OCEAN DRILLING PROGRAM

LEG 198 SCIENTIFIC PROSPECTUS

EXTREME WARMTH IN THE CRETACEOUS AND PALEOGENE: A DEPTH TRANSECT ON SHATSKY RISE, CENTRAL PACIFIC

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This Scientific Prospectus is based on precruise JOIDES panel discussions and scientific input from the designated Co-chief Scientists on behalf of the drilling proponents. The operational plans within reflect JOIDES Planning Committee and thematic panel priorities. During the course of the cruise, actual site operations may indicate to the Co-chief Scientists and the Operations Manager that it would be scientifically or operationally advantageous to amend the plan detailed in this prospectus. It should be understood that any proposed changes to the plan presented here are contingent upon approval of the Director of the Ocean Drilling Program in consultation with the Science and Operations Committees (successors to the Planning Committee) and the Pollution Prevention and Safety Panel.

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ABSTRACT

The mid Cretaceous (Barremian-Turonian) and early Paleogene were characterized by some of the most equable climates of the Phanerozoic and are among the best known ancient "greenhouse" climate intervals. In addition, these intervals contain some of the most abrupt and transient climatic changes in the geologic record, including the latest Paleocene thermal maximum, the mid-Maastrichtian deep-water event, and the early Aptian Oceanic Anoxic Event. These transitions involved dramatic changes in oceanic circulation, geochemical cycling, and marine biotas. Ocean Drilling Program Leg 198 on Shatsky Rise is designed to address the causes and consequences of Cretaceous and Paleogene global warmth. The objectives are to address the long-term climatic transition into and out of "greenhouse" climate as well as abrupt climatic events. Shatsky Rise, a medium-sized large igneous province in the west-central Pacific, contains sediments of Cretaceous and Paleogene age at relatively shallow burial depths. As a result, sediments of both ages can be reached readily through drilling and fossil materials are sufficiently well preserved for stable isotope and trace element analyses and for faunal and floral assemblage studies.

The Leg 198 sites comprise a depth transect that has been designed to characterize changes in the nature of surface and deep waters through time, including vertical gradients of temperature, oxygenation, and corrosiveness. Combined with the results of previous and future legs, Leg 198 drilling will help determine (1) the frequency, amplitude, and forcing of climate change in warm intervals; (2) latitudinal thermal gradients in discreet mid-Cretaceous to Paleogene time slices; and (3) changes in the sources of deep water and vertical ocean structure through time.

Shatsky Rise has been the target of three Deep Sea Drilling Project legs, but most sites were spot-cored or plagued by low recovery, especially in the Cretaceous. Previous drilling was centered on the southern part of Shatsky Rise. Leg 198 includes sites on the central and northern parts of the rise where the stratigraphy is less well known. Chert provides a significant recovery problem in the Cretaceous, thus, we have attempted to position sites at locations with poorly developed reflectors. In addition, the drilling strategy includes use of extended core barrel coring combined with the motor driven core barrel to increase recovery in cherty intervals. In intervals of poor core recovery, Formation MicroScanner and gamma-ray logs will help determine the stratigraphic extent of diagnostic sediments, such as black shale.

OVERVIEW OF SCIENTIFIC OBJECTIVES

Leg 198 is designed to obtain a depth transect of the Cretaceous through the Paleogene Pacific Ocean to advance our understanding of the behavior of Earth's climate during "greenhouse" intervals. The Cretaceous and Paleogene were characterized by some of the most equable climates of the Phanerozoic. In addition, these intervals contain some of the most abrupt and transient climatic changes in the geologic record. Examples include the Paleocene-Eocene thermal maximum (e.g., Kennett and Stott, 1991; Zachos et al., 1993), the middle Maastrichtian deep-water event (e.g., MacLeod and Huber, 1996), and the Cenomanian/Turonian boundary oceanic anoxic event (OAE) (e.g., Schlanger et al., 1987). These intervals were characterized by major changes in oceanic circulation, which had a pronounced effect on geochemical cycling and a major impact on marine biotas.

One of the largest obstacles facing our understanding of the climate of the Cretaceous and Paleogene is that many good stratigraphic sections have been buried at depths where diagenetic alteration has obscured stable isotope and other climate proxies. In other sequences, spot-coring, coring gaps, and drilling disturbance hinder detailed paleoceanographic studies. The result is that site coverage is uneven and almost nonexistent in some areas. This is especially the case for the Pacific Ocean. The aerial extent and importance of the Pacific in global circulation, however, makes it a critical target for drilling 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, a medium-sized large igneous province (LIP) in the west-central Pacific (Fig. 1). Shatsky Rise has been the target of three Deep Sea Drilling Project (DSDP) expeditions, Legs 6, 32, and 86, and Ocean Drilling Program (ODP) Leg 132. The highest quality record was obtained during Leg 86 at 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, sea-surface temperature (SST) estimates obtained from isotopic analyses of Shatsky Rise sediments have provided key points in our understanding of Cretaceous and Paleogene climates. The Leg 198 depth transect will provide key data from the tropical Pacific as well as a more representative open-ocean signal than exists with the current data.

The majority of sites used in current paleoceanographic investigations were situated at relatively shallow paleodepths, mostly less than 2000 m. The selected Shatsky sites provide a depth transect spanning 2500 m of the water column, providing us with the opportunity to sample true intermediate and deep waters. Even though the paleodepth estimates for the Leg 198 sites are somewhat uncertain, their broad depth range ensures that the deepest sites will lie below previously drilled sites. Existing recovery from Shatsky demonstrates that pristine, isotope-grade material will be recovered for the entire interval of interest. This will allow the following specific objectives to be addressed through depth-transect drilling.

- Fill the Pacific gap in current paleoenvironmental data sets to complete global reconstructions and modeling of the physical and chemical parameters of warm oceans.

- Reconcile the nature of climatic forcing during the Cretaceous and Paleogene by monitoring changes in the properties of surface and deep waters. This will help to constrain the character and stability of intermediate and deep-water circulation, vertical thermal gradients, and basin fractionation during ancient intervals of extreme warmth.

- Understand how apparently cool tropical sea-surface temperatures and low meridional thermal gradients were maintained during "greenhouse" climate intervals.

- Shed light on the origin of transient climatic events such as the Eocene/Oligocene boundary, the Paleocene-Eocene Thermal Maximum (PETM), late Paleocene and early Eocene hyperthermals, and the mid-Maastrichtian events. The depth transect will also help address questions concerning the nature of chemical (i.e., carbonate compensation depth [CCD], nutrients, and oxygenation) and physical oceanographic changes (temperature gradients) during these events.

- Understand water column stratification during mid-Cretaceous OAEs as well as obtain complete records of organic-rich sediments suitable for detailed paleontological and geochemical investigations. These data will allow us to more fully determine the response of marine biotas to abrupt environmental changes and to constrain changes in carbon and nutrient cycling during the OAEs.

In summary, the Leg 198 drilling plan will help reconstruction of long-term climatic trends and short-term events in the equatorial Cretaceous and Paleogene Pacific by obtaining relatively shallow-burial expanded sections spanning these critical time intervals.

TECTONIC AND STRATIGRAPHIC EVOLUTION OF SHATSKY RISE

Shatsky Rise is a broad elevation in the west-central Pacific (Fig. 1) with an area of about 7.5 x 10^5 km^2, roughly comparable to the size of California. The rise consists of three prominent highs arranged in a northeasterly trend. The southern high, Shatsky Plateau, is the largest with a length of about 700 km and a width of about 300 km. All previous DSDP and ODP drill sites are located on the southern high (Fig. 2).

The northeasterly trend of the rise lies along the trace of a triple junction (Hilde et al., 1976). The regional magnetic anomalies of the abyssal Pacific seafloor surrounding Shatsky Rise exhibit a nearly orthogonal pattern (Sager et al., 1988; Nakanishi et al., 1992) with the presumed intersection of the anomalies near the crest of the rise. The rise is bracketed by magnetic polarity Zones CM21 and CM10 (Fig. 2). Nakanishi et al. (1989) proposed that Shatsky Rise formed by a magmatic pulse before polarity Chron CM20 in the Tithonian (Late Jurassic) at a hot-spot triple-junction intersection. The subsequent flow of lava ceased at about polarity Chron CM12 in the Valanginian (Early Cretaceous).

Pelagic sedimentation on Shatsky Rise has been more-or-less continuous since at least the Early Cretaceous and shows a moderately stratified section overlying the acoustic basement. Sedimentation appears to have been interrupted by episodic erosional events identified by previous drilling (Sliter and Brown, 1993). Some of the resulting unconformities show up as major reflectors observed in seismic records. Quaternary channeling of the sediment pile is evident on seismic records, and in some places Lower Cretaceous sediments crop out at the seafloor (Sliter et al., 1990). Divergence of deep reflectors suggests that there was more rapid basement subsidence in the Early Cretaceous prior to the deposition of Upper Cretaceous and Cenozoic sediments.

The subsidence history of Shatsky Rise is not well known. Thierstein (1979) back-tracked Sites 305 and 306 (currently at 2903 and 3416 m, respectively) to close to 1000 m paleodepth in the Early Cretaceous. Recently, rudists, corals, and echinoid spines were dredged from atop the southern high at 3000 m (Sager et al., 1999), suggesting paleodepths close to sea level. Detailed studies of benthic foraminiferal assemblages are required to more accurately constrain the subsidence history of Shatsky Rise.

All eight previous DSDP and ODP drill sites on Shatsky Rise were located on the southern rise (Fig. 2). During Leg 6, drilling at Sites 47 and 48 atop the rise reached Maastrichtian cherty chalk and at Sites 49 and 50 on the lower flank, Berriasian cherty chalk was recovered. During Leg 32, 640 m of section was penetrated at Site 305 before drilling was terminated in the early Barremian, whereas drilling at Site 306 reached the Berriasian at 475 m (Fig. 3). Scraps of organic carbon-rich sediments of Aptian age were recovered at Sites 305 and 306 (Larson, Moberly, et al., 1975). Additional fragments of carbonaceous shale from Core 37 at Site 305 are early Cenomanian to early Turonian in age and apparently underlie a major unconformity that extends to the Coniacian. Drilling at Site 577 and, most recently, piston coring at Site 810 terminated in the Maastrichtian. Thus, Shatsky Rise has the stratigraphic targets needed for the recovery of sediments from the desired Cretaceous and Paleogene intervals.

DETAILED SCIENTIFIC OBJECTIVES

Long- and Short-Term Warming in the Paleogene

The most recent episode of moderate to extreme global warming occurred during the late Paleocene and early Eocene. In detail, this warming was comprised of several events that occurred on different time scales. Over a 4-m.y. period (58-54 Ma), mean global temperatures increased gradually, reaching a peak in the early Eocene that was sustained for roughly 2 m.y. (Fig. 4) (Zachos et al., 1994). Superimposed on this long-term trend was a brief but more extreme episode of warming at the Paleocene/Eocene boundary (~55.5 Ma) (Kennett and Stott, 1991; Bralower et al., 1995; Thomas and Shackleton, 1996), known as the PETM. This event lasted for ~200 k.y. (Röhl et al., 2000).

The exact cause(s) of the long- and short-term warm episodes remains enigmatic. Several pieces of geochemical evidence point toward greenhouse forcing. These include changes in the mean ocean $\delta^{13}C$ and alkalinity (Shackleton, 1986; Kennett and Stott, 1991; Zachos et al., 1993; Thomas and Shackleton, 1996). Here, we outline specific questions concerning the nature and causes of these warm episodes that can be addressed by Leg 198 drilling.

The Paleocene-Eocene Thermal Maximum (PETM)

In terms of the rate and degree of warming, the PETM is unprecedented in Earth's history. The deep-sea and high-latitude oceans warmed by 4° and 8°C, respectively. The warming, in turn, led to profound changes in precipitation and continental weathering patterns (Gibson et al., 1993; Robert and Kennett, 1994). The climatic changes also affected biota on a global scale, triggering rapid turnover of benthic and planktonic organisms in the ocean (e.g., Thomas, 1990; Kelly et al., 1996) and a sudden radiation of mammals on land (Koch et al., 1992).

