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Greenland Sea Deep Waters: A report on 1993 winter and spring cruises by RVs POLARSTERN and VALDIVIA

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Introduction

The Greenland Sea was early recognized as a source of deep water, not only for the Greenland Sea but also for the Norwegian Sea and for the Arctic Ocean (Helland-Hansen and Nansen, 1909). The improvement of observational techniques during the last decades have revealed differences in temperature and salinity between the basins of the Arctic Mediterranean Seas, which cannot be explained, if the Greenland Sea were the only important deep water source. The Arctic Ocean deep waters are warmer and more saline, a feature, which could be understood, if brine enriched, dense water from the arctic continental shelves sinks down the continental slope, entraining warmer intermediate waters. Aagard et al. (1985) proposed a circulation scheme, where the Arctic Ocean and the Greenland Sea both are sources of deep waters. The different deep waters interact along the Greenland continental slope and then flow along the Jan Mayen Fracture Zone to provide the deep water of the Norwegian Sea.

The relative strength of the two sources as well as the interactions between the different basins were estimated from Θ-S characteristics (Rudels, 1986). and by box models using additional tracers (Heinze et al., 1990; Smethie et al., 1988). These studies showed that the European Basin Deep Water, apart from contributing to the Norwegian Sea Deep Water also must supply an advective part to the Greenland Sea Deep Water. This gives the Greenland Sea Θ-S curve its characteristic hook-like shape with a deep salinity maximum located at around 2000 - 2500 m.

The outflow of deep water from the Canadian Basin, which may be identified in Fram Strait (Rudels, 1986), was thought to bypass the Greenland Sea and either enter the Icelandic Sea across or the Norwegian Sea along the Jan Mayen Fracture Zone (Aagard et al., 1991; Rudels, 1986).

A third deep water component supplied by the Arctic Ocean is the lighter Upper Polar Deep Water. It fills the Arctic Ocean between the Atlantic Layer and the sill depth of the

Lomonosov Ridge. It is formed in both basins of the Arctic Ocean and it lies in the same density range as the Arctic Intermediate Water formed in the Greenland Sea. In contrast to the latter, it is identified by vertical gradients stable in both heat and salt.
The distinct characteristics of the Arctic Ocean and the Greenland Sea deep waters make them easily recognizable and we shall examine the influence and the importance of the Arctic Ocean waters for the ventilation of the deep Greenland Sea. The work is based on observation in the Greenland Sea collected in late winter and spring 1993 from the vessels RV Polarstern (24/3 - 18/4) and RV Valdivia (15/5 - 17/6). The station positions are shown in figure 1. The winter convection had ceased and advective processes dominated the mixing. On the Polarstern cruise a NBIS Mark IIIb CTD was used while a SBE-11 CTD was employed on the Valdivia cruise. Both instruments worked properly. The conductivity was calibrated by water samples analyzed on board using a Guildline Autosal. The accuracy in p.s.u. is 0.003.

Deep water renewal in the Greenland Sea.

Recent efforts to study deep convection in the Greenland Sea (Meincke, 1991) have shown that the convection operates intermittently at most and tracer studies indicate that no deep convection has occurred in the Greenland Sea between 1982 and 1988 (Rhein, 1991). This shifts the balance in the ventilation of the Greenland Sea towards a state, where the deep water contributions of the Arctic Ocean become more prominent. A comparison between Θ-S curves taken in the central Greenland Sea from RV Valdivia with those obtained from RV Hudson in 1982 confirms this. Figure 2 displays Θ-S curves for two stations in the central Greenland Sea taken on the Hudson and Valdivia cruises respectively.

The most notable difference is the warmer and more saline deep temperature maximum observed in 1993. The salinity is in fact so high that a second shallower salinity maximum is present at about 1000 m. This maximum is seen at most stations in the western and in the southern Greenland Sea although it is absent at station 8, nearest to station 12 towards the east. The maximum is too deep and too dense to be created by an influx of Atlantic Water, either from the Norwegian Atlantic Current in the east or from the Atlantic Return Current in the west. Since the maximum is strongest to the west and to the south (compare the salinity sections given in figure 3 for the Valdivia cruise) it is probably the signal of Canadian Basin Deep Water, CBDW, penetrating from the Greenland continental slope and from the Jan Mayen Fracture Zone towards the upwelling regime in the center of the cyclonic Greenland Sea gyre.

