The R/V Johan Hjort 1994 NORDIC WOCE cruise:
On hydrography and tracers.

by

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ABSTRACT

Results from hydrographical and halocarbon tracer measurements during an oceanographic expedition with the Norwegian R V *Johan Hjort* to the Norwegian Sea, the Faroe Bank Channel, the Iceland and the Irminger Basins and the Iceland Sea are presented. Special attention has been given the overflow waters over the Iceland-Scotland ridge and through the Denmark Strait. While the Denmark Strait overflow does not mix significantly with surrounding waters during its descent into the Irminger Basin, the Iceland-Scotland overflow is significantly entrained by ambient waters within the Iceland Basin. By multivariate analysis using Principal Component Analysis (PCA) and Partial Least Square (PLS) calibration, it can be concluded that the overflow water masses contain only minor fractions of the bottom waters in the Norwegian and the Iceland Seas, respectively, which means about one fourth Norwegian Sea Deep Water (NSDW) over the Iceland-Faroe ridge, while, over the sill in the Denmark Strait, the fraction of Iceland Sea Bottom Water (ISBW) is about one third. CFC tracers were used to assign apparent ages of water masses, showing that the NSDW has an apparent age of about 30 years and the ISBW has an apparent age of more than 25 years. Through the deepest parts of the Faroe Bank Channel flows water with an apparent age of about 20 years with an origin at about 1000 m depth in the Norwegian Sea. Labrador Sea Water (LSW) with an age of around 20 years was found in the Iceland Basin, while the LSW in the Irminger Basin is significantly younger, two cores were found, one of an age of 11-12 years underlain by a 6 years younger core. The Northeast Atlantic Bottom Water in the Iceland Basin, which has an Antarctic origin, was observed circulating cyclonically within the basin.

INTRODUCTION

Understanding the global thermohaline circulation, its variability or even the shifts between different equilibrium states, is one of the major scientific challenges in climate research today. The global thermohaline circulation can be represented as intermediate water which leave the area as overflows across the Greenland-Scotland ridge and drive the global circulation system of the North Atlantic Deep Water. The mechanism driving the global thermohaline circulation is the inflow in the surface layer of warm and salty water to the Labrador Sea, the Nordic Seas and the Arctic Ocean. Through cooling and freezing this water is modified to a number of intermediate and deep waters (Swift and Aagaard, 1981; Rudels and Quadfasel, 1991), which through mixing forms the North Atlantic Deep Water (NADW) being the water mass spreading world-wide. The intermediate and deep water masses formed in the Nordic Seas and the Arctic Ocean cross the Greenland-Scotland submarine ridge, either through the Faroe Bank Channel, across the Iceland-Faroe Ridge into the Iceland Basin (Dooley and Meincke, 1981; van Aken and Eisma, 1987) or across the Denmark Strait sill into the Irminger Basin (Swift et al, 1980).

During the overflow process the properties of the various water masses are changed through mixing forming relatively homogenous water types called Iceland-Scotland Overflow Water (ISOW) (Ellett and

Martin, 1973; Schmitz and McCartney, 1993) and Denmark Strait Overflow Water (DSOW), respectively. The ISOW flows along the continental slope south of Iceland towards the slope of the Reykjanes Ridge which turns the flow southwards until the water enters the Irminger Basin through the Charlie-Gibbs Fracture Zone. Underway, its characteristics are modified through mixing with Labrador Sea Water (LSW), Northeast Atlantic Bottom Water (NEABW) (McCartney, 1992) and to some extent Mediterranean Water (MW) (Harvey and Theodorou, 1986).

Water mass classification has traditionally been based upon temperature and salinity characteristics together with some chemical parameters (oxygen and nutrients). In recent years measurements of chemical tracers, such as the chlorofluorocarbons (CFCs), ^{14}C, ^{85}Kr, ^{3}H (tritium), ^{39}Ar, ^{137}Cs and ^{90}Sr, have contributed to a more distinct water mass classification. By introducing multivariate analysis, which is a statistical method for simultaneous treatment of several parameters, an improved water mass identification can be obtained, which also leads to better estimates of the mixing between the various water masses.

In a climatic context it is important to have knowledge of the age of the water masses forming the NADW. Bullister and Weiss (1983) measured CFC-11 and CFC-12 in the Norwegian Sea in 1982. They estimate the time scale for lateral mixing between the deep Greenland Sea and the deep Norwegian Sea to be 20-

30 years. Seven years later. Rhein (1991) estimated a turnover rate for Norwegian Sea Deep Water (NSDW) with respect to Greenland Sea Deep Water (GSDW) and Eurasian Basin Deep Water (EBDW) to 12-15 years. Using ^{14}C data Gislefoss (1994) estimated NSDW to be at least 130 years older than GSDW. The reasons for the discrepancy between the ^{14}C age estimate and those from CFC tracers is not yet clear.

Smethie (1993) estimates the age of overflow water in the Faroe Bank Channel to 45 years based on CFC-11, CFC-12, tritium and ^{85}Kr measurements.

Smethie and Swift (1989) estimated the ages of DSOW in the Irminger Basin, and of ISOW passing through the Charlie-Gibbs Fracture Zone into the Irminger Basin, from the ratio of tritium and ^{85}Kr. For the flow through the Denmark Strait two components of overflow water were identified and treated separately; a low salinity component with a maximum age of 1.8 years (upper Arctic Intermediate Water, AIW) and a high salinity component with a deeper source in the Iceland Sea (lower AIW) with a tracer signal indicating an age of 15-16 years. They also estimated the propagation time for ISOW from its source in the Iceland Basin to the Irminger Basin to 1.0-11.5 years with a best estimate of 7.5 years. The isotopes ^{137}Cs and ^{90}Sr have been used together with tritium for a study in the Northern Irminger Sea (Livingston et al., 1985). From their measurements they conclude that the source of the low salinity component of the DSOW is upper AIW formed in the Iceland Sea, and that the transport over the sill is quite rapid (about 2 years).

Wallace and Lazier (1988) report, from measurements made in 1986, that the LSW is significantly undersaturated (60% saturation) with respect to CFCs, but this is likely to be variable from year to year due to varying depths of the mixed layer, as demonstrated by Haine (1995). Doney and Bullister (1992) found the age of the LSW core in the Iceland Basin to be 10-11 years, based on the assumption of 60% saturation in the Labrador Sea during formation. However, the degree of saturation at the sea surface varies with the surface boundary conditions of the compounds (Jia, 1996; Fogelqvist et al., unpublished data).

The intensity of the mixing between, and entrainment into, the overflow water masses can be illustrated by the volume transport estimates given by Dickson et al (1990). Based on current measurement off Angmagssalik, East Greenland, they found a deep water volume transport amounting to 10.7 Sv, which means that the volumes of Iceland-Scotland Overflow of 2.5-2.9 Sv (Saunders, 1990; Borenäs and Lundberg, 1988) together with the Denmark Strait Overflow of 2.9 Sv (Ross, 1984) have approximately doubled.

A detailed knowledge of the physical processes taking place in the area around the Greenland-Scotland submarine ridge, especially the transport, mixing and entrainment processes in the Iceland and Irminger Basins are therefore of vital importance to an improved understanding of the global thermohaline circulation. A number of international projects focusing the overflow processes have been carried out, for example Overflow 73 and NANSEN. In addition, Iceland, the Faroe Islands and Scotland operate nets of standard sections on a seasonal basis. Research activities in the Iceland and Irminger Basins have generally been very limited, only recently have German and Dutch research groups carried out intense observations in the area (van Aken and de Boer, 1995).

As a contribution to the international World Ocean Circulation Experiment (WOCE) the Nordic countries are conducting a five year programme, NORDIC WOCE, with the goal:

"Determining the exchange between the North Atlantic and the Nordic Seas of water, heat, salt, carbon dioxide and various other properties. This requires both a determination of typical values for the properties (temperature, salinity etc.) of the exchanged water masses and an estimation of water transport (the flux of water)".

