Antarctic Glaciation during the Tertiary Recorded in Sub-Antarctic Deep-Sea Cores

Abstract. *Study of 18 Cenozoic South Pacific deep-sea cores indicates an association of glacially derived ice-rafted sands and relatively low planktonic foraminiferal diversity with cooling of the Southern Ocean during the Lower Eocene, upper Middle Eocene, and Oligocene. Increased species diversity and reduction or absence of ice-rafted sands in Lower and Middle Miocene cores indicate a warming trend that ended in the Upper Miocene. Antarctic continental glaciation appears to have prevailed throughout much of the Cenozoic.*

An analysis of 18 Cenozoic sub-Antarctic cores taken in the Pacific sector (90° to 160°W; see Table 1) has been conducted in an effort to determine what relations, if any, exist between planktonic foraminiferal diversity, quartz origins, climatic changes in the Southern Ocean, and possible glaciation of Antarctica during Cenozoic times.

Analyses carried out were (i) the study of planktonic Foraminifera for age determinations and for measurement of species diversity, which may act as a paleotemperature indicator (*1*, *2*); (ii) the examination of surfaces of indigenous quartz sand grains by scanning electron microscopy, with the techniques and environmental criteria described by Krinsley and Margolis (*3–5*); (iii) determination of the percentage of quartz sand grains in the nonbiogenic > 63-μm fraction from selected horizons by means of point count methods (*6*).

Ages for the Lower and Middle Cenozoic cores were obtained by correlation of moderately abundant planktonic foraminiferal assemblages with established Southern Hemisphere temperate zonations (*7*). The dominant high-latitude planktonic foraminifer during the Lower and Middle Eocene was *Acarinina primitiva*. Cores E13-4 and E24-8 both contain *Globorotalia eaqua rex* of Lower Eocene age. The occurrence in cores E24-9 and E24-10 of both *A. primitiva* and *Globigerapsis index* indicates an upper Middle Eocene age. In core E23-19 the abundant occurrence of *Catapsydrax dissimilis* indicates an Upper Oligocene to Lower Miocene age. Other Foraminifera were not particularly diagnostic, but the occurrence of calcareous nannoplankton indicates an Oligocene age (*8*). An upper Lower Miocene age for core E21-2 is based on an association of *Globigerina woodi connecta, Globigerinoides trilobus trilobus*, and *Globorotalia zealandica*. The association in core E24-16 of *Globigerinoides trilobus trilobus, Globorotalia nana pseudocontinuosa*, and *Globorotalia zealandica* indicates an upper Lower Miocene or lower Middle Miocene age. Cores E21-13 and E21-3 both contain *Praeorbulina glomerosa* and *Globorotalia mayeri barisanensis* of middle Middle Miocene age. Core E25-11 contains *Globorotalia puncticulata* and Upper Pliocene Radiolaria. Evidence for ages of the remaining cores in this study based on various criteria have been presented previously (*9–11*).

Surface features of quartz sand grains can reflect their transportational and depositional history (*3, 4, 12*). Because of the remoteness of all of these cores from land, it can be assumed that quartz sand (> 63 μm) is primarily the result of either ice-rafting from Antarctica or of transport by turbidity currents. Quartz of atmospheric origin has been reported from the Pacific (*13*), but its size range is generally between 3 and 10 μm. Studies of Recent glacial-marine and deep-sea turbidite sands (*3, 14*) show that sands transported by either process may be distinguished by their surface microtextures (Fig. 1): grains of glacial and iceberg origin (Fig. 1, a, b, d, f, and g) exhibit large-scale conchoidal fractures, breakage blocks, striations, and high relief (*12*); grains of turbidite origin typically show rounded outlines and a high degree of abrasion pitting, attributed to turbulent subaqueous impact. Textures of glacial origin with superimposed rounding and abrasion pitting (Fig. 1e) are considered by us to result from reworking of pre-

