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The Double Silica Maximum in the North Pacific

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The North Pacific has two vertical silica maxima. The well-known intermediate maximum occurs between 2000 and 2500 m with a potential density relative to 2000 dbar of 36.90 in the northeastern Pacific. The deep maximum, which has not been observed extensively before, is found at or near the ocean bottom in the northern North Pacific in a narrow latitude range. Maps of silica on isopycnals which intersect the intermediate and bottom maxima show that the lowest silica is found in the western tropical North Pacific, suggesting a route for the spread of South Pacific water into the deep North Pacific. Low-silica water is found along the western boundary of the North Pacific, with a separate broad tongue south of Hawaii. The highest silica on both isopycnals is in the northeast Pacific. A bottom maximum in the Cascadia Basin in the northeastern Pacific can be differentiated from both open-ocean maxima. Four sources for the vertical maxima are considered: in situ dissolution of sinking particles, bottom sediment dissolution, hydrothermal venting, and upslope advection in the northeastern Pacific. Because not enough is known about any of these sources, only rough estimates of their contributions can be made. The bottom maximum is most likely to result from bottom sediment dissolution but requires a flux larger than some current direct estimates. The Cascadia Basin bottom maximum may result from both bottom sediment dissolution and hydrothermal venting. The intermediate maximum is likely to result primarily from dissolution of sinking particles. There is no quantitative estimate of the effect of possible upslope advection or enhancement of bottom fluxes due to the Columbia River outflow.

1. INTRODUCTION

Silica is an ideal tracer of deep North Pacific circulation because it has deep and bottom sources there, as opposed to temperature and salinity whose gradients are much smaller in the deep water. The intermediate-depth silica maximum, at 2000 to 2500 m, is a well-known feature of the world ocean, with highest silica being found in the North Pacific [e.g., *Broecker and Peng*, 1982]. The usual mechanism proposed in the past to produce this maximum is dissolution of sinking particles balanced by upwelling, but *Edmond et al.* [1979] argued that intermediate-depth silica maxima in the world ocean are laterally advective features with almost all of the silica originating from dissolution of opaline bottom sediments; they specify the northeastern Pacific as one major source region.

The North Pacific bottom silica maximum was also reported by *Edmond et al.* [1979] and *Warren and Owens* [1988], using a small number of stations from the central North Pacific. Our more recent data resolve the bottom maximum much more extensively and show that it is indeed most pronounced in the northeast Pacific and that it is limited to a narrow meridional band across the subpolar region. Because the highest silica concentration in the North Pacific deep waters coincides with the Juan de Fuca hydrothermal venting region, where very high silica concentration has been measured in the vent waters [*Von Damm and Bischoff*, 1987], we suggest that hydrothermal sources be considered in addition to sedimentary and particulate fluxes. Hydrothermal activity contributes mainly to a local bottom maximum in the Cascadia Basin. A more esoteric and perhaps unquantifiable contribution to both maxima is upslope advection in a boundary layer [*Phillips et al.*, 1986] in the northeastern Pacific, which could intensify the bottom boundary silica concentration and eject silica into the intermediate maximum.

This study is based primarily on recent, high-quality zonal and meridional sections in the North Pacific. Observations (Figure 1) at 47°N (TPS47 and SAGA II) and 152°W (Marathon 2, hereinafter called M2) were described by *Talley et al.* [1991], accompanied by vertical sections of silica and other properties (temperature, salinity, density, oxygen, nitrate, and phosphate). The TPS47 and M2 silica sections are reproduced here (Figure 2) because they are central to this paper. A section at 24°N [*Roemmich et al.*, 1991], referred to here as TPS24, is also used. Data for all four cruises were collected and processed by the Oceanographic Data Facility (ODF) at Scripps Institution of Oceanography. Some of the other data shown in Figure 1 are described below.

Nelson and Gordon [1982] discuss the confusing terminology for describing oceanic silicon. In contrast with their choice of "silicate" for all solid and dissolved phases and "silica" for solid-phase silicate only, we use "silica" throughout this paper in the same sense as *Edmond et al.* [1979] and *Fanning and Pilson* [1974] to denote the concentration of silicic acid and its dissociation products, which is the quantity measured by the colorimetric autoanalyzer, rather than using Nelson and Gordon's more precise choice of "dissolved silicate." Silica in micromoles per liter is used in most figures, but for calculations, units of micromoles per kilogram are used. Because the quantitative estimates in this paper are so rough, no additional accuracy can be obtained by careful conversion of one set of units to the other, and the units are used interchangeably.

In the following sections we describe the vertical silica maxima on M2 and TPS47, the distribution of silica on isopycnals that intersect the two open-ocean maxima, and possible sources of the high silica in all three maxima.

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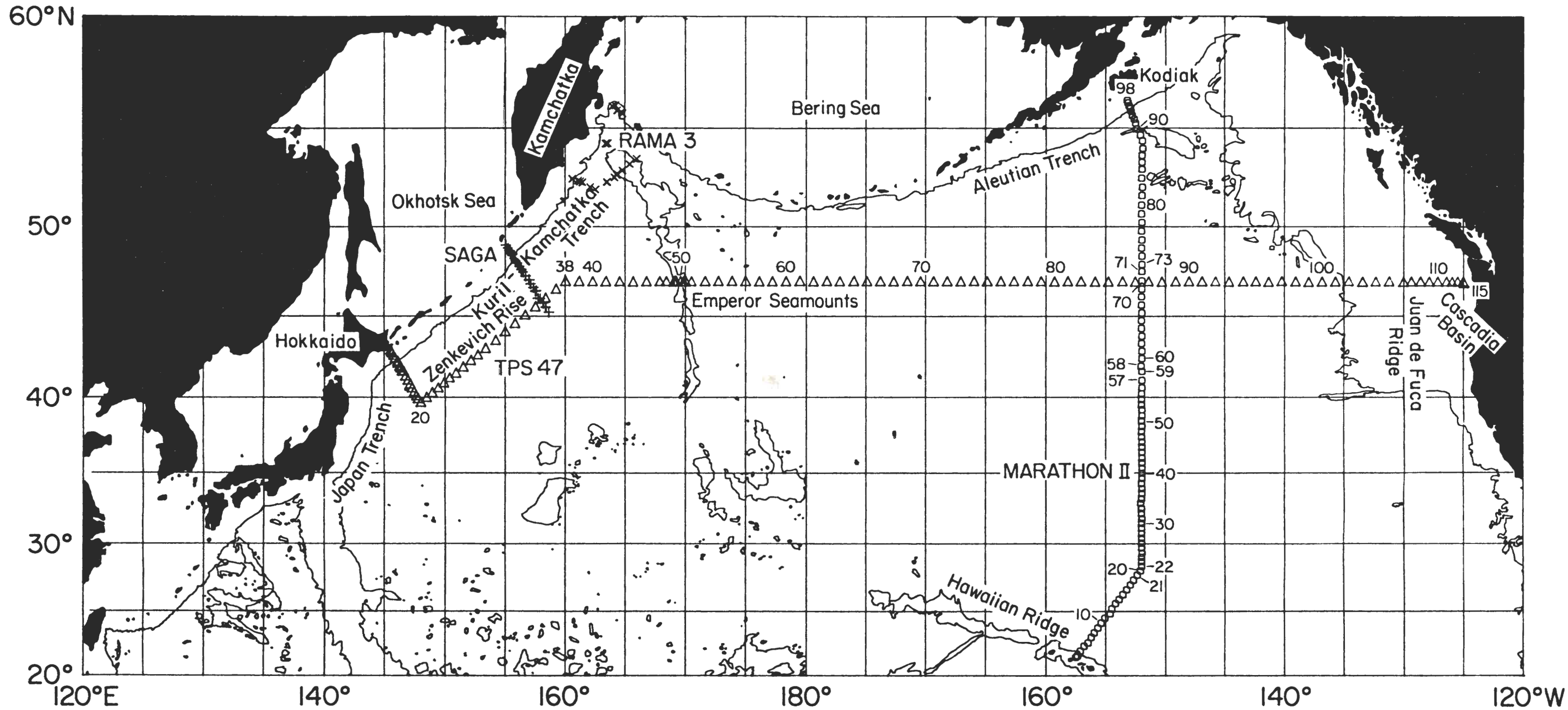

Fig. 1. TPS47 stations occupied by R/V *T. Thompson* between August 4 and September 7, 1985 (triangles), SAGA II stations in the northwest Pacific, occupied by the *Akademik Korolev* between May 11 and May 18, 1987 (plus signs), Marathon 2 stations occupied by R/V *T. Washington* between May 4 and June 4, 1984 (circles), and RAMA 3 stations occupied by R/V *T. Washington* between May 25 and June 25, 1980 (squares).

