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12. PRELIMINARY RESULTS OF SUBANTARCTIC SOUTH ATLANTIC LEG 114 OF THE OCEAN DRILLING PROGRAM[1]

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ABSTRACT

Ocean Drilling Program Leg 114 drilled 12 holes at seven sites in the subantarctic South Atlantic during March–May 1987. These sites are on the Northeast Georgia Rise (Site 698), lower flank of the Northeast Georgia Rise in the East Georgia Basin (Sites 699 and 700), Islas Orcadas Rise (Site 702), between the Islas Orcadas Rise and Mid-Atlantic Ridge (Site 701), and on the Meteor Rise (Sites 703 and 704).

The recovered sediments provide the greatest stratigraphic representation of the Late Cretaceous–Cenozoic ever obtained from the Southern Ocean. Generally well-preserved microfossil assemblages of all major microfossil groups provide excellent biostratigraphic control. A nearly continuous history of geomagnetic polarity reversals was obtained for the Late Cretaceous–Quaternary, with gaps only for the late Paleocene–early Eocene and portions of the early–middle Miocene. The magnetobiostratigraphic framework provided by these sites and those of Leg 113 provides the first high-resolution geochronologic record of the Late Cretaceous–Cenozoic Southern Ocean. We describe here the principal results, as well as the initial tectonic and paleoenvironmental interpretations, of Leg 114 drilling.

INTRODUCTION

From late 1986 through early 1987, the Ocean Drilling Program (ODP) conducted its first cruises to the Southern Ocean. Leg 113 drilled in the Weddell Sea, and Leg 114 drilled in the subantarctic South Atlantic; the latter investigation is the subject of this report. The two cruises represent the first significant effort in 7 yr to obtain lengthy stratigraphic sections from the Southern Ocean, and together, they recovered the first detailed Late Cretaceous–Cenozoic sedimentary record from the antarctic to subantarctic regions of a single sector of the Southern Ocean.

Major objectives in common to these legs are to document the climatic, glacial, and oceanographic history of the region within the context of a more complete and detailed geochronologic framework than previously available. An additional goal is to interpret the causes of southern high-latitude paleoenvironmental change. Causes for increased Cenozoic cooling and glaciation are still poorly known, but probably involved a combination of interrelated effects, including tectonics, CO_2 forcing, sea-level changes, and various feedback mechanisms within the climate system itself.

Scientific objectives specific to Leg 114 are to evaluate (1) the influence of progressive antarctic cooling and glacial expansion on the oceanography and biotic evolution of the subantarctic and (2) the influence of regional tectonics on the oceanographic history of the Southern Ocean and the exchange of antarctic water masses with the South Atlantic. Important regional tectonic events include the Eocene formation of a deep-water gap between the Islas Orcadas and Meteor rises, which promoted deep-water communication between the antarctic and South Atlantic, and the late Oligocene/early Miocene opening of the Drake Passage, which led to the establishment of the Antarctic Circumpolar Current (ACC).

The sedimentary record obtained from the sites of Legs 113 and 114 (Fig. 1) provides new opportunities to examine high-latitude climate change and oceanographic dynamics. These legs are the first in the Southern Ocean to use extensively the low sediment-disturbance, continuous-recovery techniques (advanced hydraulic piston core and extended core barrel systems) that are necessary for high-resolution paleoenvironmental studies. During the six previous Southern Ocean legs of the Deep Sea Drilling Program (DSDP), most holes were rotary drilled, resulting in drilling disturbance and poor core recovery. Other holes were drilled discontinuously (with washed intervals) to reach basement objectives. Only two DSDP sites (594 and 512) were cored with low-disturbance techniques (hydraulic piston core system).

PRELIMINARY RESULTS AND INTERPRETATION

Age and Nature of the Stratigraphic Sequences

A precise geochronologic framework has long been the key to interpreting the Cenozoic glacial history of Antarctica and its influence on regional and global oceanography and climate. Previous studies of the antarctic paleoenvironment based on land and deep-sea sequences have been hindered by the lack of an accurate time scale. This was due to the almost complete absence of pre-Pliocene paleomagnetically dated sequences, poor correlation of Southern Ocean biostratigraphic schemes to standard low-latitude zonations, and incomplete stratigraphic representation.