The carbon isotopic composition of the ocean decreased by 3‰ to 4‰ coeval with the warming event, suggesting a massive perturbation to the global carbon cycle (Fig. 5) (Kennett and Stott, 1991; Bains et al., 1999). The large magnitude and rate (~-3‰ to -4‰ per 5 k.y.) of the carbon isotope excursion (CIE) is consistent with a sudden injection of a large volume of isotopically depleted carbon into the ocean/atmosphere system. Dickens et al. (1995, 1997) suggested that the largest source of depleted carbon was the vast reservoir of methane clathrates stored in continental shelf sediments. They hypothesized that gradual warming of deep waters during the late Paleocene would have destablized shelf and slope clathrates, triggering a catastrophic release of CH_4. Much of this methane would have quickly converted to CO_2, stripping O_2 from deep waters and lowering alkalinity, thus contributing to the benthic extinction. Both CO_2 and CH_4 would have immediately contributed to greenhouse warming.

The Leg 198 depth transect will help us address the following questions.

- How much did sea-surface and deep-water temperatures increase during the PETM?

- Did the Pacific CCD shoal during the CIE, and did bottom-water oxygenation decrease? If so, how does this fit with geochemical models of clathrate release?

- What was the response of planktonic and benthic populations to the PETM in the sub-tropical Pacific? How is this interpreted in terms of primary productivity?

- Was there a change in the distribution of bottom-water carbon isotopes prior to and/or during the PETM, signaling possible circulation changes?

Paleogene Deep Water Circulation

Several investigators have suggested that early Cenozoic global warming would have altered deep-ocean circulation patterns by reducing the density of surface waters in high latitudes (Kennett and Shackleton, 1976; Wright and Miller, 1993; Zachos et al., 1993). This in turn would permit increased downwelling of highly saline but warmer waters in subtropical oceans. Such reversals or switches in circulation probably occurred suddenly rather than gradually. In fact, it has been suggested that a sudden change in intermediate water circulation patterns may have occurred just prior to the PETM, possibly triggering the dissociation of clathrates (Bralower et al., 1997b). There may have been additional abrupt warming intervals in the late Paleocene and early Eocene (Thomas and Zachos, 1999; Thomas et al., 2000). These "hyperthermals" were characterized by changes in the assemblage composition of benthic foraminifers corresponding to negative shifts in planktonic and benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ values. The ultimate cause of the hypothermals may be similar to the late Paleocene Thermal Maximum (LPTM), driven by release of greenhouse gas.

Leg 198 will provide the samples needed to assess regional-global circulation changes during the Paleogene. Major changes in the sources of waters bathing Shatsky might be reflected in the spatial and vertical distribution of carbon isotope ratios in bottom waters as well as in benthic foraminiferal assemblage patterns. Several studies have shown that throughout the late Paleocene and early Eocene, the most negative deep-ocean carbon isotope values were consistently recorded by benthic foraminifers from Shatsky Rise (Miller et al., 1987a; Pak and Miller, 1992; Corfield and Cartlidge, 1992). Such a pattern is similar to that in the modern ocean, implying older nutrient-enriched waters in the Pacific and younger nutrient-depleted waters in the high latitudes. Although Site 577 is discontinuous across the Paleocene/Eocene (P/E) boundary, isotope data from Site 865 on Allison Guyot in the equatorial Pacific suggest a possible reduction, if not reversal, in the $\delta^{13}C$ gradient between the shallow Pacific and most of the ocean (Bralower et al., 1995). If this were true, it would be consistent with increased production of intermediate waters in low latitudes. In summary, Leg 198 samples will help address the following questions.

- Is there evidence of warmer, more saline deep waters at times during the Paleogene?
- How did export production in the Pacific change from the Paleocene to the Eocene?

Eocene-Oligocene Paleoceanography

The Eocene to Oligocene represents the final transition from a "greenhouse" to an "icehouse" world. Although this transition occurred over a period of 18 m.y., stable isotopic records reveal that much of the cooling occurred over relatively brief intervals in the late early Eocene (~52 Ma) and earliest Oligocene (~33 Ma) (Fig. 4) (e.g., Kennett, 1977; Miller et al., 1987b, 1991; Stott et al., 1990; Zachos et al., 1996). Furthermore, small ephemeral ice sheets were probably present on Antarctica some time after the first event (Browning et al., 1996). The first large permanent ice sheets became established much later, most likely during the early Oligocene event (Zachos et al., 1992a). Current reconstructions of ocean temperature and chemistry for the Eocene and Oligocene, however, are based primarily on pelagic sediments collected in the Atlantic and Indian Oceans (Miller et al., 1987b; Zachos et al., 1992b, 1996). Very few sections suitable for such work have been recovered from the Pacific (Miller and Thomas, 1985; Miller and Fairbanks, 1985). As a consequence, we still lack a robust understanding of how global ocean chemistry or circulation evolved in response to high-latitude cooling and glaciation.

Eocene-Oligocene sediments are present on Shatsky Rise. Unfortunately, early coring efforts on the rise failed to recover continuous and undisturbed sequences (e.g., Site 305), whereas later coring efforts encountered major unconformities (e.g., Site 577). Leg 198 advanced hydraulic piston core (APC) drilling at or near Site 305 should provide a nearly continuous sequence of well preserved Eocene to Oligocene sediment. Recovery of similar sediments at one or two of the deeper Leg 198 sites would provide a vertical depth transect and the first opportunity to reconstruct, in a third dimension, the evolution of ocean chemistry and temperature during this important climatic transition. Leg 198 drilling will allow us to address the following questions.

- How did the basin-to-basin deep carbon isotope gradient change during the Eocene-Oligocene transition in response to high-latitude cooling and glaciation?

- How did the lysocline/CCD in the Pacific respond to the rapid high-latitude cooling/glaciations in the early middle Eocene and earliest Oligocene?

Mid- and Late Cretaceous Climate

The mid-Cretaceous (Barremian-Turonian [125-85 Ma]) Earth experienced some of the warmest temperatures and lowest thermal gradients of the entire Phanerozoic Eon. This time interval, therefore, represents one of the best ancient approximations of "greenhouse" climate. The Late Cretaceous was characterized by significant global cooling, but available oxygen isotopic records differ on the exact timing of the end of the greenhouse conditions. Records from DSDP Site 511 on the Falkland Plateau, South Atlantic (Fig. 6) (Huber et al., 1995) and the chalk from England (Jenkyns et al., 1994) suggest that peak warmth occurred in the early Turonian, about 90 Ma. Data from Shatsky Rise DSDP sites (e.g., Douglas and Savin, 1975; Savin 1977), however, indicate that peak greenhouse conditions existed in the Albian, ~105 Ma. In addition, these stratigraphies differ on whether peak warming was immediately followed by long-term cooling (English Chalk) or sustained warmth then cooling beginning in the mid Campanian (Site 511 data). Differences between the various records may reflect real latitudinal climatic variations or diagenetic alteration of stable isotope proxies.

There is also significant disparity as to exactly how much cooling occurred in the Late Cretaceous, especially in the tropics. Savin (1977) and D'Hondt and Arthur (1996) concluded that the Maastrichtian was characterized by surprisingly cool tropical SSTs (20°-21°C) based on $\delta^{18}O$ analyses of planktonic foraminifers, i.e., the "cool tropics paradox" (D'Hondt and Arthur, 1996). Wilson and Opdyke (1996), on the other hand, measured $\delta^{18}O$ values on rudists recovered from Pacific guyots and concluded that tropical SSTs in the same interval were extremely warm (between 27° and 32°C). The climate history of the Cretaceous is based on a limited number of data points from few sites with little information from the tropics. In fact, Shatsky Rise Site 305 (Douglas and Savin, 1975) is among a handful of low-latitude sites that form the basis of most Cretaceous thermal gradient estimates that are used as inputs in climate models (e.g., Barron and Peterson, 1990).

There is a limited understanding of the evolution of bottom-water circulation in the mid and Late Cretaceous, in particular, how and when the transition from low-latitude (e.g., Brass et al., 1982) to high-latitude (e.g., Zachos et al., 1993) deep-water sources took place. Benthic foraminiferal $\delta^{18}O$ records are even sparser than those based on planktonic foraminifers, and there are very few benthic data from the entire Pacific. Thus, the role of this giant basin in the evolution of deep waters during the mid and Late Cretaceous is poorly understood.

The long-term cooling of the Late Cretaceous was interrupted by a dramatic event in the mid Maastrichtian, when the source of deep waters appears to have changed abruptly from low- to high-latitude sources (e.g., MacLeod and Huber, 1996; Barrera et al., 1997; Frank and Arthur, 1999). This event appears to have coincided with the extinction of the inoceramid bivalves (MacLeod et al., 1996) and possibly also the rudistid bivalves (Johnson et al., 1996). Growing evidence, however, suggests that this benthic event is distinctly diachronous (MacLeod et al., 1996). The change to high-latitude deep-water sources appears to have been long lived, lasting until the PETM. However, more benthic data are required to accurately characterize Late Cretaceous and Paleocene deep-water properties.

Drilling of relatively shallow burial-depth Upper Cretaceous sections on Shatsky Rise will help address the following questions.

- When peak "greenhouse" conditions occurred, in the Albian (Savin, 1977) or early Turonian (Jenkyns et al., 1994; Huber et al., 1995).

- If the peak warming was immediately followed by long-term cooling (Jenkyns et al., 1994) or sustained warmth then cooling beginning in the mid Campanian (Huber et al., 1995) or whether cooling history varied between latitudes.

- Are apparent cool tropical temperatures in the Maastrichtian (the "cool tropics paradox" of D'Hondt and Arthur [1996]) real or a result of diagenetic alteration of planktonic foraminiferal tests?

- What was the nature of mid- and Late Cretaceous deep water and from what oceanic region was it derived? Benthic foraminiferal isotope stratigraphy should also help determine the timing and rate of changes in the sources of deep waters from low- to high-latitude sources. Benthic carbon isotope values will help determine changes in the relative ages of the deep waters bathing Shatsky Rise.

- Combined isotopic and paleontologic records from the Leg 198 depth transect will constrain the changes in deep-water mass properties that accompanied the mid-Maastrichtian event and their effect on benthic faunas. Long-term records will help determine whether the event led to a permanent change in deep-water source.

- Combined oxygen isotope analyses of planktonic and benthic foraminifers from the Leg 198 depth transect will also provide information on changes in vertical thermal gradients and help assess whether climate and deep-water circulation changes were coupled.

Mid-Cretaceous Oceanic Anoxic Events

The beginning of "greenhouse" climate conditions in the mid Cretaceous (Barremian-Turonian) 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 are known to occur primarily at specific stratigraphic horizons, namely, the lower Aptian, the uppermost Aptian to lowermost Albian, the upper Albian, and in the upper Cenomanian close to the Cenomanian/Turonian boundary (e.g., Jenkyns, 1980; Schlanger et al., 1987; Sliter, 1989; Arthur et al., 1990; Bralower et al., 1993) (Fig. 7). Schlanger and Jenkyns (1976) hypothesized that these OAEs resulted from the vertical expansion of oxygen minimum zones linked to transgressive sea-level pulses and the reduced oxygenation of bottom waters. Others have theorized that oxygen depletion and the deposition of C_{org}-rich sediments instead was the consequence of other paleoceanographic changes such as salinity stratification (Ryan and Cita, 1977; Thierstein and Berger, 1978) and increased flux of C_{org} from surface productivity or terrestrial sources (e.g., Dean and Gardner, 1982; Parrish and Curtis, 1982; Pedersen and Calvert, 1990). Regardless of their origin, the burial of C_{org}-rich sediments enriched in ^{12}C led to significant positive $\delta^{13}C$ excursions. These have been documented for the Cenomanian/Turonian boundary (Scholle and Arthur, 1980), the early Aptian, and the late Aptian-early Albian (e.g., Weissert, 1989; Bralower et al., 1998).

Short-lived negative $\delta^{13}C$ at the onset of the events may be related to input of mantle CO_2 during volcanic events (e.g., Bralower et al., 1994) or to disocciation of methane hydrates (Jahren and Arens, 1998; Jahren et al., 2001).