The Θ-S curves from stations in the south, close to the fracture zone (figure 4 shows 2 examples), exhibit a slope perpendicular to the isopycnals above the upper salinity maximum. This shows that also the upper part of the deep boundary current exiting the Arctic Ocean through Fram Strait might detach from the continental slope and penetrate into the deep central basin albeit along the Jan Mayen Fracture Zone.

In the winter 1992/93, the convection was limited to the upper 1000 m (compare figure 5) and only water in the range of Arctic Intermediate Water, AIW, was formed. The strength of the convection can be assessed from the thickness of the associated cold, low salinity lense. In the central gyre the lense is close to 1000 m thick but the thickness diminishes towards the periphery of the gyre (compare figure 3). The interaction between the cold lense and the periphery occurs through isopycnal interleaving and it is strongest towards the west and south. Especially prominent is the intruding shallow salinity and temperature maximum of the Atlantic Return Current, which is present on most of the western stations (2 examples are displayed in figure 6).

Thus, the shallower convection occurring in recent years must be responsible for the differences between the observations from 1982 and from 1993. Normally the convecting water would be denser and the CBDW would be entrained into and mixed downward by the convecting plumes. The upper salinity maximum would then be removed and the temperature maximum would be reduced, heat and salt being added to the bypassing convecting water.

The spreading of newly formed AIW from the center of the gyre will result in a compensating inflow of CBDW, which - because of the shallow convection - is easily detected by its salinity and temperature maximum. Inversions are seen in the profiles and in Θ-S curves which indicate intrusive mixing with older Greenland Sea Deep Water, GSDW. The deeper penetration towards the center thus also appears to be isopycnic.

The convective and the advective contributions to the deep waters of the Greenland Sea thus alternate in strength and importance. At times the local convection is even stronger than in 1982 and capable to remove not only the upper salinity maximum but to penetrate the deeper maximum also and renew the bottom water. Most of the time, however, the outflow from the Arctic Ocean dominates and rapidly reforms the temperature and salinity structure of the deep waters.

This simple picture is complicated by the observation that the freon content of GSBDW above 2000 m has increased as compared to 1988 (Rhein, pers. comm.). This is at odds with a penetration of low freon CBDW into the central Greenland Sea. It can only be understood, if the convection events down to 2200 m reported from the winter 1988/89 were more extensive than previously believed (Meincke, 1991). That would provide the necessary freon injection and the high freon content of the convecting surface water would more than compensate for the influx of "older" CBDW. The possibility that the freon content has increased by turbulent diffusion from above appears less likely, since this would mean that no convection was needed to ventilate the deeper layers of the Greenland Sea.

The most conspicuous effect of the reduced convection in the Greenland Sea is the overall decrease in density of almost the entire water column as compared to 1982. The winter 1992/93 was extremely stormy and the lower densities found at all levels in 1993 in comparison to 1982 suggest that the doming of isopycnals in the central Greenland Sea (Helland-Hansen and Nansen, 1909) might to a large extent be caused not by the wind but by the convection itself. When the convection is reduced, will slump down, spread out of the gyre and induce a compensating inflow at higher levels. If this inflow occurs along isopycnals it will, because of the relaxation of the doming, lead to a reduction in the density of the central water column. This in turn weakens the cyclonic circulation and the arctic deep waters will less be pressed against the continental slope and instead of bypassing rather enter the Greenland Sea. This will further increase the temperature and salinity in a sense which reduces the density of the water column in the central gyre.

The higher densities, found also at intermediate levels after periods of active convection, suggest that a convective build up of denser water is needed in the entire water column before the local convection can reach the bottom. This could imply that the observed trend of increasing temperature and salinity and decreasing density in the bottom layers, caused by turbulent vertical mixing of intruding European Basin Deep Water EBDW with the Greenland Sea Bottom Water, does not indicate an imminent deep convection event penetrating through and renewing the bottom water. A massive convective situation appears necessary gradually involving almost the entire water column. This requires a strong surface forcing and appropriate conditions of the upper water column, whatever those right preconditions might be.

