Early Oligocene ice-sheet expansion on Antarctica: Stable isotope and sedimentological evidence from Kerguelen Plateau, southern Indian Ocean

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ABSTRACT
Sedimentological and stable isotope data from a pelagic sequence recovered from the southern Indian Ocean provide the most convincing evidence to date for short-term expansion of a large ice sheet on Antarctica during the earliest Oligocene (36 Ma). Terrigenous debris identified as ice-rafted in origin on the basis of textural, compositional, and size criteria is present at the same stratigraphic level as the ubiquitous early Oligocene oxygen isotope shift. The highest benthic foraminiferal δ18O values (>3.0‰) of the Paleogene occur in samples from within the ice-rafted debris interval. These values are similar to those recorded by Holocene benthic foraminifera, implying that the ice sheet may have attained a volume similar to that of the present-day ice sheet on Antarctica. The stratigraphic distribution of ice-rafted debris and high oxygen isotope values indicate that these conditions persisted for roughly 100 ka.

INTRODUCTION
The pre-Pleistocene glacial history of Antarctica is poorly understood. Much of the direct sedimentary evidence of glaciation either was removed by subsequent glacial activity or remains hidden beneath present-day ice sheets. As a result, estimates of the timing and magnitude of ice-volume changes are based largely on an oxygen isotope record built from analyses of marine calcareous microfossils. This approach is complicated, however, by the fact that the oxygen isotope ratio of carbonate is influenced by both water composition and ambient temperature. In reconstructing Pleistocene ice volume, this problem was negated simply by assuming that deep-water temperatures remained more or less constant (e.g., Shackleton and Opdyke, 1973). Because a similar assumption cannot be easily extended beyond the Pleistocene, interpretations of older parts of the oxygen isotope record have been somewhat controversial (e.g., Prentice and Matthews, 1988). The origin of a ubiquitous earliest Oligocene oxygen isotope increase is a case in point. Nearly every pelagic sequence that includes the Eocene-Oligocene boundary shows a >1‰ increase in benthic foraminiferal δ18O values (e.g., Shackleton and Kennett, 1975; Kennett and Shackleton, 1976; Savin, 1977; Keigwin and Keller, 1984; Miller et al., 1987). Some investigators have invoked ice-volume increases as the principal cause of this δ18O event (Matthews and Poore, 1980; Poore and Matthews, 1984; Keigwin and Corliss, 1986; Miller and Thomas, 1985; Miller et al., 1987), whereas others have attributed the increase largely to cooling of deep waters associated with high-latitude cooling and initiation of modern thermohaline circulation (e.g., Kennett and Shackleton, 1976; Kennett, 1977).

Arguments against the presence of early Oligocene continental ice sheets were initially supported by the lack of robust physical evidence of Oligocene glacial activity, such as glacial till, dropstones, etc., in off-
level, were recovered from Prydz Bay (Barron, Larsen, et al., 1989). Such deposits clearly reflect major glacial activity in Antarctica during the Oligocene. The lack of adequate age control, however, has made it difficult to link these episodes of shallow-marine and continental glacial deposition to oxygen isotope events in the deep sea. As a result, both the timing and scale of glacial activity responsible for Oligocene ice-rafted deposits remain questionable.

We provide new evidence that the global early Oligocene oxygen isotope increase was coeval with a brief period of widespread glaciomarine sedimentation in the Southern Hemisphere. At ODP Site 748 (Kerguelen Plateau, southern Indian Ocean), ice-rafted debris was found in lower Oligocene pelagic sediments. We studied the sedimentology and geochemistry of the sediments to determine the character and source of the ice-rafted debris and to place it stratigraphically relative to biostratigraphic and oxygen isotope datum levels (Brezza and Wise, 1992; Zachos et al., 1992). The stratigraphically lowest ice-rafted debris occurs at the same level as the ubiquitous early Oligocene oxygen isotope increase, providing the first direct link between Antarctic glaciation and this isotope event. Furthermore, benthic foraminiferal oxygen isotope values recorded in this ice-rafted debris interval at Site 748 (>3.0‰) are similar to those recorded in Holocene foraminifers.