Leg 114 sedimentary sequences provide the most complete stratigraphic representation of a 90-Ma interval of the Late Cretaceous–Quaternary of the subantarctic region of the Southern Ocean (Leg 114 Shipboard Scientific Party, 1987; Leg 114 Scientific Drilling Party, 1987). Twelve holes were drilled at seven sites along a west-to-east transect from the Northeast Georgia Rise to the Meteor Rise in water depths ranging from 1807 to 4634 m (Fig. 2). Figure 3 illustrates the age and thickness of sediments recovered at the seven sites.

Sediments recovered during Leg 114 are almost entirely pelagic sediments, with little terrigenous component (Fig. 2). Upper Cretaceous sediments are predominantly nannofossil chalks and limestones. Paleogene sequences are primarily nannofossil oozes, chalks, and limestones displaying progressive diagenesis with increasing age and sub-bottom depth. An exception is the deepest site, Site 701, at 4634 m below sea level (mbsl), which

[1] Ciesielski, P. F., Kristoffersen, Y., et al., 1988. *Proc. ODP, Init. Repts.*, 114: College Station, TX (Ocean Drilling Program).
[2] Shipboard Scientific Party is as given in the list of Participants preceding the contents.

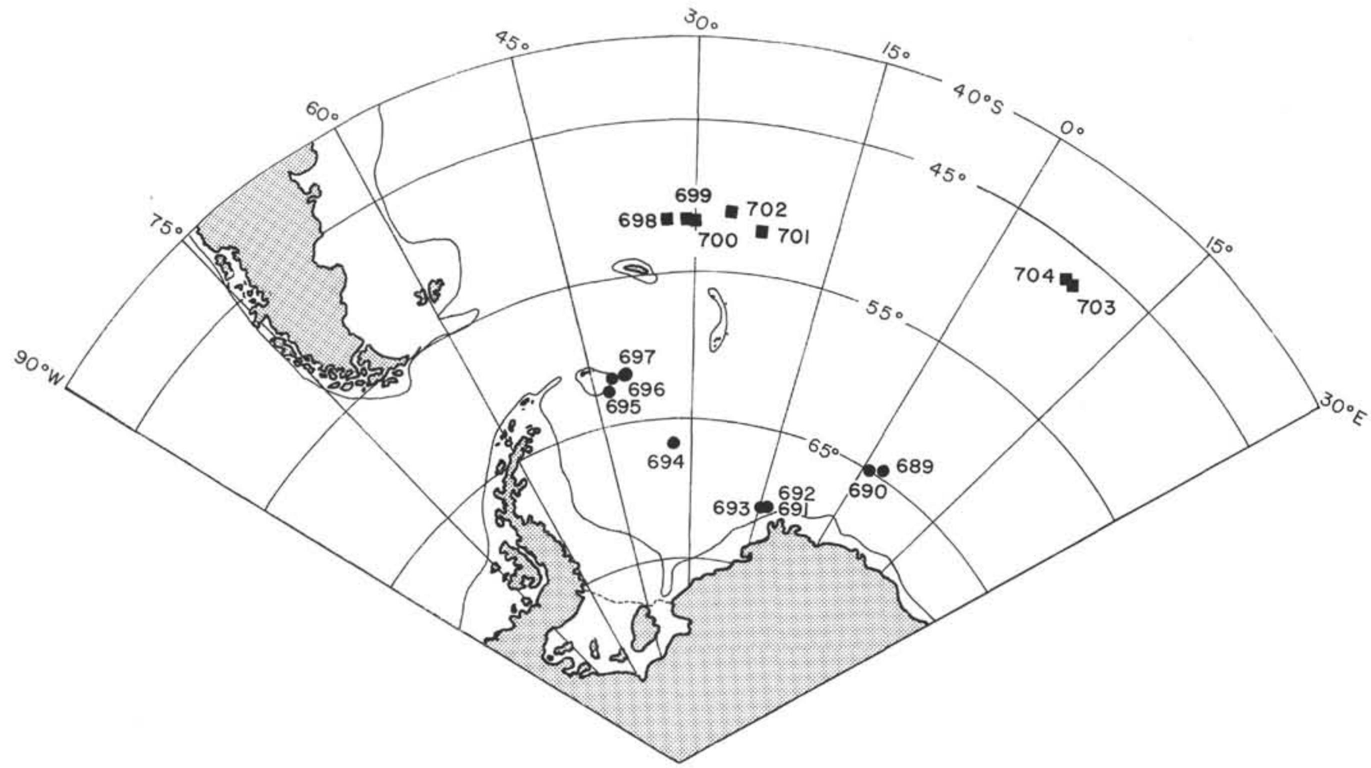

Figure 1. ODP Leg 113 (circles) and Leg 114 (squares) sites in the South Atlantic sector of the Southern Ocean.

accumulated biosiliceous sediments after its middle Eocene subsidence below the carbonate compensation depth (CCD). Calcareous sedimentation was intermittent at six of the seven sites since the earliest Miocene, after which time biosiliceous sedimentation predominated. Only at the shallow and most northerly site, Site 704 (46°52.8'S), did mixed biosiliceous and calcareous sedimentation occur during the Neogene. Abundant, discrete volcanic ash layers occur in the Upper Cretaceous of Site 700 and throughout the Neogene of Site 701. Chert nodules and stringers are common occurrences within Eocene sequences.