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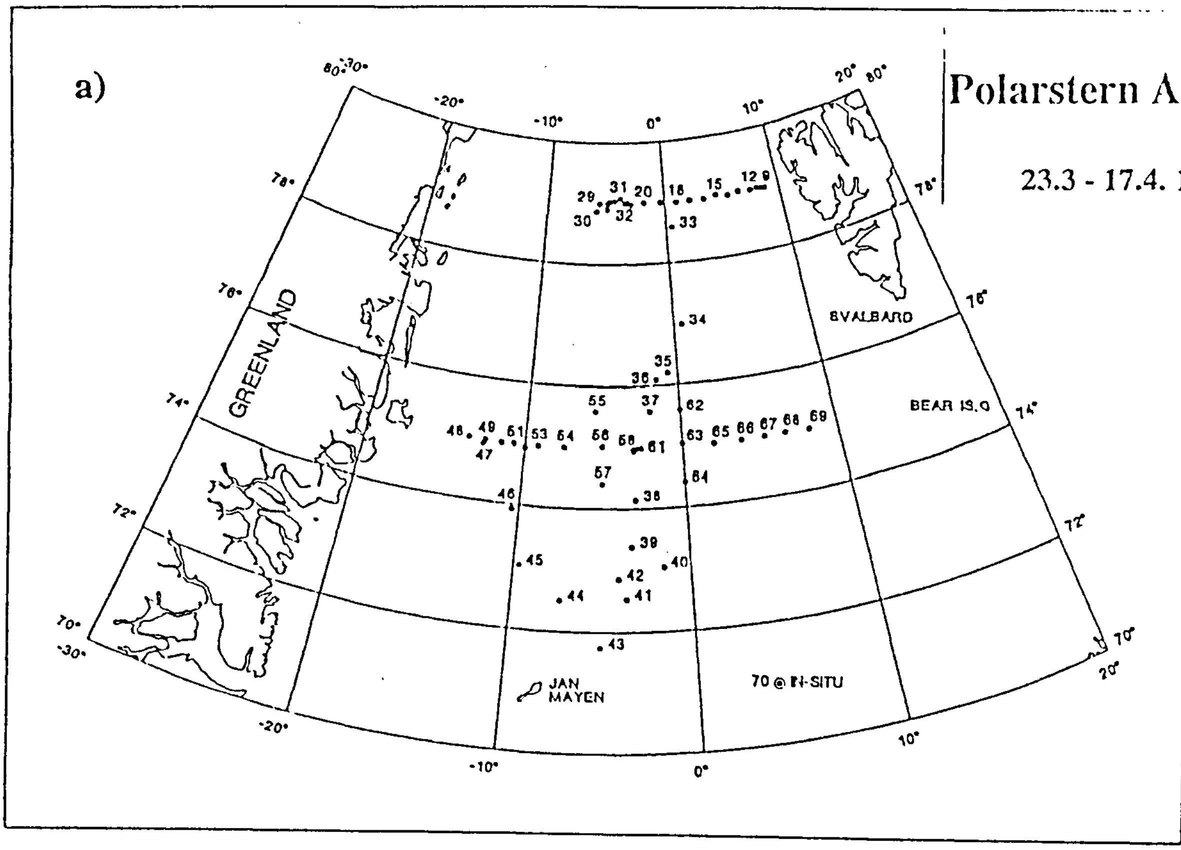
a)



