New evidence for abrupt climate change in the Cretaceous and Paleogene: An Ocean Drilling Program expedition to Shatsky Rise, northwest Pacific

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ABSTRACT

Sediments recovered during an Ocean Drilling Program Leg on Shatsky Rise in the northwest Pacific hold clues to a number of abrupt climate events that took place during the Cretaceous and early Paleogene. These transient events caused major upheaval in marine communities and profoundly altered biogeochemical cycling. Shatsky Rise cores contain organic carbon-rich strata deposited during a brief interval of open ocean dysoxia or anoxia in the early Aptian (120 Ma). Analyses of exceptionally preserved organic compounds suggest that bacterial activity helped sequester organic carbon in these strata. Graphic evidence exists in Shatsky cores for the mid-Maastrichtian (ca. 69 Ma) extinction of the inoceramids, a long-ranging, widespread group of bottom-dwelling clams. This extinction is a global event that was likely related to a profound change in deep ocean circulation. Stratigraphically expanded records of the Cretaceous-Tertiary boundary extinction event (65 Ma) were recovered at four different sites. The cores contain evidence of the response of biogeochemical cycling and the recovery of oceanic plankton in the wake of this catastrophe. A new biotic event of major evolutionary significance was found in the early late Paleocene (ca. 58.4 Ma) associated with a change in deep-water circulation, possibly as a result of a brief pulse of warming. Abundant evidence of the Paleocene-Eocene thermal maximum (PETM; ca. 55 Ma), an abrupt warming event associated with major reorganization of benthic and planktonic communities, was recovered in cores from five sites along a depth transect. PETM warming is thought to have been induced by methane derived from dissociation of methane hydrates. The Shatsky Rise depth transect shows evidence of the predicted response of such methane input: pronounced, short-term shoaling of the lysocline and calcite compensation depth (CCD).

Shatsky Rise cores record the response of the tropical Pacific to a rapid cooling event near the Eocene-Oligocene boundary (ca. 33.5 Ma) marking the transition to glacial climates that characterized the remainder of the Cenozoic. This event is reflected by a marked increase in carbonate content of the sediment preserved on Shatsky Rise, which signifies a profound drop in the CCD and markedly changed deep-sea circulation patterns.

INTRODUCTION

Predictions for modern global warming resulting from increased CO_2 levels have caused a heightened interest in the mechanics of ancient warm climates and especially of geologically abrupt warming events. The mid-Cretaceous (ca. 80–120 Ma) and early Paleogene (ca. 45–60 Ma) were characterized by some of the most equable climates of the Phanerozoic (Fig. 1). In addition, these "greenhouse" intervals contain significant abrupt and transient warming events that led to major changes in oceanic environments, profound turnover in marine communities, including extinction, and perturbations to global chemical cycles. Examples include the

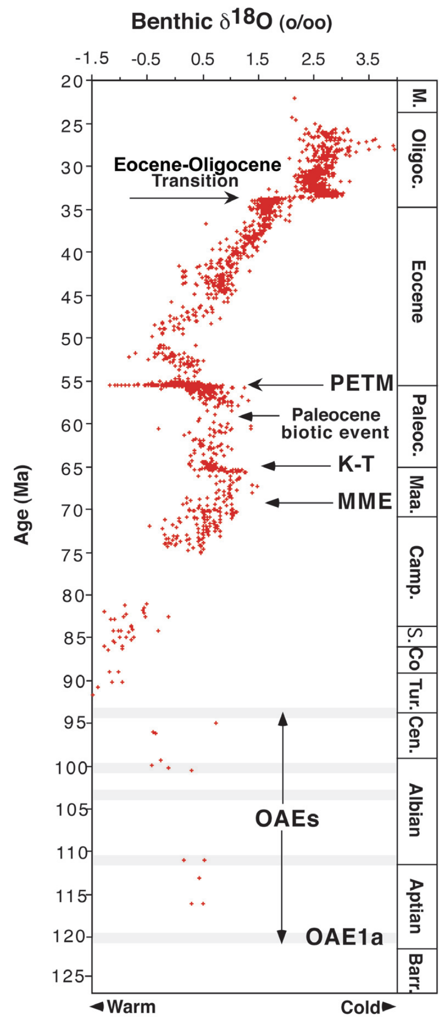

Figure 1. Generalized climate curve for the Cretaceous and Paleogene derived from deep-sea benthic oxygen isotope data (from Zachos et al., 1993, and unpublished). Also shown are locations of events discussed including: Eocene-Oligocene (E-O) transition, PETM—Paleocene-Eocene thermal maximum, late Paleocene biotic event, K-T—Cretaceous-Tertiary boundary, MME—mid-Maastrichtian event, OAE1a—early Aptian oceanic anoxic event.

Paleocene-Eocene thermal maximum (e.g., Kennett and Stott, 1991) and Cretaceous oceanic anoxic events (e.g., Jenkyns, 1980).