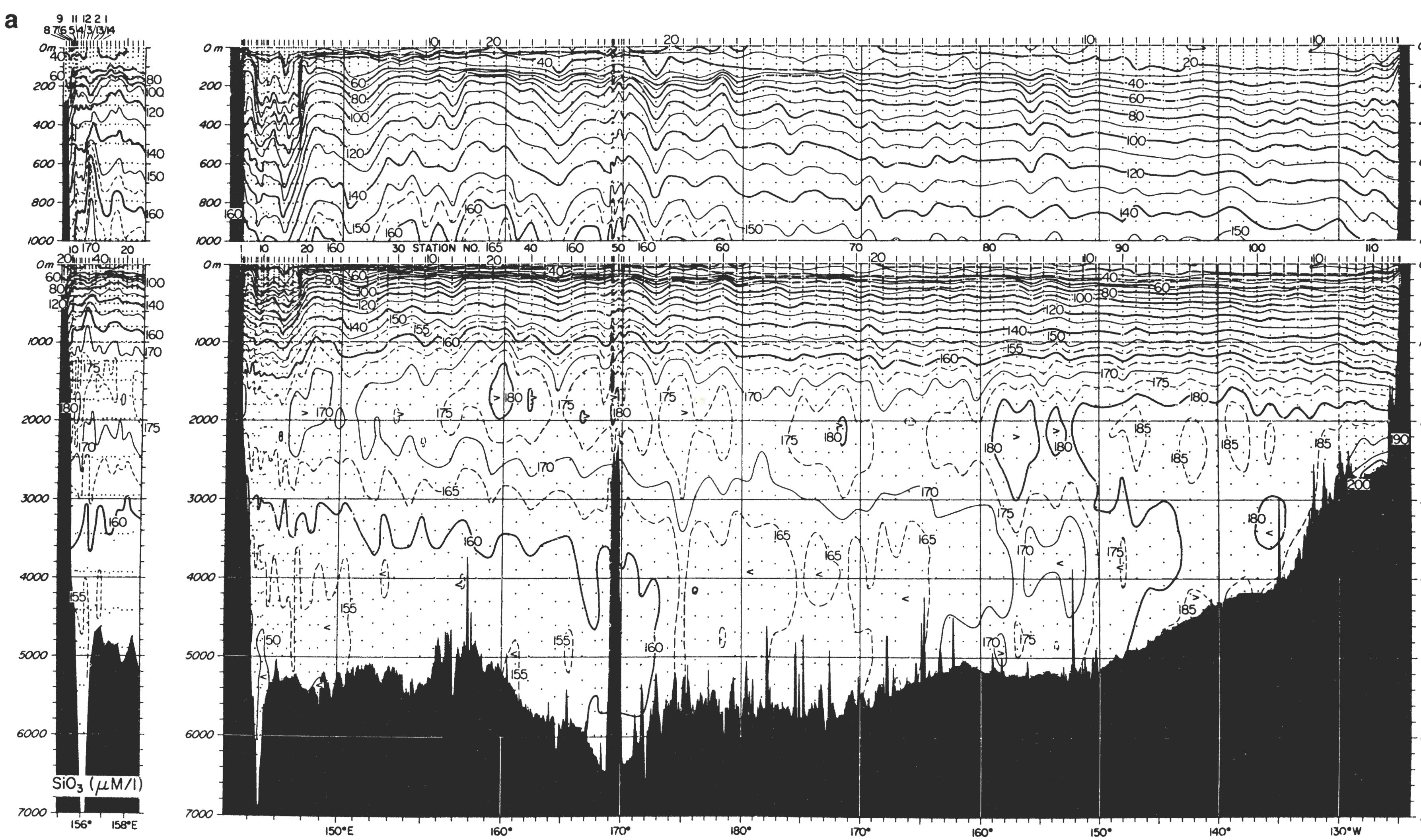

Fig. 2. Vertical sections of silica (micromoles per liter) from (*a*) TPS47 and (*b*) Marathon 2. Station locations are shown in Figure 1. These sections are reproduced from *Talley et al.* [1991].

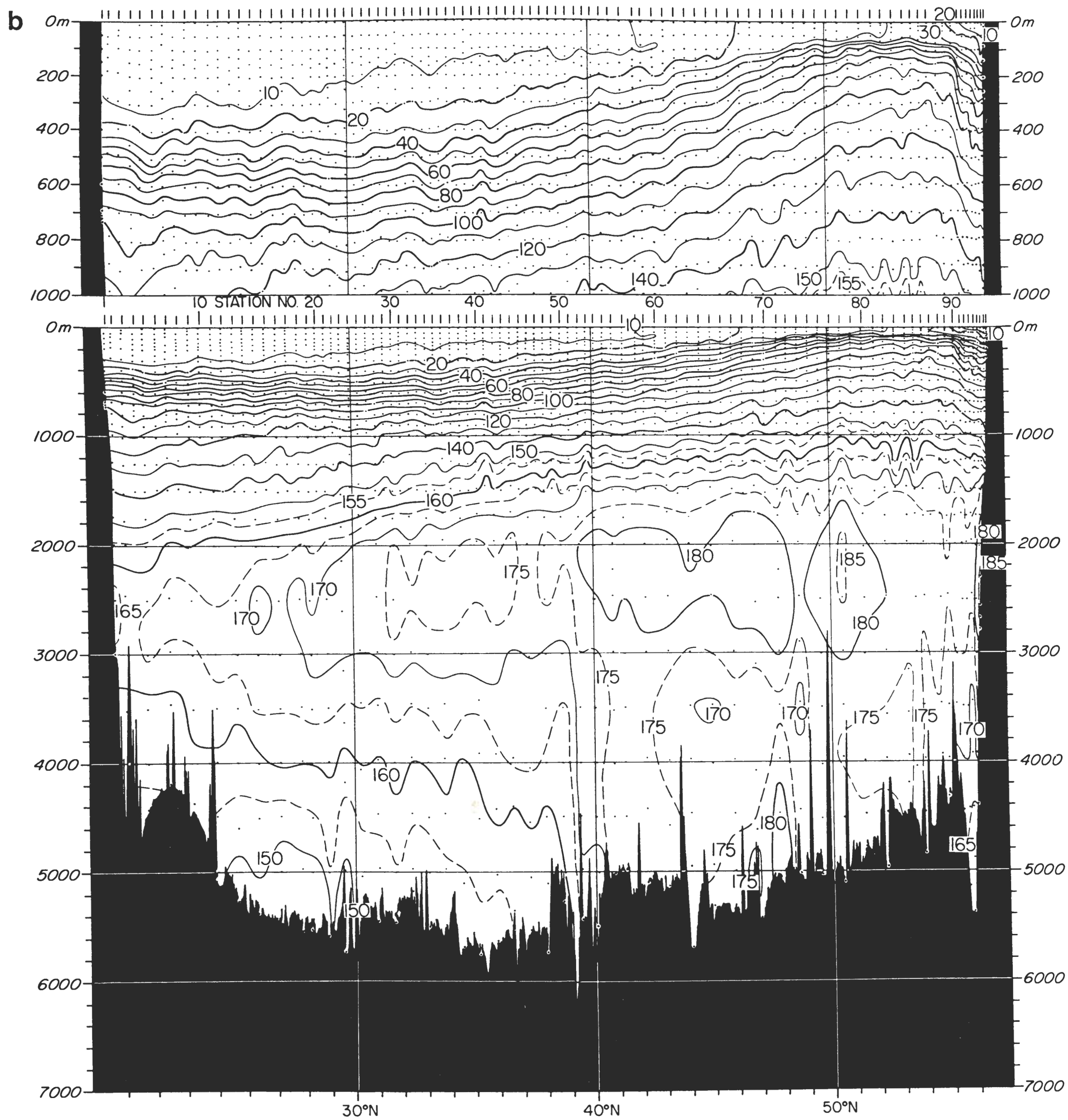

Fig. 2. (continued)

2. Intermediate And Deep Silica Distribution

2.1. Vertical Silica Maxima

The first detailed meridional and zonal sections of silica in the deep, subpolar North Pacific, M2 and TPS47, reveal both the well-known intermediate silica maximum and a well-developed near-bottom maximum (Figure 2). The latter was apparent previously from a number of stations in the northeast Pacific [*Edmond et al.*, 1979] and just south of the Aleutians at 175°W [*Warren and Owens*, 1988], but its extent had not been clearly defined prior to the new data collection. Both maxima are most strongly developed in the northeastern Pacific (Figure 2). All vertical silica maxima on TPS47, M2, and TPS24, are shown in Figure 3 regardless of the relative size of the maximum. The intermediate maximum is obvious at all locations on all sections. The near-bottom maximum appears across the entire TPS47 section in Figure 3 even though it is difficult to distinguish on the contoured vertical section (Figure 2*a*). On M2 it is found only between 35°N and 50°N. On TPS47 the maximum is on the bottom east of 152°W between 158°W and 168°W and at a number of sites at the western end. On M2 the deep maximum, when it occurs, is at the bottom at most stations north of 42°N. On TPS24, deep maxima occur only in the Philippine Basin (western end), where the deep water is relatively mixed and the weak extrema are within the noise level, and at the very eastern end where the intermediate maximum dives into the bottom. (There may be a weak, local bottom source at the eastern end of TPS24.)

The potential density σ_2 of the intermediate silica maximum on TPS47 (Figure 3*d*) is about 36.92 σ_2 offshore of the Cascadia Basin (west of 140°W), ranging noisily to lower density farther west. The potential density of the bottom maximum is 37.04 σ_2, or 45.88 σ_4, ranging to lower densities in the east as the bottom maximum follows the slope up into the Cascadia Basin. The maximum at the bottom in the Cascadia Basin, with slightly higher density (36.945 σ_2) and much higher silica than the intermediate maximum (Figure 3*e*), appears to be separated somewhat from both open-ocean maxima, but is closer in density to the intermediate maximum. Oxygen and salinity at the silica maxima (Figures 3*f* and *g*) do not really help to determine whether the Cascadia Basin maximum is a separate phenomenon, although the slight increase of oxygen westward towards 134°W suggests that the open-ocean bottom maximum influences the Cascadia Basin. This is discussed further in section 3.

Maps of the silica distribution at 36.9 σ_2 and 45.88 σ_4 (Figure 4), intersecting the intermediate and bottom maxima, are discussed in the next two subsections. Data from the new cruises were augmented with selected National Oceanographic Data Center (NODC) data provided by J. Reid and A. Mantyla. A search of all NODC data available as of June 1989 added a few more high-quality stations in the western North Pacific. M. Tsuchiya and R. Lukas provided us with recent Western Equatorial Pacific Ocean Circulation Study data in the southwest and J. Toole and H. Bryden provided us with new data collected in 1989 at 10°N. Hydrographic observations from the northern end of the Emperor Seamounts, henceforth referred to as RAMA 3 (Figure 1), were made in 1981 by P. Lonsdale and E. L. Winterer of SIO for the purpose of studying bottom sediment transport; these data were collected and processed by ODF. The quality of the RAMA 3 temperature, salinity and silica measurements is somewhat lower than from TPS47, SAGA II, M2, and TPS24 but is adequate for the purpose of horizontal mapping. The quality of silica data used to construct the maps (Figure 4) is uneven; however, no reasonable data that were less than 5 μmol L^{-1} from the contour intervals were ignored.