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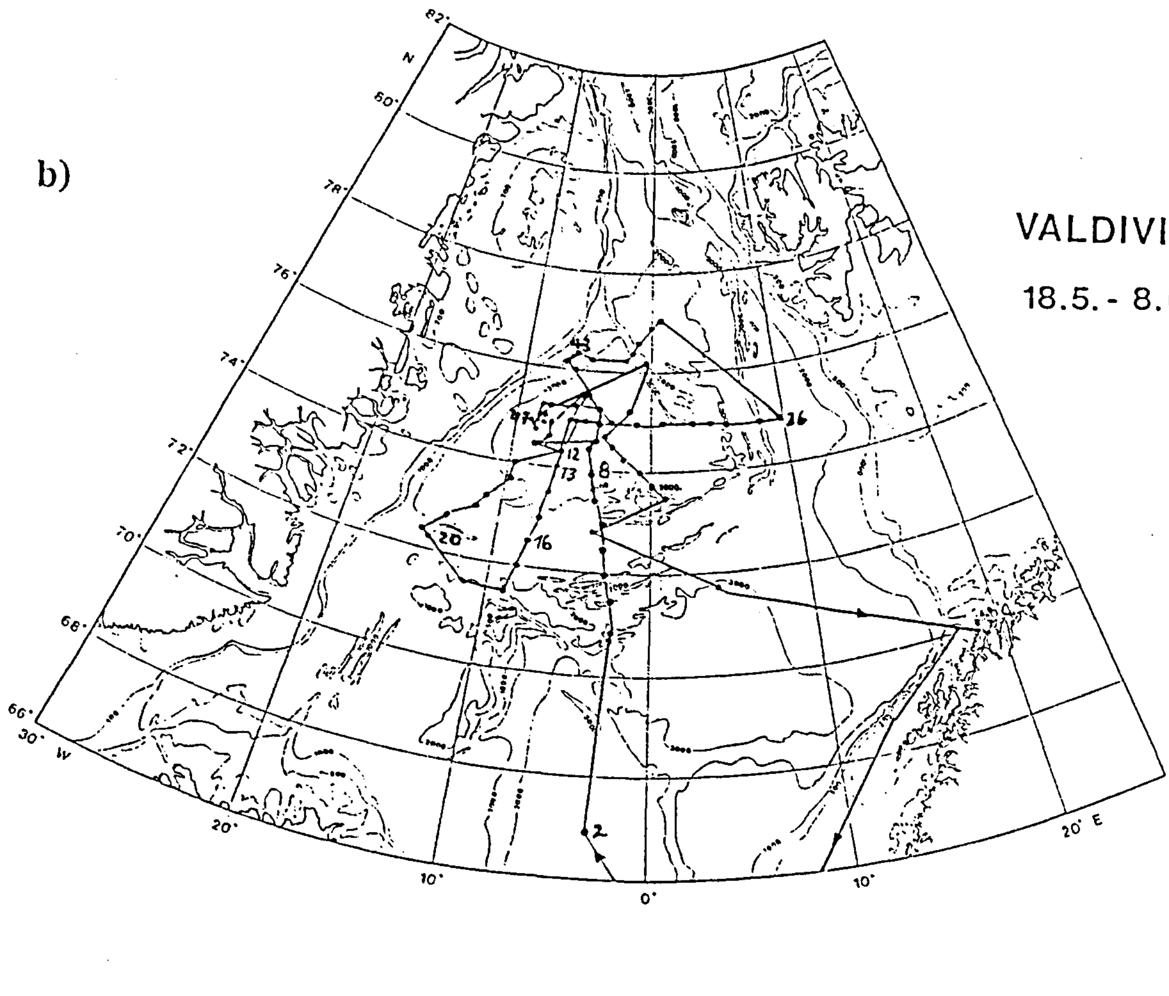