One of the greatest successes of Leg 114 was to repeatedly recover lengthy stratigraphic representations of Upper Cretaceous–Cenozoic sequences with rich microfossil assemblages (Figs. 2 and 3). Particularly noteworthy was the recovery of thick fossiliferous sections of stratigraphic sequences, including the Maestrichtian, lower Paleocene, and lower middle Eocene, that previously had not been extensively recovered from the Southern Ocean. The combined paleomagnetic data from the seven sites provide a nearly complete history of geomagnetic polarity reversals that extends from the Late Cretaceous (Santonian) through the Quaternary, with gaps only in the late Paleocene–early Eocene and the early and middle Miocene. The combination of Leg 114 biostratigraphic studies with the geomagnetic polarity record will yield the first detailed geochronologic framework for the interpretation of Southern Ocean paleoenvironment during the last 90 Ma.

Sedimentation in the subantarctic region was relatively continuous during the Late Cretaceous to earliest Miocene, and hiatuses represent short stratigraphic intervals. At six of the seven sites, major hiatuses separate overlying middle to upper Neogene sediments from the middle Paleogene to lowermost Neogene. Since ~18.5 Ma, all of the Leg 114 sites, except Site 704, were subjected to numerous erosional and nondepositional episodes. Physical-properties measurements suggest a removal of hundreds of meters of sediment at some hiatuses.

Microfossil Representation and Preservation

Calcareous nannofosssils are the dominant microfossil constituent within the Cretaceous, with planktonic and benthic foraminifers the most common minor constituents. Intervals occur with common to abundant calcispherulids (Site 698) and abundant and well-preserved radiolarians (Site 700). Late Cretaceous microfossils have a generally high diversity but exhibit signs of diagenesis.

Calcareous microfossils are also the dominant microfossil group in the Paleogene, although benthic and planktonic foraminifers are abundant in coarse-fraction residues. Above the lowermost Miocene, only sporadic, low-diversity assemblages of calcareous groups are found, except at the shallow and most northerly Site 704, where they persist through the Neogene.

Diverse assemblages of siliceous microfossils occur throughout parts of the Paleogene, where diagenesis has not resulted in their destruction. Particularly well-preserved assemblages occur within the upper Paleocene, upper Eocene, and Oligocene. The only dominance of siliceous microfossil assemblages within the Paleogene of the Leg 114 sites is within the the upper Eocene–Oligocene of deep-water Site 701. In contrast, siliceous microfossils dominate the biogenic fraction of all Neogene sections, except for Site 704 (discussed subsequently).

Tectonic Interpretation

The recovered sections give new insight into the tectonic and subsidence history and the nature of the Northeast Georgia Rise, Islas Orcadas Rise, and Meteor Rise. Three sites were drilled near the apex (Site 698) and lower eastern flank (Sites 699 and 700) of the Northeast Georgia Rise, which is thought to be a fossil arc massif formed at a convergent plate boundary between the Malvinas plate and the South American plate (LaBrecque and Hayes, 1979). Basement at Site 698 was capped by Campanian or older interbedded basalt and subaerially weath-

