GREENHOUSE WORLD AND THE MESOZOIC OCEAN

BY REISHI TAKASHIMA, HIROSHI NISHI, BRIAN T. HUBER, AND R. MARK LECKIE

Earth's climate has alternated between greenhouse (warm) and icehouse (cool) modes throughout the Phanerozoic (Figure 1A). At present, Earth is in the midst of an icehouse climate. Nevertheless, the rise of industrialization in the last two centuries has led to a dramatic increase in atmospheric CO_2 from the burning of fossil fuels, which, in turn, has led to significant global warming (e.g., Ruddiman, 2000). Global warming could profoundly impact human life as a result of consequent global sea-level rise, more numerous and increasingly powerful hurricanes, and enhanced amounts of precipitation. Understanding the ocean-climate system during past greenhouse climate modes is essential for more accurately predicting future climate and environmental changes in a warming Earth.

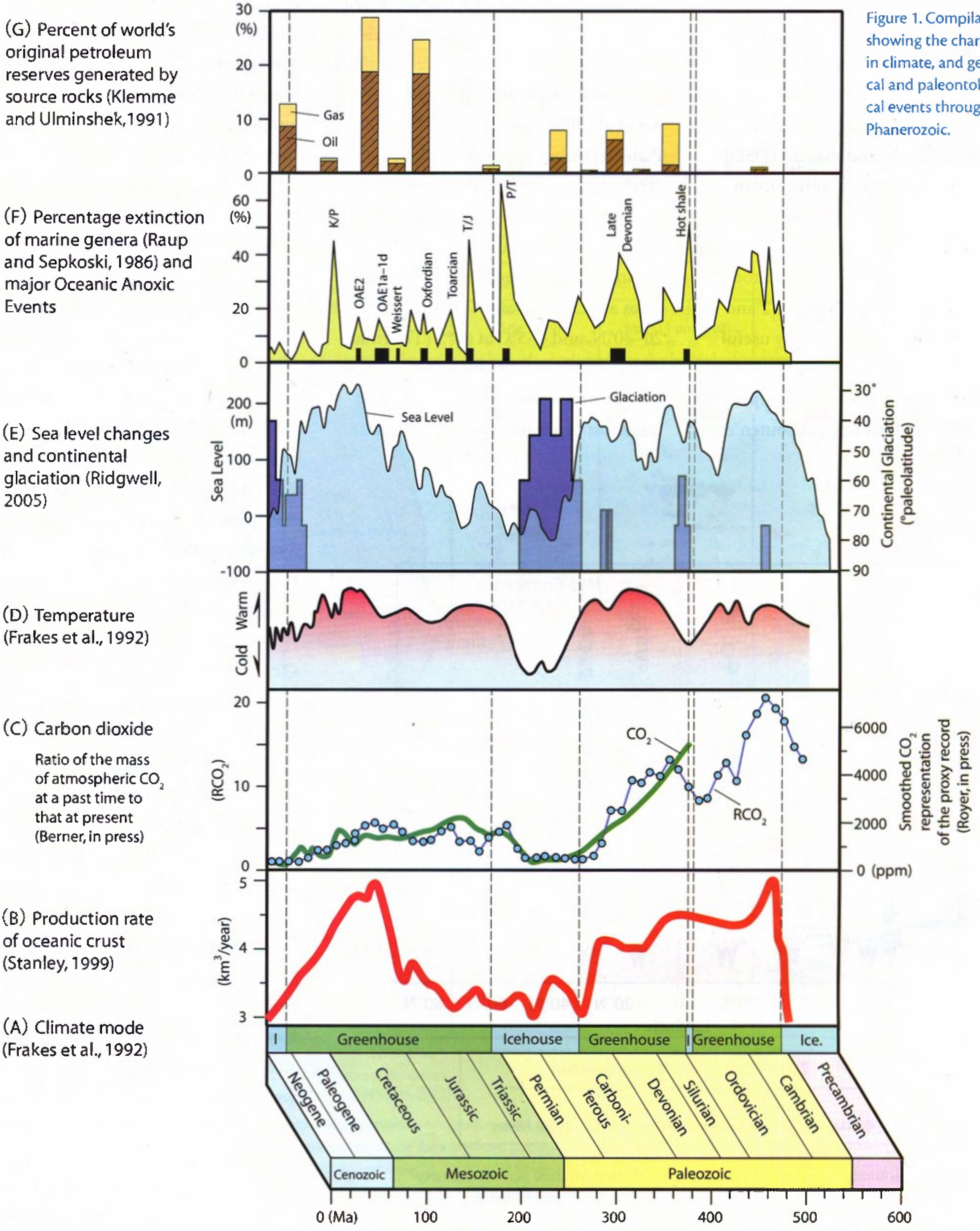
The Mesozoic-early Cenozoic is known as a typical greenhouse period caused largely by increased CO_2 from elevated global igneous activity (Figure 1A–C). The mid-Cretaceous is marked by a major warming peak (Figure 1D); it is characterized by globally averaged surface temperatures more than 14°C higher than those of today (Tarduno et al., 1998), a lack of permanent ice sheets (Frakes et al., 1992), and ~ 100–200-m-higher sea level than that of today (Haq et al., 1987; Miller et al., 2005a) (Figure 1E). Studies using Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) cores have advanced understanding of Mesozoic oceanography and climate, demonstrating that Mesozoic ocean circulation and marine ecosystems differed greatly from those of today. This paper reviews significant achievements of DSDP and ODP research and discusses future prospects for Integrated Ocean Drilling Program (IODP) investigations in the field of Mesozoic paleoceanography.