Fig. 1: Station positions. a) RV POLARSTERN, b) RV VALDIVIA

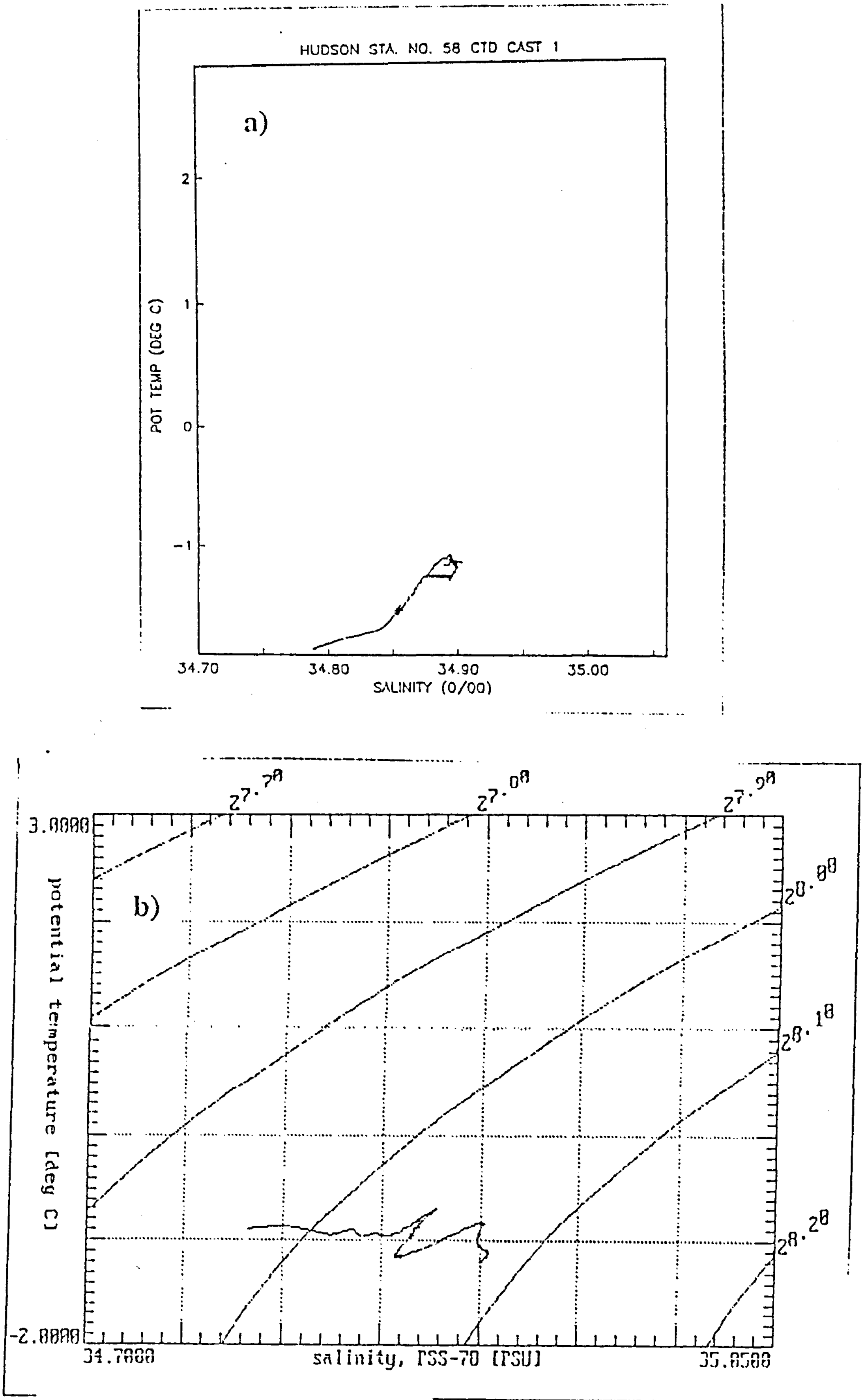

Fig. 2: Θ-S diagrams. a) RV HUDSON, station 58 (75N;06W;March 1982)
b) RV VALDIVIA, station 12 (74.5N;06W;May 1993)