Complicating the development of paleoceanographic models are apparent differences in the stratigraphic extent and paleobathymetry of C_{org}-rich deposits from the Pacific compared to the Atlantic and Tethys Oceans. In the Atlantic and Tethys, C_{org}-rich deposits occur mostly in basinal settings characterized by major inputs of terrestrial C_{org} by turbidity currents that led to vertically widespread long-lived episodes of deep-water anoxia (e.g., Arthur and Premoli-Silva, 1982; Arthur et al., 1984; Stein et al., 1986). Terrestrial C_{org}-rich deposits in the Atlantic and Tethys occur in intervals besides the OAEs (e.g., Bralower et al., 1993). The record of carbonaceous strata in the Pacific is concentrated in the OAEs dominated by marine C_{org} and almost exclusively restricted to paleobathymetric highs (e.g., Dean et al., 1981; Thiede et al., 1982). However, our understanding of the Pacific record is based on scattered occurrences of carbonaceous strata from Shatsky, Hess, and Magellan Rises, the Mid-Pacific Mountains, the Manihiki Plateau, the Mariana Basin, and the accreted oceanic limestone from the Franciscan Complex along the western margin of North America (Sliter, 1984).

Of particular importance to understanding the paleoceanography of OAEs are the changes in oceanic and atmospheric chemistry associated with the onset of black shale deposition in the latest Barremian to earliest Aptian. It was recently documented that the deposition of mid-Cretaceous C_{org}-rich sediments were coincident with a world-wide pulse in ocean crustal production (Fig. 8) (Larson, 1991; Tarduno et al., 1991; Arthur et al., 1991; Erba and Larson, 1991). The initial massive pulse of this volcanic episode was associated with doubling of ocean-crust production rates at about 5 Ma. The pulse peaked in the middle to late Aptian, tapered gradually through the rest of the mid Cretaceous, and dropped significantly at the end of Santonian time. This, the largest volcanic episode possibly in the past 250 m.y. of Earth history, included increased seafloor spreading rates and increased rates of formation of LIP oceanic plateaus, seamount chains, and continental flood basalts. The first large-scale plateau eruptions were in the Pacific Basin where eruptions in the Aptian began forming the Ontong Java and Manihiki Plateaus, the Mid-Pacific Mountains, and Hess Rise, among other features.

The release of mantle CO_2 from this enormous volcanic episode may have directly caused mid-Cretaceous "greenhouse" warming. The increased preservation and production of organic carbon may have resulted from this warming (e.g., Arthur et al., 1985) combined with increases in nutrients, while sea level rose due to creation of anomalously young and therefore shallow ocean floor (Hays and Pitman, 1973; Schlanger et al., 1981). The signature of this massive volcanic event may be detected in strontium isotope ratios (Jones et al., 1994; Bralower et al., 1997a).

The OAEs had a profound effect on the evolution and extinction of marine nekton, plankton, and benthos (Eicher and Worstell, 1970; Elder, 1987; Leckie, 1987, 1989; Roth, 1987; Bralower, 1988; Premoli-Silva et al., 1989; Erba, 1994). Planktonic foraminifers from each of the C_{org}-rich episodes show unique patterns of extinction and survival, species diversity, specimen size, morphotype, and subsequent adaptive radiation (e.g., Leckie, 1989; Sliter, 1980). In each case, the survivors were largely small globular forms that resemble modern species that proliferate in areas characterized by increased upwelling. In contrast, the larger, more morphologically complex forms that resemble modern species that live within and below the thermocline suffered extinction or severe reduction in numbers. These faunal changes across the C_{org}-rich intervals strongly suggest corresponding changes in the chemistry and physical characteristics of the upper water column (e.g., Sliter and Premoli-Silva, 1990; Premoli-Silva and Sliter, 1999).

The Barremian/Aptian boundary interval was a time of major diversification of nannoplankton (e.g., Bralower et al., 1994); however, the causes of this diversification are not understood. The early Aptian OAE was associated with the demise of the nannoconids (Coccioni et al., 1992; Erba, 1994), a group of taxa that existed in rock-forming abundances in the Early Cretaceous. Erba (1994) postulated that the nannoconid demise resulted from wholesale changes in the fertility structure of the oceans, possibly as a result of voluminous plateau-building volcanism.

Variations in productivity, oxygenation, temperature, and density structure have been suggested as potential factors that may have driven evolution and caused extinction in these time periods. However, there is little independent evidence for changes in any of these factors during the OAEs. Clearly, a better understanding in the changes of water column properties during the

OAEs will help constrain the driving forces for faunal and floral evolution and extinction that accompany these events.

Recovery of mid-Cretaceous C_{org}-rich deposits at relatively shallow burial depth from Shatsky Rise will help determine relationships between the conditions that favored the deposition of C_{org}-rich sediments, climate, and volcanism. The following specific questions will be addressed.

- How does the sedimentation (i.e., lithology and amount and type of C_{org}) differ between OAE intervals and non-OAE intervals? What are the biotic, sedimentologic, and geochemical similarities and differences between the different OAE episodes?

- Based on estimates of paleodepths of sites in the depth transect, is an oxygen minimum zone model applicable for OAEs on Shatsky Rise, and if so, what was its vertical extent?

- Are there any differences between the recovery of C_{org}-rich sediments on the northern and southern highs that might indicate that the intensity of upwelling differed as a function of latitude (i.e., did the paleoequatorial divergence play a role or is there evidence for topographic upwelling?).

- What was the effect of the world-wide, mid-Cretaceous volcanic pulse on the deposition of C_{org} and the timing of OAEs? We intend to define the "near field" response to the onset of this volcanic episode by identifying the geochemical fluxes and compositions of particulates in the sediments of Shatsky Rise that were already in existence within the region of massive Pacific volcanism.

- What was the effect of mid-Cretaceous volcanism on paleotemperature and pCO_2? Was the volcanic pulse a direct cause of "greenhouse" climate conditions? Or is methane disocciation a more likely trigger? Stable isotope analyses of mid-Cretaceous sediments from relatively shallow burial depths on Shatsky Rise will help address these questions.

- Do microplankton and microbenthos respond to the physical, chemical, and biological oceanographical changes associated with OAEs? What are the causes of apparent extinction and evolution in these time intervals?

General Early Cretaceous Paleoceanography

Microplankton Evolution

The Early and mid Cretaceous were critical times in the evolution of planktonic foraminifers and calcareous nannoplankton (e.g., Roth, 1987; Leckie, 1989). Nannoplankton underwent dramatic radiations close to the Jurassic/Cretaceous and Barremian/Aptian boundaries (e.g., Bralower et al., 1989, 1994). Both of these events have been documented in the Atlantic and Tethys but not yet from the Pacific. Pacific sites recording these diversification events would help provide an understanding of their causes.

Planktonic foraminifers appear to have evolved in the Bajocian (Middle Jurassic), but their occurrence is sporadic below the Lower Cretaceous. The diversification of this group was, until recently, thought to have occurred in the early Aptian. Coccioni and Premoli-Silva (1994), however, found the evolutionary appearance of a number of taxa far below their previous ranges in the lower Valanginian of the Rio Argos section of Spain. Documentation of this diversification event in other locations and oceanographic settings will help our understanding of its causes.

Shatsky drilling will help us determine: (1) How did the evolution of nannoplankton correlate to changes in ocean thermal structure and circulation? (2) Is there evidence for diversification of planktonic foraminifers in the early Valanginian as in Spain, and if so, did this event correlate with any obvious changes in circulation or climate?

Valanginian Greenhouse Event

A major change in stable carbon isotope ratios of marine carbonates and organic matter has been observed in the Valanginian (e.g., Lini et al., 1992). The event appears to correlate with a major burial event of C_{org}, an increase in atmospheric CO_2, and global warming, perhaps the earliest indications of the Cretaceous "greenhouse" climate (Lini et al., 1992). Increased crustal production rates at this time (e.g., Larson, 1991) suggest that the event may have a volcanic origin. Warming in the Valanginian is at odds with the evidence of Stoll and Schrag (1996) and others for glaciation in this part of the Cretaceous. Recovery of high-quality stratigraphic sections from additional locations will help resolve this issue. Shatsky coring will help us address how the Valanginian carbon isotope record correlates to indicators of climate change and volcanism and whether there is evidence for warming or cooling in this time interval.

Early Cretaceous CCD Fluctuations

The Early and mid Cretaceous were characterized by major changes in the level of the CCD (e.g., Thierstein, 1979; Arthur and Dean, 1986). These changes likely resulted from changes in fertility, sea level, ocean-floor hypsometry, and ocean circulational patterns. One of the most dramatic events occurred in the early Aptian at around the same time as the massive Pacific volcanic event, suggesting that volcanism played a direct role, perhaps through increased pCO_2. The few data that exist for the Pacific suggest a different CCD history from the Atlantic (Thierstein, 1979), and more data will help resolve the history of the Pacific CCD. Shatsky coring will help us address: (1) What was the gradient of carbonate dissolution in the mid-Cretaceous Pacific Ocean? (2) What was the history of variation in the lysocline and CCD in the Early and mid Cretaceous? (3) Was a major early Aptian CCD shoaling episode observed for the Atlantic Ocean basins characteristic of the global ocean or were the oceans out of phase as the result of the pattern of deep-water aging?

Nature and Age of Shatsky Rise Basement

LIPs such as Ontong Java Plateau and Shatsky Rise were constructed during voluminous magmatic events that took place over geologically brief (<1 m.y.) time intervals (e.g., Duncan and Richards, 1991; Tarduno et al., 1991; Coffin and Eldholm, 1994). These events are thought to be associated with massive thermal anomalies in the mantle known as "superplumes" (Larson, 1991). A likely possibility is that the voluminous phase of superplume activity was associated with the ascent of a plume "head" and that activity declined as the magma source dried up as the lithosphere rode over the plume "tail." One of the major questions concerning the origin of LIPs, such as Shatsky Rise, is whether they formed in a midplate setting or at a divergent boundary, possibly a triple junction, at times of changing plate geometry (e.g., Sager et al., 1988).

Trace element geochemistry of most samples from Shatsky Rise is close to mid-ocean ridge basalt (MORB) (Tatsumi et al., 1998), indicating that they were generated at a divergent boundary, but a few samples have an affinity closer to Polynesian alkalic basalts, suggesting a midplate origin. The latter result is not unexpected, because Shatsky Rise is thought to have formed in the South Pacific (McNutt and Fischer, 1987) near crust with the distinctive Polynesian chemistry. Additional basement coring at Shatsky will help us address whether it had some kind of a hybrid origin or whether there are other explanations for the few anomalous samples.

Although volcanic basement crops out at several localities on Shatsky Rise (Sliter et al., 1990), the only basement samples obtained are from dredges and these are heavily weathered. Ozima et al. (1970) dated volcanic rocks dredged from Shatsky Rise as Tertiary in age. Either these rocks were derived from late-stage volcanism identified in seismic data from the rise or else possibly their pervasive alteration precludes reliable age determination. Maximum estimates for the age of basement on Shatsky Rise can be obtained by adjacent magnetic anomalies (Nakanishi et al., 1989). These ages range from 148 Ma (Late Jurassic polarity Zone CM21) in the southern high to 136 Ma (Berriasian-Valanginian polarity Zone CM14) in the northern high based on the time scale of Gradstein et al. (1994). Fresh basement samples will provide valuable age information.

OPERATION PLAN

Will Sager and Adam Klaus (Texas A&M University) have kindly made available digital six-channel seismic reflection data collected during their 1994 site survey cruise of Shatsky Rise. Five primary sites and nine alternate sites have been identified (Fig. 9; Tables 1, 2). The current Leg 198 drilling plan calls for coring at the five primary sites. As explained below, we have designed an alternate strategy to be employed if recovery of soft sediment at the first drilling site is seriously impaired by chert; the alternate strategy calls for coring to a shallower total depth (TD) at the five primary sites and three alternate sites. Sites were selected based on the following criteria: (1) thick sediment packages that include the intervals of interest, (2) weaker seismic reflectors in Paleogene and Lower mid-Cretaceous intervals that are thought to indicate the presence of less significant unconformities and chert horizons, and (3) a range of paleodepths to provide depth transects for the mid-Cretaceous to Paleogene section. The anticipated section in each site is shown in Figure 10 and Table 3.