The NORDIC WOCE observational programme consists of three components: seasonal hydrographic observations on a net of Standard sections, a current meter mooring programme and intense field campaigns with observations of a variety of physical and chemical parameters. The present paper reports on results from a cruise with the Norwegian research vessel R V Johan Hjort in July-August, 1994. The cruise track and positions of stations are presented in Figure 1.

The scientific objectives of the cruise was to compare the water mass properties on both sides of the Greenland-Scotland submarine ridge, particularly in the water masses flowing out of the Nordic Seas. On sections in the Iceland Basin the intention was to follow the overflow water on its way along the bottom topography along the deeper part of the slope around the Reykjanes Ridge and by the use of tracer characteristics assess the mixing and entrainment of

other water masses into the overflow water.

Halocarbon tracers

A suite of four anthropogenic halocarbons, among them three chlorofluorocarbons (CFCs), are commonly used as transient tracers. They are CFC-12 (CF_2Cl_2), CFC-11 ($CFCl_3$), CFC-113 ($CFCl_2CF_2Cl$) and finally carbon tetrachloride (CCl_4), which is chemically closely related to the CFCs and has a similar atmospheric history, though longer. Their residence times in the atmosphere are in the order of 50 - 100 years. The atmospheric concentrations have been increasing monotonously until very recently (Figure 2), today only CFC-12 still increases. The halocarbons are transferred from the atmosphere to the ocean via gas exchange and transported into the interior of the ocean where they can be used as time dependent tracers of water mass convection, circulation and mixing.

The time dependence of the concentrations of halocarbons in the atmosphere, and thereby the surface water equilibrium concentration, provides a means of estimating the "age" of a water mass, meaning the time elapsed since the water lost contact with the atmosphere. A water parcel will then carry with it a "fingerprint" with a certain tracer composition that is typical for the time of equilibration with the atmosphere.

The ratio between two tracers is less sensitive to dilution by entrainment than the individual concentrations are. The ratios are also insensitive to different saturation levels at the surface during equilibration, as long as the saturation is the same for all halocarbons. The ratio CFC-11/CFC-12 is useful for the ageing of water masses, which equilibrated with the atmosphere before the mid 1970s. At that time the ratio ceased to increase and is of limited use for more recently ventilated waters. In these waters, other combinations must be used, for example CFC-113/CFC-11 or CFC-113/CFC-12. CFC-113 is a tracer with a short atmospheric history, and the ratios have increased so rapidly that it is possible to estimate ventilation times with a resolution of about one year (Haine et al., 1995).

Recently, increasing concern has evolved among tracer chemists about the persistence of CCl_4 in seawater (Wallace et al., 1994; Krysell et al., 1994; Tanhua et al., 1996) especially in oxygen depleted waters and in warm regions. Observations have also been made in polar regions (Meredith et al., 1996; Fogelqvist et al., unpublished data), which indicate

that CCl_4 might slowly break down even in cold seawater. Of this reason, we have chosen not to use CCl_4 for the purpose of assigning an age to water masses in this work. However, CCl_4 is as useful as any other halocarbon as a variable in multivariate analysis of oceanographic data.

Multivariate analysis of oceanographic data

Mixing processes in the ocean can be studied by simple algebraic methods as long as the number of variables, e.g. salinity, temperature and tracer concentrations, are low. Multivariate methods capable of handling a great number of variables simultaneously become more and more important, along with the increasing number of variables measured in oceanographic studies. One such method has been described by Mackas et al. (1987). The Principal Component Analysis (PCA) is a method that was introduced already 70 years ago for agricultural studies (Fisher and MacKenzie, 1923) and further developed by H. and S. Wold (Wold, 1966; Wold, 1978). It is a method for compilation of all varying data in a table into a few trends and a noise residual. These trends are projections into a subspace with orthogonal base vectors making further mathematical treatment simple and numerically stable. The method of PCA in oceanographic and meteorological applications is described in Preisendorfer (1988) and further information on the method of least squares calibration can be found in a book by Martens and Naes (1989).

Principal Component Analysis (PCA) for oceanographic use is a statistical method for characterising a seawater sample based on a number of parameters (variables) describing it. The method leads to the definition of a few characteristic water masses, we can call them the "source waters", of which all other samples taken in the area are mixtures. After defining the source waters, a calibration is made in a second operation by a so called Partial Least Square (PLS) technique, whereby the fractions of the source waters is calculated for each water sample.

METHODS

Halocarbon tracers

Subsamples for halocarbon determinations were drawn into 100 ml ground glass syringes and stored under seawater prior to analysis, which was performed within 5 hours of sampling. The halocarbons were measured with purge and trap sample work-up followed by gas chromatographic

separation and electron capture detection. A sample volume of 40 ml was injected to the purge and trap system. The halocarbons were stripped off by bubbling with an inert gas (N_2 doped with 0.5% H_2 and passed over a palladium catalyst) at a low rate of 80 ml min^{-1} for 10 minutes. The halocarbons were passed on to a cold trap consisting of an open stainless steel tube (0.5 m long and ID 0.75 mm), immersed in the vapours of liquid nitrogen in a Dewar flask at a temperature of about -150°C. The trap was then heated with boiling water, the halocarbons desorbed and transferred to a precolumn (all peaks eluting after CCl_4 were cut to waste), and further to the gas chromatographic column. Two lines of the entire analytical procedure worked in parallel employing two separate fused silica columns (J&W, DB 624, 75 m long and ID 0.53 mm) in the gas chromatograph (Varian 3400 GC) with two electron capture detectors. The gas chromatographic runs were isothermal at 70°C to achieve optimal reproducibility. The two parallel lines allowed analysis of about 8 samples per hour. The halocarbons were standardised towards a gas standard calibration curve fitted to a polynomial function of the third order. Sample to sample precision and limits of detection are reported in Table 1.

Multivariate analysis

The computerised program used for the multivariate analysis is *The Unscrambler*, Version 5.5, COMO AS, Trondheim, Norway, and practical instructions for the execution of the program were derived from Ebensen et al. (1994).

The general procedure was the following. The parameters used for the characterisation of a water sample were at most ten: salinity, temperature, oxygen, silicate, nitrate, phosphate and four halocarbons. After PCA modelling, 2-3 characteristic water samples were identified (at the end of mixing lines) representing the source waters, from which a calibration model was created by setting each source water to 100%. The PLS calibration thereby gave as a result the percentage fractions of all source waters in each sample.

The uncertainty in the prediction of water mass composition using PCA/PLS is a combination of two sources of errors: the model itself and the errors of the parameters used for the calibration. The first estimate is the prediction error of the model, which emanates from the PCA step and from which the prediction is derived, the root mean square error of prediction (RMSEP). It is based on a cross validation of the

model using a random selection of calibration samples. For example, 4 samples, out of 8 calibration samples, are randomly selected for the validation, in each case the difference between measured and modelled results are used for the calculation of the RMSEP. After the PLS calibration the program reports on each individual result's deviation from the model, which measure of the uncertainty reflects partly the construction of the calibration model and the variation in calibration samples, partly the uncertainty of the data that are calibrated. RMSEP values as well as standard deviations of calibration results are presented in Table 2.

RESULTS AND DISCUSSION

A total of 74 stations were occupied along the cruise track shown in Figure 1. In addition to CTD profiles of salinity and temperature, water was sampled for measurements of halocarbons (CFC-11, CFC-12, CFC-113 and carbon tetrachloride), salinity, dissolved oxygen, nitrate, nitrite, phosphate, silicate, partial pressure of carbon dioxide, total dissolved inorganic carbon, tritium, helium, ^{13}C and [14]C. The present paper focuses on the results from the hydrographic and halocarbon measurements, even if nutrient and oxygen data have been used for the classification of water masses and for the multivariate analysis of the results. For the discussion, the studied area will be divided into basins, starting from the Norwegian Sea (Figure 3), through the Faroe Bank Channel (Figure 4) into the Iceland Basin (Figures 3, 5 and 6), further to the Irminger Basin (Figures 7 and 8) and finally the Iceland Sea (Figure 8).

The physical and chemical properties of the water masses in the area are described in Table 3 in the same order as they appear in the following sections of the text. The description is partly based on information from the literature and partly on the observations and data collected in this work. The characteristics of Labrador Sea Water (LSW) in the Iceland and Irminger Basins differ significantly, and they are therefore described separately as LSW_1 and LSW_2, respectively.