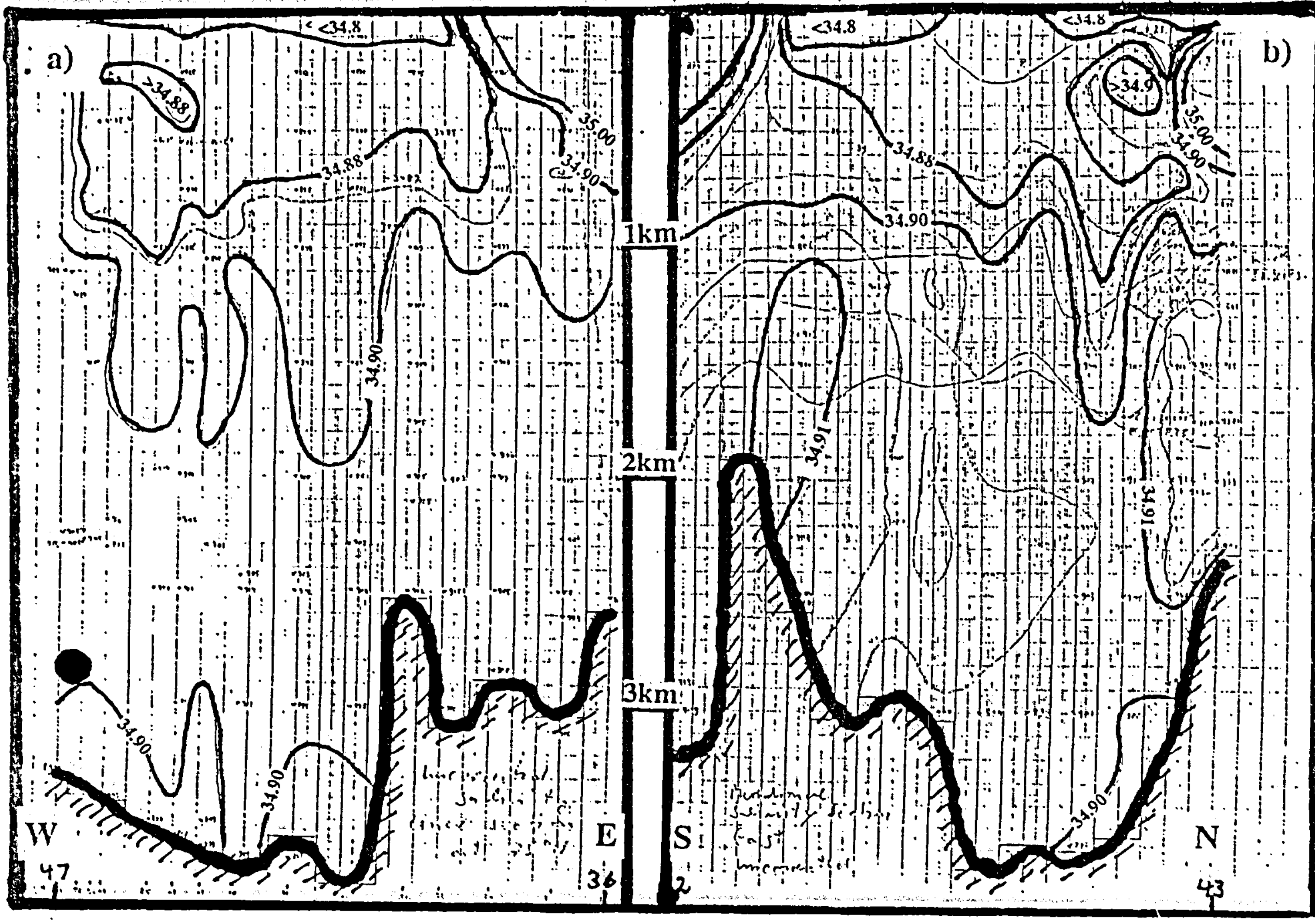

Fig. 3: RV VALDIVIA cruise 136, salinity sections. a) zonal section at 75N
b) meridional section, central Greenland Sea

