OCEAN DRILLING PROGRAM

LEG 154 SCIENTIFIC PROSPECTUS

CEARA RISE

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This Scientific Prospectus is based on pre-cruise JOIDES panel discussions. 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 Superintendent 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 Planning Committee and the Pollution Prevention and Safety Panel.

ABSTRACT

The Ceara Rise in the western equatorial Atlantic provides an ideal target for constructing a bathymetric transect of drill sites. The Ceara Rise is located in the main flow path of the two principal water masses in the oceans. Mixing between these water masses creates the initial chemical and physical properties for deep water in the eastern basins of the Atlantic and for the Indian and Pacific oceans. Therefore it is imperative to understand the history of deep water circulation and chemistry in this region in order to evaluate the changes in deep water chemistry and carbonate preservation that are observed in other ocean basins.

The objective of Leg 154 will be to construct a transect of coring sites distributed down the northeastern flank of Ceara Rise from 2901 m to 4373 m. Several questions of paleoceanographic significance can be addressed by a depth transect of this type:

1. What was the history of deep water flow in the Atlantic during the Cenozoic? What has been the relationship between deep water circulation, chemistry, and Earth's climate?
2. What was the history of carbonate production and dissolution in the equatorial Atlantic during the Cenozoic? How have changes in carbonate production and dissolution been affected by changes in deep circulation and in Earth's climate?
3. What has been the Cenozoic history of surface water and climate in the tropics? How have the $\delta^{13}C$ of nutrient-depleted surface water and oceanic $\Delta\delta^{13}C$ varied throughout the Cenozoic?

The five highest priority sites will produce a late Cenozoic depth transect down the northeastern flank of Ceara Rise. In addition, three of these sites will sample the Paleogene sediment column at present water depths of 3037 m, 3602 m, and 4373 m.

INTRODUCTION

During the last several years, a coring and drilling strategy has been employed by the Ocean Drilling Program to recover bathymetric transects of Advanced Piston Cores (APC) and Extended Core Barrel (XCB) cores in order to reconstruct the Cenozoic history of deep water chemistry, carbonate production and dissolution, and deep water circulation. This strategy has followed a successful research strategy used for the reconstruction of late Quaternary deep water chemistry and sedimentation history (Johnson, 1984; Curry and Lohmann, 1982, 1983, 1985, 1986, 1990; Peterson and Prell, 1985a, 1985b; Jones et al., 1984; Farrell and Prell, 1989, for example) and for pioneering Deep Sea Drilling Project (DSDP) transects for reconstructing Neogene and Paleogene sedimentation history (e.g., DSDP Leg 74). The research strategy invokes the basic assumption that the principal source of carbonate in the sediments is from surface water production, with little or no downslope or lateral input. If this assumption is true, then carbonate accumulation in the shallowest sites, if they are always above the lysocline, approximates the carbonate productivity of the overlying surface water. If the sites are located close together, and not near any sharp regional gradients in productivity, then the input rate of carbonate in all sites in the bathymetric transect should be equal. Then the difference in carbonate accumulation between shallow and deep sites is a quantitative indicator of the amount of carbonate lost to dissolution. With similar bathymetric transects, gradients in deep water chemistry can be reconstructed from the chemistry of benthic foraminiferal shells. Since water masses vary in three dimensions, the bathymetric distribution of water mass properties contains fundamental information about the geometric relationships and mixing between water masses of different origin. Thus, from a single suite of cores located on the slopes of an aseismic rise, past changes in productivity, dissolution and mixing of deep water can be determined. To date, this bathymetric sampling strategy has been used with success on ODP Leg 108 (eastern equatorial Atlantic), Leg 113 (Maud Rise, subantarctic region), Leg 115 (Madingley Rise, equatorial Indian Ocean), Leg 117 (Owen Ridge, Arabian Sea), Leg 130 (Ontong Java Plateau, western equatorial Pacific), and Leg 145 (Detroit Seamount).

The purpose of Leg 154 is to sample an additional bathymetric transect in the western equatorial Atlantic at the Ceara Rise (Figure 1) in order to fully evaluate the Cenozoic history of deep water circulation and chemistry. Deep water circulation in the Atlantic (and to a great extent in the world ocean) is controlled by the mixing between deep water masses in the western basins of the South Atlantic and southern ocean. The Atlantic contains the source regions for the two major water masses in the deep oceans today, and in the past this ocean probably contained the source area for at least one of the principal water masses. It is the mixing between water masses in the South Atlantic and southern ocean that produces the initial chemical and physical characteristics of the deep water that flows through the Indian Ocean and into the Pacific. Thus no reconstruction of Cenozoic deep water circulation and chemistry can be complete without a full understanding of the history of deep water circulation in the western Atlantic. On the basis of location, present oceanographic setting, and continuity of high sedimentation rates, the Ceara Rise probably provides the best target location for reconstructing this paleoceanographic history.

SCIENTIFIC RATIONALE

Neogene

Several important scientific objectives can be achieved through drilling on Ceara Rise. Sedimentation since the Miocene has been nearly continuous and with a relatively high sedimentation rate. Because of its position in the western equatorial Atlantic, in the mixing zone between North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW), Ceara Rise provides an ideal target for reconstructing the Neogene history of deep water circulation and carbonate dissolution. The rapid changes in climate during this interval produced significant changes in deep water chemistry and circulation, which in turn produced significant feedbacks for atmospheric chemistry and climate.

Pliocene-Pleistocene. Deep water circulation during the latest Quaternary is linked to and provides an important amplification to climate change. During glacial maxima, transfer of the ocean's dissolved carbon and nutrients from intermediate depths to the deep ocean provide a mechanism for reducing the pCO_2 of the surface ocean and atmosphere (Boyle, 1988). These changes in ocean chemistry are linked to changes in the production rate and depth distribution of deep water in the North Atlantic (Boyle and Keigwin, 1987) and to changes in the intensity and distribution of carbonate dissolution in the oceans (Boyle, 1988). While the history of deep water circulation is well-known for the last glacial-interglacial cycle, for older sediments the spatial coverage of data is limited. The Ceara Rise will provide significant new information about the Plio-Pleistocene history of deep water circulation because of its strategic location in the present mixing zone of NADW and AABW. The depth profile we are attempting to establish will also quantify the extent to which depth redistribution of nutrients and carbon is common to glaciations earlier in the Pleistocene or the Pliocene. On the basis of the sediments recovered at DSDP Site 354, it is likely that sedimentation has been continuous at all depths on the rise since the late Miocene. With judicious site selection, it is likely that high resolution studies over the whole depth range can be extended back to at least 6 Ma.

Miocene. The presence of a large hiatus in the middle and late Miocene throughout much of the Atlantic (and at Site 354) has made reconstructing deep water circulation and chemistry very difficult for this period of time. Given the important climatological changes occurring then, large changes in deep water circulation and chemistry were likely occurring as well. Careful drilling should reveal the extent to which erosion, as opposed to dissolution, has contributed to the reported hiatus.

Several competing hypotheses (summarized by Wright et al., 1992) about Miocene deep water circulation generally agree that deep water was produced in the northern Atlantic by the late middle Miocene, but differ as regards the timing of the initiation of northern component water mass. Miller and Fairbanks (1985) placed the initiation within the Oligocene; Blanc et al. (1980), Schnitker (1980) and Woodruff and Savin (1989) placed the initiation in the middle Miocene. Schnitker (1980) proposed that the flux of heat to the southern ocean by northern component deep water triggered an increase in the moisture flux to Antarctica and subsequently an increase in ice growth. Woodruff and Savin (1989) suggested that the closing of the Tethys resulted in a heat loss to Antarctica that triggered the glaciation. They concluded that early Miocene deep water circulation was dominated by water masses of southern and Tethyan origin and that there was little evidence for deep water production in the North Atlantic prior to 12 Ma.

Ceara Rise offers an opportunity to assess these competing hypotheses because it is located in the mixing zone between southern and northern deep water masses. Also its bathymetric range optimizes the chances of finding a complete Miocene section for the Atlantic, given the possibility that erosion caused by changes in deep water circulation is likely to be depth dependent. Thus there may be locations on Ceara Rise with more complete Miocene sections than elsewhere in the North Atlantic. The drilling strategy of Leg 154 has been focused on increasing the likelihood of coring a quality middle Miocene section in this region. Results from the site survey suggest that the Miocene section preserved on top of the rise may be 100 m thicker than observed at Site 357.

Paleogene

Because of its age and sedimentary characteristics, Ceara Rise also provides one of the best target areas for drilling a Paleogene depth transect with nearly complete recovery. DSDP Leg 74 was the first cruise designed as a depth transect on an aseismic ridge. Despite having been drilled with a primitive version of the APC and without the XCB, this leg achieved remarkable successes. Although the principle has been used in the design of several legs since then (especially Leg 130) no low latitude Paleogene transect has been drilled. The absence of cherts (at least at Site 354) makes the Ceara Rise a very good target for this objective. Several stratigraphic intervals of special interest deserve mention. In addition it is important to note that even a single continuously cored site in this region will be immensely valuable. At present some of the best material available for examining the temperature history of the low latitudes is from rotary cored material from DSDP Leg 17. Nearly all low latitude targets are plagued by chert so that continuous records are very scarce.

Biolzi (1985) has made detailed isotope measurements from a spot core at 520 mbsf at Site 354 showing that at least to this depth a good isotope record is preserved; experience suggests that even if it becomes more difficult to clean the specimens it should be possible to obtain a good isotope record for the whole section. Furthermore a very important lesson learned from Leg 74 was that in order to compile a good continuous record for the whole Cenozoic it is almost certainly necessary to attempt continuous records at several water depths. It is clear, for example, that at Site 354 (4052 m) there is one hiatus in the Miocene (7-15 Ma; Figure 2) and one in the Eocene (38-45 Ma; Figure 2), and there may well be other hiatuses that the discontinuous drilling at Site 354 (13% recovery of the section penetrated) cannot resolve. If these hiatuses are associated with erosional events, they are probably associated with particular water depths; by drilling continuous records at several water depths we will not only learn about the circulation changes that gave rise to the hiatuses, but we will also be able to piece together a continuous low latitude surface water history.

The chemistry and productivity conditions of the Paleogene ocean underwent enormous change as indicated, for example, by the single largest Cenozoic deepening of the carbonate compensation depth (CCD) close to the Eocene/Oligocene boundary. CCD variations are intimately linked to the global carbon cycle and the exchange of carbon dioxide between four major reservoirs: the atmosphere, the ocean, the carbonate bearing deep sea sediments, and the mantle. The rationale for drilling depth transects at locations such as the Ceara Rise is strongly rooted in the perception that quantification of sediment budgets as a function of water depth and time is necessary in order to establish realistic models of the interaction of the ocean-climate-sediment system. Pelagic seafloor carbonate constitutes well over 50% of all oceanic sediments, and the interplay between biogenic carbonate production and flux on the one hand and carbonate dissolution at the seafloor on the other, is therefore of critical importance for the global carbon cycle. Meaningful reconstructions of depth- and time-dependent carbonate budget variations can be addressed only through drilling depth transects in small geographic areas in order to ensure a similar pelagic input along the transect and to capture the depth dependent dissolution at any given time. Except for an early campaign in the southeastern Atlantic (DSDP Leg 74) no ocean drilling has been focused on Paleogene depth transects.

Eocene-Oligocene. The Eocene/Oligocene boundary is of particular interest because there is good evidence for a deep water cooling of several degrees, perhaps associated with some significant accumulation of ice on Antarctica. It is likely that this was associated with a major reorganization of ocean deep and intermediate circulation, but without a depth transect it is difficult to evaluate the nature of this change. Indeed,a high quality, low latitude planktonic isotope record will be of great value for testing competing interpretations of the isotope record derived from benthonic species. The drastic Eocene/Oligocene boundary event was followed by several brief Oligocene episodes of probable continental ice sheet formation on Antarctica. The forcing mechanism behind the Eocene/Oligocene event is largely unknown, although thermal isolation of Antarctica caused by plate tectonic reorganization has been proposed. This event and the subsequent Oligocene pulses of climate variability are presently thought to mark the beginning of the transition into the Cenozoic ice house world. A chief component in any attempt to understand the nature of this transition will be to distinguish high latitude ice growth from temperature change in the isotopic records, which requires access to high quality low latitude oxygen isotopes derived from both planktonic and benthonic foraminifers. Such isotope data will be of immense value also for understanding the possible ice volume connection of the sea level coastal onlap and offlap record during the later

Paleogene. Moreover, low latitude isotope records will be crucial for characterizing the higher frequency variability of Paleogene climate, in the Milankovitch band, which is essential for understanding the feedback mechanisms of Paleogene insolation cycles as well as for satisfying the strong need for improved Paleogene chronologic resolution.

