OCEAN DRILLING PROGRAM

LEG 184 PRELIMINARY REPORT

SOUTH CHINA SEA

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SCIENTIFIC REPORT

ABSTRACT

The Asian monsoon system is a major component of both regional and global climate. Evolution of monsoonal climates in southern Asia is linked to the growth of the Himalayan-Tibetan orogen, the opening and closing of marginal seas, and changes in global climate. The location of the South China Sea (SCS) between East Asia and the “maritime continent” is ideal to record the paleoceanographic responses to both winter and summer monsoons. The broad scientific themes of Leg 184 were (1) to document the Cenozoic history of the SCS, including its biostratigraphy, lithostratigraphy, chronology, paleoclimatology, and paleoceanography; (2) to reconstruct the evolution and variability of the East Asian monsoon during the late Cenozoic on millennial, orbital, and tectonic time scales; and (3) to identify and better understand the links between tectonic uplift, erosion and weathering, hemipelagic deposition, and climate change, including the evolution of the Asian monsoon and Neogene global cooling. The Leg 184 shipboard party cored 17 holes at Sites 1143–1148 in the SCS and recovered 5463 m of sediment that will enable the study of these themes, meeting the mission objectives beyond expectations. Core recovery averaged 83%–101%; all sites (except 1148) were triple cored with the advanced hydraulic piston corer and partially double or triple cored with the extended core barrel to construct continuous stratigraphic sections at the meters composite depth (mcd) scale. At all sites the hemipelagic deposits are rich in calcareous microfossils. The suite of sites yields an almost continuous record of the environmental history of the South China Sea during the last 30 m.y.

Site 1143 is located in the Spratly Islands area of the southern SCS at a water depth of 2772 m. It yielded a 516-m-long composite section recording the depositional history of the last ~10 m.y., with linear sedimentation rates (LSRs) of 3–7 cm/k.y. and mass accumulation rates (MARs) of 3–10 g/cm^2/k.y. Sites 1144 through 1148 are located on the northeast continental slope of the SCS. Site 1144 provided a 522-m-long composite section from a sediment drift at a water depth of 2037 m, spanning the last 1 m.y. and yielding a very high LSR (30–110 cm/k.y.) and MAR (25–140 g/cm^2/k.y.). At Site 1145, a 213-m-long composite section representing the last 3 m.y. was recovered from a water depth of 3175 m, with LSRs of 4–25 cm/k.y. and MARs of 4–19 g/cm^2/k.y. Site 1146, at a water depth of 2092 m, recovered a 645-m-long composite section representing a 19-m.y. record and yielding LSRs of 2–36 cm/k.y. and MARs of 2–23 g/cm^2/k.y. Site 1147 is a short record (85 mcd) recovered only 0.4 nautical miles from Site 1148 and designed to recover the top interval missing at Site 1148. Site 1148 recovered a 861-m-long composite section from a water depth of 3294 m, spanning the last 30 m.y. The LSR is 1–2 cm/k.y. for the Miocene to mid-Pliocene, up to 20 cm/k.y. for the late Pliocene and Pleistocene, and up to 30 cm/k.y. for the Oligocene. The high accumulation rate (5–20 g/cm^2/k.y.) of Oligocene sediments on the lower continental slope near the continent crust margin probably reflects active downslope transport of terrigenous sediments during the early stage of seafloor

spreading of the South China Sea basin. If the acoustic basement was penetrated at ~800 meters below seafloor (mbsf), the sediments indicate that a deep-water sequence continues below the bottom of the hole and might be a thick marine Paleogene section. A second possibility is that the acoustic reflector was not penetrated in the cored interval and the nature of the acoustic basement is unknown.

The depositional history of the late Cenozoic in the northern slope had three important stages: an Oligocene interval with extremely high sedimentation rates, a Miocene and early Pliocene interval with lower sedimentation rates and high carbonate content, and an interval of the last 3 m.y. with high clastic sediment accumulation rates. A different trend of depositional history is indicated at the southern Site 1143, where carbonate accumulation decreased from the late Miocene toward the late Pleistocene and the noncarbonate accumulation has risen again for the last 3 m.y. However, the upper Miocene sediments were similar in composition between the northern and southern sites, containing more than 50% of carbonate. The Oligocene/Miocene boundary in the northern SCS (Site 1148) is marked by sedimentary deformation, abrupt lithologic changes, and a stratigraphic hiatus (~24–27 Ma). These related features will help resolve the nature and timing of one of the most significant Cenozoic tectonic and climatic changes of the region. A general increase of noncarbonate sediment accumulation after 2–3 Ma was found at all drill sites, and for the northern sites the increase becomes even more significant in the latter part of the last million years. Excellent orbital-scale cyclicity is displayed in color reflectance, natural gamma radiation, magnetic susceptibility, and bulk density, particularly for the Pliocene–Pleistocene intervals.

INTRODUCTION

The Shipboard Scientific Party of Leg 184 sought to better understand the history and variability of the Asian monsoon system, which is a major component of the regional climate of Asia as well as of global climate. Evolution of monsoonal climates in southern Asia is linked to the growth of the Himalayan-Tibetan orogen, the opening and closing of marginal seas, and changes in global climate, including atmospheric CO_2 levels. The South China Sea (SCS) experiences both summer and winter monsoons, and its sediments record the erosion and weathering of tectonic orogens as well as changes in global and regional climate. Hence, Leg 184 was designed to recover sediment sections in the southern and northern SCS to provide records capable of unraveling both the regional and global climate changes on a variety of time scales ranging from millennial to tectonic.

The circulation patterns of the Asian summer and winter monsoons dominate the seasonal patterns of winds, precipitation, and runoff and determine, in part, the character of land vegetation over southern and eastern Asia (Hastenrath, 1991; Hastenrath and Greischar, 1993; Webster, 1987; Webster, 1994; Webster et al., 1998, Lau and Yang, 1997). The winter monsoon is characterized by continental cooling and development of high pressure over northern Asia, northeast winds across the South China Sea (which intensify during cold surges), and increased rainfall in the Austral-Asian equatorial zone (Fig. 1A, 1C). Similarly, northwest winds are found in the Indian Ocean, although they are not accompanied by cold surges. The summer monsoon circulation is characterized by continental heating, the development of low pressure over Tibet, and southerly winds across all of southern Asia. In the South China Sea, the summer monsoon is marked by moderate (5 m/s) southerly winds, weak to moderate upwelling off Vietnam, and high precipitation over southern and eastern Asia (Fig. 1B, 1D). In contrast, the summer monsoon exhibits strong (10 m/s) southwesterly winds and intense upwelling in the Arabian Sea. The location of the South China Sea between East Asia and the maritime continent is ideal to record the paleoceanographic responses to both winter and summer monsoons (Figs. 1, 2).

TECTONIC FRAMEWORK OF THE SOUTH CHINA SEA

Among the continents of the world, Asia has been subjected to the most significant Cenozoic deformation. The Cretaceous–Paleocene topography of China was generally tilted to the west, with the coastal areas of the Tethys in the west, a trans-Himalayan volcanic arc in the southwest, and relatively high land and endoreic basins in the east. These conditions lasted until the late Eocene when India collided with Asia, thereby bringing the maritime climate in western China to an end. Although some argue for a Cretaceous plateau with as much as 3 km elevation (Harrison et al., 1998), other studies indicate that uplift of the Tibetan Plateau began ~21–20 Ma (Copeland et al., 1987; Harrison et al., 1991, 1998) and was accompanied by a general subsidence of eastern China. Still other studies (Molnar et al., 1993) argue for a late Miocene (10–8 Ma) rapid uplift of the Tibetan Plateau from a low or intermediate level to its maximum elevation (>5 km) and subsidence to its current elevation (~4 km). These surface uplift changes reversed the topographic gradient in China from west tilting to east tilting. Subsequent tectonics have maintained or increased the west-east gradient, and some geologists and geomorphologists believe that the Tibetan Plateau was uplifted only 2–3 m.y. ago (e.g., Li, 1991).

Coincident with the large-scale deformation of Asia, many of the marginal seas in the western Pacific were formed during the early Miocene. One model links the opening of the SCS basin with the Red River fault zone, which has at least 500 to 600 km of left-lateral displacement created during the Oligocene and Miocene (Schärer et al., 1990; Briais et al., 1993). Alternative models relate the opening of the SCS to subduction under Borneo (Taylor and Hayes, 1983) and the influence of subduction beneath the Philippines, driving a backarc type of extension in the over-riding plate (Taylor and Hayes, 1980). The deep-water, rhomboid-shaped Central Basin is underlain by oceanic crust (Fig. 3A), which contains a sequence of seafloor-spreading magnetic anomalies ranging from 32 (magnetic Anomaly 11) to 16 Ma (Anomaly 5c), with a southward ridge jump at ~27 Ma (Anomaly 7/6b) (Briais et al., 1993). The slopes of the SCS contain numerous coral reef terrains, including the Nansha Terrain (Reed Bank and Dangerous Grounds) and the Xisha-Zhongsha Terrain (Macclesfield Bank and Paracel Island), which may have rifted southward during the opening of the SCS (Jin, 1992).

The structure of the northern SCS margin has been extensively studied through oil exploration and geophysical studies to determine the amount of crustal extension during formation of the SCS (e.g., Hayes et al., 1995a, 1995b). The shelf basins on the SCS contain >4 km of Cenozoic deposits that have been drilled by petroleum companies (Ru et al., 1994). The present shape of the SCS is also closely related to the rotation history of the Philippine Sea Plate to the east and the ongoing collision with the Australian Plate to the south (Packham, 1996). The counterclockwise rotation of the Philippine Sea Plate led to the arc-continent collision of the Luzon Arc with the underthrusting Eurasian Plate since 6.5 Ma (Huang et al., 1997), giving rise to the formation of Taiwan Island and the Bashi Strait. Both the collision processes have enhanced the enclosed nature of the SCS.

EVOLUTION OF ASIAN MONSOONAL CLIMATES

Evolution and variability of the Asian monsoon system are thought to reflect at least five types of large-scale climate forcing or boundary condition changes, including (1) the tectonic development of the Himalayan-Tibetan orography, (2) changes in the atmospheric CO_2 concentration, (3) changes in the Earth’s orbit that result in periodic variations of seasonal solar radiation, (4) changes in the extent of glacial climates, and (5) internal feedbacks within the climate system. These factors act simultaneously and over different time scales to amplify or lessen the seasonal development of continental heating/cooling, land-sea pressure gradients, latent heat transport, and moisture convergence, all of which control the strength of the monsoon circulation.

The impact of elevated orography on atmospheric circulation provides an explanation for the initiation, intensification, and long-term (10^6 yr) evolution of the Asian monsoon system (Ruddiman, 1997). Before the collision of India with Asia at ~55–50 Ma, the Himalayas and Tibetan Plateau were not the dominant orographic features of Asia, and the continent was not as large. The smaller size and lower elevations of precollision Asia and the greater extent of epicontinental seas would have resulted in lower land-sea heating contrasts, especially because of the reduced role of sensible heating over the plateau and the condensational heating over and on the flanks of the Himalayan-Tibetan Plateau Complex (HTC). Model studies suggest that the plateau must be at least half its present elevation to induce a strong monsoon circulation (Prell and Kutzbach, 1992). During the summer monsoon, the major orographic impact is thermal and results from the tendency of higher elevation to increase both sensible and latent heating of the mid-troposphere, leading to stronger monsoon circulation. During the winter monsoon, the mechanical effects of high orography, such as blocking and directing low-level winds and the development of cold surges, are the major orographic impacts of the HTC. The thermal impacts are thought to be relatively small (Murakami, 1987). The location of the South China Sea, with active winter and summer monsoons, provides an ideal site to study the seasonal monsoon system, especially the evolution of the winter monsoon and its relationship to the development of the loess plateau in central China (Ding et al., 1998).

The coincidence of high relief, southerly and easterly sloping topography, and abundant monsoon rainfall has resulted in large river systems, which discharge enormous amounts of sediment onto the coastal plains and the continental shelves and slopes of the Southeast Asian marginal seas. Prior Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) sites on the Ganges and Indus Fans have found clastic deep-sea fan sedimentation in the lower Miocene and Oligocene, which gives a minimum age for Himalayan-type erosion and transport. Although these fan sediments may be related to monsoon runoff (Cochran, 1990), they do not reflect the onset of clastic deposition from the Asian continent, which is likely to have begun with the earliest collisional arcs. In the upper Miocene, both marine and terrestrial data indicate a major intensification of the Indian monsoon around 8 Ma (Prell et al., 1992, and references within; Molnar et al., 1993; Prell and Kutzbach, 1992). However, the significance of clastic accumulation rates at this time is unclear, and various explanations invoke changes in tectonic, climatic, and sea-level conditions (Rea, 1992; Derry and France-Lanord, 1997, Prell and Kutzbach, 1997). The SCS sediments provide additional combinations of these processes and should help constrain the monsoon-related responses to tectonic forcing.

A variety of observations has suggested that CO_2 levels were higher during the Tertiary and may have been equivalent to double the present CO_2 levels at ~20 Ma (see Kump and Arthur, 1997, and other papers in Ruddiman, 1997). Higher CO_2 levels might be expected to strengthen the summer monsoon through increased land-sea contrasts and more active hydrologic budgets but might also weaken the winter monsoon through warmer continents. The Neogene decrease in CO_2 has also been linked to uplift of the Tibetan Plateau and late Cenozoic global cooling (e.g., Ruddiman and Kutzbach, 1989; Raymo et al., 1988) through long-term increased chemical erosion in rapidly uplifted areas that reduce atmospheric CO_2 (Raymo, 1994) and thereby cool the planet, enabling widespread glaciation. Other studies have linked the decreased CO_2 to uplift, erosion, and carbon burial in clastic deep-sea fans (Derry and France-Lanord, 1997). In either case, evolution of the Asian monsoon and global cooling may well be related. Lower atmospheric CO_2 is also proposed as the cause of global-scale changes from C_3- to C_4-type vegetation at ~7 Ma (Cerling, 1997) (see Fig. 4). This vegetation shift also has implications for monsoonal processes related to soil moisture, albedo, and carbon cycling (Cerling, 1997). Hence, the late Neogene trend toward lower CO_2 may covary with stronger winter monsoons and weaker summer monsoon hydrologic cycles.

Superposed on the tectonic and CO_2 trends are orbitally induced, periodic variations in the seasonal and meridional distribution of solar energy over the Earth’s surface. The variations associated with obliquity and precessional cycles can change the seasonal radiation budget over the Tibetan Plateau by as much as +12.5% (relative to modern values of 450 W/m^2) (Laskar et al., 1993; Berger and Loutre, 1991). Numerous studies of Indian Ocean and western Pacific sediments have documented that certain monsoon indicators (upwelling fauna, productivity, dust particle size, and vegetation types) vary coherently with these orbital periodicities, especially the 23 k.y. (Prell, 1984a, 1984b; Clemens and Prell, 1990, 1991a, 1991b; Clemens et al., 1991, 1996; Morley and Heusser, 1997; Schultz et al., 1998). However, the variation of monsoonal indices is not always in direct proportion or in phase with the apparent solar forcing. These phase differences indicate that other processes within the climate system are influencing the timing and amplitude of maximum monsoon responses. We expected that the phase of monsoonal responses in the SCS, especially Sites 1143,1144, and 1146, would provide high-quality records of orbital-scale variations and new constraints on the relative importance of orbital forcing and internal feedbacks to East Asian monsoonal variability.

The monsoon system is also affected by the general state of the Earth's climate, especially the extent of glacial-age surface boundary conditions, which include lowered sea levels, continental-scale terrestrial ice sheets and large areas of sea ice, lowered sea-surface temperatures, lowered CO_2, and differing vegetation and land-surface characteristics (CLIMAP, 1981; Prell and Kutzbach, 1987, 1992). In general, more extensive glacial conditions tend to weaken the summer monsoon circulation (Clemens et al., 1996), although certain glacial intervals do have strong monsoons (Clemens and Prell, 1991a, 1991b). In the SCS, studies indicate that increased upwelling during the Last Glacial Maximum (LGM) may reflect a stronger winter monsoon circulation. Also, the emergence of the maritime continent during intervals of lower sea level may affect the regional dynamics of the East Asian monsoon.

A synthesis of Cenozoic terrestrial data from China (e.g., Liu and Ding, 1993; Wang, 1990) has led to the development of a four-stage model of East Asian monsoon evolution: (1) a premonsoon stage (Paleocene and early Eocene), (2) a transitional stage (middle Eocene to Oligocene), (3) a monsoon Stage I (Miocene and Pliocene), and (4) a monsoon Stage II (late Pliocene [2.4 Ma] to present) (Fig. 5; Wang, 1997).

The Paleocene (premonsoon stage) is characterized by a broad east-west–trending arid zone traversing all of China (Fig. 5). This is similar to the Late Cretaceous environmental pattern, when evaporitic endoreic basins accumulated thousands of meters of halite- and gypsum-bearing deposits in the middle and lower reaches of the Changjiang (Yangtze) River, a region that is humid today. The subsequent middle–late Eocene and Oligocene transitional stage was characterized by variable, weak summer monsoons that brought moisture to the otherwise dry areas, which created favorable conditions for nonmarine oil accumulation in China. Beginning in the Neogene, however, palynologic, paleobotanic, and lithologic data indicate that the climate pattern in China underwent a profound reorganization (Wang, 1990; Sun and Wang, pers. comm., 1998). During the Miocene monsoon Stage I, the arid zone retreated to northwest China, and eastern China became more humid (Fig. 5) as the southeast summer monsoon strengthened and brought moisture from the sea. This general regime has existed from the Miocene to the

Holocene. The intensification of the winter monsoon in eastern Asia is thought to have occurred much later and to have marked the beginning of deposition of the Chinese loess deposits at ~2.4 Ma (monsoon Stage II; An et al., 1990). However, some recent studies suggest that the eolian component of the loess red-clay sequence may be as old as 7 Ma (Ding et al., 1998), which would have implications for the tectonic vs. glacial initiation and intensification of the winter monsoon.

A primary goal of Leg 184 was to understand the relative importance of these complex "causal" factors in the initiation, evolution, and variability of the Asian monsoon system. In short, we sought to decipher the coevolution of tectonic uplift of the HTC, the Neogene changes in global climate, and the development and variability of the Asian monsoon circulation.

SEDIMENTS OF THE SOUTH CHINA SEA

The sedimentary basins of the northern shelf show a two-layer structure, with the lower section characterized by half-grabens formed during Paleogene rifting and filled with nonmarine sequences. The upper section is typified by a wide range of terrigenous and marine sediments deposited during the Neogene subsidence of the margin (Fig. 6; Ru et al., 1994). However, reworked Paleocene and Eocene marine microfossils in the Neogene deposits from the northern shelf indicate that marine intervals existed earlier in this area. Paleocene deltaic and Eocene marine sediments have also been found in the southern part of the SCS, such as the Liyue Bank (Reed Bank) Basin, where carbonate deposition began in the middle Oligocene (ASCOPE, 1981; Jin, 1989). In the northern SCS, the Pearl River Mouth Basin (PRMB) has been extensively studied and is close to our core sites. More than 150 wells have been drilled on the shelf, and a detailed stratigraphy has been established for the marine sequence from the uppermost Oligocene to Pleistocene on the basis of planktonic microfossils (e.g., Huang, 1997). The composite stratigraphy of the PRMB documents a marine sequence from the upper Oligocene (NP23/24) to Holocene (NN20) (Jiang et al., 1994; Wu, 1994; Huang, 1997). In the PRMB, seismic reflectors have been correlated with depositional hiatuses near the Oligocene/Miocene boundary, in the lower part of the lower Miocene, near the end of the middle Miocene (T_3, 10.2 Ma), near the Miocene/Pliocene boundary (T_2, 5.2 Ma), and around the Pliocene/Pleistocene boundary (Wang, 1996; L. Huang, pers. comm., 1998). Unfortunately, the reflector terminology differs between groups, and the type sections are not correlated with our site. The distribution of wells also indicates that the nonmarine intercalations in the northern part of the basin decrease in volume and thin southward toward the slope.

The modern sediments in the SCS consist mainly of terrigenous material (biogenic carbonate and opal) and a small portion of volcanic material. Clastic sediments are discharged from the Mekong, Red, and Pearl Rivers. However, during the past glacial intervals, the paleo-Sunda River system may have contributed large amounts of sediment to the SCS. Recent sediment trap studies in the northern SCS (Jennerjahn et al., 1992) have shown that the highest particle fluxes occurred during the winter monsoon and are correlated with high wind speed rather than riverine-transported sediments. These data indicate that suspended matter from the East China Sea and the Pacific might be major sediment sources for the northern SCS. The combination of high terrigenous input and the depth (3500 m) of the modern carbonate compensation depth (CCD) blankets the extensive continental slopes of the SCS with hemipelagic sediments, whereas the deep-sea basin is covered by abyssal clay (Su and Wang, 1994). Biogenic carbonates are found around coral reef islands, especially in the southern areas. The accumulation of carbonates in the SCS exhibits two patterns during the late Quaternary. The “Atlantic” pattern, found above the lysocline, has high carbonate during interglacials and low carbonate in glacial phases and is primarily driven by terrigenous dilution. The “Pacific” pattern, found below the lysocline, has low carbonate during interglacials and high carbonate during glacials and is driven by carbonate dissolution on the seafloor (Bian et al., 1992; Thunell et al., 1992; Zheng et al., 1993; Miao et al., 1994; Wang et al., 1995).

PALEOCEANOGRAPHY OF THE SOUTH CHINA SEA

Despite the importance and interconnections of the East Asian and Indian monsoons, few marine-based studies have compared the past monsoonal variations of the two subsystems. Previous ODP studies have focused on the Arabian Sea monsoon (Prell, Niitsuma, et al., 1991; Prell et al., 1992, and references within) and on the Sulu Sea to the south of the South China Sea. Many of the East Asian and South China Sea paleomonsoon studies have used traditional and long piston cores to focus on the late Quaternary climate changes. During the Last Glacial Maximum, sea-level lowering greatly altered the configuration and area of the western Pacific marginal seas. The three major shelf areas that emerged during the LGM (East China Sea Shelf, Sunda Shelf [the Great Asian Bank], and Sahul Shelf [the Great Australian Bank]) amount to 3,900,000 km^2, which is comparable in size to the Indian subcontinent. The SCS lost half of its surface area (>52%) as a result of shelf exposure, which changed its configuration into a semi-isolated basin (Wang et al., 1997). Moreover, the most extensive shelf area of the SCS is located in the modern Western Pacific Warm Pool bounded by the 28°C surface isotherm. The reduction in size must have profoundly influenced the thermodynamic role played by the Global Warm Pool.

The central portion of the SCS experienced a considerable decline in the sea-surface temperature (SST) during the LGM. Large decreases in the winter SST in the western Pacific marginal seas and especially in the SCS (Wang and Wang, 1990; Miao et al., 1994; Wang et al., 1995; Chen et al., 1999) are interpreted to indicate that the winter monsoon strengthened, the polar front shifted southward, and the Kuroshio Current migrated eastward. Together with the negligible changes in the summer SST, the South China Sea experienced a much higher SST seasonality during the LGM (Wang et al., 1999). An important consequence of the glacial conditions in the SCS region is the intensified aridity in China. The summer monsoon is the main source of water vapor for rainfall in East China (Chen et al., 1991), and changes in shelf emergence, SST decline, and land-sea heating patterns must have led to a reduction of vapor transport to southern Asia. A rough calculation suggests that the reduction in evaporation from the SCS during the LGM could correspond to one-eighth to one-fourth of the annual precipitation in all of China (Wang et al., 1997). The glacial reduction in water vapor transport helps to explain the intensification of aridity in the China hinterland as evidenced by the extensive distribution of loess deposits. Moreover, the glacial increase of seasonality in the marginal seas may help resolve the tropical paleoclimate enigma in the Pacific; that is, the discrepancy between marine and terrestrial indicators of paleotemperature during the LGM (Stuijts et al., 1988; Anderson and Webb, 1994).

Studies of the late Quaternary have demonstrated the great potential of the SCS’s hemipelagic sediments to provide high-resolution paleoenvironment records. A core from the northern SCS (SONNE95-17940) reveals a highly detailed transition from glacial to Holocene conditions (Fig. 7; Wang et al., 1999). The LGM and isotope Stage 3 are characterized by low fluvial clay content (50%–60%) and high modal grain size (10–25 µm), whereas the Holocene is marked by high clay content (>70%) and low modal grain size (<6.3 µm). These data are interpreted to indicate a strong winter monsoon and weak summer monsoon precipitation during the glacial regime and a strong summer monsoon and weakened winter monsoon during the Holocene regime. However, with lowered sea level during glacials, a large subareal sediment source is exposed in the shelf of the East China Sea. Deflation and transport of these sediments to the South China Sea during glacials is another possible explanation for the coarser particle sizes. The δ^{18}O data from the mixed-layer planktonic foraminifer *Globigerinoides ruber* reveal numerous short-term light δ^{18}O events superimposed on the main pattern of glacial–postglacial change (Fig. 7). These events appear to reflect increases in summer monsoon intensity (i.e., reduced sea-surface salinity together with increased input of fluvial clay and decreased modal grain size). The increases in summer monsoon intensity can be correlated with Dansgaard-Oeschger Events 1–10 in the GISP2 ice core (Fig. 7). Also observed in this SCS core are four periods of relatively heavy δ^{18}O associated with low fluvial clay content and larger grain size (i.e., reduced summer monsoon rainfall and increased winter monsoon wind, which correlate with the Heinrich Events 1–4 (Fig. 7). The early Holocene/Preboreal summer monsoon maximum revealed by a broad δ^{18}O minimum and fluvial clay maximum has also been reported from the Arabian Sea (Prell, 1984b; Sorocko et al., 1993). The 8.2-ka cooling event recorded in the GISP2 ice core appears to coincide with a large increase in δ^{18}O and, hence, a decrease in summer monsoon precipitation in the SCS. Similar rapid events in the Bay of Bengal and Andaman Sea have been related to North Atlantic climate change (Colin et al., 1998). The Leg 184 cores, along with the recent cores from the joint German-Chinese Monitor Monsoon expedition (Sarnthein et al., 1994), and the 1997 IMAGES III Cruise for the first time provide systematic and high-quality material for studying the long-term evolution and variability of the monsoonal South China Sea.

SCIENTIFIC OBJECTIVES

The broad scientific themes of Leg 184 were threefold:

1. To document the Cenozoic history of the South China Sea, including its biostratigraphy, lithostratigraphy, chronology, paleoclimatology, and paleoceanography;
2. To reconstruct the evolution and variability of the East Asian monsoon during the late Cenozoic on millennial, orbital, and tectonic time scales; and
3. To identify and better understand the links between tectonic uplift, erosion and weathering, hemipelagic deposition, and climate change, including the evolution of the Asian monsoon and Neogene global cooling.

To address these broad themes, Leg 184 had a number of shipboard and shore-based scientific objectives, as discussed below.

Evolution and Variability of the Asian Summer Monsoon

The summer monsoon brings most of southern Asia’s annual rainfall; its evolution and variability have a great impact on the region’s climate, vegetation, erosion, weathering, and transport of sediments. In the South China Sea, potential proxies of the summer monsoon include isotopic and faunal indicators of lower salinity and fresh water from monsoon rains and runoff, tropical pollen carried by southerly winds, variation of clay minerals indicating provenance, the presence of upwelling/mixing faunas due to southerly winds and upwelling along Vietnam, variations of accumulation rates, and physical properties. Pollen analysis of core 17940 suggests that an increase in herbaceous pollen and charcoal can indicate aridity and hence weakened summer monsoons; the appearance of alpine conifer pollen may be used as a proxy of the winter monsoon (Sun, 1996; Sun and Li, 1999). Although these properties are not exclusively monsoon in origin, we expect to find both long-term trends and orbital-scale (as well as millennial-scale in some cases) variability in an inter-related array of these monsoon proxies.

Coevolution of South China Sea Seasonality and the Asian Winter Monsoon

Since the winter monsoon reflects cooling over northern Asia (a function of both precession and obliquity), it may exhibit a more complex response than the summer monsoon. Potential proxies of the winter monsoon include lower winter season SSTs, increased subtropical and subpolar index species, increased accumulation of loess, and enhanced transport from the East

China Sea and the Pacific. Comparison of upper Neogene sections from the northern and southern part of the SCS will enable us to construct a history of the thermal gradient within the SCS. These paleotemperature data should provide information on when the winter monsoon began to develop large seasonality, especially in the northern SCS, and on the stability and variability of temperatures in the southern SCS, which lies within the Western Pacific Warm Pool. Although seasonality reflects a number of processes, intensification of monsoon circulation is one mechanism that could increase the seasonality of the region. The onset of glacial conditions would also increase seasonality within the SCS but would likely be related to a strengthening of the East Asian winter monsoon.

Links between Himalayan-Tibetan Uplift, Erosion, Weathering, and Climate Change

A major theme of Leg 184 was to evaluate potential relationships between the Tibetan Plateau uplift, monsoon evolution, and global cooling. A wide spectrum of hypotheses has been proposed to explain various tectonic-climate relationships. These hypotheses represent a diverse set of disciplines including structural geology, micropaleontology, geophysics, geochemistry, stratigraphy of both terrestrial and marine sections, and climate modeling.

The Leg 184 drilling and logging program was designed to obtain long-term, high-resolution records of monsoonal proxies to establish the history of monsoon evolution in the SCS so that it could be compared to other marine and terrestrial records of tectonic and climatic change. Specifically, we sought to develop records of monsoon intensity, denudation/accumulation rates, and climate cooling in the SCS. However, the relationships between tectonics, erosion, and climate are complex and highly nonlinear (Ruddiman, 1997). The tectonic control of the Asian monsoons, for example, is by no means limited to the plateau uplift. Only recently has the marine factor for monsoon evolution been discussed, with only the role of the Paratethys considered (Ramstein et al., 1997). The western Pacific marginal seas, however, should have more direct impact on the evolution of the East Asian monsoon. The SCS cores should provide a new set of constraints on the pattern and timing of weathering/erosion and sediment transport related to tectonic uplift and climate.

Orbital-Scale Precessional Forcing of the Summer Monsoon

Much of the previously identified monsoonal variability in tropical oceans is precessional (23 k.y.) in scale. Shipboard construction of initial splices and age models indicate strong primary orbital periodicity in the SCS sediments. By inference, strong precessional responses are likely related to monsoonal processes. One critical objective is to use this orbital-scale variability to establish the amplitude, coherency, and phase relationships of the East Asian monsoon with orbital and glacial forcing as well as internal feedbacks of the climate system (Clemens, 1999). Initial shipboard results should resolve whether the SCS monsoonal variations are consistent with orbital models of monsoonal variability. Postcruise research will be needed to expand and refine the sedimentary time series and perform more rigorous tests.

Neogene Stationarity of the Monsoon

Stationarity is a fundamental property of a time series and defines the temporal stability of a variable's characteristics. A nonstationary property changes its mean value, amplitude (or variance), and phase over some length of time. Clemens et al. (1996) have shown that the Indian southwest monsoon is nonstationary over the past 3.6 m.y. Specifically, monsoon proxies change their phase relative to ice volume ($\delta^{18}O$) and dust content. Although the temporal changes are not large, they completely change the phase relationships at the precessional scale. The time series evolution of the SCS Neogene sections will provide a different monsoonal regime to test the stationarity of the monsoon response.

Millennial-Scale Variability of Monsoonal Climate

One objective of Leg 184 was to recover high accumulation rate sediments that would allow paleoceanographic analyses on millennial, centennial, and even decadal time scales. This objective is feasible in the northern SCS. For example, a piston core near Site 1144 (SONNE95-17940, 20°07′N, 117°23′E, 1727 m) contains a Holocene section nearly 7 m in thickness, which equates to a temporal resolution of 15 yr/cm. The remaining core has rates equivalent to ~40–50 yr/cm (Sarnthein et al., 1994; Wang et al., 1999). However, the Sonne core reaches only 40 ka. Our objective is to analyze the sediments of Site 1144 to extend this high-resolution record over the past one million years.

Evolution of Tropical and Subtropical Faunas

The paleoclimatic and paleoceanographic history of the SCS is paralleled by changes in the planktonic faunas and floras. Some changes are global ocean events whereas others, especially the population characteristics of groups, reflect the evolving oceanography of the SCS. Previous studies have found remarkable changes in relative abundances of planktonic foraminifers *Pulleniatina obliquloculata* in the Pleistocene, in the size and abundance of nannoplankton reticulafenestrids in the Miocene/Pliocene, and in species of mangrove pollen *Florschuetzia* in the Miocene—all of which are tied to environmental events. Leg 184 data will enable us to systematically compare the biological and physical processes.

Links between Terrestrial and Marine Stratigraphy

Extensive petroleum exploration and academic studies have accumulated much information on the Cenozoic paleoenvironmental history of mainland and offshore China (Zhou, 1984; Li et al., 1984; Ye et al., 1993). Because of the language barrier and commercial restrictions, however, few of these data have been available to the global scientific community. In addition, poor stratigraphic control of the mostly nonmarine deposits has made it difficult to correlate the sediment records with the global paleoenvironmental history. Leg 184 shipboard stratigraphy will provide the first direct calibration of open-marine stratigraphy to the local and regional land-based stratigraphies, thereby linking them with the record of global environmental changes.

These correlations will provide a different perspective on the identification of the timing of changes in denudation/accumulation rates, the leads or lags between terrestrial and marine records, tectonic events, and monsoon intensification. A correlation between the loess/paleosol sequence and the deep-sea sediments in the SCS will be most relevant to this purpose.

Eolian Transport to the South China Sea

A number of studies have suggested that the South China Sea accumulates eolian silts and clays (loess) during glacial climate phases (e.g., Wang et al., 1999). Leg 184 seeks to identify both the long-term evolution and orbital-scale variability of eolian sedimentation in the SCS, especially at the northern sites. This objective is difficult because of the terrigenous nature of the hemipelagic sediments that blanket the northern continental slope. We expected that combinations of the geochemical and mineralogical grain-size characteristics will help sort out the eolian component of these sediments. Numerous volcanic ash layers should also provide additional indicators of paleo-wind directions when their sources are clarified in postcruise analysis.