PRIMARY DRILLING STRATEGY

Site Location

The drilling program includes a total of five sites, SHAT-1, 2B, 3, 4, and 5C, three on the southern high of Shatsky Rise (SHAT-1, 2B, and 3) and one each on the central (SHAT-4) and northern highs (SHAT-5C) (Fig. 9; Table 1). Paleogene sediments will be recovered at all five sites, Upper (Coniacian-Maastrichtian) and mid-Cretaceous (Barremian-Turonian) sediments will be drilled at four sites (SHAT-2B, 3, 4, 5C), and pre-Barremian sediments and basement targeted at one site (SHAT-3). The five sites provide a depth transect between 2450 and 3900 m (current depths) for the Paleogene and mid Cretaceous and 2450 to 3300 m for the Upper Cretaceous. In addition, the sites provide a transect of nearly 8° of latitude. The stratigraphy of the southern high is well established but that of the other highs is poorly known (Sliter and Brown, 1993). However, the central and northern highs appear to have thicker sediment packages, particularly in the Paleogene, and less prominent seismic reflectors. The central and northern high sites also provide additional latitudinal spread.

The entire Paleogene section should be recoverable with APC coring (Table 1). Double APC coring will increase the stratigraphic completeness of the recovered sediments. Paleogene sediments will be recovered at all five sites. The post-Santonian Upper Cretaceous should have minor chert and thus will be recovered by APC and XCB coring at all five sites. The pre-Santonian record contains chert and thus will be drilled using a revised XCB/motor driven core barrel (MDCB) strategy (see below).

Drilling Problems

Unconformities

The Paleogene and Upper Cretaceous sequence on Shatsky Rise is interrupted by several distinct unconformities. Some of the unconformities, such as that close to the Paleocene/Eocene boundary may have paleoceanographic significance. We have attempted to locate the primary sites in places where seismic data indicate that the section is more complete than at previous sites cored nearby (e.g., Site 305) and where the seismic expression of the unconformities appears to be reduced. Previous drilling suggests that the sequence is laterally variable over rather short distances (e.g., Heath, Burckle, et al., 1985). For this reason, we will move the ship laterally by hundreds of meters after the first APC if critical stratigraphic intervals such as the PETM are missing.

Chert

The presence of chert has significantly reduced core recovery in previous coring of the mid- and Lower Cretaceous sections at Shatsky Rise. It is almost impossible to recover the softer interlayers with the drilling rates required to penetrate the hard chert layers using standard rotary core barrel (RCB) coring. We plan to maximize recovery in the cherty interval using the MDCB. The depth of prominent chert layers will be determined in the first XCB hole, then these intervals will be cored and recovered using the MDCB in the second XCB hole. MDCB coring is slower than standard XCB coring, because the core can only advance 4.5 m and the system requires an extra wireline trip; however, this tool is housed in the same coring assembly as the XCB, allowing alternation of coring tools in hard-soft units without tripping the drill pipe. Our coring program includes double XCB coring of the cherty mid-Cretaceous section at SHAT-5C and 2B; if any time remains, we will also use this strategy at SHAT-3.

ALTERNATE DRILLING STRATEGY

If the coring strategy to recover soft-hard interlayers outlined above proves ineffective in providing sufficient recovery at the first site (Site SHAT-5C), we propose an alternate strategy to concentrate on the uppermost Cretaceous (post-Santonian) and Paleogene section in which chert is rare. To achieve this, we have assembled eight primary sites in this alternate strategy that provide a depth transect of ~2500 m and a latitudinal transect of 8° (Figs. 9, 10; Tables 1, 2). The alternate strategy, although forfeiting the mid-Cretaceous objectives, would yield a highly detailed depth transect of the Late Cretaceous through Paleogene Pacific Ocean, allowing us to address in far more detail the major scientific objectives in this time interval. In addition to the alternate strategy sites listed in Table 2, six more alternate sites (SHAT-6, 8, 9, 10, 12, and 13; Fig. 9) have been approved for drilling, but are lower priority.

LOGGING PLAN

Under the primary operations plan, logging will be carried out at Sites SHAT-5C, 2B, and 3 (Table 2). We cannot expect exceptionally high rates of recovery in hard-soft interlayered intervals, even with double XCB/MDCB coring. Logging of these holes will provide critical information that will enable us to interpret some of the most fundamental questions we are addressing, even with poor core recovery.

Three tool strings will be run at the logged sites: the triple combo (resistivity, density, porosity, and natural gamma logs); the Formation MicroScanner (FMS)/sonic (resistivity image, acoustic velocity, and natural gamma logs); and the geologic magnetic tool (GHMT) (magnetic field, susceptibility, and natural gamma logs). The first two tool strings are the main priority. Small-scale features can be identified in the FMS image log; for example, Röhl and Abrams (2000) used FMS image logs to detect unrecovered ash layers in the uppermost Paleocene section of Site 1001 in the Caribbean and to correlate between holes. The thickness and position of black shales should be clearly identifiable in the natural gamma logs. Chert bands will appear as spikes in most of the logs. The acoustic velocity logs can be used to create a depth-traveltime curve to determine how much of the seismic section has been penetrated, and they can also be used in the generation of synthetic seismograms. The GHMT logs will probably provide a magnetic polarity stratigraphy, and magnetic susceptibility is usually the best parameter for core-log integration. In summary, a complete set of logs will be used to interpret the stratigraphy of unrecovered intervals at all of the logged sites.

SAMPLING PLAN

All sampling of recovered cores will be subject to the rules described in the ODP Sample Distribution Policy (http://www-odp.tamu.edu/publications/policy.html). Prior to Leg 198, the sampling program for the leg will be developed and approved by the Sampling Allocation Committee (SAC), consisting of the Co-Chief Scientists, Staff Scientist, and Curator. The initial sampling plan is preliminary and can be modified depending upon actual material recovered and collaborations that may evolve between scientists during the leg. In the final shipboard sampling plan, sample requests will be closely linked to proposed postcruise research.

During the leg, samples for measurements of ephemeral properties will be collected. These measurements include those for organic geochemistry for safety monitoring (free gas and 20-cm^3 sediment samples), interstitial water chemistry (whole rounds, 5-15 cm in length), and biostratigraphy (core-catcher samples).

The Paleogene and Upper Cretaceous at all Leg 198 sites will be double cored in an attempt to recover a complete stratigraphic section. No archive halves (permanent or temporary) will be sampled aboard ship, and the permanent archive will be designated postcruise. All high-resolution sampling will be deferred until after the cruise to enable the development of a composite sedimentary section from the multiple holes. All shipboard scientists will participate in shipboard sampling according to the shift schedule developed at the start of the leg. For certain investigations, it will be beneficial for scientists to conduct analyses on the same shared samples.

Critical Intervals

These include the Eocene/Oligocene, the Paleocene/Eocene, the Cretaceous/Tertiary, the Cenomanian/Turonian, the Aptian/Albian, and the Barremian/Aptian boundaries. The biostratigraphic definitions of the critical intervals will be established by shipboard paleontologists and the SAC at the beginning of the cruise. When these intervals are recovered, only toothpick samples will be taken initially to provide age control. Once this control has been obtained, the SAC will develop a sampling plan in consultation with interested scientists. If time allows, this sampling will be carried out onboard ship. Whole-round samples in these intervals will only be taken once biostratigraphic control is obtained.

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FIGURE CAPTIONS

Figure 1. Location of topographic highs in the Western Pacific Basin.

Figure 2. Shatsky Rise showing previously drilled DSDP (solid circles) and ODP (solid square) sites on the southern plateau. Magnetic lineations and trace of the hot spot (black arrow) from Nakanishi et al. (1989).

Figure 3. Lithologic columns from previous DSDP and ODP sites on Shatsky Rise showing age, lithology, and prominent unconformities (after Sliter and Brown, 1993). The water depth for each site is listed below the site number and is in meters. mbsf = meters below seafloor.

Figure 4. Compilation of benthic foraminifer oxygen isotopic composition from 34 DSDP and ODP sites plotted vs. depth and smoothed using a five-point running mean (from Zachos et al., 1993; Zachos et al., unpubl. data). MME = mid-Maastrichtian event, LPTM = late Paleocene thermal maximum, OAE = oceanic anoxic event.

Figure 5. Carbon and oxygen isotope values of planktonic and benthic foraminifers from the upper Paleocene at Sites 527, 690, and 865 (Kennett and Stott, 1991; Bralower et al., 1995; Thomas and Shackleton, 1996; Zachos and Rea, unpubl. data) plotted vs. age. Planktonic foraminifer data (upper two boxes): diamonds = Site 865, circles = Site 690, crosses = Site 527. Benthic foraminifer data (lower two boxes): diamonds = Site 690, squares = Site 527, circles = Site 865.

Figure 6. Compilation of DSDP/ODP isotope data from Albian to Maastrichtian (from Huber et al., 1995; Fassell and Bralower, 1999; Stott and Kennett, 1990; Barrera and Huber, 1990; Barrera, 1994; Barrera and Savin, 1999). Dashed lines connecting benthic foraminifer data = unconformities, solid symbols = benthic foraminifer, open symbols = planktonic foraminifers. CTBI = Cenomanian/Turonian Boundary Interval.

Figure 7. Mid-Cretaceous record of black shales and OAEs in the context of the carbon isotopic record (Erbacher et al., 1996; Bralower et al., 1999), changing global sea level (Haq et al., 1988), seawater $^{87}Sr/^{86}Sr$ (Bralower et al., 1997a), large igneous province emplacement (Larson, 1991),

plankton evolutionary events (Erbacher and Thurow, 1997; Leckie et al., unpubl. data), and carbonate platform drowning (Leckie et al., unpubl. data). The black section of the LIP indicates time periods when most of the volcanic activity took place based on exisiting ages. The dotted section indicates time periods when activity is possible, but no ages have been found.

Figure 8. World-wide volume of oceanic plateaus, seamount chains, and continental flood basalts plotted as a function of geologic time according to Harland et al. (1990) (after Larson, 1991).

Figure 9. Location map showing position of primary and alternate Leg 198 sites (after Klaus et al., unpubl. data). Location of previous DSDP sites are also shown.

Figure 10. Anticipated stratigraphic sequence for primary and alternate Leg 198 sites based on previous drilling and seismic interpretation.

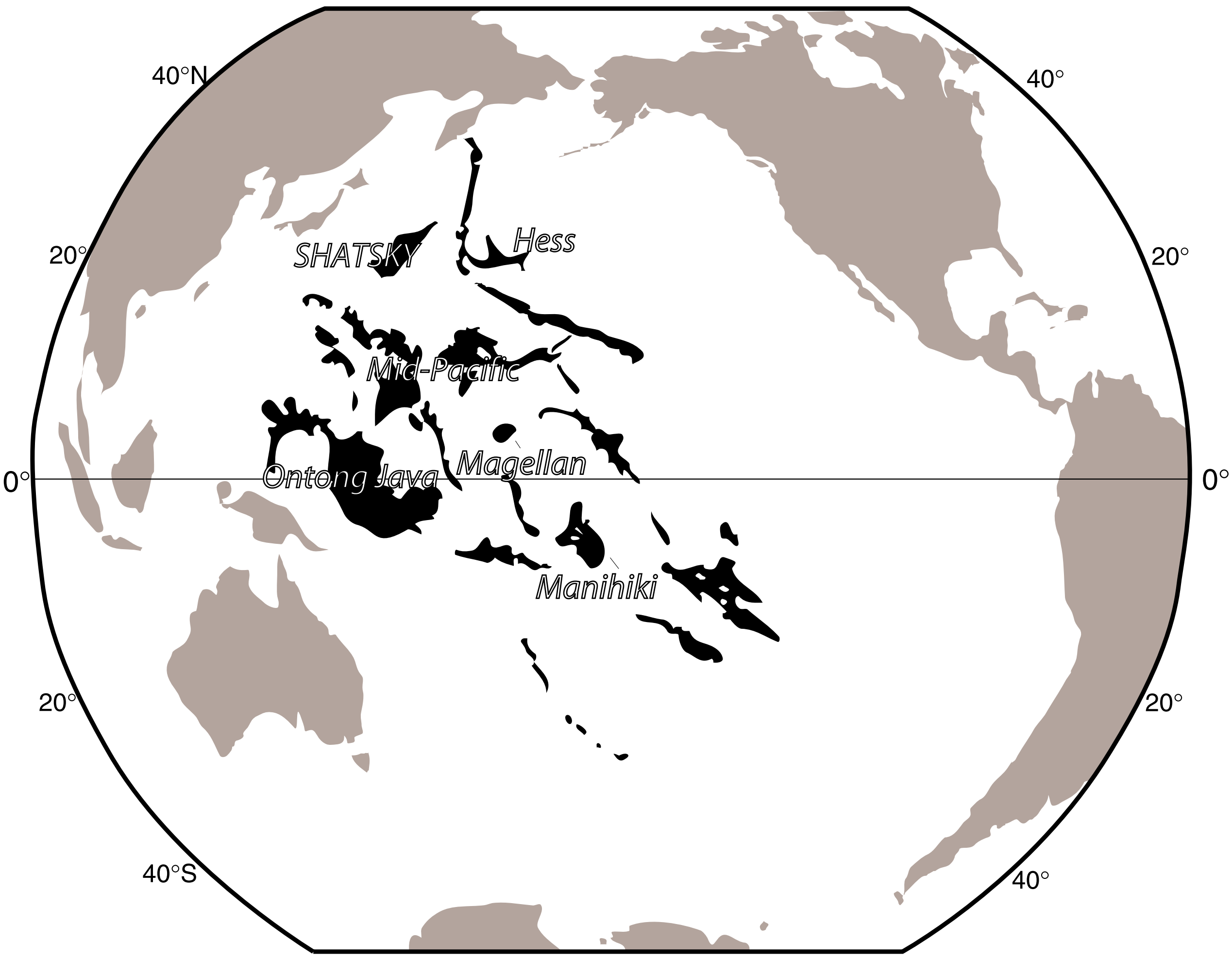
40°N
40°
20°
20°
0°
0°
20°
20°
40°S
40°
SHATSKY
Hess
Mid-Pacific
Magellan
Ontong Java
Manihiki