Paleocene-Eocene. The Paleocene/Eocene boundary represents possibly the most interesting paleoceanographic episode accessible to study in the whole Cenozoic (e.g., Rea et al., 1990, and recent ODP Leg 113 data). There is good evidence that this is an episode where tectonic and volcanic forcing on climatic and paleoceanographic change can be identified. There is convincing evidence for an interval where deep water production was dominated by warm salty bottom water (Kennett and Stott, 1991). The lowermost Eocene had a remarkably small latitudinal temperature gradient. It was a time of maximum Cenozoic warmth, when high latitudes experienced mean annual sea-surface temperatures (SSTs) in excess of 15° to 17°C, and deep ocean temperatures as high as 12°C, but only a small temperature increase near the equator. The cause of the early Eocene warming is not known. The Paleocene/Eocene boundary interval is also accompanied by the largest benthic extinction event on a global scale in the Cenozoic, and the most important benthic foraminiferal event since the Cenomanian/Turonian boundary at 90 Ma. The latest Paleocene benthic extinction occurred precisely during the single largest shift in oceanic $\delta^{13}C$ values, a rapid decrease of about 2.5‰, suggesting major changes in the physical and chemical states of the ocean and atmosphere.

Drilling the Paleocene/Eocene interval on the Ceara Rise will provide the opportunity to evaluate several aspects of this event(s). A shallow site may represent a paleodepth close to sea level in the Maastrichtian if the estimated paleodepth of 1000 m for the Maastrichtian at Site 354 (present depth: 4052 m) is correct. Thus there is a chance that the shallowest of the Ceara Rise sites (CR1) will enable us to sample intermediate waters at the time of the Paleocene/Eocene transition. On the Maud Rise, Kennett and Stott (1991) have suggested that there was a temperature inversion with cooler intermediate waters of lower salinity overlying warmer deep waters. It would be very interesting to see the vertical profile of nutrients and dissolved oxygen as reconstructed from carbon isotope and Cd/Ca measurements in the benthic foraminifers at low latitudes in such an ocean. The Ceara Rise is a much better opportunity than the Sierra Leone Rise for this purpose because on the Sierra Leone Rise cherts are present from the middle Eocene down, and the Paleocene/Eocene boundary is in limestone. At Site 354 chert was not encountered, and the entire section is unlithified.

The biostratigraphic resolution offered from Site 354 is low, yet it is suggestive of continuous sedimentation at a useful accumulation rate (1 cm/k.y.) in the latest Paleocene to middle Eocene interval (58-46 Ma) (Figure 2). In particular the biostratigraphic control in the very critical Paleocene/Eocene transition interval is sufficiently good to suggest that useful accumulation rates began ca. 1 Ma before the latest Paleocene benthic extinction and the accompanying decrease in $\delta^{13}C$. These sedimentation rates continue unbroken through the peak of the early Eocene warming and beyond to anomaly 20 in the middle Eocene. This unit ends at a distinct hiatus, inferred to have begun at about 46 Ma in the middle middle Eocene and to have terminated at 38 Ma in the middle late Eocene.

STUDY AREA: CEARA RISE

Oceanographic Setting

Deep Water. Because of westward intensification of deep water circulation, the western basin of the Atlantic provides the principal conduit for the flow of northern and southern sources of deep water. Today these water masses meet and mix in a broad zone that extends from the South Atlantic to the equatorial regions of the North Atlantic. The mixing zone between northern-source deep water (NADW) and southern-source deep water (AABW) is at 4000 m in the Ceara Rise region. Today this depth marks a large gradient in deep water chemistry that controls the dissolution of calcium carbonate in the western basin. The position of this mixing zone also affects the chemistry of deep water in the eastern Atlantic because it is deep water from the western basins that ventilates the eastern basins. Today deep water in eastern basins originates in the western basins and enters the east through low-latitude fracture zones. Flow across two fracture zones provides most of the deep water to the eastern basins: the Romanche fracture zone at the equator (Metcalf et al., 1964) and the Vema fracture zone at about 10°N (M. McCartney, pers. comm.). The sill depths for these fracture zones are close to 4000 m (the depth of the mixing zone), so small changes in the relative intensity of northern- and southern-source deep waters can have a large effect on the initial chemical composition of deep water which enters the eastern basins and on the preservation of calcium carbonate in the eastern Atlantic.

Today the mixing zone between NADW and AABW is mostly below the sill depth of the fracture zones, so the deep water entering and filling the eastern Atlantic below 3750 m is a mixture of 80% NADW and 20% AABW (Figure 3). Because it is dominated by NADW, the eastern deep water is warmer, saltier and less corrosive to carbonate than deep water at the same depths in the western Atlantic. But small changes in the depth of the mixing zone in the western basin would produce large changes in the chemical and physical properties of the deep water in the eastern Atlantic. Mixing between NADW and AABW today also affects the initial chemical and physical composition of the deep water that enters the Indian and Pacific oceans. Previous studies have shown that the relative proportion of northern-source deep water decreased during the last glaciation, resulting in a lower $\delta^{13}C$ in southern ocean deep water (Oppo and Fairbanks, 1987; Curry et al., 1988; Charles and Fairbanks, 1992). Thus the $\delta^{13}C$ composition of the deep water that entered the Indian and Pacific oceans was lowered at that time.

Surface Water. The Ceara Rise is located in the western equatorial Atlantic beneath a surface water pool that exhibits little annual variation in temperature. Surface water temperatures generally exceed 27°C. On glacial-interglacial time scales, CLIMAP (1976) has suggested that surface water cooling in this region was small, less than 2°C. Because this pool is located on the western side of the Atlantic, it is less affected by annual or glacial-interglacial variations in upwelling; therefore the nutrient concentration of the surface water mixed layer is always low (Curry and Crowley, 1987). Thus, a surface water $\delta^{13}C$ record from this location should be an ideal representation of the Cenozoic history of nutrient-depleted $\delta^{13}C$ and $\Delta\delta^{13}C$ (e.g., Shackleton and Pisias, 1985; Curry and Crowley, 1987). Because of the low variability in surface water temperature caused by upwelling, this location will also be ideal for reconstructing the history of Cenozoic surface water temperature changes caused by global, rather than local, changes in climate.

Marine Geologic Setting

The Ceara Rise is an aseismic feature that formed at the Mid-Atlantic Ridge about 80 Ma. Along with its conjugate, the Sierra Leone Rise in the eastern equatorial Atlantic, the Ceara Rise reaches a minimum depth of about 2700 m. It is surrounded by seafloor with an average depth of about 4500 m. The Ceara Rise is draped with a thick sequence (1000 m) of undisturbed lithogenic and biogenic sediments (Supko, Perch-Nielsen, et al., 1977). DSDP Site 354 was located on the northern flank of the Ceara Rise at a depth of about 4000 m. Although only spot cored, a generalized history of the area was reconstructed from this investigation.

Bathymetry and Physiographic Setting

The rise consists of a series of platform-shaped shoals oriented in a NW-SE direction (Figure 4). The platform tops of the rise reach about 3200 m below sea level, but are punctuated with small, sedimented features that reach minimum depths of about 2800 m. The shallowest portions of Ceara Rise are located in the southern half of our survey area. In two areas (4°30′ 43°40′W and 4°20′N 43°30′W), shallowest depths are 3000 m and appear to be well-sedimented targets for APC drilling. One shallow pinnacle reached a depth of 2600 m, but had little evidence for sediment accumulation on its peak or steep slopes.

Ceara Rise is an asymmetric feature in cross section (Figure 4). Slopes along the SW side exceed 5.7°, while those on the NE side are much gentler, ca. 1.4°. Ceara Rise is bounded on the NE by the Ceara Abyssal Plain and on the SW by the Amazon Fan. The Amazon Fan deposits are flat-lying and lap onto the downfaulted base of Ceara Rise at about 4100 m water depth. The seismic profiles in this area demonstrate that much of the rise on the SW side is covered by fan deposits. The abyssal plain to the NE is deeper, 4500 to 4700 m, and exhibits topographic features and surface roughness that may be associated with strong bottom currents.

Seismic Stratigraphy

Five mappable reflectors within the sediment column (Figure 5) can be identified. Reflectors Blue and Purple divide the sediments into three acoustic units; Reflectors Red, Yellow and Orange subdivide each of these units, respectively. From top down the general features of these three units are: 1) seafloor to Blue is acoustically stratified, predominantly internally conformable; 2) Blue to Purple is pervasively hummocky without lateral continuity of reflectors; and 3) Purple to basement is stratified and onlapping.

Regional Sedimentation Rates

Sedimentation rates exhibit large regional and glacial-interglacial changes that result from variations in the input of detrital components from the Amazon Cone (Figure 6). The large input of terrigenous material on the northern Ceara Rise increases sedimentation rates to about 5 cm/k.y. Toward the south, the proportion of Amazon Cone material decreases; here, sedimentation rates are usually between 3 and 4 cm/k.y.. In addition there is a strong glacial-interglacial signal in the sedimentation rates because of increased Amazon input during lowered sea level. During the Holocene (0-12 ka) sedimentation rates averaged 1.5-2 cm/k.y., but increased to about 5 cm/k.y.

during glacial stage 2 (12-24 ka). During the interglacial, sedimentation rates did not exhibit any significant changes with depth in the water column; during the glaciation a small decrease with depth is apparent, even though the noncarbonate sedimentation rate increases with water depth.

On the basis of sedimentation rates it is likely that an excellent late Neogene depth transect can be obtained from the northeastern flank of Ceara Rise. Sedimentation rates are high over wide areas and depths on the Ceara Rise. This section is suitable for APC coring down to the upper Miocene. The history of sedimentation in the region suggests that, if at all, the first hiatus will be encountered below about 240 m. Thus, a late Neogene depth transect should be mostly uninterrupted by hiatuses. The regional and bathymetric extent of the middle Miocene hiatus is still unclear.

Today and during the last glaciation, the CCD at Ceara Rise remained below 4500 m. This important oceanographic level has changed depth in both space and time. For example, from recent ODP sites in the eastern Atlantic (Leg 108, Site 665), we know that the CCD lowered sharply to below 4700 m at about 3.8 Ma (Ruddiman, Sarnthein, Baldauf, et al., 1988). Based on shallower ODP sites from Leg 108, it is clear that the CCD there was probably not shallower than 4500 m since the late Miocene. The carbonate record for Site 354 suggests that the CCD did not rise above 4000 m during much of the Cenozoic (Supko, Perch-Nielsen, et al., 1977). But McCoy and Zimmerman (1977) show that in much of the nearby South Atlantic, the CCD remained above or near 4000 m throughout most of the Cenozoic, and only recently (5 Ma) fell to below 4500 m. Thus it is likely that the CCD in the equatorial region of the western Atlantic may have been as shallow as 4000 m during parts of the Cenozoic, and that the spot coring of Site 354 missed significant variations in CCD depth.

SHIPBOARD SCIENCE STRATEGY

The work aboard ODP Leg 138 showed that it is possible to plan drilling and shipboard work so as to be able to document truly complete recovery of the stratigraphic section at each site before proceeding to the next, at least for the part of the section that can be cored with the APC. With high-resolution downhole logs and continuous data on cores (magnetic susceptibility, GRAPE density, color) we expect on Leg 154 to extend this capability through the Paleogene. Since the sites to be cored on Leg 154 are all in a rather small geographical area, we expect also to be able to demonstrate high resolution correlations between the sites using magnetostratigraphy, and high resolution biostratigraphy as well as core and downhole log data. Thus we will generate high precision age-depth profiles for all the sites.