Histories of Indian and East Asian Summer Monsoons

Another goal of Leg 184 was to compare the evolution of the East Asian monsoon in the SCS with the Indian monsoon in the Arabian Sea to identify common sources of causality. Given the development of reliable chronology and monsoonal indices, the SCS records will be correlated with the ODP Arabian Sea sites, which primarily record the summer monsoon. We predicted that the SCS and Arabian Sea summer monsoon responses would be similar in long-term trends and in their phase relative to ice volume. The winter monsoon response is expected to be stronger in the SCS.

Paleoceanographic Proxies of the East Asian Summer and Winter Monsoons

Leg 184 scientists plan to continue to develop reliable proxies of monsoonal response in the SCS, including the variability of sediment properties, the rates of sediment accumulation, and the chemical, isotopic, and species variability of flora and fauna. On the basis of previous studies, we expect that numerous sediment properties along with faunal variations will exhibit variability related to monsoonal forcing (Figs. 4, 7). Shipboard measurements included core logging of magnetic susceptibility (MS), bulk density, color reflectance (CR), and natural gamma radiation (NGR). Postcruise work will measure and refine the time series of chemical, isotopic, and faunal variability to place additional constraints on the relationship between sediment proxies and monsoonal variability.

Paleoceanographic Impacts of South China Sea Basin Evolution

The opening of the SCS basin together with crustal subsidence must have given rise to transgressive sequences during the late Oligocene and early Miocene. The formation of islands on the eastern and southern borders of the SCS resulted from collision with the Australian and Philippine Sea Plates, reducing the water exchange between the SCS and the Pacific and Indian Oceans. The appearance of the modern Bashi Strait with its sill depth ~2600 m between Luzon and Taiwan has resulted from the Luzon Arc collision begun ~6.5 m.y. ago. Before that a free connection existed between the South China Sea and the western Pacific, evidenced by similarities in deep-water faunas and CCD. The evolution of the shape and borders of the SCS should also change the source areas of terrigenous clasts; hence, tectonic models can be partly tested by provenance analyses of sediments from different stages of basin evolution.

Paleoclimate Significance of the South China Sea as a Marginal Basin

The formation of marginal seas in the western Pacific and their response to the glacial cycles must have played a crucial role in the global climate system. Since the connection between these marginal seas and the open Pacific is usually through narrow and/or shallow seaways, the seas are highly sensitive to any tectonic deformation or eustatic fluctuations. The SCS, the largest of the marginal seas, is a critical factor in heat and vapor exchanges between Asia and the ocean; its geological evolution should have significant climatic impacts. The formation of its southern border was closely related to the Australia-Asia collision that caused the closure of the Indonesian Seaway and the enhancement of the Kuroshio Current ~10–12 Ma (Kennett, 1985). The rotation of the Philippine Sea Plate created Luzon Island, which splits the west-flowing Equatorial Warm Current into the Kuroshio and Midanao Warm Currents so essential to the supply of Western Pacific Warm Pool waters. The progressive closure of the SCS has increased its amplifying effect on glacial signals and the north-south contrast in climate (Wang, 1999).

DRILLING STRATEGY

The drilling strategy for Leg 184 reflected both the scientific priorities for prospective sites and a number of operational, practical, and strategic factors. Initially, Leg 184 was planned to core six sites: one on the southern margin and five on the northern margin. Despite a delayed departure from Fremantle, Australia, and a diversion to Singapore to repair the ship’s 10-cm radar, we cored 17 holes at six sites (Sites 1143–1148) (Table 1; Figs. 8, 9). The lowest priority proposed site SCS-3 was sacrificed in favor of deepening Sites 1143, 1146, and 1148. At all sites, our drilling strategy was to triple core with the advanced hydraulic piston corer (APC) system to refusal and deepen at least one hole with the extended core barrel (XCB) system to the maximum approved depth. Site 1148 was the single site where only two holes were drilled. All sites deeper than 400 meters below seafloor (mbsf) (Sites 1143, 1144, 1146, and 1148) were wireline logged as planned.

Our drilling plan was to first core the southern Site 1143 enroute to the northern operations area. Following a brief seismic survey of proposed sites SCS-4, SCS-5C, -5D, and -5E, as required for final safety approval, we elected to core SCS-1 (Site 1144) which had prior Pollution Prevention and Safety Panel (PPSP) approval. During the occupation of Site 1144, we received approval to core the surveyed sites with minor changes in locations. Our final site selection on the northern continental margin was aimed to maximize recovery of different stratigraphic sections at different water depths. Site 1144 (proposed site SCS-1) at a water depth of 2037 m focused on the Pleistocene section, and Sites 1146 (SCS-4) and 1148 (SCS-5C) centered on the Oligocene to Pliocene section at water depths of 2092 and 3294 m, respectively.

SCIENTIFIC MEASUREMENTS STRATEGY

Because the central theme of Leg 184 was the Neogene coevolution of tectonics and climate, the shipboard focus was on recovering continuous sediment sections capable of recording millennial- to orbital-scale variations. This concentration on orbital-scale and higher resolution variability is reflected in the Leg 184 shipboard measurements program as well as its sampling plan and shore-based analysis.

Shipboard measurement strategy was to acquire high-resolution (2–5 cm) core-logging records from all holes, including MS, gamma-ray attenuation (GRA) bulk density, NGR, and CR These data were used to construct the meters composite depth (mcd) scale, which was used to evaluate the completeness of the stratigraphic section and to splice an intact, representative record for each site. Routine measurements, taken at frequencies of one per section to one per core (intervals of ~1.5–10 m), included biostratigraphy (calcareous nannofossils and foraminifers), paleomagnetism, hydrocarbon gas analysis, interstitial water chemistry, moisture and density, carbonate, and *P*-wave velocities.

The Leg 184 downhole logging plan was designed to provide (1) complete stratigraphic coverage, especially in the incomplete XCB intervals; (2) proxy data not available from core measurements, such as resistivity and yields of K, U, and Th; and (3) in situ sonic velocity for the construction of synthetic seismograms. Sites 1143, 1144, 1146, and 1148 were logged using the following three downhole tool strings:

1. The triple combo tool string, which includes the dual induction tool to measure resistivity, the accelerator porosity sonde to measure porosity, and the hostile environment lithodensity sonde that measures bulk density and general lithology. Also included on this tool string were the hostile environment natural gamma-ray sonde (HNGS) to measure total NGR and to calculate K, U, and Th yields and the Lamont-Doherty Earth Observatory temperature logging tool to measure borehole fluid temperature.

2. The FMS-sonic tool string, which includes the Formation MicroScanner (FMS) with the general-purpose inclinometry tool to measure microresistivity at centimeter resolution and the dipole sonic imager to measure compressional and shear-wave velocity.
3. The geological high-resolution magnetic tool (GHMT), which includes the nuclear magnetic remanence sonde to measure the total magnetic field and the susceptibility measurement sonde to measure the MS from induction.

SITE SUMMARIES

Site 1143

Site 1143 (proposed site SCS-9) is located 9°21.72′N, 113°17.11′E, at a water depth of 2772 m (Table 1), within a basin on the southern continental margin of the South China Sea (Figs. 8, 10). On the Admiralty charts, the site lies within the Nansha or Dangerous Grounds area, which is riddled with reefs, shoals, and small islands, some of which are within 20 to 30 miles of the site. Site 1143 was located in the southern SCS in order to provide a Neogene paleoceanographic record within the region of relatively stable sea-surface temperature, the Western Pacific Warm Pool. The sediment record of high and relatively stable sea-surface temperature will allow the reconstruction of SST gradients (with the northern sites) across the SCS and should reflect the development of climatic seasonality in this region. Climate records from Site 1143 will provide the basic data to identify and interpret the evolution of summer and winter monsoon circulation in the South China Sea. Also, the southern location of Site 1143 was chosen to capture the long-term records of sediment accumulation rates and lithologic variability associated with the Mekong and Sunda River systems that might be related to uplift and denudation of Tibetan and East Asian tectonic systems.

We cored three APC/XCB holes at Site 1143. Hole 1143A reached 400 mbsf with 95% recovery, Hole 1143B reached 258 mbsf with 95% recovery, and Hole 1143C (following PPSP approval to deepen the hole) reached 500 mbsf with 96% recovery (Table 1). We requested approval to deepen Hole1143C beyond the originally approved 400 m penetration to extend the paleoenvironmental record in time, after the sediment age turned out to be younger than expected. We had confirmed that no significant hydrocarbon concentrations occurred in the entire interval recovered in Hole 1143A. Wireline logging was accomplished in Hole 1143A with the triple combo tool suite (86–400 mbsf) and the FMS-sonic tool combination (158–380 mbsf). Hole conditions did not allow deployment of the GHMT string.

The sediments at Site 1143 represent continuous hemipelagic sedimentation of fine-grained terrigenous material and pelagic carbonate from the late Miocene (~10 Ma) to present (Fig. 11). The three holes at Site 1143 were combined into a composite (spliced) stratigraphic section that is continuous in mcd scale from 0 to 190.85 mcd, the interval of APC coring. Incomplete core recovery and decreased core quality precluded splice construction below this interval, but intervals of cores can be correlated over the 190–400 mcd interval. Overall, most of the Pliocene/Pleistocene interval has a continuous and reliable spliced record. In general, the long-term decrease in sedimentation rates observed at Site 1143 from the upper Miocene to the Pleistocene is caused by declining accumulation rates of both carbonate and noncarbonate components. The temperature gradient determined from five advanced hydraulic piston corer temperature tool (APCT) downhole measurements is ~86°C/km.

The Pleistocene-age sediments at Site 1143 consist mostly of olive, greenish, and light gray-green and greenish gray clayey nannofossil mixed sediment, clay with nannofossils, and clay. In general, bedding is not evident, and compositional changes are gradual throughout the site. Minor lithologies vary with depth and include ash layers, turbidites, and green clay layers. Carbonate content of this interval is variable but averages ~18%, with both calcareous nannofossils and planktonic foraminifers abundant and well preserved. Benthic foraminifers are generally rare throughout the site. Changes in color define lithic subunits and are mainly controlled by carbonate content. The CR measurements (lightness parameter L*) vary with the carbonate data and increase downcore. Core-logging data, especially CR, MS, and NGR, show an increasing trend within the Pleistocene, with superposed patterns of orbital-scale cyclicity, much of which can be correlated with glacial–interglacial cycles and marine oxygen isotope stages. Magnetic susceptibility data show a number of significant spikes that correspond to observed volcanic ash layers and are particularly abundant in the intervals 20–30 and 70–100 mcd. The interstitial waters of the Pleistocene-age sediments are characterized by sulfate reduction, which reaches downhole to the base of the Pliocene-age sediments (~200 mbsf). Organic carbon content decreases from ~0.9% at core top to 0.2% at the base of the Pleistocene section and remains low throughout the core. Methane concentration in the sediment is <10 ppm in the entire interval to 500 mbsf. The extended interval of sulfate reduction appears consistent with the low organic carbon and methane content in the sediments. The Brunhes/Matuyama polarity reversal was observed at ~42.5–43.8 mcd, and the Pleistocene/Pliocene boundary is located between 93.5 and 94.3 mcd. Over the Pleistocene interval, the linear sedimentation rate (LSR) averages 50 m/m.y., and the total and carbonate mass accumulation rate (MAR) ($g/cm^2/k.y.$) are 3.6 and 0.6, respectively.

The Pliocene-age sediments at Site 1143 are characterized by steadily increasing carbonate content, ranging from 20% to 40% and averaging 28%. Calcareous nannofossils and planktonic foraminifers are abundant and generally well preserved. This interval exhibits a continued increase in L* and grain density, reflecting the increase in carbonate. The MS and NGR values reach a plateau in the mid-Pliocene and rapidly decrease in the lowermost Pliocene. Magnetic susceptibility spikes related to volcanic ashes occur between 120 and 190 mcd. Cyclicity of most properties continues as in the Pleistocene section but with reduced amplitude. Near the base of the Pliocene (~200 mbsf), increases in the concentrations of dissolved silica, strontium, and lithium as well as alkalinity are consistent with a lithology change observed at that depth. Change from APC to XCB coring in the lower Pliocene significantly affected the core-logging data, particularly the NGR and MS signals. The values decreased by half across the APC/XCB coring transition, although this also partly reflects the change in lithology at that depth. NGR data from wireline logging confirm the change in lithology. The Pliocene/Miocene boundary is located between 213 and 200 mcd. Over the Pliocene interval, the average LSR is 36 m/m.y., and the total and carbonate MAR (g/cm^2/k.y.) are 3.7 and 1.0, respectively.

The Miocene-age sediments at Site 1143 are distinguished by high carbonate content (averaging 47%), which is the primary criterion for identifying lithologic Subunits I and II. The green clay layers are less frequent and turbidite layers are more frequent in the Miocene sediments. Sediments of this interval also exhibit higher CR and bulk density but lower MS and NGR. These variations probably reflect subtle compositional changes such as variations in clay content or abundance of foraminifer turbidite layers worked into the clay matrix by bioturbation. Calcareous nannofossils are abundant, but their preservation deteriorates through the Miocene, whereas planktonic foraminifers are abundant and have good preservation. Over the upper Miocene interval, the average LSR is 114 m/m.y., and the total and carbonate MAR (g/cm^2/k.y.) are 14.0 and 6.6, respectively. These higher sedimentation rates are caused by frequent turbidites that were observed in the cores and clearly distinguishable both in logging data and FMS images. The sand-rich base of the turbidites is characterized by lower gamma-ray, density, and resistivity and higher porosity and *P*-wave velocity values. The opposite is true for the top (clayey part).

Overall, Site 1143 provides an excellent continuous record with moderate accumulation rates, especially over the past 6 m.y. The site should enable researchers to develop high-resolution orbital-scale time series of paleoceanographic proxies and to reconstruct the record of seasonality in the South China Sea.

Site 1144

Site 1144 (proposed site SCS-1) is located 20°3.18′N, 117°25.14′E, at a water depth of 2037 m (Table1), on a sediment drift on the northern margin of the South China Sea (Fig. 12). Site 1144 was chosen to take advantage of the extremely high sedimentation rates to recover a continuous sequence of hemipelagic sediments that will enable reconstruction of the paleomonsoon history on a millennial, centennial, or higher resolution time scale for the mid- to late Pleistocene (~1 Ma). Site 1144 data will allow comparison of SCS records with orbital-scale and higher frequency records from ice cores, marginal seas, and terrestrial deposits. Situated along the northern margin of the SCS, Site 1144 is ideally located to reconstruct the sedimentologic, isotopic, and faunal/SST changes associated with development of the winter monsoon. This site also provided the northern constraints for reconstruction of SST gradients in the South China Sea.

We cored three APC/XCB holes at Site 1144. Hole 1144A reached the target depth (453 mbsf) with an average recovery of 104%, Hole 1144B reached 452 mbsf with 99% recovery, and Hole 1144C was APC cored to the target depth of 199 mbsf with an average recovery of 100%. The total recovery for Site 1144 was 1113 m, representing 101% of the cored interval (Table 1).

Following completion of Hole 1144A, wireline logs were successfully acquired from 87 to 452 mbsf for all three tool suites (triple combo, FMS-sonic, and GHMT). The temperature gradient within the sediment column at Site 1144 is anomalously low (24°C/km), about one-third of the expected value. Reasons for this may include the rapid sedimentation rate or subsurface flow.

Drilling at Site 1144 recovered a mid- to upper Pleistocene and Holocene sequence of rapidly accumulating, hemipelagic clays with a basal age of ~1.1 Ma (Fig. 13). The recovered sequence spans 452 mbsf (519 mcd). The continuous spliced record (mcd scale) extends from 0.0 to 235.41 mcd. Splice construction below this interval was precluded by incomplete core recovery and alignment of coring gaps. However, a discontinuous (“floating”) mcd depth scale was constructed from 235 to 519 mcd based on correlations among cores from the three holes.

The Pleistocene-age sediments at Site 1144 are notable for their high sedimentation rates and organic carbon content, the cyclicity of their physical properties, and the variations of “iron sulfide” and pyrite. The sediments represent a rapidly accumulating drift deposit with hemipelagic sedimentation of clay with quartz silt and nannofossils, completely homogenized by bioturbation. Variations in the lithology reflect the abundance of iron sulfides (dominant in uppermost interval, 0–283 mcd), siliceous biota (highest proportion in middle interval, 283–404 mcd), and pyrite (dominant in lowermost interval, 404–518 mcd). Minor lithologies (5%–10% of the sediment) include clay with quartz silt and sponge spicules, clay with quartz silt and diatoms, clay with silt, silty clay, and clay. Ash layers and green clay layers are rare throughout, but a number of rather indistinct green clay layers and patches occur over the same intervals that contain more discrete layers at Site 1143. Downslope redeposition is suggested by thin layers of foraminifer ooze with small amounts of pyrite and a variety of macrofossils, including gastropods, scaphopods, pteropods, fragments of echinoderms, and poorly defined shell debris. Wood debris as long as 4 cm was also observed. Bulk X-ray diffraction (XRD) analysis revealed that the mineralogy follows the overall visual homogeneity of the sediment.

Carbonate content of this Pleistocene section is low and ranges from 10% to 20%. Unlike at other sites, CR data did not correlate well with shipboard carbonate measurements taken at much lower sampling resolutions. However, they do show detailed, high-resolution variations with patterns similar to recognized glacial–interglacial scale variations. Once properly calibrated, these data will provide useful proxies for paleoceanographic studies. Over the upper section of Site 1144 (0–100 mcd), increases in bulk density and NGR and decreases in porosity reflect rapid compaction, with superimposed fluctuations of glacial–interglacial and higher frequencies. Both core data and downhole logging show a markedly decreased rate of compaction, and the superimposed signal variability is of larger amplitude over the next 320-m interval (100–420 mcd). Magnetic susceptibility is low and rather featureless through these two upper intervals, apart from some spikes representing ash layers. However, an abrupt, threefold increase in MS takes place at ~420 mcd and is associated with a decrease in porosity from 55% to 50% as well as increased downhole sonic velocities. These changes correspond to the depth of a prominent seismic reflector. Because of the scarcity of biostratigraphic markers in this section of high sedimentation rates, we have not yet determined if a hiatus exists at that depth and/or if the section may reflect past mass wasting events in the sediment drift.

Organic carbon is relatively high at Site 1144 and decreases from ~1.5% near the core top to 0.3% at 519 mcd. Methane ranged from 0.3% to > 6% and was biogenic in origin. No heavier hydrocarbons were observed. The interstitial waters at Site 1144 reflected sulfate reduction in the upper few meters and ammonia production throughout the remaining core. Clay alteration accounted for a number of the interstitial water profiles. A few profiles indicated a change at ~420 mcd, where physical properties and seismic records also detect a boundary. However, the chemistry gives no special insight into the nature of this boundary or layer.

The chronostratigraphy of Site 1144 is primarily derived from the calcareous nannofossil and planktonic foraminiferal zones and events and is aided by the abundance patterns of several planktonic foraminifers, siliceous microfossils, benthic foraminifers, and pteropods. Because of the extremely high sedimentation rates at this location, only eight of the standard biostratigraphic zones and markers could be identified over the past 1.1 m.y. Unfortunately, the magnetopolarity stratigraphy was also limited by the high sedimentation rates and poor magnetization. Only the Laschamp Event (0.04 Ma) is tentatively identified at 23.5–25.5 mcd. The temporal pattern of magnetic intensity apparently correlates well with other intensity records and is consistent with the biostratigraphic age model. Sedimentation rates varied within the section but tend to decrease downhole, with the exception of the lowermost 100 m. Over the upper half of the site (0–250 mcd, 0–0.31 Ma), the linear sedimentation rates average 870 m/m.y., and the total and carbonate MARs (g/cm^2/k.y.) average 85 and 11, respectively. In the lower half of Site 1144 (250–519 mcd, 0.31–1.03 Ma), the LSR averages 50 m/m.y., and the total and carbonate MAR (g/cm^2/k.y.) average 64 and 9.6, respectively.

In summary, Site 1144 offers an exceptionally high sedimentation-rate section with well-defined variability of many properties for the study of climate-ocean response on the orbital, millennial, centennial, and higher resolution time scales for the mid- to late Pleistocene (~1 Ma). The data from Site 1144 will be among the highest resolution marine records and should enable direct comparison of the South China Sea climates with records from ice cores, laminated sequences, and terrestrial deposits.

Site 1145

Site 1145 (proposed site SCS-2) is located 19°35.04′N, 117°37.86′E, at a water depth of 3175 m (Table 1), near the base of the northern continental margin of the South China Sea (Fig. 14). The location of Site 1145 was selected to provide a deep-water contrast to Site 1144 (i.e., below the depth of the Bashi Strait, 2500 m) so that the water-mass depth gradients and ventilation history of the South China Sea could be reconstructed for the Quaternary. Site 1145 was also envisioned as a mid-Pliocene through Pleistocene record of the intensification of the winter monsoon, coincident with the development of loess in China.

We cored three APC/XCB holes at Site 1145. Hole 1145A reached the target depth of 200 mbsf with average recovery of 93%, Hole 1145B reached 200 mbsf with an average recovery of 90%, and Hole 1145C reached 198 mbsf with an average recovery of 96%. The total core recovered at this site was 555 m, representing 93% of the cored interval (Table 1). Downhole and bottom-water temperature measurements revealed a thermal gradient of 90°C/km, which is consistent with the water depth of the site.

Site 1145 recovered a continuous sequence of hemipelagic clays of late Pliocene to Holocene age with a basal age of ~3 Ma (Fig. 184-SUM-15). A complete composite (spliced) section was constructed over the entire depth of 213 mcd. The site is noteworthy for its excellent paleomagnetic stratigraphy and distinct patterns of cyclicity.

The Pleistocene-age sediments at Site 1145 mainly consist of intensely bioturbated clay with distinct light carbonate-rich clay layers of ~0.5 to 4 m thickness. Although average carbonate content is low during the Pleistocene (averaging ~10%), the light carbonate-rich layers were clearly recorded in the CR data, especially the lightness parameter (L*). Other core-logging data (GRA bulk density, NGR, and MS) are also characterized by high-amplitude cyclical fluctuations over the entire section. These cycles are best defined in the NGR data from the APC interval (above ~133 mcd), where the dominant wavelength changes at ~80 mcd from ~10–15 m in the upper interval to ~2–5 m in the lower interval. The first five major CR and NGR intervals are easily correlated with the marine oxygen isotope interglacial Stages 5, 7, 9, 11, and 13. Identification of light layers became more problematic with depth as the average sediment composition became more carbonate rich and the contrast between dark and light layers decreased. In the lower half of the Pleistocene, below ~80 mcd, the average values of GRA, MS, and NGR increase to roughly double the value. The abrupt increase in these values is accompanied by a sudden decrease in porosity from ~70% to 55%. Porosity clearly defines an interval of excursion from a linear trend between 80 and 170 mcd. The porosity decrease alone cannot account for the changes observed in MS and NGR over the interval from 80 to 170 mcd; we therefore infer a significant change in lithology that affects porosity and other physical properties, including average grain density. At ~133 mcd, GRA bulk density shows a sharp offset caused by the change from APC to XCB coring. XCB cores are moderately disturbed by partial remolding and incorporation of drilling slurry.

The upper part of the section (0–86 mcd) is characterized by small amounts (<10%) of biogenic silica, mainly in the form of radiolarians, diatoms, sponge spicules, and silicoflagellates. Green layers (typically 1–3 cm thick) and less distinct green mottles, as well as slightly yellowish gray patches that probably represent traces of bioturbation, appear frequently throughout the Pleistocene section. The occurrence of complete pteropod tests in the upper section (0–~70 mcd) along with abundant calcareous nannofossils and planktonic foraminifers reflects the good carbonate preservation in the upper Pleistocene. Evidence of downslope transport at Site 1145 includes several complete echinoderms, echinoderm fragments remineralized by pyrite, and several wood fragments. Although a few cores contain fresh angular volcanic glass shards within burrows and dispersed ash in low concentrations, volcanic ash represents a very minor component of the total sequence.

Total organic carbon (TOC) declined steadily from more than 1% at the top of the section to much lower amounts (~0.2%) at the base, consisting of mostly marine organic matter. Only trace amounts of methane (<16 ppmv) and no other hydrocarbon gases were detected in sediments at Site 1145. Interstitial water profiles are characterized by relatively constant chloride values close to those of the seawater value. The sulfate, alkalinity, ammonium, and phosphate profiles show significant changes in the upper part of the sedimentary column (0–~100 mcd), which appear to be caused by the diagenesis of organic matter via sulfate reduction. Sulfate reduction is incomplete, and methanogenesis is a minor process in these sediments. Dissolved magnesium and potassium concentrations decrease linearly with depth. Dissolved calcium concentrations decrease downhole to ~44 mcd, indicating that sulfate reduction and alkalinity production are promoting inorganic calcite precipitation. Concentrations then remain low and relatively constant between 50 and 100 mcd. Below this interval, calcium increases to a maximum near the bottom of the hole. Below 80 mcd, dissolved strontium concentration increases continuously, which most likely reflects dissolution of biogenic silica and/or reactions involving alteration of volcanic glass. Low lithium concentrations at the top of the hole probably result from an uptake of Li^+ during authigenic calcite precipitation. Dissolved silica increases slightly at the top of the hole at 24.9 mbsf and then is high and constant between 24.9 and 72.4 mbsf. Below this interval, H_4SiO_4 concentrations decrease abruptly and then vary within a lower range of values. This shift was also observed at the higher accumulation rate of Site 1144 at 420 mcd and is synchronous (~1 Ma) at both sites.

The paleomagnetic records at Site 1145 clearly established the Brunhes/Matuyama transition at 93 mcd, the upper Jaramillo transition at 110 mcd, and the lower Jaramillo transition at ~116 mcd. Farther downcore the overprint resulting from the coring process increases, but long core measurements identify the Gauss/Matuyama boundary at 190 mcd as a jump of the inclination from ~25° to 45° (no declination is obtained from XCB cores). Demagnetization of the discrete samples proved to be more efficient in removing the overprint, and the Olduvai Event was clearly revealed from 155 to 165 mcd. The inclinations around the Gauss/Matuyama boundary are closer to their expected values. From 190 mcd to the bottom of Hole 1145A, two samples yield unequivocal reverse inclinations. This may indicate that the upper Kaena reversal (3.04 Ma) had been reached in this hole, although this conclusion conflicts with the biostratigraphic age for the bottom of the hole and must be confirmed with shore-based analysis. Based on paleomagnetic and biostratigraphic control, the Pleistocene/Pliocene boundary can be placed at ~160 mcd. At Site 1145, the upper Pleistocene interval (0–70 mcd) had a linear sedimentation rate of 210 m/m.y. and total and carbonate MARs of 14 and 1.4 $g/cm^2/k.y.$, respectively. The lower Pleistocene interval had lower rates, with an average LSR of 60 m/m.y. and total and carbonate MARs of 6.2 and 0.7 $g/cm^2/k.y.$, respectively.

In the Pliocene-age section at Site 1145, average carbonate contents (17%) and variability (10%–30%) increase. Although planktonic foraminifers and calcareous nannofossils remain common to abundant, planktonic foraminifer preservation degraded from good to poor downsection, and the nannofossils were occasionally to commonly reworked. Benthic foraminifers are generally few. The CR and bulk data both increase in the Pliocene section and reflect the increased carbonate content. Other properties display cyclic variability but show no longer term trends. The biostratigraphic age of the oldest sediments recovered at Site 1145 is estimated at 3.12–3.35 Ma. The Pliocene section has the lowest rates observed at Site 1145, with LSRs of 38 m/m.y. and total and carbonate MARs of 4.5 and 0.8 g/cm^2/k.y., respectively.

In general, both carbonate and noncarbonate accumulations decrease downhole at Site 1145, with a small increase in the lower Pleistocene. Overall, the variations in the noncarbonate components dominate the accumulation rate pattern as in Site 1144. Site 1145 provides a high-quality section with excellent paleomagnetic stratigraphy for the resolution of orbital-scale variations of climate changes that may be related to the onset of extensive loess deposition in China at ~2.4 Ma.

Site 1146

Site 1146 (proposed site SCS-4) is located 19°27.40′N, 116°16.37′E, at a water depth of 2092 m (Table 1), within a small rift basin on the mid-continental slope of the northern South China Sea (Fig. 16). Site 1146 was intended to take advantage of the relatively shallow slope basin with moderate sedimentation rates to recover a continuous sequence of hemipelagic sediments that would enable reconstruction of East Asian monsoon history from the middle to upper Miocene (~10 Ma). Such a long-term record at orbital-scale resolution (2 k.y.) would allow comparisons of East Asian monsoon variability with orbital forcing, glacial forcing, and internal feedbacks within the climate system and provide a new set of constraints on the possible relationship between Tibetan Plateau uplift, monsoon evolution, and global cooling. Specifically, we seek to determine whether monsoonal indices intensify or weaken during the late Miocene and whether the Miocene–Pliocene pattern of accumulation rates is consistent with models of Himalayan-Tibetan uplift, monsoon intensification, and sea-level changes. Lastly, we envisioned that the Site 1146 record of the East Asian monsoon would provide an appropriate counterpart to Site 1143 in the southern SCS and Site 722 in the Arabian Sea and that their comparison could serve to identify potential sources of common causality.

We cored three APC/XCB holes at Site 1146. Hole 1146A reached the target depth of 607 mbsf with an average recovery of 100%, Hole 1146B reached 245 mbsf with an average recovery of 99%, and Hole 1146C reached 599 mbsf with an average recovery of 101% (Table 1). We requested approval to deepen Site 1146 beyond the originally approved 520 m penetration to extend the paleoenvironmental record in time, after the sediment age turned out to be younger than expected and after we had confirmed that no significant hydrocarbon concentrations occurred in the entire interval recovered. Following completion of Hole 1146A, three successful downhole logs were acquired with the triple combo (85–600 mbsf), FMS-sonic (239–600 mbsf), and GHMT (239–600 mbsf) tool strings. Downhole and bottom-water temperature measurements yielded a thermal gradient of 59°C/km at Site 1146.

Drilling at Site 1146 recovered a lower Miocene through Pleistocene section of relatively carbonate-rich, hemipelagic nannofossil clays with a basal age of ~19 Ma (Fig. 17). The core-logging data enabled construction of a continuous mcd scale and a continuous spliced record from 0 to 266.7 mcd. A discontinuous ("floating") mcd scale and splice were also developed for the interval spanning 266.7–640.9 mcd, which is the bottom of the cored sequence. We expect that postcruise correlation with downhole logging data will allow construction of a complete, continuous section to 640 mcd.

The Pleistocene-age sediments are composed of greenish gray nannofossil clay that is relatively enriched with quartz, plagioclase, chlorite, and illite relative to lower sections. This unit grades downhole into clayey nannofossil ooze within the Pliocene section. The Pleistocene sediments average ~21% carbonate and are characterized by slightly lighter intervals with higher carbonate content. Planktonic foraminifers are abundant and have good preservation for the site's entire interval. The upper part of the section (0–110 mcd) shows constant or slightly increasing values in CR (L*), MS, and NGR, a high scatter in grain densities, and normal compaction-related increase in bulk density and *P*-wave velocity. This interval is characterized by high-amplitude variations representing orbital-scale cyclicity. Minor sediment components include large pyrite nodules that preserve organic structures (Xenophyophorians) and thin, light-gray ash layers, often strongly dispersed by bioturbation, as well as isolated pumice clasts. Large (>1 cm in diameter) pteropods, diatoms, silicoflagellates, radiolarians, and sponge spicules are common.

Total organic carbon decreases systematically from the Pleistocene sediments (1% at the top of the section) to trace abundance (<0.2%) below the mid-Pliocene (~225 mcd). Interstitial water profiles at Site 1146 were primarily driven by the removal and release of elements in the process of organic matter reduction, with sulfate reduction the dominant process above 68 mcd and methanogenesis dominant below. Depletion of methanogenesis products such as alkalinity, phosphate, and ammonium with depth suggests that methanogenesis is active only in the upper sediments. This agrees with the interpretation of higher methane levels and higher order hydrocarbons in headspace gas samples below 200 mcd as gases that have migrated into this site, either laterally or from depth. Dissolved silica and strontium correlate with the amount of biogenic silica and carbonate in the sediments, respectively. A major decrease in the dissolved silica concentration is observed between 109 and 140 mcd (~0.7–1.1 Ma) and accompanies a decrease in the amount of biogenic silica to near-zero values. A similar decrease was observed at Sites 1144 and 1145 at an age of ~0.8 Ma.

Paleomagnetic measurements reveal the Brunhes/Matuyama transition at 115 mcd, the upper Jaramillo transition at 133 mcd, and the lower Jaramillo transition at 138 mcd. Between 99.7 and 101.3 mcd, a swing in declination with correlative very low inclinations could document the Big Lost (geomagnetic) Event (dated at 510 to 650 ka). A transition from reverse declinations to normal occurs between 160.5 and 165.8 mcd, possibly marking the Olduvai Event. The biostratigraphy places the Pleistocene/Pliocene boundary between 185.5 and 195.1 mcd. At Site 1146, the sedimentation rates decrease downcore; the Pleistocene section has the highest rates, with an average linear sedimentation rate of 150 m/m.y. and total and carbonate MARs of 11.5 and 2.3 g/cm^2/k.y., respectively.