Figure 1

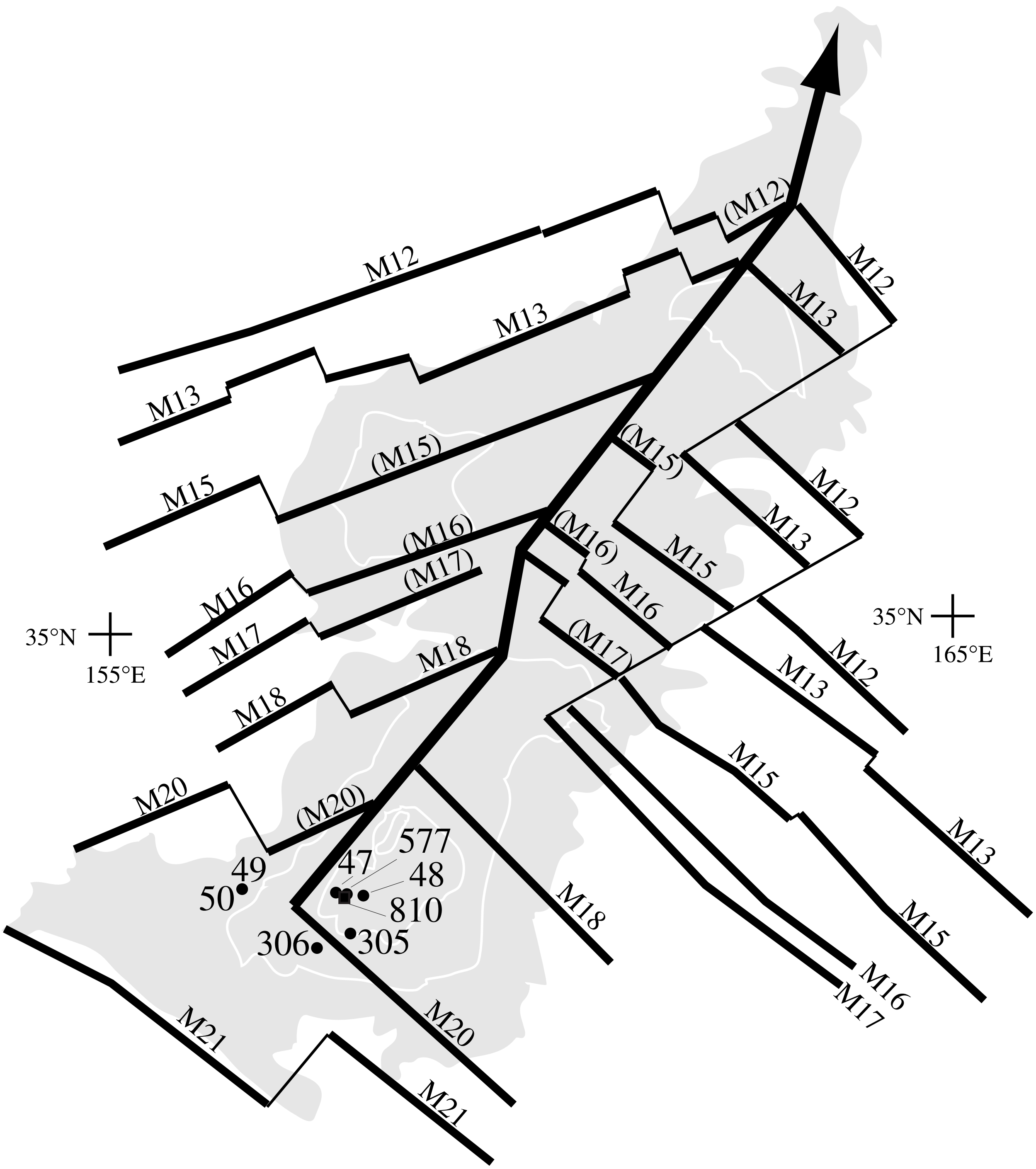
M12
M13
(M12)
M12
M13
(M15)
M15
(M15)
M12
(M16)
(M16)
M13
M16
(M17)
M15
M16
M17
35°N
155°E
M18
M18
(M17)
M12
M13
35°N
165°E
M20
(M20)
577
47
48
49
50
810
306
305
M18
M15
M13
M15
M16
M17
M20
M21
M21

Figure 2

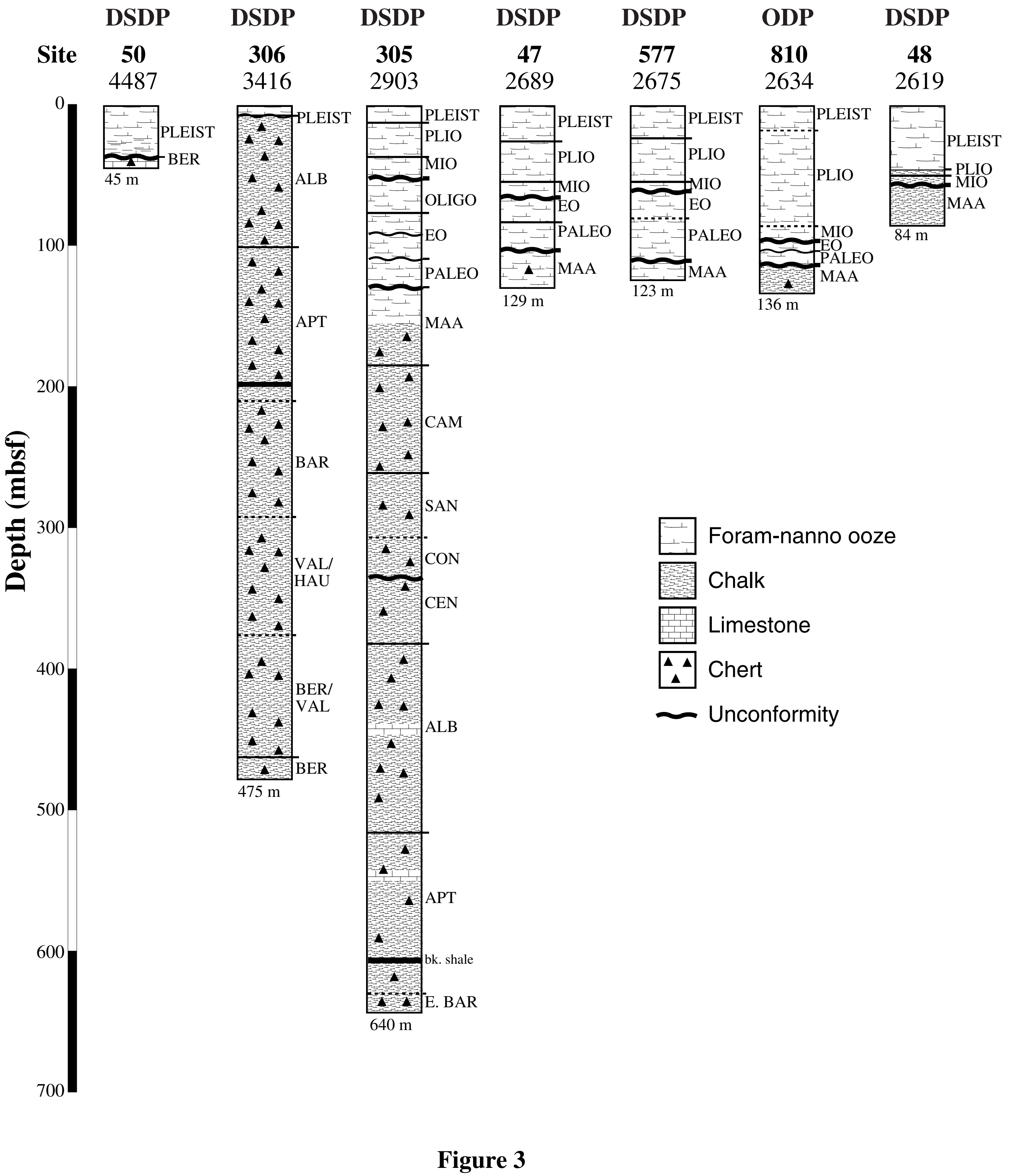
DSDP
DSDP
DSDP
DSDP
DSDP
ODP
DSDP
Site
50
4487
306
3416
305
2903
47
2689
577
2675
810
2634
48
2619
Depth (mbsf)
0
100
200
300
400
500
600
700
PLEIST
BER
45 m
PLEIST
ALB
APT
BAR
VAL/
HAU
BER/
VAL
BER
475 m
PLEIST
PLIO
MIO
OLIGO
EO
PALEO
MAA
CAM
SAN
CON
CEN
ALB
APT
bk. shale
E. BAR
640 m
PLEIST
PLIO
MIO
EO
PALEO
MAA
129 m
PLEIST
PLIO
MIO
EO
PALEO
MAA
123 m
PLEIST
PLIO
MIO
EO
PALEO
MAA
136 m
PLEIST
PLIO
MIO
MAA
84 m
Foram-nanno ooze
Chalk
Limestone
Chert
Unconformity