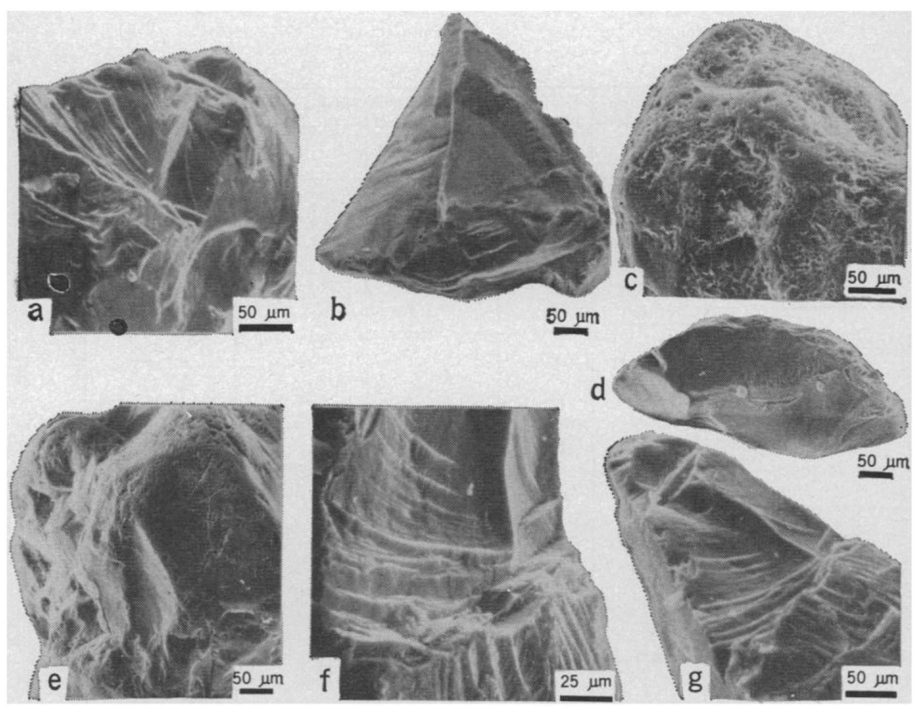

Fig. 1. Scanning electron micrographs of quartz sand grain surfaces. Bar scales indicate magnifications. (a) Grain from 450 cm in core E24-8 (Lower Eocene), which shows sharp, irregular outline and high relief. (b) Grain from basal ice, 3 m above ice-rock interface, Byrd Station deep drill hole, Antarctica (*31*). It shows large conchoidal fracture, striations, lack of chemical etching, and sharp pointed edges. (c) Grain from 402 cm in core E21-3 (Middle Miocene). It shows rounded outline and V-shaped abrasion pits indicative of subaqueous impact, such as produced in deep-sea turbidity currents. Compare with angular outline and fresh sharp fractures in (b). (d) Grain from glacial-marine deposit of late Miocene or Pliocene age from Northern Pacific, Scripps core CK13-3 (*10*). (e) Grain from 302 cm in core E21-2 (Lower Miocene), which shows rounding and abrasion pitting superimposed on original glacial features. These features resulted from subaqueous impact of an original glacial grain. (f) Grain from 450 cm in core E24-9 (upper Middle Eocene), which shows typical glacial textures. (g) Grain from 648 cm in core E23-19 (Upper Oligocene), which again shows typical glacial textures.

existing glacial sediments by turbulent subaqueous transport (*15–17*).

Quartz sand grains that exhibit surface features identical with those on Recent ice-rafted quartz grains have been found in sediments older than the Lower Miocene—in the cores of Middle and Lower Cenozoic age (Fig. 2). In contrast, Lower and Middle Miocene sediments are characterized by an apparent absence of typical ice-rafted grains. Sand grains from sediments of these ages exhibit surface features attributed to transport to deep water by subaqueous turbulent flows. Many grains in three of these cores (E21-2, E24-16, and E21-13) have a combination of glacial features with superimposed abrasional features similar to those reported on Recent reworked glacial sands from the Atlantic, Antarctic, and Bering continental shelves (*15, 17, 18*). The absence of any typical glacial grains in the Lower and Middle Miocene sediments precludes the possibility that the grains represent ice-rafting of previously reworked shallow-water sediments from near Antarctica. Of the cores with high quartz percentages (> 5 percent), all but one (core E21-2) contain only quartz of ice-rafted origin. This indicates that ice-rafting has been the dominant transporting agent of quartz sand in this sector of the sub-Antarctic Pacific. In the present-day southeastern Pacific (100° to 160°W) the maximum northern limit of iceberg drift, and thus of ice-rafted debris, is in central sub-Antarctic waters at about 45°S (*19*). The presence of ice-rafted debris in Lower and Middle Eocene cores north of this latitude indicates either Southern Ocean conditions that were slightly cooler than at present, or more northerly iceberg tracks produced by changes in wind and current systems. The latitudinal position of these cores has not altered significantly because sea-floor spreading in this area is principally in a west-northwest to east-southeast direction (*20*). According to sea-floor spreading rates and directions derived from magnetic anomaly patterns (*20–22*), we have calculated that cores E24-8, E24-9, E24-10 (Eocene), and DWHG-34 (Lower Oligocene) have been displaced in a west-northwest direction by no more than 3° of latitude since deposition, if a constant spreading rate of 3 cm per year is assumed from the crest of the East Pacific Rise (*20*). Similarly, cores E13-4 (Lower Eocene) and E23-19 (Upper Oligocene) have been displaced in an east-southeast direction by no more than 3° of latitude. The position of Antarctica during the Cenozoic is unknown, although various spreading models have been constructed (*21, 23*) on the assumption that Antarctica has remained in essentially its present-day position since the early Cenozoic. The absence of ice-rafted material in Lower and Middle Miocene cores may conceivably be related to their more northern location, although it seems reasonable to suppose that all were within the limits of iceberg drift at times during the Cenoboic. One Middle Miocene core (E21-13) is, however, not only within present-day iceberg limits but is slightly farther south of Lower and Middle Eocene cores that are outside present-day iceberg limits and yet have abundant ice-rafted material.

