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Bering Sea deep circulation: Water properties and geopotential

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ABSTRACT

Deep temperature and silicate data from the Bering Sea demonstrate patterns that are consistent and allow inference of near-bottom circulation. The cold source water enters Kamchatka Strait and mainly moves toward the southeast through a narrow topographic gap and into Bowers Basin. There is also a narrow, coherent flow eastward, and eventually southeastward, near the steep flank of Bowers Ridge. At levels ~100–300 m above the bottom, there is a suggestion of upward motion near the margins of much of the deep Bering Sea. Near-bottom geopotential gradients, referred to 3000 db, are in agreement with flow inferred from water properties.

1. Introduction

The Bering Sea is a semi-enclosed sea that extends from about 52N (southernmost Aleutian Islands; Fig. 1) to 66N (Bering Strait); its east-west boundaries are ~158W–163E. Roughly half of this vast area has depths <200 m, with most of the shelf being in the eastern and northern regions. The deep sea has maximum depths of ~4000 m and is actually comprised of three somewhat isolated basins (Aleutian, Bowers, and Kamchatka) separated by Bowers and Shirshov ridges (Sayles *et al.,* 1979; see Fig. 1). Reliable information on the underwater topography is needed to understand the movement of near-bottom water. The bathymetry shown in the various figures is from the 5-minute resolution ETOP05 data, with alterations of the 3500-m depth contours near 54N, 175E and 54N, 170E by results from individual trackline data from GEBCO 5.02 (1984). As will be shown, these two regions are important pathways for the movement of bottom water.

Only three passes permit exchange of water between the northern Pacific and the Bering Sea at levels deeper than 1000 m (Roden, 1995). Amchitka Pass (near 180°) and Near Strait have sills of ~1200 and 2000 m, respectively (see Fig. 1). Only Kamchatka Strait permits northward flow of deep water, near 4000 m, from the Pacific Ocean into the Bering Sea.

The number of near-bottom Nansen-bottle or CTD casts in the deep Bering Sea has been quite limited. Tsunogai *et al.* (1979) analyzed temperature, salinity, and chemical data from

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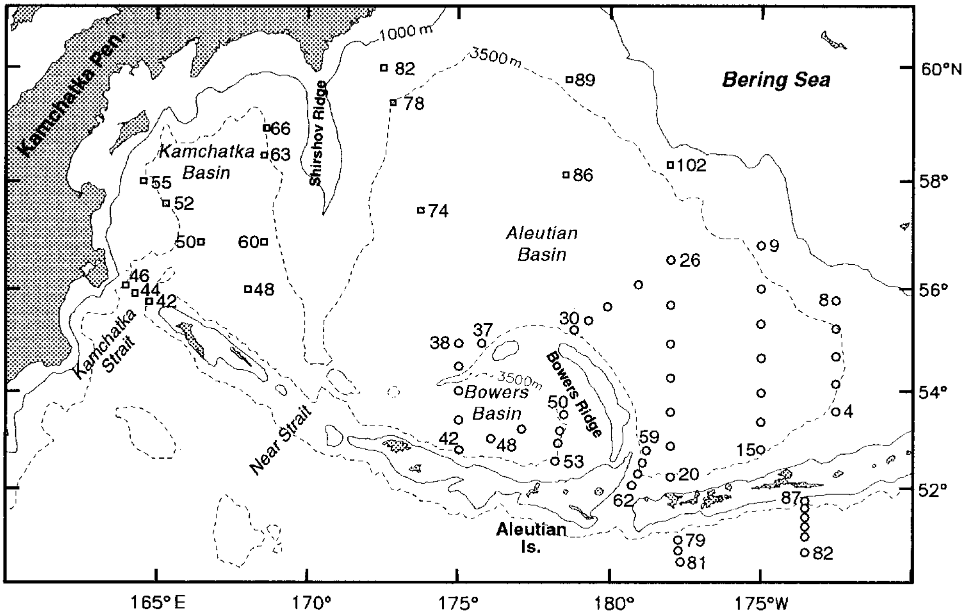