Principal Component Analysis (PCA) was especially useful for the study of the overflow from the Nordic Seas over the Greenland-Iceland-Faroe ridge and through the Faroe Bank Channel. Predictions of the fractional composition of water masses are presented in Figures 9, 10 and 11, representing three main pathways the overflow water, Iceland-Faroe ridge, the Faroe Bank Channel and the Denmark Strait, respectively. In the first model, the section from the

Norwegian Sea to the Iceland-Faroe ridge area (Figure 9), the three sources were NSBW, NSAIW and NEAW. In the second model, the Faroe Bank Channel (Figure 10), best model results were obtained with four sources, ISOW, NSAIW, NEAW and an additional surface water thereby the model stabilised at lower RMSEP values and standard deviations. This did not significantly effect the calibration results in the deep part of the channel, i.e. the percentages of ISOW and NSAIW. In the last model, the Denmark Strait section (Figure 11), the sources were ISBW, ISAIW and IW. The method has its limitations when used for systems as complex as the mixing pattern of several water masses can be. Any attempt to resolve the water masses south of the Greenland-Iceland-Faroe ridge, either in the Irminger Basin or the Iceland Basin, have caused uncertainties in the predictions (measured as the root mean square error of prediction, RMSEP) that are too large to justify any firm conclusions. The main reason for this uncertainty is the large number of source water masses in the basins, sometimes with properties that are quite similar. The same is generally true for surface water layers. In this study, a practical upper limit for the number of source waters turned out to be three.

The water masses which are of importance in the present context are those which form the sources of the overflowing water and those which modify the overflow along its pathway. Here, only waters which are dense enough to mix into the Atlantic bottom waters will be considered as overflow water. The source water masses are formed north of the Greenland-Scotland ridge while the modifying waters comprise both intermediate, deep and bottom water masses south of the ridge. These are somewhat different in the Faroe overflow in comparison with the Denmark Strait overflow. The source water masses for the overflow are mainly intermediate waters and, to a much lesser extent, deep water masses. Further, NSDW contribute more to the overflow through the Faroe Bank Channel than to the Denmark Strait overflow.

Water mass distribution.

The Norwegian Sea north of the Iceland-Faroe Ridge.

The area is dominated by three water masses: NSDW, NSAIW and NEAW. The deep and bottom waters in the Nordic Seas are formed partly in the Greenland Sea and partly in the Arctic Ocean. The Norwegian Sea Deep Water (NSDW) is a mixture of these

(Aagaard et al., 1985; Swift and Koltermann, 1988). At depths greater than about 2500 m it is a homogeeous water mass, adiabatically isothermal and of constant salinity (Figure 3). In its shallower layers it becomes warmer and slightly fresher with decreasing depth due to admixture of NSAIW. Such mixtures of NSDW and NSAIW form the denser portion of the ISOW.

Bönisch and Schlosser (1995) made a compilation of CFC-11 and CFC-12 measurements in the Norwegian Sea in 1982 and 1989. Together with data from 1994 and 1995 (Fogelqvist et al., unpublished data) collected within an ongoing project (ESOP, European Sub-polar Ocean Programme) and those from this work, one can notice a weak trend of increasing concentrations, CFC-11 from 0.16 to 0.30 and CFC-12 from 0.10 to 0.25 pmol kg^{-1}. However, the differences lie within the deviations one can expect when comparing data at such low levels. The ratios CFC-11/CFC-12, on the other hand, are all in the range 1.4-1.6 pointing at an apparent time for equilibration in 1962-1964 (assuming equal saturation).

Above the 2500 m level there is a gradient of NSDW mixed with the overlying NSAIW. This water mass, which typically falls in the range of σ_θ = 27.95 to 28.05, is the principal contributor to the flow over the Iceland-Scotland Ridge, the Iceland-Scotland Overflow Water (ISOW). Another version of the intermediate water is distributed along the Iceland-Faroe Ridge as part of the East Iceland Current, mainly on its southern side. This was described by Stefansson (1962) as North Icelandic Winter Water (NIWW). He found that it is formed in the North Icelandic coastal area during winter by mixing of Atlantic and Arctic waters. Stefansson defined this water mass as 2-3 °C and 34.85 - 34.90 in salinity, but stated that it may be variable in composition. Accordingly, as a result of later investigations, the definition of its salinity range has been expanded to the values in Table 3 (Meincke, 1978; Hopkins, 1991). With a density in the range σ_θ = 27.55 to 27.95, most of this water is not dense enough to sink into the Atlantic.

The results from PCA/PLS calibration of the data is illustrated in Figure 9. The 90 % NSDW isoline is at about 1500 m depth in the northern part of the section, but slope down to 2500 m in the southern part towards the Iceland-Faroe Ridge. This downward slope of isolines can also be seen in the halocarbon distribution, the water at 1500 m depth on the northern slope of the Faroe-Iceland Ridge, having a higher influence of NSAIW than at the same depth

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further north (see Figure 3), presumably a result of the cyclonal circulation in the Norwegian Sea. The water above the NSDW is dominated by NSAIW, overlain by North East Atlantic Water (NEAW) coming in over the ridge. From Figure 9 it can be concluded that the overflow water is a mixture of about one fourth NSDW and one half NSAIW, the rest being NEAW.

Faroe Bank Channel.

In Section II (Figure 4) across the Faroe Bank Channel, the water close to the bottom has characteristics, θ = -0.51°C and salinity 34.905, which, according to the definitions in Table 3, fall in the transition zone between NSAIW and NSDW. This gives ISOW a potential density near the bottom of σ_θ = 28.055 (σ_2 = 37.425). In general, water in the Faroe Bank Channel of potential temperatures below about +0.5°C has a density above σ_θ = 28.0 and should thereby be dense enough to descend to great depths south of the ridge. However, the density of the plume decreases significantly along the pathway on the southern slope of the ridge.

The ISOW has the same characteristics as the water found in the southern part of the Norwegian Sea at depths of about 1000 meters, which according to PCA/PLS results is a mixture of about 70 % NSDW and 30 % NSAIW. The CFC-11 and CFC-12 concentrations in the ISOW (2.1 and 0.9 pmol kg^{-1}, respectively) suggest an apparent age of about 20 years. If we assume equal saturation of CFC-11 and CFC-12 when they equilibrated at the surface, the ratio CFC-11/CFC-12 in the bottom samples points at an age of 19 years, which falls within the time-scale when this ratio is not very trustworthy, due to the levelling out of the ratio increase in the mid 1970s. The use of CFC-113 is ruled out as the concentrations in the bottom water layer are below the detection limit.

Above the overflow water is a layer with different properties, higher halocarbon concentrations, lower salinity and higher temperature. This water has an origin higher up in the water column in the Norwegian Sea (500-700m) and can best be characterised as being mainly NSAIW (>60%), as deduced from the PCA/PLS calibration illustrated in Figure 10.

Iceland Basin.

The situation in the Iceland Basin is more complex than in the Norwegian Sea. The presence of four different water masses, ISOW, NEABW, LSW$_1$ and

NEAW, was observed. As was mentioned above resolution of them all by multivariate analysis was not regarded reliable.

Obviously, the overflowing water must be denser than the water masses along its pathway at greater depths. In comparison, the density in the core of the overflow at about 2300 m depth at 61 °N on Section IV is about σ_θ = 27.92 (σ_2 =37.10). In Section I this density corresponds to approximately 2°C and a salinity of 34.9 which is found in the sharp thermocline just above an intermediate salinity minimum with values below 34.9. In the Norwegian Sea, such a salinity minimum is a clear indication of the presence of NSAIW. This shows that NSAIW is a major source component of the overflow. Also below this minimum where the salinity is higher than 34.9, the temperature/salinity properties indicate a considerable admixture of NSAIW, although there is an increasing admixture of NSDW with depth.