Reishi Takashima *(rtaka@nature.sci.hokudai.ac.jp) is Research Fellow, Department of Earth and Planetary Sciences, Hokkaido University, Sapporo, Japan.* **Hiroshi Nishi** *is Associate Professor, Department of Earth and Planetary Sciences, Hokkaido University, Sapporo, Japan.* **Brian T. Huber** *is Curator, Smithsonian Institution, National Museum of Natural History, Washington, D.C., USA.* **R. Mark Leckie** *is Professor, Department of Geosciences, University of Massachusetts, Amherst, MA, USA.*

NEW INSIGHTS

Determination of Mesozoic Ocean Temperature History

An important DSDP and ODP achievement was the reconstruction of the history of Mesozoic ocean temperature changes based on geochemical methods such as oxygen isotopes, TEX_{86}, and alkenone analyses. Oxygen-isotope data have provided the greatest source of paleotemperature reconstructions from ancient oceans. However, the increasing prevalence of diagenetic alteration in older or more deeply buried rocks limits or prevents reliable isotopic data from being gleaned from biogenic calcite preserved in terrestrial outcrops. Compared to many land-based sections, calcareous microfossils of Cretaceous age recovered from samples drilled at DSDP and ODP sites are often better preserved, and usu-


(G) Percent of world's original petroleum reserves generated by source rocks (Klemme and Ulminshek,1991)

(F) Percentage extinction of marine genera (Raup and Sepkoski, 1986) and major Oceanic Anoxic Events

(E) Sea level changes and continental glaciation (Ridgwell, 2005)

(D) Temperature (Frakes et al., 1992)

(C) Carbon dioxide

Ratio of the mass of atmospheric CO_2 at a past time to that at present (Berner, in press)

(B) Production rate of oceanic crust (Stanley, 1999)

(A) Climate mode (Frakes et al., 1992)

Figure 1. Compilation showing the changes in climate, and geological and paleontological events through the Phanerozoic.

ally have not been as seriously affected by complex tectonic and/or weathering processes. Exquisitely preserved foraminifera from the low-latitude Demerara Rise (ODP Sites 1258–1261; 4–15°N), mid-latitude Blake Nose (ODP Sites 1049, 1050, 1052; 30°N), and high-latitude Falkland Plateau (DSDP Site 511; 60°S) in the Atlantic Ocean have been especially useful for reconstructing vertical and latitudinal temperature gradients of the mid- through Late Cretaceous ocean (Figures 2 and 3). The TEX_{86} method is especially useful for organic carbon-rich sediments and has provided excellent paleo-temperature determinations (e.g., Schouten et al., 2003; Jenkyns et al., 2004).

According to isotopic records of surface-dwelling planktic foraminifera, sea surface temperatures reached a maximum of 42°C at the Demerara Rise (Bice et al., 2006), 33°C at the Blake Nose (Huber et al., 2002), and 31°C at the Falkland Plateau (Huber et al., 2002; Bice et al., 2003) during the Turonian (~ 93–89 Ma [million years ago]) (Figures 2 and 3). At comparable latitudes in the modern ocean, August surface water temperatures are 25–28°C at 0–20°N, 20–28°C at 20–40°N, and 0–5°C at 60°S (Thurman and Trujillo, 1999). Consequently, these data suggest that Cretaceous warming was most prominent at high latitudes where the difference of temperature between the mid-Cretaceous and the present oceans is nearly 30°C (Figure 2). Bice and Norris (2002) estimate that at least 4500 ppm CO_2 would be required to match the above-mentioned maximum temperatures, which is 11 times greater than the modern atmospheric concentration. Using a more recent climate model, Bice et al. (2006) conclude that 3500 ppm or greater atmospheric CO_2 concentration is required to reproduce the estimated maximum sea surface temperatures of the Mesozoic tropical ocean.