The Pliocene-age sediments at Site 1146 (~190–310 mbsf) are distinguished by significantly higher carbonate content (an average of 47% compared to 21% in the Pleistocene). The transition to higher carbonate occurs in the upper Pliocene and is accompanied by an increase in the CR L* values and a decrease in the NGR and MS. This transition interval at ~235 mcd is also characterized by a very pronounced decrease in porosity and an increase in bulk density. This corresponds to a general downhole decrease in accumulation rate at that depth. The sediments grade from the overlying greenish gray nannofossil clay to homogeneous to rarely mottled, light brownish gray foraminifer and nannofossil clay mixed sediment. A small number of thin (<1–2 cm) dark ash layers, containing large volcanic glass shards as long as 1 cm, occur in the lower part of the interval. A major increase in dissolved strontium in the Pliocene/Pleistocene section between 109 and 350 mcd corresponds to the increase in the percent carbonate in that interval. In both cases, the availability of dissolvable biogenic sediments appears to be a strong control on dissolved concentrations of silica and strontium at Site 1146. The Pliocene/Miocene boundary at Site 1146 is between 308.42 and 317.99 mcd. The Pliocene section has an average LSR of 39 m/m.y. and total and carbonate MARs of 4.3 and 1.9 g/cm^2/k.y., respectively.

The Miocene-age sediments at Site 1146 (310–642 mbsf) grade from light brownish gray foraminifers and nannofossil clay mixed sediment of the late Miocene to the green nannofossil clay of the middle to early Miocene. This transition is marked by a progressive change in the sediment color from brownish gray to a distinct greenish gray. The late Miocene to early Pliocene-age interval is slightly more carbonate rich than the middle-Miocene sediments, in which kaolinite and quartz become significant contributors to the mineral composition. In this lower interval, characteristic bluish green nannofossil clay appears, which contains large amounts of pyrite as nodular irregular layers or as finely disseminated particles. The carbonate content declines throughout the Miocene: 53% in the upper Miocene, 35% in the middle Miocene, and 30% in the lower Miocene. The green nannofossil clay of the early to middle Miocene is characterized by relatively high concentrations of smectite and illite. Over much of the Miocene–Pliocene interval, the CR L* signal correlates well with the carbonate pattern but NGR and MS signals are depressed, which implies a carbonate dilution effect. Negative excursions in the chromaticity ratio a*/b* at 325 mcd, 355 mcd, and 418 mcd correspond to distinct green intervals observed in the cores. Interval 420–550 is marked at 420 mcd by a pronounced downhole increase in NGR and MS, which is most likely the result of the lower carbonate content and associated L* reflectance below that depth. The top of interval 550–642 is defined by a sharp decrease in the chromaticity ratio a*/b*, corresponding to a visual color change in the cores. The MS values also drop at this depth, affirming that the drop in chromaticity is accompanied by a change in mineralogy. Overall, the sediment character is typical of deposition at bathyal depths on a continental slope, with oxygenated bottom water implying water depths exceeding the oxygen minimum zone (~600 m). However, the bulk mineralogy suggests that either a change in the source of the terrigenous material or a change in the weathering regime of the source region took place over time.

The concentration of methane (headspace analysis) increased downhole from <10 ppm at the top to a maximum of 85,000 ppm at 599 mcd. Ethane (C_2H_6) and propane (C_3H_8) initially appeared at 536 mcd and peaked at 608 mcd with concentrations of 155 and 7.3 ppm, respectively. The C_1/C_2 ratio reached a minimum of 345 at the bottom of the hole. A major decrease in the interstitial water salinity and chloride content occurs below 500 mcd, corresponding to the top of the interval of highest methane values, the appearance of higher order hydrocarbons, changes in lithologic color, and changes in physical properties. All of these changes appear to correlate with seismic reflector T_4, which can be traced back to a possible fault ~1 nmi from the site. This suggests that hydrocarbon and freshwater signals may have migrated laterally and that the other sedimentary changes are a diagenetic response to this change in environment.

At Site 1146 calcareous nannofossils are abundant and well preserved, although nannofossil preservation deteriorates below ~530 mcd. Benthic foraminifers are generally few but become more abundant in the lower part of the section. However, we found no clear evidence for reworked benthic foraminifers from the shelf and upper slope. Planktonic foraminifers are abundant and well preserved. The age at the bottom of the section is ~19 Ma. The Miocene section has relatively constant rates. The upper Miocene has an average LSR of 28 m/m.y. and total and carbonate MARs of 3.7 and 2.0 $g/cm^2/k.y.$, respectively; the middle Miocene has an average LSR of 28 m/m.y. and total and carbonate MARs of 4.2 and 1.4 $g/cm^2/k.y.$, respectively; and the lower Miocene has an average LSR of 31 m/m.y. and total and carbonate MARs of 4.9 and 1.4 $g/cm^2/k.y.$, respectively.

Overall, Site 1146 provides one of the most continuous Neogene sections ever recovered by the Ocean Drilling Program. The sediments are relatively high in carbonate and have rates of 30–150 m/m.y., which will enable construction of an orbital-scale stratigraphy back to the middle Miocene. This site will enable the reconstruction of monsoon proxies that can be used to test hypotheses about the late-Miocene intensification of the Asian summer monsoon and its relationship to tectonic events.

Sites 1147 and 1148

Sites 1147 (proposed site SCS-5E) and 1148 (proposed site SCS-5C) are located on the lowermost continental slope off southern China, near the continent/ocean crust boundary, and are the most offshore Leg 184 sites on the Chinese margin (Fig. 18). Site 1147 (18°50.11′N, 116°33.28′E, at a water depth of 3246 m) recovered the uppermost section that appeared to be missing on seismic profiles from Site 1148 (18°50.17′N, 116°33.94′E, at a water depth of 3294

m) (Table 1). The greater water depth and distance from terrigenous sources common to these sites combine to produce lower sedimentation rates at this location, at least within the late Neogene. The reason to locate Site 1148 on the lower continental slope was to take advantage of the thinner sediment thickness in order to recover the Oligocene and Miocene hemipelagic sediments that record the evolution and early paleoclimate history of the South China Sea. Elsewhere on the Chinese margin, the Oligocene sediments are too deep or are hydrocarbon bearing and thus cannot be cored to establish onset of monsoonal climates and variability in the SCS. We hoped that the combination of Sites 1148 and 1146 would provide a continuous history of accumulation rates that could be used to evaluate models of the SCS continental margin evolution, sea-level influence on deposition, and the impact of Himalayan-Tibetan uplift on monsoon onset and intensification. Site 1147 is located upslope ~0.45 nmi west of Site 1148 and was proposed during Leg 184 when Site 1148 was moved to a location within a surface slump scar. Hence, Site 1147 was designed to recover the continuous sequence of the uppermost hemipelagic sediments thought to be lost to slumping or channeling at Site 1148.

We cored three APC holes at Site 1147. Holes 1147A, 1147B, and 1147C were cored to depths of 81, 86, and 79 mbsf, respectively, with an average recovery of 99% (Table 1). At Site 1148, we cored two APC/XCB holes. Hole 1148A was continuously cored to 704 mbsf and then wireline logged with the full complement of logging tools: triple combo (111–711 mbsf), FMS-sonic (201–711 mbsf), and GHMT (201–711 mbsf). During logging operations, after we had confirmed that there were no significant hydrocarbon concentrations in the entire interval recovered in Hole 1148A, we requested approval to deepen Hole1148B beyond the originally approved 700 m penetration to extend the paleoenvironmental and tectonic record in time. Hole 1148B was APC cored to 152 mbsf; then, due to time constraints, drilled down from 152 to 450 mbsf, XCB cored to 650 mbsf, drilled down from 650 to 700 mbsf, and cored to 850 mbsf. The drilled-down intervals had excellent recovery in Hole 1148A. Downhole and bottom-water temperature measurements at Site 1148 yielded a thermal gradient of 83°C/km, which is consistent with the location and water depth.

The sediments at Sites 1147 and 1148 reflect a complex sequence of hemipelagic deposition, the beginning of which is coeval with the initiation of seafloor spreading in the South China Sea at ~32 Ma (Figs. 19, 20). The dominant lithologies are grayish green clay with quartz and nannofossils, olive gray and reddish brown clay with nannofossils, light grayish green clayey nannofossil ooze, brown nannofossil clay, and greenish gray nannofossil clay mixed sediment. Lower sections have the same composition but contain slumped and faulted intervals. The mcd scale and splice at Sites 1147 and 1148 are based on the stratigraphic correlation of whole-core multisensor track and split-core color spectral reflectance data (lightness, L*) collected at 5-cm intervals. Magnetic susceptibility data were the most useful stratigraphic tool for correlation at these sites. Natural gamma radiation and CR data were helpful in intervals where structure in the MS profile was ambiguous. At Site 1147, a composite spliced section was constructed from the three holes that spans the entire interval from 0 to 90.73 mcd. At Site 1148, an mcd scale was constructed over the entire cored sequence, 0 to 852 mcd. However, because of core recovery gaps throughout the sequence, the scale is discontinuous (“floating”) rather than linked to the sediment-water interface. A floating splice that extends from 46.57 to 155.34 mcd can be combined with data from nearby Site 1147 to construct a continuous mcd and splice, extending from 0 to 155.34 mcd.

Sediments of Pliocene–Pleistocene age at Sites 1147 and 1148 (0 to ~190 mcd) are composed of intensely bioturbated clay with quartz and nannofossils; the upper part is more clay rich and the lower part more nannofossil rich. Green clay layers and irregular green clay mottles decrease downsection, whereas lighter intervals with increased nannofossil content increase slightly downhole as do L*, MS, and bulk density. Siliceous microfossils are abundant in the upper Pleistocene and decrease rapidly to zero in the Pliocene. The core and wireline logging data show that the Pleistocene part of the section (to ~160 mcd) is characterized by a downhole increase in MS, which decreases during the Pliocene interval. A number of properties, including bulk density, porosity, and *P*-wave velocity, show typical downhole patterns related to compaction and dewatering. Natural gamma radiation and CR display more complex patterns related in part to the carbonate content. Almost all properties show the cyclic fluctuations that are associated with orbital-scale climate changes. The Miocene/Pliocene boundary is marked by an increase in the light carbonate-rich nannofossil clay layers and the disappearance of pyrite concretions. Total organic carbon decreases systematically from a maximum of 0.8% at the top of the hole to <0.2% by 130 mcd and remains at this level throughout the Miocene (to ~485 mcd). Based on C/N values, a purely marine organic source for organic matter is suggested for the upper 130 m of Site 1148. The variation in sulfur abundance follows that of TOC in the top 130 m of the hole, decreasing slowly with depth but exhibiting a normal marine S/C ratio (0.4). Interstitial water profiles at Site 1148 are dominated by sediment water exchanges driven by sulfate reduction in the upper 110 mcd. The upper Pleistocene interval has high H_4SiO_4 concentration indicative of the higher production of silica-bearing organisms. Sulfate values never reach zero, indicating that sulfate reduction is incomplete and methanogenesis is limited.

Calcareous nannofossils and planktonic foraminifers are abundant and well preserved in Pliocene/Pleistocene sediments. At Site 1148 (1147), the Brunhes/Matuyama boundary can be tentatively placed at 55.2 (58) mcd, the upper Jaramillo Subchron at 69.1 (71) mcd, the lower Jaramillo at 73 (76) mcd, the upper Olduvai Event at 111.4 mcd, and the lower Olduvai (tentatively) at 118.5 mcd. The age of the oldest sediments recovered at Site 1147 is estimated at 1.22–1.47 Ma. The combined biostratigraphy placed the Pleistocene/Pliocene boundary between 125.8 and 135.5 mcd and the Pliocene/Miocene boundary between 184.5 and 193.8 mcd.

The Miocene-age sediments at Site 1148 (~190–475 mcd) are a mixture of olive gray and reddish brown clay with nannofossils, light grayish green clayey nannofossil ooze, brown nannofossil clay with intervals and patches of reduced green ooze, and greenish gray nannofossil clay mixed sediment and nannofossil clay. The wireline logs of this interval reveal downhole increases in bulk density, electric resistivity, *P*-wave velocity, and photoelectric effect (PEF) but decreases in neutron porosity. Similar to the core-log data, MS has several local maxima but decreases downhole. Natural gamma radiation is variable but has no long-term trend until the lowermost Miocene, when it rapidly decreases at the slumped section. None of these units shows any evidence of sediment redeposition; they are representative of continuous hemipelagic sedimentation. These lithologic changes are reflected in the carbonate content and especially the CR a* and L* variations. The lowermost sediments have relatively high concentrations of diagenetically precipitated iron sulfide, seen as black, fine-grained material. Trace fossils are common, most notably Zoophycos and Chondrites, both characteristic deep-water (bathyal) forms. Evidence for redeposition in the lower Miocene sediments is sparse, although a few thin carbonate sand turbidites do occur.

Interstitial water profiles in the Miocene and Oligocene interval are dominated by sediment water exchanges driven by volcanic alteration, clay mineral diagenesis, and calcite recrystallization at depth. Sulfate values never reach zero, indicating that sulfate reduction is incomplete and methanogenesis is not an important process in these sediments. As a result, the high methane values at depth are related to thermogenic production of hydrocarbons.

The Oligocene-age sediments at Site 1148 (475–852 [mcd]) represent a major change in deposition. The uppermost Oligocene sediments are light tan in color, which reflects a distinct increase in carbonate content and the associated a* and L* CR values. This interval is also marked by a sharp increase in *P*-wave velocity, L* and a*/b* CR parameters, PEF, bulk density, and low porosity. These properties most likely reflect the increased carbonate content in this interval (50%–75%) and are probably responsible for prominent double reflectors seen in seismic reflection profiles. The sonic *P*-wave velocity of this interval is 2.3 km/s, which is substantially greater than the value of 2.1 and 1.9 km/s at the top and bottom of this interval, respectively. Although similar in composition to overlying sediments (i.e., dominantly clay nannofossil mixed sediments and nannofossil clays), this layer represents gravitational redeposition by mass flows and slumping as evidenced by convolute bedding, soft-sediment plastic deformation, and the occurrence of light-colored carbonate mud clasts within a massive bed of light gray to grayish brown nannofossil clay. These sediments also show clear evidence of brittle faulting in the form of small normal microfaults and thus are likely related to tectonic activity in the formation of the South China Margin. However, the matrix sediments often contain a deep-water trace fossil assemblage of Zoophycos and Chondrites and provide no evidence that water depths differed significantly from the overlying Miocene sediments. Iron sulfides, pyrite concretions, and green clay layers are rarely observed. A sudden increase in TOC is noted below 485 mcd (>0.4%), and the concentration of TOC remains in this range downhole (0.2%–0.5%). The higher C/N values in the lower section may indicate significant terrestrial input. Just below the slumped interval, salinity and chlorinity values become more variable, and ammonium and silica values increase. Changes in ammonium (as well as chloride and salinity) below 470 mcd can also be related to the dehydration reaction of clay minerals. In this interval XRD data show that below 470 mcd, smectite, illite, and kaolinite are absent and mixed-layer clays increase. The slump and the underlying chalk layer may act as a barrier to diffusion of gas and possibly to some elements. The microenvironments within fractures may also lead to variable interstitial water concentrations in this lower interval.

The bulk of the Oligocene sediment is an intensely bioturbated sequence of quartz-rich, grayish olive green nannofossil clay. The whole sequence is extremely monotonous, with little lithologic variation, and is characterized by low values of MS, bulk density (although disturbed by the XCB coring), NGR, and PEF and by decreased L* but increasing a*/b* parameter of CR. These trends generally reflect the decreased carbonate and increased clay content in the rapidly accumulating Oligocene section. The abundant bioturbation traces are strongly compacted and give the sediment a laminated appearance. High H_4SiO_4 concentration in the mid-Oligocene interval is likely associated with intervals of higher biogenic silica content. Toward the base of the section, evidence of current activity is found in the form of occasional flaser sandstone laminae that are dominated by quartz and lithic fragments as well as mica, glauconite, and foraminifer fragments. As with younger sediments, little evidence suggests that these early Oligocene sediments were deposited in substantially shallower water.

In the Oligocene sediments, total S concentration increases, following TOC. However, the S/C ratio is anomalously high for normal marine sediments (>1), suggesting the addition of S from another source. An increase in methane to the bottom of the hole (711 mcd) is accompanied by the presence of ethane and propane as well as heavier hydrocarbons downhole. Maximum methane and ethane concentrations were detected at 593 mcd (569 and 25, ppmv respectively). From the first detection of ethane at 480 mcd, the C_1/C_2 ratio declined rapidly from 99 to approach a minimum of 15 at the bottom of Hole 1148A. Between 715 and 851 mcd, methane concentrations remained low (<200 ppm) and decreased with depth downhole. The C_1/C_2 ratio decreased to as low as 4; this is expected, however, for the small amounts of organic matter in these poor source rocks as they enter the zone of petroleum maturation. As much as 50 ppm of C_5 and lesser amounts of other light hydrocarbons were detected.

Thirty-nine nannofossil and 29 planktonic foraminifer biostratigraphic datums were recognized from the lower Oligocene to Pleistocene sediments at Site 1148. A gap in the nannofossil and foraminifer datums indicates that sediments between the lowermost part of Zone NP25 (Zone N4) and Zone NN2 (Zone P22) are missing and that the base of Hole 1148B is still within Zone NP23 (P19) (<32.3 Ma). Site 1148 yields few to abundant deep-sea benthic foraminifers, and the ratio of benthic to planktonic foraminifers is high because of strong carbonate dissolution. The benthic foraminifers (e.g., *Heterolepa, Gavelinopsis, Globocassidulina*, *Martinottiela, Sigmoilopsis, Textularia,* and *Uvigerina*) in the lower part of Hole 1148A (>~510 mcd) are comparable to those observed at 1000–2000 m in the modern South China Sea. However, no clear evidence exists for reworked benthic foraminifers from the shelf and upper slope. An increase in the abundance of *Globobulimina* and *Chilostomella* (indicative of high productivity) was observed in the upper (above ~50 mcd) and lower (below ~500 mcd) sections of Hole 1148A. This corresponds to the higher organic carbon content and abundant siliceous fossil content (radiolarians and diatoms) found in the two intervals. Below the middle Miocene, nannofossils are moderately to well preserved, and planktonic foraminifers are poor to moderately preserved.

The stratigraphy at Site 1148 spans most of the postrift history of the South China Sea, including the entire duration of active seafloor spreading (Briais et al., 1993). Despite this, apart from a series of sharp color changes and associated differences in physical properties, very little lithologic variation has occurred since the early Oligocene, beyond a general trend toward decreasing carbonate content. Importantly, we found no apparent deepening or shallowing of the water depth of sedimentation, remaining hemipelagic and probably bathyal throughout. This is surprising given the anticipated thermal subsidence following middle Eocene rifting (e.g., Taylor and Hayes, 1980). The most noteworthy sedimentary feature at Site 1148 is the mass-flow sequence, which is also responsible for the prominent reflector at the base of the Miocene section. Ironically, the strong basement reflector at ~800 mbsf is within the gray-green Oligocene clays and does not show any distinct lithologic change (although recovery in this section was poor).

SYNTHESIS

Lithostratigraphic and Sedimentological Overview

The South China Sea sediments recovered on Leg 184 represent the simple mixing of nannofossil ooze and detrital clays derived from Asia, via the Pearl and Red Rivers on the northern margin and the Mekong and Molengraaff Rivers, and directly from Borneo on the southern margin. These sediments appear to represent deep-water deposition throughout the Neogene and back into the lower Oligocene. Although the dominant hemipelagic sedimentation is expected for a mature passive margin, the lack of coarse clastic material in the syn-spreading sequences cored at the base of Site 1148 (Fig. 21, Units VI and VII) is surprising given the expectation of a rugged and readily erodable syn-rift topography. Also, lower Oligocene coal-bearing swamp and littoral plain sediments are known to occur in wells of this age farther north within the Pearl River Mouth Basin (e.g., Su et al., 1989). The lack of similar coarse clastic material suggests that the Pearl River Mouth Basin and shallower slope basins were acting as efficient sediment traps. In addition, the presence of a deep-water, bathyal facies during the initial seafloor spreading period does not readily fit with simple rift models of the South China Margin. These facies may indicate that the margin extension proceeded very rapidly during the initial rifting phase in the middle Eocene (e.g., Taylor and Hayes, 1980; P. Clift and J. Lin, 1999). We note that the slumping, brittle faulting, and mineralization observed in Units VI and VII at Site 1148 (Fig. 21) indicate that the sediments do not completely postdate active tectonism.

Volcanic Ash

Although the volume of volcanic ash found in Leg 184 sediments is not large, it does provide some constraints on the activity of the volcanic arcs of the region. All recovered ashes are thin, generally <5 cm, and are light colored in the Pleistocene, reflecting a dominant dacitic-rhyolitic composition of the arc's explosive fraction. Most of the ashes were deposited since 1 Ma on the northern margin and since 2 Ma in the south. This trend is similar to the global pattern noted by Kennett and Thunell (1975), although it has been disputed by several authors (e.g., Ninkovich and Donn, 1976). The uphole increase in volcanic ash may reflect either more volcanic eruptions during the Pleistocene or the diagenetic alteration of chemically unstable volcanic glass during burial. This latter explanation may account for much of the pattern on the northern margin, since older ashes in this area tend to be devoid of glass and are simply composed of angular quartz, mica, and other accessory mineral grains. In contrast, at Site 1143, fresh glass is found in Miocene-aged ash beds. Certainly the Philippine Arc is not a recent feature; unless wind directions have radically changed, ashes from this arc were probably deposited over the entire cored interval.

Green Layers and Iron Sulfides

Green clay layers are a common, yet volumetrically small, part of the sequence at most of the Leg 184 drill sites. They occur as discrete layers as thick as 3 cm and even more commonly as disrupted layers, patches, or mottles. XRD analyses show that they are not glauconite, and no clear relationship is observed between green clay layers and depth of burial. Most of the layers are confined to the Pliocene–Pleistocene (Fig. 21) except for a lower Miocene set recovered at Site 1148. Their common association with burrows and patches caused by burrowing suggests that they may be linked to the presence of organic matter. Certainly their green color is suggestive of reducing conditions, which are linked to organic matter alteration. They do not seem to be equivalent to green layers found by Lind et al. (1993) on the Ontong Java Plateau and by Gardner et al. (1986) from the Lord Howe Rise, which were interpreted as altered volcanic ash. In the case of the South China Sea, the green clay layers are interbedded with clear tephra-bearing unaltered volcanic glass. No appreciable change in the background sediment is noted over these intervals; thus, the diagenetic environment seems uniform between beds. Other diagenetic minerals noted in the Leg 184 sediments are iron sulfide minerals (well-crystallized golden-colored pyrite often present as nodules, concretions, and replacement burrows) and fine-grained, black sulfide dispersed in the sediment. The latter style is described as FeS in the cores but as this is chemically unstable, this material must also be pyrite in mineralogy. The lack of a clear regional pattern either in depth or age in the distribution of pyrite or FeS suggests that the minerals' development reflects only local variations in sediment composition and burial.

Environmental History of the South China Sea

Leg 184, the first major Ocean Drilling Program campaign in the South China Sea, recovered a continuous sequence of deep-sea sediments that span the past 32 m.y. The geographic distribution of drill sites enables a comparison for the last 10 m.y. between the northern and southern parts of the South China Sea. The water-depth distribution of sites on the northern continental slope will enable comparisons above and below the modern sill depth (~2600 m), which connects the Pacific Ocean with the South China Sea. On the upper slope, we also recovered a section with extremely high sedimentation rates (>45 cm/k.y. on average) for the late Pleistocene. Preliminary estimations of sedimentation and MARs in combination with lithology, physical properties, geochemistry, and micropaleontological observations enable us to outline an environmental history of the South China Sea as recorded in the deep-sea sediments.

Oligocene: the Seafloor-Spreading Phase (Site 1148)

The lower and mid-Oligocene (Site 1148; 32–27 Ma, 850–480 mcd) are composed of laminated claystone with brownish gray and greenish gray stringers (Fig. 20, 21) and have high LSRs comparable to those in the Pleistocene (Figs. 22, 23). The average carbonate MAR from 480 to700 mcd (23.7–31 Ma) averages 3.45 g/cm^2/k.y. (Fig. 23), which is by far the highest observed over the past 32 m.y. at Site 1148. At the same time, the relatively high noncarbonate MAR implies a significant supply of terrigenous fine-grained clasts (Fig. 23). Because the ratio of carbonate to noncarbonate MAR is relatively constant, the high carbonate accumulation rate may reflect sediment focusing of upslope sediments as well as a higher surface productivity. The relatively high organic carbon content, the presence of siliceous microfossils, and the composition of benthic foraminiferal fauna also suggest higher productivity.

On the basis of magnetic anomaly (C11–C5c) patterns, the seafloor-spreading phase of the SCS took place between 32 and 16 Ma (Briais et al., 1993; Taylor and Hayes, 1983). Before 27 Ma, the newly opened deep-sea basin was oriented east to west and connected with the Pacific in the East. At that time, the South China Sea was a narrow basin between the Asian continent and a number of terranes that were eventually rifted to the southern part of the SCS (North Palawan and Reed Bank, among others). The high sedimentation and accumulation rates recorded at Site 1148 may be related to the incipient spreading phase, which might focus sediment input into the newly opened basin. Judging from the absence of marine sediments of this age on the northern shelf and upper slope, the ocean waters were restricted in the area. The proximity of continental runoff and sediment transport may be one of factors responsible for the higher rates of deposition in this interval. The poor core recovery in the upper part of this sequence (470–555 mbsf) suggests some lithologic changes in the latter part of the time interval. The scarcity of core samples, however, precludes any conclusion about the nature of the possible events.

A distinct and regionally consistent seismic reflector was observed to occur in the lower section of Site 1148. The *JOIDES Resolution* seismic reflection data indicated that the reflector was ~0.86 s below seafloor; the *P*-wave velocity data from downhole logging in Hole 1148A suggested that the reflector was ~800 mbsf. Although the drillers reported a distinct decrease in penetration rate at 800 mbsf, we did not recover any material that was indicative of a strong reflector. All cores in this interval were greenish gray claystone. The lack of coarse sediments, a weathering zone, or other features indicative of erosion or shallower water signify that this site was relatively deep throughout the deposition of the Oligocene sequence. The true nature of the acoustical basement reflector is unclear.

Latest Oligocene: a Turning Point (Site 1148)

The latest stage of the late Oligocene witnessed drastic changes in deposition at Site 1148. Carbonate content abruptly increased (~50%–70%) as chalk replaced clay over the depth interval of 457–478 mcd (Fig. 24). Almost all physical parameters reflect this rapid change, including sharp increases in bulk density, *P*-wave velocity, photoelectric effect, and CR parameters, and decreases in porosity, NGR, and MS values (Figs. 20, 25). However, the microfossil assemblages show the same fossil zone (P21b and NP24) as the underlying deposits. The chalk section is overlain by slump deposits of chalk and clay with a mixed nannofossil assemblage, and the absence of nannofossil zone NP25 indicates a deposition hiatus of ~1–3 m.y. at the end of Oligocene (Figs. 20, 22, 23).

The Oligocene/Miocene boundary represents one of the most significant changes in the tectonic and environmental history of the South China Sea during the Cenozoic (Wang, 1990). During this interval, the sedimentary basins of the northern SCS shelf are thought to have experienced a transition from the rifting stage to one of broad subsidence (Ru et al., 1994). According to the age model for Site 1148 (Fig. 22), the Oligocene/Miocene boundary events started ~27 Ma, at the same time that the spreading ridge of the SCS basin is thought to have jumped southward (Briais et al., 1993). Because of its position close to the boundary between continental and ocean crust, Site 1148 should have been sensitive to any tectonic episode associated with changes in the spreading of the SCS basin. Postcruise research will show whether the drastic changes in deposition regime at the site is related to the spreading event.

Early Miocene: Carbonate Deposition and Transgression (Sites 1146 and 1148)

The early Miocene (16.5–23.7 Ma) at Sites 1146 and 1148 is represented by a chalky clay with an average carbonate content of ~ 35% (Fig. 24). The total MARs for this interval average 1.13 g/cm^2/k.y. at both Sites 1146 and 1148, or about three times lower than in the Oligocene (Fig. 23). These lower rates are more representative of pelagic sedimentation and may also imply that the previously high rates were affected by sediment focusing on the margin. During the second stage of seafloor spreading (27–16 Ma), the South China Sea basin became much broader than in the Oligocene (Briais et al., 1993; Lee and Lawver, 1994). This early Miocene interval was distinguished by an expansion of reef facies in the shallow waters of the western Pacific including the Pearl River Mouth Basin. The relatively low carbonate accumulation rate but high carbonate content may be attributed to the more pelagic environment of the larger SCS basin, the lack of sediment focusing, and the wide distribution of reef facies on the shelves.

On the northern shelf, the early Miocene was a time of marine transgression. The marine intercalations in nearshore facies are first observed in the upper Oligocene (NP25) on the upper slope and shelf break in industrial wells (BY7-1-1, at a water depth of 499 m; and PY33-1-1, at a water depth of 188 m; Huang, 1997), and in the lower Miocene on the shelf (Wang, 1990). Further studies are needed to determine whether the local rise in sea level resulted from global eustatic changes or from tectonic subsidence of the basins and how this shelf transgression phase affected sedimentation at the deeper water Sites 1146 and 1148.

Middle Miocene: after the Spreading (Sites 1146 and 1148)

The seafloor-spreading phase of the SCS basin stopped at magnetic anomaly C5c or ~16 Ma, which is close to the boundary between early and middle Miocene. The middle Miocene section (~16–11 Ma) from the northern continental margin (Sites 1146 and 1148) has relatively high carbonate content (>30%), only slightly lower than the early Miocene but much higher than the modern values (Fig. 23). Carbonate increases at the shallower Site 1146 but remains high at Site 1148 despite its greater water depth, which is below the modern lysocline (~3000 m). Total accumulation rates of the early Miocene were 1.91 g/cm^2/k.y. at Site 1148, slightly lower than in the early Miocene and much lower than at Site 1146 (~4.34 g/cm^2/k.y.) (Fig. 24). Additional postcruise biostratigraphic control will be needed to establish whether the slower accumulation rates are related to a change in tectonics or to depositional hiatuses observed on the northern shelf.

Late Miocene: High Carbonate Supply (Sites 1143, 1146, and 1148)

Upper Miocene sediments were recovered in the northern SCS at Sites 1146 and 1148 and in the southern SCS at Site 1143. About half of the mass of sediments from both northern and southern sites above the modern lysocline (Sites 1146 and 1143) is composed of carbonate (Figs. 23A, 24). At Site 1143, the carbonate and noncarbonate accumulation remains high (Fig. 23A); Site 1146 shows a drastic increase in carbonate percentage (from ~40% in the middle Miocene to ~55% in the upper Miocene), but the increase in carbonate accumulation rate was not significant (from 1.46 g/cm^2/k.y. in the middle Miocene to 1.55 g/cm^2/k.y. in the upper Miocene) (Figs. 23A, 24). At Site 1148, the average carbonate percentage still exceeds 30% (Fig. 24), but the poor preservation of planktonic foraminifers shows enhanced carbonate dissolution. During this late Miocene interval, differences begin to develop between the shallower Site 1146 and the deeper Site 1148. In the shallow site, NGR values are lower and decreasing whereas PEF values are increasing; in the deeper site, the NGR values are higher and much more variable, as are the PEF values. These changes suggest more clay-carbonate contrasts in the deeper Site 1148 and are generally consistent with the higher carbonate in Site 1146.

Despite the similar carbonate concentrations in upper Miocene sediments, the accumulation rate at Site 1143 is about two times higher (~3 g/cm^2/k.y.) then at Site 1146 (~1.5 g/cm^2/k.y.) (Figs. 23, 24). The high carbonate accumulation at tropical Site 1143 might be related to the late Miocene to early Pliocene "biogenic bloom" in the equatorial Pacific but also seems partly related to redeposition of adjacent sediments as evidenced by the frequent turbidites and slumped sediments in the lower section. The preservation of siliceous microfossils in the lower section may indicate higher productivity at that time. The high carbonate percentages in the Miocene deposits from the northern sites imply a low supply of terrigenous clasts from the land that may be related to rising sea levels during this interval (Prell and Kutzbach, 1997). In general, the high carbonate sediments throughout the Miocene and the similarity between the northern and southern sites suggest a much more uniform environment than during the Pliocene–Pleistocene.

Pliocene and Pleistocene: Increase of Terrigenous Input (Sites 1143, 1144, 1145, 1146, 1147, and 1148)

Leg 184 recovered Pliocene deposits at four sites (1143, 1145, 1146, and 1148) and Pleistocene sediments at all six sites, although with substantially different accumulation rates (Fig. 23B). Despite the different LSRs, all sites exhibit a significant increase in silica at ~1 Ma, which is ascribed to increased productivity. Differences between the southern and northern SCS also begin to emerge during this interval.

At the southern Site 1143, both carbonate and noncarbonate accumulation rates decrease from the upper Miocene to Pliocene (Fig. 23B): carbonate from 2 to 4 g/cm^2/k.y. to ~1 g/cm^2/k.y., and noncarbonate from 3 to 4 g/cm^2/k.y. to ~2 g/cm^2/k.y. The decreasing trend continues to the Pleistocene for carbonate, whereas the noncarbonate rate rises up again after ~3 Ma, indicating some increased supply of terrigenous material. However, unlike the northern sites, the MAR at Site 1143 decreases toward the present despite the increase in LSR, a result of decreased bulk density within that most recent interval.

On the northern continental margin, Pliocene accumulation rates remain at the late Miocene level at Sites 1146 and 1148 but with slightly lower rates in the deeper Site 1148. Both sites exhibit the rapid increase in LSR and noncarbonate deposition that starts at ~3 Ma. Site 1145 records only the past 3 m.y., but the noncarbonate accumulation increases after ~ 2.5 Ma. This apparently regional increase in noncarbonate accumulation may be evidence for an intensification of erosion that is related to climatic/sea-level and/or tectonic events. For example, Chinese geologists report evidence for significant uplift of the Tibetan Plateau at ~3 Ma (e.g., Li et al., 1996), and the widespread accumulation of loess in central China started ~2.4 Ma. However, sea-level changes associated with increased global glaciation may have also contributed to transporting sediments to these continental margin sites.