Along its pathway toward the west from the Faroe Bank Channel, the ISOW mixes vigorously with the overlying NEAW. This is clearly indicated in Section I across the Iceland-Faroe Ridge (Figure 3), only some 100 nautical miles west of the Faroe Bank Channel. There, the core of the overflow is found at about 1000-1200 m depth and its properties have changed considerably to about 2°C and salinity 34.97, and the density has decreased to about σ_θ = 27.95.

On Section III across the slope south of Iceland (Figure 5), at about 17 °W, the core of the ISOW is best indicated by its relatively low potential temperature, below 2.5°C, close to the bottom at about 1900 m depth on station 601. Although this is a low temperature in relation to the surroundings, it represents a rise of about 0.5°C from the Faroe Bank Channel (Section II) while the salinity has decreased slightly to 34.96. The mixing and entrainment by the ambient water is therefore best reflected in the considerable temperature rise, while the moderate salinity change just shows that the salinity of the ISOW in these depth layers is not much different from the salinity of the ambient water. The small change in salinity is therefore not due to reduced mixing, but rather it indicates admixture of LSW during the descent from 1200 to 1900 m depth.

Section IV (Figure 6) south of Reykjanes cuts through the core of the ISOW at about 20°W where it is found at 1800 - 2400 m depth and is split into an upper core around 1800 m and a deeper one around 2300 m with a core of NEABW in between. Compared with Section III, about 120 nautical miles to the north-east, there is a temperature rise of 0.1°C, and there is also a

slight salinity increase which reflects the increasing salinity in the bottom water (NEABW) underneath the LSW.

The NEABW, characterised by high silicate (indicating an Antarctic origin), low tracer and low oxygen contents, is most evident at the bottom of station 613 with a silicate concentration of 17 M, CFC-11 and CFC-12 concentrations of 1.7 and 0.8 pmol kg^{-1}, respectively, and oxygen concentrations less than 270 M. The NEABW can be traced further to the northeast at stations 612-609 and at stations 597-598 along the eastern slope of the basin. The plume of NEABW can also be traced on the north-western slope of the Iceland Basin at stations 599-600 and stations 616-617. Here are the silicate values lower and the halocarbons are higher, suggesting entrainment during its cyclonal circulation around the Iceland Basin.

A distinctive core of LSW$_1$ was recognised by its low salinity (34.8-34.9) at depths of about 1400-1700 metres in the central part of the basin. The CFC values (2.2-2.4 pmol kg^{-1} for CFC-11, 1.0 pmol kg^{-1} for CFC-12 and 0.08 pmol kg^{-1} for CFC-113) suggest, assuming 100% saturation, that this water was equilibrated at the surface in the mid 1970s in the Labrador Sea. Also, the CFC-113/CFC-11 ratio, which is less sensitive to the saturation, points at an age of 19-20 years. (The CFC-11/CFC-12 ratio is less reliable on this time-scale.) The estimate made by Doney and Bullister (1992) that the core of the LSW in the Iceland Basin has an age of 10-11 years was based on an assumed saturation level of 60% in the Labrador Sea, which might explain the difference in our conclusions.

The upper layer is dominated by NEAW, which is easily identifiable by its high salinity and temperature, but also by very high halocarbon concentrations.

Irminger Basin

Three water masses dominate the deep water of the basin; ISOW, LSW$_2$ and Denmark Strait Overflow Water (DSOW).

In Section V, approximately along 63°N, across northern Irminger Basin (Figure 7), the ISOW is traceable at about 2300 - 2500 m depth. Here, it has a character more like a layer with salinities above 34.90 across the basin, somewhat in contrast to the lower salinities of the LSW$_2$ above and the NWABW or the Denmark Strait Overflow Water (DSOW) below. A core of salinity in excess of 34.92 was observed at the

foot of the slope both on the eastern and the western side of the basin. The eastern core is the ISOW, which has turned around the Reykjanes Ridge and is flowing north, while the western core is flowing southwest along the Greenland slope. The differences in tracer concentrations indicate that the ISOW transport time between stations 601 in the Iceland Basin and station 631 in the Irminger Basin is in the range 2-4 years, which is a measure of the time of conveyance through the Charlie-Gibbs Fracture Zone. Smethie and Swift (1989) estimated the propagation time of ISOW from the Iceland to the Irminger Basin to 1-11.5 years, our data point at the lower range of this estimate.

The potential temperature of the ISOW core with salinities above 34.9 is very close to 3°C in its upper part at about 2100 m depth and decreases slightly to below 2.9°C at about 2700 m. This shows that the water has become warmer and fresher along its pathway around the Reykjanes Ridge. Compared with Section IV, there has been a rise in temperature of 0.5°C while the salinity has decreased by 0.04. This indicates that the LSW has been the dominant water mass in the mixing process around the Reykjanes Ridge, because the NEABW is colder than the ISOW in Section V, and its salinity of 34.95 - 34.97 cannot cause the observed reduction. Similarly, with a temperature of about 1°C, the NWABW would tend to reduce the temperature and, therefore, cannot have mixed with the ISOW to a large extent. Temperature and salinity in the southbound core on the western side of the Irminger Basin are practically the same as in the core on the eastern side, indicating moderate mixing around the northern part of the basin. Also, only small differences in CFC-11 and CCl$_4$ concentrations were noticed between the western and the eastern core of ISOW within the Irminger Basin, the western core having the lower concentrations, indicating a circulation within the basin on a time-scale of a year.

From the tracer distribution and the CFC-11/CFC-12 and CFC-113/CFC-11 ratios it could be deduced that the LSW$_2$ at stations 631-634 consists of two layers, a shallower layer at a depth of 1000-1500 m, which is older than the layer beneath at 1500-1800 m by about 6 years, the upper layer 11-12 years and the lower 5-6 years old. There is also a significant difference between the ages of the LSW$_2$ layers in the Irminger Basin compared with the LSW$_1$ in the Iceland Basin, where the water is even older (see above).

On the westernmost station of Section V, the temperature was below 0.5°C and the salinity below 34.85 near the bottom at 2400 m depth. By definition of potential temperature and salinity this is DSOW,

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although with σ_θ = 27.94 it is slightly less dense than DSOW (Swift et al., 1980). This is suggestive of moderate mixing over the slope from the Denmark Strait sill. In contrast to the ISOW, which changes its properties considerably by mixing along the first 100 nautical miles of its pathway while descending only about 400 m, the DSOW has not changed much over a distance of about 250 nautical miles and a depth difference of almost 2000 m. Its -S values indicates mixing with LSW to a larger extent than with the warmer and saltier Irminger Sea Water (ISW). Multivariate analysis of the data (Figure 11) indicate that the DSOW, when entering the Irminger Basin, is composed mainly by Iceland Sea Arctic Intermediate Water, ISAIW (>70%) and to some extent Iceland Sea Bottom Water, ISBW (<30%).

Iceland Sea

The major component of the overflowing intermediate water in the Denmark Strait is what Swift and Aagaard (1981) classified as upper Arctic Intermediate Water. We prefer to call this Iceland Sea Arctic Intermediate Water (ISAIW), because it is mainly formed in the Iceland Sea by convective mixing during winter, although, to a varying extent it is also formed in the Greenland Sea and along the East Greenland Current (Strass et al., 1993). Its colder version is widely spread outside its formation area and intermediate waters with such characteristics are observed over the entire Norwegian Sea (Blindheim, 1990; Hopkins, 1991) and also in the Faroe-Shetland Channel (Martin, 1993). A third version appears in the East Iceland Current, where it is called North Icelandic Winter Water (NIWW, see above in the section on the Norwegian Sea).

In the deepest part of the basin, the CFC-11 and CFC-12 concentrations (1.1-1.2 and 0.41-0.42 pmol kg^{-1}, respectively) and the lack of any CFC-113 signal indicate an age of the ISBW of more than 25 years (100% saturation). The water characteristics change gradually towards the surface and at about 700 meters depth the water is mixed with 70% ISAIW according to the PCA/PLS calibration. In the light of this gradient, the age differences between the upper AIW and the lower AIW, as reported by Smethie and Swift (1989), 1.8 years or less and 15-16 years, respectively, are not surprising. They are well in line with the data obtained in this work. Polar Water, PW, dominates the surface layer of the section in the Iceland Sea and the Irminger Sea Water, ISW, does not penetrate north of the Denmark Strait.