Figure 3

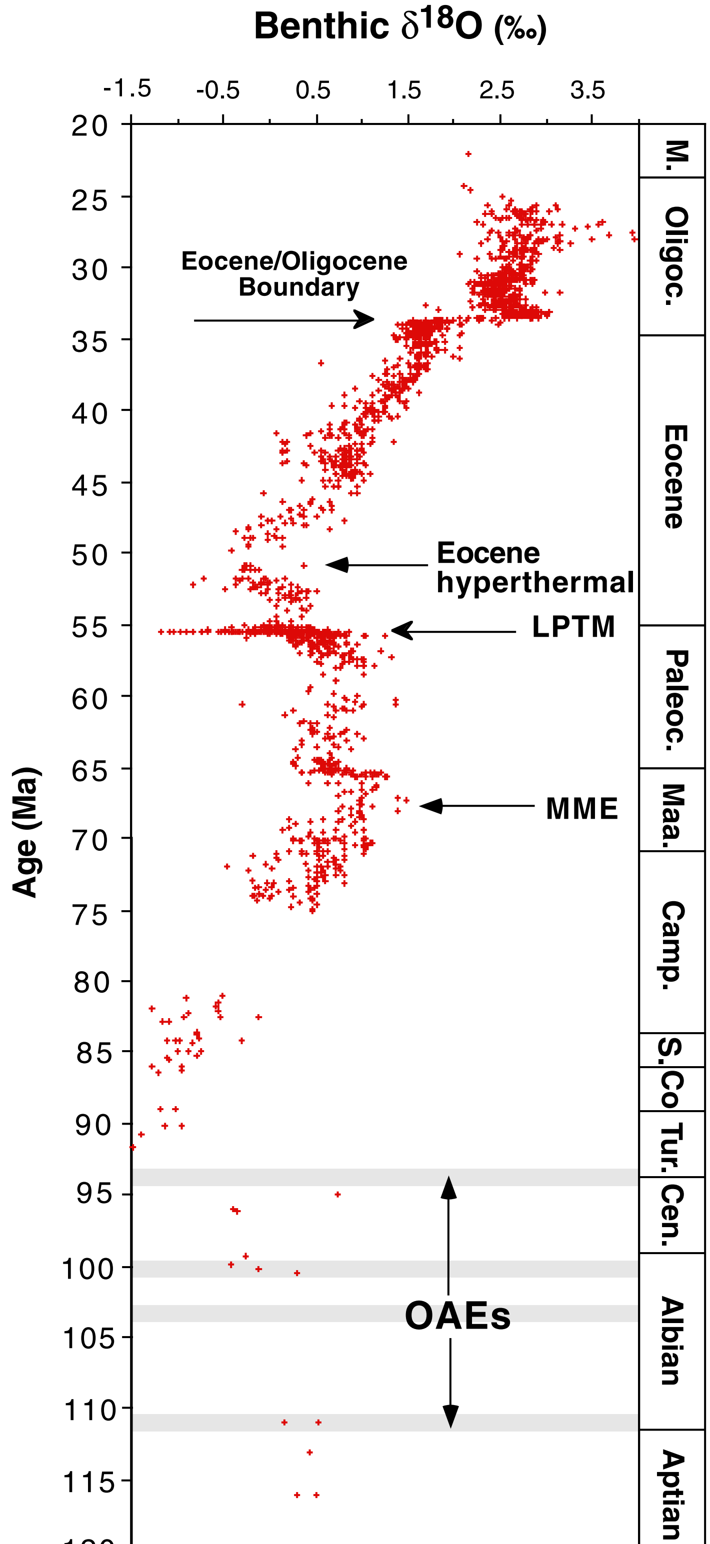
Benthic δ18O (‰)
-1.5
-0.5
0.5
1.5
2.5
3.5
Age (Ma)
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
Eocene/Oligocene Boundary
Eocene hyperthermal
LPTM
MME
OAEs
M.
Oligoc.
Eocene
Paleoc.
Maa.
Camp.
S.
Co
Tur.
Cen.
Albian
Aptian

Figure 4

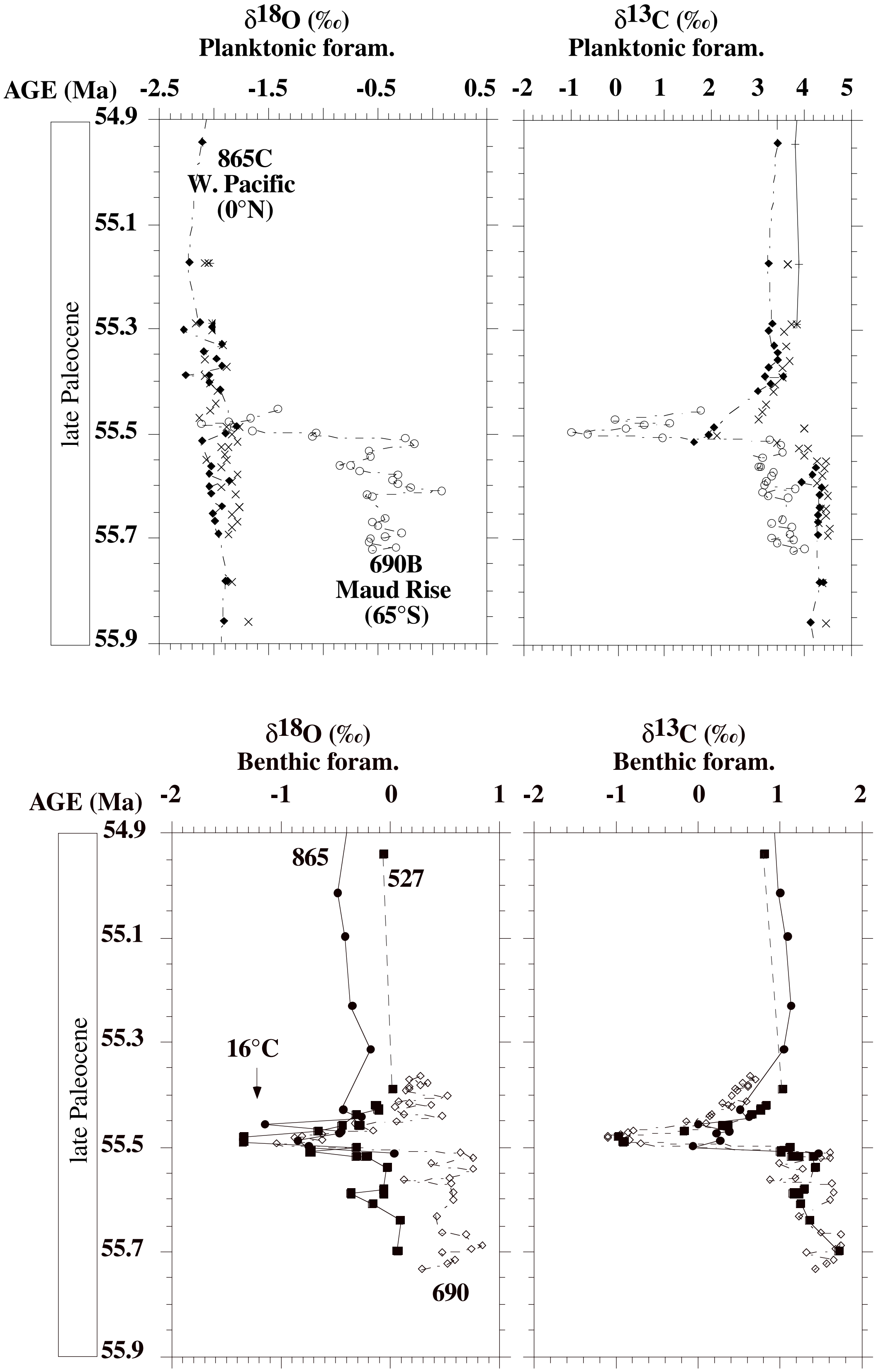
δ18O (‰)
Planktonic foram.
δ13C (‰)
Planktonic foram.
AGE (Ma)
-2.5
-1.5
-0.5
0.5
-2
-1
0
1
2
3
4
5
54.9
55.1
55.3
55.5
55.7
55.9
late Paleocene
865C
W. Pacific
(0°N)
690B
Maud Rise
(65°S)
δ18O (‰)
Benthic foram.
δ13C (‰)
Benthic foram.
AGE (Ma)
-2
-1
0
1
-2
-1
0
1
2
865
527
16°C
690

Figure 5

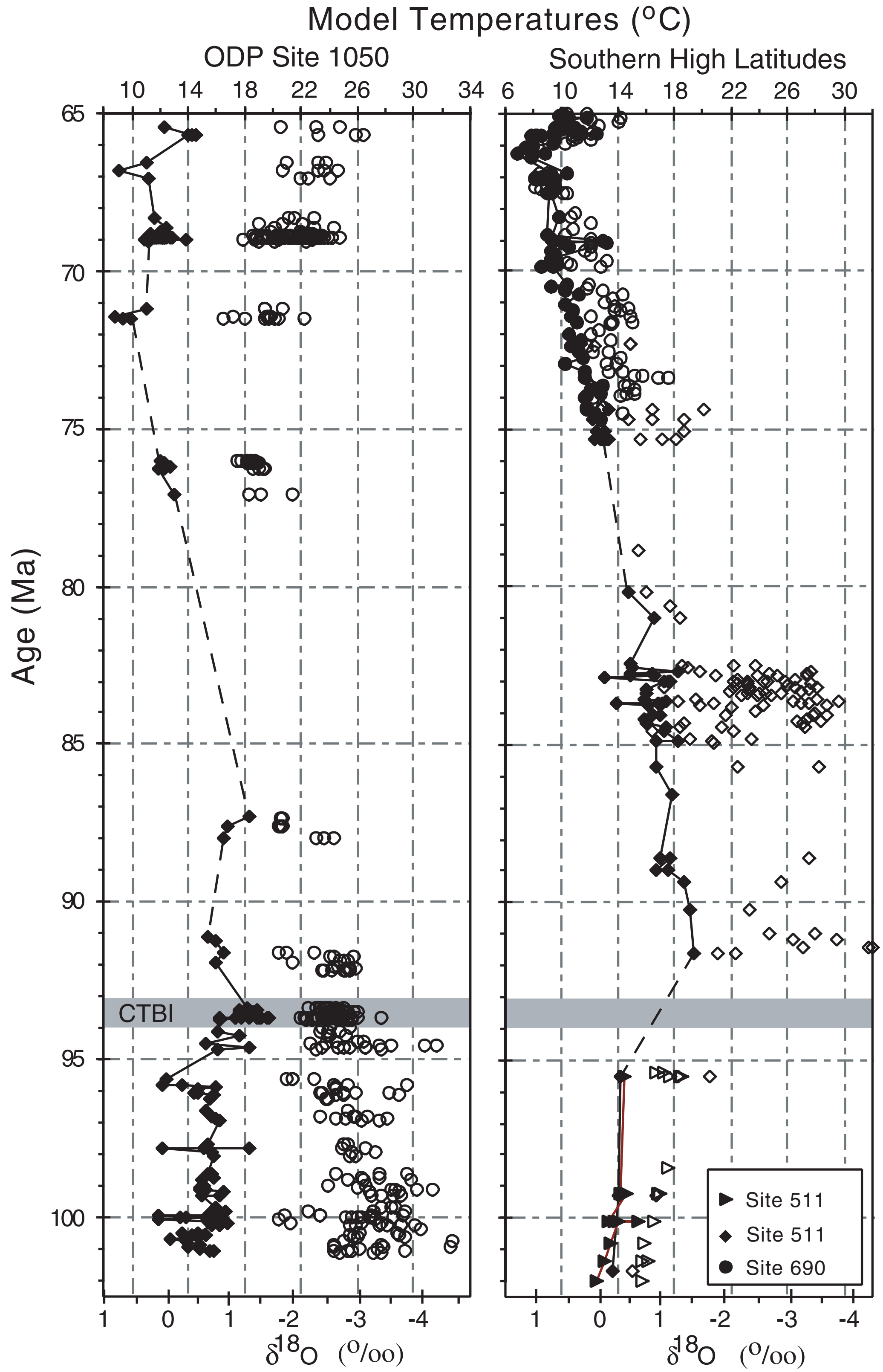
Model Temperatures (°C)
ODP Site 1050
Southern High Latitudes
10 14 18 22 26 30 34
6 10 14 18 22 26 30
Age (Ma)
65
70
75
80
85
90
95
100
CTBI
1 0 -1 -2 -3 -4
δ18O (‰)
Site 511
Site 511
Site 690