2.2. *Silica at 36.90 σ_2 (Figure 4a)*

The 36.9 σ_2 isopycnal lies between 2000 and 2200 m almost everywhere in the North Pacific; it is as shallow as 1800 m in only a small region in the northwest corner (on the SAGA II and TPS47 sections). It intersects the intermediate silica maximum along 47°N but lies slightly above it at 24°N and 10°N.

The source of low-silica water at 36.9 σ_2 is in the southwest from across the equator. A tongue of low silica is contoured extending northward toward Wake Passage (~19°N, 169°W) based on anomalies on TPS24 which could have originated only in Wake Passage. However, no one particular location in the western Pacific for northward flow of low-silica water can be discerned from Figure 4*a*. The wide

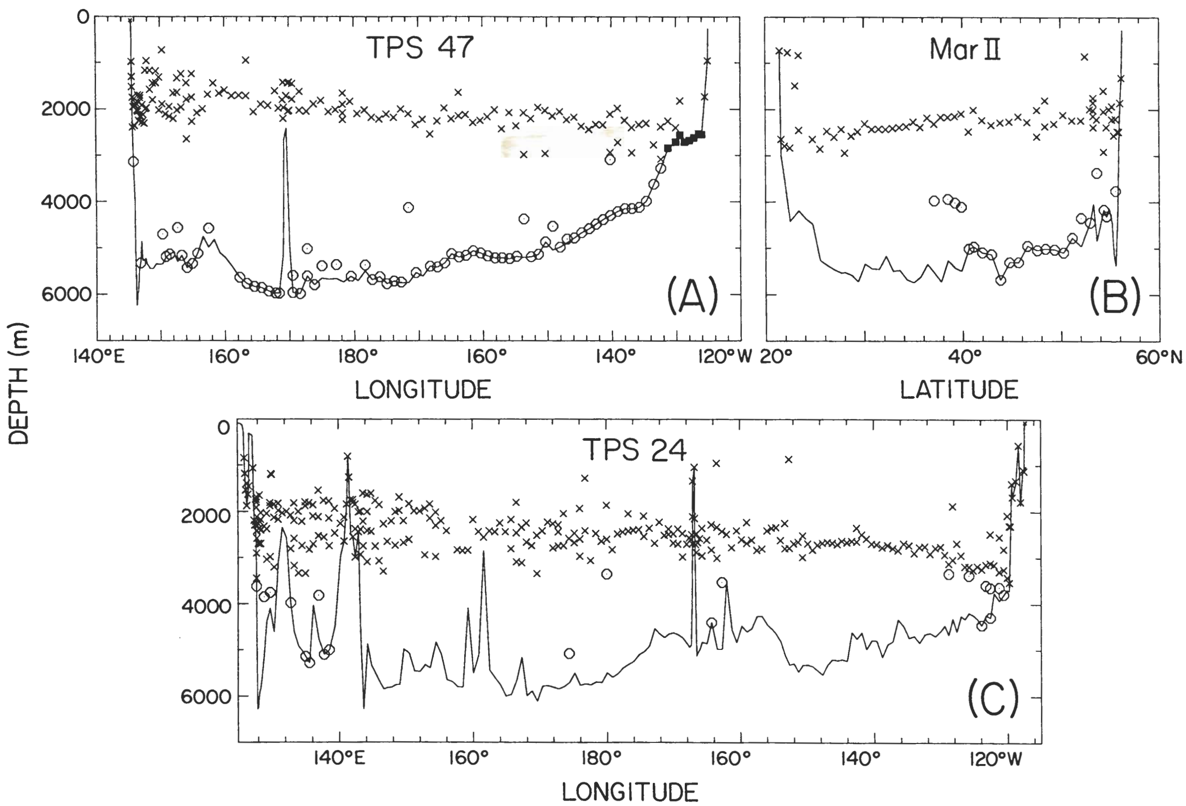

Fig. 3. All vertical maxima in silica, regardless of size of extremum, for (*a*) TPS47, (*b*) Marathon 2, and (c) TPS24, determined from bottle data smoothed using a cubic spline and interpolated to isopycnals. The smoothing removed the most insignificant extrema. (*d*) Potential density σ_2 of the TPS47 maxima. (*e*) Silica (micromoles per liter) of the TPS47 maxima. (*f*) Salinity (per mil) of the TPS47 maxima. (*g*) Oxygen (milliliters per liter) of the TPS47 maxima. For the TPS47 section a division between intermediate and bottom maxima was chosen at 36.98 σ_2. In 3*a* and 3*d* to 3*g*, crosses denote the intermediate maximum, circles are the bottom maximum, and solid squares are the Cascadia bottom maximum.

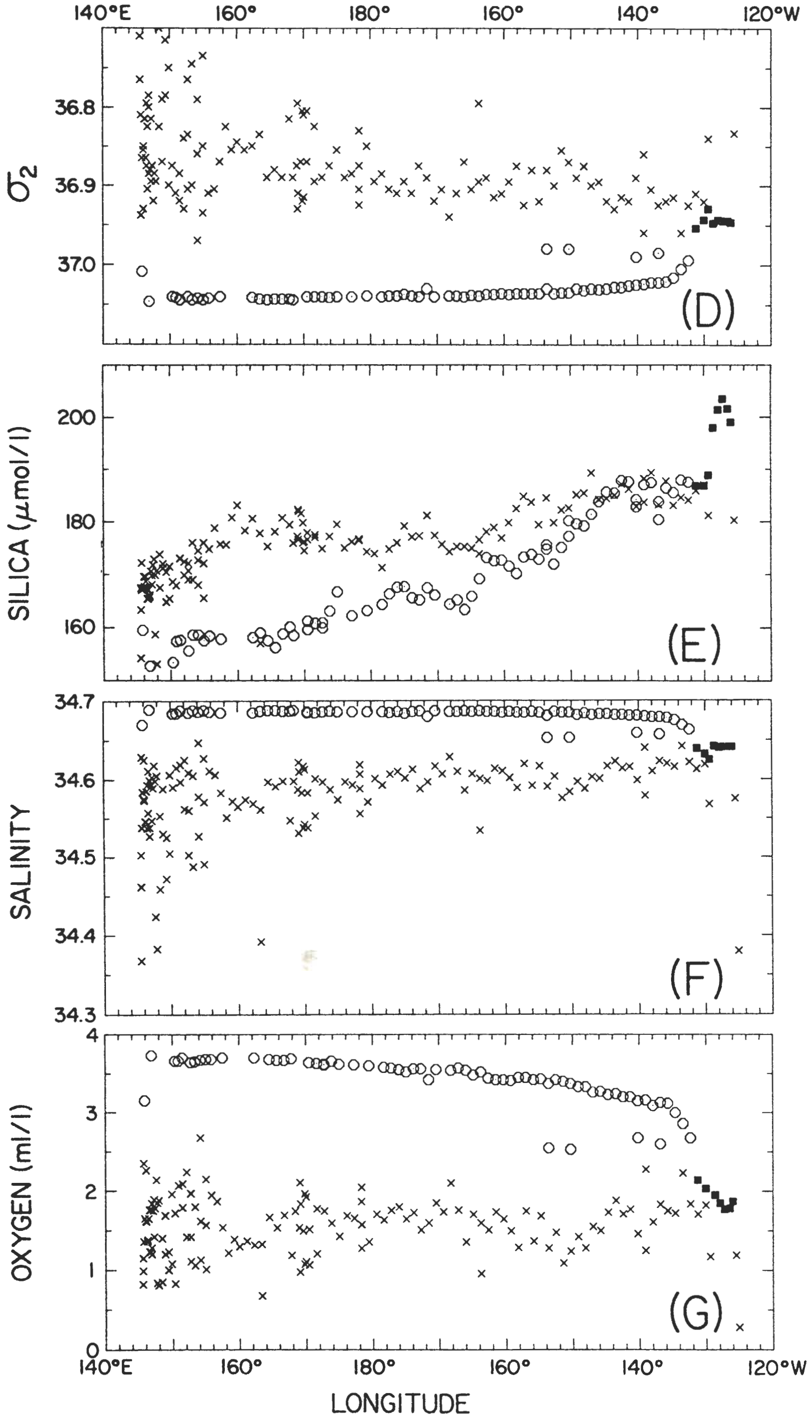

Fig. 3. (continued)

intrusion of low silica narrows to a western-intensified tongue north of about 35°N which continues northward and then eastward near the northern boundary. The low silica remains separated from the coast by a very narrow band of high-silica concentration all along both the western and northern boundaries, clearly resolved in all of the densely sampled sections across the boundary flows. This high silica may reflect westward flow along the boundary from a northeast Pacific source. *Warren and Owens* [1988] measured directly both the westward and eastward flows suggested by Figure 4*a* at 175°W. We have assumed that the low-silica band south of the Aleutians is connected with the similar low-silica band at the western boundary, with the supporting data in the northwestern Pacific being the few RAMA 3 stations at the northern end of the Emperor Seamounts.

