the deep-sea bottom. Sea water penetrates downwards into the sea floor through fractures in crust and then returns back to the sea bottom after heating by magma at depth. By this way, the hydrothermal fluids bring material and energy from the interior to maintain the specific mineralization and life system [107]. Although seafloor spreading in the SCS ceased more than ten million years ago, the ancient hydrothermal activities must have left their imprints, no matter of mineralogical, biological or chemical types, at the relict spreading ridge and surroundings. As recently found, the sub-seafloor fluid circulation is more extensive on the ridge flanks. Serpentinization of mantle peridotite, for example, is extensively observed along transform faults on both sides of the mid-ocean ridge in the Atlantic and comprises a key link to water cycling in the deep Earth. When mantle periodotite is serpentinized after exposure to sea water, it releases heat and hydrogen and causes low-temperature hydrothermal process characterized by methane generation and a specific biological community, as reported from the Lost City in the Atlantic [108]. Serpentinization has been widely discovered as a product of water-rock interactions in deep sea, and is thus worthy of attention from SCS Deep researchers. It is of interest to search whether the serpentinization process had ever taken place during seafloor spreading, and whether serpentinization exists or not in the deep lithosphere of the SCS. As shown by a recent study, the uppermost mantle can be magnetized by *in-situ* serpentinization caused by infiltration of seawater through large transform faults [109]. In the SCS, Curie isotherm is recently found to lie underneath the Mohorovicic discontinuity [110], hence raising the question whether the uppermost mantle here is also magnetized because of serpentinization. Before the origin of magnetism in the uppermost mantle is found, we need to investigate first the sub-surface liquid activities in the SCS and their impacts by testing against the above hypothesis [111]. As a frontier scientific issue in "Sub-Seafloor Ocean" studies, serpentinization deserves our closer attention [112].

Another source of energy and material fluxes at the sea bottom is the cold seepage which occurs along the subduction zone and at hydrocarbon leakage spots. When bottom sediments on the oceanic crust are subducting downward, water is squeezed out and returns back to the sea floor as cold seep. The seep contains methane if the original sediments are rich in organics, and its anaerobic oxidation produces carbonate deposits and supports cold seep biota [113]. On shallower continental slopes, dissociated gas hydrate spells out as cold seep, and similar processes with production of carbonate crust and cold-seep fauna, or mud volcanos on sea floor, may occur [114]. Besides, seepages of natural gas also provide a background for deep-water coral reef to develop [115]. China launched its exploration plan of gas hydrates more than a decade ago [116], and in 2002, carbonate crust samples were collected by dredging from ~1000 m water depth in the northeastern SCS [117]. In 2004, the joint Chinese-German RV SONNE Cruise 177 conducted a thematic survey on gas hydrates by targeting methane seep carbonate crusts and associated microbes in the NE SCS, and discovered a "Jiulong methane reef" [118, 119]. In March 2007, by applying ROV, scientists from Taiwan in collaboration with JAMSTEC of Japan discovered a chemosynthetic community at a cold seep site off SW Taiwan [120–122]. In May 2007, China drilled at sites in the NE SCS and recovered gas hydrate samples, which confirm the extensive presence of gas hydrate there [123,124]. In fact, hydrocarbon venting and mud volcanism have been reported from the northern SCS and Taiwan long time ago. Along with explorations, multidisciplinary investigations and on-site observations are needed to estimate the environmental impact of hydrocarbon venting on marine chemistry and biology.

One more area to investigate sub-seafloor fluid activities is the Manila Trench. As a window for active mass exchanges between the Earth's interior and its surface, the subduction zone is likened to "Subduction Factory" [125]. The Manila Trench is the deepest part (5500 m) of the SCS and the entry of its sudduction. There is no doubt in the role the Manila Trench plays in energy and mass fluxes in the SCS, on which the research activities should be kicked off as early as possible.

3.2 Deep biosphere and deep carbon reservoir

The hydrothermal and cold-seep environments are far below the photic zone with no light to support photosynthesis, and the life there has to rely on the energy and material of deep origin and to generate organics through chemosynthesis, making up the so-called "dark food chain". Thus, the clams, crabs and shrimps found at methane-venting cold seep sites from about 1000 m deep in the northeastern SCS remind those from hydrothermal environments, because both groups belong to the same chemosynthetic community [122]. We now know that the marine biosphere is dominated by microscopic rather than macroscopic organisms, and microbes comprise 90% of the total marine biomass, with the proportion increasing with water depth. various microorganisms thrive within the sediments under deep-sea floor and even inside the oceanic crust, constituting the so-called "deep biosphere" [126]. The largest ecosystem on the Earth is made up of these microbes living under extremely high pressure of the water column and supported by "dark energy", yet their recognition by human is just in the beginning [127].