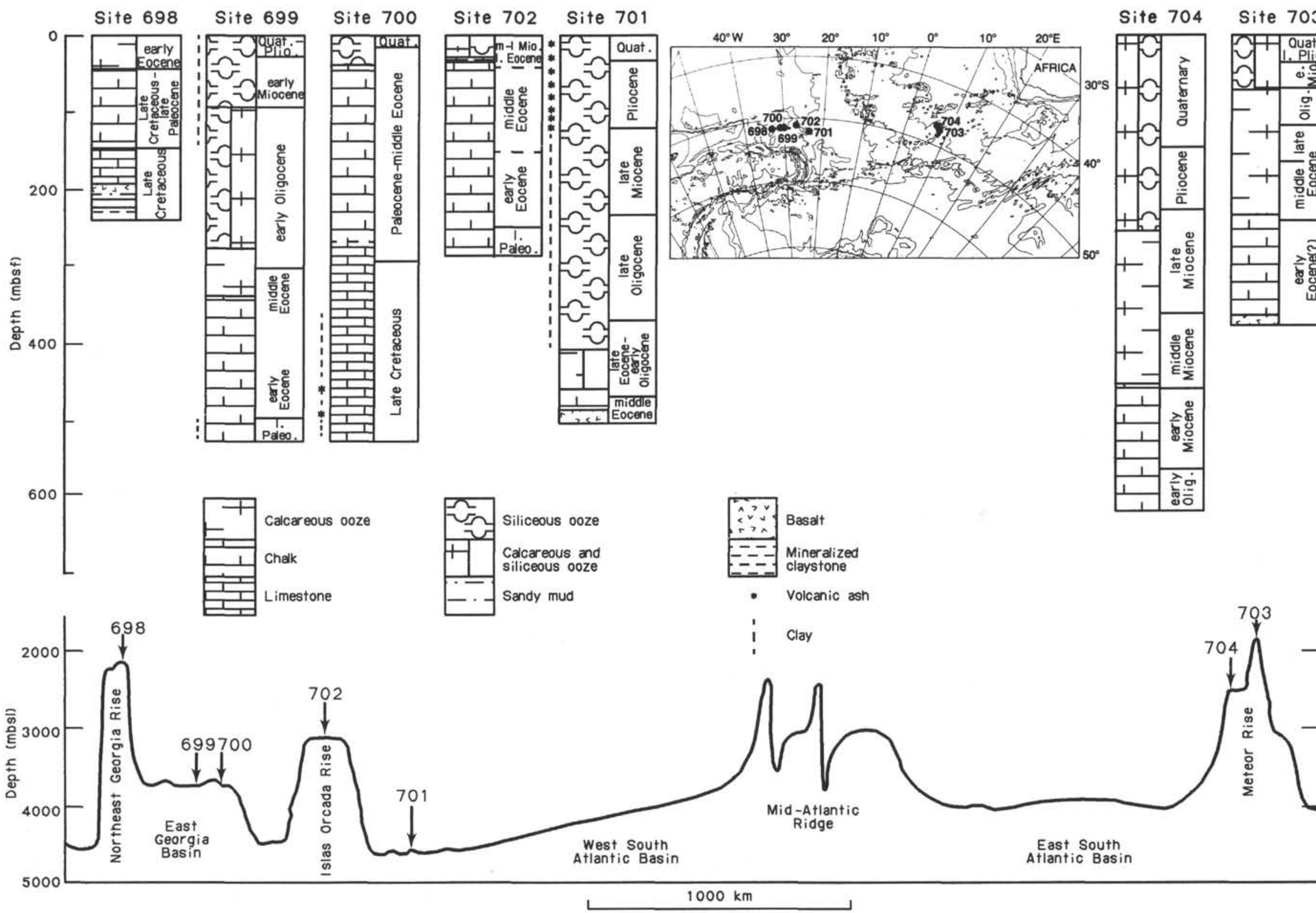

Figure 2. Twelve holes were drilled during ODP Leg 114 at seven site locations along a west-to-east traverse across the subantarctic South Atlantic (Fig. 1). Composite stratigraphic columns (top) reveal the ages, lithologies, and sediment thickness of each site. A schematic cross section (bottom) shows the site locations along the bathymetry of the transect.

