QUATERNARY RESEARCH 37, 346–360 (1992)

Sea Level, Surface Salinity of the Japan Sea, and the Younger Dryas Event in the Northwestern Pacific Ocean

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Received January 28, 1991

The Japan Sea was profoundly different during glacial times than today. Available $\delta^{18}O$ evidence indicates that sea surface salinity was lower by several per mil. This probably increased the stability of the water column and caused anoxic sedimentary conditions in the deep sea, as shown by the absence of benthic microfossils and the presence of laminated sediment. These changes are likely related to the effects of late Quaternary sea-level change on the shallow sills (ca. 130 m) across which the Japan Sea exchanges with the open ocean. The Hwang He (Yellow River) has previously been implicated as the source of fresh water to the Japan Sea during glaciation, but the possible roles of the Amur River and excess precipitation over evaporation must also be considered. Ambiguous radiocarbon chronologies for the latest Quaternary of Japan Sea cores do not adequately constrain the timing of salinity lowering. Previous studies have suggested that lowest sea surface salinity was achieved 27,000 to 20,000 ^{14}C yr B.P. However, if global sea-level fall restricted exchange with the open ocean circulation, then lowest salinity in the Japan Sea may have occurred as recently as 15,000 to 20,000 yr ago when sea level was lowest. If this alternative is correct, then as sea level abruptly rose about 12,000 yr ago, relatively fresh water must have been discharged to the open Pacific. This might have affected the dynamics of outflow, local faunal and floral expression of the polar front, and stable isotope ratios in foraminifera. These environmental changes could be misinterpreted as evidence for the cooling of Younger Dryas age, which has not been identified in nearby terrestrial records.

INTRODUCTION

Study of nearshore marine paleoclimatic records is especially important because they reflect both terrestrial and marine processes, and through their study the two can be linked. Where nearshore locations are somewhat isolated from the open ocean, as in marginal seas, local climate influences the local hydrography, geology, and biology. Whether or not local hydrographic changes in marginal seas become important on the larger (ocean basin) scale depends on the particular geographical situation. For example, the modern outflow of saline water from the Mediterranean Sea may help precondition the North Atlantic for deep-water production (Reid, 1979). Although no deep water is produced in the North Pacific Ocean at present, hydrographic conditions in the Japan Sea and the Okhotsk sea may be critical to the production of Pacific Intermediate Water (Reid, 1973; Riser, 1990; Talley, 1991).

Recently, Younger Dryas-type climatic oscillations have been reported in marine sediments near Japan. Using foraminiferal and stable isotopic techniques, Chinzei *et al.* (1987) and Kallel *et al.* (1988) claim to have identified a cooling episode that occurred 10,500 yr B.P., but in some of the very same sediment cores Heusser and Morley (1990) failed to find pollen evidence for a climatic reversal. It is important to

0033-5894/92 $5.00

identify and interpret deglacial events outside of the North Atlantic region, where they are best known, in order to determine whether they were regional or global phenomena (Rind *et al.,* 1986).

The Japan Sea experienced large environmental changes from glacial to interglacial time at least in part due to the silled straits through which its waters exchange with the open Pacific. Stable isotopic evidence for these changes was first published in the Japanese (Oba *et al.,* 1980) and Soviet (Gorbarenko, 1983) literature, but those (and subsequent) contributions have not yet seen wide exposure in the English language literature. In this paper we review some of the latest Quaternary paleoenvironmental changes in the Japan Sea, and discuss possible mechanisms linking sea-level change driven primarily by North Atlantic events and a Younger Dryas-type oscillation in the northwest Pacific off the coast of Japan.

PHYSICAL SETTING

Japan Sea water exchanges with water from adjacent marginal seas and the open Pacific Ocean through four straits (Fig. 1). A good review of the general circulation and water masses of this sea can be found in Moriyasu (1972). The broad Tsushima Strait, with a sill depth of about 130 m, separates the Japanese islands from Korea and is the principal conduit for marine water entering the sea (Fig. 2A). The Tsugaru Strait (Sangarsky St. in Russian nomenclature), between Honshu and Hokkaido, has a sill depth of 130 m, and is the main outlet from the Japan Sea (Fig. 2B). The Tsushima Warm Current originates as a branch of the Kuroshio Current and flows in through the Tsushima Strait and out through the Tsugaru Strait as the Tsugaru Warm Current. Geostrophic estimates suggest that each of these currents accounts for a net flow of about 1 or 2 Sv (1 Sv = 10^6 m^3 sec^{-1}, Yi, 1966; Toba *et al.,* 1982; Shuto, 1982). Flow through the other two straits is small by comparison because of much shallower sills. The Soya Strait (Laperuza St. in Russian), between Sakhalin and Hokkaido, has a sill depth of 55 m and the Tartarsky Strait (Mamiya St. in Japanese), between Sakhalin and Asia, has a sill of only 12 m.

Minato and Kimura (1980) modeled the dynamic interaction between a marginal sea and a western boundary current to determine why the net flux of surface waters in the Japan Sea is from south to north. They found that the flow is from the Tsushima Strait to the Tsugaru Strait due to the pressure difference between the two straits caused by the wind-driven circulation. Thus, in essence, accumulation of water in the East China Sea by the subtropical gyre drives the Tsushima Warm Current.

Since only near-surface waters exchange between the Japan Sea and other water bodies, the sea develops its own peculiar hydrographic properties below the upper few hundred meters (Yasui *et al.,* 1967; Moriyasu, 1972). Waters below the surface layer display little variability, with low temperature (0–1°C), low salinity (34.05‰), and high oxygen content (5.0–5.5 ml/liter). The well-mixed cold, fresh, oxygenated deep waters are a result of a wintertime convection in the northern part of the basin and a southward return flow along the coast of Siberia (Vasiliev and Makashin, 1991). Only near-surface waters exhibit significant seasonal and spatial variability, mostly reflecting conditions in their East China Sea source. As first noted by Niino *et al.* (1969; see also Ujiie and Ichikura, 1973), the unusual hydrography of the Japan Sea is reflected in the unusually low sedimentary content of organic carbon, and an unusually shallow calcite compensation depth.

