

End Members of Water-Masses in the Western Japan Sea

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ABSTRACT

At least thirteen distinct end members of water-masses are identified in the western Japan Sea. Their origins and conditions of formation are discussed, including the effects of continental water inputs, photosynthesis in remnant winter waters, microbial oxidation of organic matter in the water column or at water-sediments interface, and the cooling of surface waters along the Siberian coast and the northern Japan Sea.

(Key words: Water masses, Japan Sea, KEEP-MASS expedition)

1. INTRODUCTION

The Japan Sea is bounded by the Japanese islands, the Siberia and the Korean Peninsula, and has a total area of $1.013 \times 10^6 \text{ km}^2$ and a volume of $1.69 \times 10^6 \text{ km}^3$. Its mean water depth is 1669 m and its deepest depth 4036 m. It is connected to the Pacific Ocean by four shallow straits: Tsushima, Tsugaru, Soya, and Tatar Straits (Figure 1), each with a sill depth of less than 130 m (Tsunogai *et al.*, 1993). The Tsushima Warm Current branches off from the Kuroshio Current and flows into the Japan Sea through the Tsushima Strait with a magnitude of about $3 \text{ to } 4 \times 10^6 \text{ m}^3/\text{sec}$ (Miita and Ogawa, 1984). Then, it flows northward mainly along the west coast of Japan. A portion of water flows out of the Japan Sea through the Tsugaru and Soya Straits. The other portion turns anti-clockwise, mixes with fresh water inputs from Siberia and Korea and becomes the North Korean Cold Current, which flows southward along the Siberian and the north Korean coasts. Thus, the Tsushima Warm Current and the North Korean Cold Current form a cyclonic gyre and associated subsurface upwelling dome (Figures 41 to 44 of Stepanov, 1961). These two currents form a front with an E-W direction around $39\text{-}40^\circ\text{N}$ and a NE-SW or N-S direction above 40°N (Figure 28 of Stepanov, 1961).

Major water masses in the Japan Sea were identified by Yasui *et al.* (1967), using the distribution of estimated water volume as functions of potential temperature (θ) and salinity. However, their approach has a few shortcomings in that the identified water masses have

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wide ranges in both potential temperature and salinity, thus, making it difficult to pinpoint the properties of the water-mass end members. Additionally, the approach smooths out small but sometimes important changes within their water masses, and it does not take advantage of additional geochemical parameters, such as dissolved oxygen, nutrients, and "PO" ($=138 \text{ PO}_4 + \text{O}_2$) or "NO" ($=8.6 \text{ NO}_3 + \text{O}_2$; Broecker, 1974) to distinguish other possible water masses.

The objectives of this paper are to (1) identify all possible end members of water-masses in the Japan Sea using the high quality data obtained during the Kuroshio Edge Exchange Processes- Marginal Seas Study (KEEP-MASS) expedition (Chen and Bychkov, 1992) and (2) discuss their origins.

2. SAMPLING AND ANALYTICAL METHODS

The KEEP-MASS expedition was conducted by scientists from Taiwan aboard the R/V Vinogradov from July 10 to August 5, 1992. The locations of the major sampling stations in the western Japan Sea are shown in Figure 1.

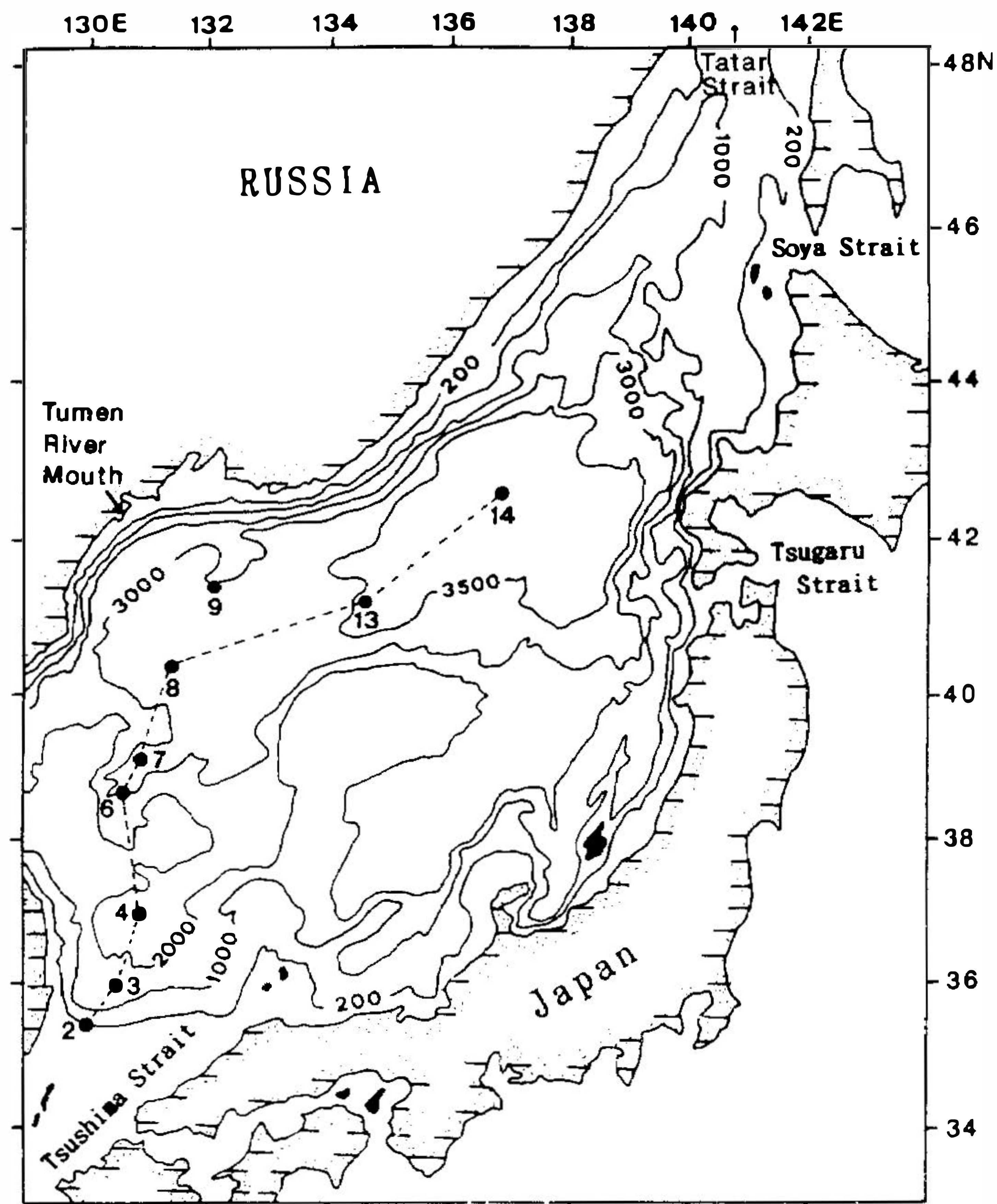


Fig. 1. Locations of major sampling stations in the western Japan Sea during the KEEP-MASS expedition. The depth contours are in meters.