The objective of the shipboard science will be to complete this high resolution stratigraphy to enable shipboard scientists to develop a thoughtful sampling strategy for post cruise-research. For example, the shipboard scientists will have the opportunity to focus on important events like the interval from about 1 Ma to 0.9 Ma, marking the onset of the 100 k.y. glacial cycles, or the major cooling event at about 2.6 Ma, or the marked 40 k.y. cycles between 1.5 and 1.2 Ma, and plan appropriate sampling strategy to investigate this event at all Leg 154 sites. Thus shore based science will be planned largely to exploit the depth transect that we will recover. Most of the actual sampling for these studies will be carried out on shore soon after the completion of the leg.

The sediments of the Ceara Rise should also contain excellent records of biological evolution in the tropical ocean; of surface water temperature and chemistry; of the history of the intensity of the Earth's magnetic field; and of the long-term history of Amazon River input into the surface Atlantic. Studies of sediment diagenesis will help to reduce the biases inherent in long sedimentary records. Coring will be planned to ensure, inasmuch as possible, that the study of these important objectives are not hampered by a shortage of material. Triple cores will be taken at most sites to ensure that high resolution sampling (e.g. U-channels) can be carried out on the last hole, but even so we expect to exceed normal sampling density in some intervals of the earlier holes to ensure that we have sampled the section completely at high resolution. Overlapping sections of several holes will be merged to produce a composite depth section that will be used to guide the high resolution sampling. It will be in these overlapping sections of the earlier (A and B) holes that we will likely exceed ODP sampling guidelines.

DRILLING STRATEGY

Leg 154 will follow a drilling strategy that will result in a depth transect of APC, XCB and rotary cores for the sedimentary sequences deposited during the uppermost Cretaceous and Cenozoic sections of Ceara Rise. The present depths of our proposed drill sites range from 2901 to 4373 m. The sites are located at the most complete sections, with minimum distance separating the sites. They will be appropriate for several important limiting assumptions:

- that the input of carbonate is the same at each site, it originates in the photic zone of the upper ocean, and the principal method of delivery is from vertical settling processes;
- that loss of carbonate is only from dissolution; and
- that downslope reworking is minimized.

At least five drill sites are required to produce a depth transect that can reconstruct gradients in deep water properties in this region of the Atlantic Ocean. Because the mixing zone between water masses spans only several hundreds of meters (see Figure 3), it is necessary to have a depth spacing in the transect on the order of every 300 m to capture past changes in deep water mass geometry. The principal sites (CR-1 through CR-5) are located at about 3037, 3317, 3602, 4018 and 4373 m. Drilling to or near to basement (0.9 to 1.3 secs below the seafloor) will be performed in only two of these sites.

The goal of the drilling will be to obtain the most complete sections possible for the drilled intervals, thus each site will include triple, overlapping APC coring to refusal. Below APC depths, the choice of XCB or RCB will depend on the observed recovery while at sea because of limited time for drilling and because of conservative drilling time estimates. In the event of poor

Paleogene recovery, an alternative drilling strategy will obtain: increasing the number of drill sites at the expense of the total penetration at some of the sites. Thus the strategy may shift toward one with a larger number of sites, but penetration limited to 400-500 m.

Logging

A suite of logs has been chosen for Leg 154 which best serve the scientific objectives of the program. For the first site the suite of logging tool strings will consist of (1) the Quad Combination tool string, (2) the Geochemical tool string, (3) the Formation Microscanner (FMS), and (4) the GHMT (a new magnetic susceptibility tool string). The logging tools for the following sites will be selected depending on (1) their usefullness and scientific value at Site CR1, (2) time constrains, and (3) the depth of the hole.

PROPOSED SITES

Because of the basic shape of Ceara Rise, the drilling sites are located on the NE flank of the northern half of Ceara Rise. It is in this region that the shallowest topography and gentlest slopes are encountered. In Figure 7 and Table 1 the seven proposed drill sites are shown, five of which are high priority and form the Neogene depth transect, and three that form the Paleogene depth transect. The CCD is unusually deep at this location today, so it is necessary to have the transect span the entire depth range to 4373 m. The shallow depth sites will ensure that the sedimentary sections are mostly free of dissolution, while the deep sites will ensure that the full range of deep water chemical composition is sampled as well as provide a history of the highly variable depth of the CCD and lysocline.

In order to ensure that a complete, undissolved and undisturbed record of surface water conditions can be obtained, we anticipate coring several shallow sites. By combining the records from several sites, a complete record of surface conditions may be obtained, if hiatuses are of limited geographic or bathymetric extent. It will be necessary to offset APC cores vertically at each location to minimize sediment disturbance and loss between APC cores. At each of the sites, three holes will be cored in order to supply enough material for extensive biostratigraphic, sedimentologic, geochemical and paleomagnetic investigations. For the three sites in the Paleogene depth transect, extended core barrel (XCB) or rotary core barrel (RCB) drilling is anticipated to as deep as time permits. If sediment recovery is good, double XCB coring is an option.

Sediment Thickness

The seismic units are the same at each location, but vary in thickness (Figure 8). The primary sites for the depth transect exhibit a systematic decrease in sediment thickness from about 1350 m at the shallow location (CR1) to about 950 m at the deepest site (CR5). This systematic decrease in sediment thickness is the expected result of calcium carbonate dissolution and also a sign that downslope reworking has not significantly altered the sediment deposition patterns in this region. Otherwise, increasing sediment thickness downslope would be expected, especially if turbidite deposition was a major redistribution process in this area.

Since it will not be clear how successful deep drilling will be on Ceara Rise until the rise is actually drilled, there will be some flexibility for at-sea decisions about coring operations. For instance, if core recovery is poor in the deep Paleogene sections high resolution depth transect comparisons cannot be accomplished. In this case wise use of the drilling time would be to sacrifice two of the deep drilling objectives and add the time to alternate sites CR6 and CR7. This would enhance the objectives of the Neogene portion of the study, but only after it is clear that poor recovery prohibits meeting the Paleogene objectives.

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TABLE 1. SUMMARY SITE INFORMATION, LEG 154.

Site	Lat./Long.	Water Depth (m)	Seismic Profile	Sediment Depth TWT (s)	Sediment Thickness (m)
CR-1	04°13.79'N 43°27.94'W	3037	SP 3840 on Ew9209 Line 2	1.20	1300
CR-2	05°27.84'N 44°28.93'W	3317	SP 5250 on Ew9209 Line 4	0.33	950
CR-3	03°43.18'N 42°54.60'W	3602	SP 2880 on Ew9209 Line 17	0.90	1200
CR-4	05°27.26'N 43°44.98'W	4018	SP 2010 on Ew9209 Line 13	0.90	1000
CR-5	05°58.57'N 43°44.40'W	4373	SP 3880 on Ew9209 Line 9	0.90	950
CR-6	04°28.02'N 43°45.33'W	2901	SP 1390 on Ew9209 Line 4	0.90	950
CR-7	05°20.78'N 43°51.92'W	3853	SP 2570 on Ew9209 Line 13	0.90	950

TABLE 2. DRILLING AND TRANSIT TIME ESTIMATES, LEG 154.

Site	Priority	Drilling Option	Transit Time (days)[1]	Time on site (days)
Transit: Barbados to CR-1			4.1	
CR-1	1	APC Holes[2]		2.8
		APC/XCB/RCB Hole[3]		10.1
		Logging[3]		2.6
Transit: CR-1 to CR-5			0.4	
CR-5	1	APC/XCB/RCB Holes[4]		11.2
		Logging		2.0
Transit: CR-5 to CR-2			0.2	
CR-2	1	APC Holes[5]		4.6
		Logging		0.4
Transit: CR-2 to CR-4			0.2	
CR-4	1	APC Holes[5]		5.2
		Logging		0.5
Transit: CR-4 to CR-3			0.4	
CR-3	1	APC/XCB Holes[6]		7.3
		Logging		1.5
Transit: CR-3 to Recife			3.4	
Subtotal			8.7	48.2
Total				56.9 days

Contingency Sites

Site	Priority	Drilling Option	Transit Time (days)[1]	Time on site (days)
CR-6	2	APC Hole		4.5
		Logging		0.3
Total				4.8
CR-7	2	APC		5.0
		Logging		0.5
Total				5.5

1 Time estimate based on average ship speed of 11 kt.
2 Two oriented APC holes to 250 mbsf.
3 Oriented APC to 250 mbsf, change to XCB, drill to 600 mbsf. Hole will then be logged. RCB coring to 1300 mbsf until basement is reached. The second part of the hole will then be logged.
4 Two oriented APC holes to 250 mbsf, one APC/XCB/RCB hole to 950 mbsf.
5 Three oriented APC holes to 250 mbsf.
6 Two oriented APC holes to 250 mbsf. One oriented APC hole to 250 mbsf, then XCB to 600 mbsf.

FIGURE CAPTIONS

Figure 1. Location of the Ceara Rise in the Atlantic ocean. A detailed map of the marked area and the proposed drilling sites are shown in Figure 7. Bathymetry in meters.

Figure 2. Sedimentation rates at DSDP Site 354. The biostratigraphic levels are from Supko, Perch-Nielsen et al. (1977) with the chronology from Berggren et al. (1985).

Figure 3. Depth distribution of temperature (°C) and ΔCO_3 (Broecker and Takahashi, 1978) in GEOSECS stations from the western and eastern equatorial Atlantic. Open symbols are from GEOSECS 42, and closed symbols are from GEOSECS 111. Note that the rapid decrease in temperature that marks the presence of southern-source deep water (AABW) occurs today below the sill depth (4000 m) separating the western and eastern Atlantic. Today the deep water below the sill depth in the eastern Atlantic is warmer and less corrosive to carbonate than water at comparable depth in the western Atlantic. The chemical and physical composition of the deep water that enters the eastern Atlantic is very sensitive to changes in water mass geometry in the western basin. Past changes in the chemistry of eastern Atlantic deep water have occurred that are related to vertical migrations of the mixing zone between northern and southern sources of deep water (Oppo and Fairbanks, 1987; Curry et al., 1988).

Figure 4. Perspective view of Ceara Rise from the NW and SE which points out the steep slopes on the SW margin and gentle dips on the NE flank. The prominent platform tops of the rise are usually shallower than 3200 m. Several of these platforms have been selected for shallow coring sites. The deeper coring sites of the bathymetric transect fall on the gently sloping NE flank.

Figure 5. Typical seismic section for the NE slopes of Ceara Rise. The three mappable seismic units are found in varying thickness on the entire rise. In no location were erosional hiatuses observed that created windows to deeper drilling objectives.

Figure 6. Depth distribution of sedimentation rates for eight gravity cores on the eastern flank of Ceara Rise. During the Holocene, sedimentation rates were usually about 2 cm/k.y.. During

the glacial maximum, the sedimentation rates were higher because of increased detrital input from the Amazon Cone.

Figure 7. Location of seven coring and drilling targets for Ceara Rise. See Figure 1 for general location. Bathymetry in meters based on site survey results (RV Ewing 9209 Hydrosweep center beam).

Figure 8. Thinning of sedimentary section with respect to the shallow coring location CR1. In the deepest location (CR5) more than 25% of the sediment appears to be missing, probably as a result of carbonate dissolution. This relationship suggests that downslope reworking has not been a major problem in the locations that were chosen for drilling.