METHODS

Even though the analytical results discussed below have been reported elsewhere (Oba, 1984; Oba *et al.,* 1991; Gorbarenko, 1983, 1987), it is important to review the methods prior to discussing the data. Stable isotope data from Japanese cores represent a group effort, having been

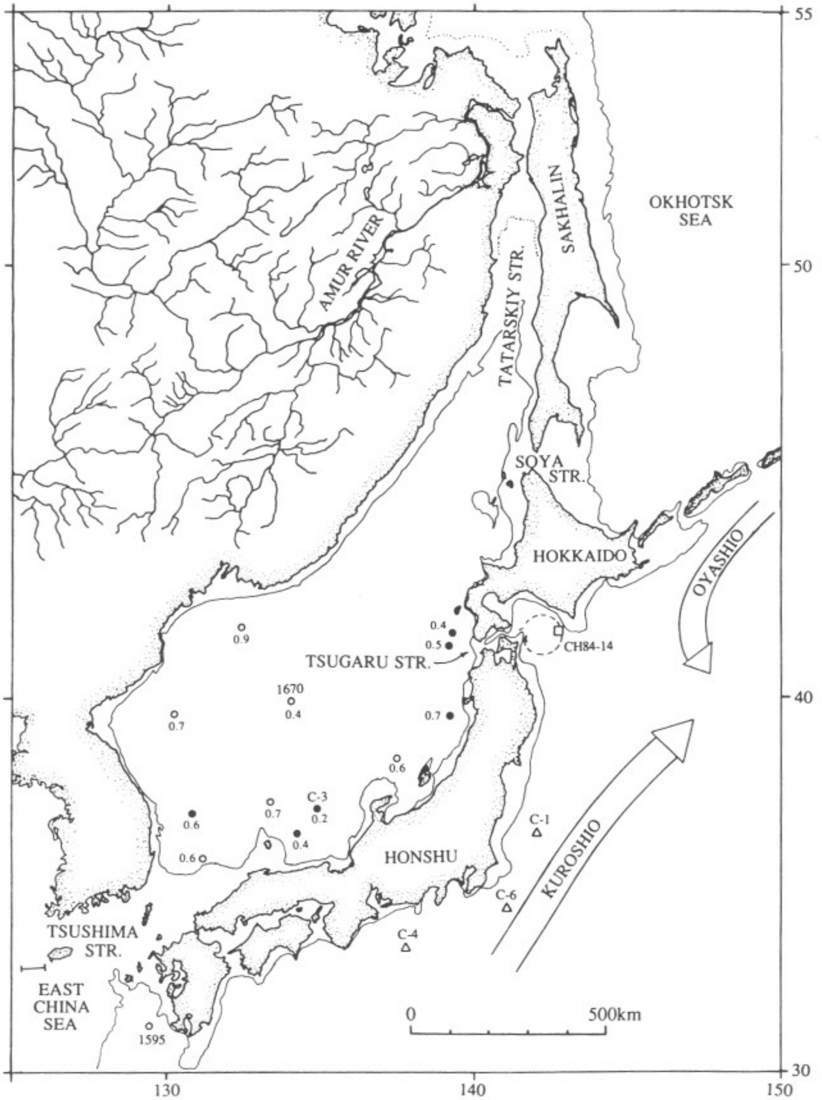

FIG. 1. Map of Japan Sea and surrounding regions showing core locations discussed in text. The solid contour is the 200-m isobath; the 50-m isobath is shown only in the region of the Tatarskiy (Mamiya) Strait to the north (dotted contour). Core locations marked as solid circles are from the work of Oba and colleagues, and cores marked as open circles have been studied by Gorbarenko and colleagues. Numbers next to the Japan Sea core locations are the minimum $\delta^{18}O$ values at each location which reflect glacial maximum conditions at the sea surface. Core locations marked with triangles are from Chinzei *et al.* (1987), and the square between Honshu and Hokkaido marks the position of core CH84-14 (Kallel *et al.*, 1988). A bar symbol in the lower left of the figure (East China Sea) marks a seismic line which shows evidence for a former position of the Hwang He channel (Milliman *et al.* 1989). A dashed circle between Honshu and Hokkaido illustrates the position of the Tsugaru Warm Current when it is in the ''gyre mode'' (Conlon, 1982).

analyzed in three laboratories, using VG Micromass 903 and Finnegan MAT251 mass spectrometers (Oba *et al.*, 1991). Sample dissolution was at 60°C, with no pretreatment, on specimens which were either >177 μm or >250 μm. Where possible, analyses were on individual species, but in intervals of very low abundance mixed