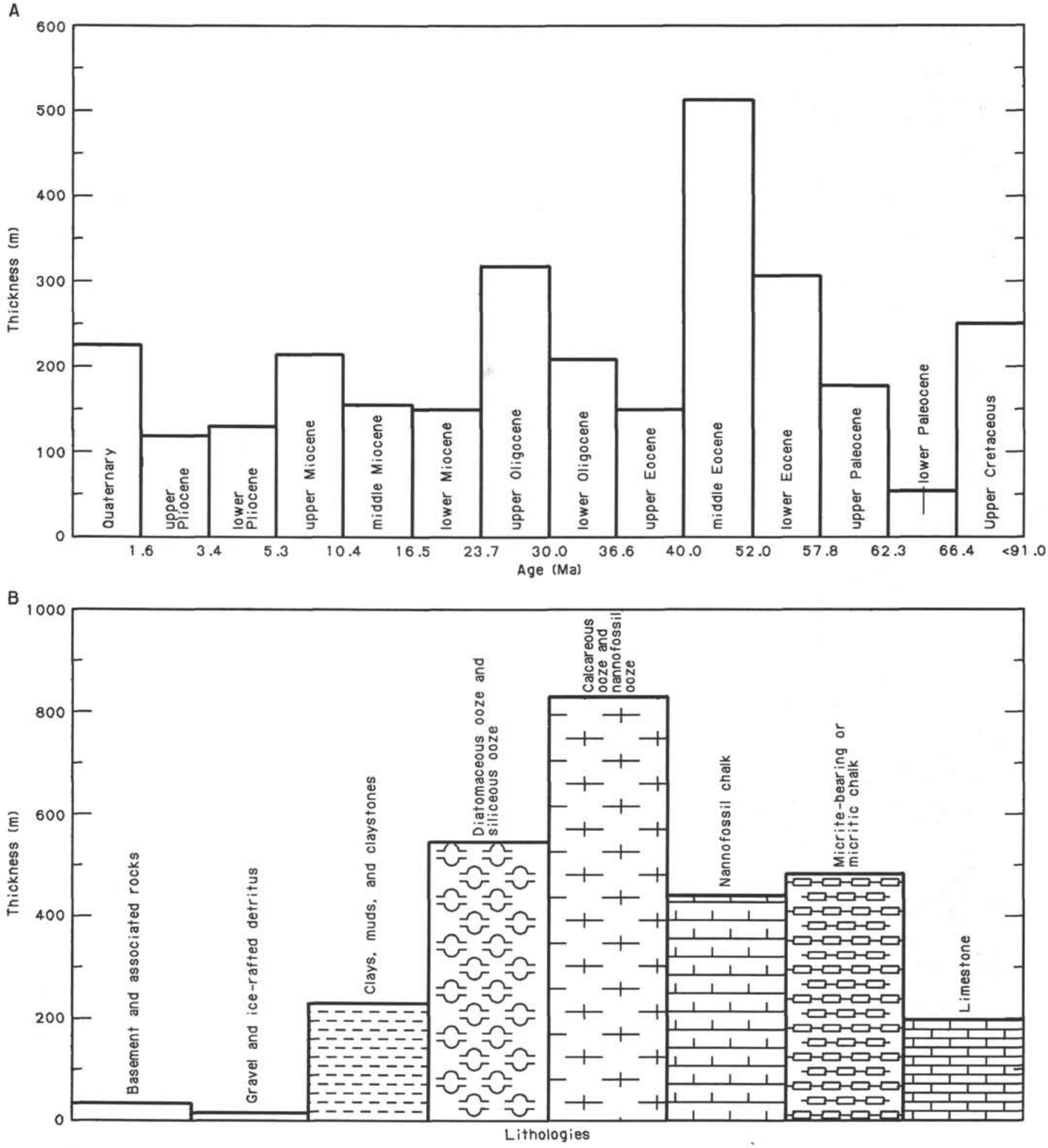

Figure 3. **A.** Histogram of sediment thickness of various ages penetrated by Leg 114 drilling. **B.** Histogram showing thickness of lithologies penetrated.

ered basalt layers. Active regional volcanism occurred during the late Turonian-Santonian; thus, any incipient subduction must be pre-early Campanian. Redeposited rocks in the Oligocene of Site 700, if in place, suggest that a continental fragment may be part of the structural framework that forms the Northeast Georgia Rise.

Major faulting involving basement and the overlying sediments occurred on the Northeast Georgia Rise between the early Oligocene and Quaternary. In the region of Site 698, the entire sedimentary section was downfaulted into a half-graben, with vertical displacement of over 1 km on the major fault. Stratigraphic control and seismic correlations between Sites 699 and

700 clearly demonstrate that corresponding stratigraphic levels and basement were vertically displaced along two major faults, with a total throw of ~900 m. This tectonic activity may be related to the opening of the Scotia Sea and interaction of Northeast Georgia Rise with the advancing South Georgia block.

Basal sediments of the Islas Orcadas Rise (Site 702) indicate that the rise is older than late Paleocene (>61 Ma) and is possibly Late Cretaceous in age. Early Eocene extension generated numerous, small half-grabens over much of the rise, and a major tectonic event formed a north-trending horst through the site location between the late Eocene and middle Miocene. By the late Paleocene most of the rise was still less than 2000 mbsl, subsiding to near its present water depth (3083 mbsl) by the middle to late Eocene.