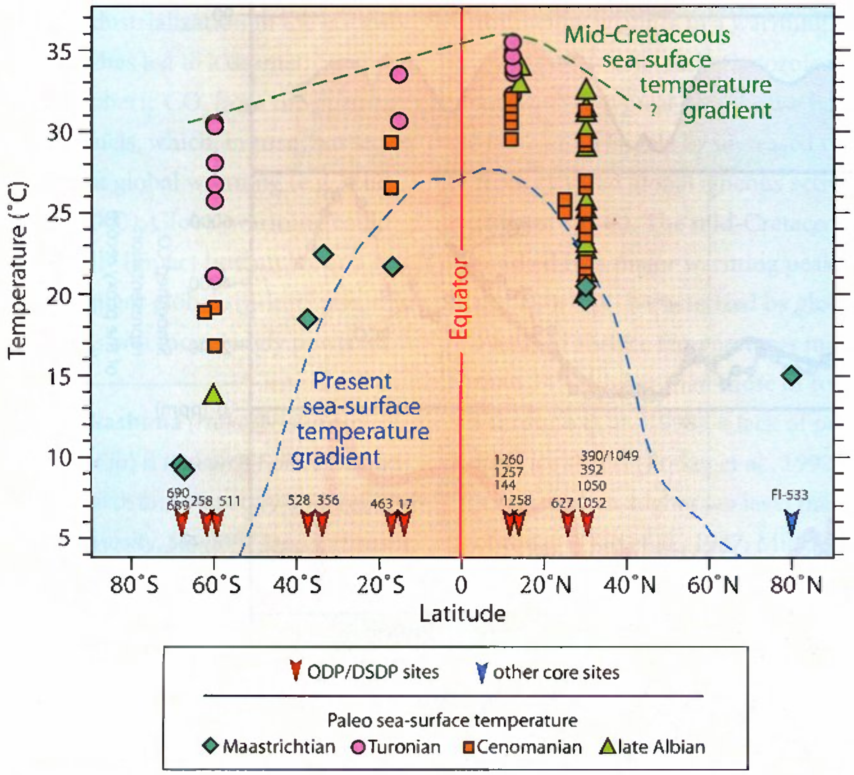


Figure 2. Latitudinal variations of surface ocean paleotemperature derived from oxygen isotopes of planktonic foraminifera and TEX_{86}. Modified from Huber et al. (2002), Bice et al. (2003), and Jenkyns et al. (2004).

Because the Mesozoic paleo-temperature estimates based on geochemical proxies are still insufficient in sediments older than Albian (> 112 Ma) and in areas outside of the Atlantic Ocean, further investigations are needed to reconstruct a reliable spatial and temporal temperature history during the greenhouse climate of the Mesozoic.

Oceanic Anoxic Events

Defining the concept of Oceanic Anoxic Events (OAEs) was one of the most important achievements of the early DSDP. Cretaceous marine sediments in Europe are mainly comprised of white limestone and chalk; however, distinct black, laminated organic-rich layers, termed "black shales," are occasionally intercalated within these sequences (Figure 4). Because organic carbon is preferentially preserved under anoxic conditions, earlier workers suggested that these black shales had accumulated locally in a weakly ventilated, restricted basin under regional anoxic conditions. In the mid-1970s, however, the discovery of black shales at many DSDP drill sites from the Atlantic, Indian, and Pacific Oceans led to recognition of widespread anoxic conditions in the global ocean spanning limited stratigraphic horizons (Figure 5). Schlanger and Jenkyns (1976) termed these widespread depositional black shale intervals "Oceanic Anoxic Events."

Burial of organic carbon, which preferentially sequesters isotopically light carbon during OAEs, resulted in a positive δ^{13}C (^{13}C/^{12}C) excursion of 2–3‰ in the geologic record (Figure 3). Even if black shales are not visible in terrestrial rocks such as dark gray- to black-colored mudstones, carbon isotope excursions are a useful marker for recognizing OAEs (e.g., Gröke et al., 1999; Takashima et al., 2004). Recent advances in biostratigraphy and correlation us-