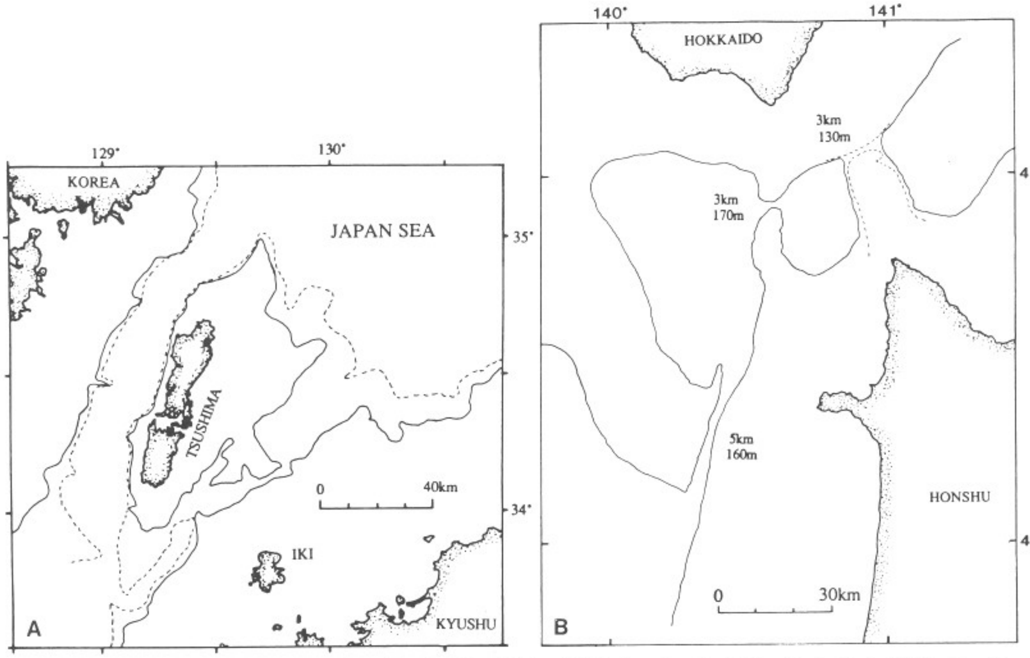

FIG. 2. (A) Map of the Tsushima Strait (after Ujiie, 1973) showing the 110-m isobath (solid line) and the 120-m isobath (dashed line). With a sea-level fall of 120 m, flow through the Tsushima Strait would be restricted to a narrow passage west of Tsushima Island. A 130-m drop in sea level would eliminate the passage in the absence of any tectonic effects. (B) Map of the Tsugaru Strait (after Mogi, 1979 and a map published by the Japan Railway Construction Corp.) showing the 150-m isobath (solid contour) and the location, width, and depth of three "choke points." The dashed contour marks the 130-m isobath. Sea-level fall of 130 m would result in a passage only 3 km wide at the northernmost sill.

planktonic specimens were used. Gorbarenko analyzed mixed specimens of planktonic foraminifera on a MU1309 mass spectrometer, after dissolution "off-line" at 50°C. His results are related to PDB through analysis of SMOW and a laboratory carbonate standard. Radiocarbon determinations on both Soviet and Japanese sediment cores were made on carbonate carbon in bulk sediment.

CORE RESULTS

Of the several Japan Sea sediment cores that have been reported by Oba, Gorbarenko, and their colleagues (Fig. 1), we will describe results of one Japanese core and one Soviet core. These cores have the highest resolution paleoenvironmental records and are believed to be most representative of the stable isotopic history of the late Quaternary of this region.

Oba's (1984) results from a site on Oki Bank (37°04′N, 134°42.4′E, 935 m) are presented in Figure 3. Cores KH79 L-3 and C-3 were taken from almost exactly the same location. Because L-3 had the higher latest Quaternary deposition rate and was radiocarbon-dated, its record is patched to the longer record from C-3 at 215 cm using the distinctive lithologic changes that mark Japan Sea cores (henceforth, and in Fig. 1, the composite record of these two cores will be referred to as C-3). These include three layers of volcanic ash that are dated on land (Ah = 6300 yr; Oki = 9300 yr; and AT = 21,000 to 22,000 yr B.P.; Machida and Arai, 1983), and the top of a thick interval of finely laminated sediment.

Maximum enrichment in ^{18}O in plank-

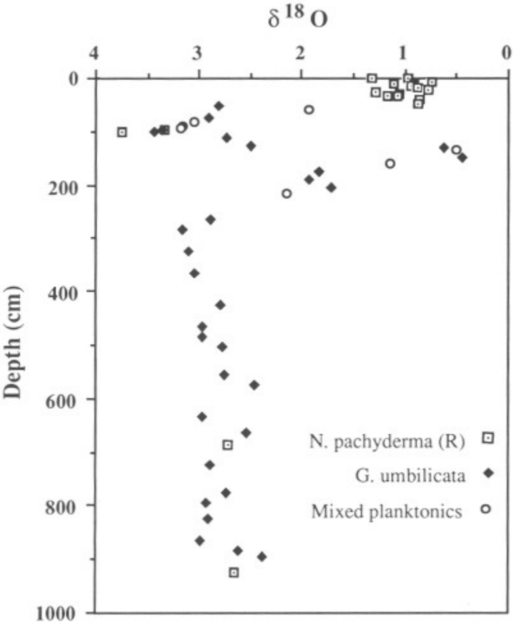

FIG. 3. Oxygen isotope values for latest Quaternary planktonic foraminifera from core C-3 (Oba, 1984). Although this is a composite record made of two species and mixed assemblages, *N. pachyderma* (right coiling) records the signal from the maximum in $\delta^{18}O$ to the core top, and *G. umbilicata* records the full range of $\delta^{18}O$ below core top values.

tonic foraminifera (mostly *N. pachyderma* and *G. umbilicata*) in core C-3 is found at about 100 cm and below about 300 cm (Fig. 3). Lowest $\delta^{18}O$ values for the entire core are found at about 150 cm, and values about 0.5‰ heavier are found throughout the upper 50 cm. Although in the whole core there are only two pairs of stable isotope analyses that allow direct comparison of *N. pachyderma* and *G. umbilicata,* the latter species records the full oxygen isotopic oscillation from heavy to light to heavy values between 100 and 300 cm (Fig. 3). For simplicity, *G. umbilicata, N. pachyderma,* and the mixed planktonics are considered together in Figure 4A.

Benthic foraminifera are common throughout most of core C-3, excepting the interval 132 to 255 cm which includes the laminated sediment (Fig. 4A). Above 132 cm, only *Cassidulina japonica* were analyzed, whereas deeper analyses were mostly on species of *Uvigerina* and on *Cassidulina norcrossi*. Considering just the $\delta^{18}O$ pattern of *C. japonica,* the signal amplitude (about 1.6‰) is less than half that of the planktonic foraminifera from the same interval. Minimum values are found at 112 cm, above the planktonic minimum, and the maximum occurs at 76 cm (Fig. 4A).

In general, the pattern of $\delta^{18}O$ changes in mixed planktonic foraminifera from core 1670 (north slope of Yamato Rise; 39°48′N, 133°27′E, 1105 m; Gorbarenko, 1987) is the same as that found in Oba's cores (Fig. 4B). A few analyses of *G. bulloides* and *N. pachyderma* (sinistral) compare favorably with the mixed planktonic data (Gorbarenko and Matunina, 1991). Maximum $\delta^{18}O$ is found at 70 cm and below about 200 cm, with minimum values found not at the core top (as in core C-3) but at about 100 cm (Fig. 4B). Fine-scale lithological features, such as tephra Ah, and sediment lamination were not recognized because the core was not split before sampling. Radiocarbon analyses of core 1670 (Fig. 4B) were published first by Derkachev *et al.* (1985).