A Guildline CTD model-875 was deployed to obtain the vertical *in-situ* temperature and salinity profiles. The temperature was calibrated against reversing thermometers, and the salinity against bottled samples. Water samples were collected by 2.5 liter Niskin or Go-Flo samplers. All chemical parameters were measured on shipboard soon after sample collection.

The bottle salinity was measured by a Guildline Autosal model-8400, which was standardized daily by standard seawater (e.g. batch p66 from Denmark, p79 and p118 from England). Both the precision and accuracy of salinity measurements were about ± 0.002 per mil when the calibration was carefully maintained. The estimated precision of the adopted analytical methods for other parameters were as follows: dissolved oxygen ($\pm 0.5 \mu\text{M}$; Pai *et al.*, 1992), nitrate ($\pm 0.3 \mu\text{M}$; Strickland and Parsons, 1972; Pai *et al.*, 1990a; Gong, 1992), phosphate ($\pm 0.01 \mu\text{M}$; Murphy and Riley, 1962; Pai *et al.*, 1990b), silicate ($\pm 0.5 \mu\text{M}$; Gong, 1992), total alkalinity and CO_2 ($\pm 1 \mu\text{M}$; Bradshaw *et al.*, 1981). All analytical results are summarized in the KEEP-MASS Initial Data Report (Chen and Bychkov, 1992).

3. RESULTS AND DISCUSSION

The plots of various parameters, such as salinity, "PO", normalized total alkalinity (NTA) to salinity 35 per mil, O_2 , PO_4 and SiO_2 against potential temperature (θ) at three different scales ($0-25^\circ$, $0-3^\circ$, and $0-0.5^\circ\text{C}$) are shown in Figures 2 to 4. Each number within an open cube identifies the water sample that is an end member (EM) of a water-mass. An end member is so chosen that at least one parameter among θ , salinity and O_2 cannot be reproduced by the mixing of two neighboring end members. Chemical properties of all end members are summarized in Table 1. Figures 5a to 5e show the cross-section of salinity, θ , O_2 , PO_4 and "PO" along the track between Stations 2 and 14 (dotted line in Figure 1). To avoid an overcrowding of the data, Station 9 data are excluded in Figure 5. This does not change the main features in Figure 5 because the water column properties of Station 9 are similar to those of Station 13 nearby (Figures 2 to 4). The end members identified from Figures 2 to 4 are also indicated in Figures 5a to 5e.

End members 8, 9 and 10 are all surface waters. EM10 is characterized by high temperature (24°C), low salinity (33 per mil) and a high NTA (Figures 2a and 2c), indicating inputs of continental freshwater with high NTA. One may call EM10 the northward-flowing surface Tsushima Warm Current. EM9 is characterized by high salinity (Figure 2a) and was probably formed by the upwelled EM7 mixing with EM10. The geographical extent of EM9-type water is limited (Figure 5a). EM8 is slightly low in θ (20°C in Figure 2a) and represents the southward-flowing Surface North Korea Cold Current (Kim *et al.*, 1991). In principle, EM8 can be produced by mixing EM10 and EM7, except that EM8 contains more O_2 or less PO_4 than predicted values from mixing.

End members 4 to 7 are subsurface waters at depths between 30 m and 250 m. EM7 is characterized by the highest salinity and lowest NTA (Figures 2a and 2c), representing the core of the Tsushima Warm Current (Figure 5d). EM7' is closely related to EM7 in terms of conservative tracers but has relatively low O_2 (Figure 5d) and high PO_4 and SiO_2 (Figures 2e and 2f), indicating the effect of microbial oxidation of organic matter in the water column or somewhere at the water-sediment interface on the continental shelf. EM6 is characterized by low PO_4 (Figure 2e) and very high O_2 , which is much higher than the O_2 saturation value at the given temperature (dotted curve in Figure 2d). EM6 probably represents the remnant of the winter surface mixed-layer water that was originally high in PO_4 but became low in PO_4