Fluctuations in the percentage of glacially derived quartz (Fig. 2) in cores of different ages may represent oscillations in temperature of the Southern Ocean, with higher percentages reflecting larger amounts of iceberg transport to sub-Antarctic water, a higher degree of glaciation on the Antarctic continent, or both. On the other hand, increases may have been due to larger amounts of debris carried in icebergs, which in turn resulted from higher erosive powers of Antarctic glaciers or greater subaerial weathering (*24*). If higher quartz percentages do reflect cooler conditions related to more intensive glaciation, the coldest conditions in pre-Upper Miocene times appear to have been during the lowermost Eocene (core E13-4), upper Middle Eocene (core E24-9), and the Upper Oligocene (core E23-19).

These suggested paleoclimatic trends have been independently investigated by using average planktonic foraminiferal diversity. Changes in number of species in the Cenozoic probably largely indicate temperature fluctuations, with fewer species occurring in cooler waters. Low foraminiferal diversity (Fig. 2) indicates a rather cool Southern Ocean throughout much of the Cenozoic. Furthermore, approximately reciprocal relations exist between sub-Antarctic foraminiferal diversity and percentage of ice-rafted quartz, with the lowest diversity coinciding with high quartz percentages in cores of lowermost Eocene and Upper Oligocene

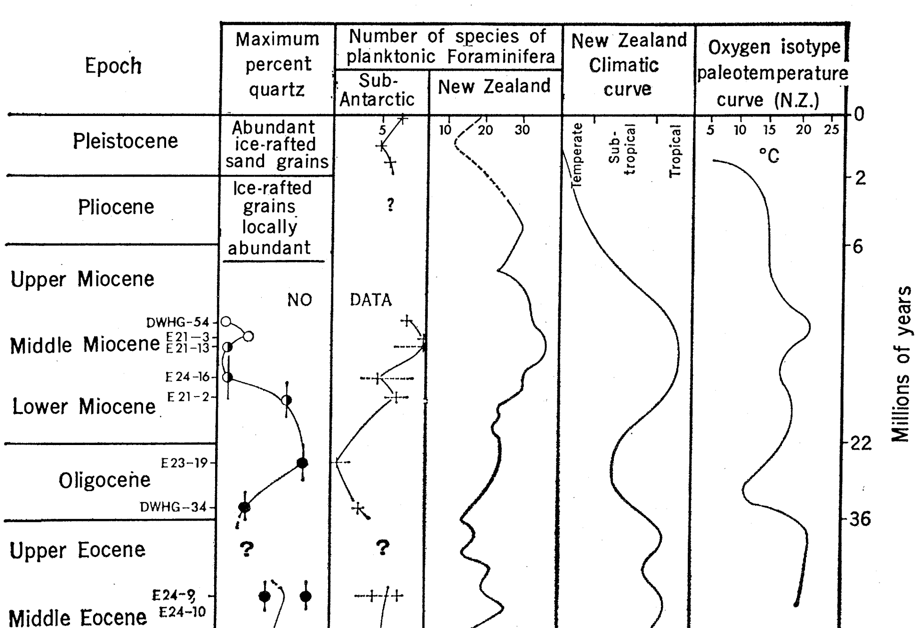

Fig. 2. Curves that show fluctuations in percentage of quartz (63 μm) and planktonic foraminiferal diversity in sub-Antarctic Cenozoic deep-sea cores. Note the approximately reciprocal relationship that reflects paleotemperature oscillations of the Southern Ocean. The degree of ice-rafting of quartz sand (the grains with glacial features) has varied in response to associated paleoglacial changes in Antarctica. The sub-Antarctic curves are compared with New Zealand planktonic foraminiferal diversity curves (*1*), paleoclimatic curves (*25*), and paleotemperature curves (*27*). In column 2 (the percentage of quartz graph), the following symbols are used: ●, glacial features; ○, abrasion-impact features; ◑, mixture of both. Also in column 2, the age ranges are shown by vertical lines. In column 3, average diversity for each core is shown by crosses, and diversity range by dashed lines.