DISCUSSION

Stratigraphy and Chronology of Japan Sea Paleoceanographic-Events

Results on cores C-3 and 1670 (and many others not discussed here) are so unlike those found in typical deep sea cores from the open ocean that the conventional $\delta^{18}O$ stratigraphy cannot be applied. For example, in open ocean cores the lowest $\delta^{18}O$ in the latest Quaternary is usually found at or near the core top, but in Japan Sea cores it may be as deep as 100 to 200 cm within the core. Nevertheless, creating a local stratigraphy for Japan Sea cores is simple using both the $\delta^{18}O$ extrema and volcanic ash layers identified as AT and Oki (Fig. 6).

A chronology is less certain because the radiocarbon age determinations performed on these cores do not agree very well. In core 1670 the $\delta^{18}O$ minimum has a ^{14}C age of about 15,000 yr (Fig. 4B), whereas the

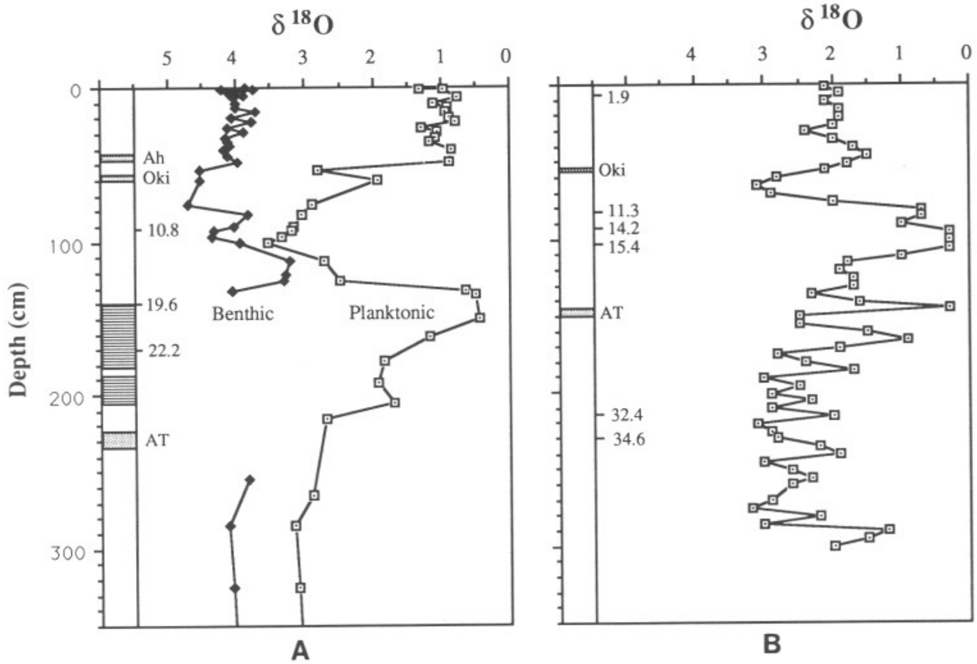

FIG. 4. Oxygen isotope results for cores C-3 (A) and 1670 (B). In each core the stippled pattern along the left axis shows the location of volcanic ash layers, the horizontal-ruled pattern shows the extent of laminated sediment (not noted in core 1670), and the numbers represent radiocarbon age determinations on bulk sediment (in 1000 yr B.P.). In core C-3 planktonic species (Fig. 3) have been lumped. Benthic species above 132 cm are *Cassidulina japonica;* and below 250 cm analyses are based on *Uvigerina* and *Cassidulina* spp. The cooccurrence of low $\delta^{18}O$ in planktonic foraminifera, the absence of benthic foraminifera, and the presence of laminated sediment indicates that during glacial times sea-surface salinity was reduced, deep-sea ventilation was reduced, and the benthic macrofauna was eliminated. Oxygen isotope results are for mixed planktonic assemblages in core 1670.

same event in core C-3 is dated at about 20,000 yr B.P. (Fig. 4A). Identification of volcanic ash beds by Oba, Gorbarenko, and their co-workers indicates that these $\delta^{18}O$ minima must correlate (Fig. 5A). One possible source of the age differences could be the ^{14}C analysis of bulk sediment which is usually required in conventional radiocarbon analysis of pelagic marine sediments. It is well known that ^{14}C age determinations on bulk sediment are frequently plagued by contamination from detrital carbonate that may be infinitely old with respect to ^{14}C (e.g., Keigwin *et al.,* 1984; Jones *et al.,* 1989). In core C-3, Oba (1983) reported a ^{14}C age of 22,000 ± 200 yr B.P. for an interval centered on 169 cm, 64 cm above ash AT which has the same age, based on more than 20 ^{14}C dates which bracket the ash on land (Machida and Arai, 1983). Oba *et al.* (1991) report that up to 30% of the coccoliths in the upper laminated sediments are pre-Quaternary in age, supporting the possibility of detrital carbonate contamination of their ^{14}C ages. In Oba's previously published work and in Oba *et al.* (1991) it is assumed that the 22,000 yr ^{14}C age for the 169 cm level is accurate because Kato (1984) reported an age for ash AT of 26,000 yr in a core from the East China Sea. Because that age was determined by bulk radiocarbon dating of sediment above and below the ash layer, contamination by detrital carbonate is possible at that location as well. Although core 1670 was not examined for detrital carbonate content, its basin center location and lower rate of sedimentation suggest that the younger (15,000 yr B.P.)