During the past 5 years microbes in deep-sea sediments from the SCS have been actively investigated. These pioneering works mostly devote to reporting microbial diversity in surface sediments [128–132], with only a few also including comparisons between microbial assemblages from different water depths [133] or discussions on a specific group of microbes such as alkane degrading bacteria [134]. Nevertheless, cold seepage studies have examined the role of chemosynthetic microbes in carbonate formation [119]. These types of biochemical reactions need to be kept in mind in geological observations in the SCS, as they are not restricted to the modern cold seep and hydrothermal vent, but also extensively reported in paleo-records [135]. To sum up, the "sub-seafloor ocean" and "deep biosphere" with emphasis on methane genesis and oxidation, opens a new research filed in the deep SCS and presents challenges to further microbiological studies.

Closely associated with microbes is the deep-sea carbon cycling. Dissolved organic carbon (DOC) accounts for about 90% of the total organic carbon in the ocean, and refractory dissolved organic carbon (RDOC), resistant to bacterial degradation, makes up 90%–95% of DOC in the ocean and dominates in deep waters. Since RDOC remains inert in carbon cycling over millennia, it offers an alternative way for "carbon sequestration" [136]. The C-14 age of DOC in the modern ocean is measured to be a few thousands years in average, with the maximal values over 20 ka. A possible source of the old water is the deep biosphere. Aged inorganic carbon circulating through the crustal aquifer is synthesized by chemosynthetic microbes into organic matter using "dark energy". DOC produced this way has distinctly old C-14 age and exports from seafloor into the ocean with circulating water from the "sub-seafloor ocean", providing a major source of old DOC in the ocean (Figure 8) [137]. Old DOC over 10 ka in age has been reported from a cold seepage off Vancouver Island [138], NE Pacific, from a low-temperature hydrothermal vent on ridge-flank off Juan de Fuca spreading ridge [139], and from deep-water hydrocarbon seepage in the Gulf of Mexico [140].

As discovered by ocean drillings, the microbial metabolism is extremely slow in the "deep biosphere" [141,142], and the water circulation is extremely sluggish in the "sub-seafloor ocean" [143]. In result, the deep-sea carbon cycling, controlled by microbes and DOC, is by several orders of magnitude lower than in the upper ocean, and therefore remains a common loophole in all carbon cycling models of current studies on global change. ODP Leg 184 to the SCS has discovered a long-term cyclicity of 400–500 ka in foraminiferal carbon isotope records [144,145], which suggests that organic carbon in the oceanic carbon reservoir may be subject to long-term variations across several glacial cycles, probably related to the processes in the deep biosphere discussed above. Over the decades, the deep sea carbon cycle has been studied mostly in terms of inorganic carbon, i.e. carbonates, but the stable isotope records have revealed significant variations also in the organic carbon reservoir. As a marginal basin, the SCS is a suitable place to integrate observations of deep-water groundwater, microbes