Highest silica (>230 μmol L^{-1}) occurs in the Bering Sea, with a hint of high values in the Okhotsk Sea, based on only one station located there. These highest values do not appear to be advected into the open North Pacific according to this data set; the highest open ocean values occur in the northeast, where the isopycnal intersects the bottom in the Cascadia Basin. In addition to the Juan de Fuca region, lateral maxima at the eastern boundary are suggested by the sparse data at the Gulf of California. While sparse NODC

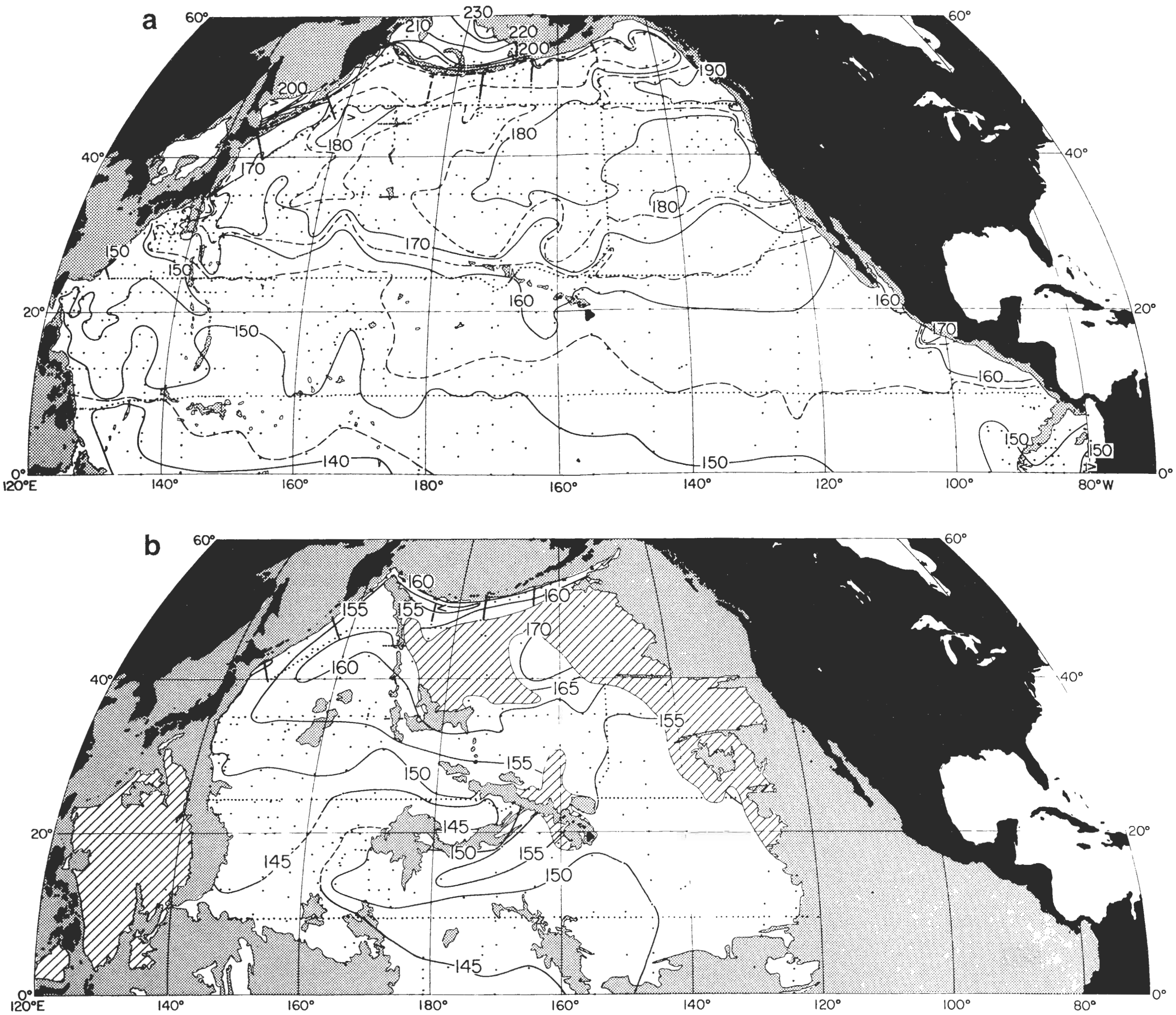

Fig. 4. (*a*) Silica (micromoles per liter) at 36.90 σ_2, which intersects the intermediate silica maximum, with a 2000-m isobath (shaded). (*b*) Silica (micromoles per liter) at ~~36.90~~ 45.88 σ_4 with a 4500-m isobath (shaded). Hatching indicates regions where the depth is greater than 4500 m but where no water this dense is found.

bottle data near 10°N also suggest an eastern boundary maximum, this was not found along the densely sampled 10°N section collected in 1989 and provided to us by J. Toole. Farther south, a lateral maximum is apparent and, in fact, is found all along the South American coast as well (e.g., silica at 37.0 σ_2 from *Reid* [1981]. (A similar pattern of high-silica concentration along the eastern boundary is also found in the Atlantic.) We do not suggest that there is continuous southward flow of intermediate water all along the eastern boundary, from high to low silica, but that the eastern boundary is a source of silica, perhaps because the circulation is weak and the residence time is long. Hydrothermal vents are also suggested here as an important source in the Cascadia Basin and possibly the Gulf of California. Finally, productivity is high in the subpolar gyre and in the eastern boundary upwelling regions; the contribution to the high intermediate depth silica from the dissolution of sinking particles combined with a circulation pattern with oldest water in the east must also be considered. The relative importance of these sources is considered in section 3.

2.3. *Silica at 45.88 σ_4 (Figure 4b)*

The second isopycnal shown in Figure 4, 45.88 σ_4, intersects the bottom maximum in the northeast Pacific. Although the bottom maximum is not approximated by any isopycnal, we assume that near-bottom flow is more likely to conserve density than to follow the bottom silica maximum. This isopycnal is somewhat shallower than 4000 m in the tropics, about 4500 m deep at mid-latitudes, and deeper than 5000 m where it intersects the bottom in the north. The hatched regions in Figure 4*b* denote areas where the bottom density is less than 45.88 σ_4; the lower density of the bottom water in the northeast Pacific may be due to geothermal heating [*Joyce et al.*, 1986].

Water with the lowest silica crosses the equator in the central western North Pacific, north of Samoa Passage (9°S, 169°W). Two large, topographically guided, clockwise "swirls" with low silica on the west are found, one between the equator and 30°N and the other between 30°N and the northern boundary. The southern cell has not been mapped before, although it is similar to middepth (1000 to 2500 m) oxygen patterns previously mapped by *Reid and Mantyla* [1978] and *Reid* [1981]. The tongue of low silica between 20° and 25°N is well resolved by TPS24; its source appears to be from around the western side of Wake Island. This low silica occupies the region between the Hawaiian Ridge and the Mid-Pacific Seamounts. The source of the tongue of high silica southwest of the Hawaiian Ridge is probably the 4500-m-deep gaps through the ridge, which have not been sampled. The tongue is also strong and evident at 45.86 σ_4, which lies at about 3800 m in this region but is nearly gone at 45.84 σ_4 at about 3300 m. The flow direction implied by the high-silica tongue is ambiguous; it is located in precisely the region where *Edmond et al.* [1971] inferred deep eastward flow through Horizon Passage and around the Hawaiian Ridge. A "core-following" flow would be southwestward; a diffusive flow could be eastward toward a ridge source. Clearly, more data are required in this region to define the direction of circulation.

The low-silica tongue along the western and northern boundaries is defined for the first time with these data; in particular, the TPS47 and SAGA II data show that the high silica concentrations observed on the Boreas expedition west of the Emperor Seamounts [*Reid*, 1973] could not have come from the western boundary. The absolute lateral minimum along the TPS47 and SAGA boundary sections occurs over the deepest part of the underlying trench, indicating northward flow at this depth (see the vertical sections). Along the northern boundary the silica minimum occurs offshore, over the "lip" of the Aleutian Trench and the offshore slope, in agreement with *Warren and Owens*' [1988] observation of deep eastward flow in this region. At the M2 crossing of the Aleutian Trench the isopycnal occurs only in the trench. All six northern and western boundary sections show a narrow band of high silica concentration at the boundary, implying either southward and westward flow or a boundary source of silica in slow-moving waters; the first explanation is preferred, particularly because of *Warren and Owens*' [1988] direct measurements.

Two areas of high silica concentration in the open North Pacific occur north of 38°N, one in a cul-de-sac in the northeast Pacific and the other west of the Emperor Seamounts. More data are needed to resolve it, but the latter may come from the eastern North Pacific through a gap in the seamounts from the Bering Sea along the seamounts (although this would imply an interruption in the low-silica boundary core) or from local sources at the seamounts combined with sluggish flow in the region.

3. SILICA SOURCES

The previous section described what can be said with certainty about the intermediate and deep silica distribution in the North Pacific. In this section we consider sources of the maxima, but quantitative estimates of the relative importance of each source are poor because of large uncertainties in silica fluxes. The bottom maximum in the Cascadia Basin of the northeast Pacific is considered separately from the intermediate and bottom silica maxima even though the density and properties of the intermediate and Cascadia maxima may suggest a common source. Sources considered for the intermediate silica maximum are (1) vertical flux divergence of particulate silica [e.g., *Broecker and Peng*, 1982]; (2) dissolution from opaline bottom sediments [e.g., *Berelson et al.*, 1991; *Fanning and Pilson*, 1974; *Edmond et al.*, 1979], possibly enhanced by high surface productivity and Columbia River outflow [e.g., *Van Bennekom and Berger*, 1984]; (3) upslope advection in a bottom boundary layer in the northeastern Pacific, with ejection of silica into the intermediate maximum; and (4) hydrothermal venting. Contributions to the bottom maximum are possible from (2) and (3) but are not likely from (4) and are not possible from (1). All sources except (1) may contribute to the Cascadia Basin bottom maximum. Understanding the occurrence of the vertical maxima also requires explaining why there are surrounding minima. A summary of the following discussion is provided in Table 1.