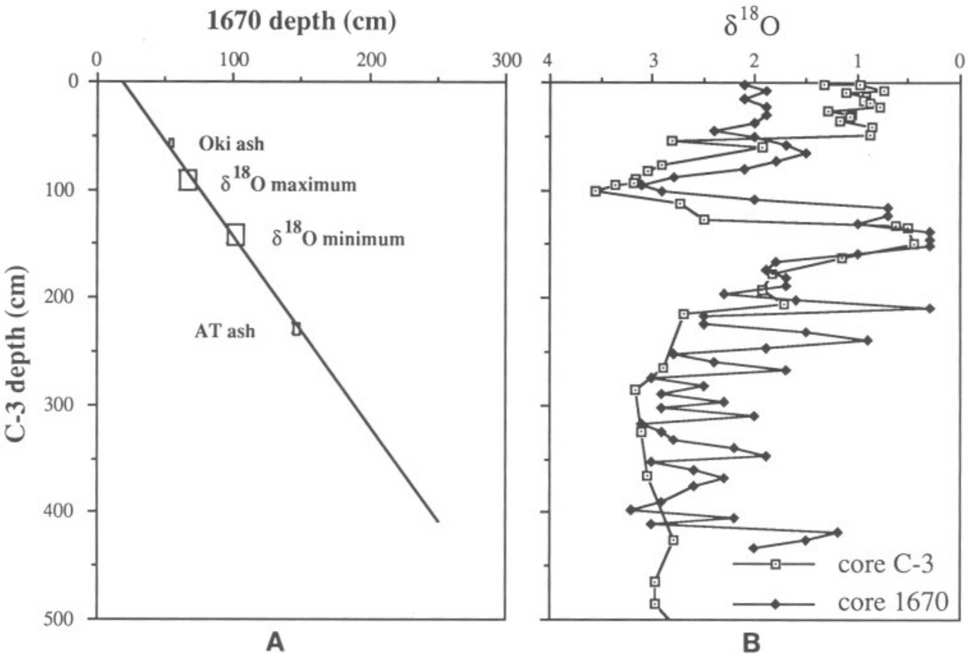

FIG. 5. (A) Correlation of volcanic ash layers and features in the oxygen isotope records between cores 1670 and C-3. Levels in core 1670 can be scaled to those in C-3 by multiplying by 1.44. (B) Composite $\delta^{18}O$ record from cores C-3 and 1670, after scaling the latter. Results from the two cores are in excellent agreement at the oxygen isotopic maximum and minimum. Local hydrographic differences at the core sites and sampling differences probably account for differences between the isotopic records.

age for the minimum in $\delta^{18}O$ may be accurate.

In this paper we assume that the uppermost laminated interval in Japan Sea cores, which contains the minimum $\delta^{18}O$ in planktonic foraminifera, is equivalent to the level of maximum latest Pleistocene glaciation marked in open-ocean cores by maximum $\delta^{18}O$. Thus, the greatest oceanographic change in the Japan Sea may have coincided with the period of harshest terrestrial and atmospheric conditions, which persisted from about 20,000 to 15,000 yr B.P. This interpretation is consistent with the radiocarbon dating on core 1670, and is likewise consistent with the terrestrial age for volcanic layer AT in core C-3. Firm establishment of a Japan Sea chronology for the latest Quaternary must await accelerator mass spectrometry (AMS) ^{14}C dating of hand-picked foraminifera from these cores.

Our proposed correlation of ''events'' in Figure 5A allows scaling of depth in core 1670 to that of C-3 by multiplying the former by 1.44. It also indicates that there may be about 20 cm missing from the top of core 1670, although this is not supported by a young ^{14}C age (1900 yr) near the core top. Scaling core 1670 to C-3 and plotting the two records on a common depth axis shows excellent agreement between the pronounced $\delta^{18}O$ maximum and minimum with important differences above and below the $\delta^{18}O$ oscillation (Fig. 5B). Such differences might result from different sampling intensities of the two cores in the deeper interval, the choice and mixture of species, and differences in Holocene properties of near-surface waters at these two locations (Fig. 1). For example, Holocene planktonic foraminifera at the basin-center location of core 1670 are subject to cooler waters outside the influence of the warm Tsushima Current. Summer sea-surface temperatures (SST) at the location of core 1670 are about 3°C lower than over core C-3, and at 100 m this difference increases to 10°C (Yasui *et al*. 1967).

Late Quaternary Environmental Changes in the Japan Sea

Late Quaternary changes in sea level must have had profound effects on the hydrography of the Japan Sea since the sill depths of the Tsushima and Tsugaru Straits (about 130 m) are close to the 120-m fall of eustatic sea level 15,000 ^{14}C yr ago documented by Fairbanks (1989). Circulation through narrow straits no deeper than 10 m was probably restricted and may have been completely shut off if maximum sea-level lowering was greater than 120 m or if there were any local tectonic effects at the straits. As discussed previously by Oba *et al*. (1980, and in subsequent papers) and Gorbarenko (1987), the δ^{18}O of planktonic foraminifera during glacial times in the Japan Sea was so low that salinity must have been lowered in near-surface waters. Without the influence of salinity on δ^{18}O, unreasonably high SSTs would be indicated. Low salinity probably could have been maintained only if the basin was in restricted communication with saltier waters from the Pacific surface. Thus, we disagree with the conclusion of Morley *et al*. (1986) that the Japan Sea must have been in open communication with the Pacific during full lowering of glacial sea level because of the presence of open sea radiolaria and foraminifera. An alternate interpretation is that the Japan Sea was large enough to maintain its own planktonic fauna and that the fauna was able to live in waters of reduced salinity.

There are only two ways of lowering surface ocean salinity: (1) through increased precipitation relative to evaporation and (2) through dilution by iceberg or river discharge. Iceberg flux can probably be ruled out as a cause of the δ^{18}O minimum in the Japan Sea because of the lack of ice-rafted sediment in the laminae of these cores. Oba (1983) and Chinzei and Oba (1986) proposed that during glacial lowering of sea level the mouth of the Hwang He (Yellow River) moved seaward and discharged fresh water very close to or into the Tsushima Strait. However, Milliman *et al*. (1989) conducted a seismic survey of the East China Sea and found what is probably an ancient channel of the Hwang He seaward of the deepest entrance to the Tsushima Strait (Fig. 1). This indicates that the river may have bypassed the Tsushima Strait at some time in the past, although it still could have influenced the salinity of local waters in the East China Sea. Oxygen isotope results from a core in the East China Sea (core 1595; Fig. 1), however, show a typical δ^{18}O stratigraphy which Gorbarenko (in press) cites as evidence of normal sea-surface salinity.