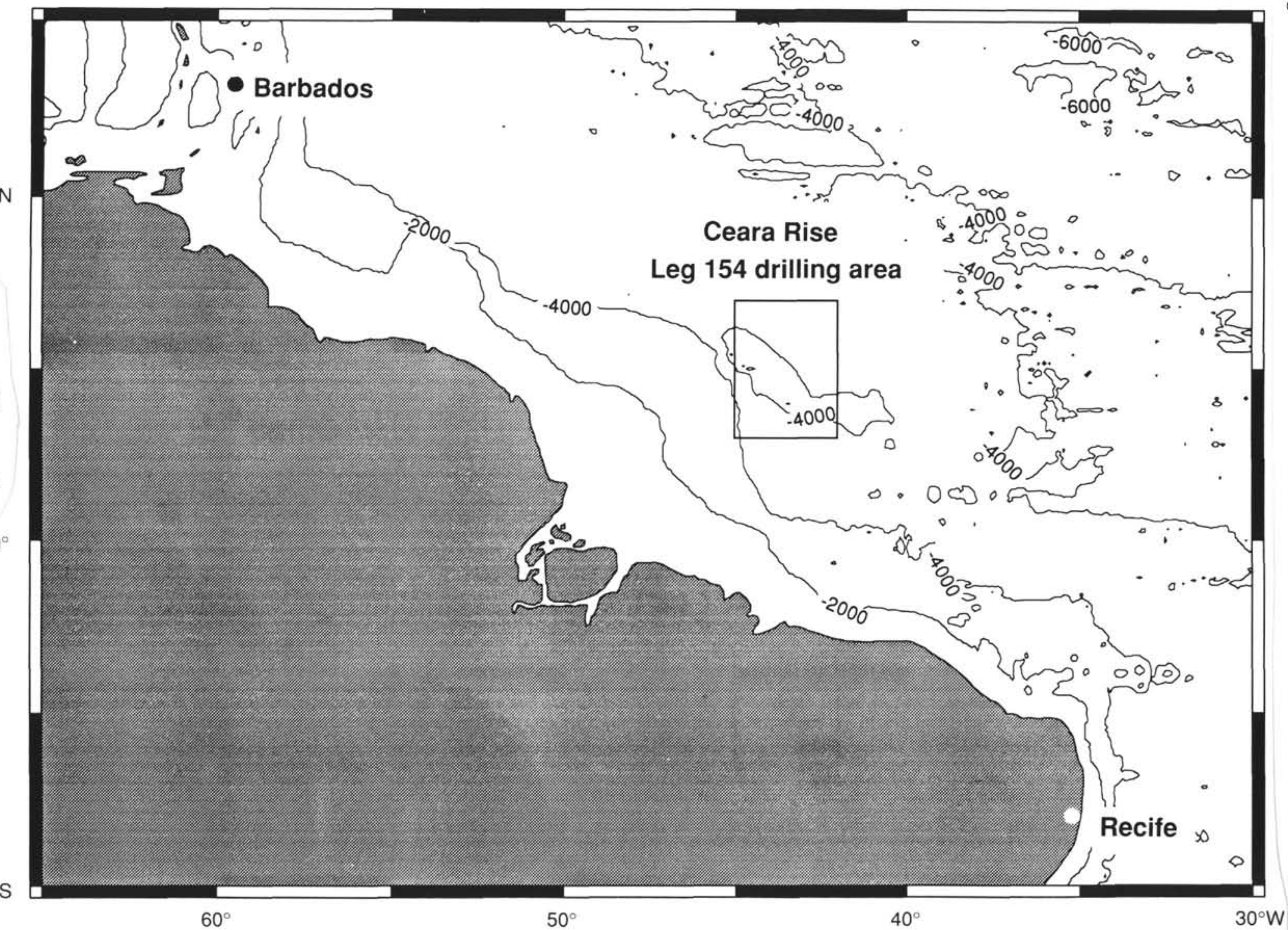

Barbados
Ceara Rise
Leg 154 drilling area
Recife
-2000
-4000
-6000
10°N
0°
10°S
60°
50°
40°
30°W

Figure 1

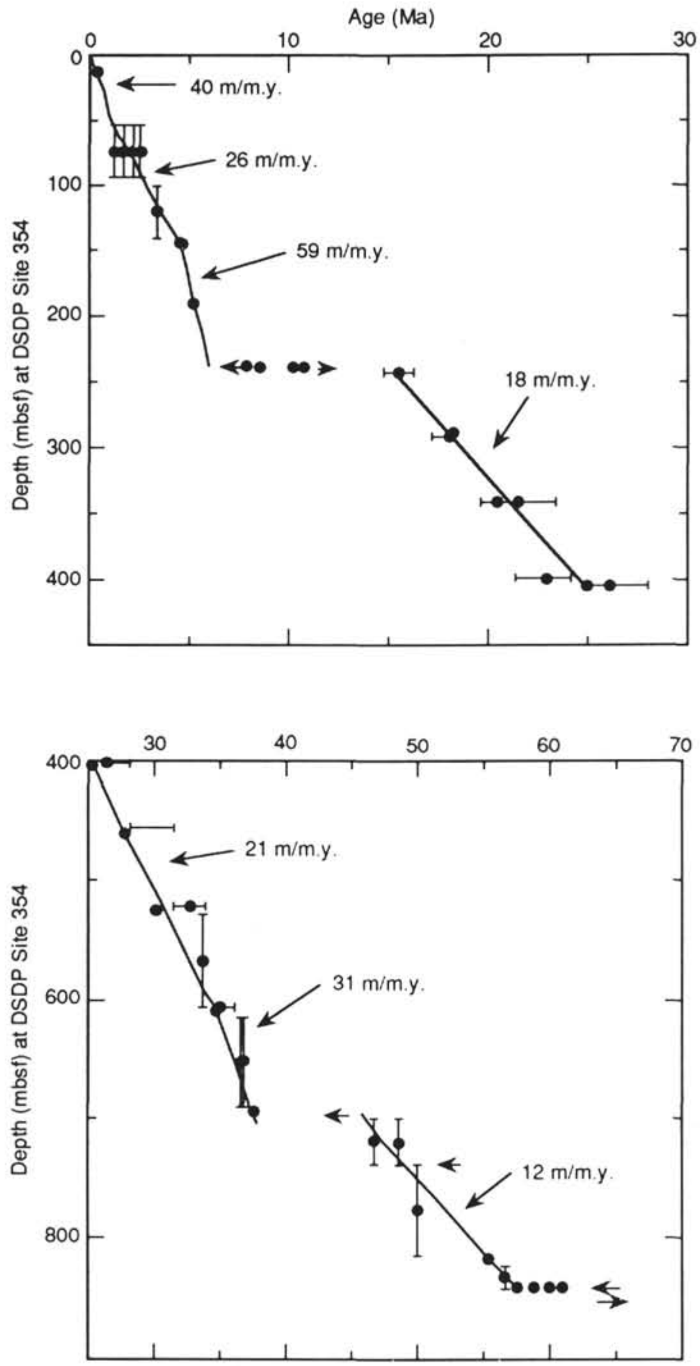

Age (Ma)
0
10
20
30
0
100
200
300
400
Depth (mbsf) at DSDP Site 354
40 m/m.y.
26 m/m.y.
59 m/m.y.
18 m/m.y.
30
40
50
60
70
400
600
800
Depth (mbsf) at DSDP Site 354
21 m/m.y.
31 m/m.y.
12 m/m.y.

Figure 2

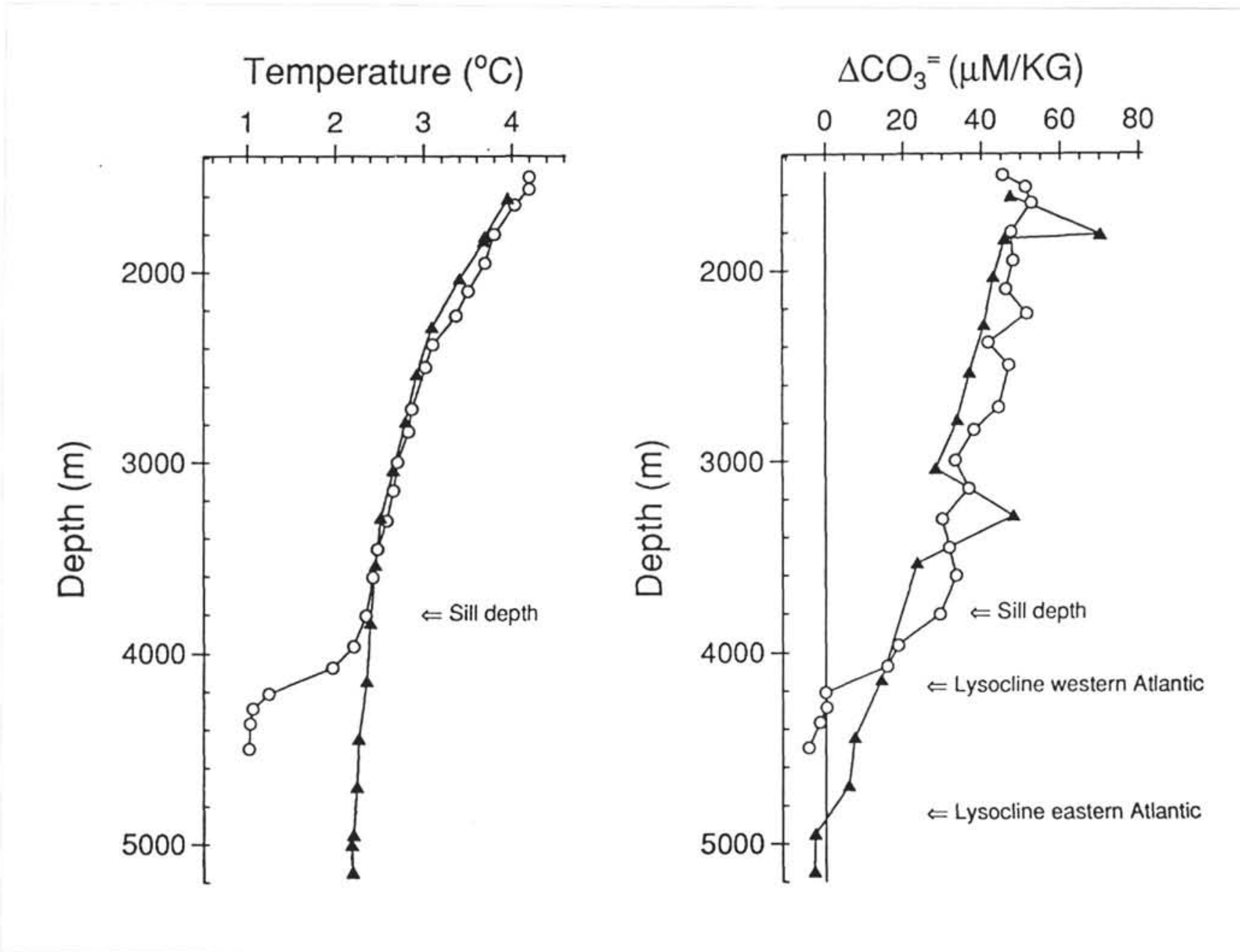

Temperature (°C)
1
2
3
4
Depth (m)
2000
3000
4000
5000
⇐ Sill depth
ΔCO3= (μM/KG)
0
20
40
60
80
Depth (m)
2000
3000
4000
5000
⇐ Sill depth
⇐ Lysocline western Atlantic
⇐ Lysocline eastern Atlantic

