Fossil diatoms indicate that an active photic zone was present in the Ross Sea region during the late middle Miocene. Erratics suggest floating ice, but it is not possible to prove the existence of winter pack ice.

One sample, taken 92 cm below the sediment layer of the sea bottom and examined for pollen, contained a fairly low pollen content in a moderate state of preservation (Table 1). *Nothofagidites* spp. far outnumber all the others. This assemblage is similar to a late Oligocene assemblage from the Ross Sea (*4*), except that it is less diverse.

Assemblages of this general character are found in southeastern Australia from the middle Eocene to the middle Miocene, and the poor representation of *Proteacidites* spp. favor the latter part of this time range. Barrett and Kemp (*4*) found that *Proteacidites* spp. were well represented in their late Oligocene assemblage, so that poorer representation in J9 is consistent with a later age. The decreased diversity would be consistent with the hypothesis that conditions for plant growth were harsher with a larger ice cap in the middle Miocene than with a lesser ice cap in the late Oligocene (*5*), provided that the decreased diversity not be the result of comparing the one sample here with a composite assemblage of more than one sample (probably four) examined by Barrett and Kemp. The most notable difference between the late Oligocene assemblage and J9 is the lack of *Myrtaceidites* spp. (Myrtaceae) in the latter.

These spores and pollen may have been derived from vegetation nearby or they may have been recycled in the glacial flour or erratics. Modern sediments on the Antarctic continental shelf contain recycled spores and pollen ranging in age from Palaeozoic to early Tertiary (*4*). Nonetheless, no forms have been obviously recycled or are of a different age in the J9 sample.

The assemblage suggests vegetation of low diversity, probably restricted to the most favorable habitats by the coast and between the glaciers. It appears to have changed little since the Eocene, and taxa that had evolved in the Eocene or later (for example, Gramineae and Compositae) were probably unable to become established under the harsh conditions there. The reduction in diversity probably continued until all vegetation was eliminated from Antarctica.

The pollen assemblage in these sediment cores is wholly consistent with the middle Miocene age of the diatoms. At that time the Ross Sea, with a productive photic zone, was not covered with permanent ice but was receiving a steady input of glacial flour and erratics from the continent. Continental vegetation would have been similar to that of Australia, New Zealand, and South America but with a much reduced diversity.

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Ross Ice Shelf Sea Temperatures

Abstract. *Two temperature profiles recorded by a sensitive bathythermograph at the Ross Ice Shelf Project site (82°22.5′S, 168°37.5′W) are presented. From the shape of the profiles it is concluded that an inflow of water at intermediate depths provides a source of heat to drive a regime in which ice is melted from the interface at a depth of 360 meters. Melting maintains the temperature of a thick layer under the ice at about −2.14°C, close to the ambient freezing temperature. A very well mixed layer about 35 meters thick was found at the seabed.*

The hydrology of the water under the Ross Ice Shelf has long been a matter for conjecture. In December 1977 a hole was drilled through the ice at 82°22.5′S, 168°37.5′W as part of the Ross Ice Shelf Project (RISP). This is a report on some measurements obtained with a bathythermograph designed to have high sensitivity. The sensitivity was gained at the expense of response time, which was about 4 seconds.

An instrument was assembled to record temperature (20 bits) and pressure (12 bits) internally once per second on a digital tape cassette. The temperature transducer was a quartz crystal oscillator system made with components from a previously described instrument (*1*). Pressures were detected by an oscillating taut-wire transducer. The least significant bit corresponded to a change of 4×10^{-5} °C for the temperature data channel and 0.4 decibar (equivalent to about 0.4 m of water depth) for the pressure channel. It was intended to lower the instrument at a steady rate and to use smoothing during processing to specify the spacing between sampling depths, thus overcoming the limited pressure resolution.

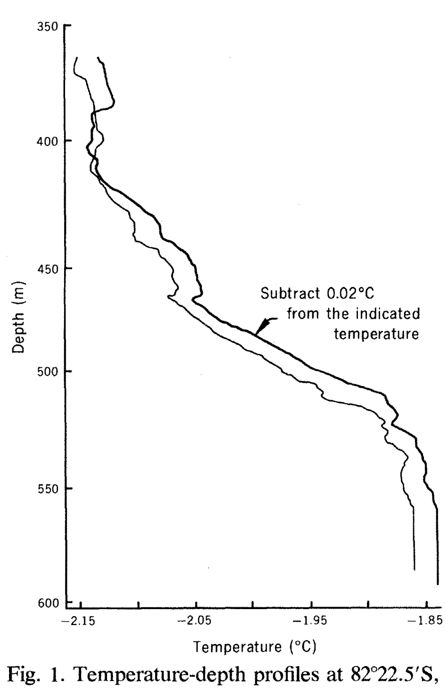

Fig. 1. Temperature-depth profiles at 82°22.5′S, 168°37.5′W.

Data are shown in Fig. 1. The first profile was obtained at approximately 0400 hours Greenwich mean time, 24 December 1977, and the second, which has been offset to the right in Fig. 1 by 0.02°C, was obtained 8 hours later. The ice thickness was 420 m, the ice-water interface was at 360 m, and the sea depth was 597 m.

The first profile was obtained by lowering the instrument at about 0.08 m/sec, the minimum rate possible with the winch. Because the rate was not quite regular, the second profile was obtained by raising the instrument at about the same rate. To penetrate the slush ice at the water surface in the hole, the instrument was used with an additional lead weight suspended below the temperature sensor level. This would not affect the profiles very much because of the low travel rates. The raw data from the second profile may be slightly impaired by heat loss from the instrument, although this would not appear in Fig. 1.