Possible influence of the Amur River (Fig. 1) on Japan Sea salinity should be considered. The Amur River drains a substantial region of the Asian continent adjacent to the Japan Sea and has an annual discharge of 325 km^3 yr^{-1} (Milliman and Meade, 1983). Today, the Amur River empties into the middle of the Tartarsky Strait and its discharge flows toward the Okhotsk Sea, but this pattern might have changed during glacial times with lowered sea level. If the Amur River influenced Japan Sea salinity during the late Quaternary, then we would expect the interval of low δ^{18}O to have begun earlier and lasted longer because for most of latest Quaternary time the shallow sill at Tartarsky Strait (12 m) would have been flooded. Seismic studies should be conducted to trace the former channel of this river and locate its fan, and additional coring of the Japan Sea should be conducted in higher latitudes to test for gradients in δ^{18}O.

Gorbarenko (in press) recently asserted that lowered surface salinity in the Japan Sea could have resulted from increased precipitation relative to evaporation during glacial times rather than transport of low-salinity surface waters through the Tsushima Strait. Making assumptions about the mass balance, Gorbarenko (in press) estimates that salinity may have been 6 to 7‰ lower than today. In addition, he mapped minimum glacial $\delta^{18}O$ to show its limited geographic variability, with no evidence of lowest values nearest the Tsushima Strait. Combining the available Japanese and Soviet data on the $\delta^{18}O$ minimum indicates a range of only 0.7‰ with no evidence for lowest values closest to the Tsushima Strait (Fig. 1). Within the limits of the available data, this indicates that either there was no one point source (i.e., river) of fresh water discharge to the southern Japan Sea during glacial maximum times, or that surface waters were very well mixed.

Assuming restricted exchange between the Japan Sea and the open ocean, a simple calculation shows that the modern excess of precipitation over evaporation (P–E) over the Japan Sea (about 30 mm yr^{-1}; Baumgartner and Reichel, 1975) is more than sufficient to account for glacial lowering of sea-surface salinity. Multiplying P–E by the area of the Japan Sea (0.9×10^6 km^2) gives a net flux of fresh water of 27 km^3 yr^{-1} which is comparable to the freshwater discharge of the Hwang He (40 km^3 yr^{-1}; Milliman and Meader, 1983). If we assume that the upper 100 m of the sea was freshened, then the volume under consideration was 90,000 km^3 (neglecting reduced surface area due to lowered sea level), which could be completely replaced by fresh water in about 3000 yr. Unfortunately, available climate model results do not resolve P–E for an area as small as the Japan Sea, but there is some evidence for a slight increase over modern values in the annual zonal mean during glacial times (Kutzbach and Guetter, 1986).

Local pollen data, however, indicate that effective precipitation in the coastal zone of the Japan Sea at about 36°N was reduced by ~50% relative to today (Tsukada, 1986). Even if precipitation reduction of this amount was typical of the entire Japan Sea, there would still be sufficient excess P–E to have substantially lowered the salinity of surface waters during maximum glaciation. Thus, it is not necessary to call on the Hwang He as a source of fresh water.

Substantial changes in the salinity of the Japan Sea surface during glacial time must have affected the convection which ventilates that basin today. As first noted by Ujiie and Ichikura (1973), at some depth below the seafloor Japan Sea sediments are laminated. Both Gorbarenko and Oba proposed that low-salinity surface waters must have stratified the water column, preventing convection in the northern part of the sea and leading to deep anoxia. This hypothesis accounts for the laminated sediments and the absence of benthic foraminifera in the interval marked by anomalously low $\delta^{18}O$ in core C-3 (Fig. 4A) and in many other cores. Both Gorbarenko (1987) and Oba *et al.* (1991) presented other sedimentary evidence for restricted convection during glaciation. Their evidence includes higher carbonate and authigenic pyrite contents in the low $\delta^{18}O$ interval, which they attributed to better preservation during sulfate reduction on the seafloor, and higher opal and organic C content during the deglacial and Holocene intervals due to increased surface water productivity.

Oba (1984) showed that benthic foraminifera reappear in C-3 at 132 cm, just above the laminated sediment and the planktonic $\delta^{18}O$ minimum (150 cm). Shortly after they reappeared, the $\delta^{18}O$ of *C. japonica* decreased, at a level where $\delta^{18}O$ of planktonic species was increasing (Fig. 4A). Oba (1984) interpreted this pattern of change to indicate that as sea level increased and exchange with the open ocean resumed, deep convection was renewed and water of lower salinity (but not as low as at full-glacial times) was carried to depth.

Marine conditions in the Japan Sea before the deposition of the latest interval of laminated sediments (equivalent to $\delta^{18}O$

stage 3) must have been unlike those of either the Holocene or the glacial maximum. Planktonic foraminifera had greater $\delta^{18}O$ than in the Holocene, suggesting communication with a colder open ocean than today or higher local salinity, but benthic foraminifera had $\delta^{18}O$ values similar to the Holocene (Fig. 4A). Although global sea level is not known with the same precision before 20,000 yr B.P. as it is since then, it was probably not as low as that at glacial maximum times. Deep convection in the Japan Sea must have been reduced, judging from the scarcity of benthic foraminifera and the occasional presence of laminae. It is likely that salinity was lower in the region of deep convection because of the relatively low $\delta^{18}O$ of benthic foraminifera. This scenario would require a significant latitudinal gradient in surface salinity for pre-glacial maximum conditions or ventilation of the basin at lower latitudes.

We propose that the abrupt maximum in planktonic $\delta^{18}O$ values following the glacial minimum in $\delta^{18}O$ reflects the reestablishment of normal marine conditions during latest glacial time. Previously, Oba (1983) proposed that maximum $\delta^{18}O$ (with minimum $\delta^{13}C$) and cold faunal elements were consistent with flushing of the basin from the north with cold subpolar (Oyashio) waters through the Tsugaru Strait. However, during the glacial maximum the sense of the pressure differential between the two straits produced by the wind-driven ocean circulation was probably the same as today: the North Equatorial Current would still have caused higher pressure at the Tsushima Strait and southerly advance of the polar front may have caused even lower pressure at the Tsugaru Strait. Thus, building on the model of Minato and Kimura (1980), we speculate that as soon as exchange with the open ocean was renewed, the flow must have been from south to north as it is today. In this alternate scenario the maximum $\delta^{18}O$ in the Japan Sea resulted from renewed exchange with open ocean waters still enriched in ^{18}O by the effect of excess continental ice volume. By 11,000 yr ago, deglaciation was only half complete and open marine waters were still enriched in ^{18}O (by about 0.6‰). Low $\delta^{13}C$ at that time was probably due to the seawater-reservoir effect (currently thought to be a few tenths per mil; Duplessy *et al.*, 1988; Curry *et al.*, 1988).