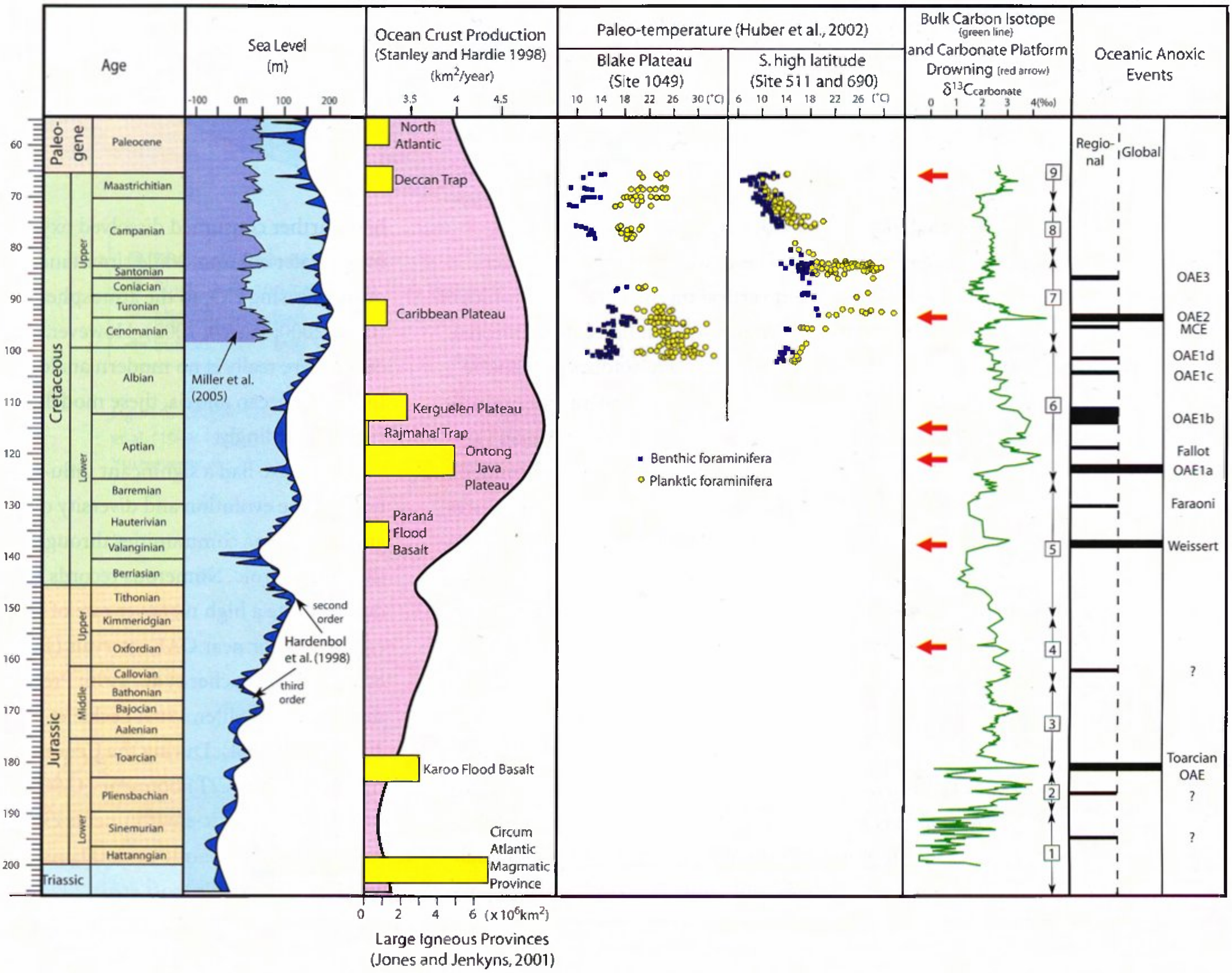


Figure 3. Compilation showing Jurassic–Cretaceous changes in sea level, oceanic-crust production, paleo-temperature, bulk carbon isotopes, carbonate-platform drowning events and OAEs. Large Igneous Province data are from Jones and Jenkyns (2001). Bulk carbon isotopes are from (1) Van de Schootbrugge et al. (2005); (2) Hesselbo et al. (2000); (3) Morettini et al. (2002); (4) Dromart et al. (2003); (5) Weissert et al. (1998); (6) Erbacher et al. (1996); (7) Jenkyns et al. (1994); (8) Jarvis et al. (2002); and (9) Abramovich et al. (2003). Carbonate-platform drowning data are from Simó et al. (1993) and Weissert and Mohr (1996).

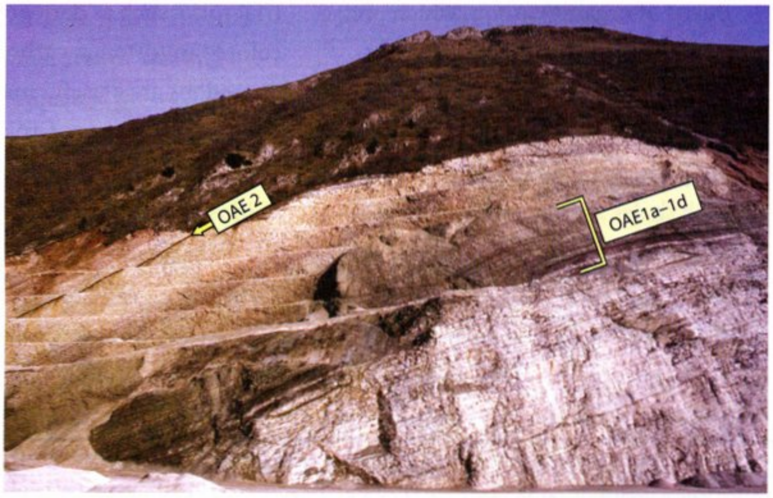


Figure 4. Cretaceous black shales intercalated in pelagic limestone sequence, central Italy. Figure courtesy of R. Coccioni.

ing carbon isotopes have revealed that OAEs occurred at least eight times in the Cretaceous and at least one to four times in the Jurassic (Figure 3). The Toarcian OAE, Weissert OAE, OAE 1a, and OAE 2 are global-scale anoxic events associated with prominent positive excursions of $\delta^{13}C$ and worldwide distribution of black shales (Figure 3).

Two models, that of a stagnant ocean and expansion of the oxygen-minimum layer, have been proposed to explain black shale in the OAEs (e.g., Pedersen and Calvert, 1990). The stagnant ocean model (STO model) attributes OAEs to depletion of bottom water oxygen as a result of dense vertical ocean stratification (Figure 6A). A modern analog is seen in stratified silled basins such as the Black Sea. The expanded oxygen-minimum layer model (OMZ model) proposes that increased surface ocean productivity caused expansion of the oxygen-minimum layer in the water column (Figure 6B). Upwelling sites such as the Moroccan and Peruvian margins provide modern examples for this model.