Figure 1. Location of CTD casts: squares, 13–26 August 1991; circles, 27 May–13 June 1998. Only casts that reached 3000 db are shown. The 1000- and 3500-m isobaths are indicated.

four deep stations taken in 1975. Mantyla and Reid (1983) showed fewer than 20 stations reaching ~3500 m. Sayles *et al.* (1979) did not examine water properties below 2500 m. In July 1993, the World Ocean Circulation Experiment (WOCE) P14N section (from ~58N, 175W to ~52N, 179W) was occupied in the Bering Sea (Roden, 1995). Eleven stations reached near-bottom depths of 3500 m or greater, and analyses of oxygen, silicate, nitrate, and phosphate were performed from discrete samples. Warren and Owens (1988) also presented results from three full-depth sections extending southward from near the Aleutian Islands.

Potential temperature in the Bering Sea near Kamchatka Strait decreases rather smoothly from ~2.7°C at 1000 m to slightly greater than 1.2°C near 3800 m (Tsunogai *et al.,* 1979). There is a modest increase (~0.1°C) of near-bottom temperature eastward. Salinity increases downward from ~34.3 at 1000 m to ~34.675 at 3800 m near Kamchatka Strait (Tsunogai *et al.,* 1979). It then decreases eastward at 3800 m by <0.010. Because of this very small range, and typical measurement errors of perhaps 0.003, we do not present salinity data here. Tsunogai *et al.* (1979) showed that silicate increases downward from 1000 m (with concentrations of roughly 170 μmol kg^{-1}), to a weak maximum at 3000–3500 m, with near-bottom concentrations of ~180–240 μmol kg^{-1}. They also estimated a deep-water residence time of ~350 yr.

Our goal has been to obtain data over the entire deep Bering Sea so that near-bottom water properties and their gradients could be derived and hence the direction and relative magnitude of flow inferred. Here we use data in the western and northern Bering Sea from a cruise in August 1991 and combine the results with those from another cruise in May–June 1998 in the central and southern Bering Sea. The distributions of potential temperature and dissolved silicate (hereafter silicate) are examined. The horizontal structure of near-bottom geopotential is also used.

2. Data and methods

During August 1991, a cruise was conducted aboard the NOAA ship *Miller Freeman* in the western and northern Bering Sea (in both Russian and U.S. waters; Fig. 1). Data from eight stations that reached 3500 db or greater are used here. Sampling was with a Seabird SBE-9 conductivity, temperature, depth (CTD) system. Salinity data were corrected after analyses of discrete samples on a laboratory salinometer. Silicate was measured on this cruise, but the data now appear to be too high (by roughly 15 μmol kg^{-1}) because of standardization errors.

In May–June 1998, on a NOAA cruise aboard R/V *Wecoma* (operated by Oregon State University), 33 stations were taken to 3500 db or greater in the Bering Sea proper, plus eight stations to at least 3500 db were occupied just south of the Aleutian Islands (Fig. 1). CTD casts were taken with a Seabird 911 plus CTD, with dual temperature and salinity sensors. Salinity samples were analyzed on a salinometer to provide corrections to the CTD salinities. An altimeter was used to position the CTD within $<$25 m of the bottom.

Analyses for silicate in 1998 were conducted in a temperature-controlled laboratory aboard ship with a modified Alpkem RFA autoanalyzer, using methods of Gordon *et al.* (1993). The standard material was sodium fluorosilicate, which was referenced against a fused-quartz standard. The instrument was monitored regularly for nonlinear behavior. Analytical precision was 0.6 μmol kg^{-1} (mean SD, $n = 209$) as determined by replicate analyses. We did not measure phosphate or nitrate because they have very small near-bottom gradients and are not useful for inferring deep flow patterns (Roden, 1995).