Among the largest obstacles facing our understanding of the climate of the Cretaceous and Paleogene is that many good stratigraphic sections on land and in the oceans have been buried at depths where diagenetic alteration has obscured interpretations of stable isotope and other climate proxies. In many oceanic sequences, spot-coring, coring gaps, drilling disturbance, and hiatuses hinder detailed studies of ancient climate. Site coverage is

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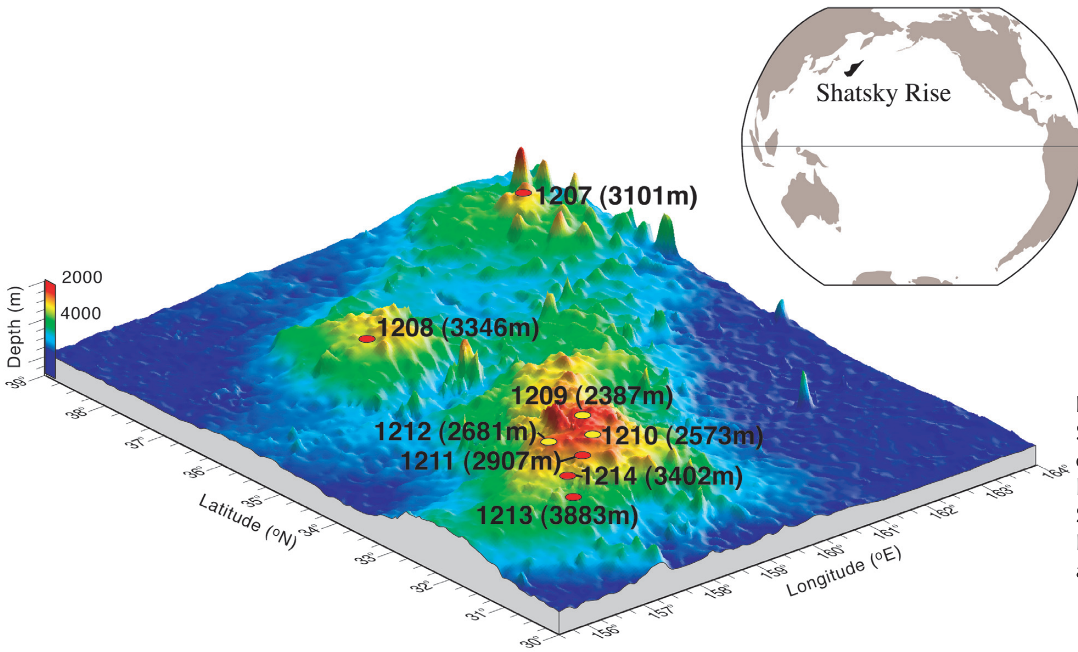

Figure 2. Bathymetric map of Shatsky Rise showing location of Leg 198 sites. Site 1207 is located on the Northern High, Site 1208 is on the Central High, and Sites 1209 to 1214 are on the Southern High.

uneven and almost nonexistent in some regions, especially the tropics and the Pacific Ocean. The aerial extent and importance of the Pacific in global circulation, however, make this a critical target for investigation of warm climatic intervals.

One of the most promising locations in the Pacific for recovering Cretaceous and Paleogene sediments at relatively shallow burial depths is Shatsky Rise (Fig. 2). This feature, a medium-sized large igneous province in the west-central Pacific was formed in the Late Jurassic and Early Cretaceous between 147 and 135 Ma (Nakanishi et al., 1989). Shatsky Rise was the target of three Deep Sea Drilling Project (DSDP) expeditions: Legs 6, 32, and 86. The latter leg drilled one site on Shatsky Rise (Site 577), which was limited to the Paleogene and uppermost Maastrichtian. Some sites in the older legs were spot-cored, and chert lowered recovery in others, especially in the Cretaceous. Yet even with an extremely patchy record, analyses of Shatsky Rise sediments have provided key data in our understanding of Cretaceous and Paleogene climate; these data are especially significant given that the rise was located in tropical latitudes during this time period.

Ocean Drilling Program (ODP) Leg 198 in August–October, 2001 was designed to understand the causes, nature, and mechanics of the long-term Cretaceous and Paleogene "greenhouse," as well as of transient but critical climate events during this period. A key aspect of the drilling plan was to locate sites along depth and latitudinal transects to provide additional dimensions to reconstructions of the paleoenvironment through time (Fig. 2). Intermediate- and deep-water chemistry (i.e., carbonate solubility, oxygenation) and circulation are sensitive to changes in climate and can be reconstructed using depth transects. One site each was drilled on the North and Central Highs of Shatsky Rise (Sites 1207 and 1208, respectively) and six were drilled on the Southern High (Sites 1209–1214) (Bralower et al., 2002).

An impressive 140 m.y. package of pelagic sediment was recovered at depths between 170 and 623 m below the sea floor (Fig. 3). The Cretaceous and Paleogene section recovered at sites across the depth transect provides a unique opportunity to understand long-term climate change on a warm Earth. However, the key success of the drilling was the abundant evidence for short-lived (<1 m.y.) warming events, and other major intervals of rapid climate and environmental change.

A CLASSIC RECORD OF THE EARLY APTIAN OCEANIC ANOXIC EVENT

The beginning of greenhouse climate conditions in the mid-Cretaceous was associated with widespread deposition of organic-carbon (C_{org})-rich sediments, informally known as black shales, in the oceans. These C_{org}-rich deposits were the result of fundamental oceanographic changes that drastically affected biogeochemical cycling and marine ecosystems, resulting in geographically extensive or global oxygen-deficient water masses. C_{org}-rich sediments are known to occur primarily in specific stratigraphic intervals that have been termed oceanic anoxic events (OAEs: Schlanger and Jenkyns, 1976). The ultimate trigger(s) of OAEs, however, remain elusive.