Possible Influence of the Japan Sea on Surrounding Regions

The following discussion assumes that the interval of minimum $\delta^{18}O$ in the Japan Sea was coincident with maximum sea-level lowering. Discussion of the sequence of events in the "older" chronology (minimum $\delta^{18}O$ from about 27,000 to 20,000 yr B.P.) can be found in Oba *et al.* (1991).

When the rate of sea-level rise increased abruptly 12,000 yr ago (Fairbanks, 1989), low-salinity surface water must have been flushed from the Japan Sea to the Pacific Ocean via the Tsugaru Strait. Sediment cores close to the Tsugaru Strait outflow might be expected to record some evidence of that event. Recently, such a core (CH84-14) from the bight between Honshu and Hokkaido was described by Kallel *et al.* (1988; Fig. 1). AMS ^{14}C dates on planktonic foraminifera from that core showed that a distinct event of low $\delta^{18}O$ occurred about 12,000 yr ago (Fig. 6). Kallel *et al.* (1988) found decreased abundance in the polar planktonic foraminiferal species *N. pachyderma* (sin.) at about the same time, and linked that event indirectly with temperature by suggesting that the polar front must have shifted northward. Kallel *et al.* described a readvance of the polar front at Younger Dryas time based on increased abundance of *N. pachyderma* and increased $\delta^{18}O$.

Polar front movement was discussed previously by Chinzei *et al.* (1986), based on three sediment cores taken from the Pacific coast of Honshu (Fig. 1). Those authors reported faunal and floral evidence for a southern advance of the polar front at

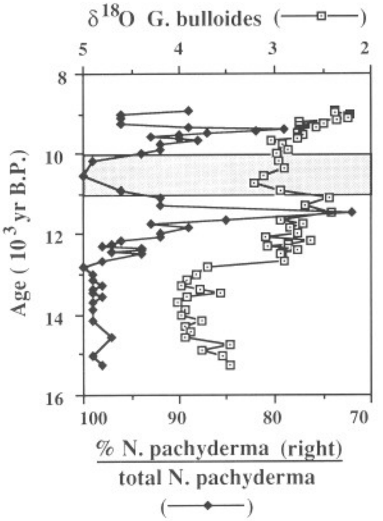

FIG. 6. Late-glacial to early Holocene oxygen isotope results for core CH84-14 in the bight between Honshu and Hokkaido (after Kallel *et al.*, 1988). The isotopic minimum and minimum in abundance of *N. pachyderma* (left coiling), which are AMS ^{14}C-dated to about 12,000 yr B.P., may be a response to abrupt sea-level increase and discharge of low-salinity surface water from the Japan Sea at that time. If that hypothesis is correct, then the isotopic maximum and the faunal maximum between 11,000 and 10,000 yr B.P. do not necessarily reflect cooling similar to the Younger Dryas event in the North Atlantic region.

Younger Dryas time in northern cores C-1 and C-6, but not in core C-4. A comparable δ^{18}O oscillation was found only in the middle core (C-6), although it might have been missed in the northern core (C-1) which is only about 12,000 yr old at the bottom.

There is reason to believe that a link exists between faunal evidence for local movement of the Kuroshio–Oyashio (polar) front, deglacial δ^{18}O changes in planktonic foraminifera, and discharge from the Japan Sea. Conlon (1982) pointed out that the Tsugaru Warm Current exits the Japan Sea in two modes. In the first mode, occurring during summertime, the outflow forms an anticyclonic gyre about 100 km in diameter, that dominates the gulf between Honshu and Hokkaido (Fig. 1). In the second mode, the flow turns abruptly southward along the coast of Honshu. Conlon (1982) proposed that the prevalence of either mode is governed by the Rossby radius of deformation, $R = (g(\Delta\rho/\rho)D)^{1/2}f^{-1}$, where g is the acceleration of gravity, $\Delta\rho$ is the difference in density between the surface and deeper layers, D is the thickness of the surface layer, and f is the Coriolis parameter. In addition, Conlon speculated that the presence of the gyre mode might effectively block the penetration of Oyashio waters into coastal Japan south of Hokkaido, thus controlling the local expression of the polar front.

Since the important variables in R are (1) the thickness of the surface layer and (2) the density contrast, and since these parameters must have changed seaward of the Tsugaru Strait over the last 20,000 yr as sea level and the Japan Sea salinity changed, it is important to estimate how R (and the local polar front) might have changed on deglaciation. Although Ichiye (1982) questioned the strict dependency of circulation mode on R because the modern pycnocline is not very sharp seaward of the Tsugaru Strait, the pycnocline must have been much sharper 12,000 yr ago due to the salinity contrast between the Tsugaru outflow and the open Pacific waters.

For the following analysis we make two important assumptions: (1) that sill depth in the Tsugaru Strait approximates the surface-layer thickness (D) and (2) that $\Delta\rho$ is affected mostly by salinity (for our calculations we assume a temperature of 10°C). Figure 7 illustrates the dependency of R on layer thickness and the salinity contrast between outflowing low-salinity water from the Japan Sea and the underlying Pacific water. In the modern situation, Conlon (1982) found that the gyre mode dominated for conditions where $R > 15$ km, and the coastal mode was found for $R < 10$ km. Thus, for example, with outflowing surface waters less dense due to 5‰ lower salinity, the gyre mode would prevail for layer thicknesses greater than about 60 m (Fig. 7).