Site 703 was drilled at a depth of 1807 m on the flank of a basement pinnacle of the Meteor Rise, an aseismic ridge extending southwest from the Agulhas Fracture Zone. Having been unsuccessful at obtaining basement on the once conjugate Islas Orcadas Rise, a major objective at this site was to determine its nature, age, and subsidence history. Weathered early(?) or early middle Eocene porphyritic plagioclase basalts and basaltic tuffs, which may represent basement or part of a volcanic rubble zone, were encountered. The oldest *in-situ* or reworked microfossils at this site are Eocene, whereas Late Cretaceous microfossils were found on the Islas Orcadas Rise. Either the Islas Orcadas Rise is older than the Meteor Rise or, more likely, the Meteor Rise has experienced more recent volcanism, which would account for its younger, shallower basement and more rugged relief. Site 703 was between 600 and 1000 mbsl during the Eocene and subsided to >1000 mbsl during the Oligocene. Reworked Eocene and Oligocene microfossils indicate the presence of nearby islands, which have since subsided to below neritic depths.

Site 701 was drilled to basement to the east of the Islas Orcadas Rise (Fig. 2) on oceanic crust generated by an extension of the Mid-Atlantic Ridge that separated the Islas Orcadas and Meteor rises. Drilling results confirm previous identification of magnetic anomaly patterns, indicating an Eocene initiation of spreading between these features.

Paleoceanographic Interpretation

Planktonic microfossil assemblages yield a detailed record of the progressive and punctuated cooling of subantarctic surface waters during the Late Cretaceous–Cenozoic. The warmest surface waters in the subantarctic occurred during the Late Cretaceous–middle Eocene, resulting in a relatively high percentage of warm-water taxa such as *Globotruncana*, *Rosita*, *Morozovella*, *Acarinina*, *Discoaster*, and *Sphenolithus*. Peak abundances of warm-water planktonic taxa in the Cenozoic occur within the lower Eocene (57.8–52 Ma). A mixture of lower latitude planktonic groups with austral assemblages occurs in the Upper Cretaceous to lower Paleogene. We infer this assemblage mixture to be the result of an influx of shallow and cooler Pacific waters (entering the southwest Atlantic through the unglaciated West Antarctic archipelago), mixing with warmer waters of the southern limb of a larger South Atlantic subtropical gyre.

Surface waters began cooling significantly between 51.0 and 46 Ma, and by the late Eocene (~38 Ma) had led to much cooler water planktonic fauna and flora. This middle Eocene cooling episode begins the progressive and punctuated long-term trend toward subpolar conditions. The middle Eocene cooling coincides in age with the anomaly 18 advent of more rapid seafloor spreading between Antarctica and Australia, which may have caused the establishment of a more vigorous "shallow circum-Antarctic Current" entering the Atlantic through the West Antarctic seaway. We tentatively infer the cause of the middle Eocene cooling of subantarctic surface waters to be a northward displacement of the large South Atlantic subtropical gyre by the pre-ACC.

Additional episodes of pronounced surface-water cooling occurred at or near the middle/late Eocene and early/late Oligocene boundaries, accompanied by the successive disappearance of warm-water species in all major microfossil groups. By the late Oligocene, assemblages were dominated by cosmopolitan and cool-temperate species.

Paleogene sedimentation contrasts greatly with that of the Neogene in the region of the Leg 114 sites. Sedimentation was more continuous during the Paleogene, with the accumulation of calcareous nannofossil ooze above the CCD. Below the CCD (Site 701), biosiliceous sedimentation prevailed, with the only significant change in sedimentation being an increase in terrigenous clay deposition during the middle Oligocene. In general, Paleocene circulation appears to have been weak. Suboxic benthic conditions prevailed for much of the time in response to weak benthic flow and poor mixing. Sites 699 and 700 in the East Georgia Basin reveal no evidence for strong, deep circulation through this potential deep-water passage between the Weddell and South Atlantic prior to the Eocene opening of the Islas Orcadas Rise–Meteor Rise gateway.

A brief warming interval occurred at the Oligocene/Miocene boundary, followed by the earliest Miocene northward advance of the polar front and biosiliceous province. The latter event pushed the long-term position of the calcareous productivity zone permanently to the north of 51°S. The advance of the polar front appears to have been intimately related to the opening of the Drake Passage and establishment of the ACC.

Soon after the earliest Miocene advance of the polar front, a major increase occurred in the intensity of Circumpolar Deep Water (CPDW) and Antarctic Bottom Water (AABW), producing regional hiatuses. Deep-cutting erosion and nondeposition caused by the full development of the ACC formed hiatuses of differing stratigraphic extent. Numerous hiatuses were found within the Neogene of all sites, except at Site 704, which remained north of the influence of the ACC throughout most of this period. Multiple erosional and nondepositional episodes resulted in very attenuated Neogene sections at five of the sites (less than 70 m thick). At the shallower sites on the Northeast Georgia Rise and Islas Orcadas Rise, erosion cut deeply to expose Eocene sediments (Sites 698, 700, and 702).