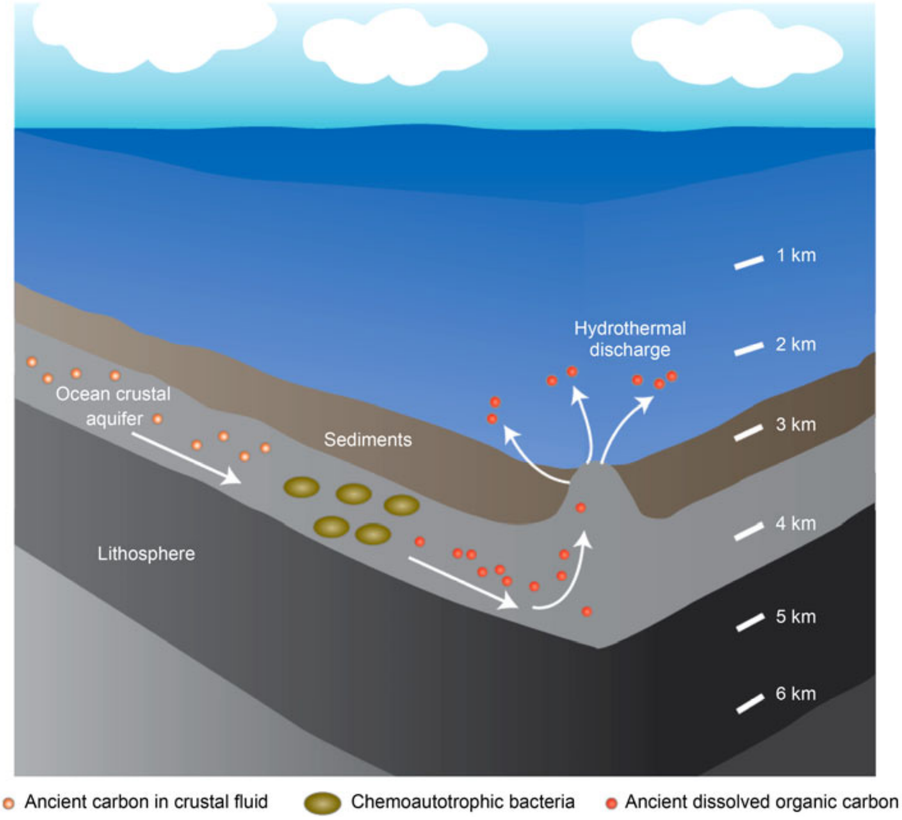

Figure 8 A diagram showing hydrological flow of water and generation of "old DOC" in the oceanic crustal aquifer [137].

and carbon cycling, to compare geological records with numerical simulations, and finally to explore the mechanism of the deep sea carbon cycling.

The above discussions address microbiology and geochemistry in the SCS from three aspects: the sub-seafloor ocean, the deep biosphere and gas hydrates. In other words, the biogeochemical processes in the deep sea below and above its bottom are to be investigated, and the research object is the "blood" in the life history of a marginal sea. This part of the program covers many new research fields and has challenging but promising perspectives. By focusing on methane genesis and oxidation, for example, microbiology is an interdisciplinary endeavor of Life and Earth sciences in the deep sea.

4 Evolution of marginal sea and sea-land interaction

The three parts of the SCS Deep program discussed above—basin evolution, sediment response and deep-sea biochemistry, are self-sustaining but interconnected topics combined to explore the life history of a marginal sea. This is believed to be an efficient approach to understanding not only marginal seas themselves but also the interactions between land and sea. The scientific merits of the SCS Deep program, therefore, are to be considered from these two aspects.

4.1 Comparative life histories of marginal seas

The Major Research Program "Deep Sea Process and Evolution of the South China Sea" is to explore the life history of a marginal sea. Among the three parts of its science plan, the tectonic evolution of the basin from seafloor spreading to plate subduction comprises the "skeleton" of the program, the deep-sea sedimentation process and basin filling make up its "flesh", and the deep sea biogeochemical processes provides its "blood". The evolution process of the SCS deep basin will be reconstructed from the view point of interactions between litho-, hydro-, and bio-spheres, and its impacts on resource formation and environment changes will be estimated (Figure 9). The program targets on 8 key scientific questions: (1) Age and process of seafloor spreading; (2) time and cause of the volcanic seamount chain activities; (3) response of the deep sea sedimentation process to sea basin evolution; (4) variations of bottom circulation and sediment transport mechanism; (5) development and effect of carbonate platforms; (6) distribution and effect of submarine overflows and down-hole fluids; (7) Deep sea carbon cycle and the role of microorganism; and (8) Biogeochemical background of deep sea energy resource formation. As the first China's large-scale basic research program in ocean

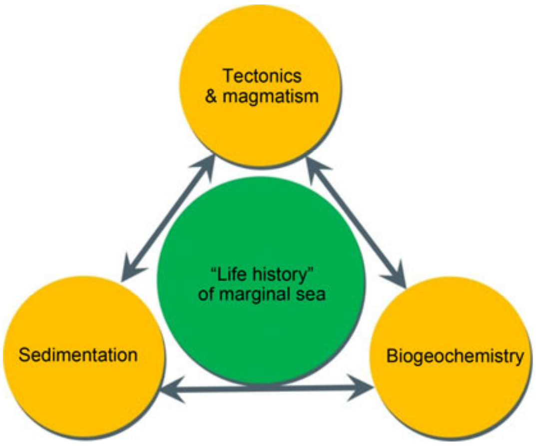

Figure 9 Three major parts of the Major Research Program "Deep Sea Processes and Evolution of the South China Sea" (the SCS Deep) supported by the National Natural Science Foundation of China (NSFC).

science, the SCS Deep endeavors to bring together scientific communities of various affiliations in the country to enhance China's contributions to scientific understanding of the SCS.