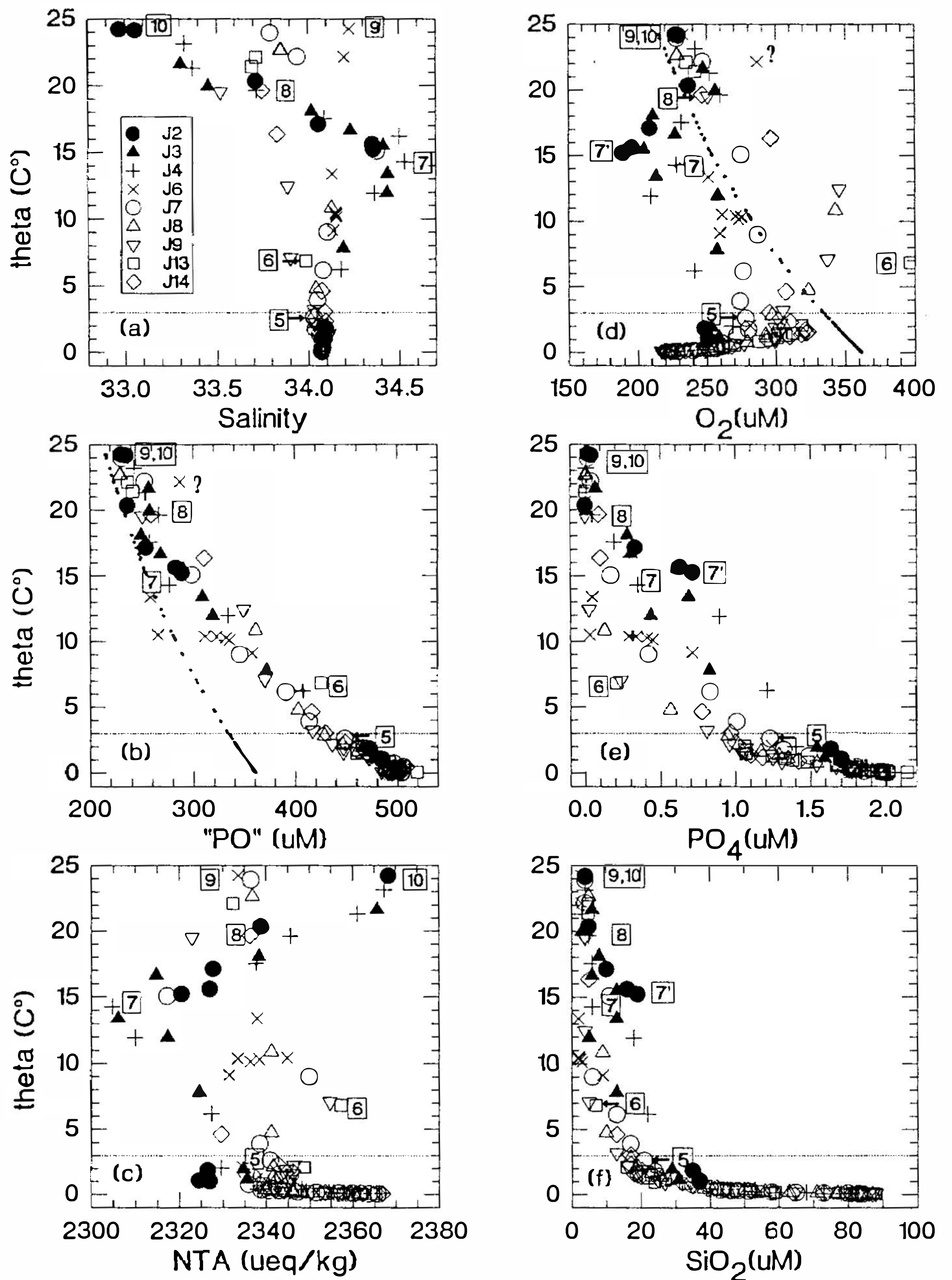


Fig. 2. Plots of potential temperature against (a) salinity (b) "PO" (c) normalized total alkalinity (NTA) (d) O₂ (e) PO₄ and (f) SiO₂, based on the data obtained during the KEEP-MAS expedition. Numbers in the open cubes indicate water samples that represent distinct end members of water-masses. Symbols with question marks represent doubtful data. The heavy dotted curves in diagrams (b) and (d) indicate the saturated oxygen concentrations at given potential temperature and salinity. The portions below the dotted lines are expanded into Figure 3.

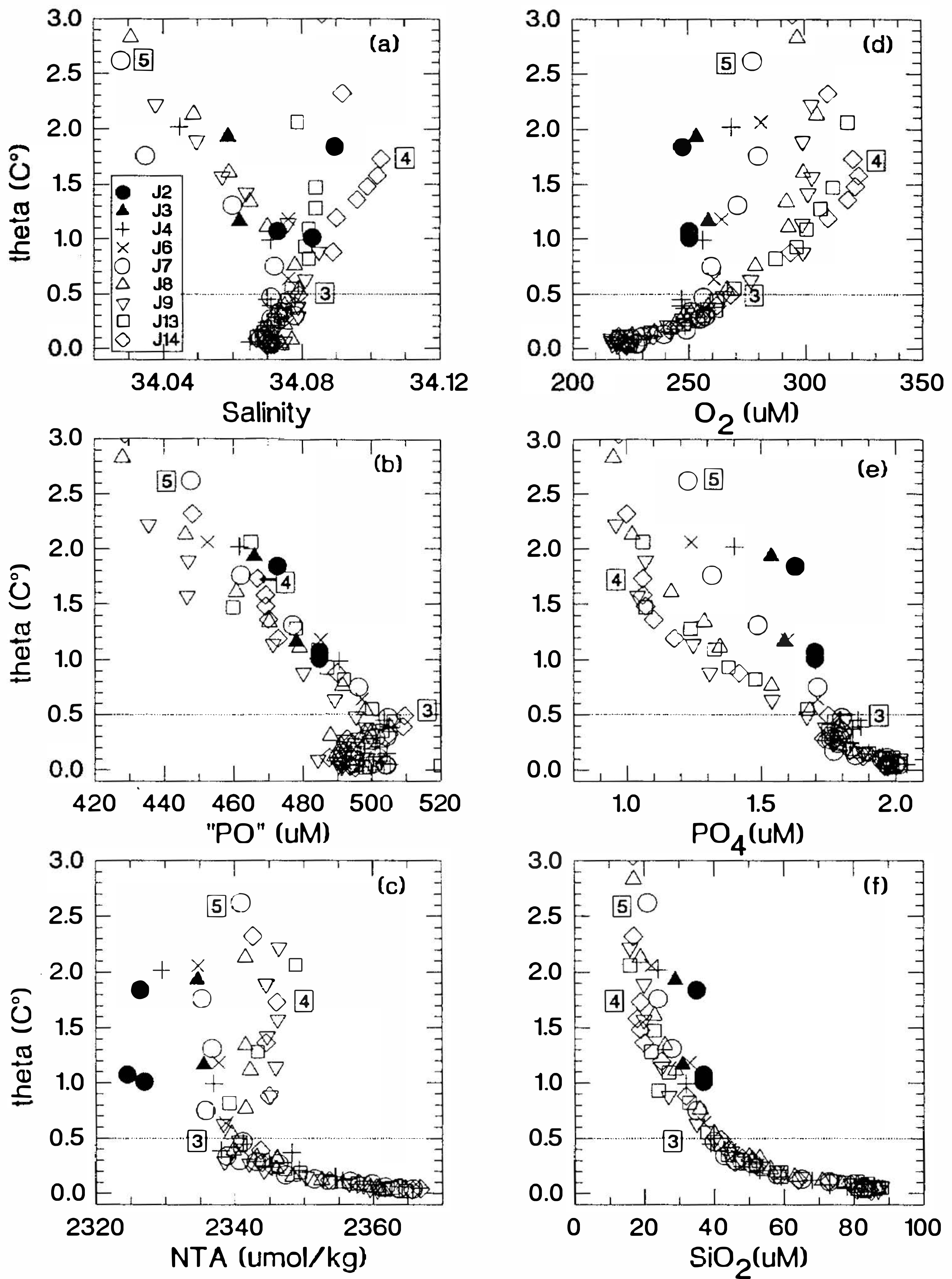


Fig. 3. As in Figure 2, except that the potential temperature is on an expanded scale of 0 to 3°C. The portions below the dotted lines are expanded into Figure 4.