In contrast to the southern site, all the northern sites show an increase in MAR in the late Pleistocene, especially the last 0.25 m.y. (Fig. 23B). The higher MAR is mainly the result of increased supply of terrigenous material, as the carbonate contribution is insignificant for that time interval. The trend is most prominent for Sites 1144, 1145, and 1146. The cause of this most recent increase is not clear at this stage. The relatively high content of biogenic silica and organic carbon indicate an enhanced productivity for the latter part of the Pleistocene.

The general decrease in carbonate concentration upsection, particularly since the mid-Pliocene (Figs. 21, 23, 24), could also reflect decreasing carbonate productivity as well as increasing clastic input, both of which might be expected from an intensification of glaciation at that time. Glaciation is known to have produced arid conditions in Asia and reduced runoff into the South China Sea, although windblown material such as loess may be more important at these times. However, glaciation in the Himalayas (and possibly Tibet) would be expected to produce more clastic debris that would then be available for redeposition when rainfall increased again at the start of deglaciation. The increasing strength of glacial cycles, especially since ~2.5 Ma, correlates well with the general increase in the detrital component since that time. The variation from darker to lighter sediment intervals noted at a number of the northern margin sites—more precisely represented as cyclic variations in core-logging data such as CR, NGR, and MS—most likely reflects such glacial–interglacial variation in clay and carbonate accumulation.

Summary

In summary, the sequence of hemipelagic sediments over 30 m.y. is rich in calcareous microfossils and yields almost continuous records of the environmental history of the South China Sea. The depositional history of the northern slope had three important stages: the Oligocene, with extremely high sedimentation rates; the Miocene and early Pliocene, with a low sedimentation rate and high carbonate content; and the last 3 m.y., with high clastic sediment accumulation rates. A different trend of depositional history is indicated at the southern Site 1143: the carbonate accumulation rate decreases from the late Miocene toward the late Pleistocene, and the noncarbonate rate rises again after 3 Ma. However, the upper Miocene sediments were similar in composition between the northern and southern sites, containing more than 50% of carbonate.

Geothermal Gradients: Tectonics and Hydrocarbon

The downhole temperature measurements at Leg 184 sites revealed two distinct temperature gradients as a function of the water depth (Fig. 26). At Sites 1143 (2772 m), 1145 (3175 m), and 1148 (3294 m), the gradients were relatively high (83° to 90°C/km) and were quite similar between the sites. These sites are all deep and relatively close to the boundary between continental and ocean crust. Preliminary calculations suggest that temperature gradients at these sites are close to predictions based on the pure shear stretching model of continental lithosphere, the corresponding water depth of the drill sites, and the assumed age of initial rifting (32 Ma). The two sites on the mid-continental slope (Sites 1144, 2037 m; and 1146, 2092 m) have smaller gradients (24° and 59°C/km, respectively) and differ from the deeper sites and from each other. The gradient at Site 1144 is substantially smaller than the predicted value based on water depth and spreading age, and a local process must be inferred to explain the low temperatures at this high sedimentation rate site.

Significant hydrocarbon concentrations were detected at three sites during Leg 184 (Fig. 27). Abundant methane of biogenic origin was inferred only from Site 1144. High TOC abundance and complete sulphate reduction in the upper few meters of this site (and the absence of significantly heavier hydrocarbons downhole) are characteristic of methanogenesis in immature sediments.

In contrast, the downhole increase in hydrocarbon abundance at Sites 1146 and 1148 is characteristic of thermogenic generation with age and increasing temperatures with depth. These two deeper penetration sites on the continental margin have predicted bottom-hole temperatures of only 35°C at Site 1146 (607 mbsf) but 71°C at Site 1148 (853 mbsf). The temperatures in the lower interval of Site 1148 are thought to be high enough to begin the process of thermal generation of hydrocarbons from the low amounts of organic carbon (0.3% to 0.5%) and may well explain the observation of sparse heavy hydrocarbons (C_{2+}) at the site. None of the Leg 184 sites revealed conditions for source rock production, and no gas hydrates were observed.

Interstitial Waters: Silica and Sulfate

The interstitial water profiles measured during Leg 184 reflected sulfate reduction and methanogenesis in the upper sediments. Below the zone of organic matter reduction, interstitial water profiles reflected alteration of volcanic ashes, diagenesis of clays, dissolution of silica, and dissolution/recrystallization of calcite at depth. These data revealed two clear trends in the SCS sediments:

1. The extent and depth of sulfate reduction reflects both the supply of organic matter and the large range of sedimentation rates.
2. Dissolved silica increases across the SCS at ~1 Ma.

We found that the sulfate gradient (i.e., the decrease in sulfate values from oceanic values, 28.9 mM, to the value of the sulfate plateau) increased linearly with sedimentation rate but not with the TOC concentration. The sulfate gradient is controlled both by the supply of organic matter to be consumed by sulfate reduction and by the extent to which seawater sulfate can continue to diffuse into interstitial water and replenish the sulfate removed by sulfate reduction. Hence, the linear relationship between sulfate gradient and sedimentation rate is established both by the correlation between high LSR and higher TOC flux to the seafloor, and by the length of time that near-surface sediments continue to receive new sulfate from seawater. The extreme sulfate gradient observed at Site 1144 appears to be more a function of high sedimentation rates than the supply of organic matter because the LSR is so high (>62 cm/k.y.) that sediments move out of the diffusional contact with seawater faster than organic matter can be depleted. This rapid removal of organic matter from the zone of sulfate reduction is consistent with the good preservation of organic matter with depth at this site. All other sites follow a more linear relationship between sulfate gradient and both LSR and TOC. Site 1143 has the lowest values observed and is the most distant from continental sources.

All the dissolved silica profiles showed an increase of similar magnitude between ~1 and 0.5 Ma, which corresponds to an increase in the abundance of biogenic silica in the sediments (Fig. 28). This increase in dissolved silica occurs at very different depths at different sites, suggesting that it is not related to diagenetic changes in silica. Instead, the increase in dissolved silica implies that an increase in biogenic silica observed in the sediments is a real change in silica flux to the sediments. This increase is somewhat coincident with increasing sedimentation and organic carbon accumulation rates, which could imply increased preservation related to LSR or overall increased silica productivity. In either case, the increase in silica appears to be a regional change, suggesting climatic or tectonic changes.

CONCLUSIONS

Leg 184 recovered a sequence of hemipelagic sediments that record the past 31 m.y. of environmental history of the South China Sea. For the first time in the lower latitude western Pacific, these cores provide a high-resolution continuous record of relatively carbonate-rich fine-grained sediments and a possibility of sea-land correlation of the upper Cenozoic stratigraphy for the region.

The lithologies, microfossils, and physical properties of the hemipelagic sequence reveal significant trends, clear cyclicities, and abrupt changes that provide detailed records of environmental transformations, including provenance and volcanism. The most prominent are variations in CR, MS, and NGR, which exhibit obvious orbital-scale and finer fluctuations in monsoonal climate.

The discovery of high accumulation rate (5–20 g/cm^2/k.y.) Oligocene hemipelagic sediments on the lower continental slope near the continent crust margin probably reflects active downslope transport of terrigenous sediment during the early stage of seafloor spreading of the South China Sea basin. This “deep-water” sequence continues below the “acoustic basement,” which might be a thick marine Paleogene section.

The Oligocene/Miocene boundary in the northern SCS is marked by sedimentary deformation, abrupt lithologic changes, and a stratigraphic hiatus. These related features will help resolve the nature and timing of one of the most significant Cenozoic tectonic and climate changes of the region.

Cores from all drill sites show a high carbonate content for the Miocene and lower Pliocene in both the northern and southern South China Sea. The low terrigenous input and partly high carbonate production resulted in a sediment environment in the northern slope similar to that near the reef areas in the southern part of the sea in the Miocene; accumulation rates, however, are significantly different in the northern and southern SCS after the Miocene.

A general increase of noncarbonate sediment accumulation after 2–3 Ma was found at all drill sites; for the northern sites, the increase has become even more significant in the latter part of the last million years. A site with exceptionally high rates of hemipelagic fine-grained sedimentation (Site 1144, 450 m of sediment for the last 1 m.y.) offers a unique opportunity for fine-resolution paleoenvironmental studies at decadal scale.

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TABLE CAPTION

Table 1. Leg 184 operational summary.

FIGURE CAPTIONS

Figure 1. Climatology of the summer and winter monsoon circulation. Surface winds for the **(A)** winter (January) and **(B)** summer (July) seasons along with areas of high (H) and low (L) pressure. Precipitation (6 and >9 mm/day contours) for the **(C)** winter (January) and **(D)** summer (July) seasons. The pressure gradients and resulting wind and precipitation patterns reflect the land-sea heating contrasts, which are a function of solar radiation, elevation, and land-surface boundary conditions. Monthly data, 1990–1997, from National Oceanic and Atmospheric Administration, National Centers for Environmental Prediction/National Center for Atmospheric Research, Climate Data Assimilation System-1 (Kalnay et al., 1996).

Figure 2. Map of the South China Sea showing locations of Leg 184 drilling areas. BS = Bashi Strait, SCS = South China Sea.

Figure 3. Tectonic setting of the South China Sea. **A.** Major tectonic elements of the northern and central parts of the South China Sea. Thick dotted line outlines the Central Basin with selected magnetic anomaly lineaments. Thin dotted and solid lines are isobaths of 200 and 2000 m (Hayes et al., 1995a). Thick dashed box corresponds to Figure 3. **B.** Geological framework of the northern margin of the South China Sea (Ru et al., 1994). YGHB = Yinggehai Basin, QDNB = Qiongdongnan Basin, BBWB = Baibiwan Basin, PRMB = Pearl River Mouth Basin, SWTB = Southwest Taiwan Basin. Leg 184 sites are located south of Dongsha Island on the continental margin between the Pearl River Mouth Basin and the South China Sea Basin.

Figure 4. Marine and terrestrial observations indicating an intensification of the monsoon in the late Miocene (10–8 Ma) and a model simulation of a possible evolution of monsoon runoff. **A.** Abundance of planktonic foraminifer *Globigerina bulloides* and radiolarian *Actinoma* spp. that indicate active upwelling induced by southwest monsoonal winds (from ODP Site 722, Arabian Sea). **B.** Oxygen and carbon isotopes measured in pedogenic carbonates from Pakistan indicating more seasonal climates and a decrease in atmospheric CO_2, possibly from monsoon-related weathering (data from Quade et al., 1989). Open circles = $\delta^{13}C$ (‰); solid circles = $\delta^{18}O$ (‰). **C.** Normalized, mean terrigenous sediment flux to the northern Indian Ocean that suggests active uplift and fluvial deposition in the late Miocene (from Rea, 1992). **D.** A model simulation of

monsoon runoff, relative to control simulation, using the Molnar model for uplift history (11–8 Ma) and the coupled effects of elevation change and orbitally induced solar radiation changes.

Figure 5. Summary of monsoonal stages defined from land-based studies in China, after Wang (1997), Wang (1990), and Liu and Ding (1982). SCS = South China Sea.

Figure 6. A composite stratigraphy from industrial wells in the eastern part of the Pearl River Mouth Basin, which lies on the shelf and uppermost continental slope northwest of the northern sites (PRMB in Fig. 3 for bathymetry). These wells provide the seismic reflector sequence and general age structure to be correlated with the more marine ODP sites on the slope. Note the nonmarine sequence beginning from the upper Oligocene (modified from Jiang et al., 1994).

Figure 7. East Asian monsoon climate change in the northern SCS during the last glacial cycle from a core recovered during the SONNE 17940 cruise. The plots shown are, from top to bottom: total grain-size mode, clay content, stable oxygen isotope values from *Globigerinoides ruber*, and, for reference, the oxygen isotope record from the GISP2 ice core. EHPB = early Holocene/Preboreal, Y.D. = Younger Dryas, B/A = Boelling/Alleroed, H1–H4 = Heinrich Events 1–4, O.D. = Oldest Dryas, LGM = Last Glacial Maximum. Data from Wang et al. (1999).

Figure 8. Site location map for the southern South China Sea Site 1143. The irregular seafloor bathymetry reflects both the highly irregular bathymetry and the low abundance of survey data in the Spratly Island or Dangerous Grounds area.

Figure 9. Site location map for the northern South China Sea Sites 1144–1148.

Figure 10. Precruise seismic line across Site 1143. Line NS95-240, common depth point (CDP) 3617. Water depth = 2774 m. Penetration depth = 500 mbsf. Graphic presentation is approximate.

Figure 11. Summary diagram of coring results at Site 1143 on the mcd scale. Maximum penetration measured with the drill pipe is 500 mbsf. The core recovery column is a graphic presentation of the cored and recovered intervals for each hole. Larger gaps are the result of coring problems (<100% nominal recovery); smaller gaps (typically 0.5–2.0 m), revealed by hole-to-hole correlation, occur even when nominal core recovery is 100% or more. The graphic lithology column presents the major sediment types: horizontal line patterns are clay; diagonal dashed patterns are nannofossil ooze with foraminifers. Lithologic units are also shown. Mass accumulation rates (MARs) were calculated for total sediment (light gray histograms) and carbonate only (darker gray, solid histograms) from 5-m interval sampling of the smoothed

depth-age model, dry density, and carbonate concentration. The smoothed depth-age curve (line) is overlain with control points from nannofossil (squares) and foraminifer (circles) biostratigraphy and magnetostratigraphy (crosses [shown for other sites]). The color reflectance lightness (L*) parameter (solid line) was measured every 2–4 cm and smoothed with a 20-point moving average for this figure. Carbonate concentration, expressed as percent calcite (dots with dashed line), was measured every ~3.5 m. Magnetic susceptibility (thicker line) and natural gamma radiation (thinner line) were measured every 2–5 cm, and the records presented here are smoothed with a 20-point moving average. Porosity (solid line) and grain density (dots with dashed line) were calculated from moisture and density measurements on samples taken every 1.5–3.0 m. Bulk density (solid line) and dry density (dots with dashed line) were calculated from moisture and density measurements on samples taken every 1.5–3.0 m.

Figure 12. Precruise seismic line across Site 1144. Line SO95-10, CDP 9700 (4:20). Water depth = 2037 m. Penetration depth = 453 mbsf. Graphic presentation is approximate.

Figure 13. Summary diagram of coring results at Site 1144 on the mcd scale. Maximum penetration measured with the drill pipe is 453 mbsf. See Figure 11 for further explanation.

Figure 14. Precruise seismic line across Site 1145. Line SO-95-10, CDP 4680 (11:10). Water depth = 3175 m. Penetration depth = 200 mbsf. Graphic presentation is approximate.

Figure 15. Summary diagram of coring results at Site 1145 on the mcd scale. Maximum penetration measured with the drill pipe is 200 mbsf. See Figure 11 for further explanation.

Figure 16. Leg 184 seismic line across Site 1146. Line JR184-3, shot point (SP) 3240. Water depth = 2092 m. Penetration depth = 607 mbsf. Graphic presentation is approximate.

Figure 17. Summary diagram of coring results at Site 1146 on the mcd scale. Maximum penetration measured with the drill pipe is 607 mbsf. See Figure 11 for further explanation.

Figure 18. Leg 184 seismic line across Sites 1147 and 1148. Site 1147: Line JR184-1, SP 1940. Water depth = 3246 m. Penetration depth = 86 mbsf. Site 1148: Line JR184-1, SP 1980. Water depth = 3294 m. Penetration depth = 853 mbsf. Graphic presentation is approximate.

Figure 19. Summary diagram of coring results at Site 1147 on the mcd scale. Maximum penetration measured with the drill pipe is 86 mbsf. See Figure 11 for further explanation.

Figure 20. Summary diagram of coring results at Site 1148 on the mcd scale. Maximum penetration measured with the drill pipe is 853 mbsf. See Site Figure 11 for further explanation.

Figure 21. Coring penetration and lithologic units as a function of age in the Leg 184 drilling sites. Horizontal dashed pattern = clay, brick pattern = nannofossil ooze with foraminifers. Gray bands = the occurrence of frequent green clay layers.

Figure 22. Age-depth relationships for Leg 184 sites. Solid lines = smoothed depth-age models, gray dots = the actual shipboard age calls from nannofossil and foraminifer biostratigraphy and from paleomagnetism. The thicker line highlights the different trend for the southern South China Sea Site 1143 as compared to the northern sites. The inset presents the past 3 m.y. at a greater resolution than the main diagram.

Figure 23. Summary of total (stippled histograms) and carbonate (solid histograms) mass accumulation rates (MARs) vs. age, and linear sedimentation rates (LSRs; solid line). **A.** The three longest records from Leg 184. **B.** Close-up for the last 3 m.y. for all Leg 184 sites.

Figure 24. Summary of carbonate concentration vs. age for the three longest records obtained on Leg 184. Note the common pattern of high values in the upper Miocene that decline toward the present.

Figure 25. Downhole logs as a function of depth. **A.** Total gamma radiation (American Petroleum Institute [API] units) and *P*-wave velocity. **B.** Magnetic susceptibility and photoelectric effect (PEF). Because the sedimentation rates differ greatly between the sites, epoch boundaries are shown to correlate with similar age intervals between the sites.

Figure 26. **A.** Downhole temperature gradients from Leg 184 sites, presented as linear best fits to 4–5 measurements per site. **B.** Temperature gradients plotted as functions of the water depths for Leg 184 drill sites.

Figure 27. Summary of methane concentrations (headspace method) at the Leg 184 sites that showed significant amounts of gas.

Figure 28. Summary of silica (H_4SiO_4) concentration trends in interstitial water from all Leg 184 sites (except Site 1147), plotted **(A)** vs. meters composite depth (mcd), **(B)** vs. age (Ma), and **(C)** vs. the last 3 m.y. (Ma).

Table 1. Leg 184 operational summary.

Site/hole	Latitude	Longitude	Water depth (m)	No. of cores	Interval cored (m)	Core recovered (m)	Recovery (%)	Drilled (m)	Penetration (m)
Leave Fremantle									
1143A	9° 21.720'N	113° 17.102'E	2771.0	44	400.0	378.28	94.6	0	400.0
1143B	9° 21.717'N	113° 17.104'E	2772.5	28	258.2	246.37	95.4	0	258.2
1143C	9° 21.713'N	113° 17.119'E	2773.5	54	500.0	477.54	95.5	0	500.0
Site 1143	**9° 21.72'N**	**113° 17.11'E**	**2772**	**126**	**1158.2**	**1102.19**	**95.2**	**0**	**1158.2**
1144A	20° 3.180'N	117° 25.133'E	2035.7	48	452.8	468.88	103.6	0	452.8
1144B	20° 3.180'N	117° 25.143'E	2038.5	49	452.0	445.83	98.6	0	452.0
1144C	20° 3.182'N	117° 25.152'E	2036.9	21	198.7	198.17	99.7	5	203.7
Site 1144	**20° 3.18'N**	**117° 25.14'E**	**2037**	**118**	**1103.5**	**1112.88**	**100.9**	**5**	**1108.5**
1145A	19° 35.040'N	117° 37.868'E	3175.6	22	200.0	186.54	93.3	0	200.0
1145B	19° 35.042'N	117° 37.858'E	3174.4	22	200.0	179.44	89.7	0	200.0
1145C	19° 35.039'N	117° 37.850'E	3176.4	21	198.1	189.15	95.5	0	198.1
Site 1145	**19° 35.04'N**	**117° 37.86'E**	**3175**	**65**	**598.1**	**555.13**	**92.8**	**0**	**598.1**
1146A	19° 27.402'N	116° 16.363'E	2091.1	64	607.0	603.85	99.5	0	607.0
1146B	19° 27.401'N	116° 16.376'E	2091.7	26	245.1	241.71	98.6	0	245.1
1146C	19° 27.403'N	116° 16.385'E	2091.7	63	598.5	606.66	101.4	5	603.5
Site 1146	**19° 27.40'N**	**116° 16.37'E**	**2092**	**153**	**1450.6**	**1452.22**	**100.1**	**0**	**1455.6**
1147A	18° 50.108'N	116° 33.271'E	3245.9	9	81.4	81.7	100.4	0	81.4
1147B	18° 50.108'N	116° 33.280'E	3245.4	9	85.5	85.5	100.0	0	85.5
1147C	18° 50.109'N	116° 33.280'E	3245.3	9	78.6	76.6	97.5	0	78.6
Site 1147	**18° 50.11'N**	**116° 33.28'E**	**3246**	**27**	**245.5**	**243.84**	**99.3**	**36.4**	**245.5**
1148A	18° 50.167'N	116° 33.932'E	3297.1	77	704.0	632.1	89.8	0.0	704.0
1148B	18° 50.170'N	116° 33.946'E	3291.8	56	500.6	364.4	72.8	352.6	853.2
Site 1148	**18° 50.17'N**	**116° 33.94'E**	**3294**	**133**	**1204.6**	**996.50**	**82.7**	**193.5**	**1557.2**
Arrival in Hong Kong									
Leg 184 totals:				**622**	**5760.5**	**5462.76**	**Mean: 94.8**	**234.9**	**6123.1**

Table 1 (continued).

Site/hole	Arrival (local)	Departure (local)	Time on hole (hr)	Time on hole (days)	Transit (days)	No. of APC cores	No. of XCB cores	No. of RCB cores	Seafloor (mbrf)	Rig floor elevation (m)	Total penetration (mbrf)
Leave Fremantle		2/19/99 17:30									
					11.94						
1143A	3/3/99 16:00	3/6/99 23:45	79.75	3.32		21	23	0	2782.0	11.0	3182.0
1143B	3/6/99 23:45	3/8/99 0:10	24.42	1.02		19	9	0	2783.5	11.0	3041.7
1143C	3/8/99 0:10	3/10/99 5:45	53.58	2.23		19	35	0	2784.5	11.0	3284.5
Site 1143			**157.75**	**6.57**		**59**	**67**	**0**	**2783.3**	**11.0**	**3169.4**
					3.50						
1144A	3/13/99 17:45	3/16/99 6:55	61.17	2.55		25	23	0	2047.0	11.3	2499.8
1144B	3/16/99 6:55	3/17/99 21:15	38.33	1.60		22	27	0	2049.8	11.3	2501.8
1144C	3/17/99 21:15	3/18/99 16:45	19.50	0.81		21	8	0	2048.2	11.3	2251.9
Site 1144			**119.00**	**4.96**		**68**	**58**	**0**	**2048.3**	**11.3**	**2417.8**
					0.13						
1145A	3/18/99 19:45	3/20/99 0:30	28.75	1.20		14	9	0	3187.1	11.5	3387.1
1145B	3/20/99 0:30	3/20/99 19:00	18.50	0.77		13	0	0	3185.9	11.5	3385.9
1145C	3/20/99 19:00	3/21/99 16:45	21.75	0.91		13	8	0	3187.9	11.5	3386.0
Site 1145			**69.00**	**2.88**		**40**	**17**	**0**	**3187.0**	**11.5**	**3386.3**
					0.29						
1146A	3/21/99 23:45	3/25/99 13:50	86.08	3.59		21	43	0	2102.6	11.5	2709.6
1146B	3/25/99 13:50	3/26/99 14:15	24.42	1.02		23	3	0	2103.2	11.5	2348.3
1146C	3/26/99 14:15	3/29/99 6:15	64.00	2.67		17	46	0	2103.2	11.5	2706.7
Site 1146			**174.50**	**7.27**		**61**	**92**	**0**	**2103.0**	**11.5**	**2588.2**
					0.18						
1147A	3/29/99 10:30	3/30/99 2:00	15.50	0.65		9	0	0	3257.5	11.6	3338.9
1147B	3/30/99 2:00	3/30/99 10:00	8.00	0.33		9	0	0	3257.0	11.6	3342.5
1147C	3/30/99 10:00	3/30/99 19:15	9.25	0.39		9	0	0	3256.9	11.6	3335.5
Site 1147			**32.75**	**1.36**		**27**	**0**	**0**	**3257.1**	**11.6**	**3339.0**
					0.04						
1148A	3/30/99 20:15	4/4/99 16:00	115.75	4.82		16	61	0	3308.7	11.6	4012.7
1148B	4/4/99 16:00	4/10/99 22:15	150.25	6.26		15	41	0	3303.4	11.6	4156.6
Site 1148			**266.00**	**11.08**		**31**	**102**	**0**	**3306.1**	**11.6**	**4084.7**
Arrival in Hong Kong	4/12/99 8:30				1.43						
Leg 184 totals:			**819.00**	**34.13**	**17.50**	**286**	**336**	**0**	**2383.5**	**Mean: 9.8**	**18985.4**

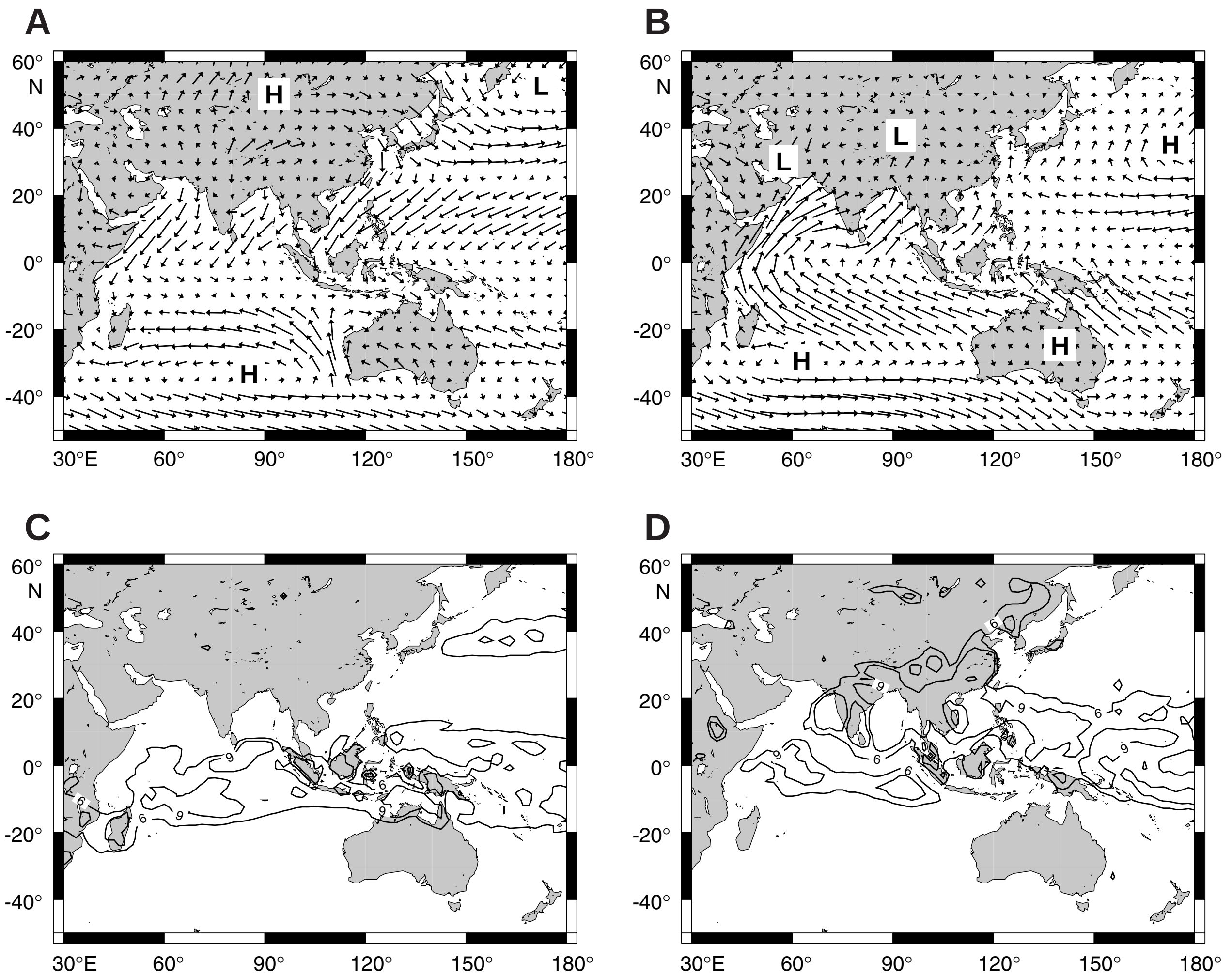
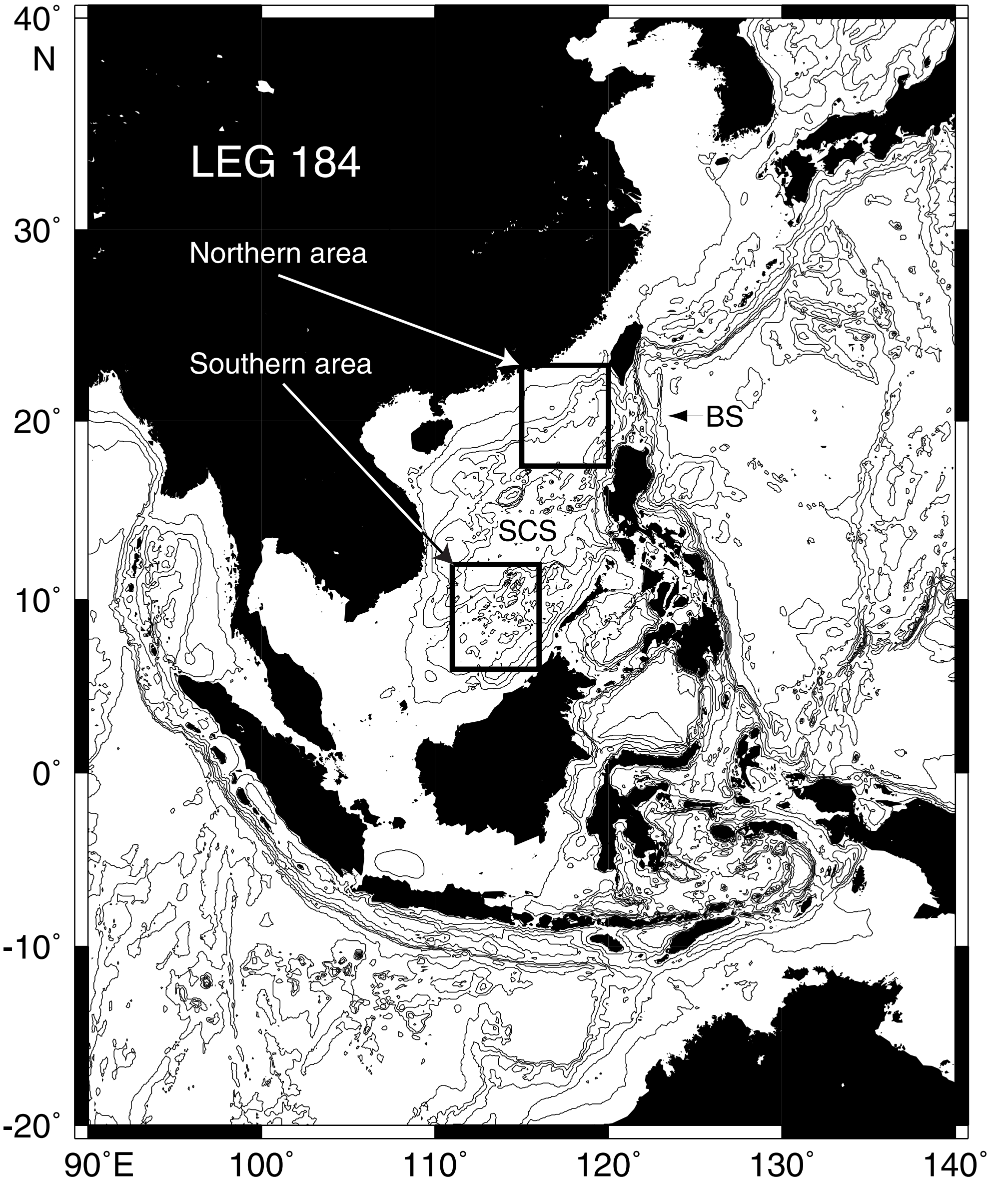


Figure 1



40°
N
30°
20°
10°
0°
-10°
-20°
90°E
100°
110°
120°
130°
140°
LEG 184
Northern area
Southern area
SCS
BS