C_{org}-rich sedimentary rocks at Sites 1207 and 1213 (Fig. 4) are evidence for OAE1a during the early Aptian (120 Ma) (Arthur et al., 1990), an event that is well documented in Tethyan sections (Coccioni et al., 1992). At Site 1207, OAE1a is found within 45 cm of finely laminated, dark brown radiolarian claystone. The Site 1213 C_{org}-rich units include clayey porcellanites and radiolarian porcellanites with associated minor tuff. At Site 1214, a black laminated claystone unit contains a distinctive radiolarian assemblage that suggests that the recovered sediments correlate to the OAE1a interval (e.g., Erbacher and Thurow, 1997), but low-C_{org} contents indicate the peak of the event was not recovered.

In Tethys early Aptian OAE1a corresponds to prominent C_{org}-rich horizons that were deposited in open ocean environments; for example, the original Selli level in Italy is in a truly pelagic section (Coccioni et al., 1992). However, the same interval in the North Atlantic is not C_{org} rich (Bralower et al., 1994). C_{org}-rich horizons of OAE1a age have been found

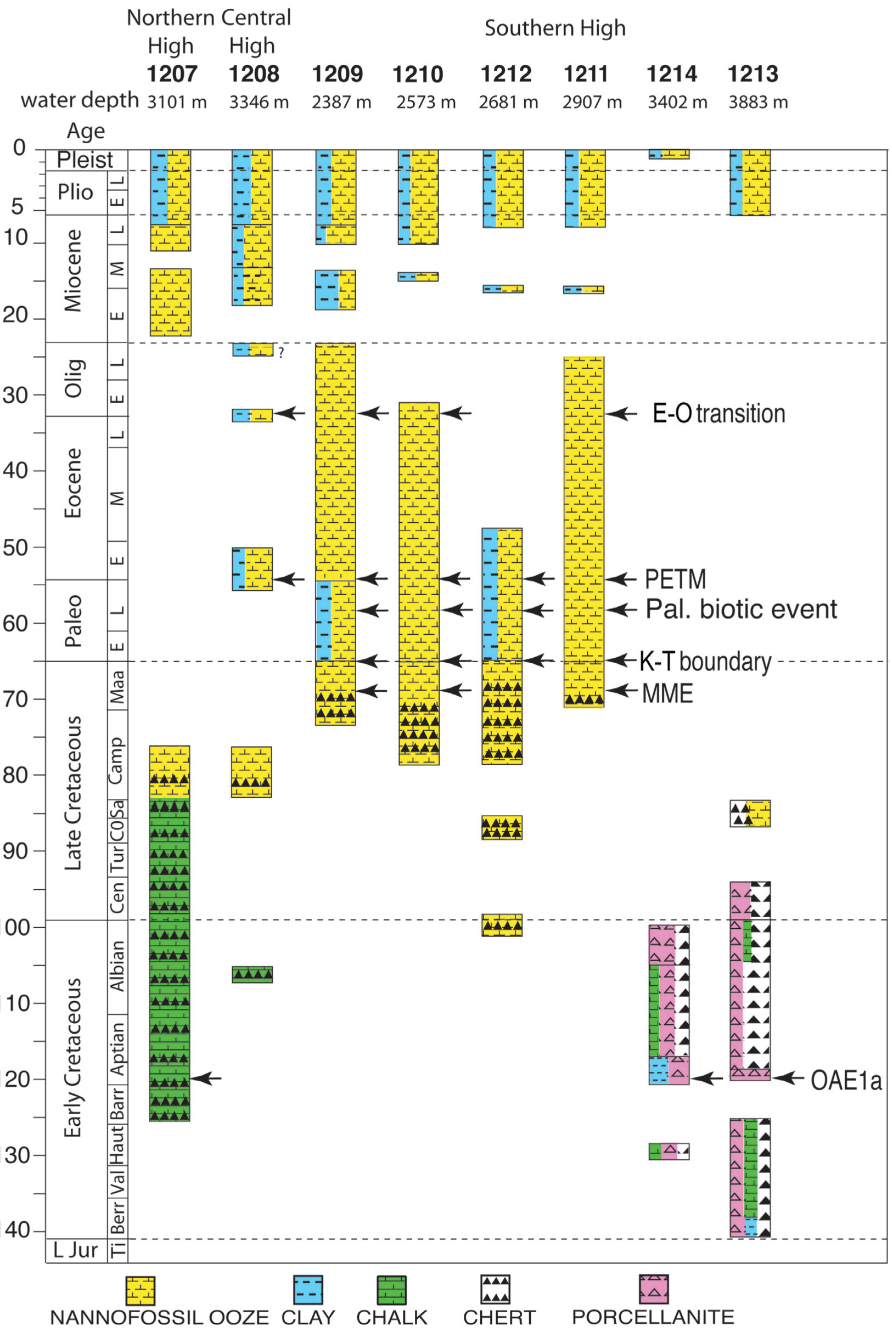

Figure 3. Summary of stratigraphy and lithologic succession from Sites 1207 to 1214. Lithology is plotted against time to show duration of periods of deposition and location of unconformities. Southern High Sites 1209–1214 are ordered by water depth. Arrows show stratigraphic position of transient events discussed (see Fig. 1 for abbreviations).