These two models predict different vertical thermal gradient profiles of the water column that can be inferred from the oxygen isotopes of planktic and benthic foraminifera. For example, the OAE 1b in the earliest Albian (about 112 Ma) is characterized by a sudden increase in surface water temperatures and strengthening of the vertical stratification of the water column (Erbacher et al., 2001), suggesting similarity to the STO model (Figure 7A). On the other hand, the OAE 2 (about 93.5 Ma) shows sudden warming of deep water and collapse of vertical stratification (Huber et al., 1999), which probably induced enhanced upwelling and productivity similar to the expanded OMZ model (Figure 7B). Deep-water warming may have contributed to a decrease in oxygen solubility in the deep ocean and may have triggered the disassociation of large volumes of methane hydrate buried in sediments of the continental margins. Oxidation of the released methane could have further consumed dissolved oxygen in the water column, while simultaneously releasing CO_2 to the atmosphere (Gale, 2000; Jahren, 2002). However, because there really is no modern analog for global ocean anoxia, these models suffer accordingly.

OAEs have had a significant influence on the evolution and diversity of ancient marine communities through the Phanerozoic. Numerous records demonstrate a high turnover rate of microfossils at or near OAE intervals (Jarvis et al., 1988; Erbacher et al., 1996; Premoli Silva and Sliter, 1999; Leckie et al., 2002; Erba, 2004). During the Cenomanian-Turonian (C/T) boundary OAE 2, for example, anoxic environments expanded from the photic zone (Damsté and Köster, 1998; Pancost et al., 2004) to greater than 3500-m depth in the Atlantic Ocean (Thurow et al., 1992), resulting in about 20 percent of marine organisms becoming extinct in various habitats within an interval of less than one million years (Figure 1F). Black shales in the

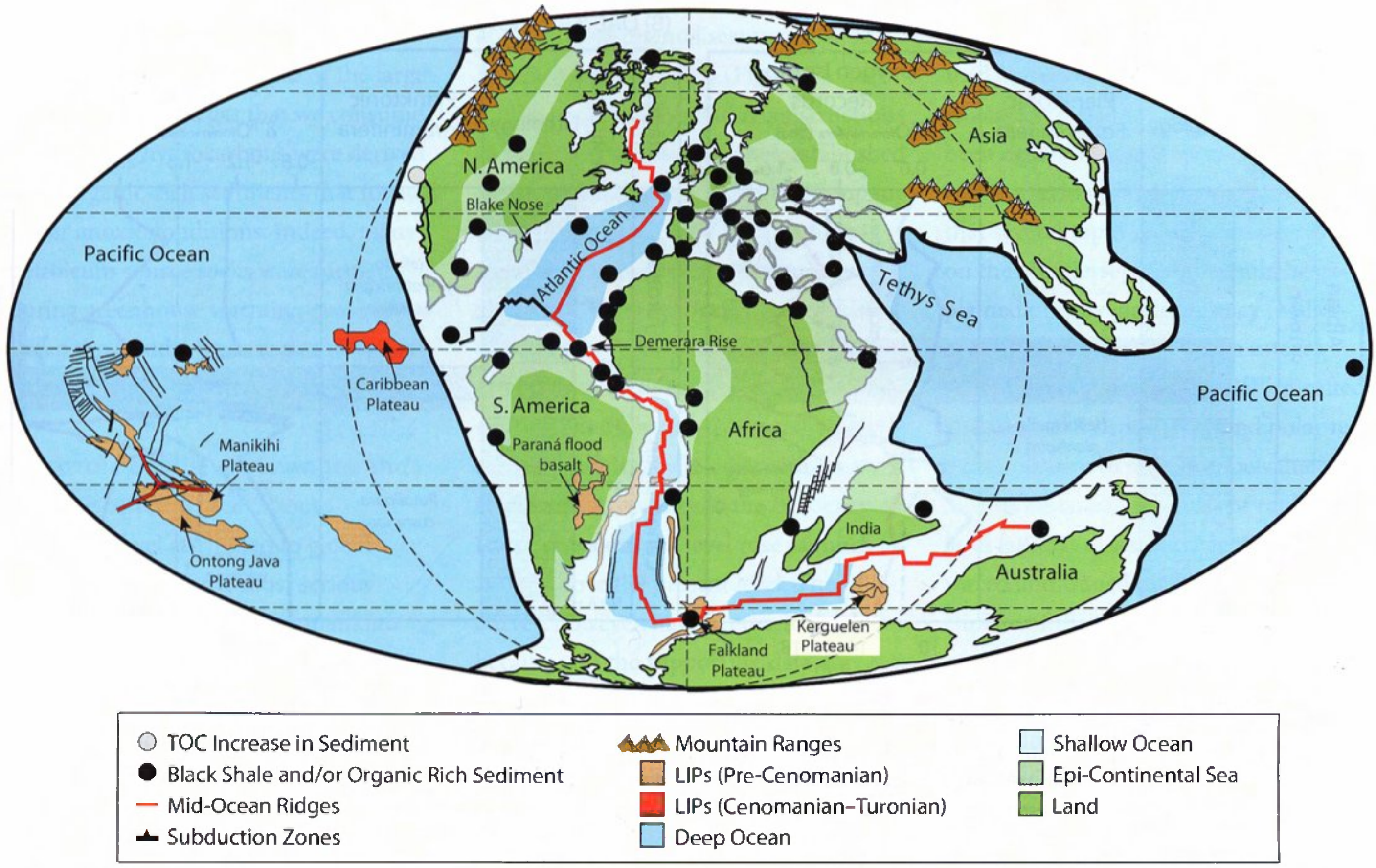


Figure 5. Distribution of black shales and/or increased organic carbon sediments at OAE 2. Data are from Schlanger et al. (1987); Arthur et al. (1987, 1988); Jenkyns, (1991); Thurow et al. (1992); Kassab and Obaidalla (2001); Wang et al. (2001); Lebedeva and Zverev (2003); Yurtsever et al. (2003); Coccioni and Luciani (2005); Fisher et al. (2005); and Takashima and Nishi (unpublished data).