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Table 1.

Precision and limits of detection for the two parallel channels of the analytical system for halocarbon measurements.

Tracer	Precision Channel A	Precision Channel B	Limit of detection (pmol kg⁻¹)
CFC-11	0.8 %	1.0 %	0.02
CFC-12	1.0 %	1.5 %	0.04
CFC-113	6.0 %	2.4 %	0.06
CCl.	1.1 %	1.1 %	0.02

Table 2.

Estimates of uncertainties of the PCA/PLS calibrations of fractional percentages.

	Iceland Sea			Norwegian Sea			Faroe Bank Channel	
Water mass	RMSEP (%)	Stand. dev. (%)	Water mass	RMSEP (%)	Stand. dev. (%)	Water mass	RMSEP (%)	Stand. dev. (%)
IW	4.15	5.29	NEAW	3.36	4.79	SW*	0.43	3.73
ISAIW	7.38	9.71	NSAIW	5.05	5.31	NEAW	2.05	6.78
ISBW	6.53	9.96	NSDW	4.55	5.76	NSAIW	2.88	4.45
						ISOW	2.87	3.10

* Surface water in the Faroe Bank Channel, with properties slightly different from NEAW, and used for the PCA modeling only.

Table 3.

Physical and chemical properties of the water masses in the studied area.

Norwegian Sea Deep Water (NSDW)

True NSDW is found at depths greater than approximately 2500 m in the deep basins of the Norwegian Sea. At these depths NSDW is close to homogeneous both in salinity and temperature as it is adiabatically isothermal.

T	-1.05°C
S	34.91
O_2	297-299 µmol kg^{-1}
Si	13 µmol kg^{-1}
CFC-11	< 1 pmol kg^{-1}
CFC-12	0.2 - 0.5 pmol kg^{-1}
CFC-113	Not detectable
CCl$_4$	1 - 2 pmol kg^{-1}

Norwegian Sea Arctic Intermediate Water (NSAIW)

NSAIW is found in the Norwegian Sea in an approximately 200 m thick layer **between water mainly of Atlantic origin in the upper layers** and underlying deep water, NSDW

T	-0.5 < T < +0.5°C
S	34.87 < S < 34.90
O_2	295 - 305 µmol kg^{-1}
Si	7 - 8 µmol kg^{-1}
CFC-11	3.5 - 4.0 pmol kg^{-1}
CFC-12	1.6 - 2.0 pmol kg^{-1}
CFC-113	0.2 - 0.5 pmol kg^{-1}
CCl$_4$	4 - 5 pmol kg^{-1}

North Icelandic Winter Water (NIWW)

This water was defined by Stefansson (1962) to be formed in North Icelandic waters by mixing of Atlantic and Arctic waters. It is variable in composition.

T	2 < T < 3°C
S	34.6 < S < 34.9

Atlantic Water in the Nordic Seas (NSAW)

Traditionally any water in the Nordic Seas with temperatures above 0 °C and salinities above 35 has been defined as Atlantic Water. However, almost all waters of salinities higher than 35 are warmer than 2 °C.

T	> 2°C
S	> 35

Northeast Atlantic Water (NEAW)

NEAW is also defined as Subpolar Mode Water. (Lee and Ellett (19-65) claimed that North Atlantic water in the vicinity of the Faroe Islands can be taken as having a temperature of 9°C and a salinity of 35-.33.)

T	8 - 10°C
S	35.25
O_2	265 - 270 µmol kg^{-1}
Si	2.0 - 6.0 µmol kg^{-1}
CFC-11	4 - 4.5 pmol kg^{-1}
CFC-12	1 - 2 pmol kg^{-1}
CFC-113	0.15 - 0.17 pmol kg^{-1}
CCl$_4$	3 - 5 pmol kg^{-1}

Iceland - Scotland Overflow Water (ISOW)

Water which overflows the Iceland-Scotland Ridge through the Faroe Bank Channel.

T	-0.7 < +0.5°C
S	34.87 - 34.91
O2	290 - 300 µmol kg^{-1}
Si	9 µmol kg^{-1}
CFC-11	2 pmol kg^{-1}
CFC-12	< 1 pmol kg^{-1}
CFC-113	Not detectable
CCl$_4$	3 - 4 pmol kg^{-1}

Northeast Atlantic Bottom Water (NEABW)

The water appears in the bottom of the Iceland Basin, and is also called Lower Deep Water (LDW). It has an Antarctic origin.

	2 - 3°C
S	34.95 - 35.00
O$_2$	< 280 µmol kg^{-1}
Si	**> 12 µmol kg^{-1}**
CFC-11	< 2 pmol kg^{-1}
CFC-12	< 1 pmol kg^{-1}
CFC-113	< 0.1 pmol kg^{-1}
CCl$_4$	< 3 pmol kg^{-1}

Labrador Sea Water (LSW$_1$) in the Iceland Basin

This water originates from deep convection in the Labrador Sea. It advects into the Irminger and Iceland Basins below Irminger and Atlantic water, respectively.

T	3.0 - 3.5°C
S	34.8 - 34.9
O$_2$	270 - 280 µmol kg^{-1}
Si	11 - 12 µmol kg^{-1}
CFC-11	2 - 3 pmol kg^{-1}
CFC-12	1 pmol kg^{-1}
CFC-113	0.10 pmol kg^{-1}
CCl$_4$	3 - 4 pmol kg^{-1}

Labrador Sea Water (LSW$_2$) in the Irminger Basin

See above.

T	2 - 3°C
S	> 34.9
O$_2$	290 - 300 µmol kg^{-1}
Si	10 - 11 µmol kg^{-1}
CFC-11	1 - 3 pmol kg^{-1}
CFC-12	1.3 - 1.9 pmol kg^{-1}
CFC-113	< 0.2 pmol kg^{-1}
CCl$_4$	3 - 4 pmol kg^{-1}

Denmark Strait Overflow Water (DSOW)

Water flowing through the Denmark Strait sinking to the bottom of the Irminger Basin.

T	< 1°C
S	34.8 - 34.9
O$_2$	300 - 310 µmol kg^{-1}
Si	< 8 µmol kg^{-1}
CFC-11	4 - 5 pmol kg^{-1}
CFC-12	1.8 pmol kg^{-1}
CFC-113	0.3 pmol kg^{-1}
CCl$_4$	5 - 6 pmol kg^{-1}

Irminger Sea Water (ISW)

Upper water layer in the Irminger Basin which is mainly supplied by the Irminger Current. It is therefore an Atlantic water mass.

T	5 - 7°C
S	35.05- 35.10
O_2	280 µmol kg⁻¹
Si	8-10 µmol kg⁻¹
CFC-11	4 - 5 pmol kg⁻¹
CFC-12	1.5 - 2.0 pmol kg⁻¹
CFC-113	> 0.3 pmol kg⁻¹
CCl₄	4 - 5 pmol kg⁻¹

Iceland Sea Bottom Water (ISBW)

This water mass is very similar to NSDW but has a slightly higher salinity due to larger admixture of deep water from the Arctic Ocean.

T	-1°C
S	34.910 < S < 34.912
O_2	290 - 300 µmol kg⁻¹
Si	10 - 12 µmol kg⁻¹
CFC-11	1.1 - 1.4 pmol kg⁻¹
CFC-12	0.4 - 0.6 pmol kg⁻¹
CFC-113	Not detectable
CCl₄	1.5 - 2.5 pmol kg⁻¹

Iceland Sea Arctic Intermediate Water (ISAIW)

This water mass is also known as upper Arctic Intermediate Water. It is the main source of NSAIW.

T	< 2°C
S	34.7 - 34.9
O_2	310 - 330 µmol kg⁻¹
Si	5 - 7 µmol kg⁻¹
CFC-11	4 - 6 pmol kg⁻¹
CFC-12	1.7 - 2.0 pmol kg⁻¹
CFC-113	0.4 - 0.5 pmol kg⁻¹
CCl₄	5 - 8 pmol kg⁻¹

East Greenland Current Intermed. Water (EGCIW)

This is mainly water of Atlantic origin which has circulated into the EGC from the Spitsbergen Current. Also known as Lower Arctic Intermediate Water

T	0 - 2°C
S	34.9 - 35.0

Polar Water (PW)

The water has its origin in the East Greenland Current. The salinity is low and variable due to melting of glacier ice and a contribution from Arctic Ocean surface water.