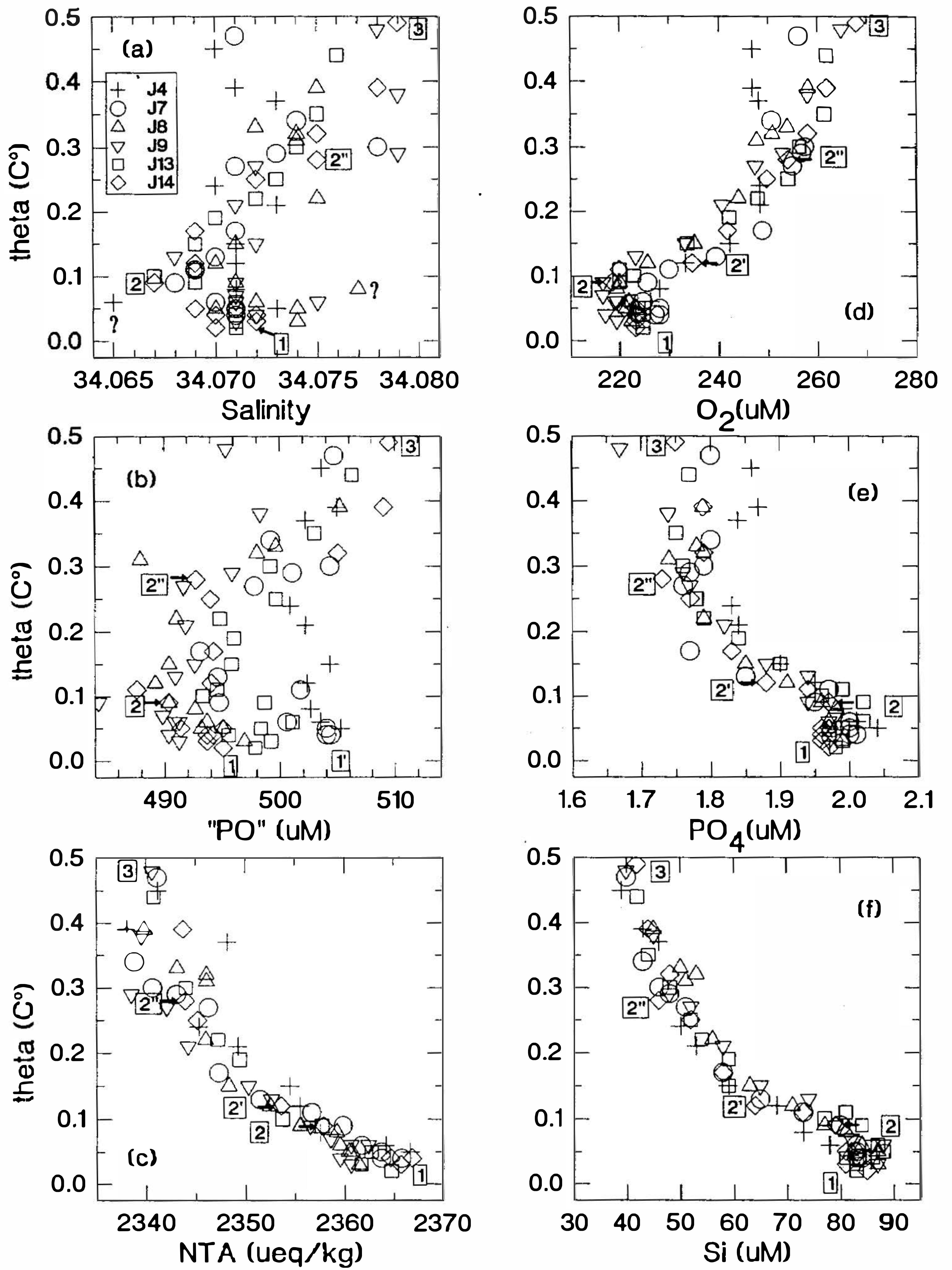


Fig. 4. As in Figure 2, but potential temperature is on an expanded scale of 0 to 0.5°C.

Table 1. Properties of water-mass end members in the western Japan Sea.

end member	station number	depth (meters)	θ ($^{\circ}\text{C}$)	S (per mil)	O_2 (μM)	PO_4 (μM)	NO_3 (μM)	SiO_2 (μM)
10	J2	0	24.24	32.97	228	0.02	0.03	4
9	J6	0	24.23	34.23	233	0	0.01	3
8	J14	0	19.63	33.75	247	0.09	0	4
7'	J2	100	15.24	34.36	190	0.72	9.2	19
7	J4	103	14.30	34.53	228	0.35	4.1	6
6	J13	25	6.84	33.99	397	0.21	0.02	7
5	J7	124	2.63	34.02	278	1.23	14.3	21
4	J14	103	1.74	34.10	321	1.06	12.1	19
3	J14	517	0.49	34.08	268	1.75	21.2	42
2''	J14	810	0.28	34.08	254	1.73	21.9	46
2'	J14	1774	0.11	34.07	220	1.94	24.1	73
2	J14	2026	0.09	34.07	219	1.97	24.4	79
1	J14	3639	0.04	34.07	224	1.96	24.3	84

and high in O_2 through photosynthesis in summer. The extent of EM6-type water is limited (Figure 5d). EM5 is distinguished by a subsurface salinity minimum (Figures 2a, 3a, and 5a). It was probably formed along the Siberian and northern Korean coasts in winter (Kim *et al.*, 1991). It also forms a salinity front against the Tsushima Warm Current water (EM7) and flows southward underneath (Figure 5a). EM5 corresponds to the East Sea Intermediate Water (ESIW) of Kim *et al.* (1991). EM4 is characterized by subsurface salinity and oxygen maxima at q around 1.8°C (Figures 3a, 3d, 5a, and 5d) and was likely formed along the Siberian coast further north in winter and flows southward beneath EM5-type water (Figure 5a).