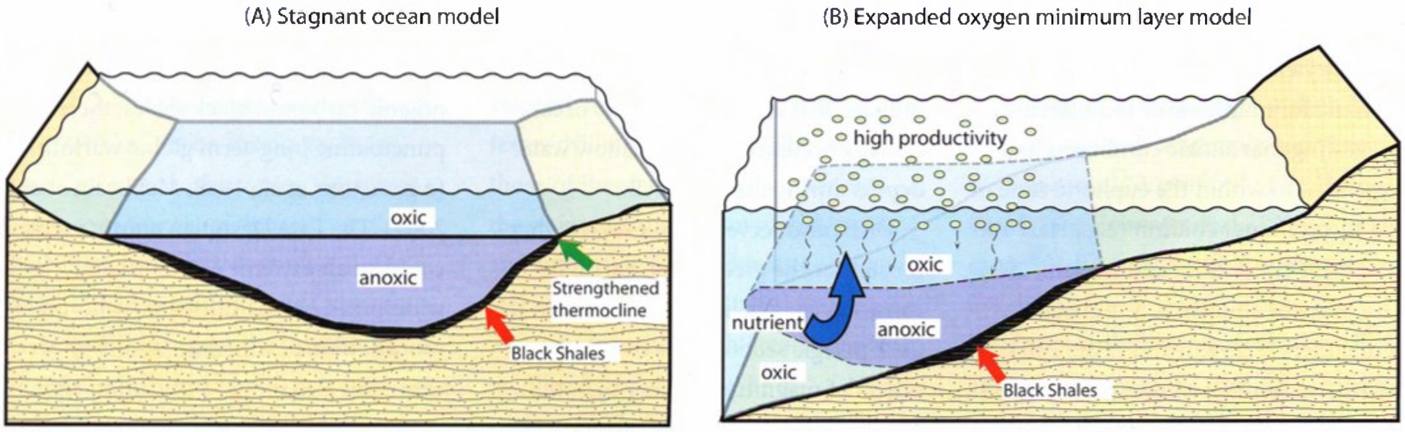


Figure 6. Representative models for black shale deposition: (A) the stagnant ocean model, and (B) the oxygen-minimum-layer model.