The methods that we use in our analysis are as follows. First, we map the distribution of water properties (potential temperature and silicate) on constant deep pressure surfaces. Then we examine the vertical structure of silicate through use of plots of concentration in the vertical. Finally, we attempt to infer circulation from the horizontal distribution of geopotential anomaly. We have not mapped near-bottom properties on potential density surfaces because differences of sigma-theta of 0.001 are $\sim$50 db apart, with potential temperature differences of at least 0.003°C.

3. Property distributions at 3800 db

The 3800-db surface is a feasible near-bottom level for a substantial part of the Bering Sea basin. The distribution of potential temperature (θ) at 3800 db is shown in Figure 2. The coldest water ($\sim$1.20°C) is on the eastern side of Kamchatka Strait (station 42; Fig. 1), the sole source of deep ($\sim$4000 db) inflow from the North Pacific to the Bering Sea (Sayles *et al.,* 1979; Mantyla and Reid, 1983). The water warms (to $>$1.25°C) to the north in

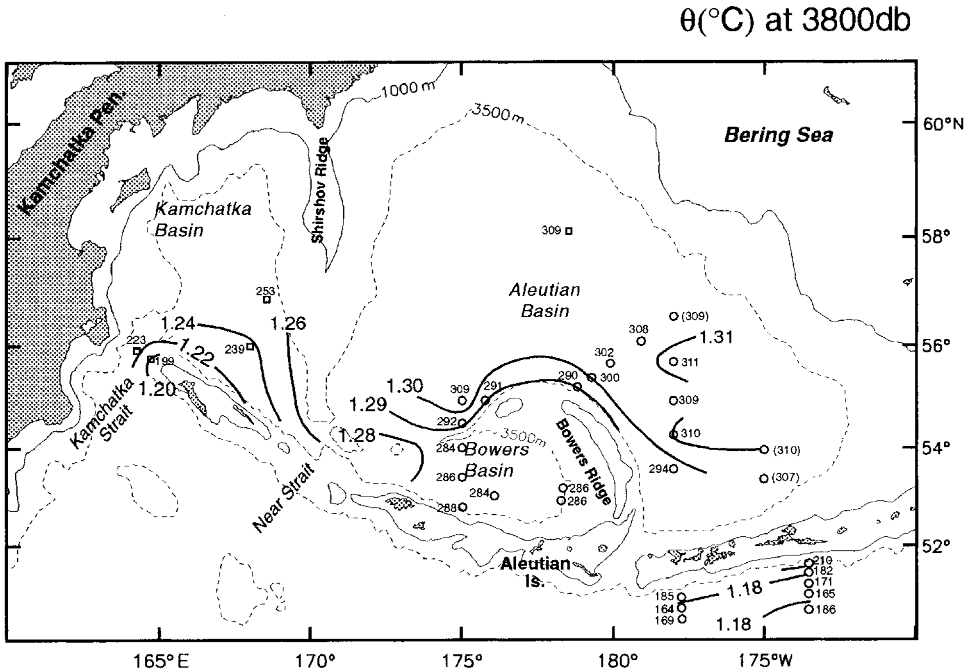

Figure 2. Potential temperature (θ, °C) at 3800 db during 13–22 August 1991 (squares) and 29 May–12 June 1998 (circles). Station values in parentheses were extrapolated as much as 50 db. The digits listed are the decimal part of temperature times 10^3 (i.e., 1.290°C = 290).

Kamchatka Basin and to the southeast toward the narrow gap between Shirshov Ridge and the Aleutian Island ridge. There is a further increase (to 1.28–1.29°C) in Bowers Basin and on the north side of the westward extension (3500 m isobath) of Bowers Ridge. The quite narrow zone of relatively cold water (1.290–1.292°C) on the northern side of Bowers Ridge is coherent toward the southeast (1.294°C at station 22; Fig. 1). Note also that the potential temperature at station 38 (Fig. 1; 1.309°C) is nearly 0.02°C higher than at the nearby stations. Thus there is strong evidence for a narrow, near-bottom flow that brings cold, "young" bottom water around Bowers Ridge towards the east and southeast. The one 1991 station well north (near 58N, 178E) of our 1998 data, that reached 3800 db, suggests no major warming of near-bottom water in that direction.