SITE 748: KERGUELEN PLATEAU

The Kerguelen Plateau is a submerged, north-south–trending plateau located about 1000 km north of the Antarctic continent in the southern Indian Ocean (Fig. 1). Although tectonically active, the Kerguelen Plateau has remained stationary relative to Antarctica and the geographic South Pole since its initial formation at 110 Ma (e.g., Mutter and Cande, 1983). Because of its geographic isolation and position in the Antarctic circumpolar current, Kerguelen is an ideal location to study the history of ice-rafted debris deposition in the Antarctic region. The absence of a direct connection between the plateau and the Antarctic continent has prevented input of continentally derived material via bottom currents or turbidites, so that one can safely assume that all nonvolcaniclastic, nonoligocene material (>250 μm) deposited on this plateau has been delivered by ice.

ODP Site 748 was drilled on the southern part of the plateau in the western Raggatt Basin, east of Banراء Bank (lat 58°26.45'S, long 78°58.89'E) at a water depth of 1290 m (Schlich, Wise, et al., 1989; Fig. 1). Hydraulic piston coring yielded a nearly continuous 120-m sequence of middle Eocene to Miocene foraminifer-bearing nannofossil ooze. The major components are biogenic (calcareous nannofossils, foraminifera, diatoms, and radiolarians), indicating pelagic deposition. The nonbiogenic constituents, predominantly clays, never exceed 5% of the total sediment. Traces of terrigenous debris interpreted to be ice-rafted in origin were found in a 40-cm interval of the lower Oligocene part of the hole.

An ice-rafted debris index was developed to quantify temporal changes in debris concentration (Brezza and Wise, 1992). Only clastic grains larger than 250 μm were considered to be ice-rafted because wind transport of grains larger than this size is unlikely (Kent et al., 1971). The ice-rafted debris index is the number of detrital grains >250 μm per gram of dry weight of bulk sample. The stratigraphically lowest clastic material at Site 748 occurs within lower Oligocene sediments at 115.85 m below sea floor (bsf). The concentration of debris, mainly angular quartz sands and heavy minerals, increases over the next 20 cm and reaches a peak of

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Figure 2. Site 748 upper Eocene to lower Oligocene stable carbon and oxygen isotope record of planktonic and benthic foraminifers from 100 to 130 m below sea floor (bsf) (Zachos et al., 1992) and ice-rafted debris concentrations (grains/g) from 113 to 118 m bsf (Brezza and Wise, 1992). Core recovery, planktonic foraminifer, and calcareous nannofossil last occurrences (Berggren, 1992; Wei et al., 1992) and lithology are in left column.

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228 grains/g at 115.68 m bsf before disappearing at >115.40 m bsf (Fig. 2). The original distribution of debris was probably more limited because bioturbation tends to disseminate grains; burrows were observed over the entire length of the core. The biosiliceous component increases from <5% to 27% in the debris interval. Ichthyoliths are also common in this interval (Fig. 3B). Absence of increased grain size indicates that this is not a lag deposit (Schlich, Wise, et al., 1989).

MINERAL CONTENT

The debris mineral assemblage was determined by light microscopy, scanning electron microscopy, and energy-dispersive X-ray analysis (Breza and Wise, 1992). The major constituents are quartz, feldspar, heavy minerals, and glauconite. Quartz grains are most abundant, comprising >75% of the clastic material from the ice-rafted debris-enriched interval. Individual grains range in size from 250 μm to greater 3.5 mm (pebbles). There are three varieties of predominantly angular to subangular smaller grains: (1) gray and translucent, (2) milky, and (3) clear with inclusions. Surface textures include arc-shaped, steplike fractures and dish-shaped conchoidal fractures (Fig. 3, C and D), features typically of glacially worked grains (Krinsley and Donahue, 1968; Margolis and Kennett, 1971). In addition to quartz, seven heavy minerals were identified in the clastic material: garnet (Fig. 3, E and F), hornblende, ilmenite, mica, rutile, tourmaline, and staurolite (Fig. 3B). Green to black-green glauconite was also identified. All minerals display highly fractured surfaces.

The presence of heavy minerals in the ice-rafted debris at Site 748 clearly indicates that the debris originated from a terrane dominated by metamorphic and/or plutonic rocks. Since the Kerguelen islands and basement are predominantly basaltic tholeiites (Barron, Larsen, et al., 1989; Schlich, Wise, et al., 1989), the minerals in the ice-rafted debris must have been derived from the Antarctic continent. The only viable mechanism for transporting the larger grains from Antarctica to kerguelens is by ice-rafting.