3.1. Intermediate and Cascadia Basin Silica Maxima

Silica at middepths in the western tropics is about 140 μmol L^{-1} (Figure 4*a*); its average value over the North Pacific is about 160 μmol L^{-1}, requiring a general increase of 20 μmol L^{-1}. This is true both for isopycnals intersecting the vertical maximum and the maximum itself. The west-to-east difference in ^{14}C at its vertical minimum, which occurs at about the same depth as the intermediate silica maximum [*Ostlund and Stuiver*, 1980], indicates an approximate age difference of 100 years (C. G. H. Rooth, personal communication, 1991), so the required vertical silica flux divergence at this density is 0.2 μmol L^{-1} yr^{-1}. Near the bottom of the Cascadia Basin, silica at 36.94 σ_2 (Figure 5*a*) is 13 μmol kg^{-1} higher in the basin (stations 108-112) than immediately offshore (stations 94-98). Estimates of the flux divergence required for this maximum are given as part of the following discussion. Each of the four mechanisms listed above is now considered for its possible importance in creating the intermediate and Cascadia Basin bottom silica maxima.

1. A vertical balance between dissolution of sinking particles and upwelling has been a common explanation for the worldwide silica maximum at intermediate depth [e.g., *Broecker and Peng*, 1982]. From sediment trap deployments east of Hawaii, *Honjo et al.* [1982] found a vertical flux of silica at middepth of the order of 40 μmol m^{-2} d^{-1} with a small loss of 3 μmol m^{-2} d^{-1} (0.11 μmol cm^{-2} yr^{-1}) from 2780 to 4280 m. This corresponds to a dissolution rate of 7.3x10^{-4} μmol L^{-1} yr^{-1}, which is too small by a factor of 270 for the intermediate maximum. However, at Ocean Weather Station P in the northeastern Pacific (50°N, 145°W), *Honjo* [1984] reported a much higher vertical flux of silica, of the order of 1300 μmol m^{-2} d^{-1}, with large seasonal fluctuations. On the basis of Honjo's Figure 4*c*, the flux difference between 1000 and 3800 m averaged on the order of 30 mg m^{-2} d^{-1} of opal. If a small amount of water is ignored, 1 mol of opal (containing 1 mol of silica) weighs 60 g. Therefore the silica flux difference was 500 μmol m^{-2} d^{-1} (18.3 μmol cm^{-2} yr^{-1}), giving a flux divergence of 0.065 μmol L^{-1} yr^{-1} of silica, which is about a third of what is required for the observed isopycnic increase. In another high latitude region, the Southern ocean, *Nelson and Gordon* [1982] indirectly estimated a vertically integrated dissolution rate of about 1.3 μmol m^{-2} d^{-1} (47 μmol cm^{-2} yr^{-1}); over 5000 m this is equivalent to a rate of 0.095 μmol L^{-1} yr^{-1}, about half of what we require. Thus the high-latitude measurements suggest that this mechanism could be important for the intermediate silica maximum, but the large geographical and seasonal variations in the existing data and the lack of measurements specifically constraining dissolution below the productive upper ocean make it difficult to quantify its relative contribution.

2. A second mechanism for creation of the intermediate silica maximum and also the Cascadia Basin bottom maximum is dissolution from sediments where the isopycnals intersect the bottom. Dissolution of silica from bottom sediments causes an incremental change in the silica relative to some initial value as

$$\delta SiO_3 = F_s t/(\rho h)$$

where F_s is the flux of silica from the sea bottom in μmol cm^{-2} yr^{-1}, t is time, ρ is the density of seawater, and h is the layer thickness. The silica change is thus linearly related to the residence time and the flux. The lowest bottom flux values appear to be 2-6 μmol cm^{-2} yr^{-1} over abyssal plains in regions of low productivity such as the central North Atlantic subtropical gyre [*Fanning and Pilson*, 1974]. In the central equatorial Pacific, which is a region of high productivity, *Berelson et al.* [1991] measured fluxes of 11-15 μmol cm^{-2} yr^{-1}. In shallower water (900-1800 m) off the productive southern California continental shelf, *Berelson et al.* [1987] measured even higher fluxes of 26-40 μmol cm^{-2}

TABLE 1*a*. Silica Sources: Intermediate Silica Maximum

	Parameter	Value
	Global Silica Increase Over North Pacific	
Required for entire isopycnal	ΔSi	20 μmol L^{-1} in 100 years
	F_s	2 μmol cm^{-2} yr^{-1} over 100 m
	$F_s/\rho H$	0.2 μmol L^{-1} yr^{-1}
Particle dissolution		
15°21'N, 151°29'W [*Honjo et al.*, 1982]	F_s	0.11 μmol cm^{-2} yr^{-1} over 1500 m
(sediment traps)	$F_s/\rho H$	0.00073 μmol L^{-1} yr^{-1}
50°N, 145°W [*Honjo*, 1984]	F_s	18.3 μmol cm^{-2} yr^{-1} over 2800 m
(sediment traps)	$F_s/\rho H$	0.065 μmol L^{-1} yr^{-1}
60°S, 174°W [*Nelson and Gordon*, 1982]	F_s	47.5 μmol cm^{-2} yr^{-1} over 5000 m
(inferred)	$F_s/\rho H$	0.095 μmol L^{-1} yr^{-1}
Sediment flux		
Edmond et al., [1979] average value	F_s	3 μmol cm^{-2} yr^{-1} at bottom or $3x10^{-3}$ μmol cm^{-2} yr^{-1} on isopycnal
Fanning and Pilson [1974] or Berelson *et al.* [1991] representative of productive region	F_s	15 μmol cm^{-2} yr^{-1} at bottom or $15x10^{-3}$ μmol cm^{-2} yr^{-1} on isopycnal
Hydrothermal vents		
1 megaplume [*Baker et al.*, 1989]	$F_s/\rho H$	0.00074 μmol L^{-1} yr^{-1}
	Local Silica Increase at the Intermediate Maximum Over Northeast Pacific	
Required (for $\Delta\theta$ = 0.02°C and ΔS = 0.003‰ at 36.90 σ_2)	ΔSi	3-5 μmol L^{-1}
Hydrothermal vents: direct plus entrainment		
Model after *Speer and Rona* [1989] for initial plume velocity 40 cm s^{-1}	ΔSi	6.1 μmol kg^{-1}

TABLE 1*b*. Cascadia Basin Bottom Silica Maximum

Local Silica Increase	Parameter	Value
Required (for $\Delta\theta$ = 0.08°C between bottom water at 36.94 σ_2 and offshore source at 36.95 σ_2, assuming h = 100 m)	ΔSi	13 μmol kg^{-1}
Sediment flux for age of 5.9 years		
Edmond et al., [1979]	F_s	3 μmol cm^{-2} yr^{-1}
	ΔSi	1.8 μmol kg^{-1}
Fanning and Pilson [1974]	F_s	15 μmol cm^2 yr^{-1}
or *Berelson et al.* [1991] representative of productive region	ΔSi	8.9 μmol kg^{-1}
Hydrothermal vents		
Von Damm and Bischoff [1987]	ΔSi	6.4 μmol kg

TABLE 1*c*. Silica Sources: Bottom Silica Maximum

Global Silica Increase	Parameter	Value
Required (for h = 1000 m, t = 100 years)	ΔSi	25 μmol kg^{-1}
	F_s	25 μmol cm^{-2} yr^{-1}
Sediment flux		
Edmond et al. [1979]	F_s	3 μmol cm^{-2} yr^{-1}
	ΔSi	3 μmol kg^{-1}
Fanning and Pilson [1974] off the Grand Banks	F_s	15 μmol cm^{-2} yr^{-1}
or *Berelson et al.* [1991] for equatorial Pacific	ΔSi	15 μmol kg^{-1}

yr^{-1}. *Fanning and Pilson* [1974] similarly found fairly large values (7-17 μmol cm^{-2} yr^{-1}) in 2400-m-deep water off the productive Grand Banks.

The sediment fluxes appear to depend on interstitial water silica concentration [*Fanning and Pilson*, 1974] and the overlying silica concentration, both of which may depend on productivity and possibly depth. Measurement techniques also affect the results [*Berelson et al.*, 1991]. Dependence on depth is inferred from the quoted measurements and may make some sense because of dissolution of falling particles in the water column, which after all contributes to the intermediate silica maximum.

In their discussion of benthic silica fluxes, *Edmond et al.* [1979] used an average value of 3 μmol cm^{-2} yr^{-1}, which is reasonable for abyssal plains in subtropical gyres but may be a gross underestimate for regions of higher productivity or shallower shelves. For our purposes we use their value as the most conservative and a value of 15 μmol cm^{-2} yr^{-1} as typical of a productive, deep region. The appropriate value for the shallower Cascadia Basin is difficult to guess but should probably be even higher.

For the entire 36.9 σ_2 isopycnal, using *Edmond et al.*'s [1979] low flux of 3 μmol cm^{-2} yr^{-1} and a high flux of 15 μmol cm^{-2} yr^{-1}, we find that it would take about 66,000 years and 13,000 years, respectively, to diffuse enough silica onto the isopycnal to raise it from its inflow value of 140 μmol kg^{-1} to its average value of 160 μmol kg^{-1}, assuming a 100-m-thick layer which intersects the boundary over an area which is about 10^{-3} of the total isopycnal area. (Although not required for this calculation, the area is used below; it is estimated at 8×10^{17} cm^2 from *Emig* [1967].) If these were to be reduced to a more reasonable age of 100 years, the combined choice of F_S/h would need to be increased, for instance, by reducing the layer thickness to 10 m and increasing the flux to 200 μmol cm^{-2} yr^{-1}. Thus sediment dissolution does not seem to be a likely source for the intermediate silica maximum.