The appearance of sand-size and larger ice-rafted detritus appears to be restricted to sediments of late Miocene age or younger, with a significant increase in abundance in the Pliocene. This finding is consistent with previous studies (Ciesielski et al., 1982) that described a rapid middle to late Miocene northward expansion of the zone of ice rafting around the Antarctic continent. A widespread increase in ice rafting to the northern antarctic and subantarctic is attributed to the development of a fully glaciated Antarctic continent with fringing ice shelves. The increased abundance of ice-rafted detritus in the uppermost Miocene and Pliocene of the southwest Atlantic sector of the Southern Ocean may be related to the establishment of the West Antarctic ice sheet, which did not form until this time, according to the drilling results of Leg 113 (Barker, Kennett, et al., 1988).

A 576-m-thick Neogene carbonate-siliceous sequence was recovered from Site 704 on the Meteor Rise. Shipboard studies revealed a strong climate signal characterized by numerous, high-amplitude variations in carbonate content, biogenic silica, organic carbon, temperature affinities of microfossils, physical properties, and logging parameters. Unlike the other Leg 114 sites, which were farther south in the axis of the ACC, Site 704 was the recipient of Neogene pelagic sediments at almost uninterrupted high accumulation rates. The result was the formation of a remarkably continuous record of the Neogene environment of the subantarctic.

Changes in the mode and variability of the carbonate record of Site 704 coincide with major paleoclimatic events. Carbonate content was high, averaging 86% from the lower to upper Miocene (Fig. 4). The initial significant decrease in carbonate (a 33% drop) occurred in Chron C3AR.6 (~6.5–6.37 Ma) and was accompanied by an increase in the amplitude of the carbonate variability. This change is inferred to represent the initial migration of the polar front to within close proximity of Site 704.

Preceding the increase in late Miocene carbonate variability at Site 704 was the deposition of a nearly monospecific ooze of the diatom *Bruniopsis* below the CCD at Site 701. This remarkable finely laminated ooze was deposited during Chron C3AR and also contains abundant silicoflagellates (*Dictyocha*), indicative of extremely warm surface waters. The combined evidence of fine lamination, absence of bioturbation and benthic foraminifers, high organic carbon content, and pyrite strongly suggest an oxygen-poor benthic environment. Monospecific diatom assemblages of similar age were previously noted in the South Atlantic at DSDP Sites 520 and 519, where low $\delta^{18}O$ surface-water values were interpreted as warming periods. Comparison of the late Miocene record of Sites 704 and 701 suggests an unusual and perhaps brief period of warm, and possibly low-salinity, surface waters in the eastern South Atlantic prior to the latest Miocene advance of the polar front and associated cooler conditions.

Several other changes noted in the mode and frequency of the Pliocene-Quaternary carbonate record of Site 704 represent fundamental changes in subantarctic surface waters. During the early Gilbert to middle Gauss Chrons (~4.8–3.2 Ma), a return to high carbonate values (averaging 77%) with low variability suggests a warm period and polar front retreat. During the middle Gauss (3.2–2.9 Ma), carbonate values decreased to 64% and the variability of the signal increased. This event correlates with an advance of the polar front and an increase in marine oxygen isotope values. These changes preceded the first major influx of ice rafting to the North Atlantic by 0.5 to 0.7 Ma. Another increase in the amplitude of the signal followed during the Olduvai Subchron (1.66–1.88 Ma), coincident with the Pliocene/Pleistocene boundary.

The most remarkable sedimentary change at Site 704 occurred during the middle Matuyama Chron and was marked by (1) decreased carbonate content to as low as 15%, (2) increased biogenic silica accumulation, (3) increased organic carbon deposition, and (4) the onset of strikingly intense color variations. These cyclic alternations were probably caused by migration of the polar front over Site 704 in response to glacial-interglacial forcing. Higher silica accumulation occurred during the glacial advance of the biosiliceous productivity belt to Site 704, only to be followed by the dominance of carbonate productivity upon the retreat of the front.

In summary, the recently recovered Leg 114 stratigraphic sequences provide a virtually complete record of sedimentation within the subantarctic during the last 90 Ma. Rich microfossil assemblages and excellent biostratigraphic and magnetostratigraphic control promise to provide a much more detailed history of the Late Cretaceous–Cenozoic paleoenvironment of the subantarctic than was previously possible.