Figure 2

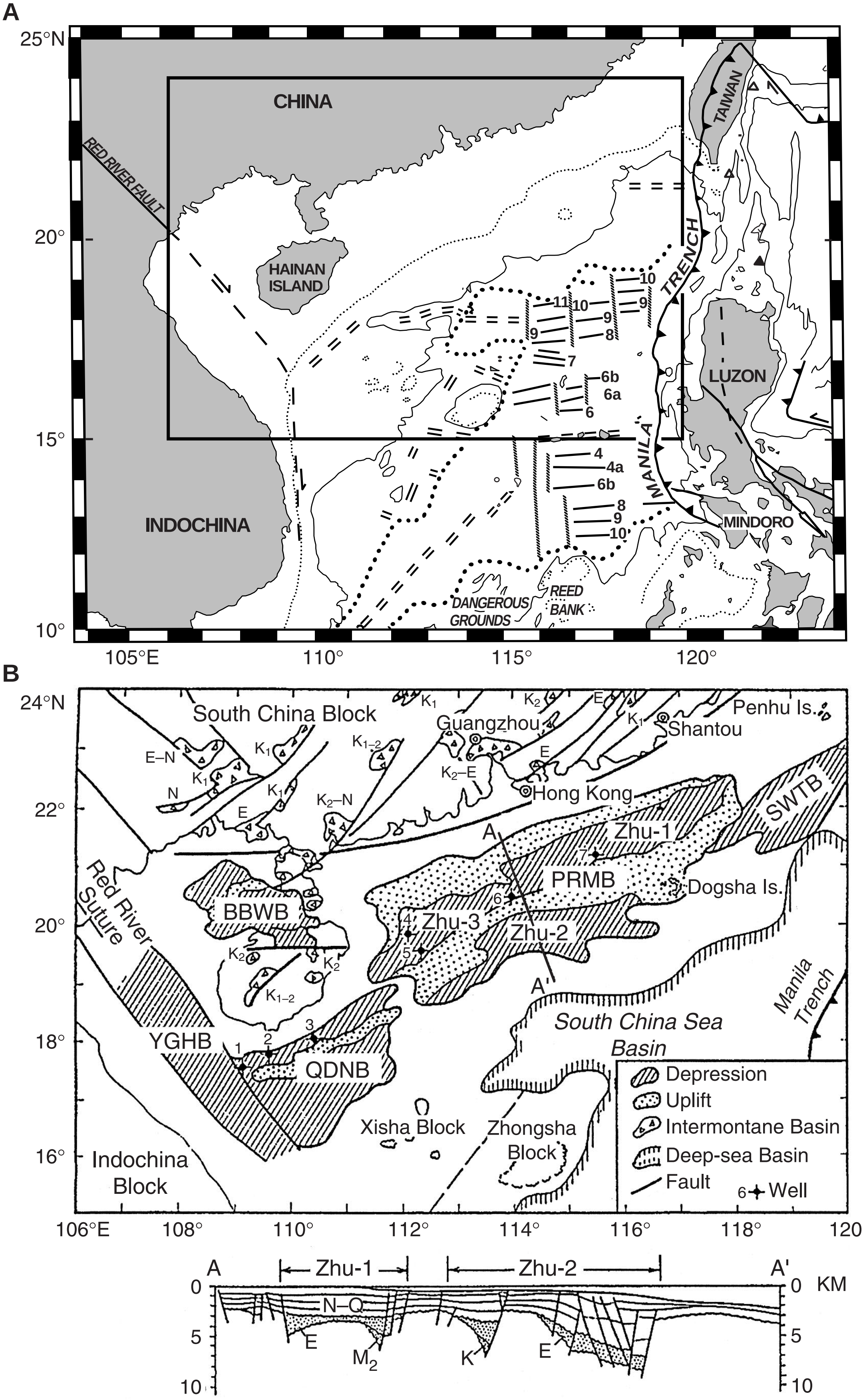
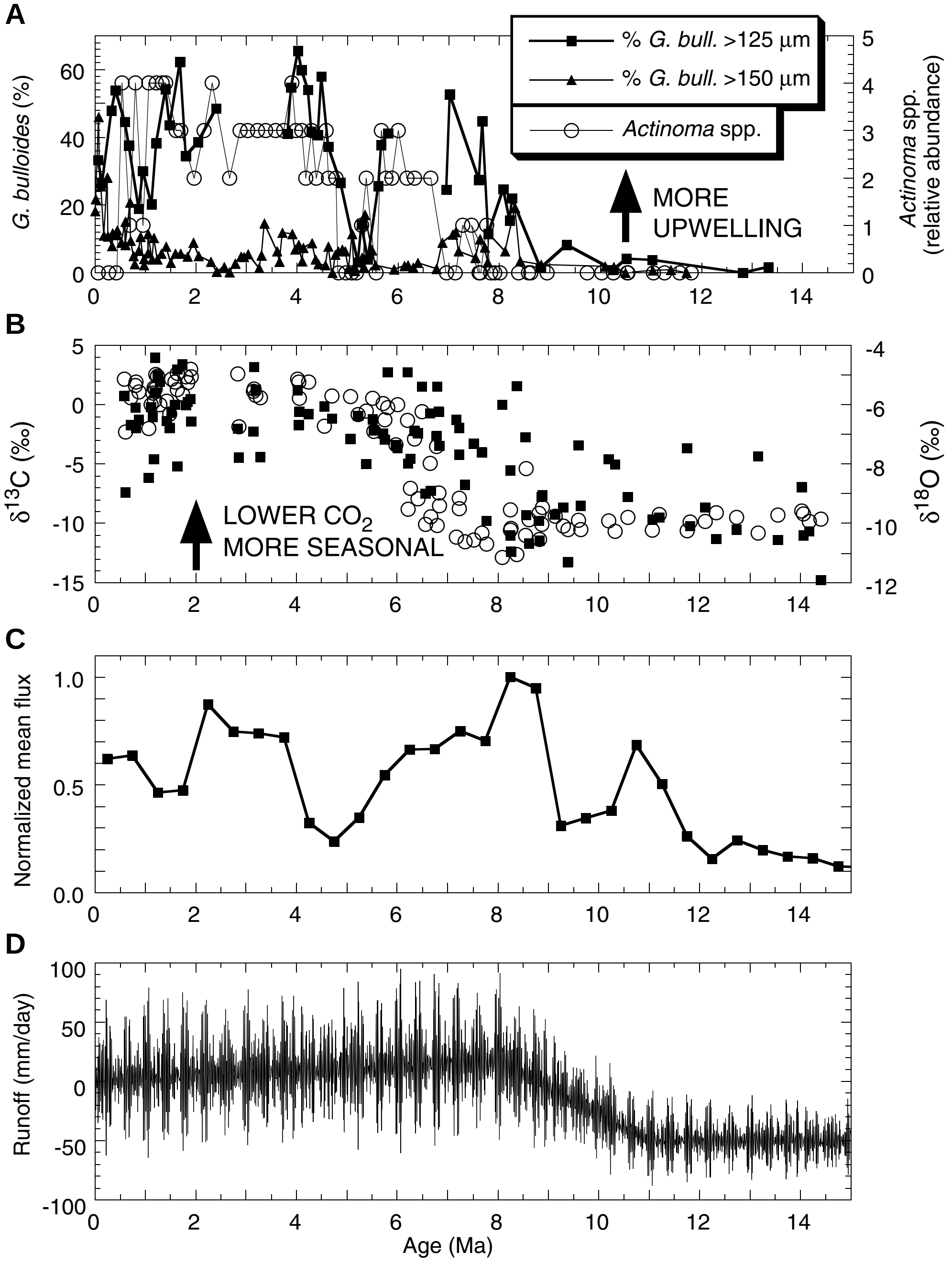
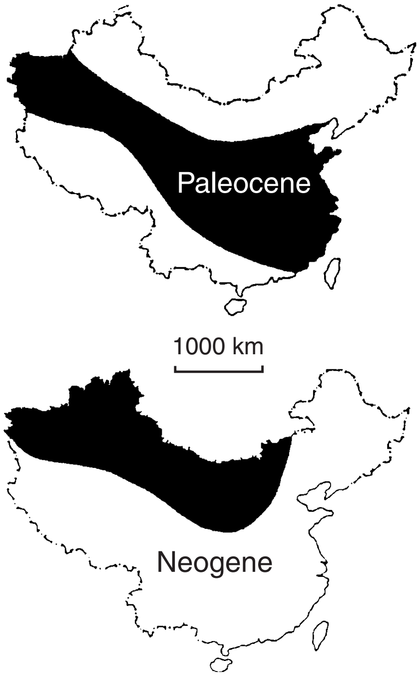

A
25°N
20°
15°
10°
105°E
110°
115°
120°
CHINA
RED RIVER FAULT
HAINAN ISLAND
TAIWAN
MANILA TRENCH
LUZON
MINDORO
INDOCHINA
DANGEROUS GROUNDS
REED BANK
11
10
9
8
7
6b
6a
6
4
4a
6b
8
9
10
B
24°N
22°
20°
18°
16°
South China Block
Guangzhou
Shantou
Penhu Is.
Hong Kong
E–N
K_1
N
E
K_{1-2}
K_2–N
K_2–E
K_2
SWTB
A
Zhu-1
PRMB
Dogsha Is.
BBWB
Zhu-3
Zhu-2
A'
Red River Suture
YGHB
QDNB
South China Sea Basin
Manila Trench
Xisha Block
Zhongsha Block
Indochina Block
1
2
3
4
5
6
7
Depression
Uplift
Intermontane Basin
Deep-sea Basin
Fault
6 Well
106°E
108°
110°
112°
114°
116°
118°
120°
A
A'
Zhu-1
Zhu-2
0
5
10
KM
N–Q
E
M_2
K
E

Figure 3



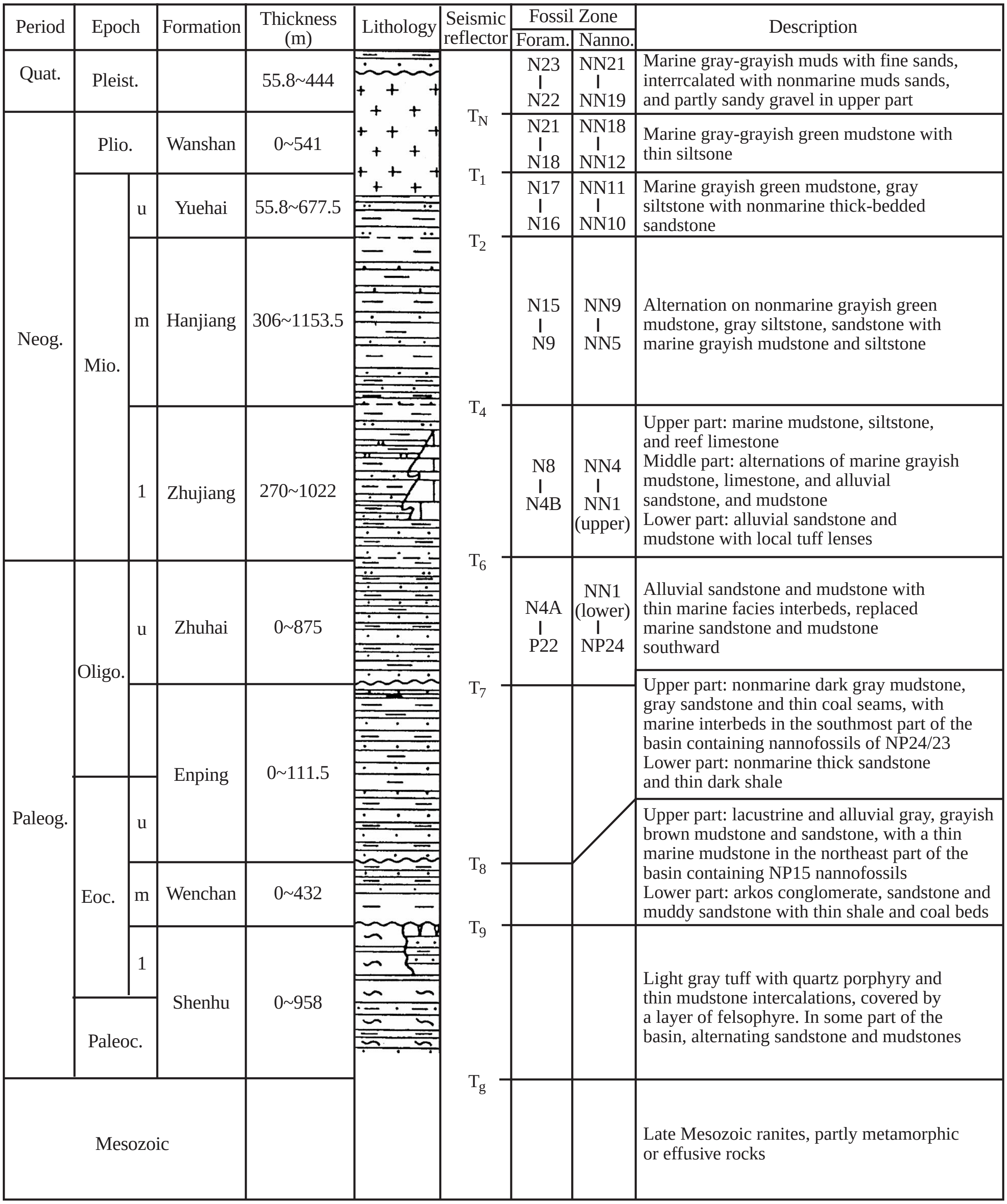
A
G. bulloides (%)
Actinoma spp. (relative abundance)
% G. bull. >125 µm
% G. bull. >150 µm
Actinoma spp.
MORE UPWELLING
B
δ13C (‰)
δ18O (‰)
LOWER CO2
MORE SEASONAL
C
Normalized mean flux
D
Runoff (mm/day)
Age (Ma)

Figure 4



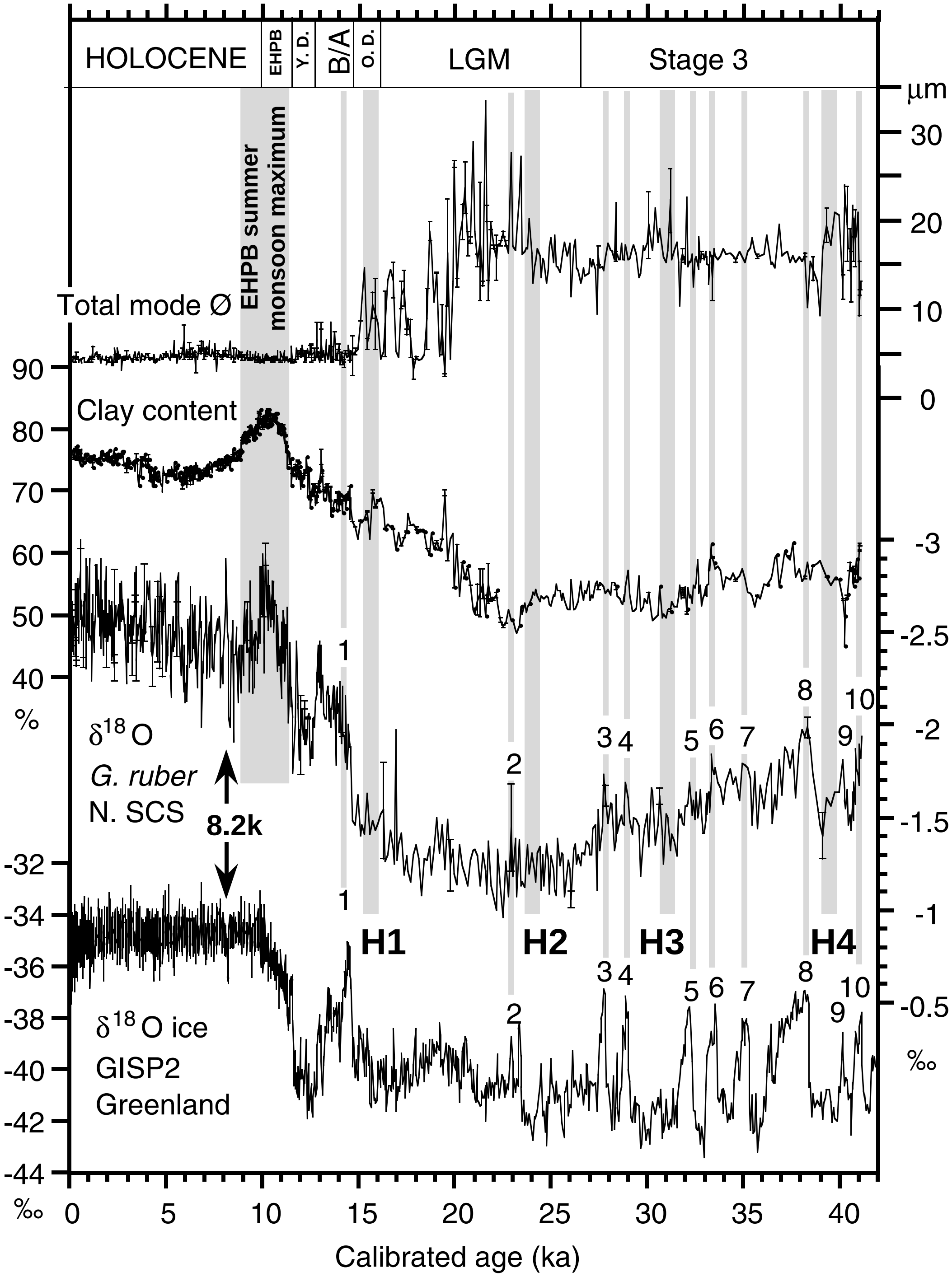
Distribution of arid zone	Stage		Time interval	Monsoon	Paleogeography
	Premonsoon		Paleocene early Eocene	Absent or insignificant	Smaller Asia without Tibetan Plateau
		~50 Ma			
	Transitional		middle Eocene Oligocene	Unstable	India joined with Asia
		~20 Ma			
	Monsoon I		Miocene Pliocene	Summer monsoon	Plateau uplift started; SCS opened
		~2.4 Ma			
	Monsoon II		late Pliocene Pleistocene	Summer and winter monsoon (loess deposits)	Intensive plateau uplift

Figure 5



Period	Epoch		Formation	Thickness (m)	Seismic reflector	Fossil Zone Foram.	Fossil Zone Nanno.	Description
Quat.	Pleist.			55.8~444	T_N	N23–N22	NN21–NN19	Marine gray-grayish muds with fine sands, interrcalated with nonmarine muds sands, and partly sandy gravel in upper part
Neog.	Plio.		Wanshan	0~541	T_1	N21–N18	NN18–NN12	Marine gray-grayish green mudstone with thin siltsone
	Mio.	u	Yuehai	55.8~677.5	T_2	N17–N16	NN11–NN10	Marine grayish green mudstone, gray siltstone with nonmarine thick-bedded sandstone
		m	Hanjiang	306~1153.5	T_4	N15–N9	NN9–NN5	Alternation on nonmarine grayish green mudstone, gray siltstone, sandstone with marine grayish mudstone and siltstone
		1	Zhujiang	270~1022	T_6	N8–N4B	NN4–NN1 (upper)	Upper part: marine mudstone, siltstone, and reef limestone Middle part: alternations of marine grayish mudstone, limestone, and alluvial sandstone, and mudstone Lower part: alluvial sandstone and mudstone with local tuff lenses
Paleog.	Oligo.	u	Zhuhai	0~875	T_7	N4A–P22	NN1 (lower)–NP24	Alluvial sandstone and mudstone with thin marine facies interbeds, replaced marine sandstone and mudstone southward
	Oligo. Eoc.	u	Enping	0~111.5	T_8			Upper part: nonmarine dark gray mudstone, gray sandstone and thin coal seams, with marine interbeds in the southmost part of the basin containing nannofossils of NP24/23 Lower part: nonmarine thick sandstone and thin dark shale
	Eoc.	m	Wenchan	0~432	T_9			Upper part: lacustrine and alluvial gray, grayish brown mudstone and sandstone, with a thin marine mudstone in the northeast part of the basin containing NP15 nannofossils Lower part: arkos conglomerate, sandstone and muddy sandstone with thin shale and coal beds
	Eoc. Paleoc.	1	Shenhu	0~958	T_g			Light gray tuff with quartz porphyry and thin mudstone intercalations, covered by a layer of felsophyre. In some part of the basin, alternating sandstone and mudstones
Mesozoic								Late Mesozoic ranites, partly metamorphic or effusive rocks

Figure 6



HOLOCENE
EHPB
Y. D.
B/A
O. D.
LGM
Stage 3
μm
30
20
10
0
EHPB summer monsoon maximum
Total mode Ø
Clay content
90
80
70
60
50
40
%
δ18 O
G. ruber
N. SCS
8.2k
-3
-2.5
-2
-1.5
-1
-0.5
‰
1
2
3
4
5
6
7
8
9
10
H1
H2
H3
H4
-32
-34
-36
-38
-40
-42
-44
‰
δ18 O ice
GISP2
Greenland
0
5
10
15
20
25
30
35
40
Calibrated age (ka)

Figure 7

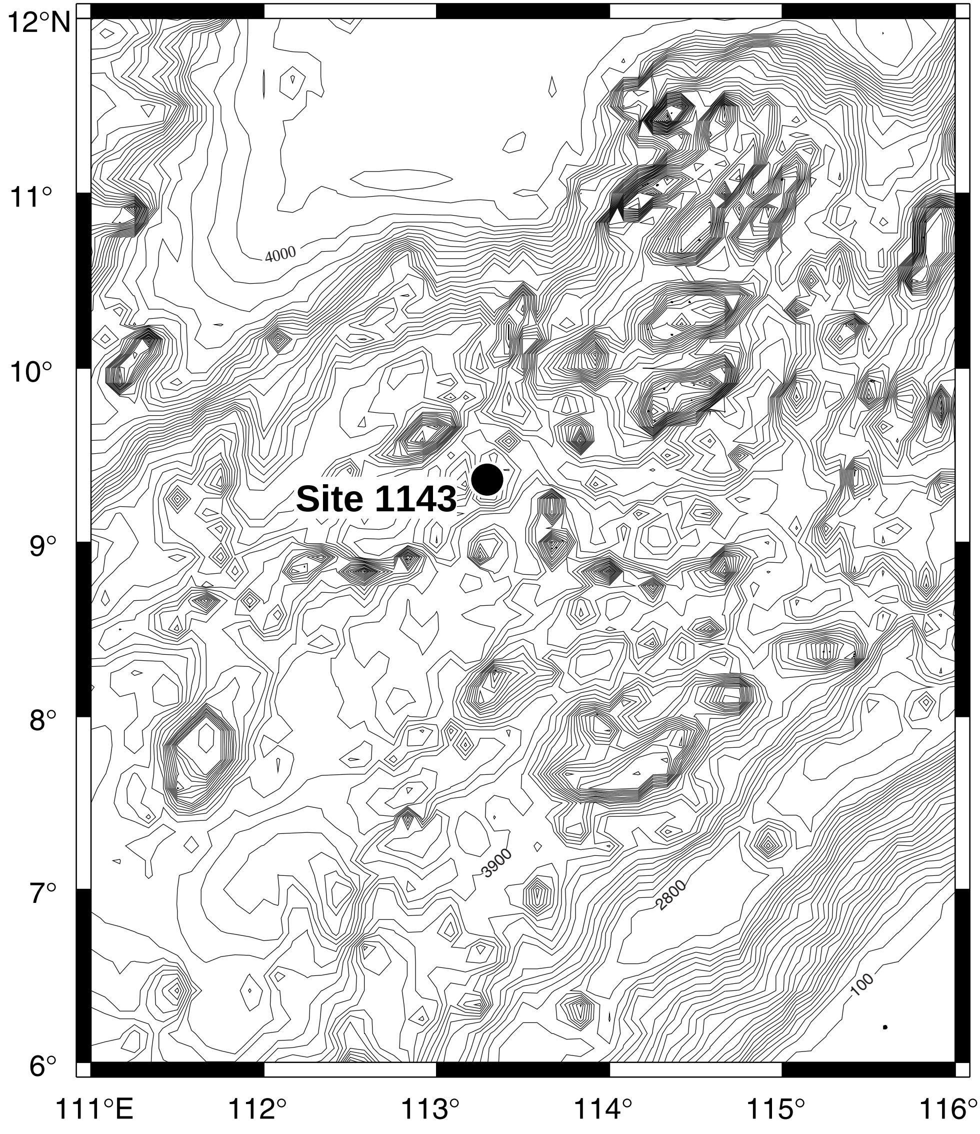

12°N
11°
10°
9°
8°
7°
6°
111°E
112°
113°
114°
115°
116°
Site 1143
4000
3900
2800
100

Figure 8

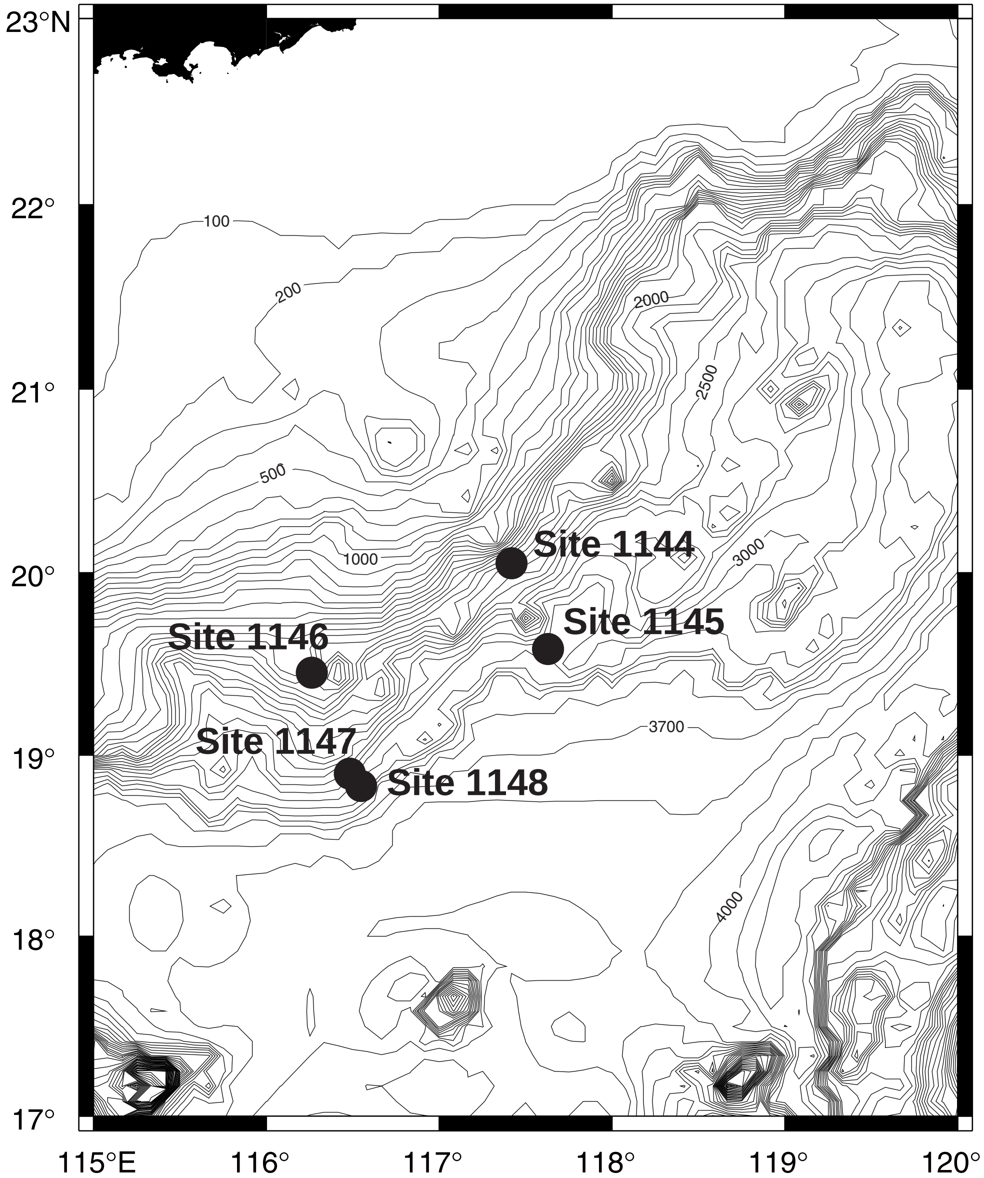

23°N
22°
21°
20°
19°
18°
17°
115°E
116°
117°
118°
119°
120°
100
200
500
1000
2000
2500
3000
3700
4000
Site 1144
Site 1145
Site 1146
Site 1147
Site 1148

Figure 9

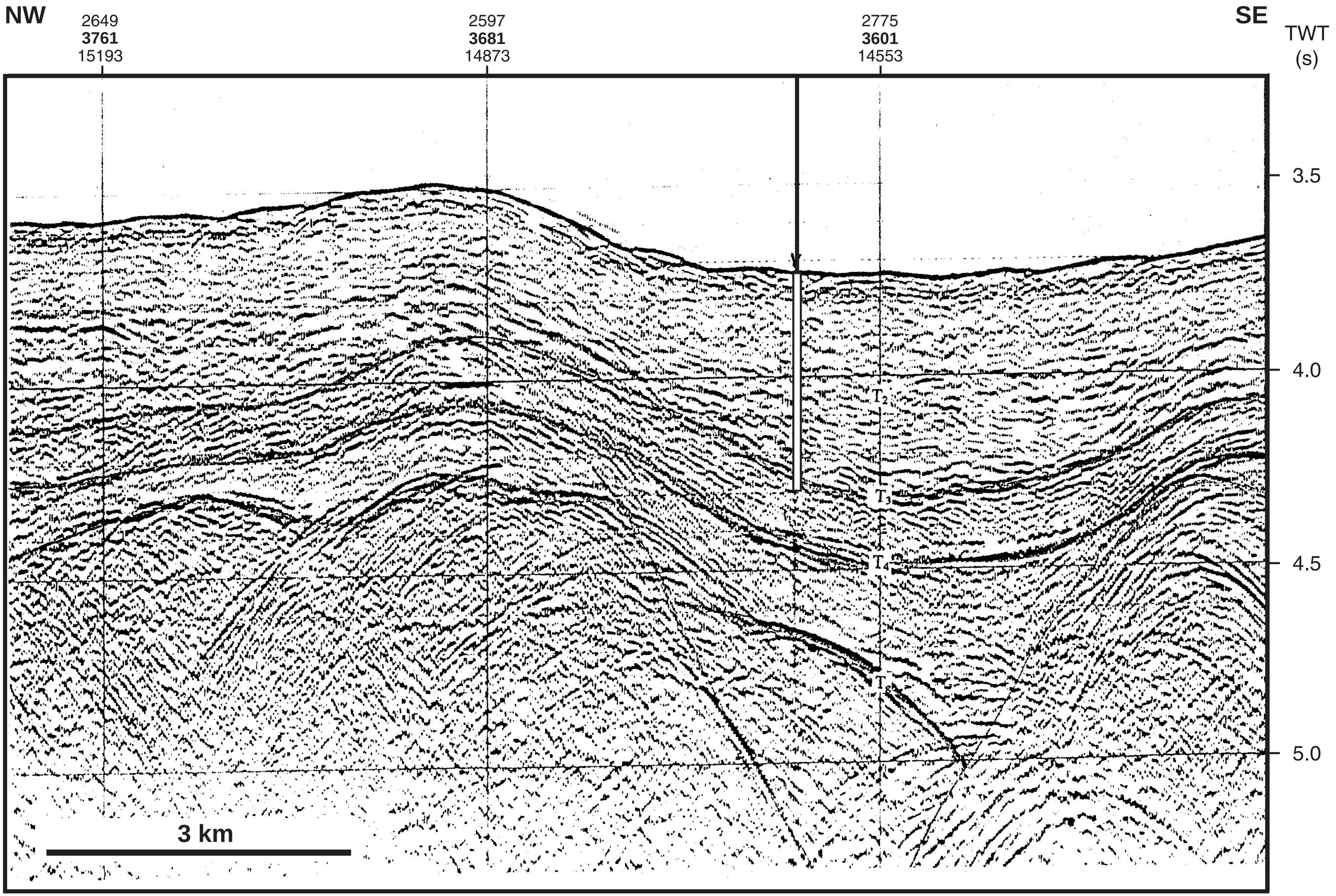

NW
2649
3761
15193
2597
3681
14873
2775
3601
14553
SE
TWT
(s)
3.5
4.0
4.5
5.0
T_2
T_3
T_4
T_5
3 km