There is also a problem of understanding how a bottom source can create a middepth silica maximum: even if a bottom source were important, why is silica not increased equally on all isopycnals which intersect the bottom? A possibility is that the intermediate maximum lies near the depth and density of the Cascadia Basin bottom maximum and also near the sill depths of the Okhotsk and Bering seas, in which bottom silica is very high. Isopycnals above and below the intermediate maximum would have even less area intersecting the bottom, so if there were enough flux from the bottom intersection to produce the observed lateral increase in silica at the maximum, the isolated vertical maximum might be due to the Cascadia Basin. Data from near the Bering and Okhotsk seas (Figure 4*a*) suggest that these seas do not contribute to the open-ocean maximum; additional surveys of these areas would be useful in addressing this possibility.

Even though silica dissolution along isopycnals from the bottom sediments is too weak to explain the entire 36.9 σ_2 distribution, it could produce part of the Cascadia bottom water anomaly of 13 μmol kg^{-1} at 36.94 σ_2. A conservative age for the Cascadia bottom water is 4.8 to 5.9 years relative to waters offshore, if *Langseth and Von Herzen*'s [1970] conductive heat fluxes of approximately 4 to 5 μcal cm^{-2} s^{-1} produce an observed temperature anomaly of 0.08°C over a vertical thickness of 100 m. (The temperature anomaly is discussed in section 4 below.) Other heat flow measurements near active spreading centers like the Galapagos are similarly high [*Green et al.*, 1981]; the unincluded convective component due to fluid motion below the sea bottom would only decrease the age. In 5.9 years the silica would increase by 1.8 μmol kg^{-1} for the *Edmond et al.* [1979] diffusive flux value, about 12% of the required amount, or by 8.9 μmol kg^{-1} for a 15 μmol cm^{-2} yr^{-1} flux. This latter is about the right size and may be representative of the productive subpolar North Pacific, but we have not found any published direct measurements of sediment fluxes for the Cascadia Basin.

An additional possibility for enhancing diffusive bottom silica flux is the Columbia River outflow, which disgorges over the Cascadia Basin. *Van Bennekom and Berger* [1984] demonstrated the correspondence between the Zaire River outflow, high primary productivity, excess sedimentation, and enhanced bottom silica in the Angola Basin in the South Atlantic. They modeled the bottom dissolution rate, obtaining 3-5 μmol cm^{-2} yr^{-1}, which is about the same size as *Edmond et al.*'s [1979] average (low) flux. Although this flux seems unremarkable, the same model applied to the basin outside the Zaire River fan produced only one third of the sedimentary flux, indicating the local importance of the Zaire River outflow. The results are undoubtedly model-dependent and mainly demonstrate that flux is significantly enhanced above the outflow fan. We do not know how to estimate the impact of the Columbia River outflow.

3. A third source of silica at the intermediate maximum could be upslope advection in a bottom boundary layer in the northeastern Pacific. The bottom maximum discussed in the next section may result from bottom sources and age; eastward interior flow and upslope advection would confine the maximum to the region near the boundary, keeping it from spreading westward on deep isopycnals, and could also contribute to the intermediate maximum by ejecting water offshore at the slope break at the Juan de Fuca Ridge. As the water moves up the slope, silica flux from the bottom would increase its dissolved silica concentration. When it reaches the slope break, it would eject offshore, carrying its own originally high silica and entraining some of the high-silica Cascadia Basin bottom water.

4. A final possible mechanism for producing the excess silica at the bottom of the Cascadia Basin and perhaps contributing to the entire intermediate maximum is hydrothermal venting. The concentration of silica in hydrothermal vent waters is high [e.g., *Von Damm and Bischoff*, 1987] with depleted oxygen, phosphate, and nitrate [*Thompson*, 1983]. The region of highest open-ocean silica at 36.90 σ_2 (Figure 4*a*) and silica at the silica maximum (Figure 4*e*) coincides with the Juan de Fuca venting region, which we take to encompass the Cascadia Basin east of the Juan de Fuca Ridge and all of the other vent fields in the region. The highest TPS47 silicas occur at the bottom of the Cascadia Basin, near where *Kulm et al.* [1986] report low-temperature venting. Silica at 36.90 σ_2 is also enhanced in the southeastern North Pacific near the hydrothermal zones of the Gulf of California and the East Pacific Rise; however, the signal there is not large (and was entirely absent on the detailed 10°N section), implying that advection, mixing, and other sources of silica are more important for this region.

Hydrothermal effects on TPS47 are striking. Potential temperature anomalies of 0.01°C to 0.05°C on σ_2 isopycnals are found relative to the average from stations 94-98 (Figure 5*a*), with a "plume" stretching offshore centered at 36.90 σ_2. (Thermal anomalies at densities lower than 36.82 σ_2 are associated with the general circulation.) The western edge of the plume at station 99 is abrupt, as seen in the vertical profiles of potential temperature anomaly, relative to the average from stations 80-85 (Figure 5*b*). A helium 3 plume measured on TPS47 is centered at 36.86-36.88 σ_2, slightly above the thermal plume (J. L. Lupton, personal communication, 1991), confirming the hydrothermal source of the potential temperature anomaly. Lupton's helium 3 plume extends westward at least as far as the Emperor Seamounts. However, the temperature plume cannot be traced past station 99, regardless of which group of stations is used for an average for the thermal anomalies. The highest deep temperature anomaly in Figure 5 is at the bottom of the Cascadia Basin, where isotherms and isopycnals slope upward to the east (see vertical sections in paper by *Talley et al.* [1991]); gentle geothermal heating may both heat and vertically mix the bottom layer so that with an offshore source of colder, more saline water, a pool of relatively warm water is formed at the bottom of the Cascadia Basin.

The highest silica on TPS47 is found at the bottom of the Cascadia Basin, coinciding with the high thermal anomalies in Figure 5. The offshore hydrothermal plume, at 36.90 σ_2, nearly coincides with the intermediate silica maximum (36.91 σ_2), shown in Figure 5*a* as well as Figure 3*d*. The isopycnic temperature anomaly at 36.90 σ_2 is 0.01°C to 0.02°C (stations 99-112, relative to 94-98). Silica in the thermal plume can be deduced from isopycnal distributions (Figure 6*a*). At the lowest densities, below 36.89 σ_2, the lateral silica maximum lies offshore of the eastern boundary, west of 140°W; at densities greater than 36.90 σ_2 it lies inshore over the Cascadia Basin. Along 36.89-36.90 σ_2, coinciding with the thermal plume, silica is uniform. At all these densities there is a drop-off in silica around 150°W (stations 85-90), considerably west of the edge of the thermal plume. If this drop-off is specified as the edge of the hydrothermal silica plume, the anomaly in the plume, relative to water farther offshore, is about 3-5 μmol L^{-1}.

An estimate of the possible contribution of hydrothermal venting to these thermal and silica anomalies requires a model of the hydrothermal plume and its entrainment. We used

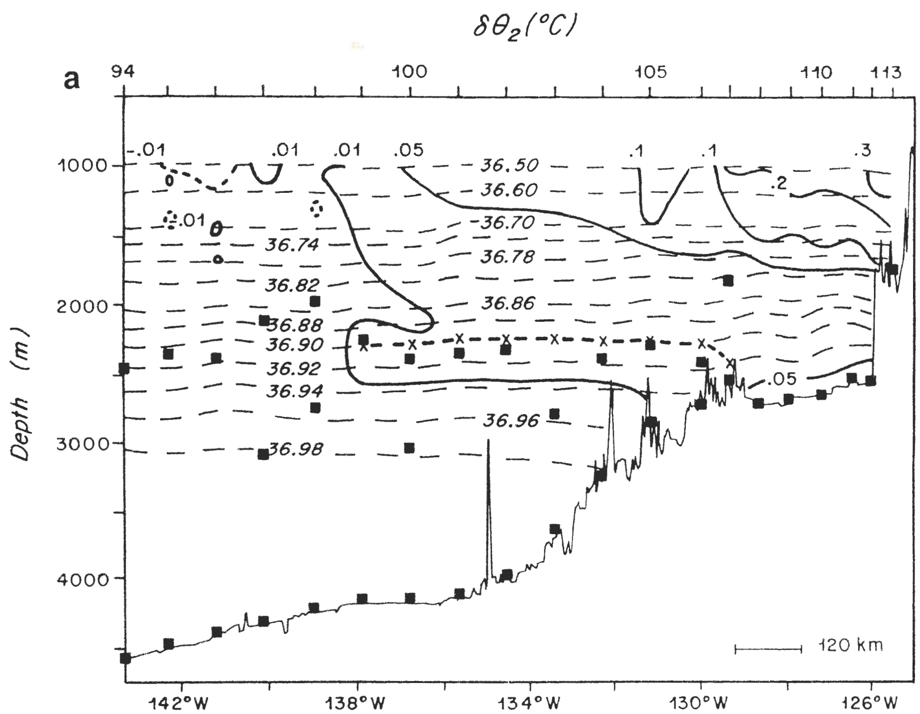

Fig. 5. (*a*) Contours of the anomaly of potential temperature relative to 2000 dbar, θ_2, on σ_2 isopycnals for TPS47 stations east of 143°W, superimposed on the σ_2 section. The anomaly was calculated relative to the isopycnic mean for stations 94-98. The curve with crosses dashed follows the maximum anomaly in the vertical. Squares denote the vertical silica maxima at each station. (*b*) Potential temperature (θ_2) anomaly at stations 86-114, relative to the isopycnic (σ_2) mean for stations 80-85. The abrupt changes in anomalies centered at 36.9 σ_2, occur between stations 98 and 99 (left group with slightly negative anomaly to center group with positive anomaly) and between stations 106 and 107 (center group to right group with large bottom anomaly).