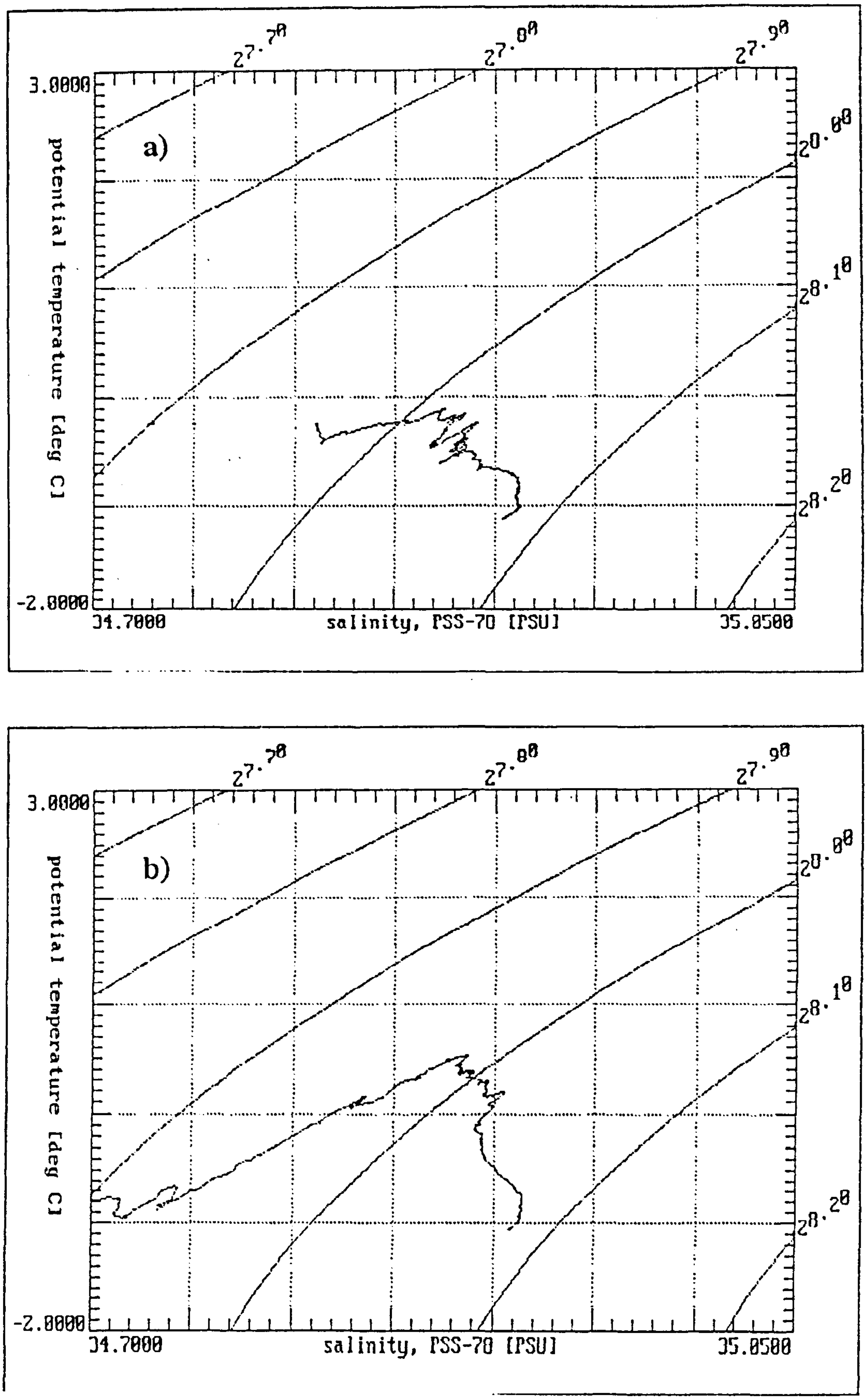

Fig. 4: Θ-S diagrams, RV VALDIVIA cruise 136. a) station 16 (72.5N;08W;May 1993)
b) station 20 (72.25N;14.3W;May 1993)

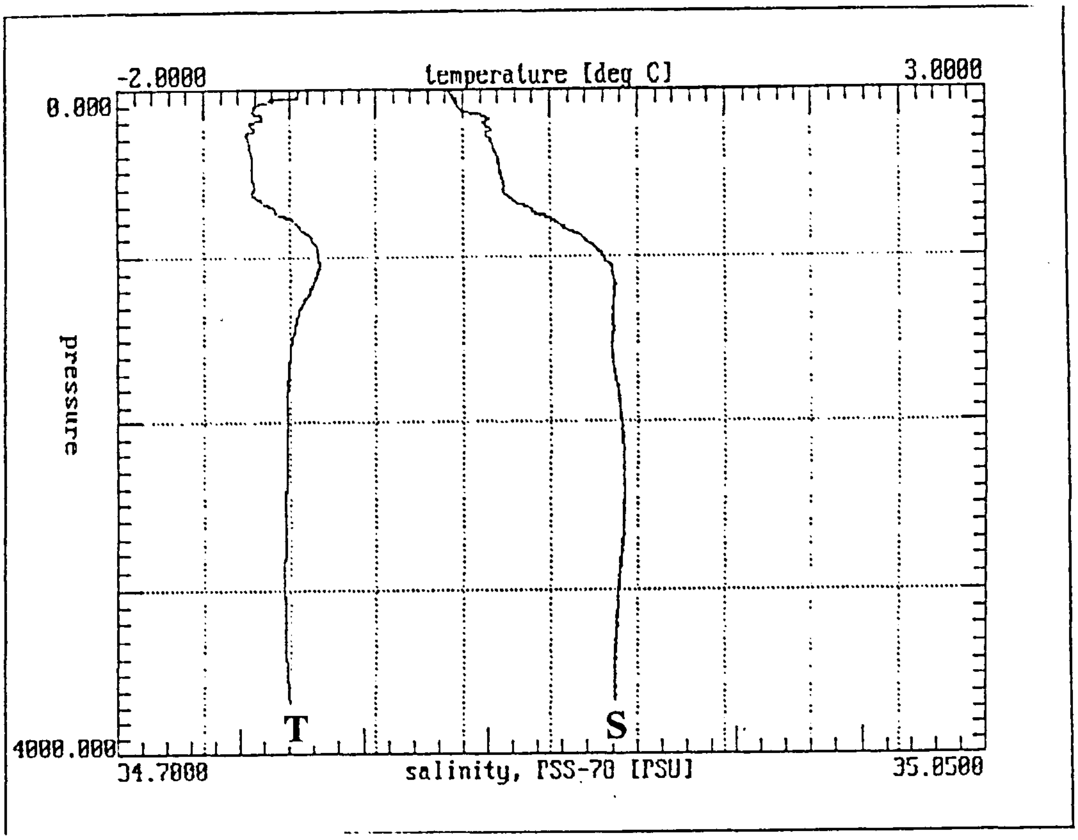

Fig. 5: T,S-profiles, RV VALDIVIA cruise 136, station 8 (74N;04.3W;May 1993)

