of 144 and 129, respectively, for amplitude in centimeters and depth in meters, yielded minimum root-mean-square errors of 1.0 and 2.4 cm. This observed relationship, together with a map of water-layer thickness beneath the ice shelf (*7*), was used to guide the location of the K_1 and O_1 coamplitude contours.

The spatial variation of the M_2 constituent is more complicated. The condition that our cotidal lines merge with the global M_2 cotidal chart of Zahel (*8*) requires a complex pattern of cotidal contours within the Ross Sea. The pattern presented in Fig. 1 displays no amphidromic points in the region, and none are definitely indicated by the amplitude data (Table 1). Other patterns requiring at least two amphidromic points in the Ross Sea are also consistent with Zahel's charts. For M_2 there is no simple relationship between amplitude and water-layer thickness. We would expect the complex cotidal contours to preclude a relationship analogous to the canal-type dependence observed for the diurnal constituents.

The ocean tide in the southern Ross Sea is dominated by the diurnal constituents. In this respect it is different from the tide in most parts of the world ocean, where the semidiurnal constituents are usually the largest. The range of tropic tide is between 1 and 1½ m along the northern edge of the ice shelf, near 78°S, and increases to more than 2 m toward the southeast, near the Siple Coast. The equatorial range is generally less than one-third of the tropic range. The amplitudes of the diurnal constituents, particularly K_1 and O_1, are too large to be explained simply in terms of the lunisolar tide-raising force [equilibrium tide theory (*4*)]. They are also larger than might be anticipated from their amplitudes in the southern Pacific Ocean (*9*). Thus a diurnal resonance related to the shape of the embayment and the water depth is indicated. The wavelengths of the diurnal constituents are seen (Fig. 1) to be approximately four times the length of the Ross Sea, measured in the direction of a progressing tide from the edge of the continental shelf. This is a condition for diurnal resonance.

Waves having periods in the range 1 to 15 minutes and amplitudes near 1 cm are superposed on the tidal water-level fluctuations beneath the Ross Ice Shelf (*5*). These waves appear on the tidal gravity records from all our recording sites. On our field records the dominant wave periods are between 1 and 2 minutes near the northern margin of the ice shelf. The waves are attenuated with increasing distance from open water, and the shorter periods are attenuated relatively rapidly so that in the region farther south than 84°S the dominant period is near 10 minutes.

To obtain data on the speed and direction of propagation of these waves, we operated three gravimeters simultaneously in a 5-km triangular array near site J9 (Table 1). From 22 to 26 November 1977 we obtained more than 38 hours of simultaneous data in five segments, varying in length from 2½ to 16 hours. These data were digitally recorded at 4-second intervals by microprocessor-based digitizers of our own design. Before the 1977–1978 season, our data were recorded on strip-chart recorders having a paper speed of 1 inch per hour, and data in the period range 1 to 15 minutes were not well recorded. Figure 3 shows 200-minute segments from the three gravimeter records and the orientation of the array.

We calculated the wave speed and direction from the time offsets of the wave between the three recording sites. The time shifts along each leg of the array were determined by cross-correlating the simultaneous record segments from the two stations on the leg. We found the wave speed to be 57 ± 11 m/sec and the wave direction to be N139°E ± 10° (Fig. 3). The wave speed is consistent with the speed of a flexural wave (*10*), given the ice and water-layer thickness at site J9. For wave periods greater than 9 minutes this speed is the same as the shallow-water gravity wave speed, and is 48.3 m/sec for the 238-m water thickness at J9. The influence of the ice layer increases the flexural wave speed to 50.5 m/sec at the 6-minute period, and 62.5 m/sec at the 3-minute period. We found that our data were not adequate to resolve the subtle difference in wave speed at different periods in the range 3 to 9 minutes, but the value of 57 m/sec that we measured is appropriate as an average for the periods evident on the records (Fig. 3). The direction of propagation is consistent with the supposition that the flexural waves are excited at the ice front by infragravity waves in the open ocean north of the ice shelf.

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Tritium and Carbon-14 Distributions in Seawater from Under the Ross Ice Shelf Project Ice Hole

Abstract. *The tritium and carbon-14 activities of seawater samples collected from 22 to 200 meters below the ice at the Ross Ice Shelf Project ice hole are reported. The tritium results show that the waters below the ice have exchanged with Ross Sea water since the advent of nuclear testing. The carbon-14 results indicate that waters in the upper layer exchange in time periods of less than 6 years. Measurements of these isotopes in seawater under the Ross Ice Shelf in McMurdo Sound show that this water has a different history.*

Tritium and carbon-14 were introduced into the atmosphere in major quantities as a result of nuclear weapons testing in the early 1960's. Tritium (half-life, $t_{1/2}$ = 12.3 years) is a valuable tracer since it is a radioactive isotope of hydrogen and will follow the path of water exactly in the world ocean (*1*). There are no particulate or biological effects that will alter tritium concentrations in seawater. The natural concentrations of tritium present before the bomb tests are negligible as compared to the amounts produced by weapons testing and can be ignored (*2*). Tritium concentrations attained a maximum of 1 to 2 tritium units [1 TU is one tritium atom per 10^{18} hydrogen (protium) atoms] in the late 1960's and early 1970's and have been decreasing since then. Tritium found in seawater

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under the Ross Ice Shelf must have been brought in within the last 20 years. Carbon-14 ($t_{1/2}$ = 5730 years) is added to surface seawater by gas exchange across the air-sea interface. As explained below, it appears that ^{14}C concentrations are still increasing in Ross Sea surface water.