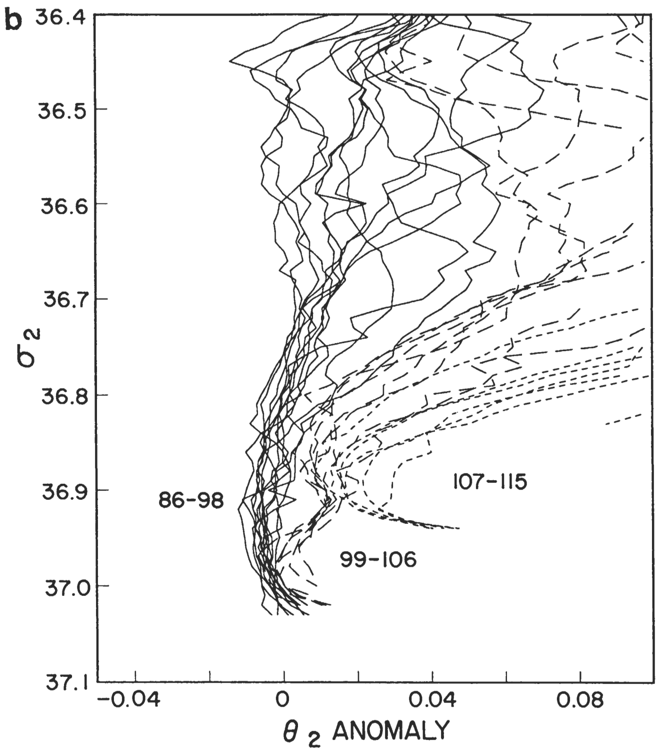

Fig. 5. (continued)

Speer and Rona's [1989] suggestions for an equation of state, entrainment rate, initial plume area, and velocity, and usage of background properties which vary linearly with height, and integrated the *Morton et al.* [1956] plume model. Choice of the background profiles is difficult because the observed waters already include the effects of the hydrothermal sources; the calculated anomalies may therefore be difficult to interpret. Characteristics of the ambient water which the vent water entrains were taken from our own vertical profiles in the Cascadia Basin where silica is high at the bottom. The background and plume characteristics in our application are listed in Table 2. The equilibrium height for the plume was chosen to be where the plume density equals the background density, with z=0 at the vent. The listed anomalies are relative to the model background at the plume density. The plume density for both choices of vertical velocity is 36.91 σ_2, Which is somewhat denser than the observed thermal plume and the same as the density of the silica maximum. The temperature anomaly in the plume is about the same as the observed anomaly (Figure 5), but the modeled silica anomaly is larger than we observe. The relative positions of the observed temperature and silica anomalies (thermal above silica) are consistent with the plume model, since the background temperature increases upward and background silica decreases upward.

A final way of calculating the possible effect of hydrothermal venting on the intermediate silica maximum is to consider its potential contribution to the overall lateral increase of 20 μmol kg^{-1} from the newest waters in the southwestern North Pacific. Hot "megaplumes" such as those observed by *Baker et al.* [1989] on the Juan de Fuca Ridge (cleft segment) had an estimated net heat flux of 4-9x10^9 W. This could raise the temperature of an entire isopycnal layer of 100-m thickness and 8.3x10^{17}cm^2 area by 9.2x10^{-6}K yr^{-1}. By using *Von Damm and Bischoff*'s [1987] vent water measurements of silica (22,800 μmol kg^{-1}) and temperature (285°C) and assuming that mixing occurs with surrounding water, a corresponding silica flux of 7.4x10^{-4} μmol kg^{-1} is obtained. Thus one vent segment alone could raise the silica in a basin-wide 100-m-thick layer by 20 μmol kg^{-1} in 27,000 years, which is about the same as dissolution from sediments. We conclude therefore that hydrothermal venting is not a significant source for the entire isopycnal.

Silica is shown as a function of salinity (Figure 7) for several stations in the Cascadia Basin, to compare with a subpolar station at 47°N, 160°E and with stations from 160°E and the eastern end of TPS24. The bottom silica maximum found for all of the Cascadia Basin stations does not occur on TPS24 or in the west on TPS47. The combination of thermal and silica anomalies near the Cascadia Basin and not elsewhere suggests that this is the only important site for venting on TPS47, M2, and TPS24. An oxygen deficiency is also found where silica and temperature indicate hydrothermal effects (Figures 6 and 7).

Since heating is not an isopycnal process, the true thermal anomaly at the bottom of the Cascadia Basin is larger than one would assume from the isopycnals in Figure 7. If the process does not change salinity, the Cascadia Basin bottom water at 36.94 σ_2 with salinity 34.636‰ (average from stations 108-112) derives from offshore water at 36.95 σ_2 (average of stations 94-98). The difference in potential temperature between these is 0.08°C, which is therefore the thermal anomaly supplied by the vents to the bottom water. (This is the value used earlier in this section.) Silica in the

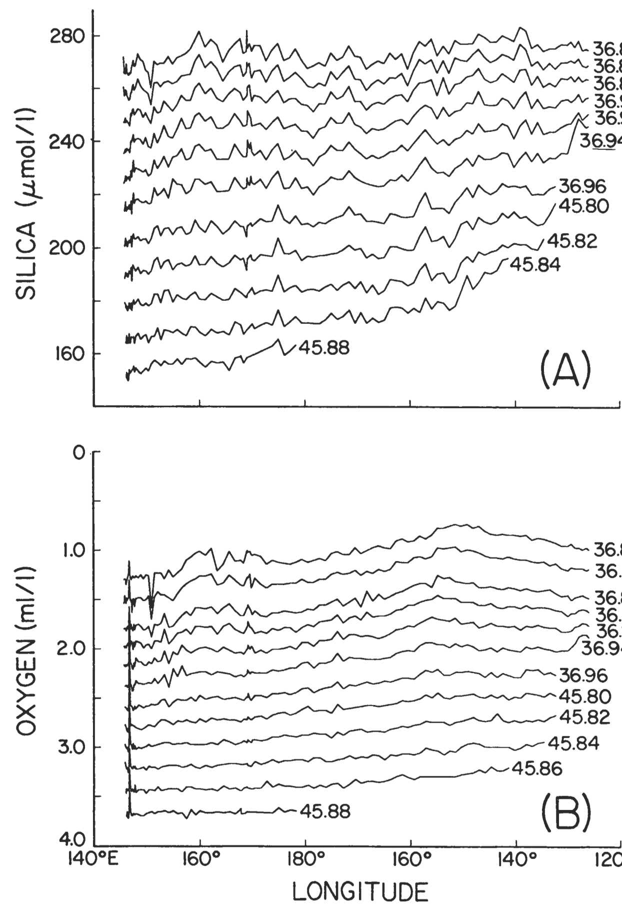

Fig. 6. (*a*) Silica (micromoles per liter) and (*b*) oxygen (milliters per liter) on σ_2 and σ_4 isopycnals from TPS47. Silica units are correct for 45.88 σ_4; each subsequent curve of lower density is offset by +10 μmol L^{-1}. No offsets are applied to the oxygen.

TABLE 2. Hydrothermal Plume Model

	Background	Vent Water at z=0
θ,°C	$1.6 + 5\times10^{-4} z$	285
Salinity, ‰	$34.630 - 6\times10^{-5} z$	34.630
SiO_3, µmol kg^{-1}	$190 - 0.01 z$	22,800
	Equilibrium Plume Characteristics	
w (z=0), cm s^{-1}	40	10
Plume height, m	231	161
Plume density, σ_2	36.907	36.914
Δθ, °C	0.019	0.015
ΔSalinity, ‰	0.006	0.004
ΔSiO_3, µmol kg^{-1}	6.1	4.3

bottom water (stations 88-112) is 197 µmol L^{-1}, which is 13 µmol L^{-1} higher than at both 36.94 σ_2 and 36.95 σ_2 at stations 94-98. Hot vent water over the southern Juan de Fuca Ridge was observed to have a silica concentration of 22,800 µmol kg^{-1} at a temperature of 285°C [*Von Damm and Bischoff*, 1987]. If the 0.08°C anomaly at the bottom of the Cascadia Basin is due to cooled, off-axis hydrothermal flows with the same relative contribution of hot vent water silica, the silica anomaly would be 6.4 µmol L^{-1}. While the basis for this assumption about the silica content of off-axis