According to Kim *et al.* (1991), both EM4 and EM5 belong to the East Sea Intermediate Water. For example, along 37.5°N latitude east of the Korean Peninsula, either EM4 or EM5 or both were detected in different seasons (see Figure 6 of Kim *et al.*, 1991). The seasonal and spatial distribution patterns of temperature and chlorinity at 100 m-depth horizon in the Japan Sea (Figures 2a to 2d of Yasui *et al.*, 1967) confirm that EM4-type water ($\theta < 4^{\circ}\text{C}$, $\text{Cl} > 18.85$ per mil or $\text{S} > 34.054$ per mil) is prominent along the Siberian coast during the fall, winter and spring seasons. EM5-type water ($\theta < 4^{\circ}\text{C}$, and $\text{Cl} < 18.85$ per mil) is found in the bay around the Tumen River mouth during winter and spring, and covers the entire Siberian and north Korean coasts in summer.

End members 1 to 3 are deep waters found below 250 m. EM3 is characterized by a "PO" maximum at q around 0.5°C and at depth around 500 m (Figures 3b and 5e). Other parameters such as salinity, O_2 , PO_4 and NTA converge to the EM3 values as temperature decreases from a high value (Figures 3c, 3d, and 3e). The distribution patterns of temperature

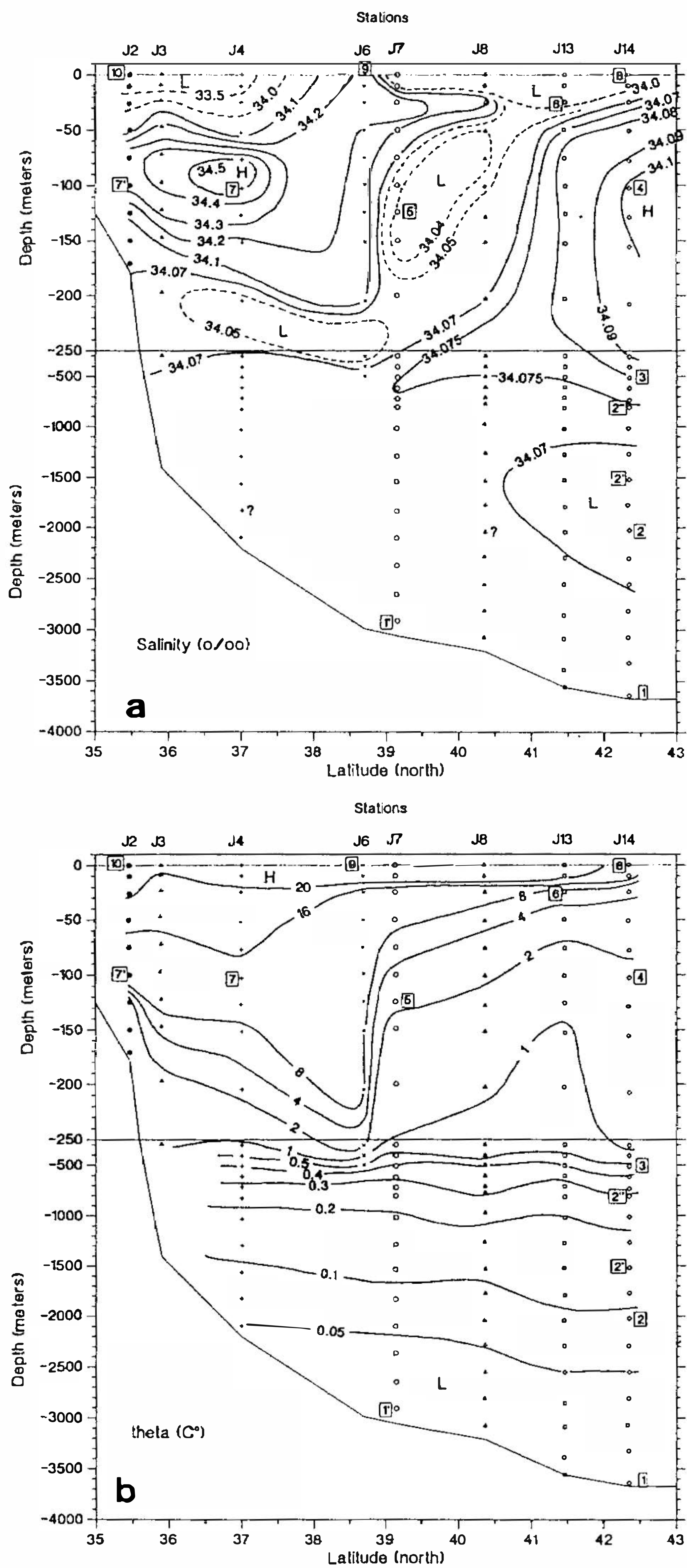


Fig. 5. Cross-sectional profiles along stations between J2 and J14 for (a) salinity (b) potential temperature (c) PO_4 (d) O_2 and (e) "PO". All symbols are the same as in Figure 2. The capital letters H and L represent the high and low values respectively.