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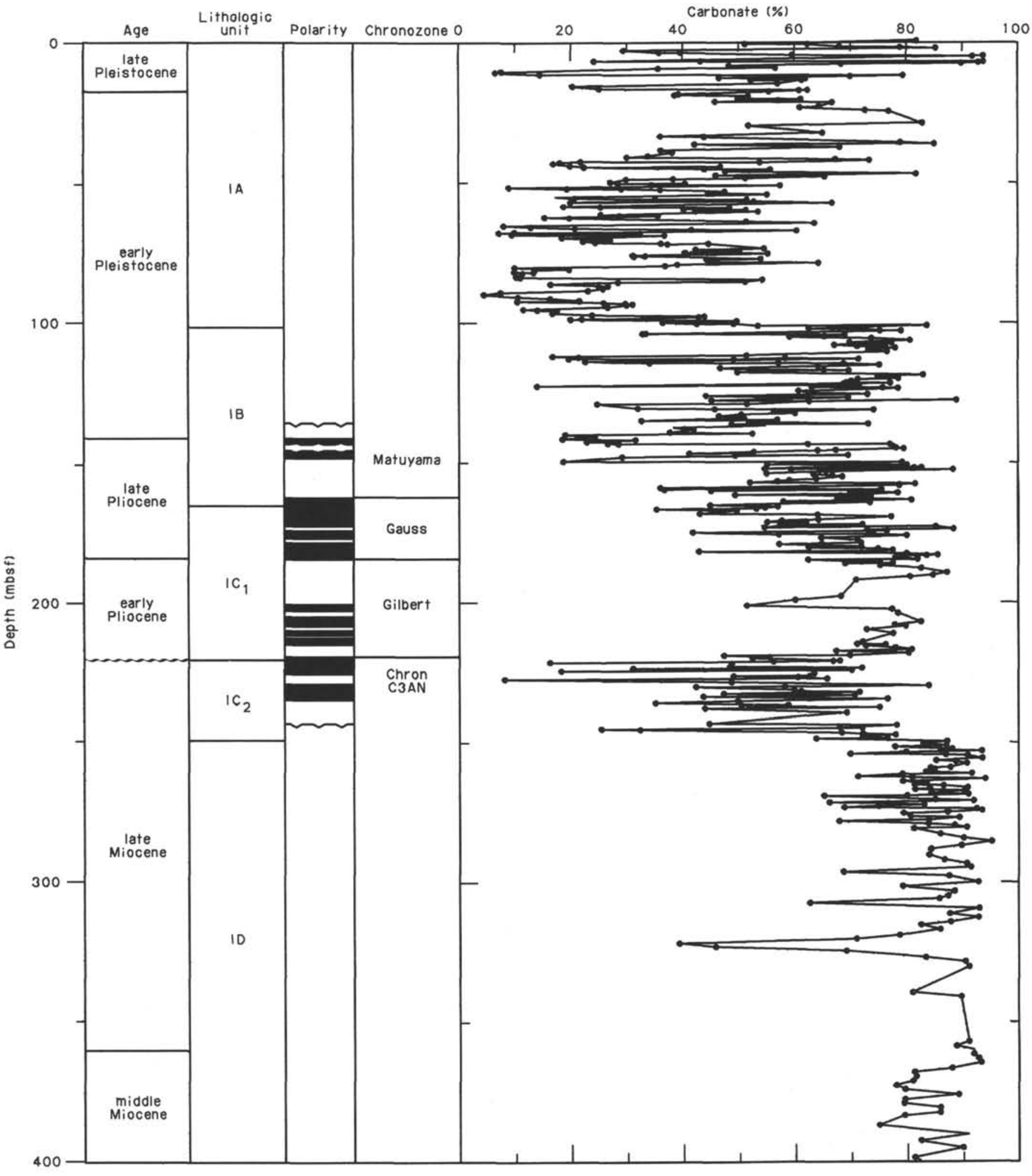

Figure 4. Fluctuations in the percent of calcium carbonate in the upper middle Miocene to Quaternary section of Site 704 on the Meteor Rise. The older lower Oligocene to middle Miocene section is not included in the figure because it has little variation in percent calcium carbonate. Also shown are sedimentation rates and paleomagnetic stratigraphy. Final paleomagnetic data for the Miocene will be determined from measurements of discrete samples to clarify the pattern of numerous reversals.