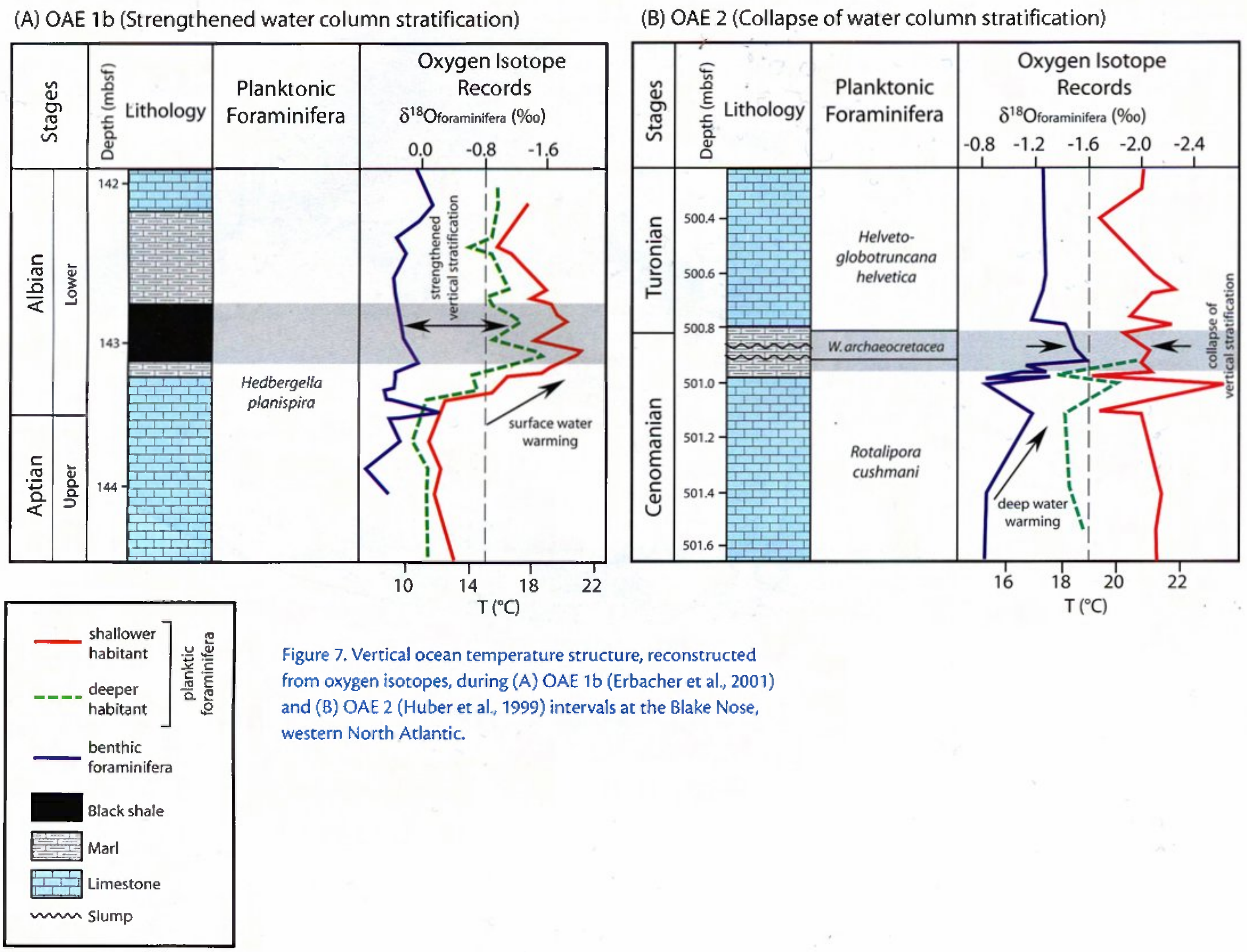


Figure 7. Vertical ocean temperature structure, reconstructed from oxygen isotopes, during (A) OAE 1b (Erbacher et al., 2001) and (B) OAE 2 (Huber et al., 1999) intervals at the Blake Nose, western North Atlantic.

OAEs, especially OAE 1a and OAE 2, frequently yield no calcareous nannofossils, planktic foraminifera, or radiolarians, suggesting that anoxic conditions had expanded to within the euphotic zone of the surface water column (e.g., Hart and Leary, 1991; Coccioni and Luciani, 2005). Discovery of abundant cyanobacteria biomarkers (e.g., Kuypers et al., 2004), nonthermophilic archaea (e.g., Kuypers et al., 2001), and green sulfur bacteria (e.g., Damesté and Köster, 1998) within the black shales provides strong support for this hypothesis. These proxies further indicate that anoxic conditions occasionally occurred at very shallow water depths during the C/T OAE.

OAEs also served as an effective thermostat for the greenhouse Earth. Because the change in organic burial in the OAE pelagic sections was two to three orders of magnitude greater than the mean conditions at other time intervals, burial of massive organic carbon during OAEs may have drawn down CO_2 from the ocean–atmosphere by burying organic carbon in black shales, thereby punctuating long-term global warmth (e.g., Arthur et al., 1988; McElwain et al., 2005). The Late Devonian anoxic event could be an extreme example where widespread anoxia caused not only significant biotic extinction (about 40 percent), but also induced glaciation after deposition of black shales (Caplan and Bustin, 2001).

OAEs have benefited human life because they are a major cause of the large volumes of oil and gas that we consume today. These hydrocarbons were derived from organic-rich sediments that formed under anoxic conditions. Indeed, many petroleum source rocks were formed during greenhouse warming peaks between the Middle Jurassic and mid-Cretaceous (Figure 1G).

Mesozoic Sea-Level Changes and the Existence of Ice Sheets

Rising sea level attributed to global warming is one of the most serious and imminent problems for mankind because of the concentration of human populations in coastal areas. Fluctuations in global sea level result from changes in the volume of the ocean or the volume of ocean basins. The former depends mainly on the growth and decay of continental ice sheets over short (10^4–10^5 year) timescales, while the latter fluctuates on longer (10^6–10^7 year) timescales resulting from tectonic effects such as variations in seafloor-spreading rates, ocean-ridge lengths, and collision/break-up of continents (e.g., Ruddiman, 2000; Miller et al., 2005a, b). Because the Mesozoic era exhibited the break-up of Gondwana, predominantly ice-free climates, high rates of seafloor spreading, as well as the emplacement of large igneous plateaus on the ocean floor (see Coffin et al., this issue), the Mesozoic ocean was characterized by much higher sea level than at present. Sea level peaked in mid- to Late Cretaceous (~ 100–75 Ma) when the total land area flooded was more than 40 percent greater than at present, resulting in the expansion of continental shelf environments and intra-continental seaways (e.g., Hays and Pitmann III, 1973) (Figure 5).

The most widely cited reconstructions of past sea-level changes were established by Exxon Production Research Company (EPR) (Haq et al., 1987), which have since been refined (e.g., Hardenbol et al., 1998). These sea-level plots consist of short- (10^5–10^6 year) and long-term (10^7–10^8 year) curves that are correlated with detailed chrono-, bio-, and magnetostratigraphies for last 250 million years (Figure 3). According to the EPR curves, Late Cretaceous sea level rose as much as 260 m above the present level. The EPR curves, however, have been criticized because: (1) the supporting data are proprietary, (2) the sequence boundaries do not translate into eustatic (global) sea-level changes, and (3) inferred amplitudes of sea-level fluctuations appear to be conjecture (e.g., Christie-Blick et al., 1990). ODP drilling on the New Jersey passive continental margin (ODP 174AX) provided new insights into the amplitudes of, and mechanisms for, sea-level changes for last 100 million years. The area around the drilling sites is an excellent location for sea-level studies because of quiescent tectonics and well-constructed biostratigraphic and Sr isotopic age control (Sugarman et al., 1995). The proposed sea-level curve developed using data collected during New Jersey drilling is well correlated with those of Russian and EPR curves, but the estimated maximum global sea-level amplitude is ~ 100 m during Late Cretaceous (Miller et al., 2005a) (Figure 3), in contrast to the much greater sea-level amplitude estimated by EPR.