Table 1. Data for cores.

Core	Age	Latitude (°S)	Longitude (°W)	Depth (m)	Length (cm)
13-4	Lower Lower Eocene	57°46′	90°48′	3052	1677
24-8	Lower Eocene	42°53′	134°39′	4986	525
24-9	Upper Middle Eocene	40°35′	135°08′	4753	578
24-10	Upper Middle Eocene	37°58′	134°59′	4784	209
DWHG-34	Lower Oligocene	44°13′	127°20′	4600	111
23-19	Upper Oligocene	57°36′	115°09′	4004	960
21-2	Upper Lower Miocene	32°59′	87°57′	3640	445
24-16	Upper Lower to Lower Middle Miocene	35°13′	124°59′	3913	1150
21-13	Middle Miocene	43°59′	120°03′	3925	340
21-3	Middle Middle Miocene	34°57′	91°57′	3603	508
DWHG-54	Upper Middle Miocene	38°49′	83°21′	4080	90
13-17	Upper Miocene to Recent	65°41′	124°06′	4720	2642
14-8	Upper Miocene to Recent	59°40′	160°17′	3875	1830
13-3	Pliocene to Recent	57°00′	89°29′	5090	1603
25-11	Upper Pliocene to Recent	50°02′	127°31′	3949	649
21-5	Upper Pliocene to Lower Pleistocene	36°41′	93°38′	3121	483
21-17	Middle Pleistocene to Recent	55°28′	119°56′	2802	1004
15-16	Middle Pleistocene to Recent	56°03′	119°55′	3039	1200

age and the highest diversity coinciding with an apparent absence of ice-rafted quartz in cores of Middle Miocene age. The Lower Oligocene core (DWHG-34) is anomalous in having low diversity and low quartz percentage, although the sand grains examined from this core exhibited typical glacial surface textures. At present, sediments of Upper Eocene age have not been recovered from this segment of the Pacific.

A sub-Antarctic planktonic foraminiferal diversity curve (Fig. 2), although lacking details, is similar to one for the New Zealand area (*1*) except during the Oligocene. Both indicate relatively low diversity in the Eocene and Oligocene, however, and a steady increase from the Oligocene to a peak in the Middle Miocene, which possibly represents the climax of Cenozoic climatic warming. In addition, an apparent marine Oligocene cooling and Middle Miocene climax of warming have been indicated in New Zealand, with other criteria, by Hornibrook (*25*), Devereux [(*26, 27*); see Fig. 2], and Edwards (*28*).

Paleoclimatic studies of Lower to Upper Cenozoic sub-Antarctic sediments therefore show that the Antarctic continent was glaciated at least at times during the Lower and Middle Eocene and during the Oligocene. Insufficient numbers of cores are available at the moment to determine if essentially unglaciated intervals also occurred during these epochs. Furthermore, the extent of glaciation is still unknown, but glaciation would need to have been sufficiently extensive to cause considerable ice-rafting of continental sediments to present-day sub-Antarctic regions. The Lower and Middle Miocene were considerably warmer (as indicated by faunal diversity), and no marine evidence of glaciation is available, although the Jones Mountains possibly glaciated more than 10 million years ago (*29*). A cooling trend commenced near the end of the Miocene, which led to Antarctica's Pleistocene glaciation (*9, 30*).

Changing glacial conditions on Antarctica have almost certainly played an important role in glacioeustatic sea-level changes throughout much of the Cenozoic and in worldwide climatic change. Continued coring operations in the Southern Ocean will inevitably delineate Antarctica's paleoglacial history.

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6. Cubic plugs (8 cm^3 before desiccation) were taken at intervals of approximately 50 cm down the cores, were weighed dry, and were washed over a 63-μm Tyler screen. A modified Otto microsplitter was used to obtain a representative sediment fraction. The detrital fraction in pre-Miocene cores typically consists of poorly sorted angular quartz sand grains from 0.25 to 3 mm in diameter, a few rock fragments, and micromanganese nodules. The percentage of quartz was computed from a point count of either 300 detrital grains from each sample or on the total number of grains present in samples with less than 300 grains. No grains smaller than 63 μm were examined. Twenty-five grains from each sample were examined with the scanning electron microscope.
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