During the Ross Ice Shelf Project of 1977–1978, seawater samples were collected at the J9 drilling site (82°22.5′S, 168°37.5′W) 400 km south of the edge of the Ross Ice Shelf. The samples were analyzed for tritium and the ^{14}C activity of dissolved inorganic carbonate (DIOC) by the Mt. Soledad Tritium and Radiocarbon Laboratory. Four tritium samples and one ^{14}C sample from the water column under the drilling site were analyzed by gas proportional counting (*3, 4*) (Table 1). The ^{14}C activities are reported as $\Delta^{14}C$ (*5*). The blank for the tritium samples is 0.1 TU, and the uncertainty in the data is ± 0.1 TU.

The tritium concentrations in the upper 100 m of the seawater at site J9 are similar to a surface tritium concentration of 0.5 TU reported by Jacobs (*6*) for seawater from the open Ross Sea during the austral summer of 1976–1977. Thus water under this area of the Ross Ice Shelf may be rapidly renewed. Since tritium concentrations were higher in the past (*7*), it is also possible that the water under the Ross Ice Shelf is older water that has had its tritium concentration modified under the ice shelf by decay and mixing with low-tritium water. There could also be mixing during the winter in the open Ross Sea before the water flowed under the Ross Ice Shelf. However, the presence of tritium concentrations of 0.5 TU under the shelf indicates that this water has been renewed within the period since the nuclear weapons testing (1957 through 1962) in the atmosphere.

Tritium concentrations below 110 m are lower but still above the blank value. There is evidence of a possible minimum of 154 m, but the difference in results is close to the uncertainty level of the measurements. The deeper water layer has a temperature of approximately −1.86°C (*8*), and the 200-m sample can be considered Ross Sea Shelf Water (RSSW) (*9*). The presence of measurable amounts of tritium in RSSW shows that surface water has been mixed into it since the advent of nuclear weapons testing.

Very few ^{14}C measurements have been obtained in the Ross Sea. Rafter (*5*) collected several samples in that area in 1960 and found $\Delta^{14}C$ values of less than −200 per mil at the sea surface. Measurements of $\Delta^{14}C$ made by researchers at this laboratory in surface water just north of the Ross Sea in 1971 were on the order of −100 per mil (*4*). Krill collected at 77°05′S, 172°44′E, in 1972 was found to have a $\Delta^{14}C$ = −107 per mil (*10*). This value is close to the values found in seawater just north of the Ross Sea. If it is assumed that the ^{14}C contents of krill are similar to those found in DIOC, then the $\Delta^{14}C$ value for the Ross Sea water in the early 1970's was less than −100 per mil.

Table 1. Tritium and ^{14}C contents of seawater at the J9 drilling site (the depths are below the lower edge of the Ross Ice Shelf).

Depth (m)	TU	$\Delta^{14}C$ (per mil)	Salinity (per mil)
22	0.47	−74 ± 8	34.374
110	0.50		34.506
154	0.24		34.698
200	0.35		34.810

Table 2. Tritium and ^{14}C contents of McMurdo Sound seawater, 1977.

Position	Depth (m)	TU	$\Delta^{14}C$ (per mil)
166°20′E, 77°52′S	5	0.82	− 69 ± 7
163°54′E, 78°13′S	10	0.64	−109 ± 7
164°38′E, 77°57′S	9	0.53	−114 ± 7
167°21′E, 78°01′S	5	0.57	−106 ± 7

The most recent measurements were made in McMurdo Sound in 1977 (*11*). Carbon-14 samples were collected from both sides of the sound and from two sites on the western side of the Ross Ice Shelf. Results of the ^{14}C and tritium analyses of these samples are given in Table 2. The sample on the east side of McMurdo Sound had a $\Delta^{14}C$ value of −69 per mil, whereas the other samples had $\Delta^{14}C$ values of −106 to −114 per mil. Tritium measurements showed the same trends. Thus, surface waters from two different sources were present in McMurdo Sound. McMurdo Sound receives surface water from both the open Ross Sea and from under the Ross Ice Shelf. The water on the east side of McMurdo Sound is influenced mostly by water from the open Ross Sea, whereas water flows out from under the Ross Ice Shelf on the west side (*12*). The differences in ^{14}C and tritium can be attributed to the fact that water from the open sea has had a much more recent and extensive contact with the atmosphere where ^{14}C and tritium specific activities are higher.

The one ^{14}C sample collected from the water column under the ice at the drilling site has a $\Delta^{14}C$ value of −74 per mil (Table 1). Since this value is much higher than ^{14}C activities found in 1972, the water at a depth of 22 m under the ice hole must have been in the open Ross Sea within the past 6 years. The value is much higher than the ^{14}C activities found in water under the Ross Ice Shelf on the western side of McMurdo Sound but similar to the water on the east side of McMurdo Sound, that is, water from the open Ross Sea. Two possible explanations may be offered to account for the differences in the $\Delta^{14}C$ values at the two locations under the Ross Ice Shelf. The first is that water under the western shelf may have mixed with a deeper layer having a lower $\Delta^{14}C$ value. As noted from the tritium profile at site J9, tritium concentrations decrease in the deeper water and ^{14}C concentrations can be expected to follow the same pattern. The second possibility is that the water under the western shelf was advected under the ice at an earlier time when ^{14}C concentrations were lower. The $\Delta^{14}C$ values of DIOC in the Ross Sea in the early 1970's were similar to values found in seawater in 1977 in western McMurdo Sound under the ice. In either case, waters found under different areas of the Ross Ice Shelf have different histories.

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