Figure 10

Site 1143

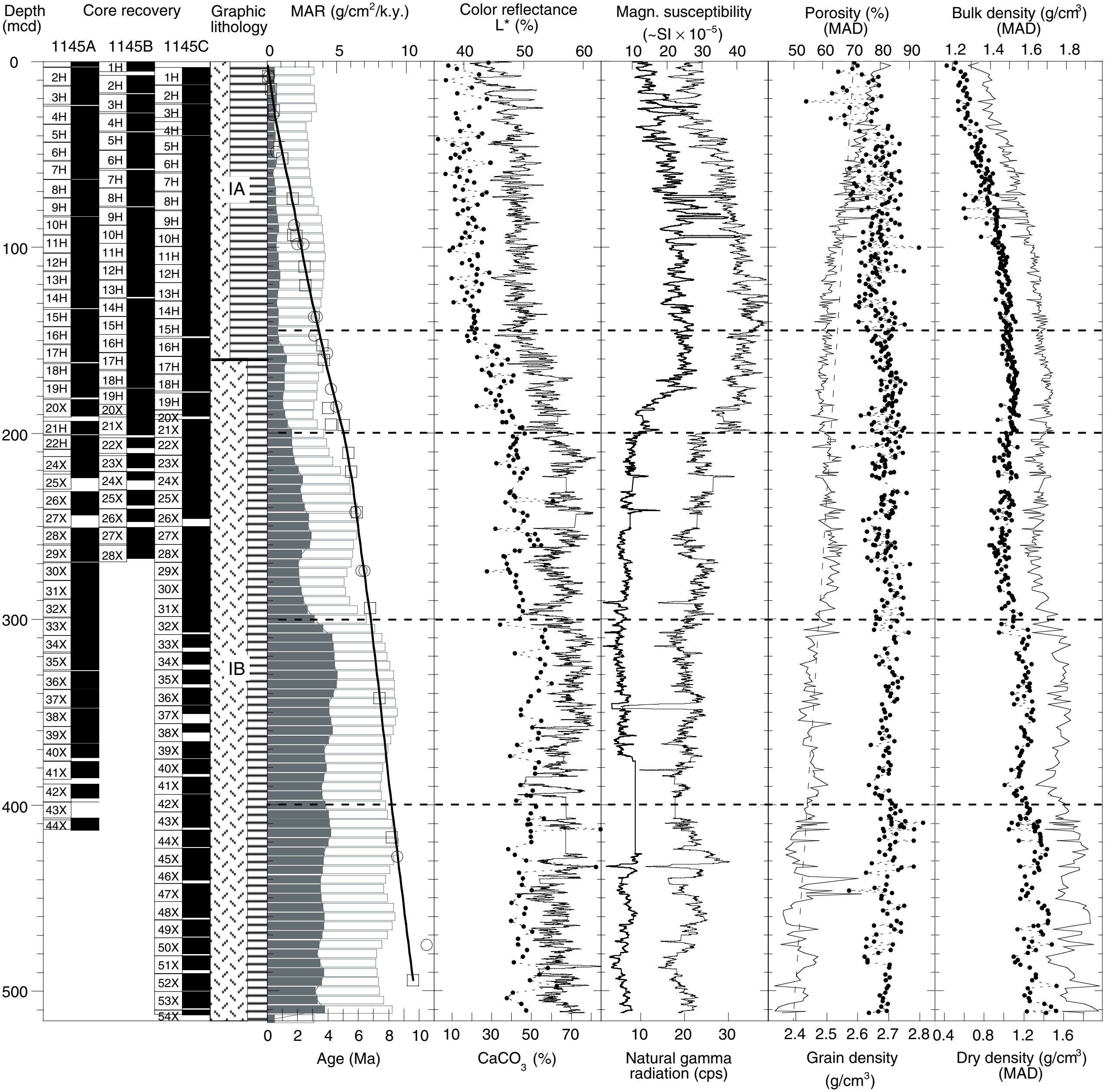


Figure 11

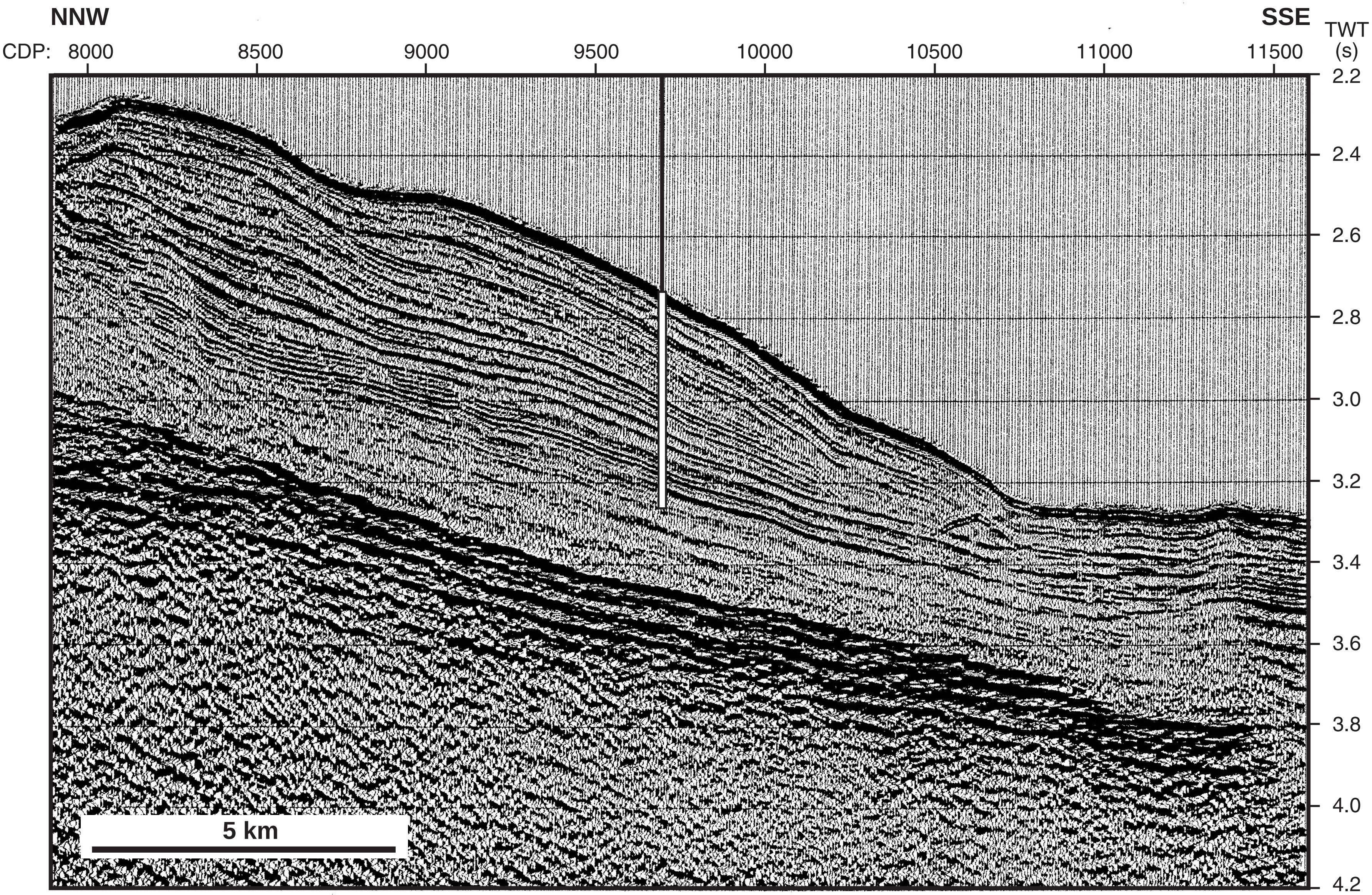

NNW
SSE
CDP:
8000
8500
9000
9500
10000
10500
11000
11500
TWT (s)
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
5 km

Figure 12

Site 1144

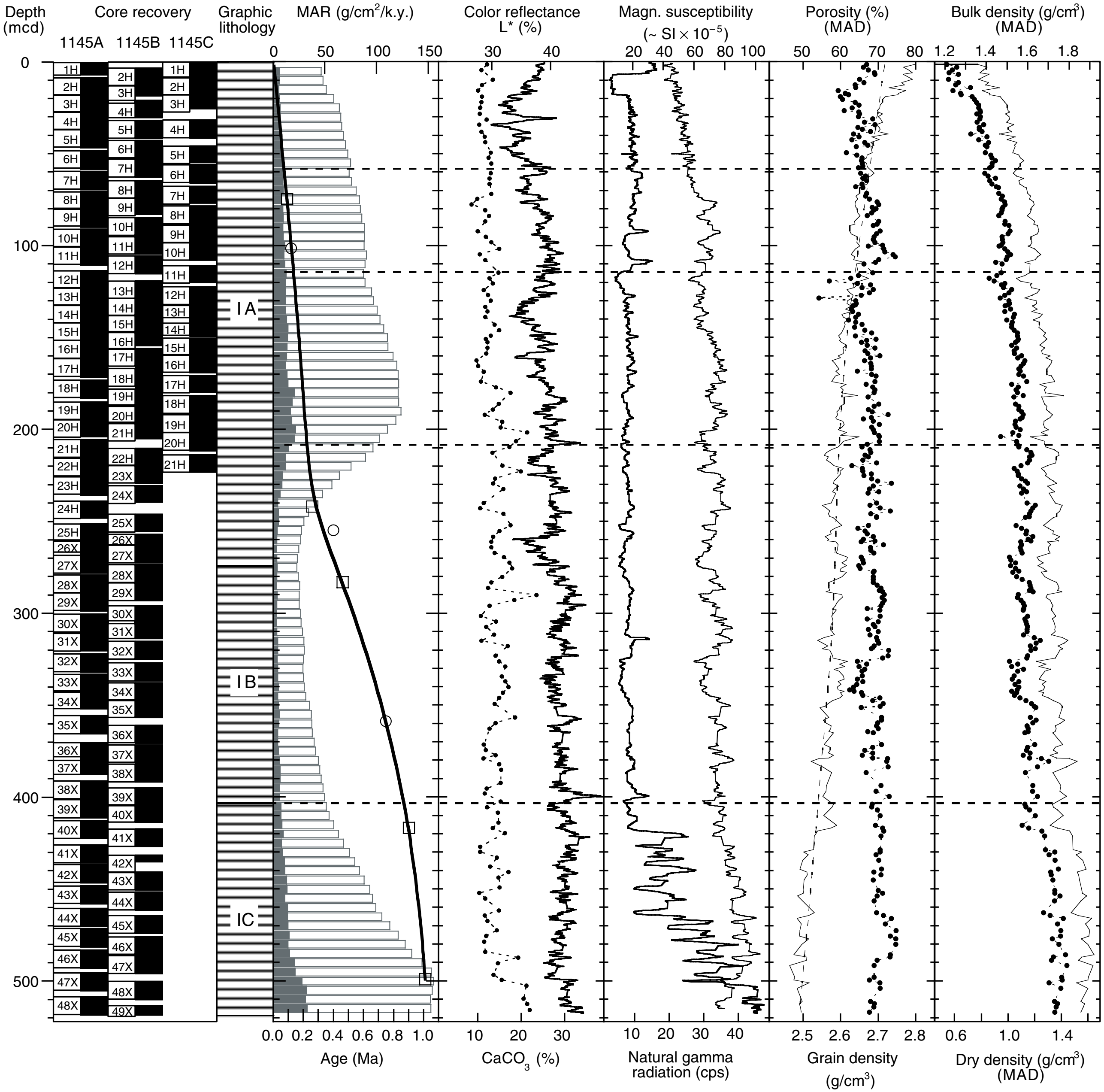


Figure 13

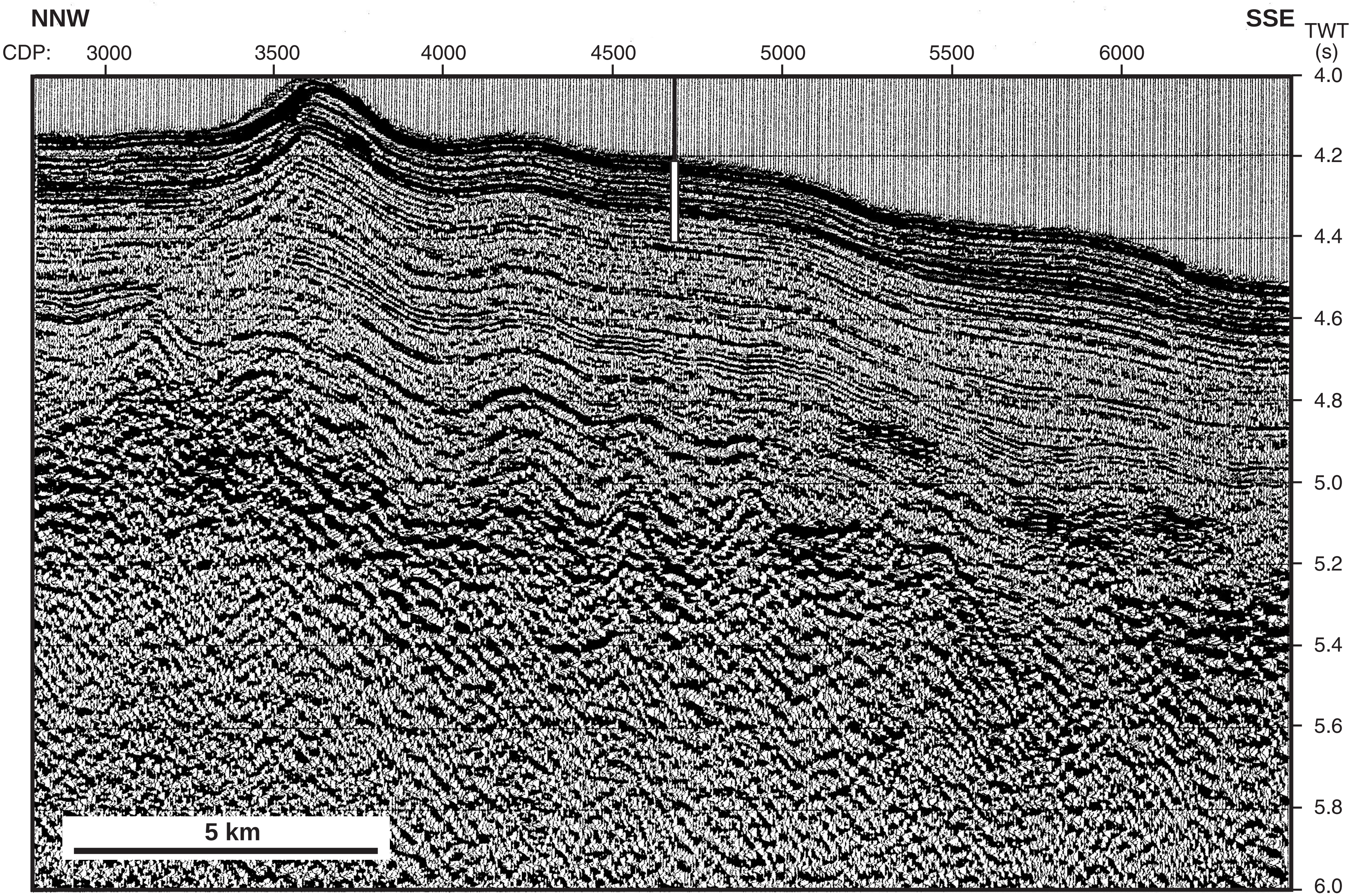

NNW
SSE
CDP:
3000
3500
4000
4500
5000
5500
6000
TWT
(s)
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
5 km

Figure 14

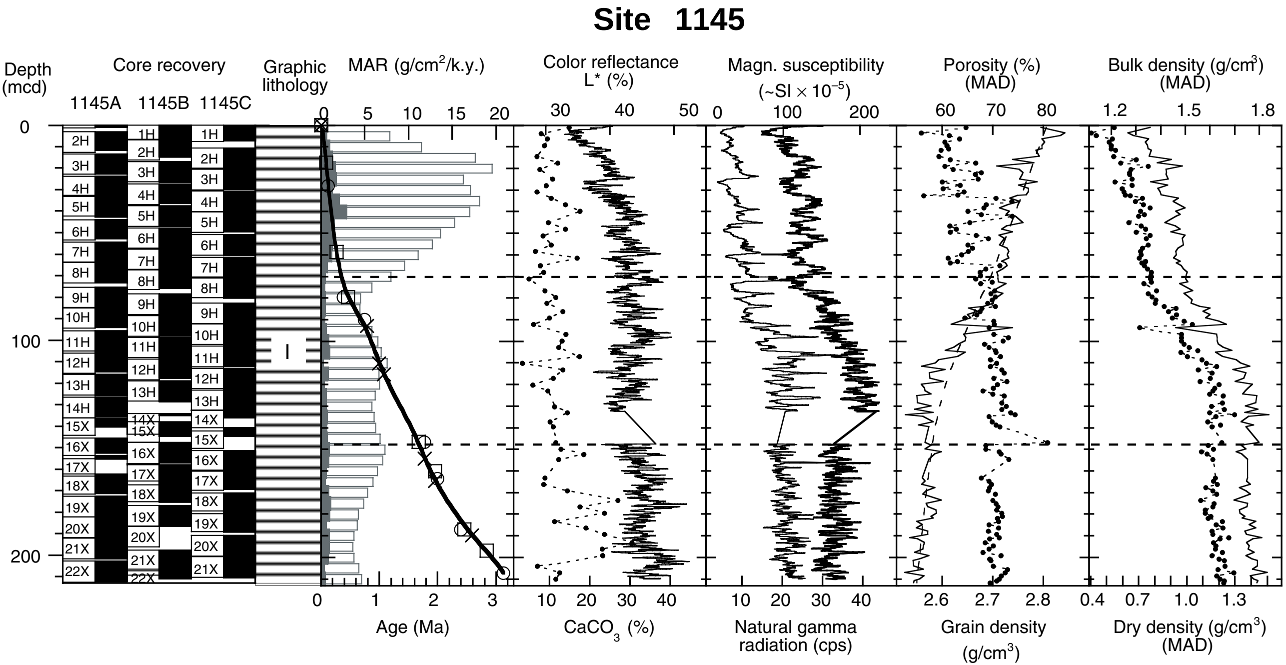

Site 1145
Depth (mcd)
0
100
200
Core recovery
1145A
1145B
1145C
2H 3H 4H 5H 6H 7H 8H 9H 10H 11H 12H 13H 14H 15X 16X 17X 18X 19X 20X 21X 22X
1H 2H 3H 4H 5H 6H 7H 8H 9H 10H 11H 12H 13H 14X 15X 16X 17X 18X 19X 20X 21X 22X
1H 2H 3H 4H 5H 6H 7H 8H 9H 10H 11H 12H 13H 14X 15X 16X 17X 18X 19X 20X 21X
Graphic lithology
I
MAR (g/cm^2/k.y.)
0 5 10 15 20
Age (Ma)
0 1 2 3
Color reflectance L* (%)
30 40 50
CaCO$_3$ (%)
10 20 30 40
Magn. susceptibility (~SI × 10^{-5})
0 100 200
Natural gamma radiation (cps)
10 20 30 40
Porosity (%) (MAD)
60 70 80
Grain density (g/cm^3)
2.6 2.7 2.8
Bulk density (g/cm^3) (MAD)
1.2 1.5 1.8
Dry density (g/cm^3) (MAD)
0.4 0.7 1.0 1.3

Figure 15

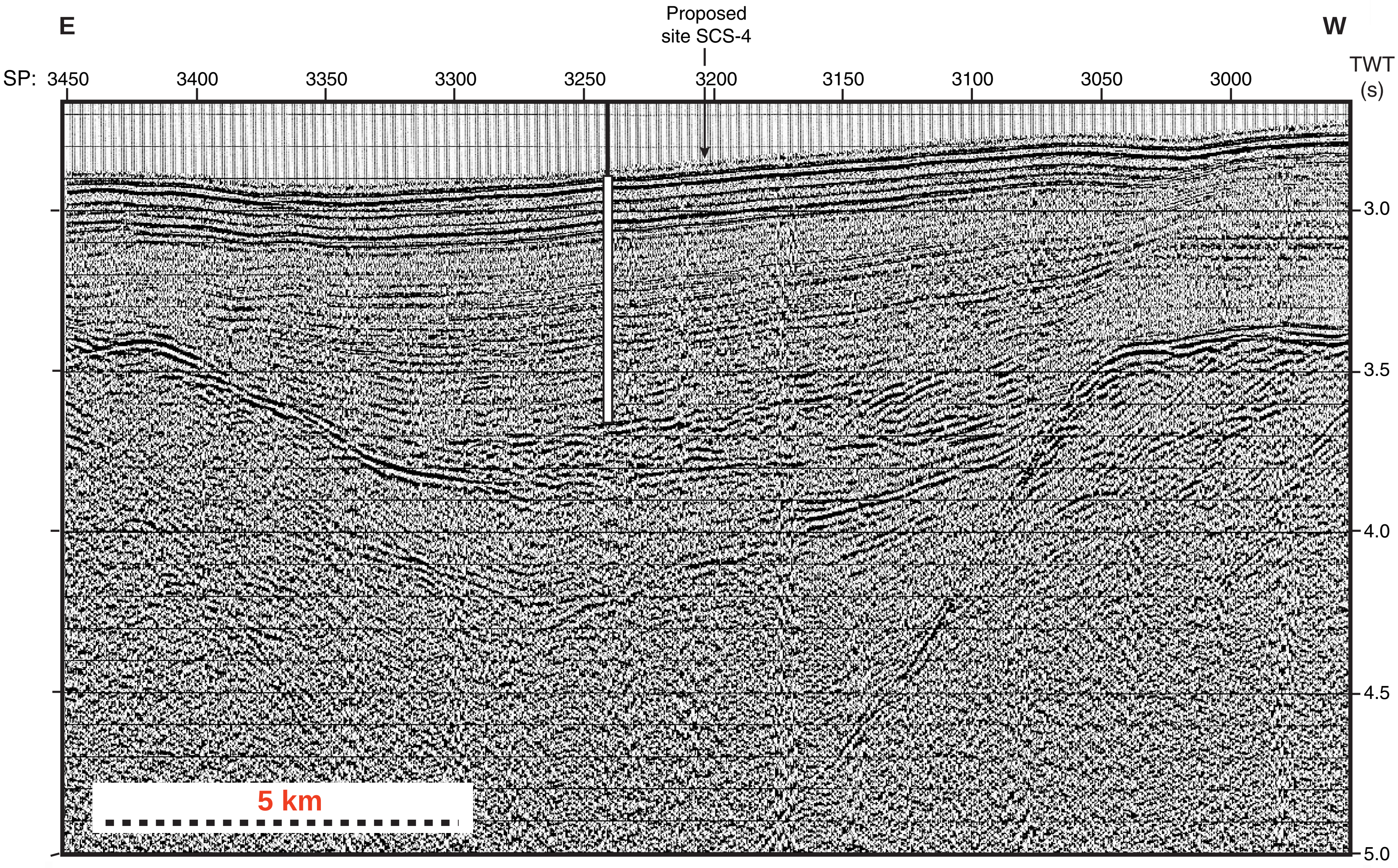
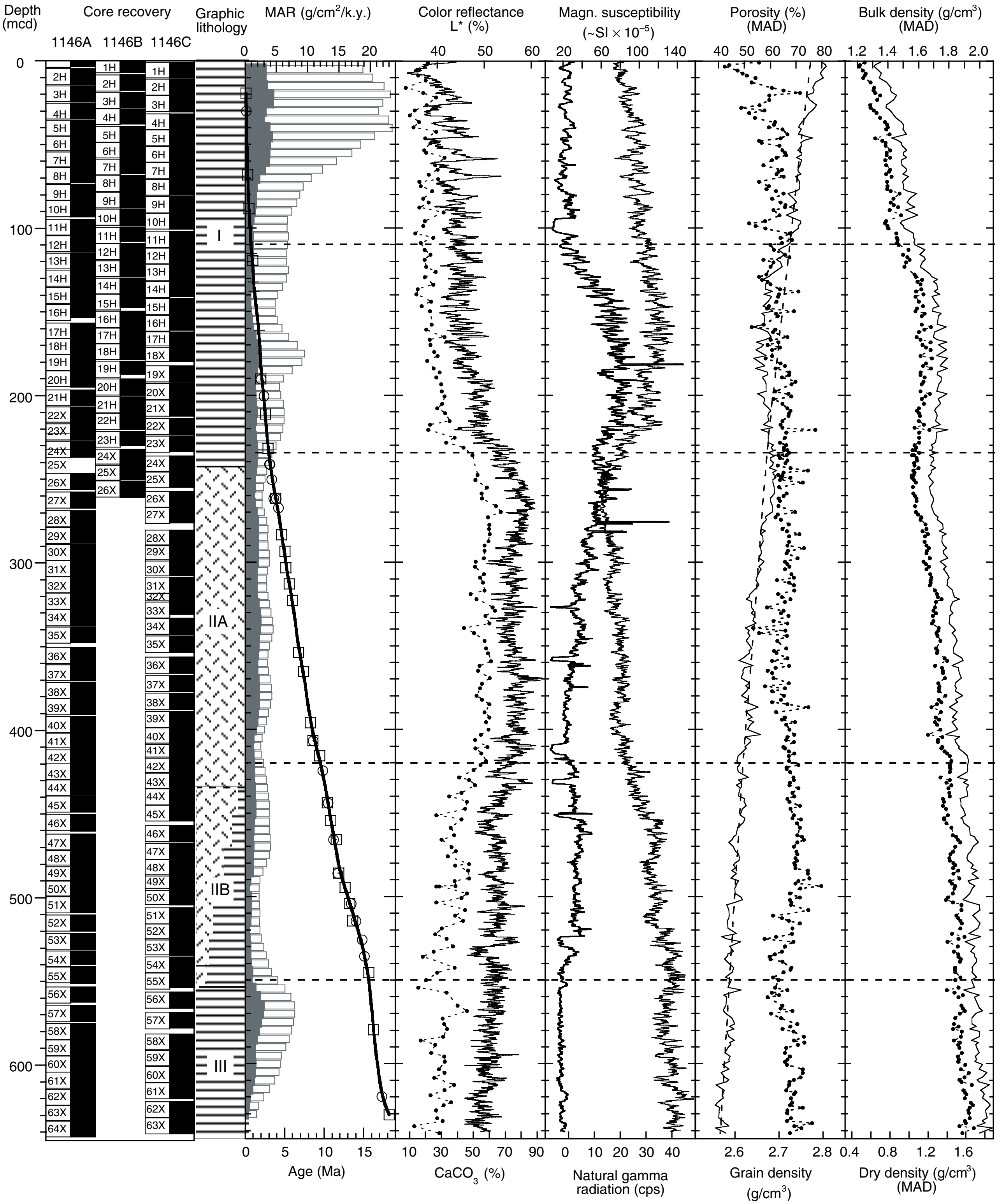

E
W
Proposed
site SCS-4
SP: 3450
3400
3350
3300
3250
3200
3150
3100
3050
3000
TWT
(s)
3.0
3.5
4.0
4.5
5.0
5 km

Figure 16



Site 1146

Figure 17

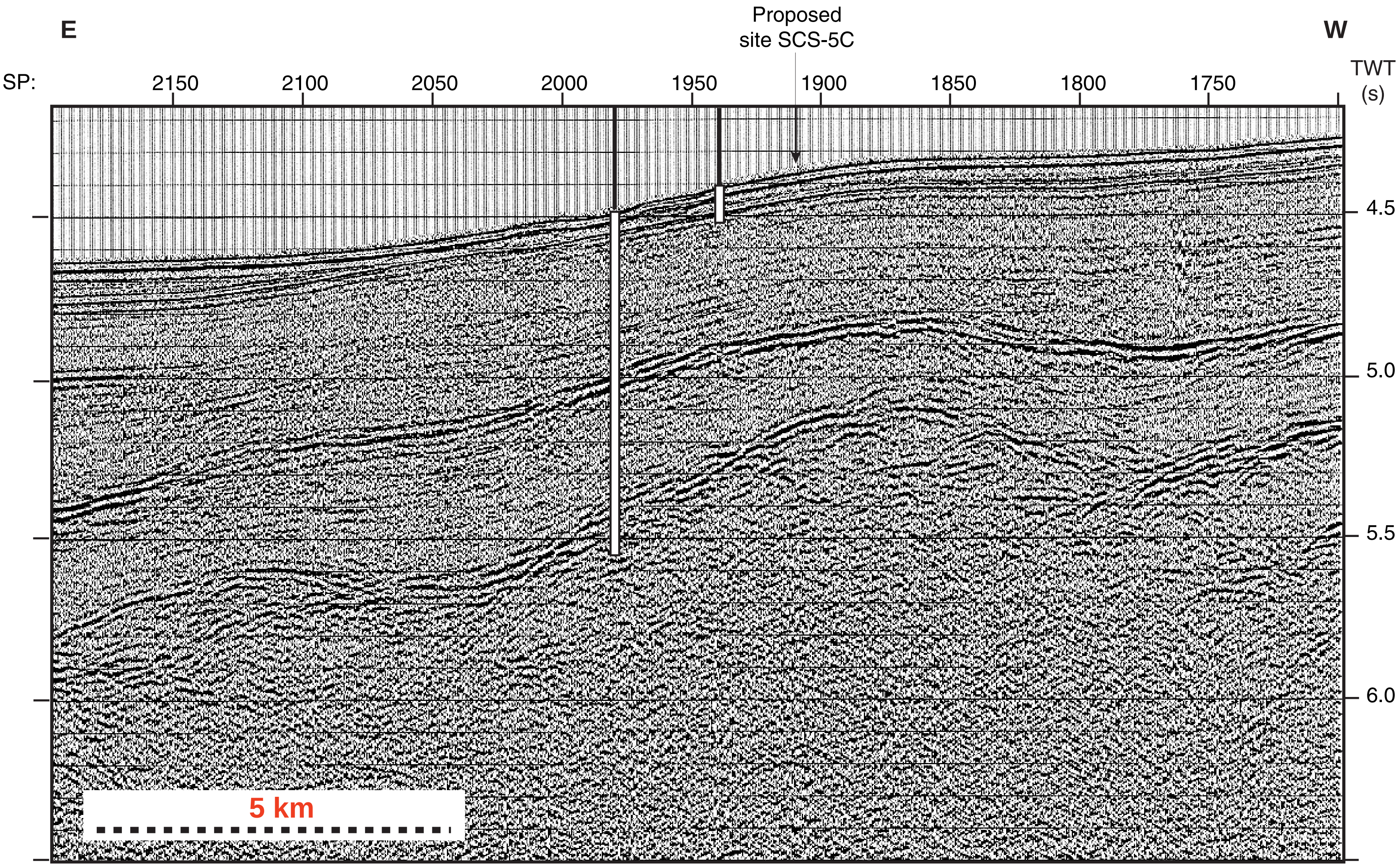

E
W
Proposed
site SCS-5C
SP:
2150
2100
2050
2000
1950
1900
1850
1800
1750
TWT
(s)
4.5
5.0
5.5
6.0
5 km

Figure 18

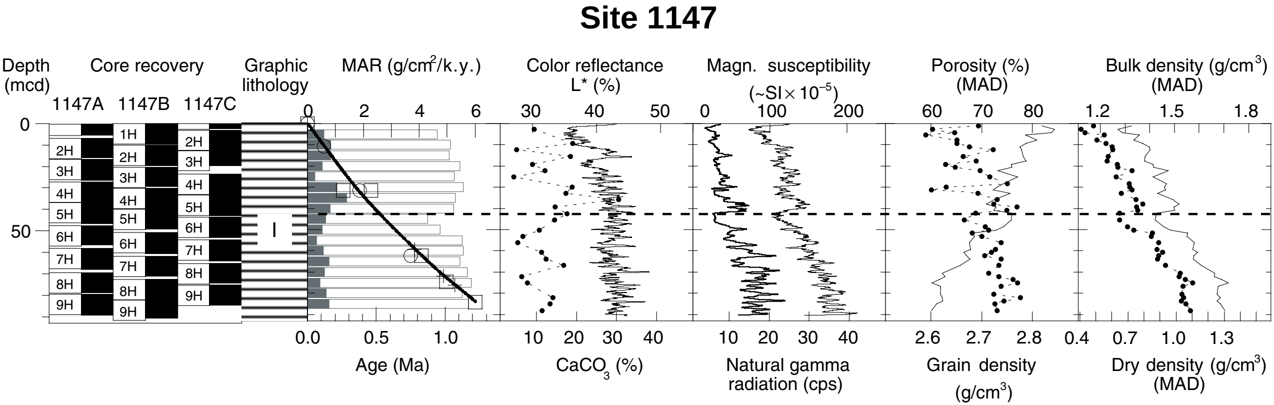

Site 1147
Depth (mcd)
Core recovery
1147A
1147B
1147C
Graphic lithology
MAR (g/cm^2/k.y.)
Color reflectance L* (%)
Magn. susceptibility (~SI × 10^{-5})
Porosity (%) (MAD)
Bulk density (g/cm^3) (MAD)
0
50
0 2 4 6
30 40 50
0 100 200
60 70 80
1.2 1.5 1.8
1H
2H
3H
4H
5H
6H
7H
8H
9H
I
0.0 0.5 1.0
Age (Ma)
10 20 30 40
CaCO$_3$ (%)
10 20 30 40
Natural gamma radiation (cps)
2.6 2.7 2.8
Grain density (g/cm^3)
0.4 0.7 1.0 1.3
Dry density (g/cm^3) (MAD)