in a number of other locations in the Pacific Ocean, but only DSDP Site 463 (Mid Pacific Mountains) and ODP Site 866 (Resolution Guyot) have good recovery (Sliter, 1989; Jenkyns, 1995). Both of these sites have a shallow-water influence: Site 866 is located in shallow-water carbonates and Site 463 has a considerable fraction of material derived from shallow-water carbonate environments. Thus the Leg 198 C_{org}-rich units represent the most pelagic records of OAE1a outside of Tethys, and provide important information about the nature of environmental change during the event.

The C_{org} contents of lower Aptian intervals from Sites 1207 and 1213 (Fig. 4) are among the highest ever recorded in pelagic Cretaceous sequences. They attest to the extraordinary nature of the depositional conditions that led to enhanced sequestration of organic matter. Exceptional preservation of organic compounds, combined with lamination in sediments at Site 1207, indicate that conditions were highly dysoxic or anoxic at the time of deposition. Rock-Eval analyses and gas chromatography–mass spectrometry (GC-MS) of extractable hydrocarbons and ketones indicate that the organic matter is almost exclusively algal and bacterial in origin. GC-MS data show biomarkers associated with cyanobacteria. The prevalence and character of bacterial biomarkers suggest the existence of microbial mats at the time of deposition. Compounds identified in Leg 198 sediments also include the oldest known alkenones, a signature of haptophyte algae (S.C. Brassell, 2002, personal commun.). Thus, biomarker data indicate that profound changes in prokaryote and protistan populations were intimately associated with processes that led to sequestration of C_{org} during OAE1a. Further studies of the well-preserved organic compounds are planned to elucidate these processes.

At Sites 1207 (~1.3 km paleodepth during OAE1a) and 1213 (~2.8 km paleodepth), the C_{org}-rich units lack carbonate, but calcareous sediments occur directly underneath the C_{org}-rich sediments at Site 1213, indicating that the calcite compensation depth (CCD) shoaled by at least 1.5 km during the event. The magnitude of the change in the CCD during OAE1a was at least partially a result of increased rates of CO_2 outgassing that may also be directly responsible for global warmth at this time (e.g., Arthur et al., 1985; Larson, 1991).

EXTINCTION EVENTS IN THE MID-MAASTRICHTIAN AND AT THE CRETACEOUS-TERTIARY BOUNDARY

Stable isotope evidence indicates that cooling in the Late Cretaceous was interrupted by a significant event in the mid-Maastrichtian at 69 Ma when the source of deep waters changed abruptly from low to high latitudes (e.g., MacLeod and Huber, 1996). This event appears to have coincided with the extinction of the inoceramid bivalves (MacLeod et al., 1996). Growing evidence, however, suggests that the *Inoceramus* extinction is diachronous. Moreover, the magnitude and direction of stable isotope changes are quite variable at different sites (Frank and