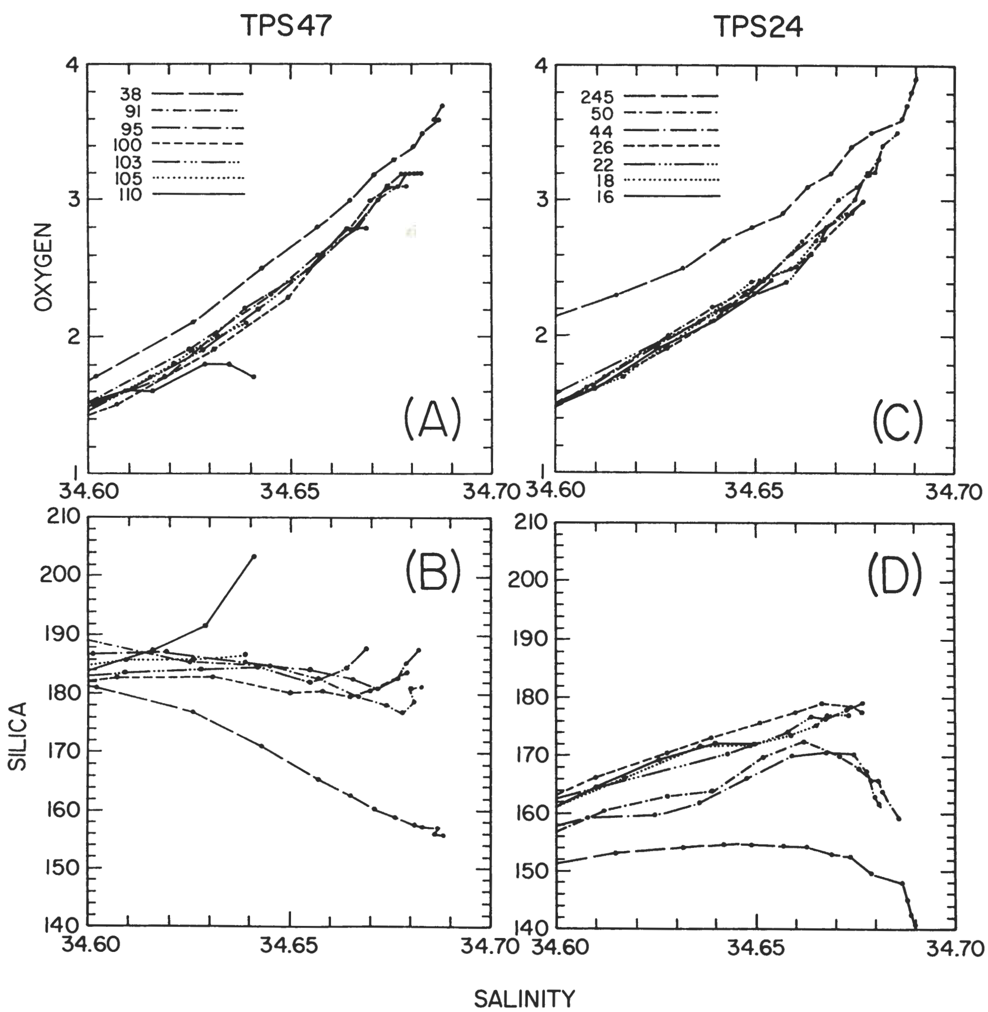

Fig. 7. (*a*) Oxygen (milliliters per liter) *versus* salinity (per mil), (*b*) silica (micromoles per liter) *versus* salinity (per mil) on TPS47 at 47°N (station 38 at 160°E and stations 91-110 at 147°W-127°W). (*c*) and (*d*) same plots for TPS24 at 24°N (station 245 at 160°E; stations 44-50 at 128°-130°W; stations 16-26 at 119°-122°W).

venting is questionable, it can explain an appreciable fraction of the required 13 μmol L^{-1} anomaly; the remainder could be provided by diffusive fluxes as described above. We note that even if vent water were anoxic, the oxygen anomaly would be immeasurable, so it is unlikely that the oxygen anomaly has a direct hydrothermal source. However, its coincidence with the positive silica and temperature anomalies may indicate enhanced biological utilization which could arise from either oxidation of reduced species (Mn, Fe, and H_2S) in the vent water or excess oxygen consumption in the bottom sediment of the region (comment from anonymous reviewer).

3.2. Bottom Silica Maximum

The deep silica maximum is found on the bottom at all TPS47 stations east of about 150°W and on and off the bottom in patches across most of the rest of the section. From the M2 section it was seen that the deep maximum is confined to a fairly narrow latitude range in the subpolar North Pacific, corresponding with a marked bottom thermal anomaly [*Joyce et al.*, 1986]. Of the mechanisms described above which might contribute to the intermediate and Cascadia Basin maxima, only sedimentary dissolution and the bottom boundary layer are relevant for the bottom maximum. There appears to be no evidence of hydrothermal venting west of the Juan de Fuca region, where the bottom maximum is found, so we ignore this possibility. Since the bottom boundary layer we postulate would result in upslope advection, down-slope flow of high-silica waters from the Cascadia Basin is eliminated. On the other hand, Figure 6*b* shows that there are marked positive thermal anomalies at the bottom on the slope offshore of the Cascadia Basin. Do these reflect local hydrothermal effects, down-slope advection from the Cascadia Basin, or extreme age?

The slope of silica isopleths intersecting the bottom is radically different from those of other properties (temperature, salinity, density, oxygen, nitrate, and phosphate [*Talley et al.*, 1991], whose isopleths strike the bottom nearly perpendicularly. The fluxes of the latter from the bottom should be small; the oblique angle between silica isopleths and the bottom implies much more important silica flux. The high-silica bottom layer is about 1000 m thick, based on the onset of high silica concentration on isopycnals (Figure 6*a*) and the height of these isopycnals above the ocean bottom (potential density section in paper by *Talley et al.* [1991]. The high-silica bottom layer corresponds to a slightly warmed bottom layer in the subarctic Pacific, which *Joyce et al.* [1986] attributed to weak geothermal heating. Heat fluxes of 50 mW m^{-2} are not large enough to affect the circulation, so deep potential temperature was used as a passive tracer indicating relative age of the water. Bottom water in the northeastern Pacific was found to be 50-100 years older than in the northwest Pacific, consistent with radiocarbon data. Silica in the abyssal waters of the 47°N transect is about 155 μmol kg^{-1} on the western side of the section, increasing to about 180 μmol kg^{-1} in the east, hence a change of 25 μmol kg^{-1}, implying an integrated flux divergence of 25 μmol cm^{-1} yr^{-1}, using an age of 100 years and a layer thickness of 1000 m. This value is not too different from *Berelson et al.*'s [1991] equatorial Pacific dissolution rate and *Fanning and Pilson*'s [1974] dissolution rate off the Grand Banks. In both regions, productivity is high, as it is in the subpolar North Pacific. (If the smaller sediment flux estimate of 3 μmol cm^{-2} yr^{-1} from *Edmond et al.* [1979] is used, with t = 100 years and h = 1000 m from *Joyce et al.* [1986], we estimate δSiO_3 to be 3 μmol kg^{-1}.)

Why is there a vertical silica minimum between the intermediate and bottom maxima? The minimum indicates a more limited isopycnic spread of silica into the deep interior than at middepth. This implies that the inflow of low-silica waters is higher at depth and/or that the boundary source is stronger or more efficient at middepth. Isopycnal slopes on the meridional M2 section are nearly flat near 2000 m; relative to 2000 m, flow both above and below is eastward. *Roemmich and McCallister*'s [1989] inversion of North Pacific data shows weak eastward flow along M2 below 1000 m at all latitudes north of 34°N. Our own calculation of M2 velocities using Roemmich and McCallister's large-scale smoothed velocity at 1000 m as a reference velocity shows mostly weak eastward flow below 1000 m between about 34°N and 52°N which is the region of the double maximum (deep minimum) [*Talley et al.*, 1991]. The abyssal flow could thus confine the high-silica layer to the sloping bottom. Independent of the interior flow, the configuration of the bottom maximum is similar to theories of the boundary layer on a sloping wall in a stratified fluid [e.g., *Phillips et al.*, 1986]; upslope flow at the boundary, caused by the no-flux condition on temperature and salinity, can be interrupted and injected into the interior by a change in stratification. Presumably, a change in the boundary slope such as occurs at 2000 m could also cause "slope" injection. The intermediate silica maximum could be enhanced and advected offshore by this injection as well as by injection from geothermal heating of Cascadia Basin water. A bottom boundary layer in which flow is confined along the boundary could also contribute to the bottom maximum by increasing the near-bottom residence time of water parcels.

4. SUMMARY AND RECOMMENDATIONS

In conclusion, we find anomalously high silica concentration on isopycnals which intersect the intermediate and bottom maxima in the northeast Pacific in and near the hydrothermally active Juan de Fuca region. The high Cascadia Basin silica and the intermediate silica maxima offshore of the Juan de Fuca Ridge coincide with warm water originating from hydrothermal vents. The highest silica in the intermediate and bottom maxima also occurs in the subpolar gyre where there might be much higher flux divergence of silica and high opal concentrations in the sediments due to overlying high productivity. Rough estimates of the potential contribution of silica from various sources suggest the following points.

1. The intermediate maximum is maintained primarily by vertical particle flux divergence, of the order of what was measured by *Honjo* [1984] at Ocean Weather Station P; hydrothermal venting and flux from bottom sediments appear to be much too weak to contribute significantly. There may also be a contribution from injection from the bottom boundary layer at the bottom slope break.

2. The bottom maximum in the Cascadia Basin is maintained by hydrothermal sources and sediment dissolution. Off-axis hydrothermal sources could contribute significantly to the silica anomaly if these flows contain as high a proportionate amount of silica as the high-temperature plumes. If representative of the subpolar North Pacific, *Berelson et al.*'s [1991] and *Fanning and Pilson*'s [1974] measured values of 11-15 μmol cm^{-2} yr^{-1} in the equatorial Pacific and of 7-17 μmol cm^{-2} yr^{-1} in the Grand Banks region, could account for most but not all of the bottom maximum.

3. The bottom maximum in the subpolar North Pacific offshore of the Cascadia Basin is maintained by diffusion from the sediments, with flux of the order of 25 μmol cm^{-2} yr^{-1}, which is of the order of (but somewhat larger than) *Berelson et al.*'s [1991] and *Fanning and Pilson*'s [1974] values. Some mechanism, such as deep eastward advection or a *Phillips et al.* [1986] bottom boundary layer, is necessary to maintain a bottom boundary layer and a vertical silica minimum in the interior.

Our attempts to account for the increased silica laterally in both the intermediate and bottom maxima were hampered by inadequate knowledge of a number of processes as well as by a lack of silica measurements in critical regions. Denser hydrographic sampling, including good silica measurements, is recommended for the northwestern Pacific to determine whether the Okhotsk and Bering seas contribute to the intermediate maximum, and along and southwest of the Hawaiian Ridge to determine if there is a circulation of high-silica water through the ridge or whether the ridge merely shadows the circulation, increasing the residence time of waters to the southwest. Much more information about the spatial and temporal distribution of silica flux divergence in the water column is needed. Knowing whether vertical flux divergence is an important source for the intermediate maximum would have implications for the amount of deep-ocean upwelling needed to balance the downward flux. More information about the number of hydrothermal vents and which isopycnals they affect is also needed since it appears that vents could contribute significantly to the Cascadia bottom silica maxima. Finally, better knowledge of the North Pacific's sediment dissolution rate, including dependence on overlying productivity and large river outflow, is needed to determine if it is similar to that measured in the equatorial Pacific and off the Grand Banks [*Fanning and Pilson*, 1974] and at the Zaire River outflow [*Van Bennekom and Berger*, 1984].

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