Figure 3

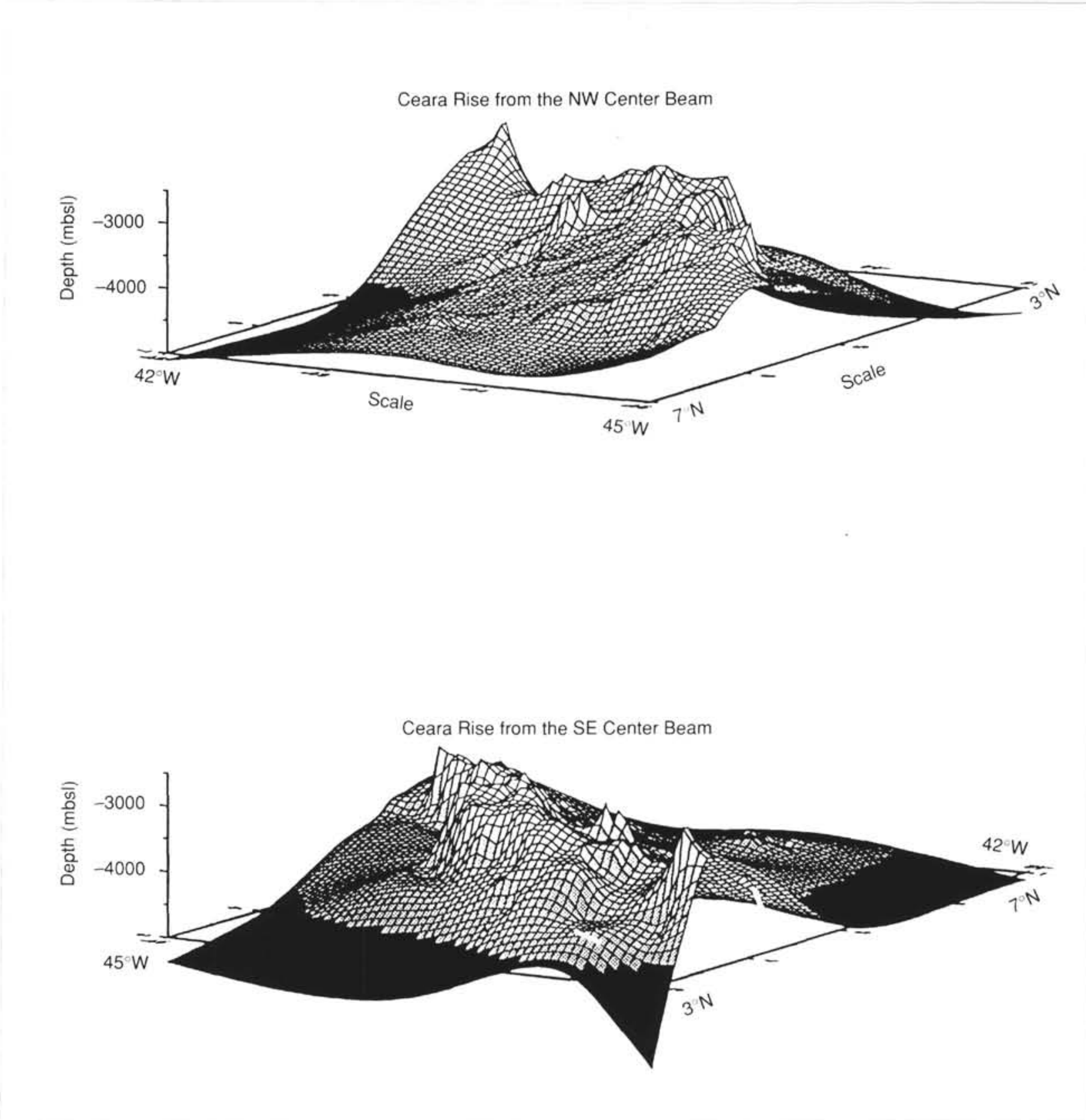

Ceara Rise from the NW Center Beam
Depth (mbsl)
-3000
-4000
42°W
Scale
45°W
7°N
Scale
3°N
Ceara Rise from the SE Center Beam
Depth (mbsl)
-3000
-4000
45°W
3°N
42°W
7°N

Figure 4

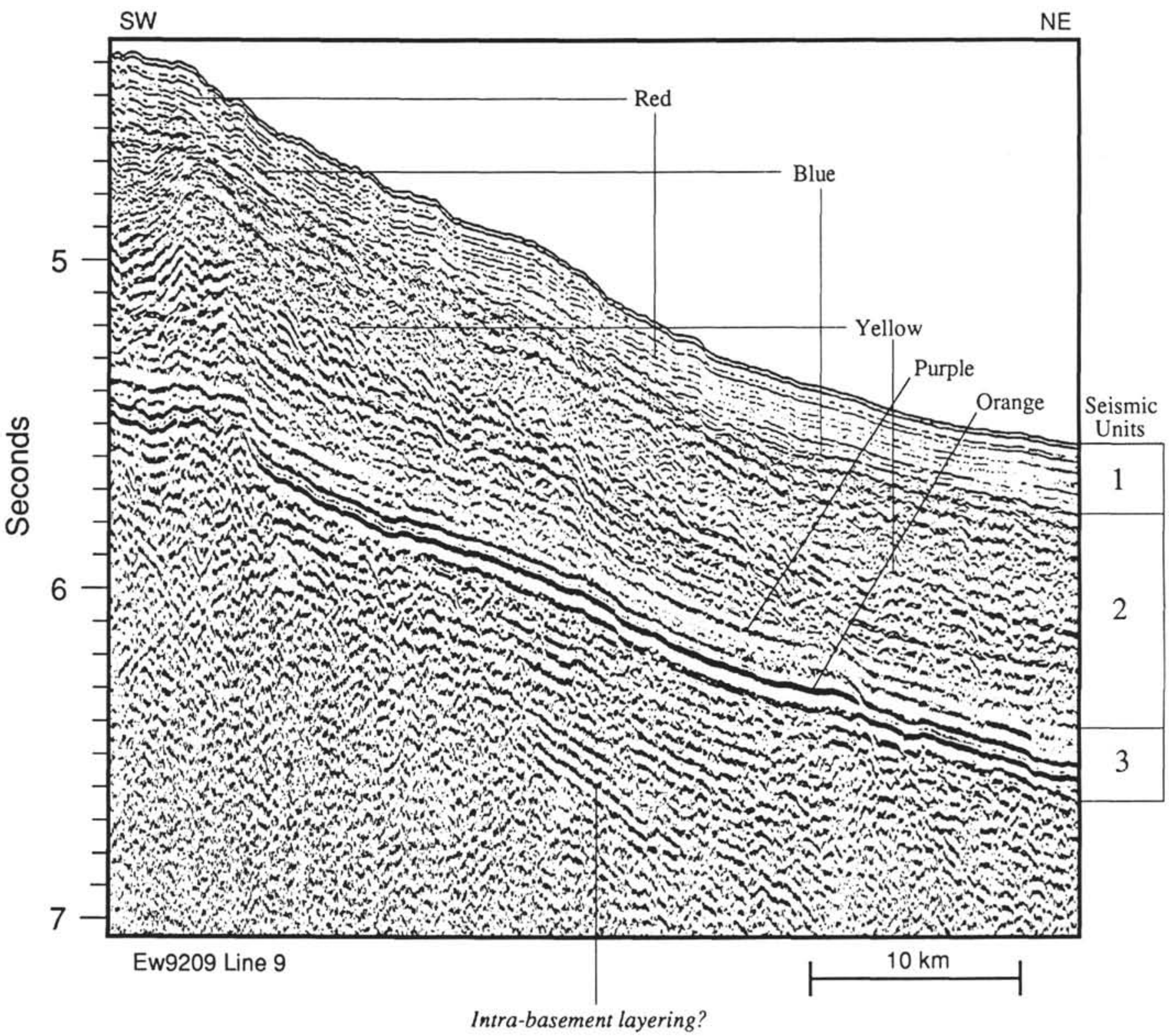

SW
NE
Red
Blue
Yellow
Purple
Orange
Seismic Units
1
2
3
5
6
7
Seconds
Ew9209 Line 9
10 km
Intra-basement layering?

Figure 5

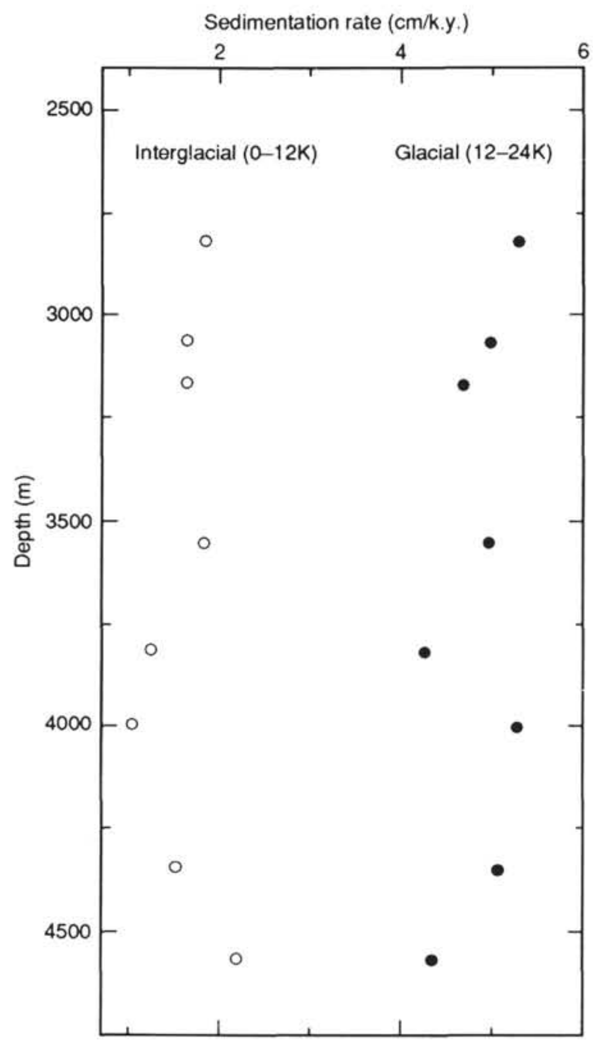

Sedimentation rate (cm/k.y.)
2
4
6
2500
3000
3500
4000
4500
Depth (m)
Interglacial (0–12K)
Glacial (12–24K)

Figure 6

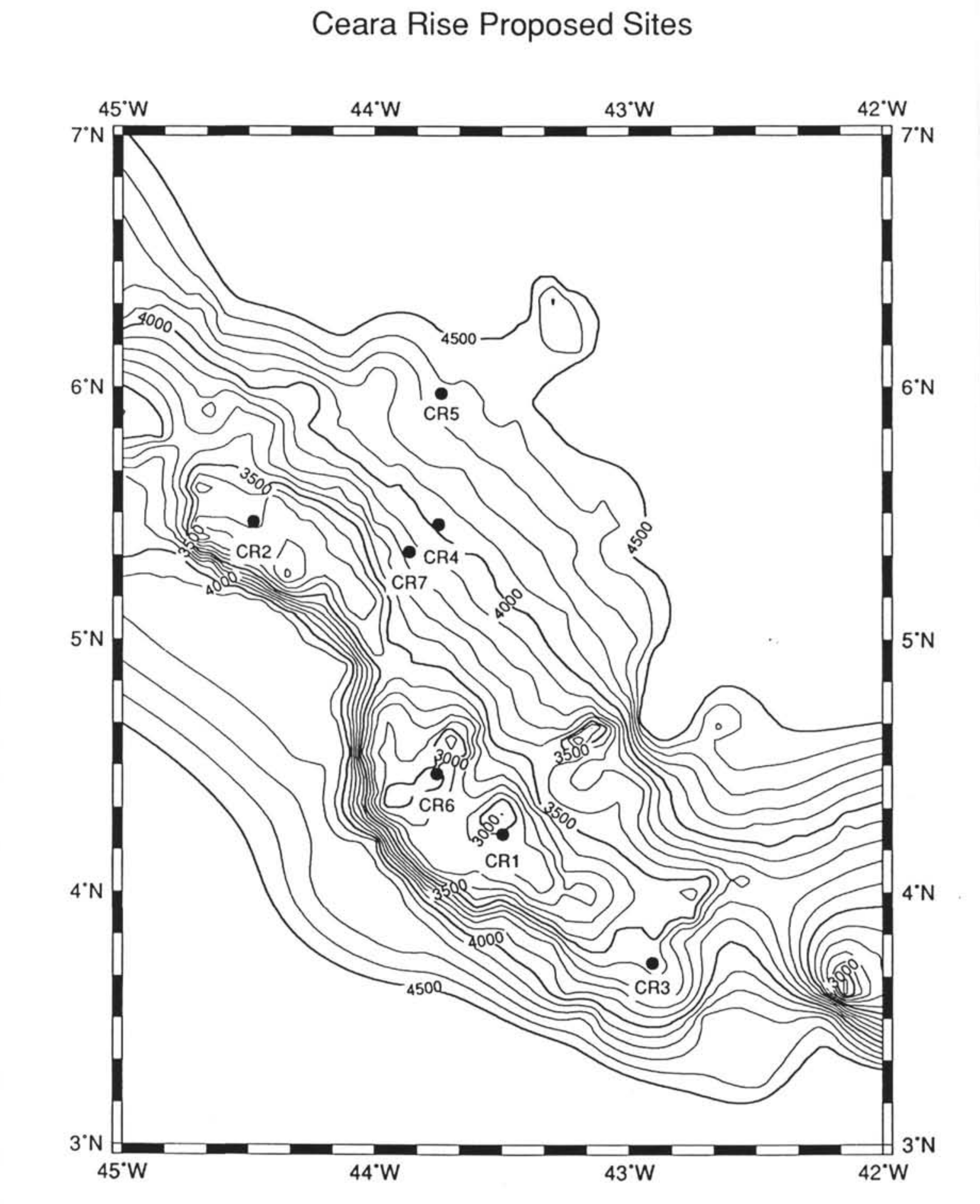

Ceara Rise Proposed Sites
45°W
44°W
43°W
42°W
7°N
6°N
5°N
4°N
3°N
4000
4500
CR5
3500
CR2
CR4
CR7
4000
4500
3500
3000
CR6
3000
3500
CR1
3500
4000
CR3
4500
3000