Silicate distribution (Fig. 3) is quite similar to that of potential temperature (Fig. 2). Both properties increase along the path of flow. Potential temperature increases by mixing with warmer, overlying water (diffusion from above; Thompson and Johnson, 1996) and possibly by heat flow through bottom sediments (Joyce *et al.,* 1986). Silicate increases along its path mainly by contact with silica-rich bottom sediments (Tsunogai *et al.,* 1979) and perhaps through sinking of diatoms from above and subsequent dissolution in the water above the bottom (Talley and Joyce, 1992). Note also that the lowest silicate concentrations are south of the Aleutians, as are the lowest temperatures (Fig. 2).

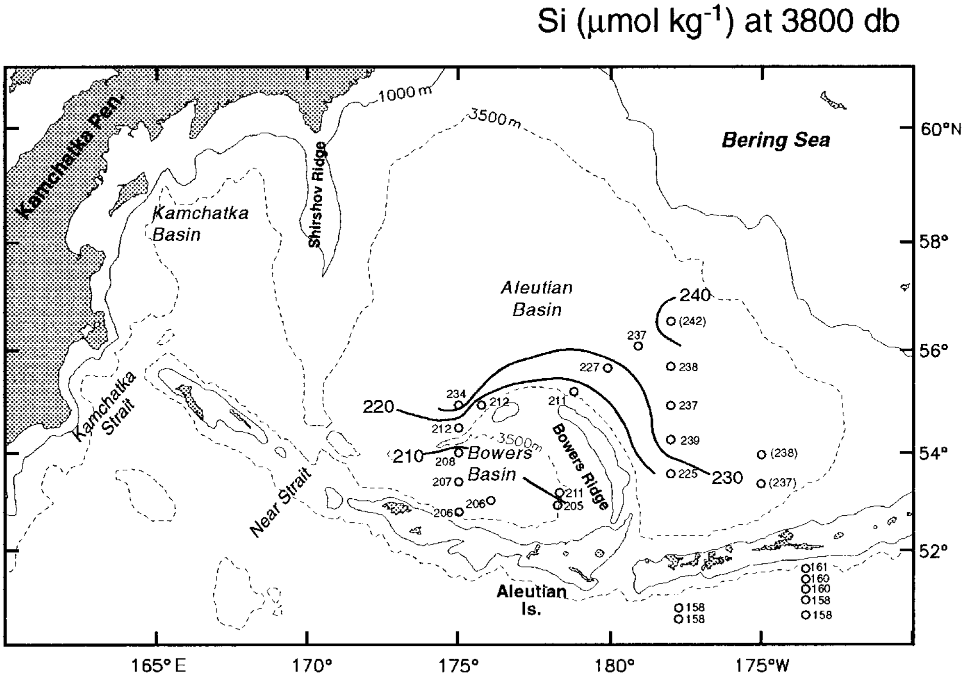

Figure 3. Silicate (Si, μmol kg^{-1}) at 3800 db during 29 May–12 June 1998. Digits listed are in μmol kg^{-1}. Station values in parentheses were extrapolated as much as 50 db.

Concentrations in Bowers Basin are mainly <210 μmol kg^{-1} (Fig. 3). The strong gradients north and east of Bowers Ridge are quite similar to those of potential temperature (Fig. 2). The highest silicate concentration was to the northeast (station 26; 242 μmol kg^{-1}). Note the high concentration (234 μmol kg^{-1}) at station 38 in comparison with nearby stations (37 and 39; both with 212 μmol kg^{-1}). This then also suggests that the flow north of Bowers Ridge is narrow and that it bypasses station 38.