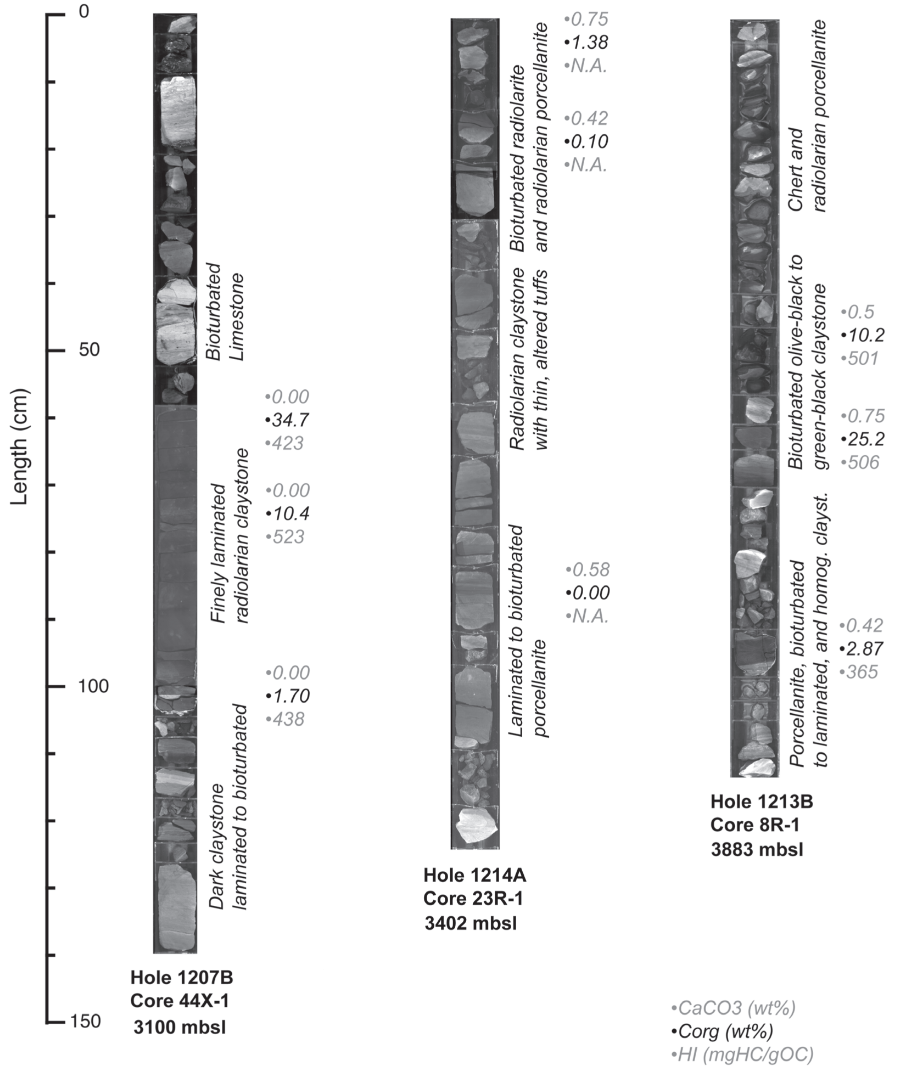

Figure 4. Cores of early Aptian OAE1a interval recovered on Leg 198. Core photo, % carbonate, % C_{org}, and hydrogen indices for lower Aptian sedimentary rocks recovered at Sites 1207, 1213, and 1214. Note that Sites 1207 and 1213 recovered C_{org}-rich intervals that represent OAE1a.

Arthur, 1999), possibly as a result of uncertainties in stratigraphic correlation or of true differences in deep-water properties. Thus the relationship between the extinction event and changing deep-water properties is not firmly established.

An unusual record of the mid-Maastrichtian event was observed in the sedimentary record at two sites on the Southern High of Shatsky Rise. At Sites 1209 and 1210, large *Inoceramus* shell fragments are common for several meters, but disappear abruptly. This disappearance is in the same stratigraphic position at both sites. Furthermore, isolated *Inoceramus* prisms were recovered in foraminiferal separates at correlative levels at Site 1211. The significance of the short range of visible specimens in this open ocean setting is not currently understood. However, such occurrences have previously been noted in the Pacific (MacLeod et al., 1996) and the stratigraphic position suggests they are related to the *Inoceramus* extinction and deep-water changes in the mid-Maastrichtian determined at other deep-sea locations (e.g., Barrera et al., 1997; Frank and Arthur, 1999). Benthonic and planktonic foraminiferal isotope and assemblage data from Shatsky Rise will help characterize changes in deep- and surface-water properties as well as constrain the timing and origin of the extinction.

The origin of extinctions at the K-T boundary (65 Ma) is well understood, however, the effect of the event on biogeochemical cycling and marine ecosystems is still not completely constrained. A remarkable set of cores was taken across the K-T boundary on the Southern High at Sites 1209, 1210, 1211, and 1212 (Fig. 5).

The lithologic sequence in the K-T boundary interval is similar at all of these sites (Fig. 5). The boundary succession includes uppermost Maastrichtian (nannofossil Zone CC26) white to very pale orange, slightly indurated, nannofossil ooze overlain by an 8–12-cm-thick layer of basal Paleocene (foraminiferal Zone Pα) grayish orange foraminiferal ooze. This layer grades into 19–23-cm-thick white foraminiferal nannofossil chalk, then into grayish orange nannofossil ooze. The boundary between the uppermost Maastrichtian and the lowermost Paleocene is clearly bioturbated as shown by the irregular nature of the contact and the pale orange burrows that extend as much as 10 cm down into the white Maastrichtian ooze (Fig. 5). Sampling of the deepest sections of the burrows of Paleocene ooze within the uppermost Maastrichtian yields highly abundant, minute planktonic foraminiferal assemblages that are dominated by *Guembelitria* with rare *Hedbergella holmdelensis*, suggesting a possible Zone P0 age (Smit, 1982). Burrows also contain common light brown to amber spherules up to 100–150 µm in diameter with textures similar to the spherules composed of glauconite and magnetite from the K-T boundary in other locations (Smit and Romein, 1985).

The substantial thickness of the uppermost Maastrichtian *M. prinsii* (CC26) Zone and the lowermost Danian *P. eugubina* (Pα) Zone indicates that the K-T boundary is expanded compared to the majority of deep-sea sites (the Pα Zone is either unrecovered or poorly preserved at most other deep-sea sites). Moreover, the Zone Pα interval in Shatsky cores bears similarities to other sites such as ODP Site 1049 (western North Atlantic), where the correlative interval corresponds to a dark, burrow-mottled clay underneath 5–15-cm-thick white foraminiferal nannofossil ooze (Norris et al., 1998). A similar white unit is found directly above the boundary at DSDP Site 536 (Gulf of Mexico; Buffler et al., 1984), and ODP Sites 999 and 1001 (Caribbean; Sigurdsson et al., 1997). The ultrafine micrite in this oceanwide white layer may be related to the collapse of the