Figure 7

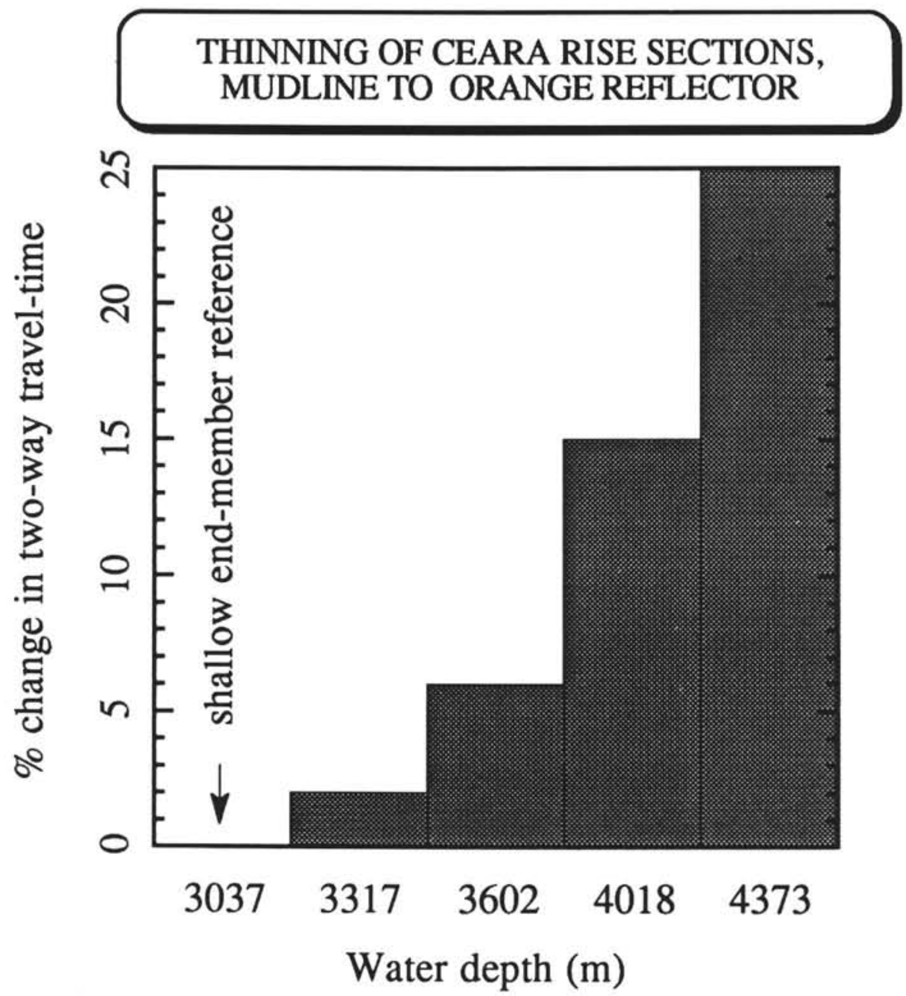

THINNING OF CEARA RISE SECTIONS,
MUDLINE TO ORANGE REFLECTOR
% change in two-way travel-time
0
5
10
15
20
25
shallow end-member reference
3037
3317
3602
4018
4373
Water depth (m)

Figure 8

Site: CR-1

Priority: 1

Position: 4°13.79'N, 43°27.94'W

Water Depth: 3037 m

Sediment Thickness: 1300 m

Seismic Coverage: SP 3840 on Ew9209 Line 2

Objectives: Determine Cenozoic history of deep water chemistry, carbonate productivity and dissolution, and surface temperature. Shallow end-member of the Cenozoic depth transect.

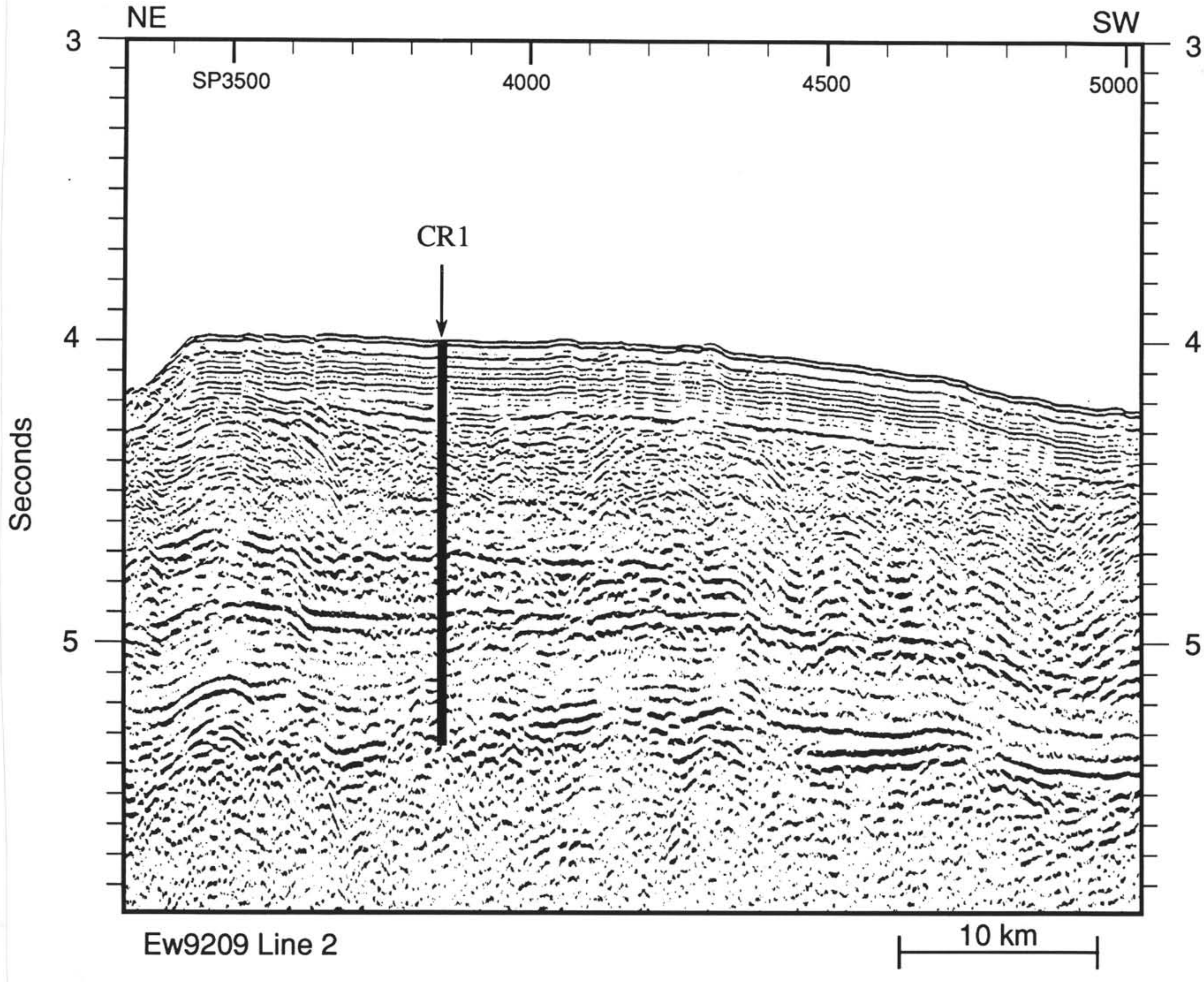
Drilling Program:

1. APC coring to 250 mbsf (oriented): holes A and B.
2. Hole C will be cored by APC (oriented) to 250 mbsf followed by deepening to 600 mbsf by XCB. The hole will be logged to 600 mbsf and then deepened until the basement is reached (1300 mbsf) by RCB. Finally, the hole will be logged between 600 mbsf and 1300 mbsf.

Logging and Downhole Operations:

Scheduled logging tools for the first site are (1) the Quad Combination tool string, (2) the Geochemical tool string, (3) the Formation Microscanner (FMS), and (4) the GHMT (magnetic susceptibility tool string).

Nature of Rock Anticipated: Nannofossil-foraminifera ooze, chalk, marls, diatomaceous chalk, reef limestone.


NE
SW
3
SP3500
4000
4500
5000
3
CR1
4
4
Seconds
5
5
Ew9209 Line 2
10 km

Site: CR-2

Priority: 1

Position: 5°27.84'N, 44°28.93'W

Water Depth: 3317 m

Sediment Thickness: 950 m

Seismic Coverage: SP 5250 on Ew9209 Line 4

Objectives: Determine Neogene history of deep water chemistry, carbonate productivity and dissolution, and surface temperature. Shallow member of the Cenozoic depth transect.

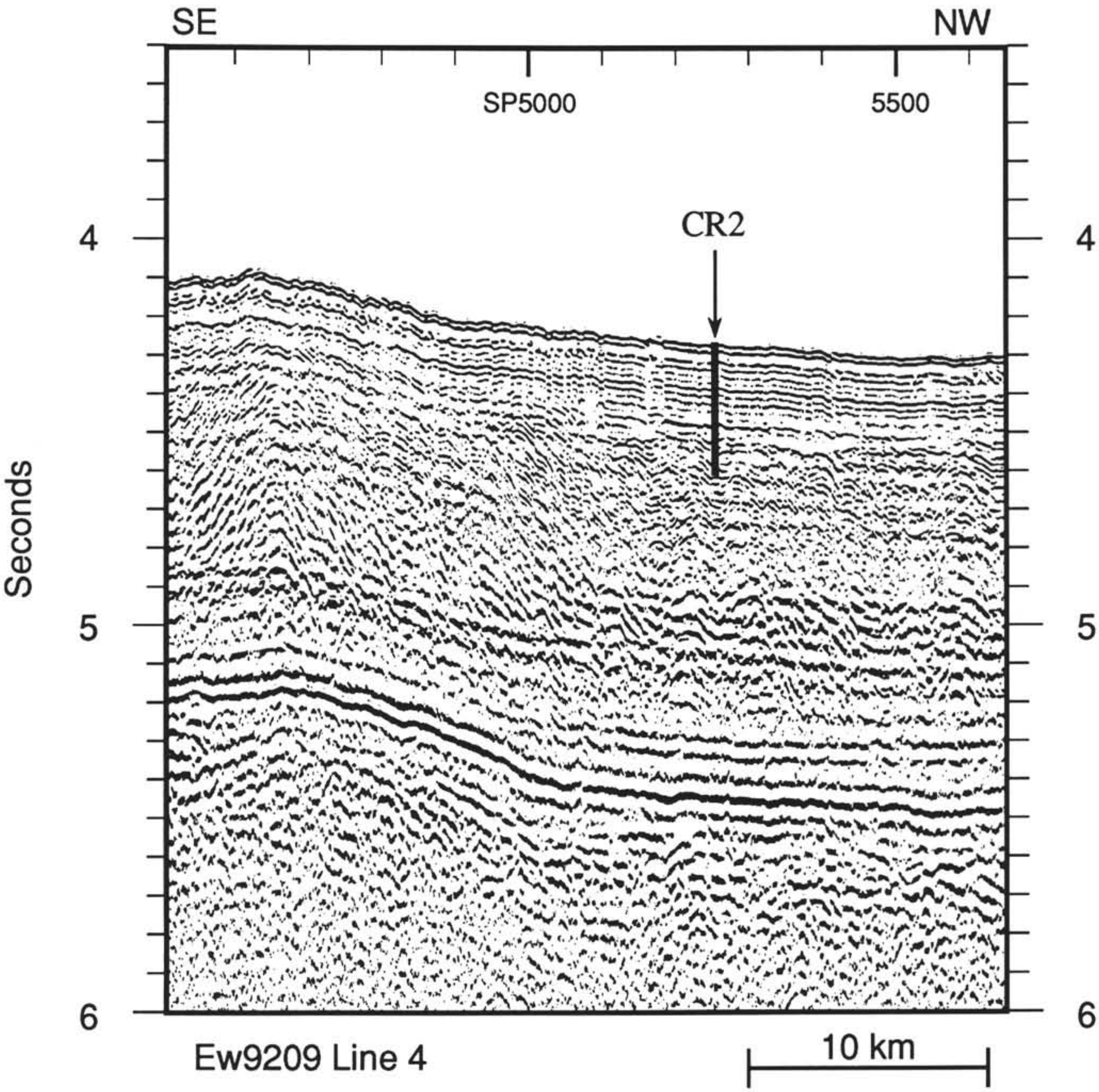
Drilling Program:

Holes A, B, C will be APC cored (oriented) to 250 mbsf.