We do not imply that conditions near the bottom in the deep Bering Sea are entirely in a steady state. Data from station 21 here (Fig. 1) may be compared with those from station 58 during 28 May 1997 (Reed and Stabeno, 1999). The stations are 9 km apart. The near-bottom potential temperature at the two stations differed by only 0.001°C. Our station 22 was 19 km distant from WOCE station 12 (Roden and Fredericks, 1995) of 9 July 1993. At 3800 db, potential temperature and silicate differed by 0.001°C and 1 μmol kg^{-1} at the two stations. Cokelet *et al.* (1996), however, presented evidence for occasional deep-reaching eddies, which may alter water properties.

4. Property distributions at 3500 db

Properties at this level show distinct differences from properties at 3800 db. Water on the eastern side of Kamchatka Strait is ~1.26°C; potential temperature increases substantially

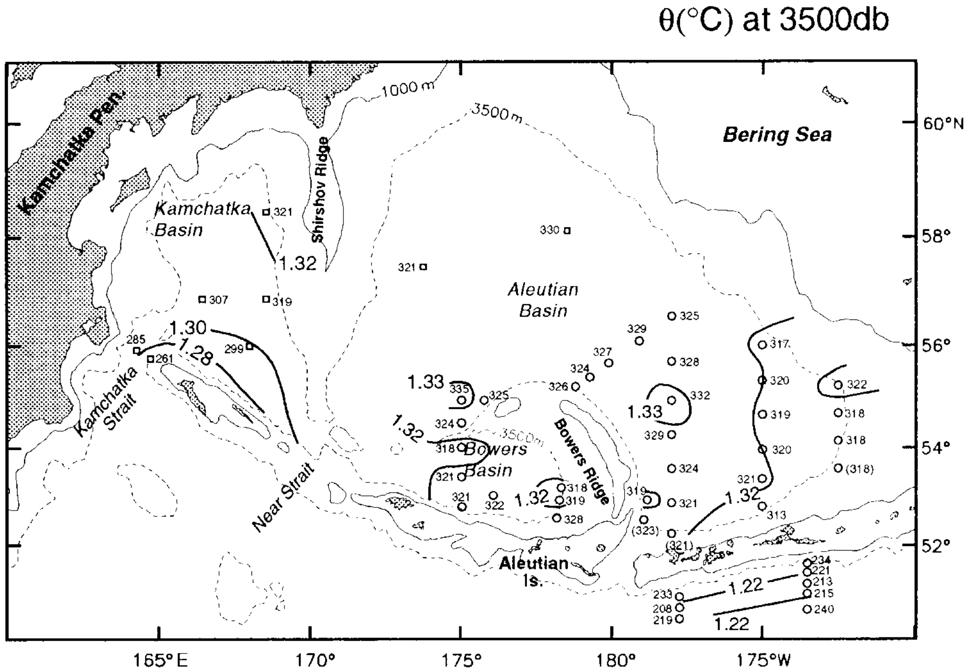

Figure 4. Potential temperature (θ, °C) at 3500 db during 13–22 August 1991 (squares) and 27 May–12 June 1998 (circles). Other information as for Figure 2.

(to >1.32°C) northward in Kamchatka Basin (Fig. 4). There is considerable uniformity in θ from the Aleutians to ~57N along ~174–175E, except the water at station 38 seems relatively "old," as in Figs. 2 and 3. The "Bowers Ridge" flow is suggested but does not have horizontal gradients as strong as at 3800 db. To the north (near 58N, 178E), the temperature (1.330°C) is similar to that northeast of Bowers Ridge. Near the eastern and southern regions of the Aleutian Basin, there is a sizeable zone with temperature <1.32°C. This seems likely to be caused by weak upward motion of cooler water from below 3500 db.

The silicate distribution at 3500 db (Fig. 5) shows relatively low values south of 54°N in Bowers Basin. The data just north of Bowers Ridge show little evidence of flow. Silicates are >240 μmol kg^{-1} on the section at 172.5W, in agreement with the relatively cold water there (Fig. 4), which again suggests upward motion near the margin of the basin. (In the eastern area of our data, as will be shown in Figure 6, deep silicate increases to the bottom, rather than decreasing as in the central region.)