Figure 19

Site 1148

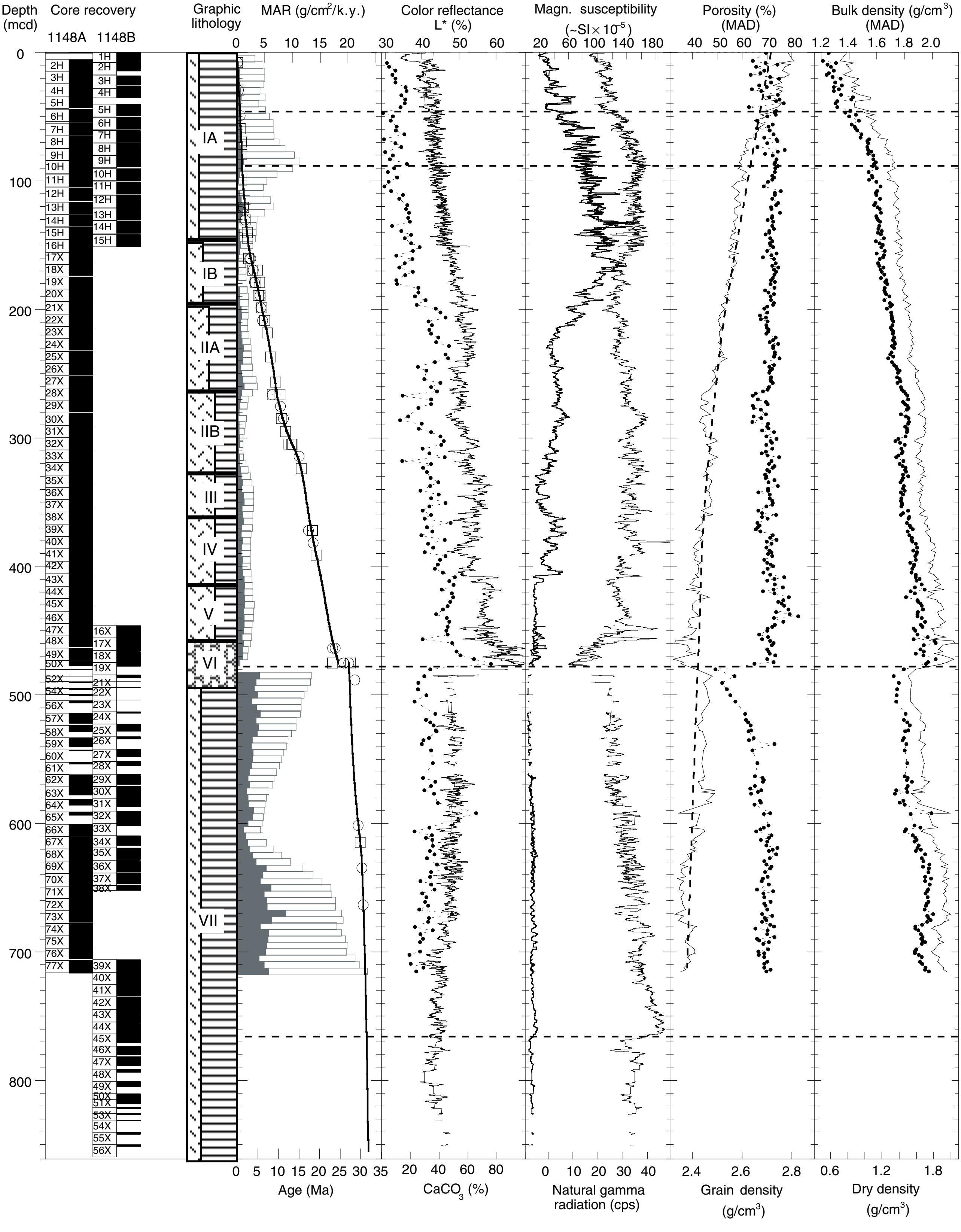


Figure 20

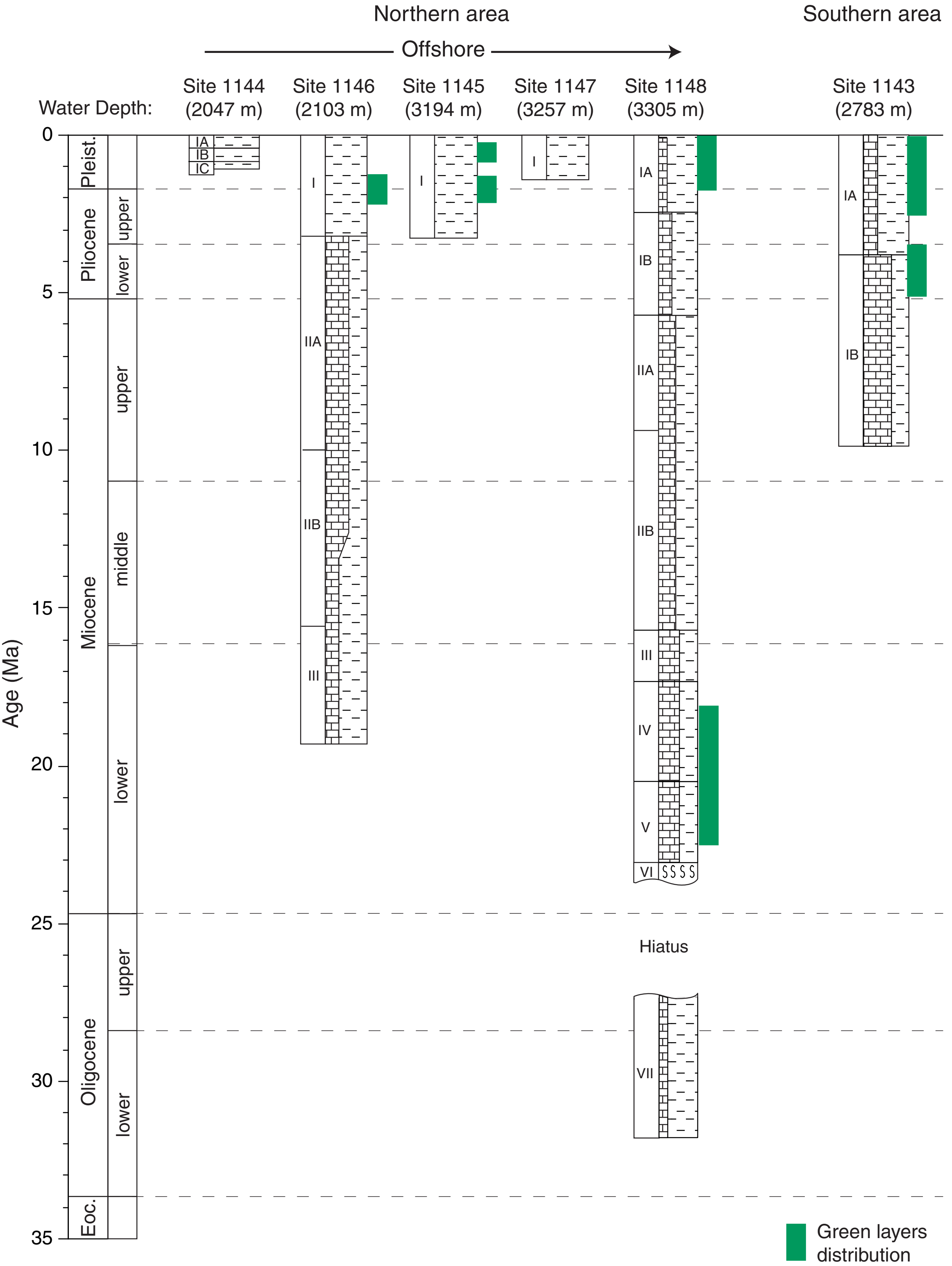

Northern area
Southern area
Offshore
Water Depth:
Site 1144 (2047 m)
Site 1146 (2103 m)
Site 1145 (3194 m)
Site 1147 (3257 m)
Site 1148 (3305 m)
Site 1143 (2783 m)
Age (Ma)
0
5
10
15
20
25
30
35
Pleist.
Pliocene
upper
lower
Miocene
upper
middle
lower
Oligocene
upper
lower
Eoc.
IA
IB
IC
I
IIA
IIB
III
IV
V
VI
VII
Hiatus
Green layers distribution

Figure 21

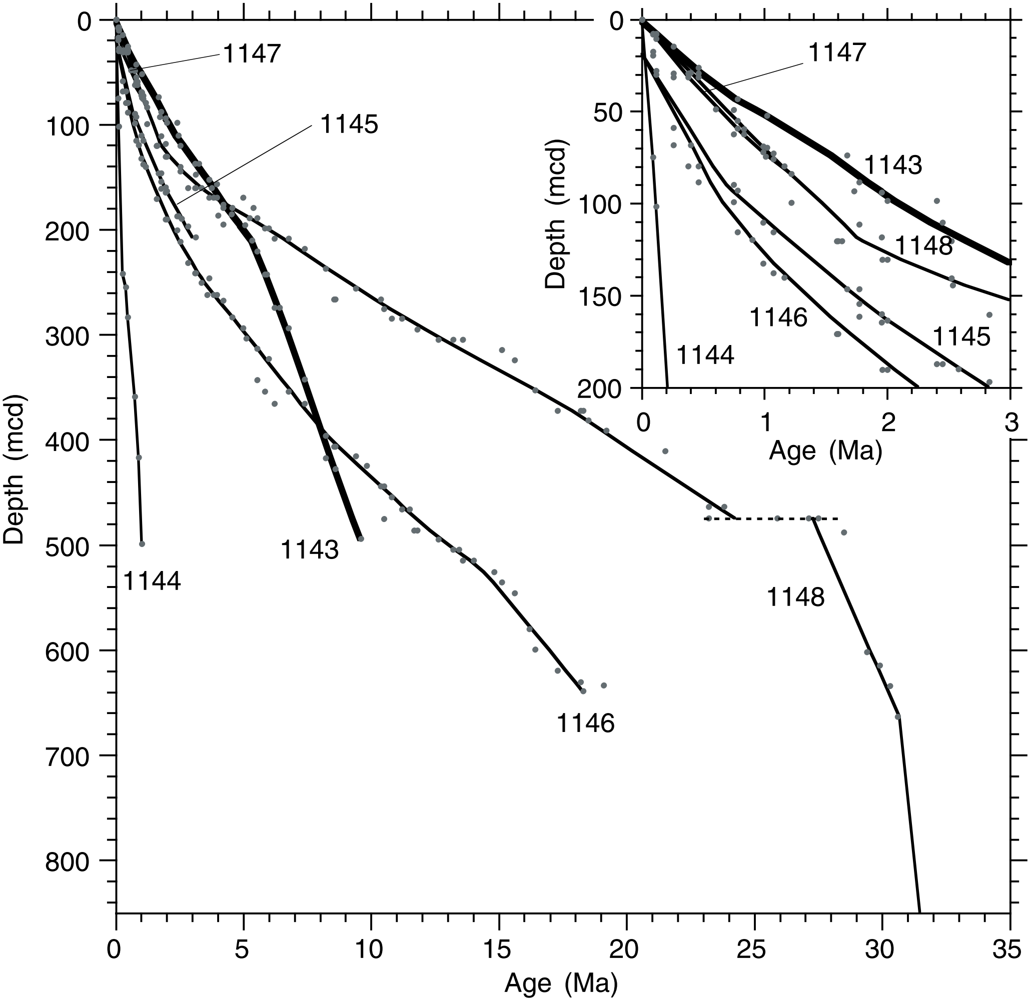
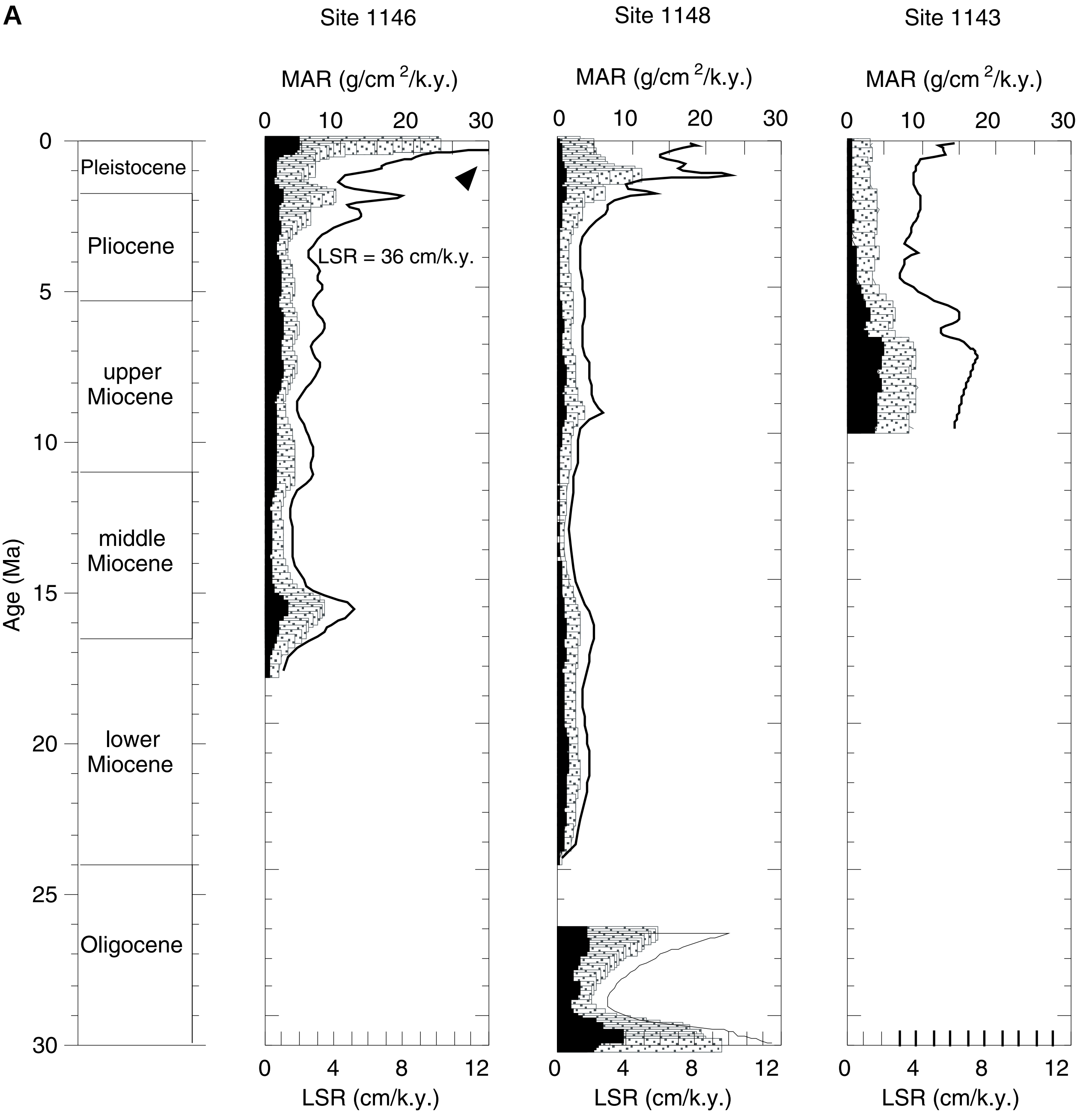

Depth (mcd)
0
100
200
300
400
500
600
700
800
Age (Ma)
0
5
10
15
20
25
30
35
1147
1145
1143
1144
1146
1148
Depth (mcd)
0
50
100
150
200
Age (Ma)
0
1
2
3
1147
1143
1148
1146
1145
1144

Figure 22



A
Site 1146
Site 1148
Site 1143
MAR (g/cm²/k.y.)
0
10
20
30
Age (Ma)
0
5
10
15
20
25
30
Pleistocene
Pliocene
upper Miocene
middle Miocene
lower Miocene
Oligocene
LSR = 36 cm/k.y.
LSR (cm/k.y.)
0
4
8
12

Figure 23

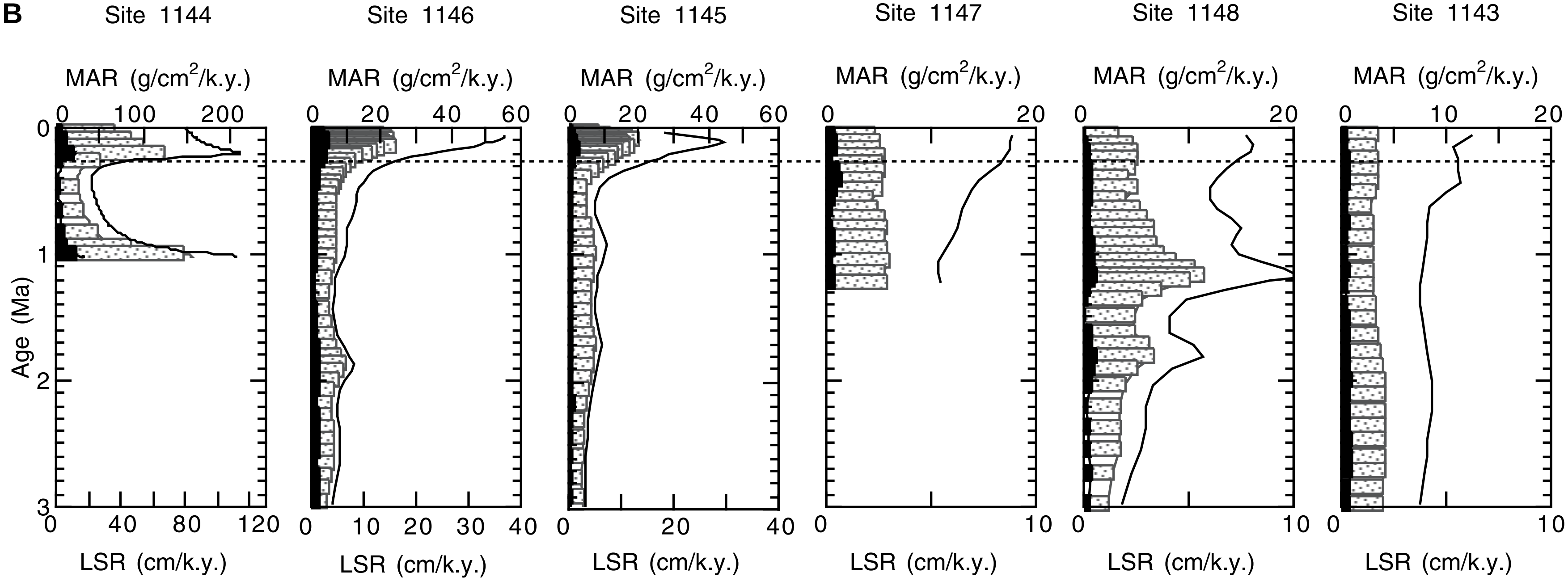


Figure 23 (continued)

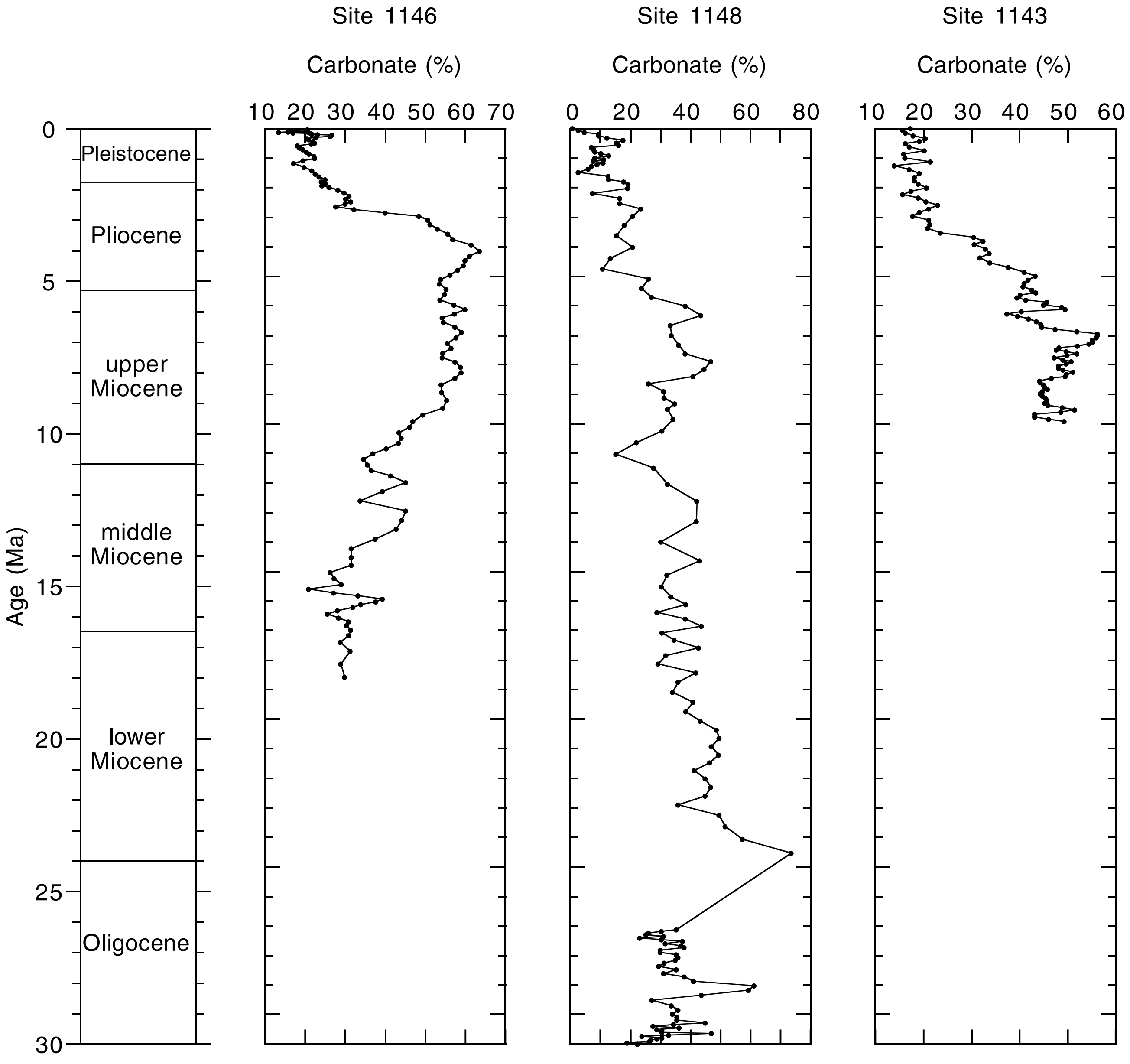

Site 1146
Carbonate (%)
10 20 30 40 50 60 70
Site 1148
Carbonate (%)
0 20 40 60 80
Site 1143
Carbonate (%)
10 20 30 40 50 60
Age (Ma)
0
5
10
15
20
25
30
Pleistocene
Pliocene
upper Miocene
middle Miocene
lower Miocene
Oligocene

Figure 24

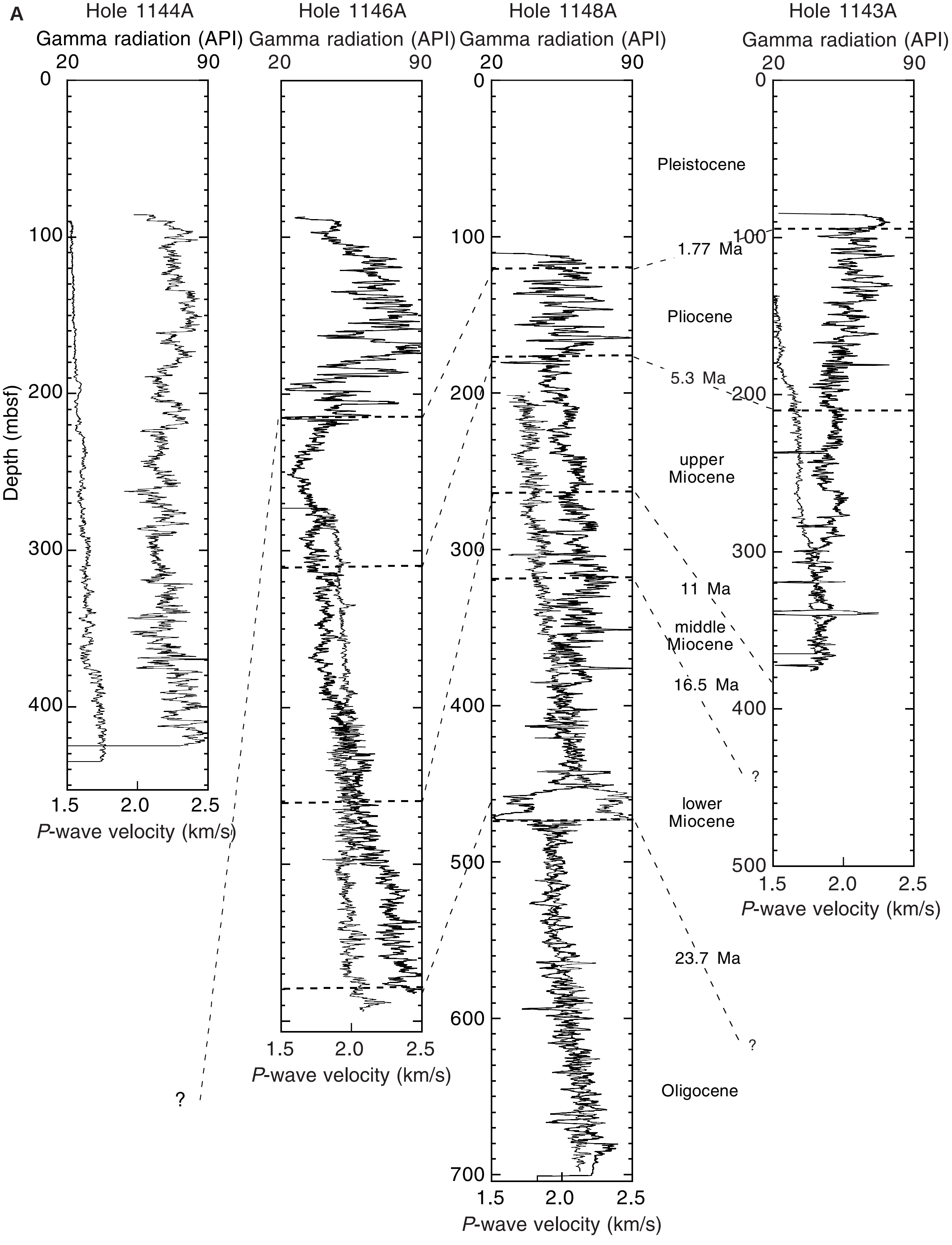

A
Hole 1144A
Gamma radiation (API)
20
90
Hole 1146A
Gamma radiation (API)
Hole 1148A
Gamma radiation (API)
Hole 1143A
Gamma radiation (API)
Depth (mbsf)
0
100
200
300
400
500
600
700
1.5
2.0
2.5
P-wave velocity (km/s)
Pleistocene
1.77 Ma
Pliocene
5.3 Ma
upper Miocene
11 Ma
middle Miocene
16.5 Ma
lower Miocene
23.7 Ma
Oligocene
?

Figure 25

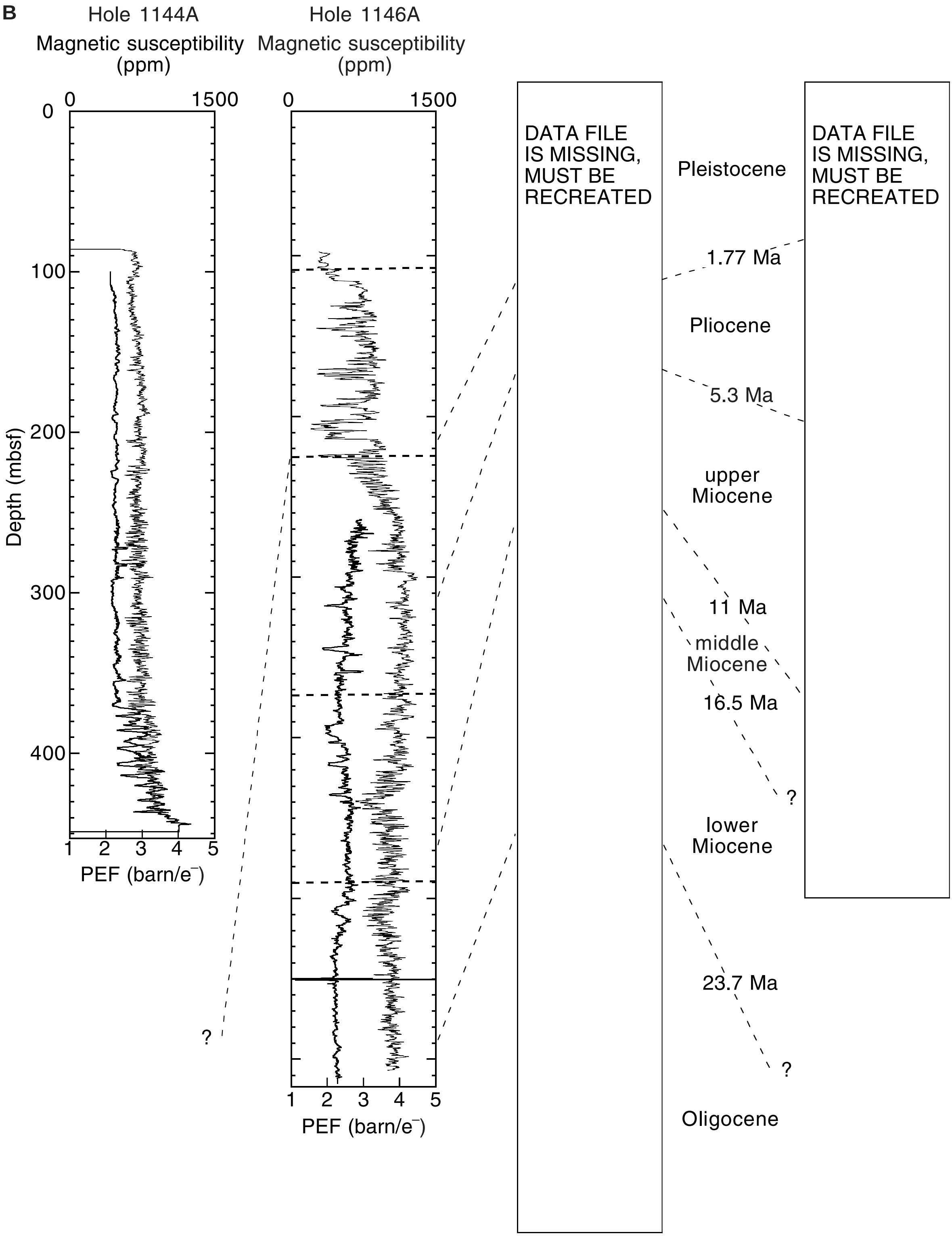


Figure 25 (continued)

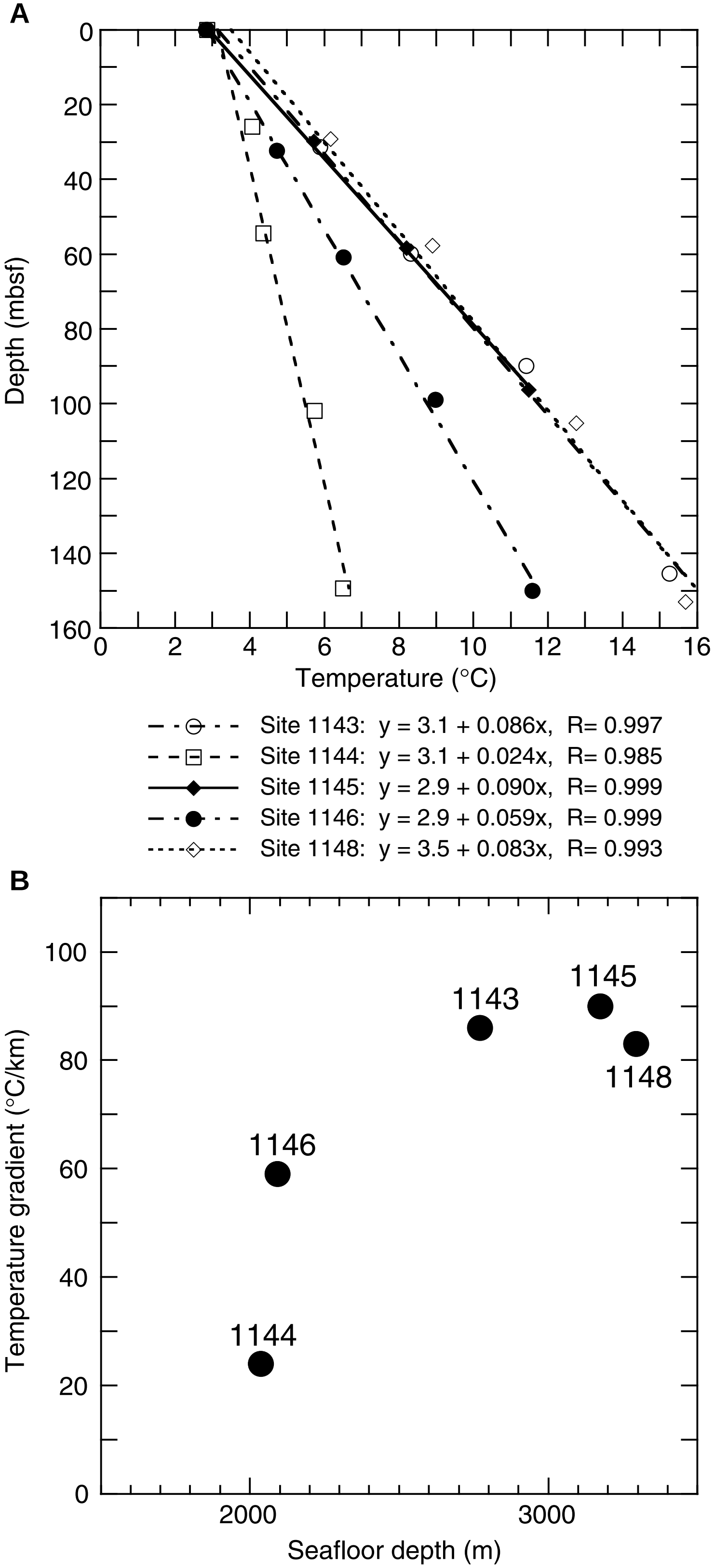

A
Depth (mbsf)
0
20
40
60
80
100
120
140
160
Temperature (°C)
0
2
4
6
8
10
12
14
16
Site 1143: y = 3.1 + 0.086x, R= 0.997
Site 1144: y = 3.1 + 0.024x, R= 0.985
Site 1145: y = 2.9 + 0.090x, R= 0.999
Site 1146: y = 2.9 + 0.059x, R= 0.999
Site 1148: y = 3.5 + 0.083x, R= 0.993
B
Temperature gradient (°C/km)
0
20
40
60
80
100
Seafloor depth (m)
2000
3000
1143
1144
1145
1146
1148

Figure 26

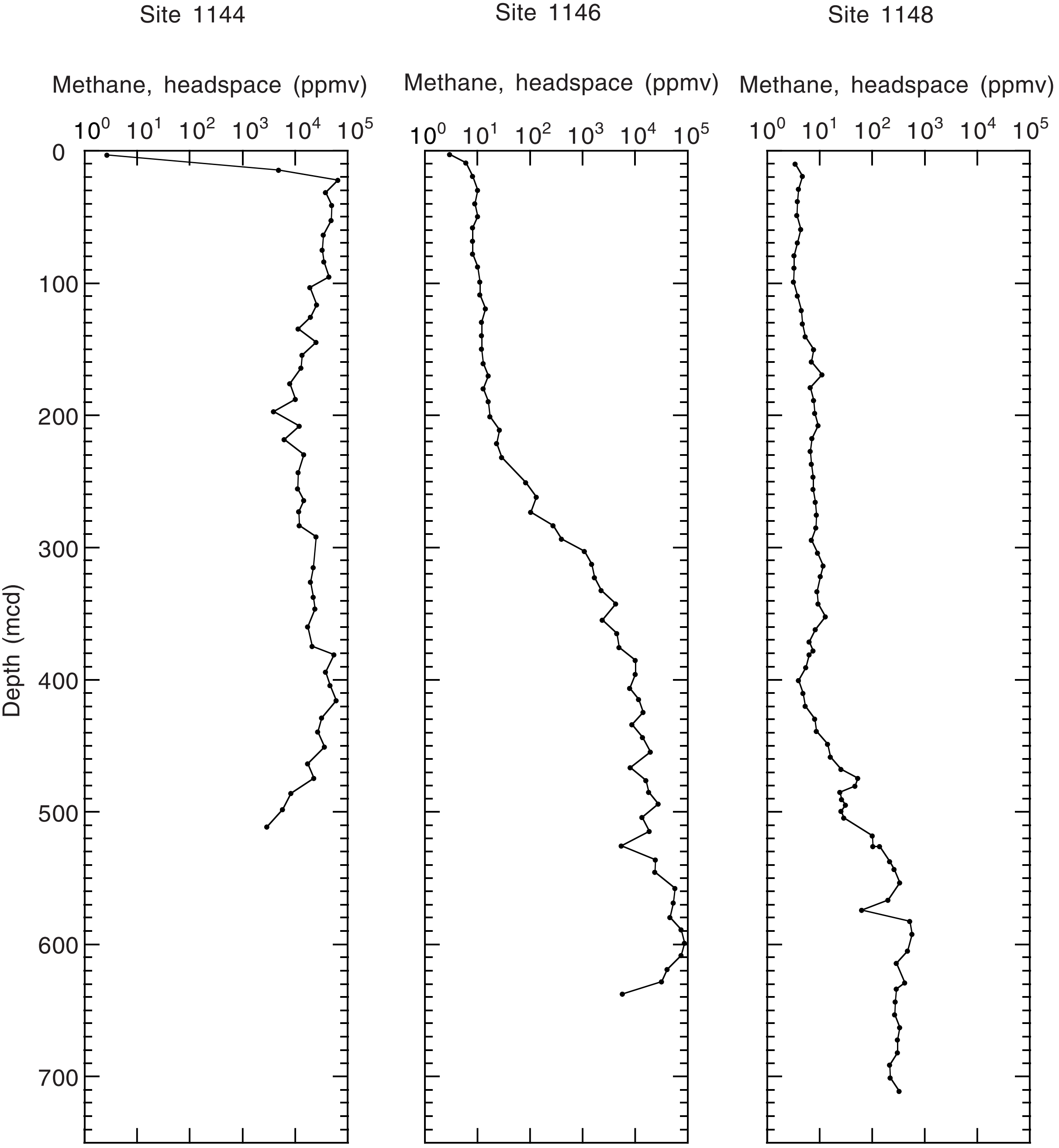

Site 1144
Site 1146
Site 1148
Methane, headspace (ppmv)
Methane, headspace (ppmv)
Methane, headspace (ppmv)
10^0 10^1 10^2 10^3 10^4 10^5
10^0 10^1 10^2 10^3 10^4 10^5
10^0 10^1 10^2 10^3 10^4 10^5
Depth (mcd)
0
100
200
300
400
500
600
700