Because the Mesozoic greenhouse period is generally assumed to have been an ice-free interval, the mechanisms for the large and rapid observed sea-level changes during the Cretaceous have long been debated (e.g., Skelton et al., 2003). Miller and his colleagues demonstrated that several rapid sea-level falls recorded on the New Jersey margin could be explained only by glacio-eustacy (Miller et al., 1999; 2005a). Through integration of data on occurrences of ice-rafted and/or glacial deposits around polar regions, positive oxygen isotope values of foraminifera, and intervals of rapid sea-level fall, it is quite possible that glaciers waxed and waned during the greenhouse climate of the Mesozoic. Although uncertainty remains in age and ice volume, several geologically short-term glacial events during the Cretaceous have been proposed (e.g., middle Cenomanian [96 Ma], middle Turonian [91–90 Ma], middle Campanian [the Campanian is from 83.5–70.8 Ma], and earliest and late Maastrichtian [70.6 and 66.1 Ma]). These results imply that greenhouse periods can exhibit significant short-term climatic variability, in contrast to previously proposed models suggesting long-term stable and equable climates.

Biocalcification Crises During the Mesozoic Ocean

The Mesozoic is marked by the poleward expansion of shallow-water carbonate platforms as well as several occurrences of their global "drowning" or "collapse" events (e.g., Johnson et al., 1996; Simo et al., 1993). These drowning events were not due to sea-level rise because shallow-water carbonate platforms usually grow upwards much faster than sea level rises. Although eutrophication of surface oceans associated OAEs were considered to be the cause of these drowning events, ODP Legs 143 and 144 revealed that some shallow-water carbonate platforms survived during OAE 1a in the central Pacific (Wilson et al., 1998). Weissert and Erba (2004) pointed out that the coincidence between drowning events of shallow-water carbonate platforms and the crisis of heavily calcified plankton groups, and termed these events "biocalcification crises." Although the mechanism responsible for biocalcification crises remains poorly constrained, recent hypotheses point to elevated pCO_2-induced lowered surface ocean pH, which affected carbonate-secreting organisms (e.g., Leckie et al., 2002; Weissert and Erba, 2004).

FUTURE PROSPECTS OF THE IODP FOR MESOZOIC OCEANOGRAPHY

The greenhouse climate of the mid-Cretaceous was likely related to major global volcanism and associated outgassing of CO_2. OAEs may be recognized as a negative feedback in response to sudden warming episodes by preventing further acceleration of warming through removal of organic carbon from the ocean-atmosphere (CO_2) reservoir to sediment reservoirs. This process resulted in the emplacement of a large volume of organic matter during the mid-Cretaceous, which now serves as a major source of fossil fuels (Larson, 1991). However, present human activities are rapidly consuming these fuels, returning the carbon to the ocean-climate system. Pre-industrial CO_2 levels of about 280 ppm have increased over the past 200 years to the current levels exceeding 380 ppm, mainly as a result of human activities. Bice et al. (2006) estimated that Cretaceous CO_2 atmospheric concentration ranged between 600 and 2400 ppm, 1.5 to 6 times the present concentration. If the current rate of CO_2 increase continues, Cretaceous values may be attained within 1500–6000 years, but current trends are already having clear affects on both the ocean-climate system and the biosphere. In fact, a recent ocean-climate model predicts that rapid atmospheric release of CO_2 will produce changes in ocean chemistry that could affect marine ecosystems significantly, even under future pathways in which most of the remaining fossil fuel CO_2 is never released (Caldeira and Wickett, 2005).

Improved understanding of the Mesozoic ocean-climate system and formation of OAEs is important to better predict environmental and biotic changes in a future greenhouse world. However, Cretaceous DSDP and ODP cores with continuous recovery and abundant well-preserved fossils suitable for isotopic study are very limited. To better understand the ocean-climate dynamics of the Mesozoic greenhouse Earth, a denser global array of deep-sea cores is needed to provide more detailed reconstructions of global climate changes and oceanographic conditions. Though far from complete, the Mesozoic paleoceanographic record is much better studied in areas of the Atlantic Ocean and Tethys Sea than in the Indo–Pacific Oceans because most seafloor formed there in the Mesozoic has already been subducted (Bralower et al., 1993). Mesozoic marine sequences deposited at middle to high latitudes of the Pacific Ocean, such as the continental margin of eastern Asia and the Bering Sea, are appropriate future drilling targets. Submerged continental rift sites such as the Somali Basin should also be targeted as they record a continuous paleoceanographic history from the Early Cretaceous or older. We expect that new IODP research from these Cretaceous sites could provide new insights to the process of abrupt global warming and its impact on Earth's biosphere.

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