5. Vertical structure of silicate

The vertical structure of silicate at selected sites is presented in Figure 6. The station data are shown in, what seems to be, the general age order: that is, youngest to oldest

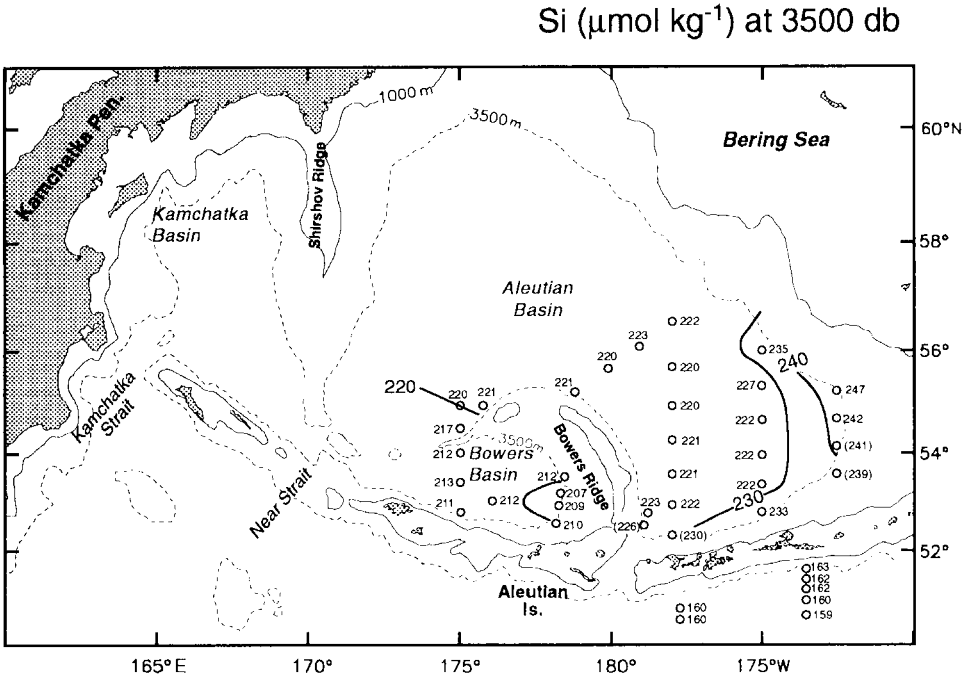

Figure 5. Silicate (Si, µmol kg^{-1}) at 3500 db during 27 May–12 June 1998. Other information as for Figure 3.

near-bottom water (stations 41, 37, 22, 38, 26, and 6; see Fig. 1 for locations and Figs. 3 and 5 for Si distributions). Figure 6 shows that concentrations near the bottom (3800 db and deeper) are as follows: 188, 206, 219, 235, and 241 µmol kg^{-1} at stations 41, 37, 22, 38, and 26, respectively. This is in general agreement with the horizontal distribution at 3800 db (Fig. 3) and is supported by the θ distribution in Figure 2.

The silicate-maximum values also increase from stations 41, to 37, to 22. Stations 38, 26, and 6 have no significant maxima above the bottom. It seems difficult to account for the increase in depth and concentration of the maximum solely by relatively new, near-bottom water flow or its diminution. Talley and Joyce (1992) concluded that the near-bottom maximum in the northeastern Pacific likely results from bottom sediment dissolution but that the intermediate maximum is influenced by sinking particles. We estimated an upward flux, over the bottom 100 m between stations 37 and 22, using observed changes in concentration, the distance, and the mean geostrophic speed (see next section), of 25 µmol kg^{-1} cm^{-2} yr^{-1}, in agreement with the bottom sediment dissolution flux value of Talley and Joyce (1992). The silicate maximum here, however, occurs roughly 300 m above bottom and would require a flux three times that above. We suggest that there is an effect (increase in concentration) from dissolution of diatoms in water well above the bottom.