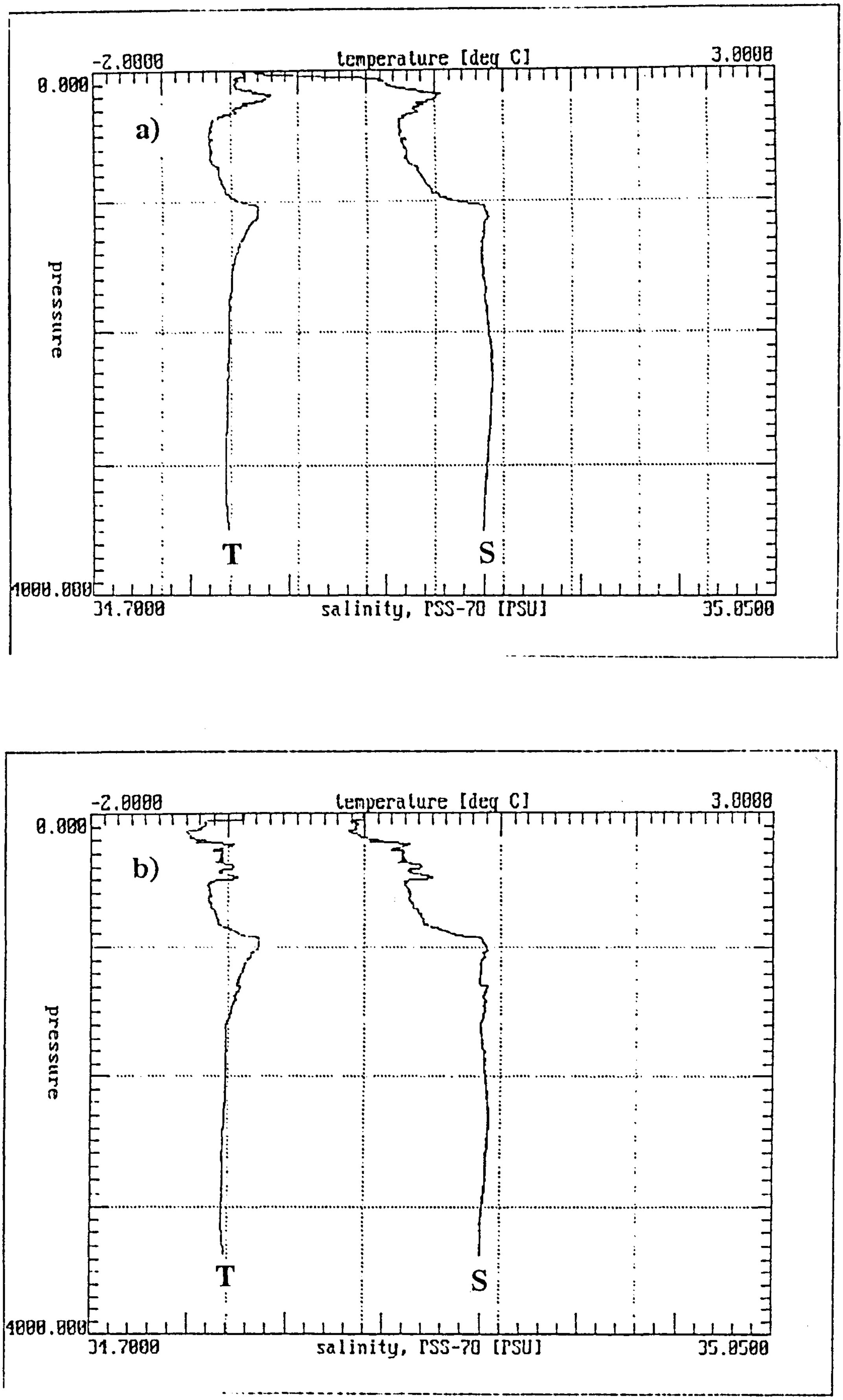

Fig. 6: T,S-profiles, RV VALDIVIA cruise 136. a) station 12 (74.5N;06W;May 1993)
b) station 13 (74N;06.5W;May 1993)