Compared to the open ocean, the marginal sea is much more closely related to the human society, and there is a more pressing need for scientific understanding of marginal seas because of their resources and environmental effects. Since the SCS is the largest low-latitude marginal sea on Earth, its life history offers a particular scientific interest. The southern part of the SCS is located in the Western Pacific Warm Pool which gives rise to three major divergent atmospheric circulations and hence acts as the centre of energy flow on the Earth's surface. The region of the southeast part of Asia, including the SCS, is the largest source of terrigenous suspended sediment supply to the global ocean, and hence functions as the global centre of material flow. This region is also labeled the "East Indies Triangle" marked by highest biodiversity both for its marine and terrestrial assemblages, and thus can be considered as the centre of genetic flow on the Earth [53]. Therefore, the SCS enjoys a number of advantages in its life history studies relative to other marginal seas.

The Gulf of Mexico shares many aspects of similarities with the SCS, such as the semi-enclosed sea basin with oceanic connection to the east, broader shelf in the north and south than in the west, and well ventilated deep waters. Comparatively, the Gulf of Mexico is smaller in size (1.6 million km^2) and shallower in depth (maximum 3800 m) with submarine sill depths of 1500–1900 m and deep water renewal time of 250 years [146,147]. The Gulf of Mexico has a tremendous amount of offshore hydrocarbon resources, and voluminous geological data have accumulated mainly through petroleum and gas hydrate exploration over decades. However, the Gulf of Mexico has an opening history in the Mesozoic basin, which is much older than the SCS, and its multi-kilometer thick sediment cover makes direct access to the basement very difficult. This is why the age of its oceanic crust and the driving force of the basin opening remains a mystery even today [148,149]. Despite of the fact that the Gulf of Mexico is the best and the most investigated marginal basin in the world, and the DSDP was inaugurated in this basin in 1968, its history as of a marginal basin is not at all easy to reconstruct.

The Sea of Japan is the most investigated marginal basins in the West Pacific. The opening of the Japan Sea started in 20–25 Ma and ended in 12 Ma, which is younger than the SCS. The three ocean drilling legs to the Sea of Japan and the exposure of marine deposits in the surrounding islands have rendered excellent conditions for reconstructing its history [150,151]. Compared to the SCS, however, the Japan Sea suffers from its greater isolation, with a smaller size (~1 million km^2), shallower depths (maximum 4000 m), and a sill depth of only ~100 m. Due to a higher-latitude position, surface water in the Sea of Japan partially freezes in winter and sinks in its northern part to form deep water near 0°C, which is unfavorable for carbonate preservation including foraminiferal tests. In addition, the sedimentation rate in the Japan Sea is low because of the absence of large river input, and its bottom sediments with less than 10% of $CaCO_3$ are also less promising in preservation of geological records of its evolution [152]. In brief, the poor preservation of sediment records is an intrinsic disadvantage for life history reconstruction of the Japan Sea.

Compared to other marginal seas, the SCS possesses a number of merits in preserving its history record, and as such a systematic integrated study on its history is promising in setting up an example for marginal sea studies worldwide.

4.2 Evolution of Interactions between Asia and Pacific

The significance in reconstructing the history of the SCS goes far beyond the marginal sea itself. Located between continent and ocean, a marginal sea is an interface of sea-land interactions. One of the outstanding features of the modern world geography is having a series of marginal basins sandwiched between the largest continent and the largest ocean, namely the Okhotsk Sea, the Japan Sea, the East and South China Seas between Asia and the Pacific. The development of the marginal seas has caused large changes in material and energy fluxes between continent and ocean, as clearly illustrated from a comparison between the Pacific and Indian Oceans. East and South Asia together contributes 70% terrigenous suspended sediment to the global ocean. The sediment input has helped the build-up of huge deep-sea fans in the Indian Ocean without marginal seas, but the extensive continental shelves in the above-named marginal seas in the western Pacific. As the largest marginal sea off the Asian coast, the SCS supplies valuable archives through its life history to trace back the evolution of sea-land interactions.