OXYGEN ISOTOPE STRATIGRAPHY

The oxygen isotope ratios of monospecific and monogenic samples of benthic-dwelling and surface- and intermediate-dwelling planktonic foraminifera from the Eocene and Oligocene at Site 748 were determined. The oxygen isotope ratios of all species show a conspicuous positive excursion across the ice-rafted debris interval (Fig. 2) (Zachos et al., 1992). From 115.85 to 115.57 m bsf, the δ18O of benthic foraminifera Cibicidoides spp. and Gyroidina spp. increase by >1.4‰ and by 115.5 m bsf exceed 2.5‰ and 3.0‰, respectively. The 0.5‰ offset between the two, a genus-specific vital effect, remains constant (±0.1) over the entire sequence. The δ18O values of planktonic foraminifera Subbotina angiporoides, an inferred intermediate dweller, and Chilougembelina cubensis, an inferred surface dweller (Poore and Matthews, 1984; Keigwin and Corliss, 1986), increase by >1.2‰ over the same interval, peaking at 2.5‰ and 2.0‰, respectively. The δ18O values of both planktonic and benthic foraminifera remain relatively high to 114.80 m bsf, where they decrease by 0.4‰. The peak values are the highest recorded over the entire 120 m Eocene/Oligocene interval at Site 748 (Zachos et al., 1992).

CHRONOLOGY OF OXYGEN ISOTOPE AND ICE-RAFTING EVENTS

Primary age control of upper Eocene and lower Oligocene sediments is provided by calcareous nanofossil and planktonic foraminiferal stratigraphy (see Fig. 2). The Eocene-Oligocene boundary was placed at 120.5 m bsf, the level of the last occurrence of Globigerinatheca index (Berggren, 1992), and just below the last occurrence of nanofossil Renticulofenestra omozaensis, an alternative high-latitude marker species for the boundary (Wey et al., 1992). The placement of the Eocene-Oligocene boundary was independently confirmed by Sr isotope stratigraphy (Pospelch et al., 1991; Zachos et al., 1992). Using the time scale of Berggren et al. (1985), an age of 35.85 Ma was assigned to the peak of the oxygen isotope increase (Fig. 4), an age well within the range of ages estimated for the δ18O increase at other pelagic sites (e.g., Miller et al., 1987, 1988).

The deposition of debris and increase in δ18O occurred suddenly. Assuming no reworking, ice-rafting of debris is estimated to have lasted for about 100 ka. Debris accumulation began at ~35.90 Ma, at precisely the same level where the oxygen isotope increase began, peaked at 35.85 Ma, and ceased by 35.80 Ma. The high oxygen isotope values for benthic foraminifers, in excess of 2.5‰ for Cibicidoides and 3.0‰ for Gyroidina, persisted for a slightly longer period of 150 ka. The actual timing of this event may have been more brief; bioturbation has probably disseminated the ice-rafted debris beyond its original distribution. A simple model was developed to factor out the potential effects of bioturbation and to restore the original distribution of sediments (Breza and Wise, 1992). The model indicates that the original thickness of ice-rafted debris-bearing sediment may have been less than 10 cm, representing a period of less than 10 ka. Thus, the episode of ice-rafted debris deposition and high oxygen isotope values probably occurred over a period of 10 to 150 ka. The relatively brief duration of this event may explain the absence of ice-rafted debris or high oxygen isotope values in other sequences that include the Eocene-Oligocene boundary (i.e., Maup Rise, Kennett and Barker, 1990). The typical resolution employed in the sampling of Paleogene sequences, one
Figure 4. Benthic foraminiferal $\delta^{18}$O values and ice-rafted debris distributions for 34.38-36.5 Ma interval at Site 748. Age model is based primarily on calcareous nanofossil and planktonic foraminifer zonations and lime scale of Berggren et al. (1985). Distribution of ice-rafted debris or isotopes was not corrected for effects of reworking by bioturbation, as described in text.

sample per section (~1.5 m), is inadequate for detecting such short-term events.

DISCUSSION

Matthews and Poore (1980) argued for the existence of large Antarctic ice sheets during the Paleogene, with one possible period of major growth near the Eocene-Oligocene boundary. We believe early Oligocene deposition of ice-rafted debris on the Kerguelen Plateau was related to growth of a continental ice sheet on Antarctica. A viable source of icebergs is Prydz Bay to the south where thick, uniform sequences of lower Oligocene diamictites were recently recovered (Barron, Larsen, et al., 1989). The character of the Prydz Bay deposits and their location near the outer shelf suggest the presence of a partially grounded ice sheet with an extensive ice shelf, possibly larger than exists today.