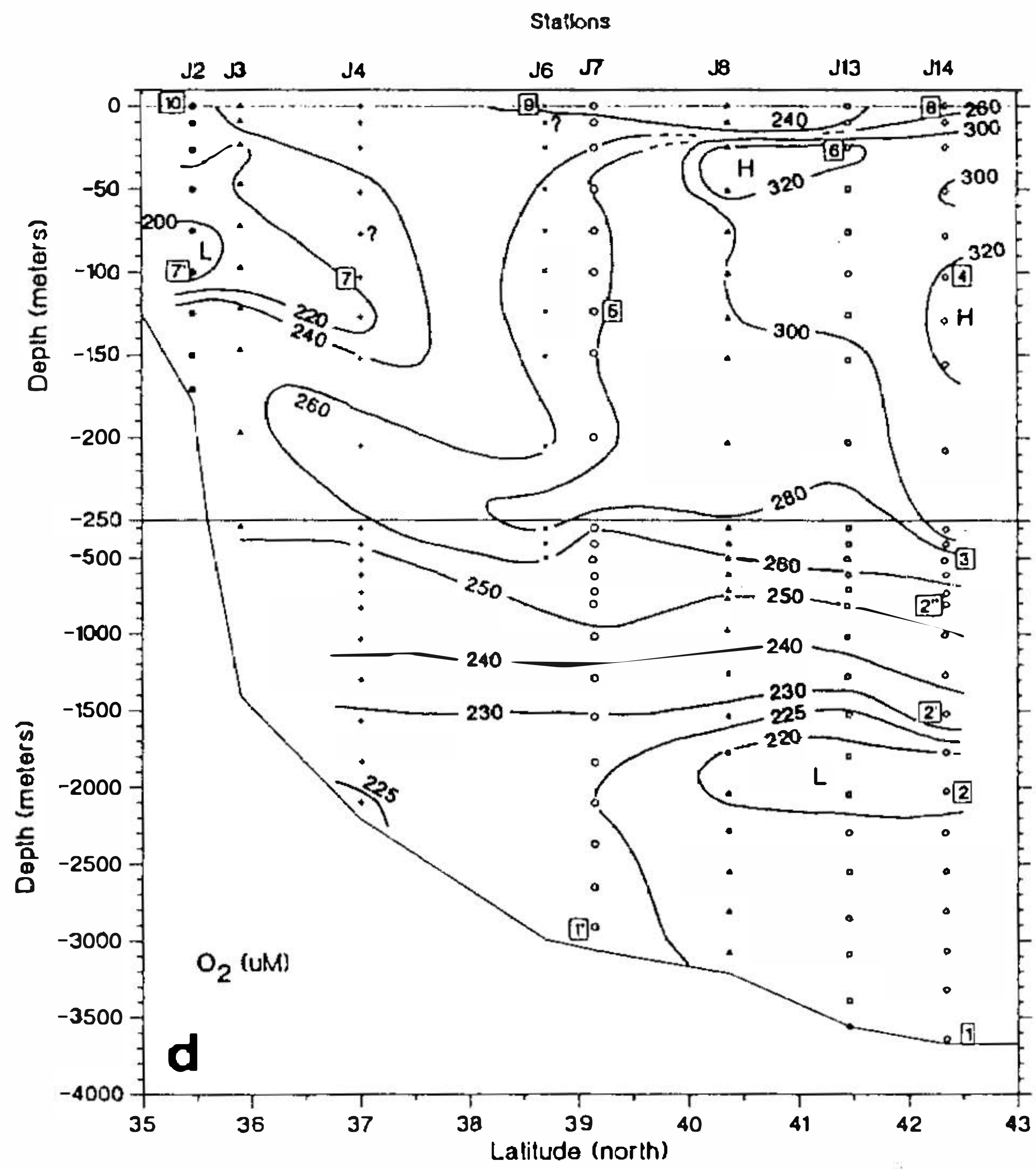
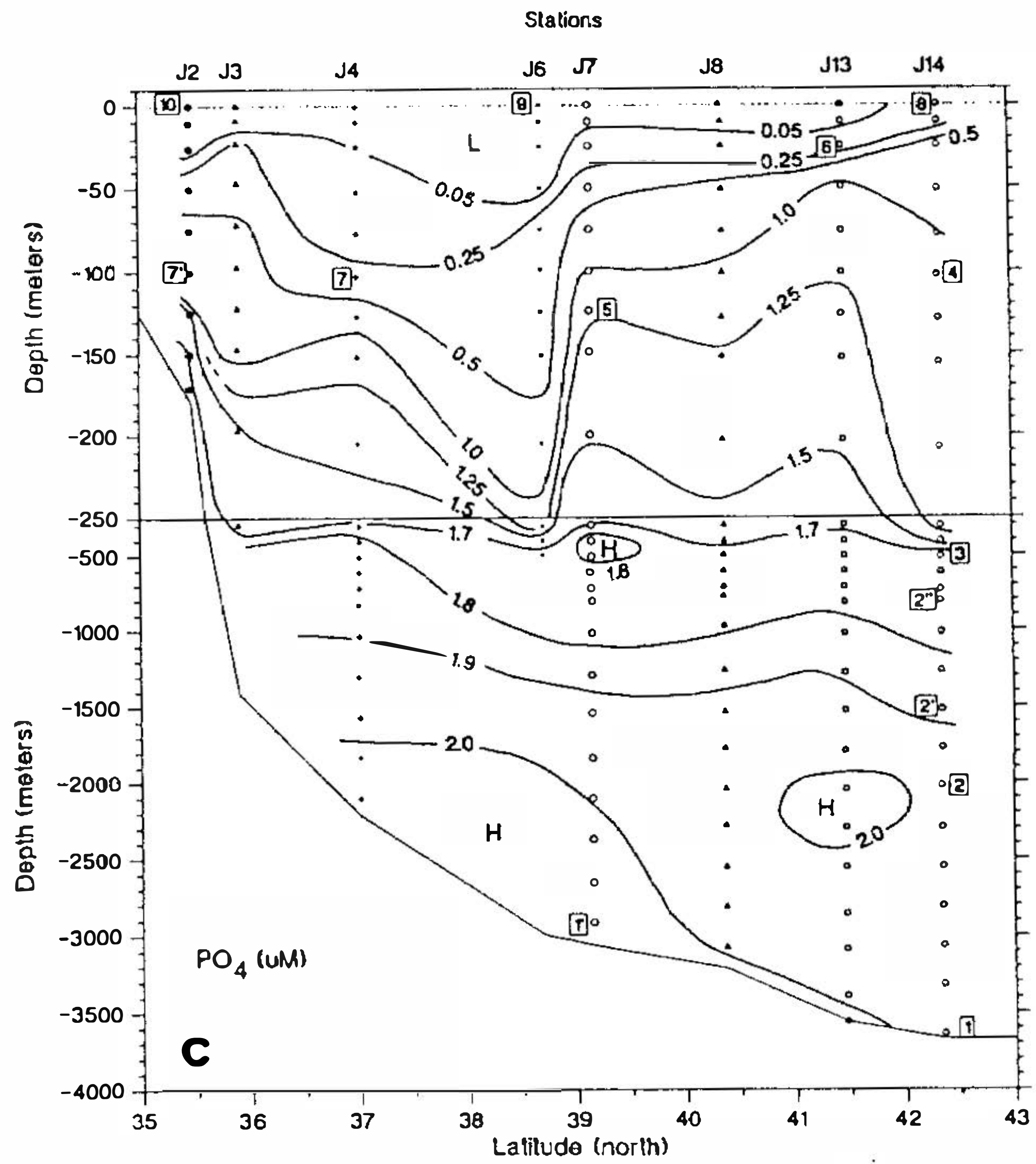


Fig. 5. (Continued)