T	< 0.0°C
S	< 34.4
O_2	330 - 350 µmol kg⁻¹
Si	< 7 µmol kg⁻¹
CFC-11	6 - 7 pmol kg⁻¹
CFC-12	2.5 - 3.0 pmol kg⁻¹
CFC-113	0.4 - 0.6 pmol kg⁻¹
CCl₄	> 8 pmol kg⁻¹

Northwest Atlantic Bottom Water (NWABW)

This water mass is found near the bottom away from the sills and is mainly DSOW. It has a potential temperature near 1 °C and salinities near 34.9
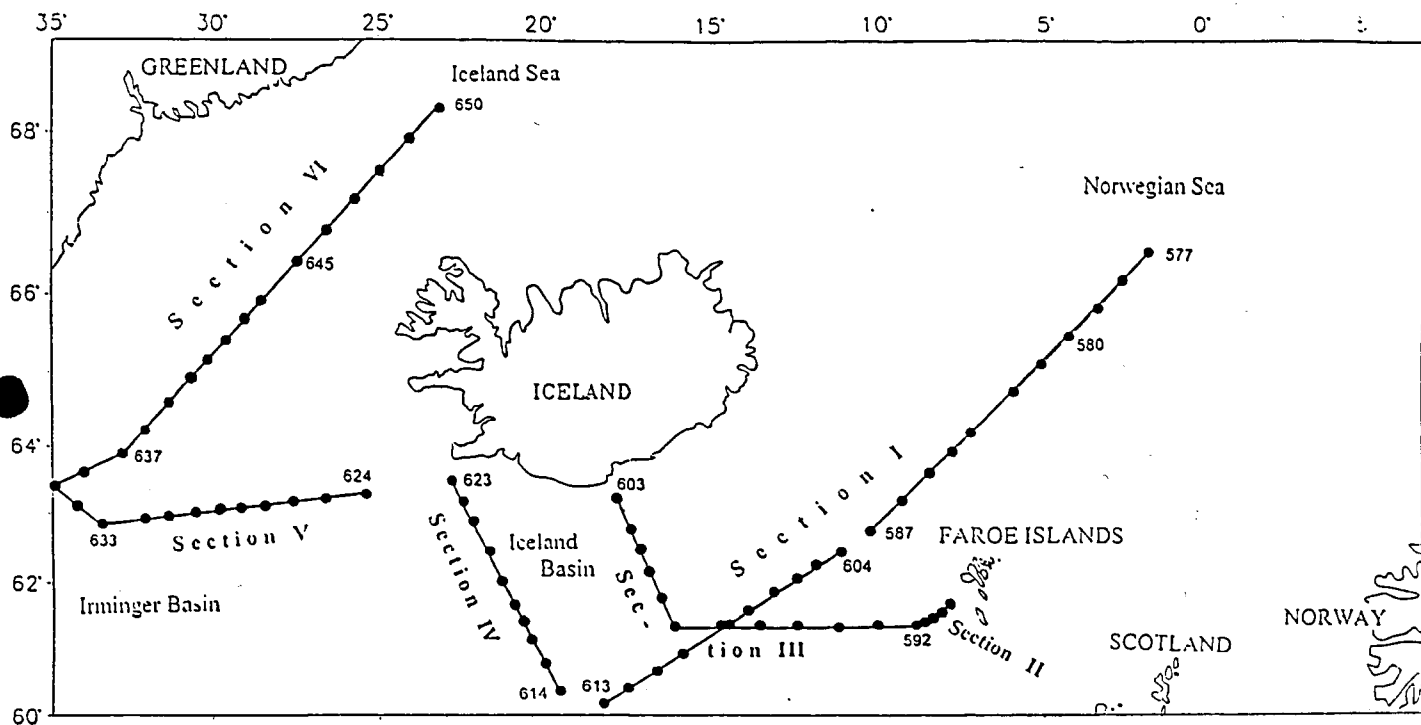
θ	1°C
S	34.9