Figure 27

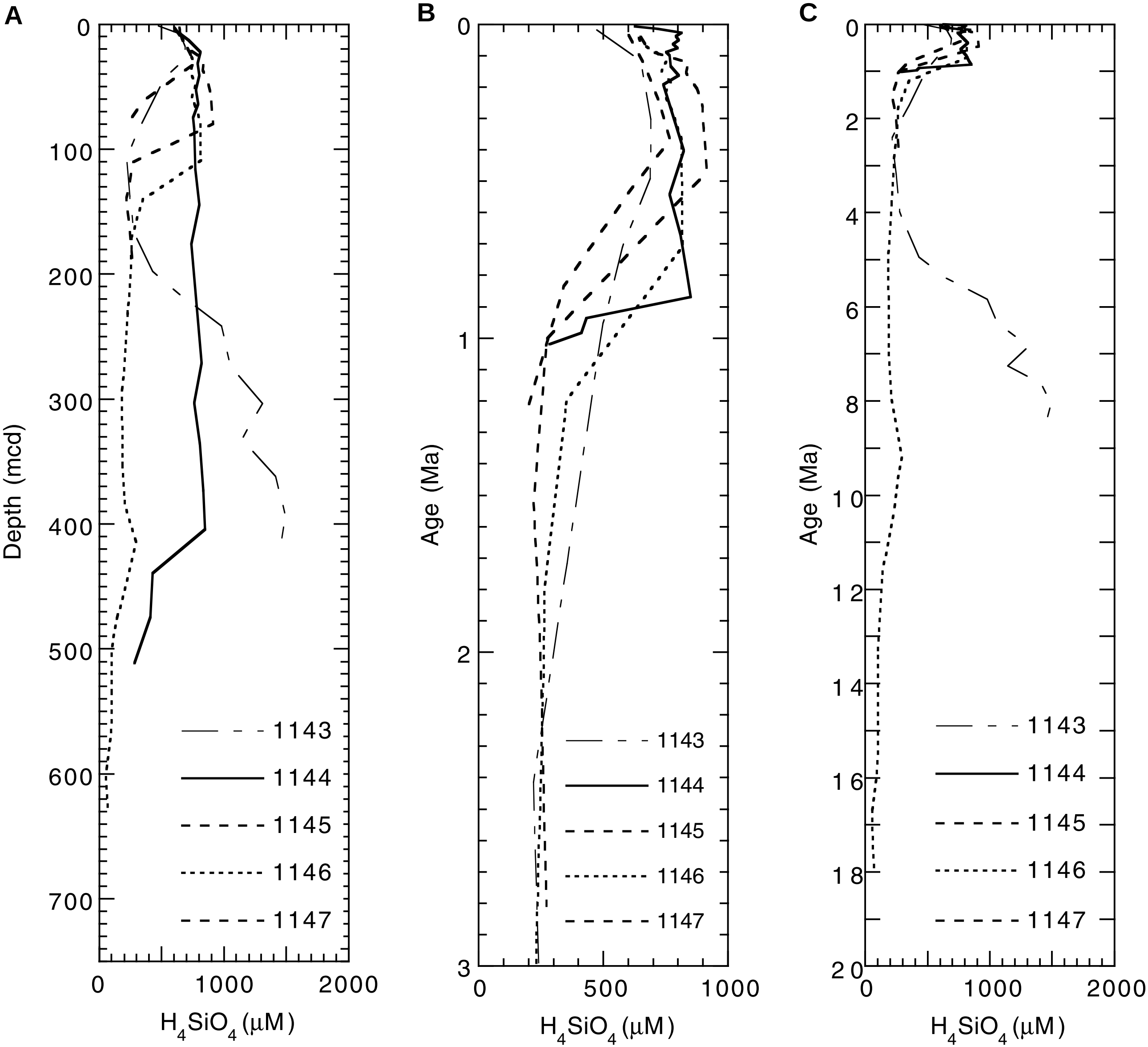

A
B
C
Depth (mcd)
0
100
200
300
400
500
600
700
0
1000
2000
H_4SiO_4 (µM)
1143
1144
1145
1146
1147
Age (Ma)
0
1
2
3
0
500
1000
H_4SiO_4 (µM)
1143
1144
1145
1146
1147
Age (Ma)
0
2
4
6
8
10
12
14
16
18
20
0
1000
2000
H_4SiO_4 (µM)
1143
1144
1145
1146
1147

Figure 28

OPERATIONS SYNOPSIS[1]

Port Call

Leg 184 began at 0730 hr on 11 February 1999 when the first line was passed ashore at the Victoria Quay in Fremantle, Australia. A number of engineering tasks were accomplished during the port call, including the installation of a new housing unit (penthouse), a container to house the microbiology laboratory on top of the lab stack, and a vegetable chiller on the sun deck, and the replacement of the boom on crane no. 2. The arrival of several freight containers that contained critical engine parts was delayed, and the vessel had to remain in port 2.5 days beyond the planned departure on 16 February, 0600 hr. At 1730 hr on 18 February, the last line was released from Victoria Quay, and the vessel cleared the harbor.

Transit to Site 1143 (Proposed Site SCS-9)

Site 1143 in the Spratley Island area is located in an area that required special diplomatic efforts and safety protocols, which were finalized during the eventful 2800-nmi transit. Before the *JOIDES Resolution* could proceed to the prospective site, it required approval of the four political entities that lay claim to the region. Three countries (People's Republic of China [PRC], Vietnam, and the Philippines) had given formal consent before leaving Australia. The approval from Chinese Taipei was received on 26 February, a few days before drilling operations began.

Site 1143 is situated in poorly charted waters labeled Dangerous Grounds on the Admiralty charts. Although the site had been surveyed, extra precautions were necessary to ensure that the passage to the site was done in the safest possible manner. The 60-nmi transit across Dangerous Grounds was to be made at reduced speed, only during daylight hours, and only with calm seas and clear visibility.

Another issue was the piracy threat in the region. The vessel received a warning on 20 February from the Regional Piracy Center (RPC) in Kuala Lumpur via the Singapore Inmarsat C station (Sentosa Island) that the area around Sunda Strait and Karimata Island are the most prone to pirate raids. In response to this alert, the captain decided to adjust the speed of the ship to ensure a daylight transit across the Sunda Strait. The RPC alerted the vessel that persons in military uniforms and using military vessels had recently attacked ships passing close to the location of Site 1143. This information plus data from other sources raised serious questions regarding the security of the vessel while operating at Site 1143. The matter was referred to Ocean Drilling Program (ODP) management, who in turn consulted with senior program officials in Washington, D.C. On 22 February, a request was issued to the director of the Office of Ocean Affairs of the U.S. Department of State to review this matter and to provide advice, procedures, and assurances for the vessel's safety at Site 1143. On 23 February, the captain met briefly with the scientists and technicians and discussed ship security issues, including precautions that would

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[1] The Operations and Engineering personnel aboard the *JOIDES Resolution* on Leg 184 were Ron Grout, ODP Operations Manager, and Robert Laronga, Schlumberger Engineer.

be followed during the transit through the Sunda Strait. Also discussed were procedures to be followed should persons unknown attempt to board the vessel. Although an attack on the vessel was deemed highly unlikely, prudence and diligence required that this issue be addressed before crossing the strait.

At 0600 hr on 25 February, the vessel left the Indian Ocean and entered the Sunda Strait between Java and Sumatra. The ship entered the strait while it was still dark and with heavy rain punctuated by an occasional lighting flash. The eruption of Anak Krakatoa ("child of Krakatoa") was visible through the gloom from a distance of 20 nmi. The vessel passed within 6 nmi of the cone that is now growing in the caldera left by the 1883 eruption.

On the morning of 23 February, the S-band (10 cm) radar failed. During the subsequent trouble shooting by the Overseas Drilling Limited electronic technicians, the problem was ascertained to be in the rotary joint and/or associated cabling located in the antenna assembly. No spares for these items were on the vessel. The approach to Site 1143 required that both X-band and S-band radar units be operational. The vessel was therefore diverted to Singapore at 0830 hr on 26 February to allow factory representatives with the proper parts to work on the defunct unit. The ship arrived at the Changi holding anchorage in Singapore at 1500 hr on 27 February. At 1030 hr on 28 February, two technicians from Aeradion Technology Pte Ltd. and the vessel agent, Victor Chan, boarded the *JOIDES Resolution,* and the repairs were concluded in less than 2 hr. The vessel was under way to Site 1143 at 1215 hr on 28 February.

As the ship neared Dangerous Grounds, a fax was received on 3 March from the deputy director-general of the State Oceanic Administration of the Peoples' Republic of China in Beijing. This fax provided additional emergency contact phone and fax numbers in Beijing as well as reassurances that the PRC naval base at Yong-Shu-Jiao ("always summer reef") had been instructed "to keep a close eye on the cruise." This reef is located ~20 nmi northwest of Site 1143. This fax furnished the necessary assurances for vessel security that were required before establishing station keeping at Site 1143.

At 0445 hr on 3 March, ~5 nmi from the entry position to Dangerous Grounds, the forepeak tank was filled to adjust vessel trim bow down. This was done so that if the vessel were to ground on a reef, the bow would be the first point of contact. If the bow were to strike a shoal, the forepeak tank would be drained and the vessel backed off and diverted to a safe port for a hull inspection. At 0500 hr the speed was reduced to 6 kt; at 0600 hr, the *JOIDES Resolution* altered course from 49° to 90° at position 09°20.0′N, 112°5.5′E, and entered uncharted waters. Lookouts were posted as the vessel made its way to the location that marked the beginning of the 3.5-kHz survey point.

At 1215 hr, a PRC navy patrol vessel, *SOUTH TUG 156,* was sighted. After an initial attempt by our Chinese co-chief to inform the PRC vessel of our identity, no radio communication was established. The patrol craft followed us to the site location. At 1530 hr another vessel, named *TRUONG SA-12*, approached the *JOIDES Resolution,* and the crew attempted to hail us. This ship identified itself as Vietnamese. Our captain was unable to communicate with the *TRUONG SA-12* because of the language barrier.

From 1500 to 1530 hr, a 3.5-kHz survey was conducted over an existing seismic line as the vessel approached the site from the southwest. The survey was aborted earlier than planned as a result of the proximity of the Chinese and Vietnamese vessels and accompanying communication problems. At 1605 hr, after verifying site location with bathymetry, the positioning beacon was dropped on precise Global Positioning System (GPS) coordinates.

Site 1143 (Proposed Site SCS-9)

After the hydrophones and thrusters were extended and the vessel located on position, the corrected precision depth recorder (PDR) depth referenced to the dual elevator stool (DES) was obtained and indicated 2782.4 m. The advanced hydraulic piston corer (APC) and extended core barrel (XCB) bottom-hole assembly was made up and deployed. During the tripping of the drill string, the vessels *TRUONG SA-12* and *SOUTH TUG 156* remained visible until nightfall. At 2200 hr, the *SOUTH TUG 156* moved away from the site and was lost to radar. The *TRUONG SA-12* lingered in the area and kept us company until the site was abandoned.

Hole 1143A

Hole 1143A was spudded with the APC at 0330 hr on 4 March. Piston coring advanced to 190.4 meters below seafloor (mbsf) with excellent recovery (102%). The cores were oriented starting with Core 3H. APC refusal resulted when Core 21H did not allow a full stroke into the indurated sediment. The hole was deepened with the XCB to the depth approved by the Pollution Prevention and Safety Panel (PPSP), 400 mbsf. The average recovery for the entire hole was 95%. Only a trace amount of methane was measured at concentrations <10 ppm. No higher hydrocarbons were detected. Downhole temperature measurements were obtained using the APC temperature tool (APCT) before the retrieval of Cores 4H, 7H, 11H, and 16H, at 31, 60, 98, and 145 mbsf, respectively. A temperature gradient of 84°C/km was calculated from these data.

Three wireline logging runs were planned. After the hole was flushed with a 30-bbl mud treatment, it was displaced with an additional 100 bbl of sepiolite. During the pipe trip to the logging depth of 86 mbsf, the driller did not observe any increased weight caused by a restriction in the size of the hole. The first log was conducted with the triple combo tool suite. Results of the first run determined that the hole was in generally good condition below 210 mbsf and provided satisfactory results below this depth. Above 210 mbsf, there were alternating swollen clays and washouts as large as 45 cm. Several tight spots were measured, and a 3-hr wiper trip was performed the next tool string was deployed. Later deployment of the Formation MicroScanner (FMS) and sonic tool combination encountered an obstruction in the hole at <20 m below the bit. Several attempts to pass this obstruction proved fruitless. The mud pumps were used in an attempt to hydraulically push the tool suite past the hole constriction, but this maneuver gained only about 3 m. A moderate overpull was required to free the tool from the mud. After recovering the logging tool, the drill pipe was lowered past the obstruction to a depth of 163 mbsf and then pulled back with the bit positioned at 134 mbsf. The second deployment of the FMS required well over an hour for the logging tool to be worked through the clays. The hole was logged in one pass from 380 to ~158 mbsf. The planned deployment of the geological high-resolution magnetic tool (GHMT) was canceled. The logging equipment was disassembled, and the drill string was pulled clear of the seafloor.

Hole 1143B

The vessel was offset 20 m east for Hole 1143B. Before coring was begun in this hole, a bottom-water temperature measurement was obtained with the APCT. At 0130 hr on 7 March, Hole 1143B was spudded with the APC. The inferred seafloor depth from the mudline recovery was 2783.5 m. After advancing to 175.4 mbsf, APC refusal resulted when Core 19H did not effect a full stroke. The hole was deepened with nine XCB cores to 258.2 mbsf, which was considered the target depth for this hole. All piston cores were oriented starting with Core 3H. The bit cleared the seafloor at 0010 hr on 8 March. The average recovery for the hole was 95%.

Hole 1143C

The vessel was offset 10 m east, and the last hole of the site was spudded with the APC at 0100 hr on 8 March. The seafloor depth calculated from a presumed mudline recovery of 9.4 m was 2784.5 m, but hole-to-hole correlation showed that the top of the core was actually 4 m below the mudline. The hole was APC cored to 177.4 mbsf. The piston cores were oriented starting with Core 3H. The hole was deepened with the XCB to 286 mbsf when approval was received to extend the depth of the hole to 500 mbsf. XCB coring continued until 2315 hr on 9 March when the last core (54X) was recovered from 500 mbsf. The average recovery for the hole was 96%. The average recovery for the site was 95%.

The drill pipe was pulled out of the hole and cleared the seafloor at 0045 hr on 10 March. As the drill string was being recovered, both primary and backup beacons were retrieved, and the hydrophones and thrusters were retracted. The bit was at the rotary table at 0530 hr, and by 0545 hr the drilling equipment was secured for the voyage to the next site. At 0655 hr, a submarine periscope was clearly visible as it crossed our bow and pursued a reciprocal course that brought it within one-quarter mile of the starboard side of our vessel. The *JOIDES Resolution* cleared Dangerous Grounds at 1300 hr at 10°0′N, 113°17.1′E.

Site Survey

Several of the proposed sites on the continental slope of China were selected on the basis of a single seismic line. Final approval of these sites by the PPSP was contingent upon the *JOIDES Resolution* acquiring crossing seismic lines. A single-channel survey was designed to cover all such proposed sites that we were likely to drill: SCS-4, SCS-5C, and SCS-5E. At 1100 hr on 12 March, the vessel slowed to deploy the seismic equipment. Two seismic cross tracks a few nmi in length were acquired at each of the three proposed sites. The survey was finished by 1200 hr on 13 March, with a total distance surveyed of 133 nmi and an average speed of 5.5 kt. After the seismic equipment was retrieved, the vessel continued at full speed to proposed Site SCS-1.

Site 1144 (Proposed Site SCS-1)

The beacon was dropped on GPS coordinates for proposed site SCS-1 at 1745 hr on 13 March. The corrected PDR depth referenced to the DES was 2051.4 m.

Hole 1144A

Hole 1144A was spudded with the APC at 2245 hr on 13 March. The seafloor depth was inferred to be 2047.0 m from the recovery of the first core. Piston coring advanced to 234.9 mbsf with an excellent average recovery of 104.4%. The high recovery percentage was in part a result of the gas expansion of many of the cores. APC refusal was encountered when the core barrel for Core 25H could not be pulled free of the sediment with an overpull of 120,000 lb. The core barrel had to be drilled over to free it from the sediment. The cores were oriented starting with Core 3H. During piston coring, heat-flow measurements were obtained at 26, 64, 102, and 149 mbsf. A low temperature gradient of 24°C/km was calculated from these data. The hole was deepened with the XCB to the target depth of 452.6 mbsf. The XCB average recovery was 102.6%; the average recovery for this hole was an exceptional 103.6%. Only moderate amounts of biogenic methane were measured in the cores.

After the hole was flushed with a 30-bbl mud treatment, the bore was displaced with an additional 115 bbl of sepiolite. During the pipe trip to the logging depth of 87 mbsf, the driller did not observe any increased weight resulting from restriction in the size of the hole. Logging began at 1200 hr on 15 March. Three successful wireline logging runs were completed with all three tool suites (triple combo, FMS-sonic, and GHMT) covering the open hole from 452 to 87 mbsf. Hole conditions, were good with some washouts detected in the lower portion. No problems with the swelling clays were encountered at Site 1144. At 0615 hr on 16 March, the logging equipment was disassembled and the drill string pulled back. The bit cleared the seafloor at 0655 hr on 16 March.

Hole 1144B

The vessel was offset 20 m east of Hole 1144A. Hole 1144B was spudded with the APC at 0800 hr on 16 March. The seafloor depth inferred from recovery was 2049.8 m. Piston coring advanced to 199.6 mbsf with an average recovery of 98.3%. The cores were oriented starting with Core 3H. Time saved at the previous hole and wireline logging permitted us to deepen Hole 1144B with the XCB to provide a stratigraphic overlap with Hole 1144A. The hole was deepened to 452.0 mbsf by 1930 hr on 17 March. Once again, the XCB did well with an average recovery of 100.0%. The recovery for the entire hole was 98.6%. After the hole was abandoned with 30 bbl of heavy mud, the bit was pulled clear of the seafloor at 2115 hr on 17 March.

Hole 1144C

Hole 1144C was spudded with the APC at 2230 hr on 17 March and advanced to a depth of 198.7 mbsf, which was considered the target depth for this hole. The average recovery for the hole was 99.9%; all cores were oriented starting with Core 3H. The interval from 37.2 to 42.2 mbsf was washed ahead without coring to obtain a proper stratigraphic overlap with Hole 1144B.

The total recovery for Site 1144 was 1113.3 m, 100.9% of the cored interval. After the bit cleared the seafloor at 1245 hr on 18 March, the drilling crew temporarily interrupted the pipe trip to perform the routine maintenance of slipping and cutting 115 ft of drilling line. The bit was at the rotary table by 1630 hr. Both primary and backup beacons were recovered. The drilling equipment, hydrophones, and thrusters were secured for the short voyage to the next site. The vessel was under way at 1645 hr on 18 March.

Site 1145 (Proposed Site SCS-2)

The short voyage to Site 1145 (proposed site SCS-2) covered the 31 nmi at an average speed of 10.3 kt. The beacon was dropped on precise GPS coordinates at 1950 hr on 18 March. The corrected PDR depth referenced to the DES was 3194.4 m.

Hole 1145A

Hole 1145A was spudded with the APC at 0245 hr on 19 March. The seafloor depth was inferred from the recovery of the first core as 3187.1 m. Piston coring advanced to 125.0 mbsf with an average recovery of 100.1%. The cores were oriented starting with Core 4H. During piston coring, heat-flow measurements were obtained at 30, 58, 96, and 200 mbsf. The last measurement was made with the Davis-Villinger temperature probe (DVTP). A temperature gradient of 90°C/km was calculated from these data. The hole was deepened with the XCB to the target depth of 200.0 mbsf. The XCB average recovery was 81.9%; the average recovery for this hole was 93.3%. Only a trace amount of methane was detected in the cores.

Hole 1145B

The vessel was offset 10 m west of Hole 1145A, and Hole 1145B was spudded with the APC at 0145 hr on 20 March. The seafloor depth, inferred from the recovery of the first core, was 3185.9 m. Piston coring advanced to 120.6 mbsf with an average recovery of 99.5%. The cores were oriented starting with Core 3H. The hole was deepened to the target depth of 200.0 mbsf with the XCB. The XCB-cored portion of the hole averaged only 74.8% because of zero recovery in one of the core barrels (20X). The average recovery for the hole was 89.7%.

Hole 1145C

The vessel was offset 10 m west of Hole 1145B, and Hole 1145C was spudded with the APC at 2015 hr on 20 March. The seafloor depth was inferred to be 3187.9 m. Piston coring advanced to 121.6 mbsf with an average recovery of 101.4%. The cores were oriented starting with Core

3H. The hole was deepened to the target depth 198.4 mbsf with the XCB; the average XCB recovery was 86.0%. The average recovery for the hole was 95.4%.

The total core recovered at this site was 555.2 m, or 92.8% of the cored interval of 598.1 m. The bit was at the plane of the rotary table by 1630 hr on 21 March, and the vessel began the 78-nmi voyage to Site 1146.

Site 1146 (Proposed Site SCS-4)

The 78-nmi transit to Site 1146 (proposed site SCS-4) was accomplished in 7 hr at an average speed of 11.1 kt. The beacon was dropped on precise GPS coordinates at 2345 hr on 21 March. The PDR depth referenced to the DES was 2108.4 m.

Hole 1146A

Hole 1146A was spudded with the APC at 0500 hr on 22 March. The seafloor depth was defined at 2102.6 m from the recovery of the first core. Piston coring advanced with 21 APC cores to 193.9 mbsf. The cores were oriented starting with Core 3H and then continuously from 6H through 21H. During piston coring, downhole temperature measurements were obtained at 32, 61, 99, and 146 mbsf. A temperature gradient of 62°C/km was calculated from the data obtained by the last three measurements. The hole was deepened with the XCB to the target depth of 607.0 mbsf. The average recovery for this hole was 99.5%. Methane concentration increased with depth and peaked at 563 mbsf with 87,000 ppm, then dropped to 5,000 ppm at the bottom of the hole. The maximum ethane concentration of 200 ppm (and <10 ppm propane) was found in samples at the bottom of the hole.

The hole was flushed with 30 bbl of mud and displaced with an additional 190 bbl of sepiolite. No restrictions in hole size were observed by the driller when the pipe was raised to the logging depth of 88 mbsf. Wireline logging began at 1615 hr on 24 March and was completed with three successful runs: triple combo (85–600 mbsf), FMS-sonic (239–600 mbsf), and GHMT (239–600 mbsf). The drill string was lowered to move the bit from 88 to 239 mbsf after the first run because of numerous washouts and ledges in the upper part of the hole. After logging, the hole was abandoned with 30 bbl of 10.5-lb/gal heavy mud. The drill string was pulled back, and the bit cleared the seafloor at 1330 hr on 25 March.

Floats associated with a long-line fishing array were observed drifting near the ship as Hole 1146A was being displaced with sepiolite mud. As the drill string was pulled up to logging depth, a small amount of monofilament fishing line (30 m) replete with hooks and some live bait was removed from two stands. Two small fishing boats were observed in the area. The drill crew also retrieved two mahi-mahi (3–4 ft long) at the rig floor. The fish had safely passed up through the guide horn and out the DES and ended up in our barbecue grills. A diver inspection of the thrusters and main propeller shafts was planned for the Hong Kong port call.

Hole 1146B

The ship was offset 20 m east of Hole 1146A, and Hole 1146B was spudded with the APC at 1500 hr on 25 March. The seafloor depth inferred from the recovery of the first core was 2103.2 m. Piston coring advanced to 216.3 mbsf, and the cores were oriented starting with Core 3H. The hole was deepened to 245.1 mbsf with three XCB cores. The average recovery for the hole was 98.7%. The bit was pulled clear of the seafloor at 1415 hr on 26 March.

Hole 1146C

The vessel was offset 10 m east of Hole 1146B. To obtain a stratigraphic overlap with data from the previous holes, the initial APC core of Hole 1146C was shot after placing the bit one meter below the mudline depth of Hole 1146B. Hole 1146C was spudded at 1540 hr on 26 March, and piston coring advanced to 162.5 mbsf. The cores were oriented starting with Core 3H. The hole was deepened to the maximum target depth of 603.5 mbsf with 46 XCB cores. During XCB coring, the interval from 220.1 to 224.1 mbsf was drilled ahead to maintain an overlap with Hole 1146A. The average recovery for the hole was 101.4%.

The total core recovered at this site was 1452.2 m, representing 100.1% of the cored interval of 1450.6 m. The bit cleared the seafloor at 0100 hr on 29 March as the drill string was recovered. Before leaving the site, the components of the bottom-hole assembly were subjected to the routine end-of-leg magnetic particle inspection. At 0615 hr on 29 March, the vessel began the short voyage to Site 1147.

Site 1147 (Proposed Site SCS-5F)

During operations at Site 1146, the vessel received approval for coring Site 1147 (newly proposed site SCS-5F) to a depth of 100 mbsf. This site was less than 1 mile west of Site 1148 (proposed site SCS-5C). The plan was to piston core three holes to a depth of ~80 mbsf to recover the upper part of the Pleistocene section that, judging from seismic records, appeared to be missing at Site 1148. The 40-nmi transit to Site 1147 took 4 hr at an average speed of 9.5 kt. The beacon was dropped on GPS coordinates at 1035 hr on 29 March. The corrected PDR depth referenced to the DES was 3256.4 m.

Hole 1147A

Hole 1147A was spudded with the APC at 1815 hr on 29 March. The seafloor depth was inferred at 3257.5 m from the recovery of the first core. Piston coring advanced with nine APC cores to 81.4 mbsf with an average recovery of 100.4%. Cores were oriented starting with Core 3H.

Hole 1147B

The vessel was moved in dynamic positioning mode 10 m east of Hole 1147A. Hole 1147B was spudded with the APC at 0245 hr on 30 March. The inferred seafloor depth was 3257.0 m.

Piston coring advanced with nine APC cores to 85.5 mbsf with an average recovery of 100.0%. Cores were oriented starting with Core 3H.

Hole 1147C

The ship was moved 10 m east of Hole 1147B. Hole 1147C was spudded with the APC at 1045 hr on 30 March. The inferred seafloor depth was 3256.9 m. Piston coring advanced with nine APC cores to 78.6 mbsf with an average recovery of 97.5%. Cores were oriented starting with Core 2H.

The total recovery for this site was 243.8 m, or 99.3% of the cored interval of 245.5 m. After the bit was pulled clear of the seafloor at 1820 hr on 30 March, it was raised ~50 m above the seafloor in preparation for the move to Site 1148. After the beacon was released and recovered at 1915 hr, the JOIDES Resolution was moved to Site 1148, ~0.6 nmi east of Site 1147, in dynamic positioning mode.

Site 1148 (Proposed Site SCS-5C)

The beacon was deployed on the GPS coordinates of Site 1148 (proposed site SCS-5C) at 2015 hr on 30 March.

Hole 1148A

Hole 1148A was spudded with the APC at 2215 hr on 30 March. The seafloor depth calculated from the recovery of the first core was 3308.7 m. Piston coring advanced with 16 APC cores to 143.3 mbsf with an average recovery of 101.1%. The cores were oriented starting with Core 4H. During piston coring, downhole temperature measurements with the APCT were obtained at 29, 58, and 105 mbsf. Based upon these measurements, a temperature gradient of 83°C/km was calculated.

Coring was resumed with the XCB and advanced to 450 mbsf with 100% recovery. At 152.9 mbsf, the DVTP was deployed. The data obtained at 153 mbsf confirmed the temperature gradient calculated from the three APCT measurements. At ~460 mbsf, a sharp transition from clayey chalk to an underconsolidated clayey formation was encountered, and recovery dropped off sharply. From 460 to ~600 mbsf, the average recovery was 47%, with several cores around 500 mbsf having almost no recovery. In an effort to increase recovery, some core barrels were recovered after advancing only 5 m instead of the nominal 9.6 m. Between 600 mbsf and the bottom of the hole at 704 mbsf, average recovery returned to almost 100%. The XCB average recovery for Hole 1148A was 86.9%; the average recovery for this hole was 89.8%.

Headspace analysis indicated that the concentration of methane was below 10 ppm down to 430 mbsf. It then increased gradually to a maximum concentration of 569 ppm at 580 mbsf. More complex hydrocarbon molecules were not detected above 468 mbsf. Below this depth, the abundance of both ethane and propane followed a trend similar to that of methane, peaking at 570–580 mbsf (25 and 10 ppm, respectively). Butane and pentane were detected from samples taken below 570 mbsf, with maximum readings of 28 and 32 ppm, respectively, from the last core (77X).

A wiper trip was made up to 107 mbsf and then back to bottom. Approximately 19 m of soft fill was found at the bottom of the hole. The hole was washed and reamed from 685 to 704 mbsf. After the hole was flushed with a 30-bbl mud treatment, the bore was displaced with an additional 215 bbl of sepiolite. The bit was pulled back and positioned at 107 mbsf for logging. Wireline logging in Hole 1148A was completed with three successful runs: triple combo (107–704 mbsf), FMS-sonic (180–704 mbsf), and GHMT (166–704 mbsf). With the exception of a washed-out interval above 200 mbsf, the hole was in the best condition of any of those logged on this leg. The drill string was lowered after the first and second logging runs because of several zones of reduced hole diameter that were attributed to swelling clays. After logging, the hole was abandoned with 30 bbl of 10.5-lb/gal mud. The bit cleared the seafloor at 1600 hr on 5 April.

Hole 1148B

The vessel was offset 20 m east of Hole 1148A. Before spudding the new hole, a near-bottom-water temperature was obtained with the APCT. Hole 1148B began at 2045 hr from a seafloor depth of 3303.4 m, and piston coring advanced to 145.1 mbsf with 96.2% recovery. Several liners split during the piston coring, which resulted in less than expected recovery. Cores were oriented starting with Core 3H. A 4-m interval was washed ahead from 36.6 to 40.6 mbsf to ensure a stratigraphic overlap with Hole 1148B.

While piston coring in Hole 1148B, we received permission from ODP to deepen Hole 1148B to basement or to a maximum of 850 mbsf, as long as rigorous safety monitoring did not preclude further drilling. After piston coring in Hole 1148B, it was decided to drill ahead with a center bit in place through the interval 145–440 mbsf that was well recovered in Hole 1148A in order to save time for deepening the site. The XCB recovery from 460 to 600 mbsf was 44%, slightly less than in the same interval in Hole 1148A. Recovery in the interval 600–646 mbsf improved again to 92%.

To save further time for coring the deep objectives of this site, the interval 646–700 mbsf was drilled ahead with the center bit in place. At midnight on 8 April, XCB coring resumed and advanced from 700 to 809 mbsf with 83.5% average recovery at an average rate of penetration of 15 m/hr. Results of the headspace analysis were closely monitored to observe any trends suggesting that we were approaching an accumulation of hydrocarbons. The drillers had instructions that if any sudden change in drilling rate or torque was observed, the core barrel would be recovered and a headspace analysis performed before coring resumed. While coring from 774 to 775 mbsf, the drillers experienced higher than normal torque with an apparent increase in bit weight of ~5,000 lb. These symptoms suggested that there was some hydraulic levering of the bit off bottom due to a packed-off annulus. The core barrel was recovered early, and the core-catcher sample was subjected to hydrocarbon analysis. While we waited for the results, a 30-bbl sepiolite mud sweep was circulated through the annulus. After the headspace analysis results confirmed that there was no change in hydrocarbon concentration, coring resumed.

The interval 809–853 mbsf was cored at a low rate of penetration of 6 m/hr with very low recovery (22%) because of frequent jamming of the brittle claystone in the core catcher. At 1300 hr on 10 April, the last core was recovered from the target depth of 853 mbsf. The total core recovered in this hole was 364.4 m, representing 72.8% of the cored interval of 500.6 m. The drilled-down interval was 352.6 m, with a total penetration of 853.2 m. The hole was displaced with 30 bbl of 10.5-lb/gal mud, and the bit cleared the seafloor at 1535 hr on 10 April. The drill string was recovered, and the beacon was retrieved before the drilling equipment, hydrophones, and thrusters were secured. At 2215 hr on 10 April, the vessel began the 267-nmi voyage to the Hong Kong pilot station.