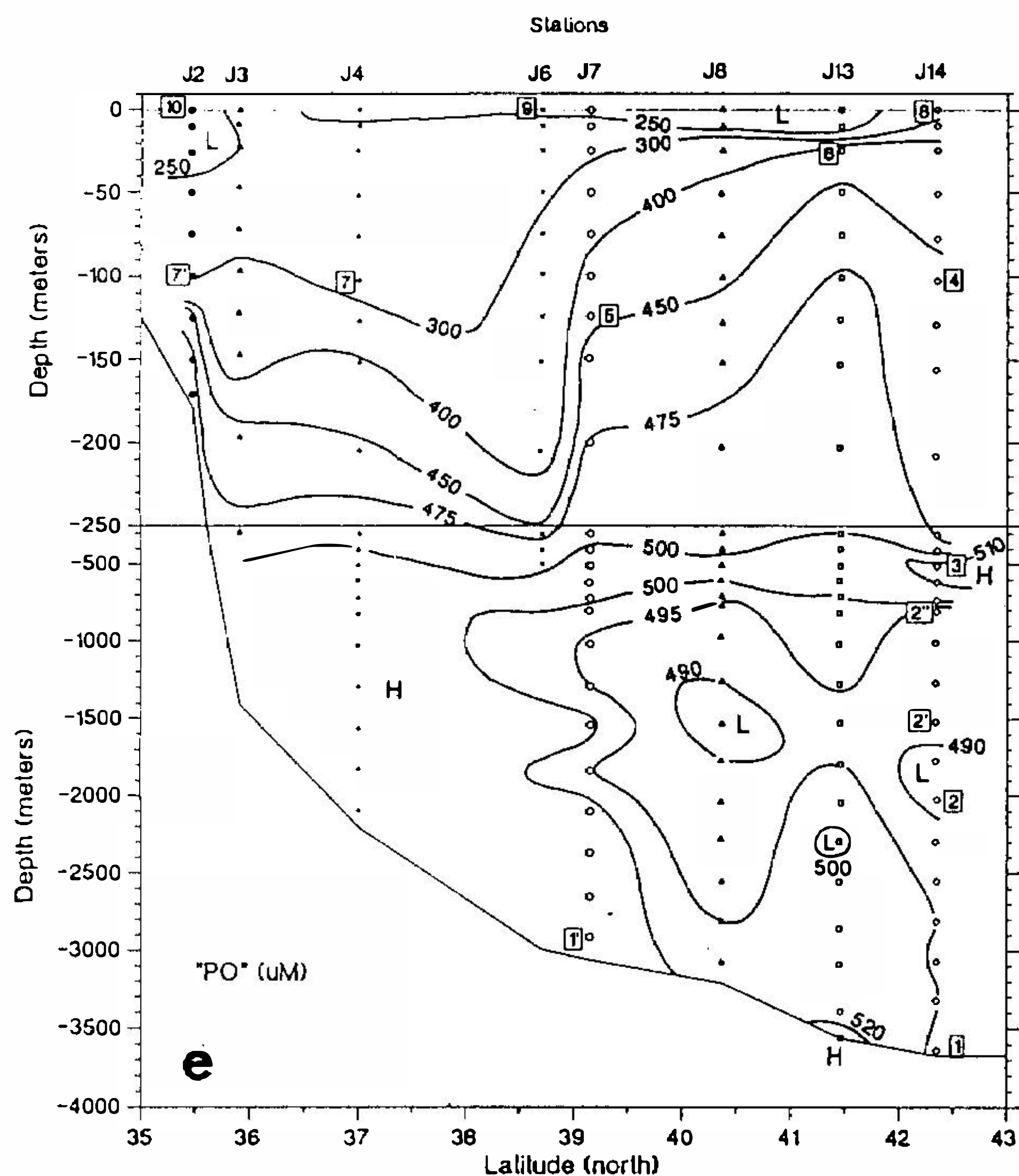


Fig. 5. (Continued)

and chlorinity at the 400-m horizon (Figures 3a and 3b of Yasui *et al.*, 1967) suggest that EM3-type water ($\theta = 0.5^{\circ}\text{C}$, and $\text{Cl} = 18.86$ or $\text{S} = 34.072$ per mil) also originated along the Siberian coast. As shown in Figure 2b (as well as in Figure 2d), the dotted line represents the saturated O_2 concentrations at given q and salinity (Weiss, 1970). Therefore, for the surface water more than 90% of "PO" is contributed by O_2 and less than 10% by PO_4 . In contrast, if EM3 was formed at surface and fully equilibrated with O_2 in the air, it should contain $1.1 \mu\text{M PO}_4$ in order to have the observed "PO" value (Figure 2b). Interestingly, EM4 and EM5 also have the same amount of PO_4 (Figure 2e). It is quite feasible that the cooling of EM4 and EM5 waters and the uptake of O_2 at surface with a suitable adjustment of salinity in winter can produce EM3. It is well known that the surface mixed-layer can be as deep as 150 to 200 m along the Siberian and north Korean coasts in winter (Hidaka, 1966). Therefore, EM4- and EM5-type waters can easily mix up to the ocean surface.

EM2 is characterized by salinity, "PO" and O_2 minima (Figures 4a, 4b, 4d, 5a, 5e, and 5d), and PO_4 and silicate maxima (Figures 4e and 4f). One notices that the O_2 minimum in Figure 5d is around 2000 m, which is much deeper than the 1400 m obtained for the eastern Japan Sea in 1984 (Gamo *et al.*, 1986). This difference is likely real because the depth of O_2 minimum has deepened only about 200 m in one decade in the eastern Japan Sea (Gamo *et al.*, 1986). Between EM2 and EM3, there are additional end members 2' and 2'', which are identified by breaks in the plots of θ versus O_2 (Figure 4d), PO_4 (Figure 4e) and SiO_2 (Figure 4f). The O_2 concentrations of EM2' and EM2'' cannot be reproduced by mixing between EM2 and EM3 (Figure 4d) without acquiring additional O_2 sources. The formative modes of EM2, 2', and 2'' are probably similar to that of EM3, except that the former must have been formed at the surface under more severe winter conditions than the latter (Nitani,

1972). Vasilev and Makashin (1992) suggested that the frequency of a severe cold winter is about once in a decade. EM1 is the bottom water with θ less than 0.05°C at a depth below 2000 to 2500 m (Figure 5b) and is relatively homogenous in chemistry except for NTA (Figures 4a to 4f). EM1' has an unusually high "PO" value (Figure 4b); otherwise, is indistinguishable from EM1 (Figure 4). EM1 and EM1' must have been formed under even colder conditions than EM2 and EM3. The end members 1 to 2 were most likely formed in the surface areas of northern and northeastern Japan Sea (Gamo *et al.*, 1986).