Logging and Downhole Operations:

Standard strings (Quad Combo geophysical, geochemical and FMS - depending on results from CR1). The GHMT (magnetic susceptibility) may be run if time permits.

Nature of Rock Anticipated: Nannofossil-foraminfera ooze, chalk.


SE
NW
SP5000
5500
CR2
4
5
6
Seconds
Ew9209 Line 4
10 km

Site: CR-3

Priority: 1

Position: 3°43.18'N, 42°54.60'W

Water Depth: 3602 m

Sediment Thickness: 1200 m

Seismic Coverage: SP 2880 on Ew9209 Line 17

Objectives: Determine Cenozoic history of deep water chemistry, carbonate productivity and dissolution, and surface temperature. Intermediate deep member of the Cenozoic depth transect.

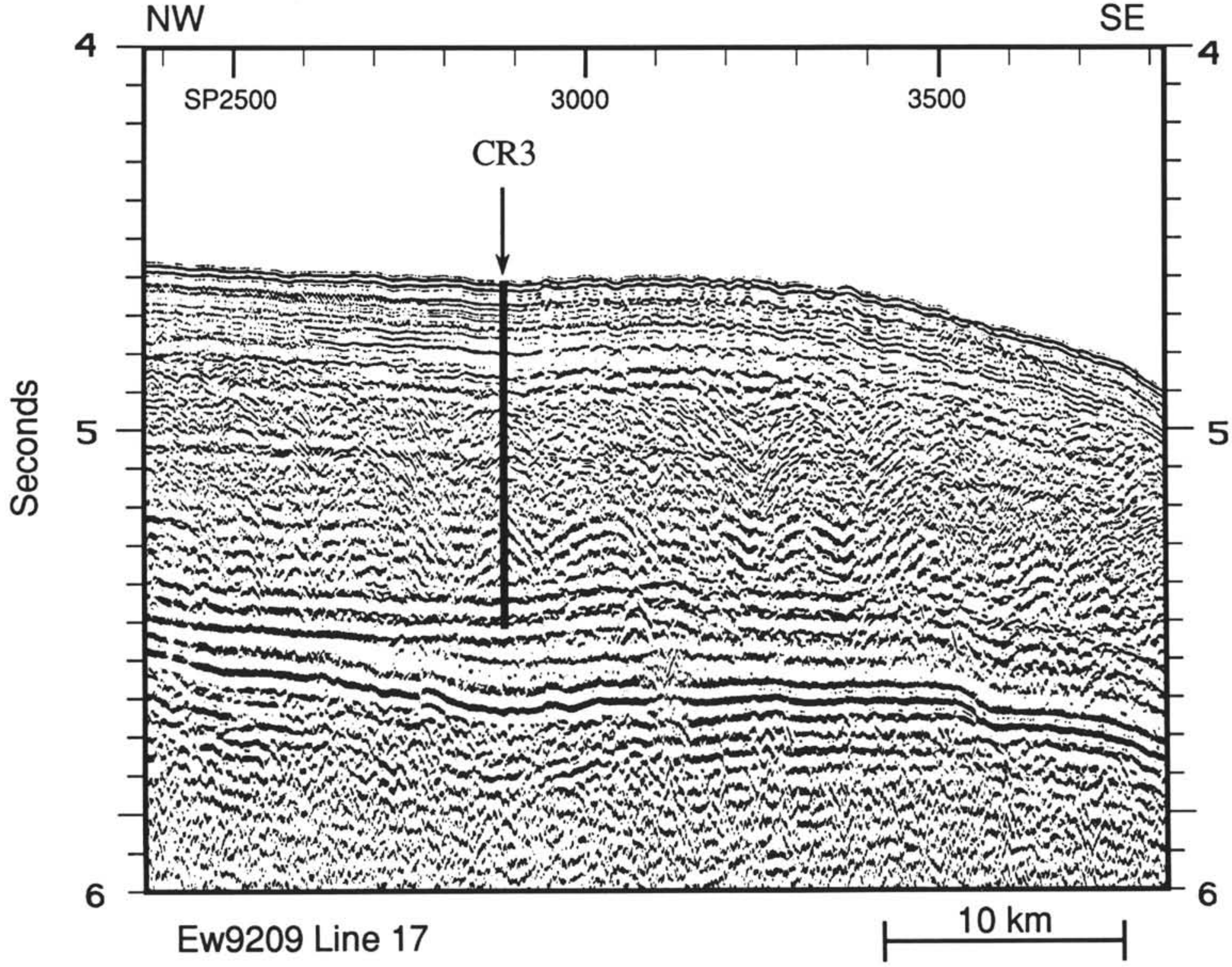
Drilling Program:

Three oriented APC holes will be cored to 250 mbsf. Hole C will be deepened by XCB to 600 mbsf.

Logging and Downhole Operations:

Standard strings (Quad Combo geophysical, geochemical and FMS - depending on results from CR1). The GHMT (magnetic susceptibility) may be run if time permits.

Nature of Rock Anticipated: Nannofossil-foraminifera ooze, chalk, marls, diatomaceous chalk, reef limestone.


NW
SE
4
4
SP2500
3000
3500
CR3
Seconds
5
5
6
6
10 km
Ew9209 Line 17

Site: CR-4

Priority: 1

Position: 5°27.26'N, 43°44.98'W

Water Depth: 4018 m

Sediment Thickness: 1000 m

Seismic Coverage: SP 2010 on Ew9209 Line 13

Objectives: Determine Cenozoic history of deep water chemistry, carbonate productivity and dissolution, and surface temperature. Deep end-member of the Cenozoic depth transect.

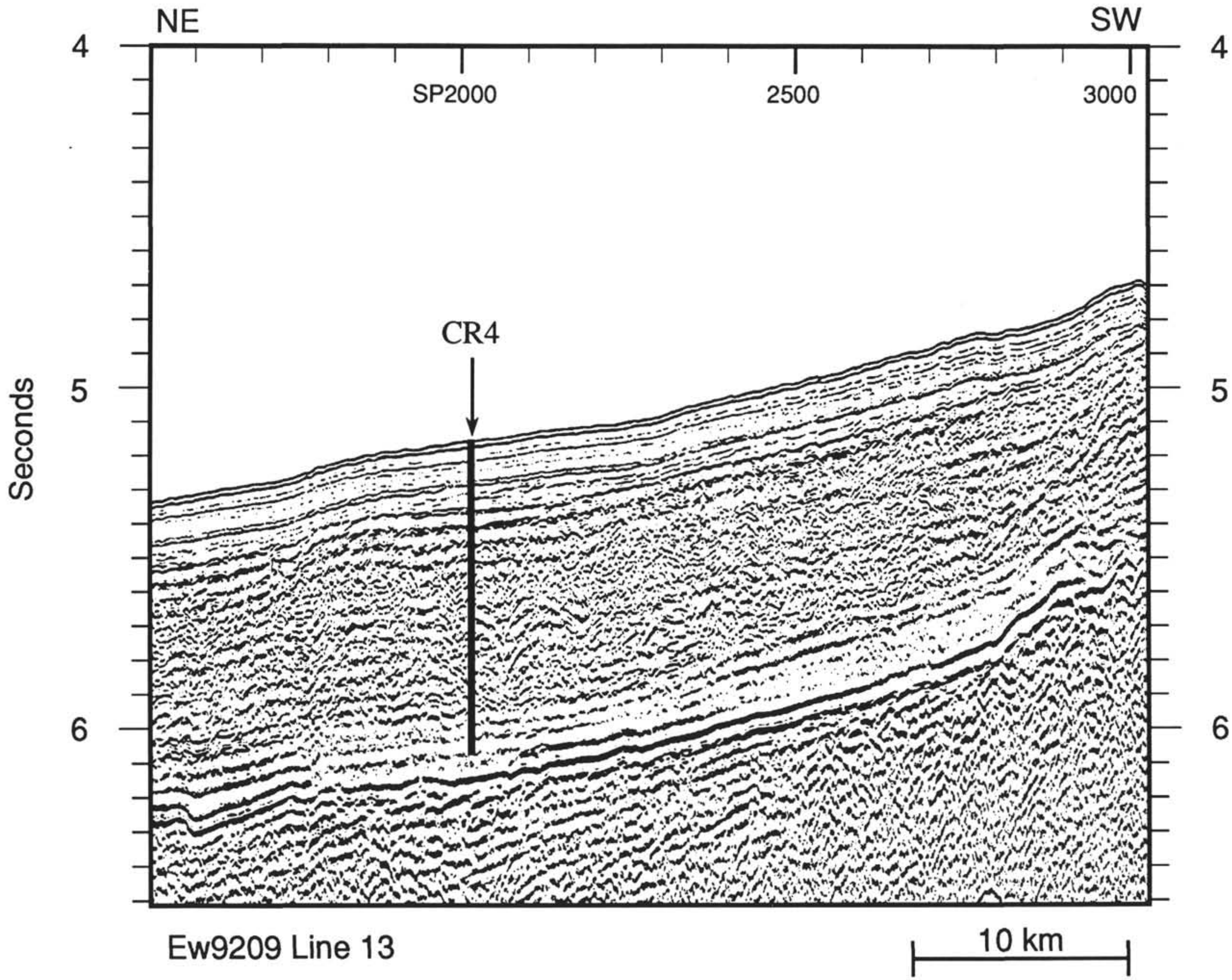
Drilling Program:

Holes A, B, C will be APC cored (oriented) to 250 mbsf.

Logging and Downhole Operations:

Standard strings (Quad Combo geophysical, geochemical and FMS - depending on results from CR1). The GHMT (magnetic susceptibility) may be run if time permits.

Nature of Rock Anticipated: Nannofossil-foraminifera ooze, chalk, marls, diatomaceous chalk, reef limestone



NE
SW
4
SP2000
2500
3000
CR4
Seconds
5
6
Ew9209 Line 13
10 km

Site: CR-5

Priority: 1

Position: 5°58.57'N, 43°44.40'W

Water Depth: 4373 m

Sediment Thickness: 950 m

Seismic Coverage: SP 3880 on Ew9209 Line 9

Objectives: Determine Cenozoic history of deep water chemistry, carbonate productivity and dissolution, and surface temperature. Deepest end-member of the Cenozoic depth transect.