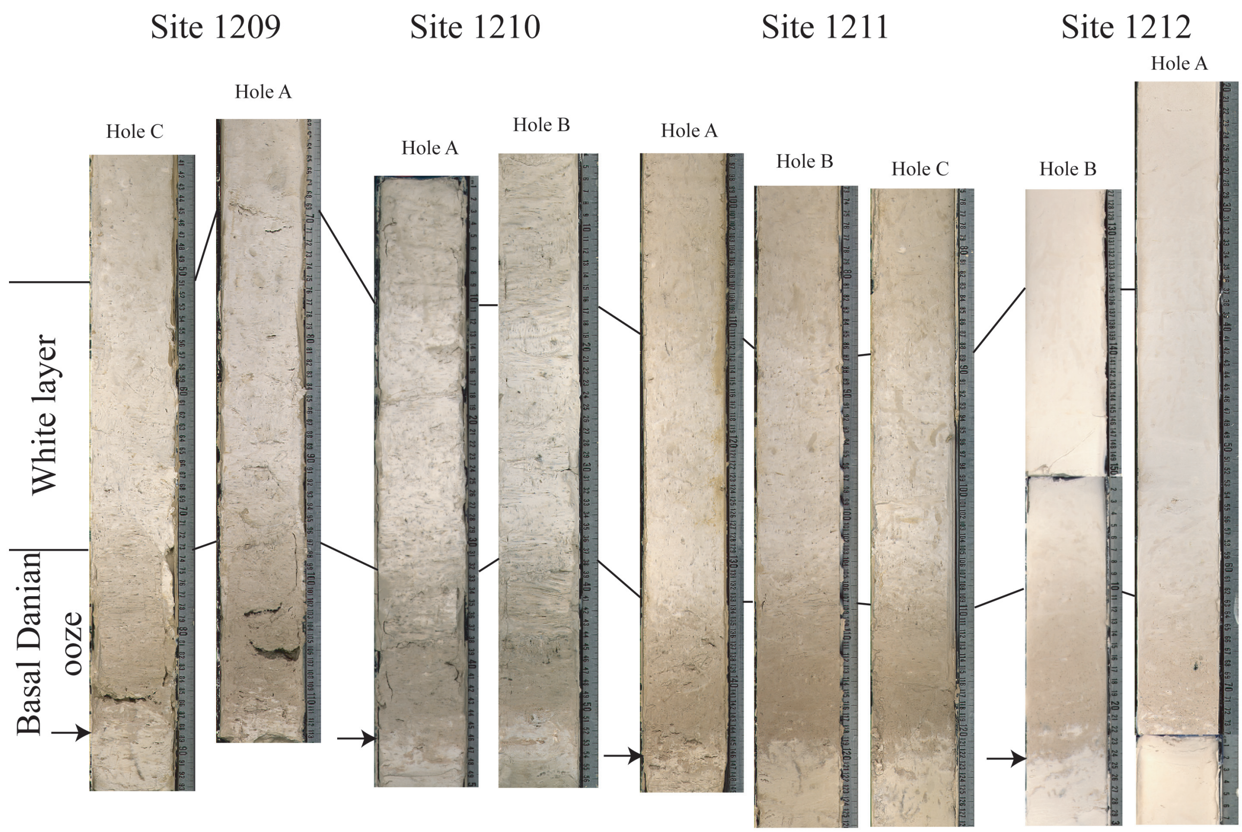

Figure 5. The Cretaceous-Tertiary boundary on Shatsky Rise. Arrows show level of paleontological boundary as recognized by planktonic foraminiferal biostratigraphy (see text for details).