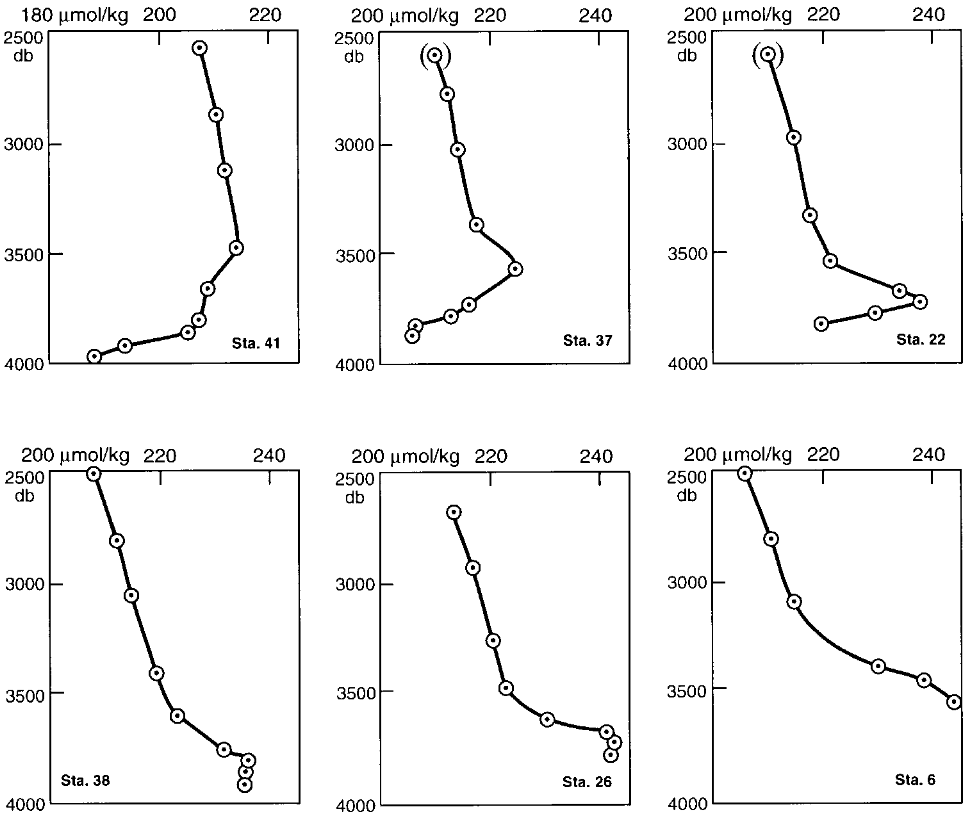

Figure 6. Plots of silicate concentration (μmol kg^{-1}) below 2500 db at stations listed (see Fig. 1). Values in parentheses were interpolated. Note that the concentration scales vary.

6. Geopotential topography

No deep current measurements were made during either the 1991 or 1998 cruises. We attempt, however, to examine evidence for organized deep flows, especially in the vicinity of Bowers Ridge and in the Kamchatka Basin. We examine deep geopotential topography and its gradients and then estimate near-bottom speeds. Our main concern is ascertaining if the near-bottom geopotential field, referred to some suitable level, can provide useful information that would supplement results from the distributions of properties.