Following the late Quaternary maximum lowering of sea level (120 m) and minimum sill depth in the Tsugaru Strait (10 m), sea

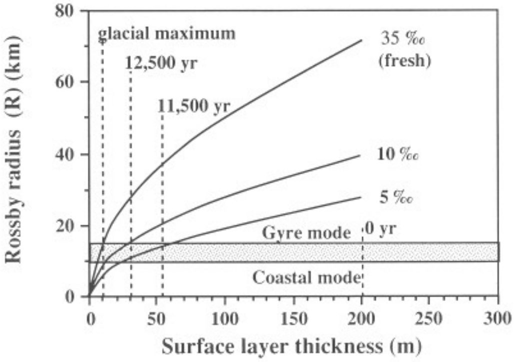

FIG. 7. Rossby radius of deformation (R) as a function of surface layer thickness and salinity (density) contrast in the Tsugaru Strait outflow for various times in the past. For reference, the surface layer thickness today (0 yr) is 200 m, the density contrast is small, and for $R > 15$ Tsugaru Strait outflow is in the "gyre mode" (Conlon, 1982). This situation is typical of summer months, and the gyre blocks cold Oyashio waters from the bight between Honshu and Hokkaido (Fig. 1). In contrast, Conlon (1982) found the "coastal mode" of circulation prevailed in winter months ($R < 10$), with cold waters invading the bight. As sea level rose abruptly about 12,000 yr ago during deglaciation, Tsugaru outflow would have changed from the "coastal mode" to the "gyre mode," assuming a 5‰ salinity contrast between Japan Sea surface waters and Pacific surface waters and a layer thickness the same as sill depth. This model could account for the apparent Younger Dryas age temperature oscillation between about 12,000 and 10,000 yr B.P. found by Chinzei *et al.* (1987) and Kallel *et al.* (1988).

level slowly increased by 20 m until 12,500 yr ago (from Fairbanks' 1989 curve). Assuming for that time a 5‰ salinity contrast and a layer thickness of only 30 m, the Tsugaru outflow still would have been in the coastal mode (Fig. 7). In the ensuing millennium, however, when sea level rapidly rose an additional 24 m, the circulation regime between Honshu and Hokkaido would have clearly left the coastal mode, approaching the modern threshold for the gyre mode. R may have actually exceeded the modern threshold for the gyre mode, considering that our assumptions are conservative. For example, by using only salinity in calculating $\Delta\rho$, we may have underestimated the density contrast. Surface temperatures in a well-stratified Japan Sea at 12,000 yr ago, close to the time of the deglacial maximum in seasonality, may have been warmer than those of the open Pacific, enhancing the density contrast in the Tsugaru outflow. In addition, we have probably underestimated the thickness of the outflowing surface layer by substituting the sill depth. Today, the average layer thickness seaward of the Tsugaru Strait is about 200 m, 70 m greater than the sill depth (Conlon, 1982). Finally, the glacial depression of sea-surface salinity probably exceeded 5‰ (Gorbarenko, in press).

The northward movement of the polar front along coastal Japan 12,000 yr ago (Chinzei *et al.,* 1987; Kallel *et al.,* 1988) possibly was a response to Tsugaru outflow which must have intensified at that time as sea level rose abruptly. Thus, since $\delta^{18}O$ evidence for a Younger Dryas-aged oscillation is as much a function of low ratios 12,000 yr ago as high ratios between 11,000 and 10,000 yr ago, the oxygen isotopic record in the northwestern Pacific may be significantly influenced by events in the Japan Sea. Although we have provided an alternate interpretation for the $\delta^{18}O$ record of the Younger Dryas in the northwestern Pacific, faunal and floral oscillations like those presented by Chinzei *et al.* (1987) and Kallel *et al.* (1988) are still important evidence for brief events of local cooling. Elsewhere in the Pacific Ocean, AMS ^{14}C-dated cores from the Sulu Sea (Linsley and Thunell, 1990) and the Gulf of California (Keigwin and Jones, 1990) contain Younger Dryas-aged oscillations that most likely reflect widespread climatic forcing. Our main point in this paper is that caution should be exercised in interpreting parallel records of faunal and isotopic change as evidence for paleotemperature change where there is the possibility of significant salinity overprinting of a $\delta^{18}O$ record. Our argument is analogous to that made by Fairbanks (1989) concerning interpretation of the Younger Dryas in the North Atlantic, although the mechanism is different. In the North Atlantic, low $\delta^{18}O$ may have been a direct response to the stratification changes occurring during meltwater events, whereas in the northwest Pacific off Japan low $\delta^{18}O$ may be a direct response to sea-level rise.

CONCLUSIONS

A review of Japanese and Soviet paleoceanographic results for cores from the Japan Sea, which are not widely available in the English language literature, has resulted in some new interpretations of paleoenvironmental change occurring in that basin and surrounding waters during the latest Quaternary.

As recognized previously, lowered sea level during glaciation isolated the Japan Sea because of its shallow sills, leading to lowered sea-surface salinity. With sills in the Tsushima and Tsugaru Straits at 130 m and sea-level lowering of 120 m, exchange with the open ocean may have been much less than the 1–2 Sv estimated for today. Low salinity of surface waters could have been maintained by a small excess of regional precipitation over evaporation, or by discharge of the Amur River and/or the Hwang He into the isolated basin. Either of these mechanisms could have quickly led to stable stratification of surface waters and deep anoxia. These hypotheses should be tested by further coring. Our chronology for latest Quaternary events is based primarily on knowledge of the timing of global sea-level change (Fairbanks, 1989) and interpretation of how dated sea-level changes might have affected the Japan Sea hydrography. This chronology is a testable alternative to the interpretations presented by Oba (1984) and Oba *et al.* (1991). Our assertions should be checked by AMS ^{14}C dating of foraminifera from the Japan Sea.

By 12,000 yr ago, when the rate of sea-level rise increased rapidly, the Japan Sea was probably flushed of its low-salinity lid. This process may account for low $\delta^{18}O$ at that time in cores from the Pacific side of Japan, and dynamics of the Tsugaru outflow may account for evidence for local movement of the polar front at that time. Thus, Younger Dryas-type oscillations in sediment cores off Japan may contain an important component of local oceanographic change that is independent of global cooling. Sometime after 12,000 yr B.P., but before melting of northern hemisphere ice sheets was complete, the Japan Sea was probably in full exchange with the open ocean, which was still partially enriched in ^{18}O.

ACKNOWLEDGMENTS

We thank R. Dunbar, D. Oppo, and L. Peterson for critical reviews of the manuscript and L. Pratt for helpful discussions on the dynamics of flow through straits. We are especially indebted to T. Oba, who despite disagreeing with some of our interpretations of his data, generously provided his unpublished data, helpful discussions, and comments on the text. S. Honjo and T. Tanaka helped with translating Japanese. This research was supported by NSF Grant OCE90-00434.

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