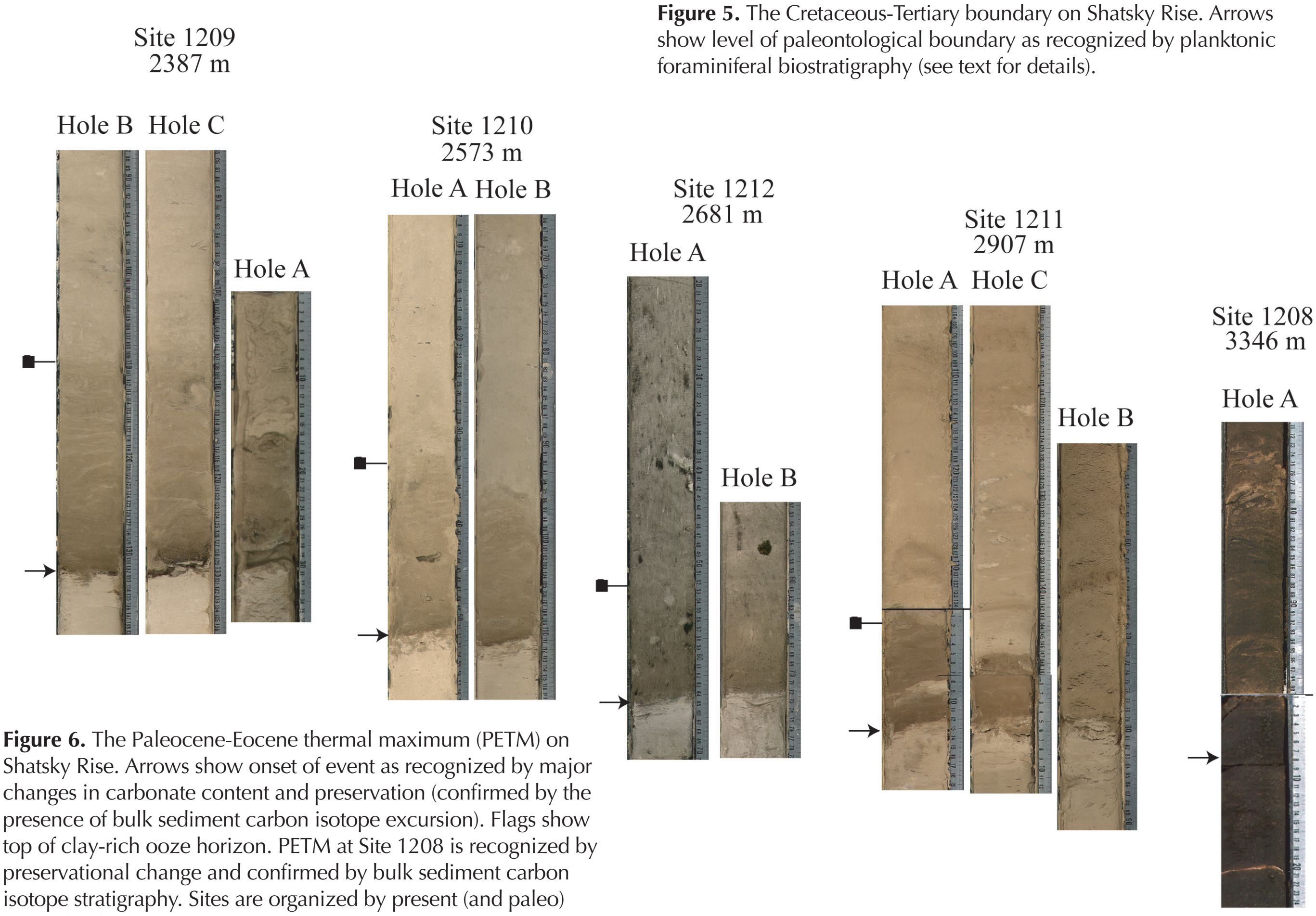

Figure 6. The Paleocene-Eocene thermal maximum (PETM) on Shatsky Rise. Arrows show onset of event as recognized by major changes in carbonate content and preservation (confirmed by the presence of bulk sediment carbon isotope excursion). Flags show top of clay-rich ooze horizon. PETM at Site 1208 is recognized by preservational change and confirmed by bulk sediment carbon isotope stratigraphy. Sites are organized by present (and paleo) water depth.

marine biosphere and inorganic production of carbonate in the surface ocean (e.g., Kump, 1991), a hypothesis that requires further testing. The Leg 198 sections represent some of the best-preserved and least-disrupted deep-sea records of the K-T extinction event and the subsequent biotic radiation.

KEY EVIDENCE FOR ABRUPT, TRANSIENT WARMING EVENTS IN THE PALEOGENE

An abrupt warming event is well documented at the Paleocene-Eocene boundary (the Paleocene-Eocene thermal maximum [PETM; 55 Ma]). However, a number of other intervals of rapid temperature increase, or hyperthermals, akin to the PETM although smaller in magnitude, may also exist in the midst of the warm early Paleogene (Thomas et al., 2000). Leg 198 discovered a new transient climate event of evolutionary significance in the early late Paleocene at ca. 58.4 Ma. A prominent clay-rich ooze found at Sites 1209, 1210, 1211, and 1212 coincides with the evolutionary first occurrences of *Heliolithus kleinpellii* and primitive discoasters, both of which are important, and often dominant, components of late Paleocene and younger nannoplankton assemblages. Planktonic foraminifers in the clay-rich layer are characterized by a low diversity, largely dissolved assemblage dominated by representatives of the genus *Igorina* (mainly *I. pusilla* and *I. tadjikistanensis*). The clay-rich layer contains common crystals of phillipsite, fish teeth, and phosphatic micronodules. The abundance of phillipsite and fish teeth suggests either very slow sedimentation or intervals of seafloor exposure, possibly resulting from pervasive dissolution of carbonate. Even though microfossil assemblages are clearly altered by dissolution, they appear to record a significant environmental perturbation in surface waters as the underlying cause of the biotic event. We speculate that the event was a hyperthermal, an abrupt warming that possibly caused a brief switch in the source of deep waters bathing Shatsky Rise.

Sediments cored on Shatsky Rise show evidence of a strong deep-ocean response to warming in the PETM. The PETM interval was cored in nine holes at Sites 1209, 1210, 1211, and 1212 on the Southern High (Fig. 6). The Paleocene-Eocene boundary interval was also recovered at Site 1208 on the Central High. At the Southern High sites, the PETM corresponds to an 8–23-cm-thick layer of yellowish brown clayey nannofossil ooze with a sharp base and a gradational upper contact. The clay-rich layer is often bioturbated into the underlying sediment. A thin (1 mm) dark brown clay seam lies at the base of the PETM in several holes.

Preliminary biostratigraphy and stable-isotope stratigraphy suggest that the PETM is complete. This biostratigraphy also shows that the PETM interval at the Southern High sites is condensed compared to continental-margin records from the Atlantic and Tethys (e.g., Kennett and Stott, 1991), but somewhat expanded compared to other deep-sea sites. At the relatively deep Site 1208, biostratigraphic and bulk stable isotopic data confirm that the recovered PETM is a highly condensed (~3 cm) record.