Near-surface direct current measurements (Stabeno and Reed, 1994) clearly showed a large-scale cyclonic motion around the Bering Sea basin, with southward outflow on the western side of Kamchatka Strait. This motion extends to 1400 db (Sayles *et al.,* 1979) and even in much-weakened form to 3000 db (Reid, 1997). The potential temperature and silicate distributions (Figs. 2 and 3) suggest that the near-bottom flow, which is greatly affected by local topography, does not easily fit the concept of cyclonic circulation around the basin. The inferred existence of upward deep motion (Figs. 4–5), however, may provide

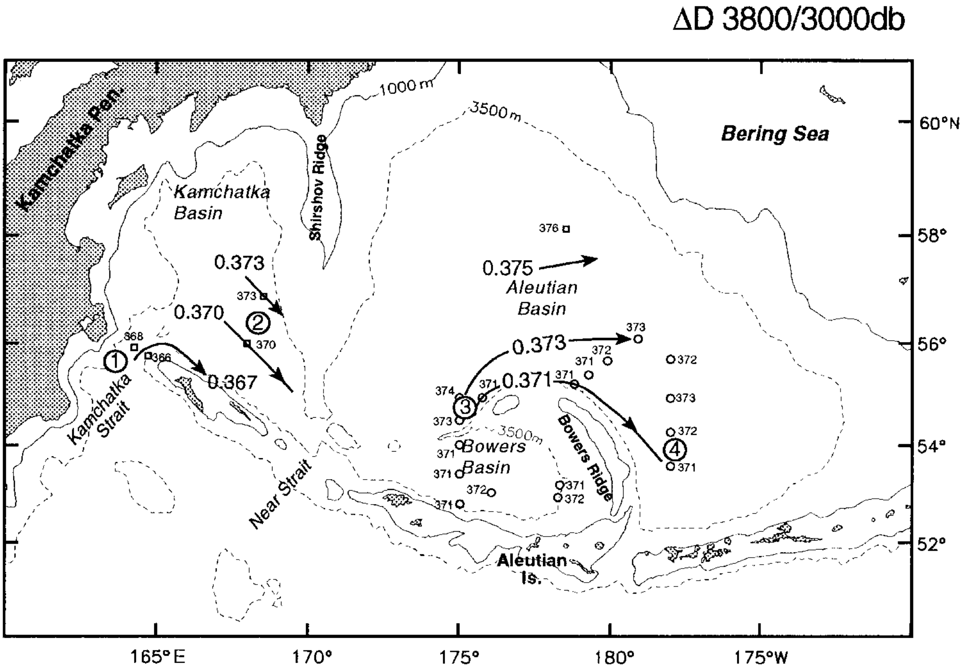

Figure 7. Dynamic topography at 3800 db, referred to 3000 db, during 13–22 August 1991 (squares) and 1–7 June 1998 (circles). Digits listed are in dyn m (labeled isolines) or in 10^3 dyn m (values at stations).

a means for the removal of mass and a link to the large-scale cyclonic flow above ~3000 db.

After consideration of these factors, we mapped the geopotential topography at 3800 db, referred to 3000 db (Fig. 7). The near-bottom flow pattern is quite similar to that inferred from water properties (Figs. 2 and 3). The computed near-bottom geostrophic speeds, referred to 3000 db, at station pairs 1, 2, 3, and 4 are: 0.4, 0.3, 0.5, and 0.1 cm s^{-1} in the directions indicated by the differences in Figure 7. The stability of these near-bottom flow features, however, is uncertain.

7. Summary

Data from cruises in 1991 and 1998 have allowed us to map deep-water properties over the Bering Sea. The bottom-water source for the Bering Sea is an inflow from the Pacific northward through Kamchatka Strait. This water is cold, saline, and relatively low in silicate; the water warms, becomes fresher, and gains silicate along its path of near-bottom flow.

There is some northward movement of the source water into Kamchatka Basin. A striking feature, however, is the southeastward flow through a narrow topographic gap near 54N, 170E, with a continuation eastward into Bowers Basin. There is also a narrow, coherent eastward-southeastward flow along the northern-eastern flank of Bowers Ridge. The evidence for these features is consistently similar in both potential temperature and silicate patterns. A few hundred meters above the bottom, there is cool, silicate-rich water near the eastern margin of the basin that seems to result from upward motion.

Finally, results from an examination of near-bottom geopotential gradients, referred to a level above, were in agreement with paths inferred from water properties. Derived speeds were 0.1–0.5 cm s^{-1}.

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