The re-plotting of the tritium data given by Watanabe *et al.* (1991) as a function of depth in the Japan Sea is shown in Figure 6. The tritium concentration is high between the surface and 800 m, indicating good ventilation between the surface ocean and subsurface end members 3 to 7. The moderate tritium concentrations at depths between 800 m and 2000 m indicate moderate ventilation of EM2' and 2". A model calculation by Watanabe *et al.* (1991) gives a turn-over time of 100 years for the Japan Sea water between 200 m and 1500 m. EM2 around 2000 m has the lowest O_2 (Figure 5d), and below 2000 m the lowest tritium (Figure 6) concentrations. Therefore, EM2 is likely the least ventilated water in the Japan Sea. EM1 has only one tritium datum with a finite value (Figure 6), probably indicating a finite ventilation. Certainly, additional tritium as well as freon data are badly needed to constrain the turn-over time of the bottom water. Also, the future deployment of the oxygen probe along with CTD probe will provide important information on the formative processes of the deep waters in the Japan Sea. The deployment should be focused in the northern part of the Japan Sea as suggested by Gamo *et al.* (1986).

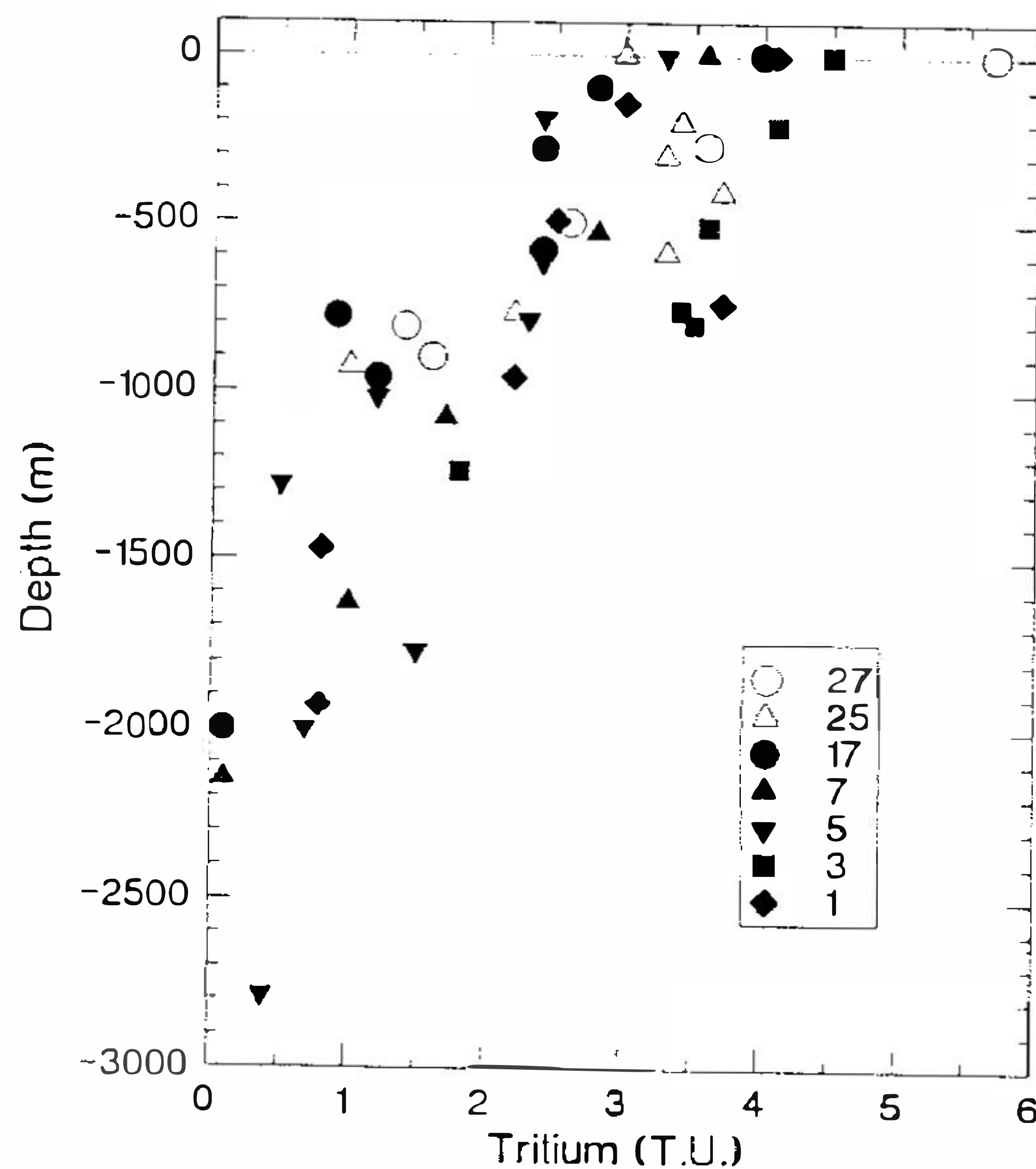


Fig. 6. Vertical profiles of tritium concentrations at different stations in the Japan Sea given by Watanabe *et al.* (1991).

4. SUMMARY

- (1) At least thirteen distinct end members of water-masses are identified in the western Japan Sea, based on chemical data obtained during the KEEP-MASS expedition during the summer of 1992.

- (2) The effect of river water inputs to surface water of the Japan Sea is to decrease salinity and increase normalized total alkalinity (NTA).
- (3) The localized intense oxidation of organic matter at the sediment-water interface or in the water column or both resulted in low oxygen and high nutrient concentrations for some Tsushima Warm Current water (EM7').
- (4) Intense photosynthesis in remanent winter mixed-layer during warmer seasons can produce a subsurface water with unusually high O₂ and low nutrient contents (EM6).
- (5) The East Sea Intermediate Water consists of at least two end members EM4 and EM5. The former was probably formed along the Siberian coast and the latter in the bay around the Tumen River mouth.
- (6) At least five end members are identified at a depth below 500 m to the bottom. They were probably formed intermittently in the surface areas of the northern or northeastern Japan Sea under extremely cold and variable winter conditions.

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