Figure 6

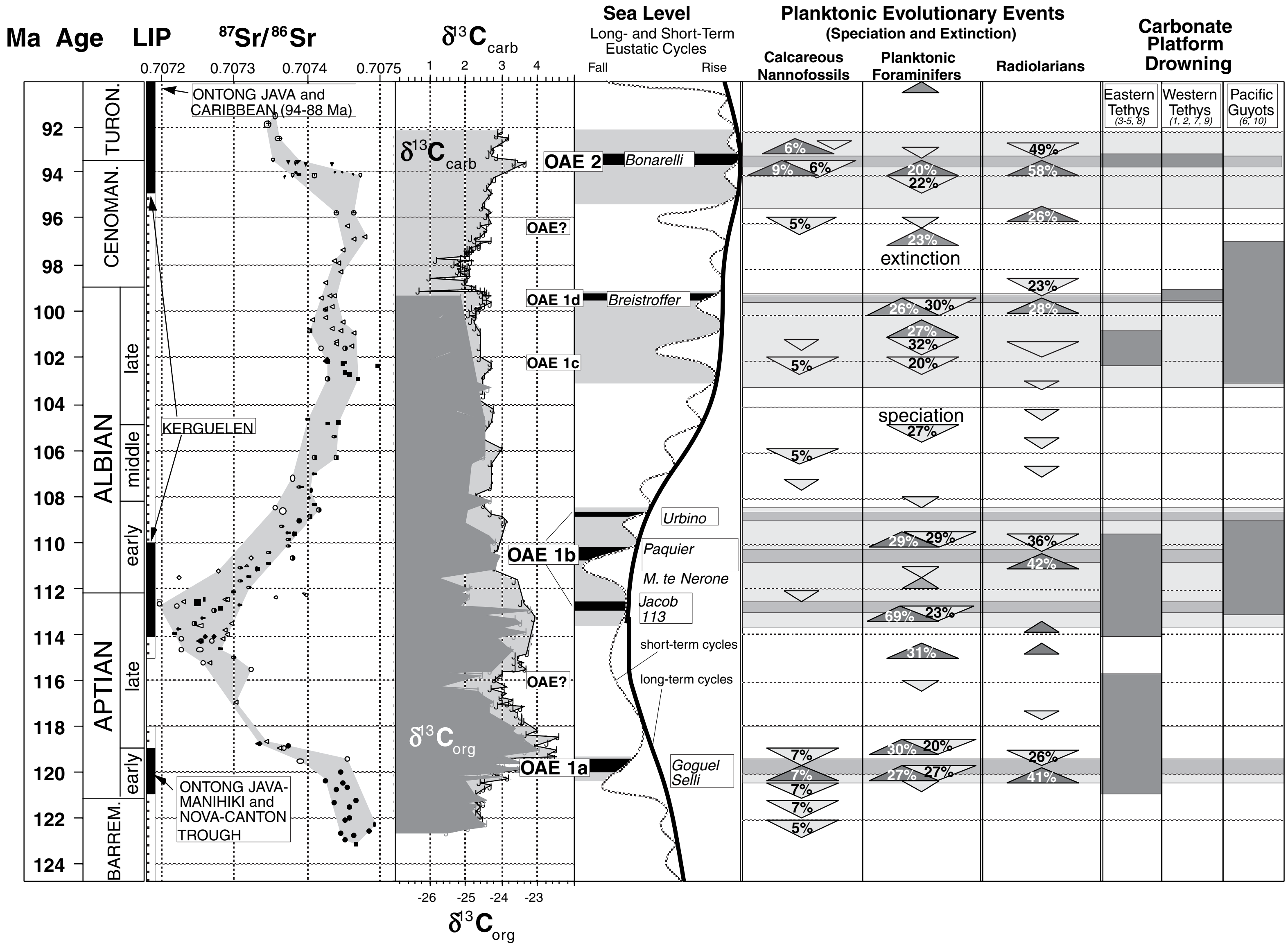
Ma
Age
LIP
87Sr/86Sr
0.7072
0.7073
0.7074
0.7075
δ13Ccarb
1
2
3
4
Sea Level
Long- and Short-Term Eustatic Cycles
Fall
Rise
Planktonic Evolutionary Events
(Speciation and Extinction)
Calcareous Nannofossils
Planktonic Foraminifers
Radiolarians
Carbonate Platform Drowning
Eastern Tethys
Western Tethys
Pacific Guyots
TURON.
CENOMAN.
ALBIAN
late
middle
early
APTIAN
late
early
BARREM.
92
94
96
98
100
102
104
106
108
110
112
114
116
118
120
122
124
ONTONG JAVA and CARIBBEAN (94-88 Ma)
KERGUELEN
ONTONG JAVA-MANIHIKI and NOVA-CANTON TROUGH
δ13Ccarb
δ13Corg
OAE 2
Bonarelli
OAE?
OAE 1d
Breistroffer
OAE 1c
OAE 1b
Urbino
Paquier
M. te Nerone
Jacob
113
short-term cycles
long-term cycles
OAE?
OAE 1a
Goguel
Selli
extinction
speciation
6%
9%
6%
5%
5%
5%
7%
7%
7%
7%
5%
20%
22%
23%
26%
30%
27%
32%
20%
27%
29%
29%
69%
23%
31%
30%
20%
27%
27%
49%
58%
26%
23%
28%
36%
42%
26%
41%
-26
-25
-24
-23
δ13Corg

Figure 7

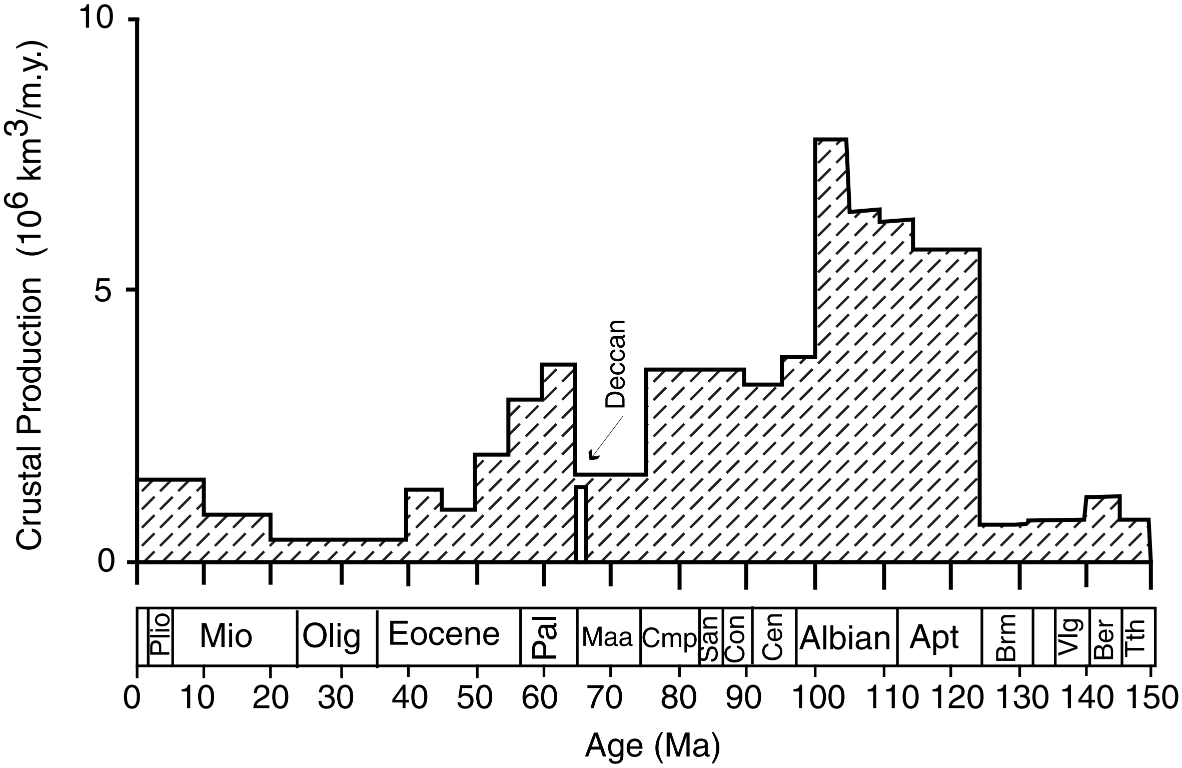
10
5
0
Crustal Production (10^6 km^3/m.y.)
Deccan
Plio
Mio
Olig
Eocene
Pal
Maa
Cmp
San
Con
Cen
Albian
Apt
Brm
Vlg
Ber
Tth
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Age (Ma)

Figure 8

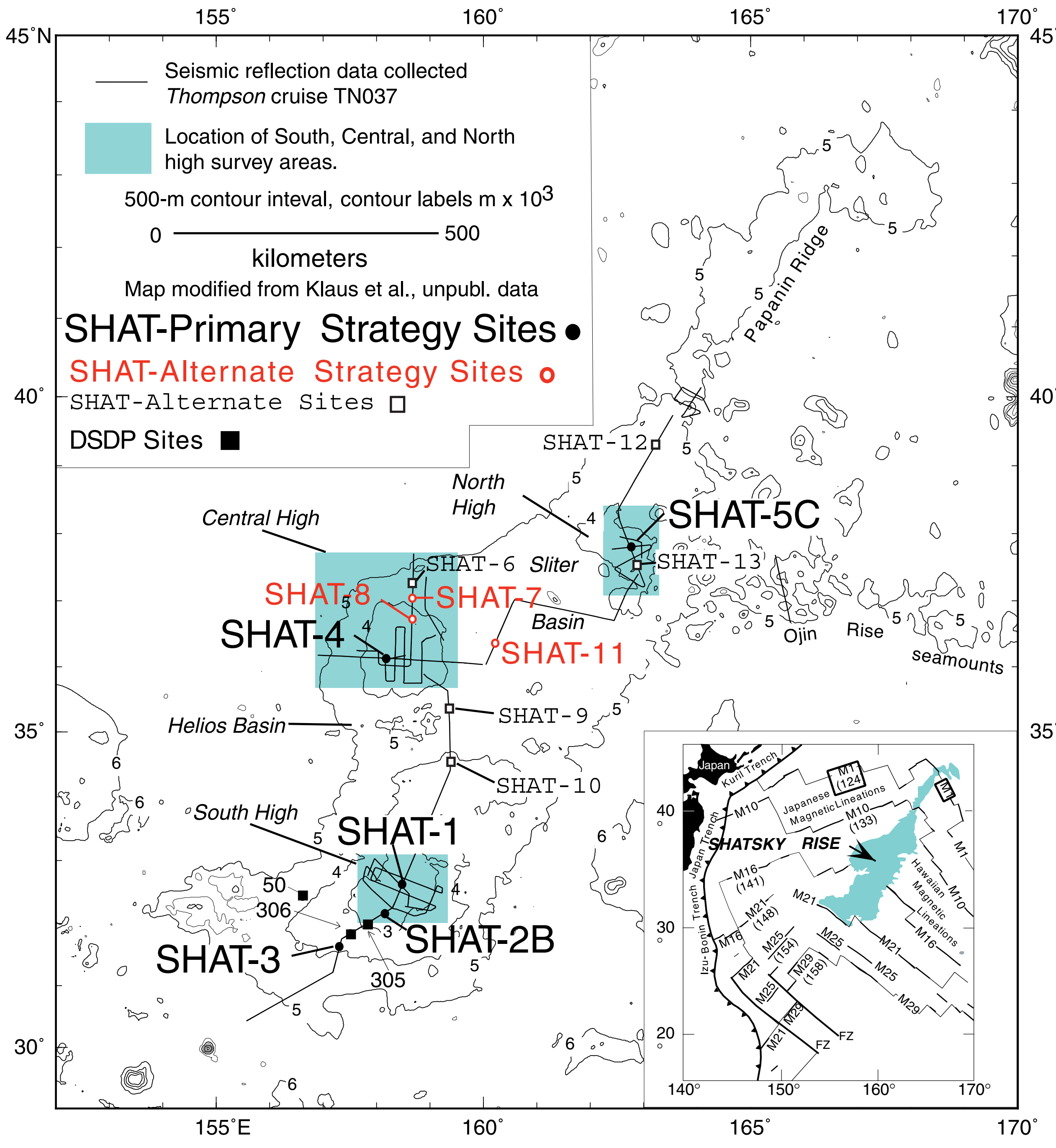
Seismic reflection data collected
Thompson cruise TN037
Location of South, Central, and North high survey areas.
500-m contour inteval, contour labels m x 10^3
0 500
kilometers
Map modified from Klaus et al., unpubl. data
SHAT-Primary Strategy Sites
SHAT-Alternate Strategy Sites
SHAT-Alternate Sites
DSDP Sites
Papanin Ridge
North High
Central High
Sliter Basin
Helios Basin
South High
Ojin Rise seamounts
SHAT-12
SHAT-5C
SHAT-13
SHAT-6
SHAT-8
SHAT-7
SHAT-4
SHAT-11
SHAT-9
SHAT-10
SHAT-1
SHAT-2B
SHAT-3
50
306
305
155°E
160°
165°
170°
45°N
40°
35°
30°
Japan
Kuril Trench
Japan Trench
Izu-Bonin Trench
SHATSKY RISE
Japanese Magnetic Lineations
Hawaiian Magnetic Lineations
M1 (124)
M10 (133)
M16 (141)
M21 (148)
M25 (154)
M29 (158)
FZ