The transition from active to passive margin was the most radical change in Asia-Pacific interactions and has exerted far-going influence on both the continent and the ocean. Over decades, researches on deformation of the East Asian continent have mostly focused on its western side, i.e. uplift of the Tibetan Plateau, but overlooked the role of the Pacific on the eastern side. It remains unclear how the western Pacific margin was transformed from the mountainous Andean-type coasts in the late Mesozoic to the series of marginal basins in the late Cenozoic. The transition from Mesozoic subduction and transpression to Cenozoic breakup and transtension must have its profound environmental impact on East Asia and the Pacific, even the global climate, although this research area is largely beyond the scope of our program. During the Cenozoic, the topography in China has reversed from West-tilting to East-tilting. To understand this topographic reversal we should consider not only the India-Asia collision and the Tibet uplift, but also the change of the Pacific Plate. Once the SCS Deep program facilitates integrating land-based with offshore researches and correlating and understanding better the records of river system reorganization in East Asia and marine basin evolution in the Pacific together with changes in deep lithosphere, it will lead to a breakthrough in our studies of the evolution of sea-land interaction in the western Pacific.

The development of the marginal basins has also reorganized the ocean circulation in the western Pacific, as well as the regional climate. The present oceanographic feature in the North Pacific marked by the flow of two western boundary currents, i.e. the Kuroshio and the Oyashio, through several marginal seas to mix there with large river runoff from Asia, is geologically new. Before the Middle Miocene, the equatorial Pacific water was running directly into the Indian Ocean; and by the end of Miocene, the East China Sea was still connected to the SCS until the emergence of Taiwan island as a result of island-continent collision. Correspondingly, the early Kuroshio Current had a much weaker intensity and a very different route relative to it is today. Therefore, two modes of sea-land interactions exist in the western Pacific depending on whether or not the western boundary current flow through marginal seas, and they may have exerted different climate consequence through different air-sea exchanges. The birth and strengthening of the summer monsoon and cyclones or typhoons are largely related to enhanced sea surface temperature in the SCS and the Philippine Sea. However, the influence of marginal seas not only comes from the surface ocean but also from the deeper part, as the voluminous semi-enclosed modern SCS serves as the western terminal of the subtropical North Pacific Intermediate Water [153]. Therefore, new research topics will emerge if the SCS evolution is approached from the broader aspect of sea-land interactions.

5 Concluding remarks

The deep-sea process study is at the international research frontiers. The US government has launched its OOI program with a budget of ~300 million US dollars to set up seafloor observation systems for long-term real time observation of the deep-sea processes. The ocean drilling program, which was initiated in 1968, is striding towards a new phase of scientific drilling and research [112]. Within the Earth system science, the deep-sea process is a new element and the research is just at its beginning, but it is a vital element that plays and has played a crucial role in the Earth system. Whenever the seafloor spreads or plate subducts, there is fluid venting from the sea bottom that modifies the seawater composition and supports specific deep-sea lives. Plate tectonics may lead to reorganization of the surface and bottom currents through topographic changes, and consequently influence the transport and deposition of terrigenous particles. All incoming fluids and particles, no matter from sub-seafloor or from the land, exert their influence on microbial life above or below the sea bottom and finally cause changes in the deep sea carbon cycling. A research program combining the modern deep-sea process and geological records of a marginal sea will be scientifically highly promising. By dissecting this particular case, the program will be able to reveal the evolution patterns of the marginal basin and their effects on submarine resources and macro-environment development. Among the world’s marginal seas, the SCS is the best candidate for implementing such a program.

The SCS has long been the focus of China’s deep-sea investigations. From its northern slope, deep-sea gas was discovered in 2006, and gas hydrate was recovered in 2007. On the other hand, the 1991 volcanic eruption in the Philippines and the earthquake to the South of Taiwan at the end of 2006 underscored the urgent need in safety assurance around the SCS. Thanks to the ODP cruise to the SCS in spring 1999 and the subsequent research, as well as the numerous domestic and international expeditions, the SCS has now become a scientific focus of international deep-sea studies. Currently, deep-sea research is on the agenda of various governmental agencies and industries in China, and the development of deep-sea science and technology has become a priority. The SCS Deep program will provide a link with other research endeavors in the region, and actively support international collaborations. It is our sincere wish that the SCS Deep program will lead to research breakthroughs and contribute greatly to the international ocean science.

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