Figure 1.
Map of the area covered during the R/V *Johan Hjort* cruise 23 July to 16 August 1994 with marked station locations.
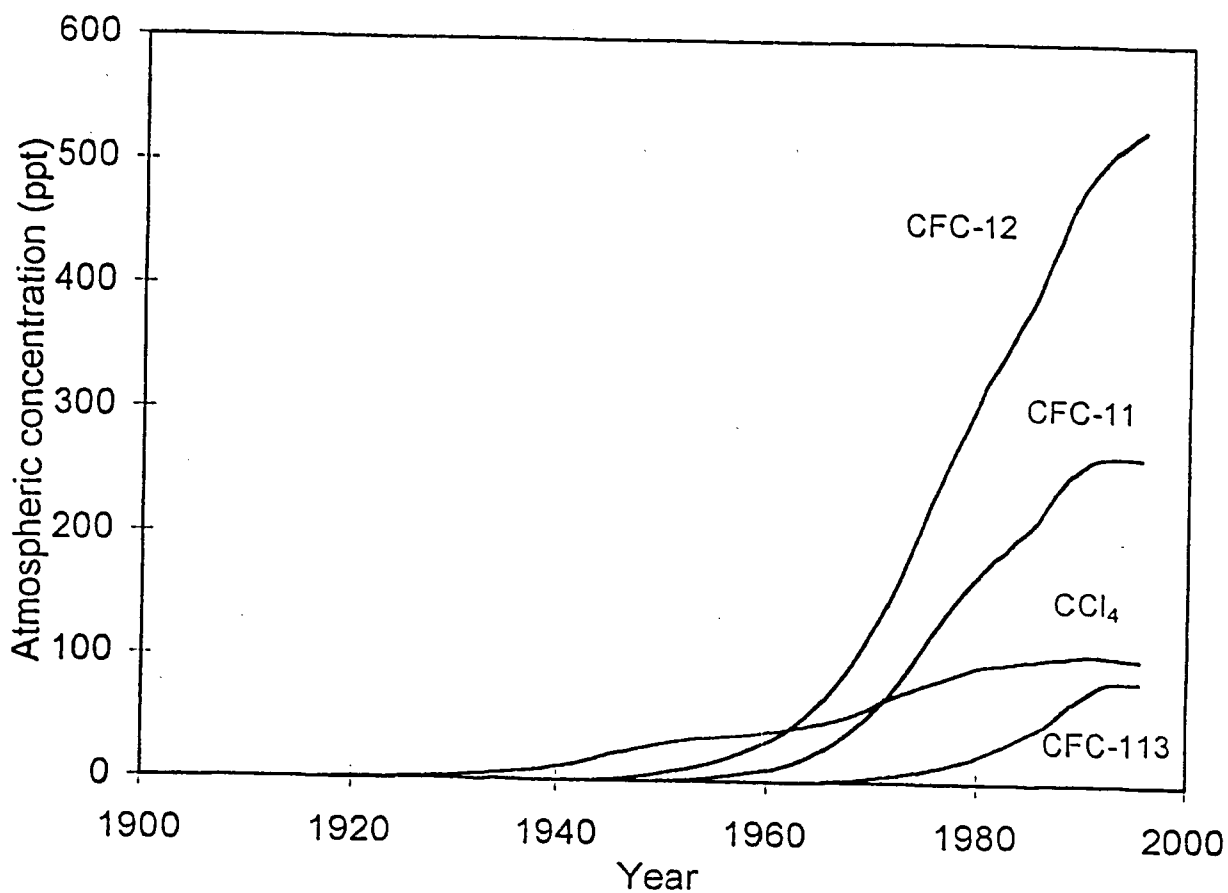
Figure 2.
The atmospheric concentrations of halocarbons are time dependent and well known since they where first measured in the 1970s. Concentrations before 1970 are based on production data and release estimates (S. Walker, P. Salameh and R. Weiss, personal communication, 1996). The figure shows the atmospheric records in the northern hemisphere.
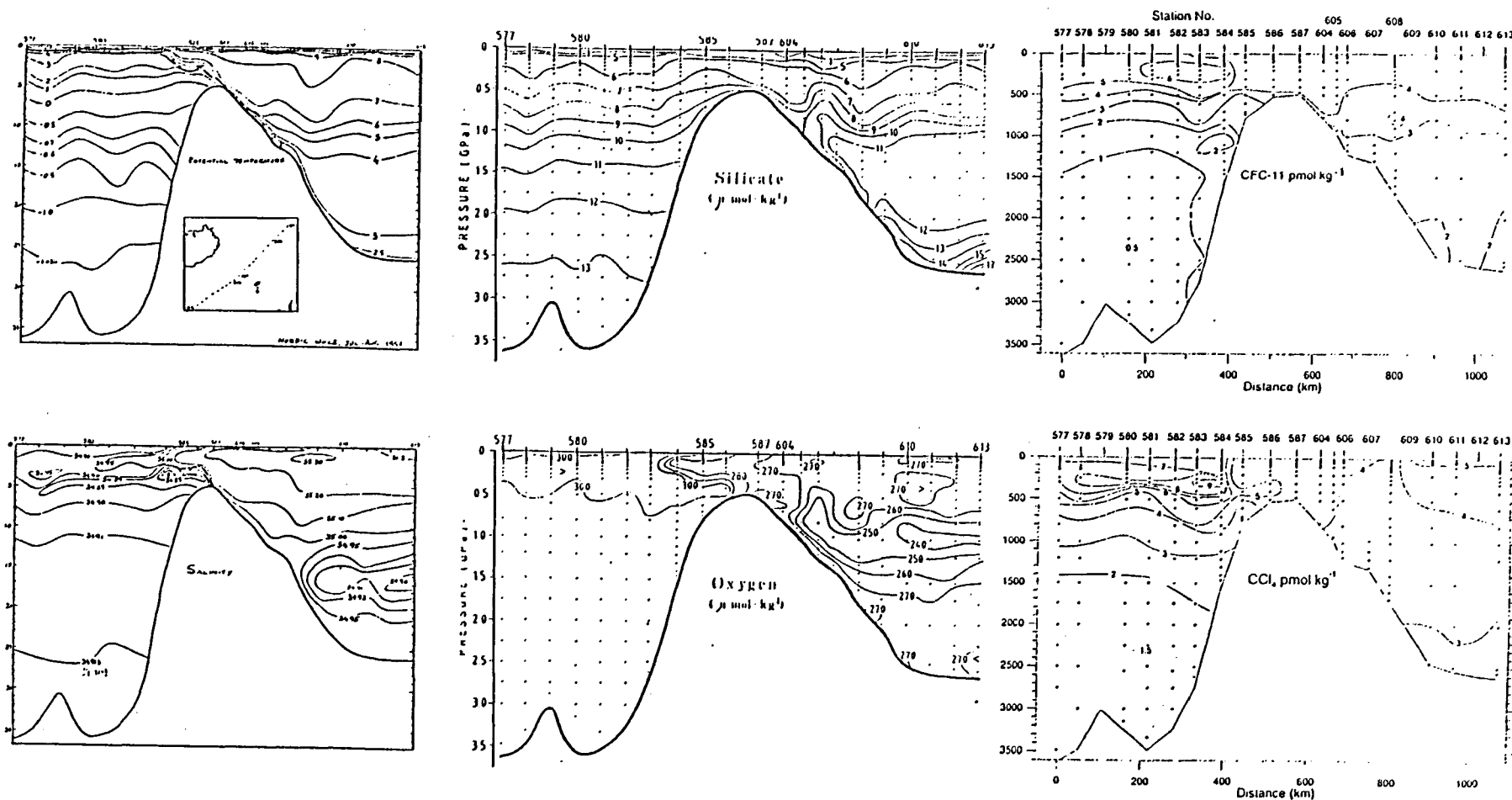
Figure 3.
Section I from the Norwegian Sea (station 577) over the Iceland-Faroe Island ridge to the Iceland Basin (station 613). The figure shows the