Figure 1 shows a region about 50 m thick just below the ice with temperatures in the range $-2.13°$ to $-2.16°C$; this is close to the freezing point of seawater at these depths. Jacobs *et al.* (*2*) observed salinities of about 34.39 per mil close to the interface. The corresponding freezing point, based on the formula of Fujino *et al.* (*3*), is $-2.16°C$. Differences between the two profiles are most marked in this region below the interface. There are discontinuities in the profile slopes at about 460 m. Between 400 and 560 m the temperature generally increases with depth, but there are a number of layers from 1 to 10 m thick where the temperature decreases with depth. Below 560 m the temperature is very uniform.

Glaciological evidence indicates that melting occurs at the undersurface of the Ross Ice Shelf near its northern margin. Zumberge (*4*) concluded that the rate of melting decreased toward the south and that freezing might occur in the southern shelf. However, the increase of temperature toward the bottom shown in Fig. 1 suggests that melting is occurring.

Aspects of the hydrology of the Ross Sea have been described by Jacobs *et al.* (*2, 5*). Although a full description of the circulation under the shelf is not available, it is apparent that the water passing under the shelf cannot be much above the freezing point. Because of the high value of the latent heat of melting, for every (net) cubic meter of meltwater produced, there must be many cubic meters of water exchanged across a boundary defined by the northern edge of the Shelf.

Figure 1 is consistent with a circulation in which water flows in from the north at middle depths, heat being transferred through a layer under the ice by convective and mechanical mixing processes, producing meltwater. Because of the net buoyancy production there will be a tendency for the water layer just under the ice to form an outflow.

To stabilize the water column it is required that there be an increase of salinity with depth. The mechanism by which this is produced, and by which heat is transferred upward from the deeper water, is not apparent from the limited data. There seems to be no pronounced "step" structure in the temperature profiles that could be associated with vertical heat transport by processes involving double diffusion.

Below 560 m the profiles indicate very homogeneous water. A straight line was fitted to the data for the lower 20 m of the first profile, using smoothed pressure data. The root-mean-square deviation for the temperature data was about 4×10^{-5} °C and the slope corresponded to a temperature increase with depth of 0.034°C per 10^3 decibars. An approximate value of 0.027°C per 10^3 decibars for the expected adiabatic temperature gradient in well-mixed water was calculated from a formula of Fofonoff (*6*), assuming a salinity of 34.82 per mil based on data from Jacobs *et al.* (*2*).

The presence of this exceptionally well-mixed water would be consistent with the complete breakdown of any stratification in a boundary layer over the seabed. Very homogeneous water is not usually found in the sea except when trapped by a sill, and this is a possibility. Under these conditions geothermal heat flux, which is typically about 4.2×10^{-2} J m^{-2} sec^{-1} ($1 - 10^{-6}$ cal cm^{-2} sec^{-1}), can cause convective mixing.

The fact that there is no water at the seabed as cold as that at the ice-water interface suggests that melting is taking place. It seems reasonable that this should be the case since the sea, with its great capacity for horizontal heat advection, lies below a thick thermally insulating layer of ice. The presence of the well-mixed layer at the seabed is curious unless the flow velocities there are very low.

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Circulation and Melting Beneath the Ross Ice Shelf

Abstract. *Thermohaline observations in the water column beneath the Ross Ice Shelf and along its terminal face show significant vertical stratification, active horizontal circulation, and net melting at the ice shelf base. Heat is supplied by seawater that moves southward beneath the ice shelf from a central warm core and from a western region of high salinity. The near-freezing Ice Shelf Water produced flows northward into the Ross Sea.*

Floating shelves of glacial ice ring half of the Antarctic coastline and constitute nearly 15 percent of the ice sheet. A knowledge of the amount of melting, cooling, and freezing that occurs beneath these ice shelves is important to an understanding of the oceanography of the adjacent oceans, and to the mass balance of the ice sheet (*1*). Oceanographic measurements were made between 15 December 1977 and 3 January 1978 through an access hole melted through the Ross Ice Shelf at 82°22.5′S, 168°37.5′W (J9) (*2*). In the Ross Sea, observations were made along the shelf terminal face (barrier) in December 1976 and January 1978 from the U.S. Coast Guard icebreakers *Northwind* and *Burton Island* (*3*).

The *Northwind* temperature and salinity observations adjacent to the ice shelf (Fig. 1) are similar to other austral summer measurements made from *Burton Island* and *Eltanin* (*4*). The density field is determined primarily by the salinity distribution, and there is less stratification than in temperate and tropical seas. The shallow pycnoclines on stations 31 through 27 and 11 through 10 lie beneath surface water freshened by melted sea (pack) ice. The pycnocline extending from near bottom on station 23 to near surface on station 17 separates water of low salinity on the eastern shelf from water of high salinity (Ross Sea Shelf Water) in the western sector. The latter water mass, which forms primarily from freezing at the sea surface, has the highest salinity and density of any seawater in the Antarctic oceans. It is concentrated in the western Ross Sea by the cyclonic circulation pattern on the continental shelf and by geostrophically induced upwelling along the Victoria Land coast (*5*).

We have observed a warm core of water near the depth of the ice shelf terminal face on three cruises on which measurements were made along the barrier between 170° and 180°W. In Fig. 1 it is approximately 200 km wide and averages 100 m thick, with a mean temperature near 0.5°C above freezing and a salinity near 34.5 per mil. The warm core originates over the continental slope in the upper levels of the Circumpolar Deep Water (*4*). Its position along the barrier

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