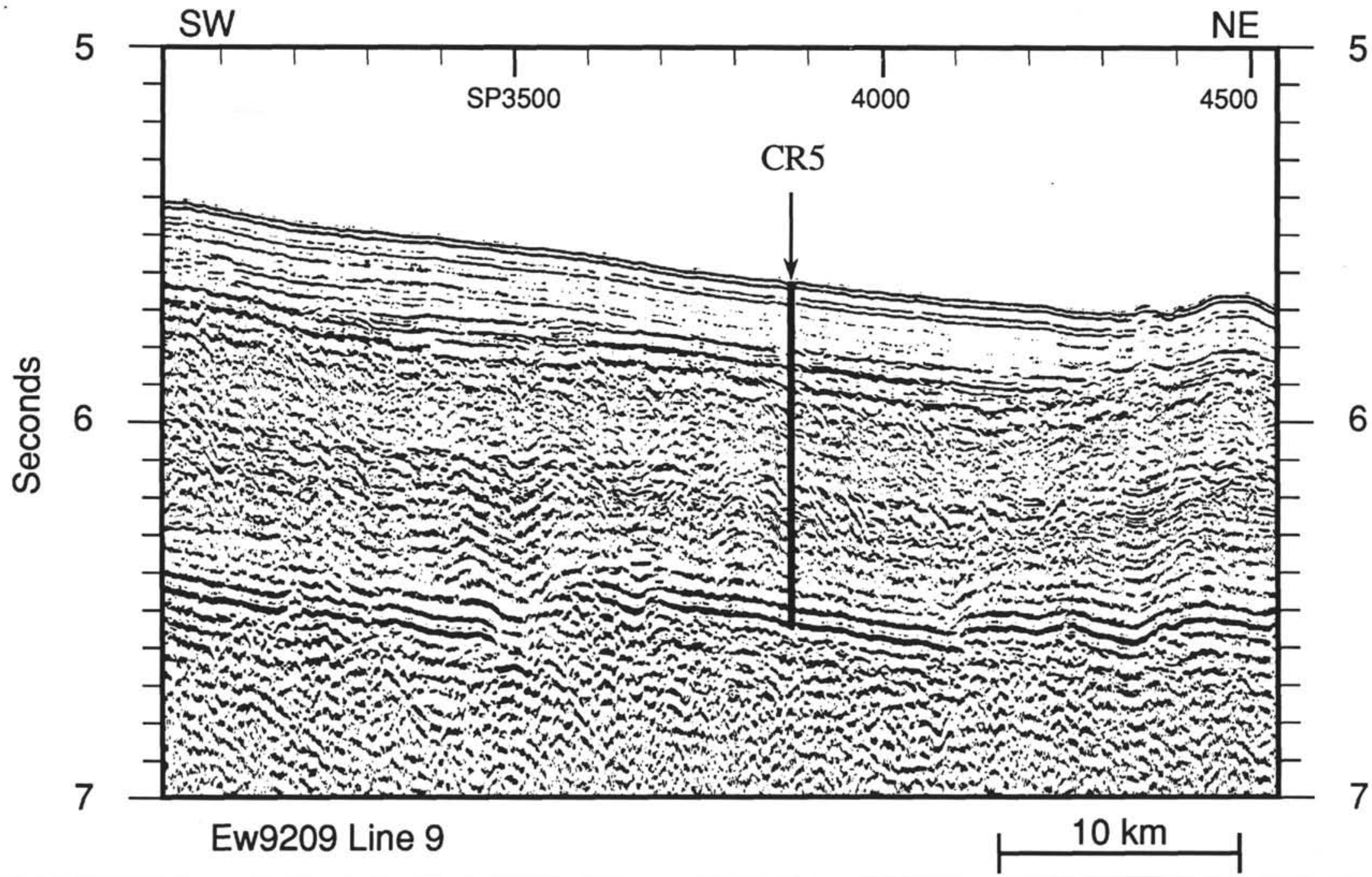
Drilling Program:

Hole A will be drilled with RCB to 400 mbsf, then cored to 950 mbsf. The BHA will then be changed and three oriented APC holes will be cored to 250 mbsf, the last one will be deepened by XCB to 400 mbsf.

Logging and Downhole Operations:

Standard strings (Quad Combo geophysical, geochemical and FMS - depending on results from CR1). The GHMT (magnetic susceptibility) may be run if time permits.

Nature of Rock Anticipated: Nannofossil-foraminifera ooze, chalk, marls, diatomaceous chalk, reef limestone.


SW
NE
SP3500
4000
4500
CR5
Seconds
5
6
7
Ew9209 Line 9
10 km

Site: CR-6

Priority: 2

Position: 4°28.02'N, 43°45.33'W

Water Depth: 2901 m

Sediment Thickness: 950 m

Seismic Coverage: SP 1390 on Ew9209 Line 4

Objectives: Determine Cenozoic history of deep water chemistry, carbonate productivity and dissolution, and surface temperature. Shallowest end-member of the Cenozoic depth transect.

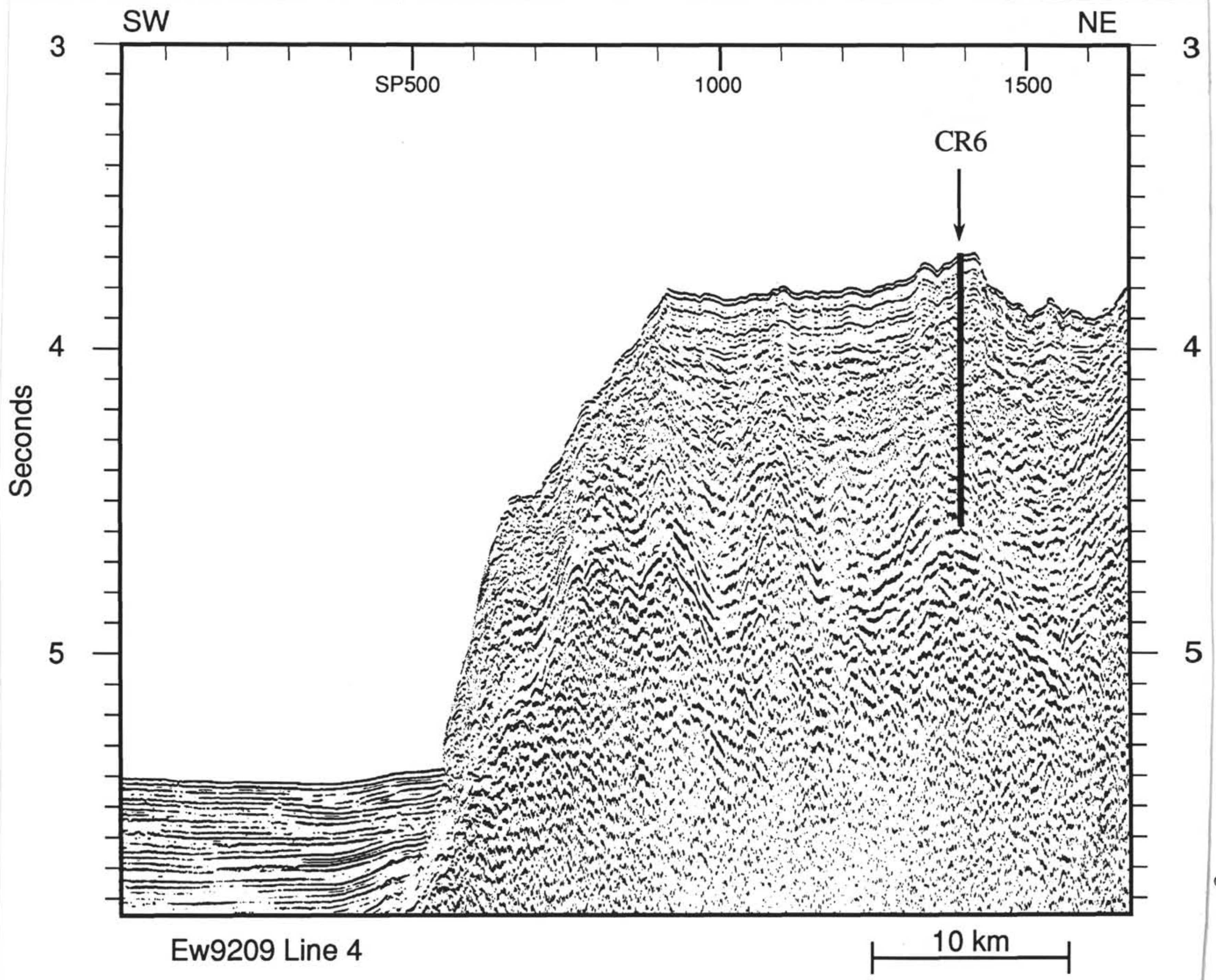
Drilling Program:

Holes A, B, C will be APC cored (oriented) to 250 mbsf.

Logging and Downhole Operations:

Standard strings (Quad Combo geophysical, geochemical and FMS - depending on results from CR1). The GHMT (magnetic susceptibility) may be run if time permits.

Nature of Rock Anticipated: Nannofossil-foraminifera ooze, chalk, marls.


SW
NE
3
4
5
Seconds
SP500
1000
1500
CR6
Ew9209 Line 4
10 km

Site: CR-7

Priority: 2

Position: 5°20.78'N, 43°51.92'W

Water Depth: 3853 m

Sediment Thickness: 950 m

Seismic Coverage: SP 2570 on Ew9209 Line 13

Objectives: Determine Cenozoic history of deep water chemistry, carbonate productivity and dissolution, and surface temperature. Intermediate deep member of the Cenozoic depth transect.

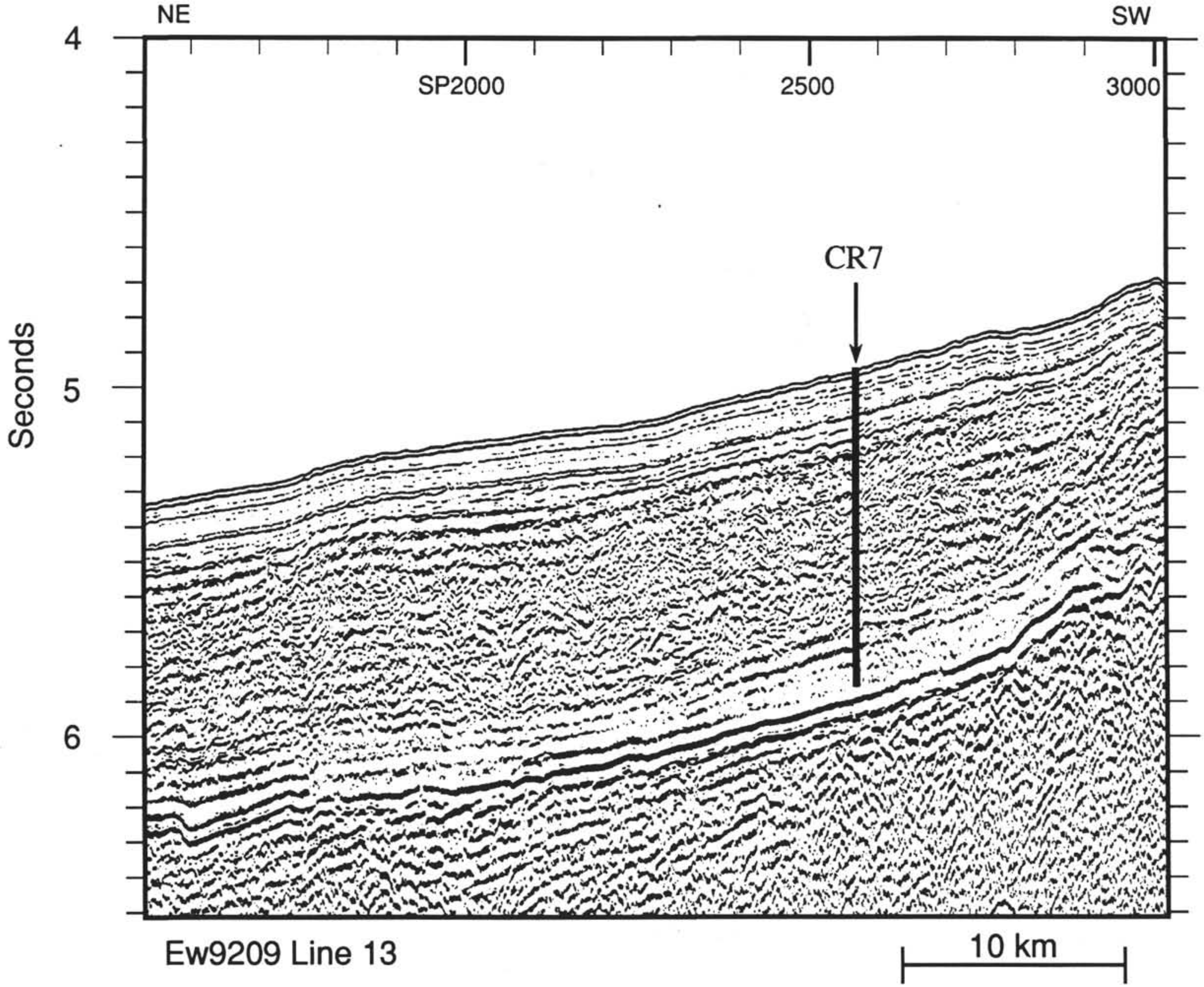
Drilling Program:

Holes A, B, C will be APC cored (oriented) to 250 mbsf.

Logging and Downhole Operations:

Standard strings (Quad Combo geophysical, geochemical and FMS - depending on results from CR1). The GHMT (magnetic susceptibility) may be run if time permits.

Nature of Rock Anticipated: Nannofossil-foraminifera ooze, chalk, marls.


NE
SW
4
5
6
Seconds
SP2000
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3000
CR7
Ew9209 Line 13
10 km

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