The PETM interval at all of the sites contains a clear record of nannofossil and planktonic foraminiferal assemblage transformation at this time of environmental upheaval. One of the dominant nannolith genera, *Fasciculithus*, is replaced by *Zygrhablithus bijugatus*, a holococcolith species that is often a highly abundant component of Eocene assemblages. The genus *Discoaster* is highly abundant, likely as a result of warming or increased oligotrophy (Bralower, 2002). Also found are abundant calcispheres, which are possibly calcareous resting cysts produced by dinoflagellates at times of environmental perturbation. Planktonic foraminiferal assemblages contain an ephemeral group of ecophenotypes or short-lived species of the genera *Acarinina* and *Morozovella* (Kelly et al., 1996).

The depth transect strategy of Leg 198 was specifically designed to address the response of the ocean to the greenhouse forcing mechanism proposed for the PETM. This warming is generally thought to have resulted from a massive release of methane from clathrates into the ocean-atmosphere system (e.g., Dickens et al., 1997). Methane can explain the magnitude of the warming and the rate of carbon isotopic change at the onset of the event. The oceanic response to this methane input has been predicted but is currently untested (e.g., Dickens, 2000). Regardless of how the transfer to the ocean took place, oxidation of methane would generate CO_2, which would lower the saturation state of seawater with respect to calcite and cause a dramatic shoaling in the depth of the lysocline and CCD. This response should be recorded in changes in carbonate content and preservation in sections below the mid-slope. Shallower sections should show less change in dissolution and carbonate content than deeper sections. The range of present water depths (PETM paleodepths were broadly similar), from 2387 m at Site 1209 to 3346 m at Site 1208, provides a significant transect to observe changes in dissolution at the PETM as a function of depth.

Nannofossil preservation is moderate to good below the PETM at all of the Southern High sites, indicating that they were located in the upper part of the lysocline. All sites show a short-lived deterioration in nannofossil preservation at the onset of the event. Carbonate contents have been measured in detail across the PETM at Site 1210. These data record a decrease from ~96 to ~86 wt% $CaCO_3$ at the base of the event, a change that would involve a substantial increase in dissolution, indicating a shoaling of the lysocline. Shallower sites (Sites 1209, 1210, 1212) show less lithologic and fossil preservational change at the base of the PETM than deeper sites (Sites 1208, 1211) (Fig. 6); changes in carbonate solubility at the onset and the termination of the event are more marked at the deep sites, suggesting that they were close to the CCD as it shoaled. The Shatsky Rise depth transect shows clear evidence for an abrupt rise in the level of the lysocline and CCD during the PETM, and thus supports the predicted ocean response to massive methane input.

THE END OF THE GREENHOUSE: EOCENE-OLIGOCENE BOUNDARY COOLING IN THE TROPICAL PACIFIC OCEAN

The Eocene-Oligocene (E-O) boundary interval recovered on Shatsky Rise records the response of the tropical Pacific Ocean to a major global cooling event when ice sheets developed on Antarctica and cold water circulated throughout the deep ocean (e.g., Shackleton and Kennett, 1975). This cooling that signaled the end of the warm Paleogene occurred largely in a rapid step in the earliest Oligocene at ca. 33.5 Ma

(Zachos et al., 1996; Fig. 1). The boundary interval was identified at four sites across a large depth range. At the Southern High sites (Sites 1209, 1210, and 1211), a gradual change from light brown to tan nannofossil ooze with clay to a light gray to white nannofossil ooze, is observed over a 4–7.5 m interval of the uppermost Eocene to lowermost Oligocene. The E-O boundary interval at Site 1208 on the Central High is much more abrupt, corresponding to a 1–2 cm transition from a dark brown zeolitic claystone with extremely low carbonate content to a gray-orange nannofossil ooze.

The distinctive color change across the E-O boundary in all of the Leg 198 records reflects an increase in carbonate content as a result of a deepening of the lysocline and CCD. This interpretation is consistent with the observation that the lithologic change is more pronounced at the deepest site, Site 1208. Microfossil preservation in the interval above and below the transition suggests that the CCD dropped from just below the depth of Site 1211 to well below the depth of Site 1208, thus by at least 450 m. This significant change is observed in other ocean basins and possibly reflects an increase in mechanical and chemical weathering rates on continents associated with cooling (e.g., Zachos et al., 1996).

CONCLUSIONS

Drilling on Leg 198 recovered diverse evidence for abrupt environmental changes in the Cretaceous and Paleogene warm climate interval. These changes include a short period of anoxia in the early Aptian (ca. 120 Ma) that led to deposition of highly carbonaceous sediments; an abrupt reorganization of oceanic circulation in the Maastrichtian (ca. 69 Ma) that caused extinction of a group of deep-sea mollusks; the extinction event at the K-T boundary (65 Ma); a prominent biotic event in the late Paleocene (ca. 58.4 Ma); the PETM (ca. 55 Ma) that shows lithologic and geochemical evidence consistent with methane outgassing; and changes in circulation and rapid cooling near the E-O boundary (ca. 33.5 Ma) that correspond to a sharp lithologic change.

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