Figure 9

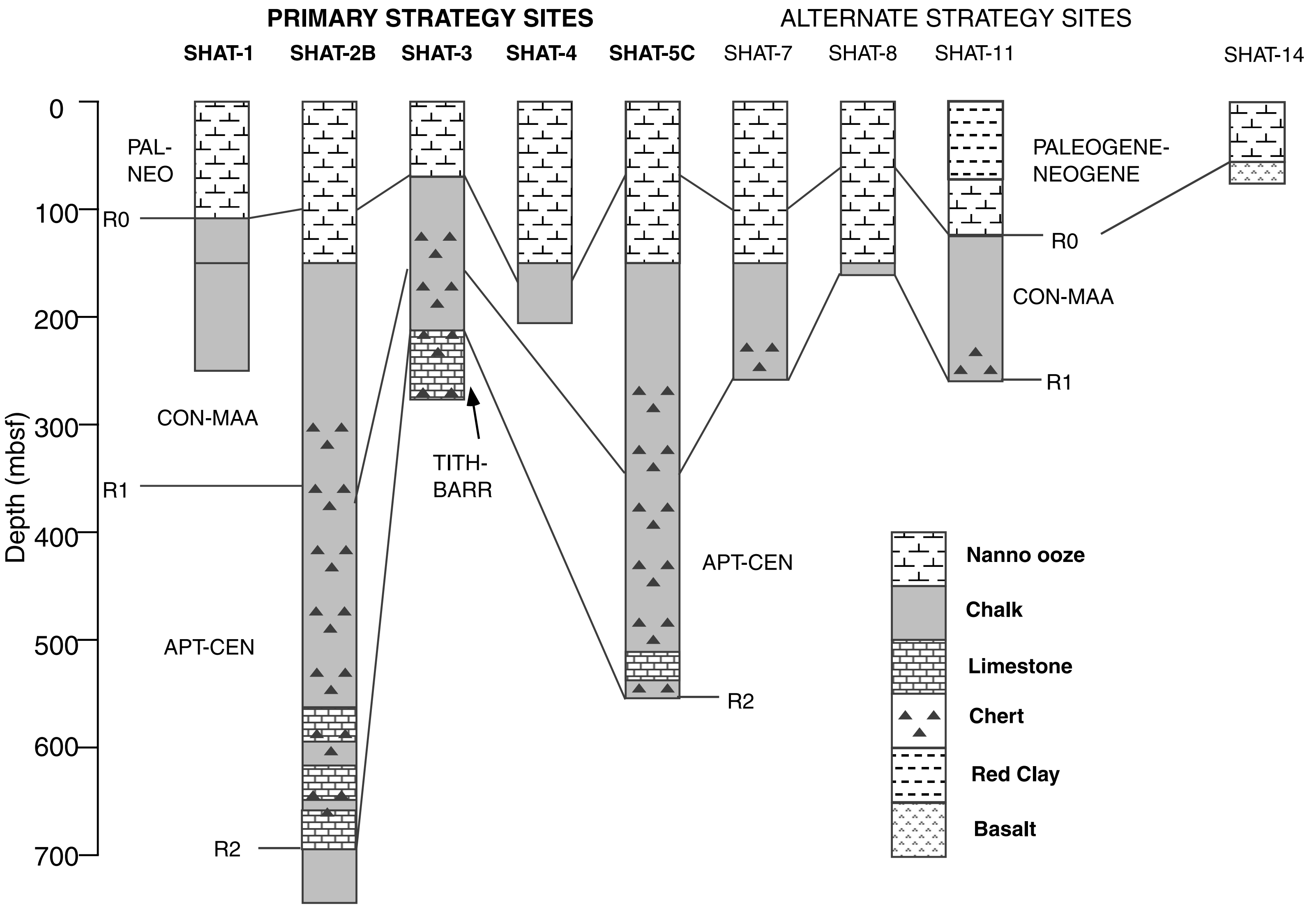
PRIMARY STRATEGY SITES
ALTERNATE STRATEGY SITES
SHAT-1
SHAT-2B
SHAT-3
SHAT-4
SHAT-5C
SHAT-7
SHAT-8
SHAT-11
SHAT-14
Depth (mbsf)
0
100
200
300
400
500
600
700
PAL-
NEO
R0
CON-MAA
R1
APT-CEN
R2
TITH-
BARR
APT-CEN
R2
PALEOGENE-
NEOGENE
R0
CON-MAA
R1
Nanno ooze
Chalk
Limestone
Chert
Red Clay
Basalt

Figure 10

Table 1. Leg 198 - Shatsky Rise
Primary Operations Plan and Time Estimate

Site	Location (Lat/Long)	Water Depth (mbrf)	Operations Description (mbsf)	(hr)	Transit (days)	Drilling (days)	Logging (days)	Total On-site (days)
Yokohama	35.5°N, 139.7°E		Transit 1116 nmi f/Yokohama to SHAT-5C @ 10.5 kt	106.25	4.4			
SHAT-5C	37°47.429'N	3127	Hole A: APC to refusal (~200 mbsf), XCB to ~555 mbsf	110.00		4.6		
	162°45.053'E		Hole B: APC to ~200 mbsf, XCB/MDCB to ~555 mbsf	160.25		6.7		
			Note: Core 155 m with MDCB (4.5 m cores)					
			Wireline log: triple combo/FMS-sonic/GHMT	28.00			1.2	12.5
			Transit 258 nmi from SHAT-5C to SHAT-4 @ 10.5 kt	24.50	1.0			
SHAT-4	36°7.629'N	3318	Hole A: APC to refusal (~200 mbsf)	35.00		1.5		
	158°12.094'E		Hole B: APC to ~200 mbsf	32.25		1.3		2.8
			Transit 209 nmi from SHAT-4 to SHAT-1 @ 10.5 kt	20.00	0.8			
SHAT-1	32°39.099'N	2418	Hole A: APC to refusal (~200 mbsf)	30.00		1.3		
	158°30.357'E		Hole B: APC to ~200 mbsf	27.00		1.1		2.4
			Transit 32 nmi from SHAT-1 to SHAT-2B @ 10.5 kt	3.00	0.1			
SHAT-2B	32°6.865'N	2782	Hole A: APC to refusal (~200 mbsf), XCB to ~700 mbsf	120.25		5.0		
	158°3.030'E		Hole B: APC to ~200 mbsf, XCB/MDCB to ~700 mbsf	184.75		7.7		
			Magnaflux (NDT) inspect BHA/drill collars					
			Wireline log: triple combo/FMS-sonic/GHMT	31.00			1.3	14.0
			Transit 52 nmi from SHAT-2B to SHAT-3 @ 10.5 kt	5.00	0.2			
SHAT-3	31°34.641'N	3881	Hole A: APC to refusal (~70 m)	20.25		0.8		
	157°17.862'E		Hole B: APC to ~70 mbsf, XCB to ~210 mbsf	51.25		2.2		
			Lay out BHA/DC/secure for transit to port					
			Wireline log: triple combo/FMS-sonic/GHMT	22.25			0.9	3.9
Honolulu	21°30'N, 158°W		Transit 2487 nmi f/SHAT-3 to Honolulu @ 10.5 kt	237.00	9.9			
			SUBTOTAL:		**16.4**	**32.2**	**3.4**	**35.6**
			TOTAL OPERATING DAYS (w/ 5 day port call):		**57.0**			

Table 2. Leg 198 - Shatsky Rise

Alternate Operations Plan and Time Estimate

Site	Location (Lat/Long)	Water Depth (mbrf)	Operations Description (mbsf)	(hr)	Transit (days)	Drilling (days)	Logging (days)	Total On-site (days)
Yokohama	35.5° N, 139.7° E		Transit 1116 nmi f/Yokohama to SHAT-5C @ 10.5 kt	106.25	4.4			
SHAT-5C	37°47.729'N	3123	Hole A: APC to refusal (~200 m), XCB to ~555 mbsf	110.00		4.6		
	162°45.053'E		Hole B: APC to ~200 mbsf, XCB/MDCB to ~555 mbsf	160.25		6.7		
			Note: Core 155 m with MDCB (4.5 m cores)					
			Wireline log: triple combo/FMS-sonic/GHMT	28.00			1.2	12.5
			Transit 166 nmi from SHAT-5C to SHAT-11 @ 10.5 kt	15.75	0.7			
SHAT-11	36°27.601'N	4818	Hole A: APC to refusal (~180 mbsf)	40.00		1.6		
(alternate)	160°16.955'E		Hole B: APC to ~180 mbsf	37.25		1.6		3.2
			Transit 95 nmi from SHAT-11 to SHAT-4 @ 10.5 kt	9.00	0.4			
SHAT-4	36°7.629'N	3318	Hole A: APC to refusal (~200 mbsf)	35.00		1.5		
	158°12.094'E		Hole B: APC to ~200 mbsf	32.25		1.3		2.8
			Transit 66 nmi from SHAT-4 to SHAT-7 @ 10.5 kt	6.25	0.3			
SHAT-7	37°9.900'N	4143	Hole A: APC to refusal (~175 mbsf)	37.25		1.6		
(alternate)	158°40.529'E		Hole B: APC to ~175 mbsf	34.50		1.4		3.0
			Transit 271 nmi from SHAT-7 to SHAT-1 @ 10.5 kt	25.75	1.1			
SHAT-1	32°39.099'N	2418	Hole A: APC to refusal (~200 mbsf), XCB to 300 mbsf	44.50		1.9		
(modified)	158°30.357'E		Hole B: APC to ~200 mbsf, XCB to 300 mbsf	47.25		2.0		
			Wireline log: triple combo/FMS-sonic/GHMT	26.50			1.1	5.0
			Transit 32 nmi from SHAT-1 to SHAT-2B @ 10.5 kt	3.00	0.1			
SHAT-2B	32°6.865'N	2782	Hole A: APC to refusal (~200 mbsf), XCB to ~240 mbsf	39.00		1.7		
(modified)	158°3.030'E		Hole B: APC to ~200 mbsf, XCB to ~240 mbsf	41.75		1.7		
			Wireline log: triple combo/FMS-sonic/GHMT	26.50		1.1		4.5
			Transit 52 nmi from SHAT-2B to SHAT-3 @ 10.5 kt	5.00	0.2			
SHAT-3	31°34.641'N	3881	Hole A: APC to refusal (~70 mbsf)	20.25		0.8		
(modified)	157°17.862'E		Hole B: APC to ~70 mbsf, NDT inspect BHA	21.50		0.9		1.7
			Transit 9 nmi from SHAT-3 to SHAT-14 @ 10.5 kt	1.00	0.1			
SHAT-14	31°25.51'N	4340	Hole A: RCB to 100 mbsf (50 m into basement)	37.0		1.5		
(alternate)	157°15.43'E		Lay out BHA/DC/secure for transit to port					1.5
Honolulu	21°30'N, 158°W		Transit 2485 nmi f/SHAT-14 to Honolulu @ 10.5 kt	236.50	9.9			

SUBTOTAL:		17.2	31.9	2.3	34.2
TOTAL OPERATING DAYS (w/ 5 day port call):		56.4			

TABLE 3

THICKNESSES AND VELOCITIES OF SHATSKY SEQUENCES

SEQ.	AGE	Interval Velocity km/sec*	Site 305 (Est.)	Site 305 (Act.)	SHAT 1	2B	3	4	5C	6	7	8	9B	10	11	12	13	14
					Thickness (m)													
1	Neogene																	
2	Paleogene	1.65	82.5	130	110	100	70	165	66	75	103	62	153	188	120	100	143	50
3	Con-Maa	2.2	286	206	385	275		110	303	193	154	105	176		138	83		
4	Apt-Cen	2.8	329	284	280	322	140	105	203	42	42	210	210		245	168		
5	Tith-Barr	3.1			372	186	390	405	426		186	310	264		543	217		
	Basement				200	200	200	200	200	200	200	200	200	200	200	200	200	200
	TOTAL				**1347**	**1083**	**800**	**985**	**1198**	**510**	**685**	**887**	**1003**	**388**	**1246**	**768**	**343**	**250**

Notes: * = velocity estimates from Sites 305 and 306 (see *Initial Reports* DSDP Volume 32, pages 88, 166), Site 305 estimates using indicated interval velocities; actual Site 305 intervals are based on interpreted seismic reflectors. Sequences after Sliter and Brown (1993). All depths are in meters. SEQ. = sequence.