One could argue, however, that large ice sheets may not be necessary to produce icebergs capable of transporting ice-rafted debris from Antarctica to the Kerguelen Plateau. For example, terrigenous debris blown onto sea ice, which can be perennial or seasonal, may be transported significant distances away from Antarctica (Kennett and Barker, 1990), or small ice sheets or alpine and valley glaciers that extend to the coast may produce icebergs large enough to survive long journeys (Brezza and Wise, 1992). It is also possible that prior to the early Oligocene, ice sheets were present (Barron, Larsen, et al., 1989), but were producing icebergs with trajectories or sea-surface temperatures that kept them close to the Antarctic margin (Wise et al., 1991). One major repercussion of scenarios that require no change in ice volume, however, is that the entire early Oligocene oxygen isotope increase must be attributed to a temperature decrease of about 6°C. Three simple observations of fossil and oxygen isotope records show this to be highly unlikely. First, paleontological studies have revealed no turnover in benthic foraminifera assemblages during the early Oligocene at this or any other deep-sea location (e.g., Thomas, 1991; Mackensen and Berggren, 1992). A temperature decrease of that magnitude should have had some effect on benthic assemblages, if not because of cooling alone, then possibly by the associated effects on the chemistry of deep waters (i.e., dissolved oxygen, pH). Second, several workers have demonstrated that the early Oligocene oxygen isotope increase was ubiquitous, with at least 0.3°/00-0.4°/00 recorded in both planktonic and benthic foraminifers at all DSDP and ODP sites with continuous records (Matthews and Poore, 1980; Poore and Matthews, 1984; Keigwin and Cortiss, 1986; Miller et al., 1987; Zachos et al., 1992). This pattern is observed at Site 748 as well; the $\delta^{18}$O values of planktonic and benthic foraminifers show a high degree of covariance during the increase (Fig. 2). This observation supports the interpretation that at least a sizable fraction of the oxygen isotope increase was ice volume related since the alternative interpretation, a uniform decrease in global temperatures, seems climatically unattainable. Because many of these older sections were sampled at >500 ka intervals, they probably underestimate the shorter term peak increase in $\delta^{18}$O.

The third observation involves consideration of absolute oxygen isotope values and estimates of ice volume and bottom-water temperature. Within the ice-rafted debris interval at Site 748, peak $\delta^{18}$O values recorded by specimens of Gyroidina—a genus thought to have precipitated its test in near isotopic equilibrium with seawater (Shackleton, 1984)—exceed 3.0°/00 (PDB). These values are very high for pre-Negocene benthic foraminifer $\delta^{18}$O values, which, with the exception of a mid-Oligocene excursion, rarely exceed 2.5°/00 (e.g., Miller et al., 1987; Prentice and Matthews, 1988; Kennett and Stott, 1990). In fact, values of this magnitude are more typical of values obtained for Pliocene-Pleistocene benthic foraminifers. The implications of this observation are relatively straightforward. If one were to assume that the isotopic composition of the early Oligocene ocean was lower than today, as would be expected for a world with less continental ice volume, the calculated bottom-water temperatures over the Kerguelen Plateau would have had to have been colder than present-day temperatures (e.g., Miller et al., 1987). Only if we assume a mean ocean $\delta^{18}$O value similar to the present-day value (0.30°/00 SMOW) can ~2°C bottom-water temperatures be obtained. This simple but important observation indicates that the effect of the early Oligocene Antarctic ice sheet(s) on mean ocean $\delta^{18}$O was similar to that of present-day Antarctic ice.

Why would a large ice sheet suddenly appear on Antarctica in the early Oligocene and for only a brief period? It is generally believed that the long-term cooling of the high southern latitudes during the Eocene was caused by the gradual thermal isolation of Antarctica brought about by tectonic widening of oceanic passages between Antarctica and Australia and South America (Kennett and Shackleton, 1976). Ice sheets may have formed suddenly when seasonal temperatures in Antarctica fell below a certain threshold level. Modeling experiments have indicated that climatic response to gradual changes in boundary conditions can be rapid as "critical" threshold conditions are surpassed (e.g., Crowley and North, 1988). Furthermore, because of nonlinear responses of feedback mechanisms, during such transitions, an unstable nonequilibrium state may be temporarily achieved. The initial growth of ice sheets, coupled with cooling in high latitudes and changes in atmospheric and oceanic circulation patterns, may have generated short-term positive feedbacks in the ocean-atmosphere system that briefly promoted further ice-sheet expansion. Thus, the brief appearance of a large ice sheet during the early Oligocene may simply represent a transgression of equilibrium during the abrupt transition between a nonglaciated and glaciated world.

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