distribution of the following parameters; potential temperature, salinity, silicate, oxygen, CFC-11 and CCl₄.
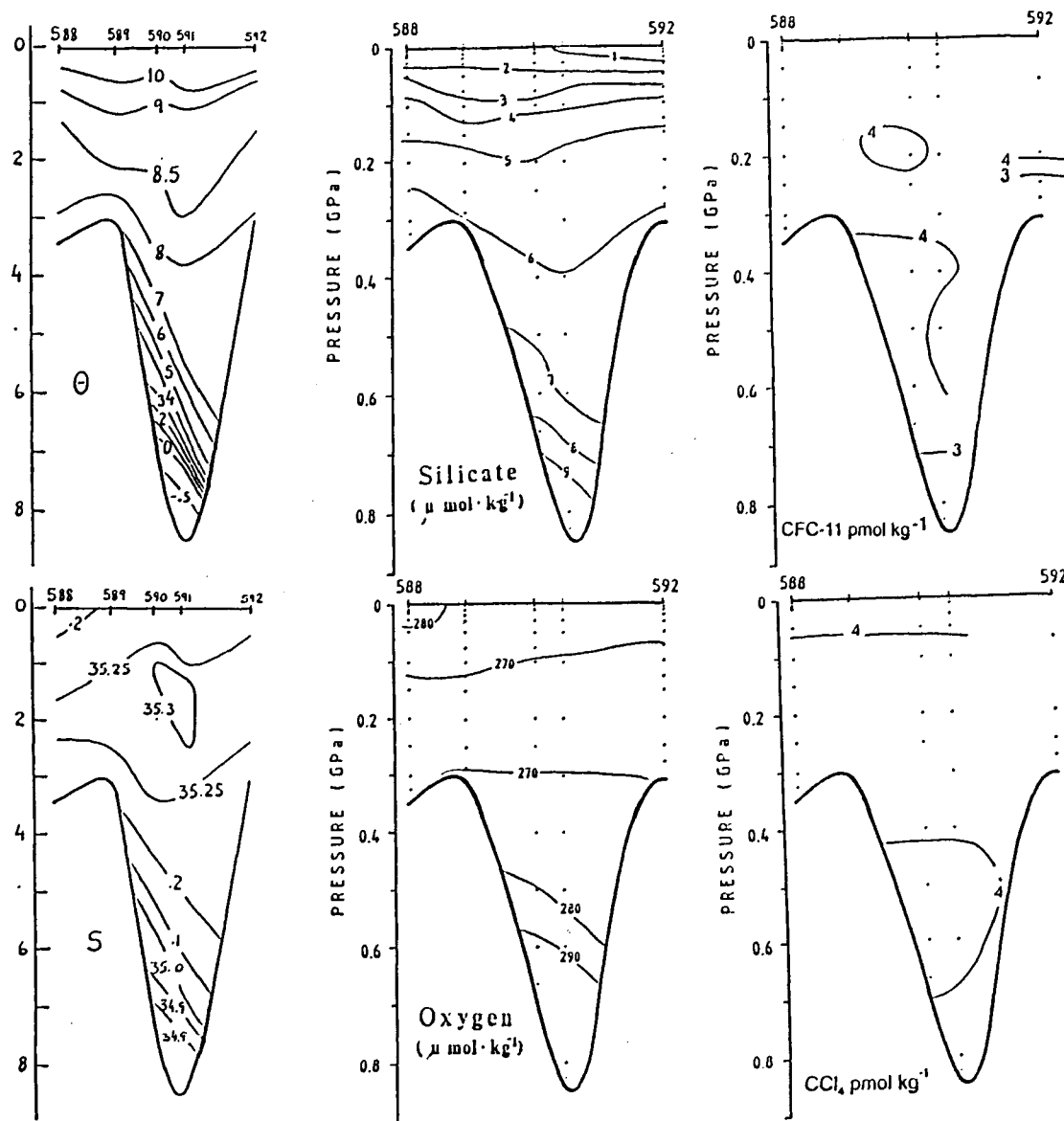
Figure 4.
Section II, the Faroe Bank Channel, stations 588-592. The same parameters are shown as in Figure 3.
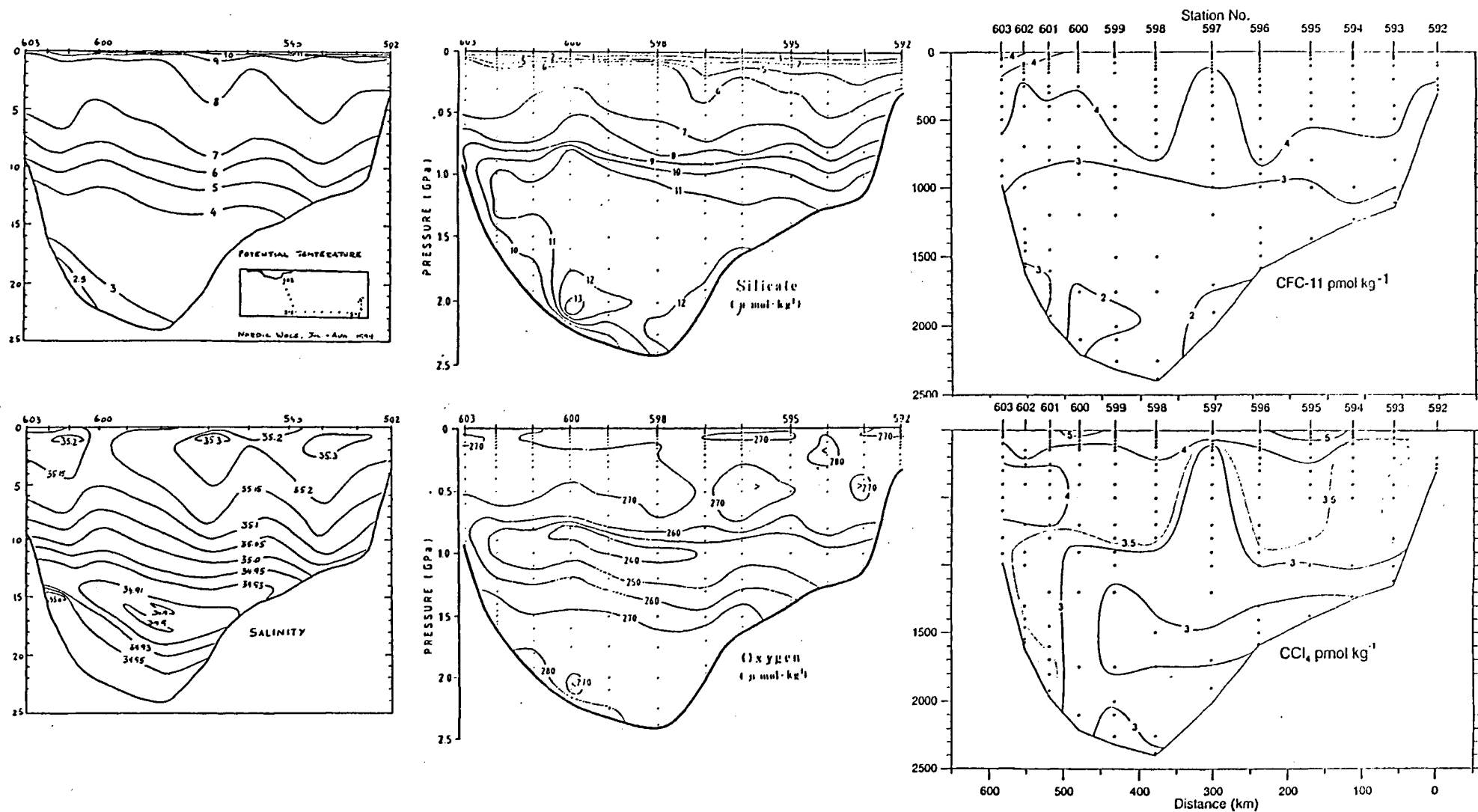
Figure 5.
Section III through the Iceland Basin from the Faroe Bank Channel (station 592) to the Icelandic coast (station 603). The parameters are same as in Figure 3.
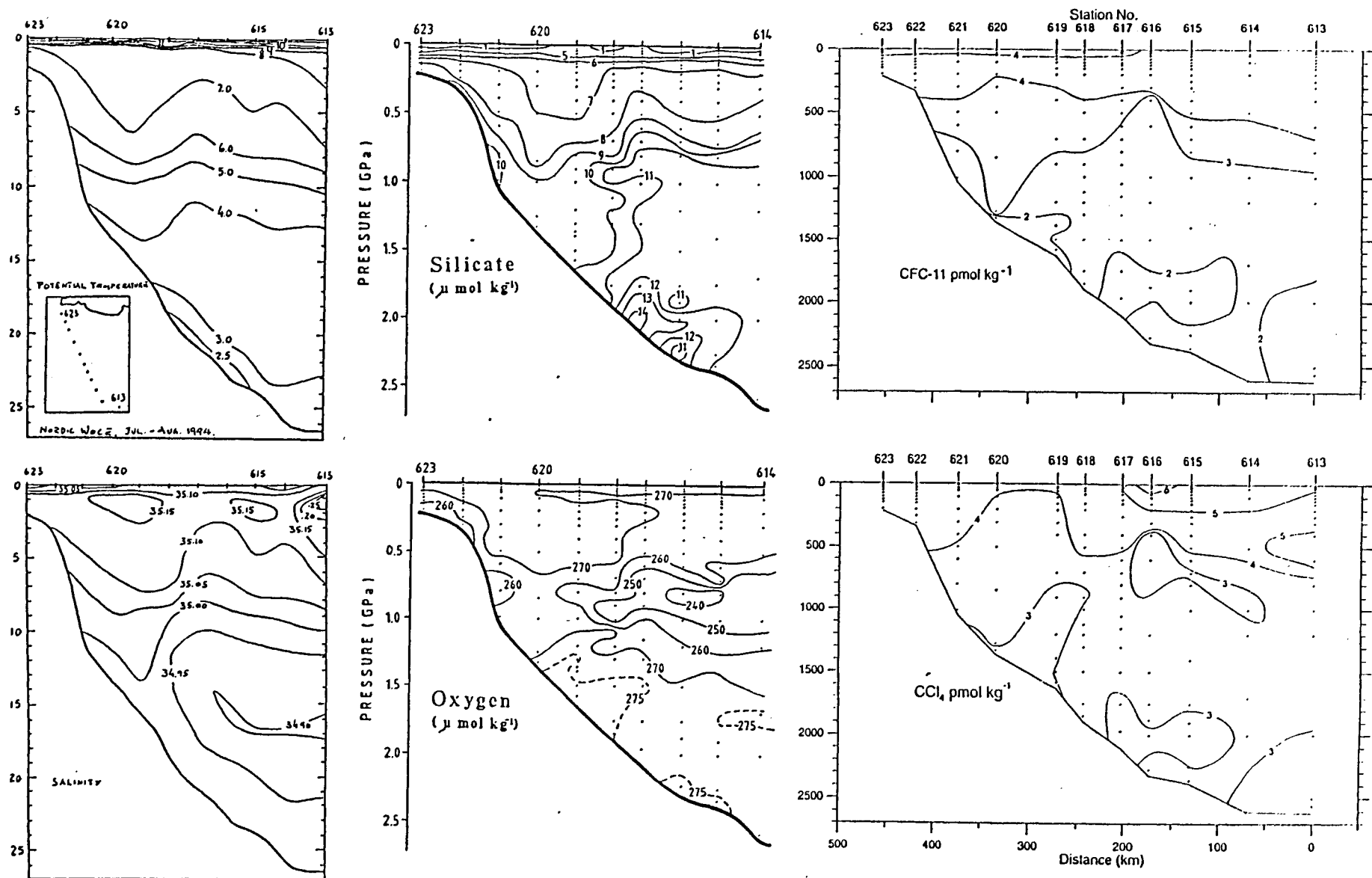
Figure 6.
Section IV, the south-western transect in the Iceland Basin, from station 613 in the central part
of the basin to station 623 on the Reykjanes ridge. The parameters are same as in Figure 3.
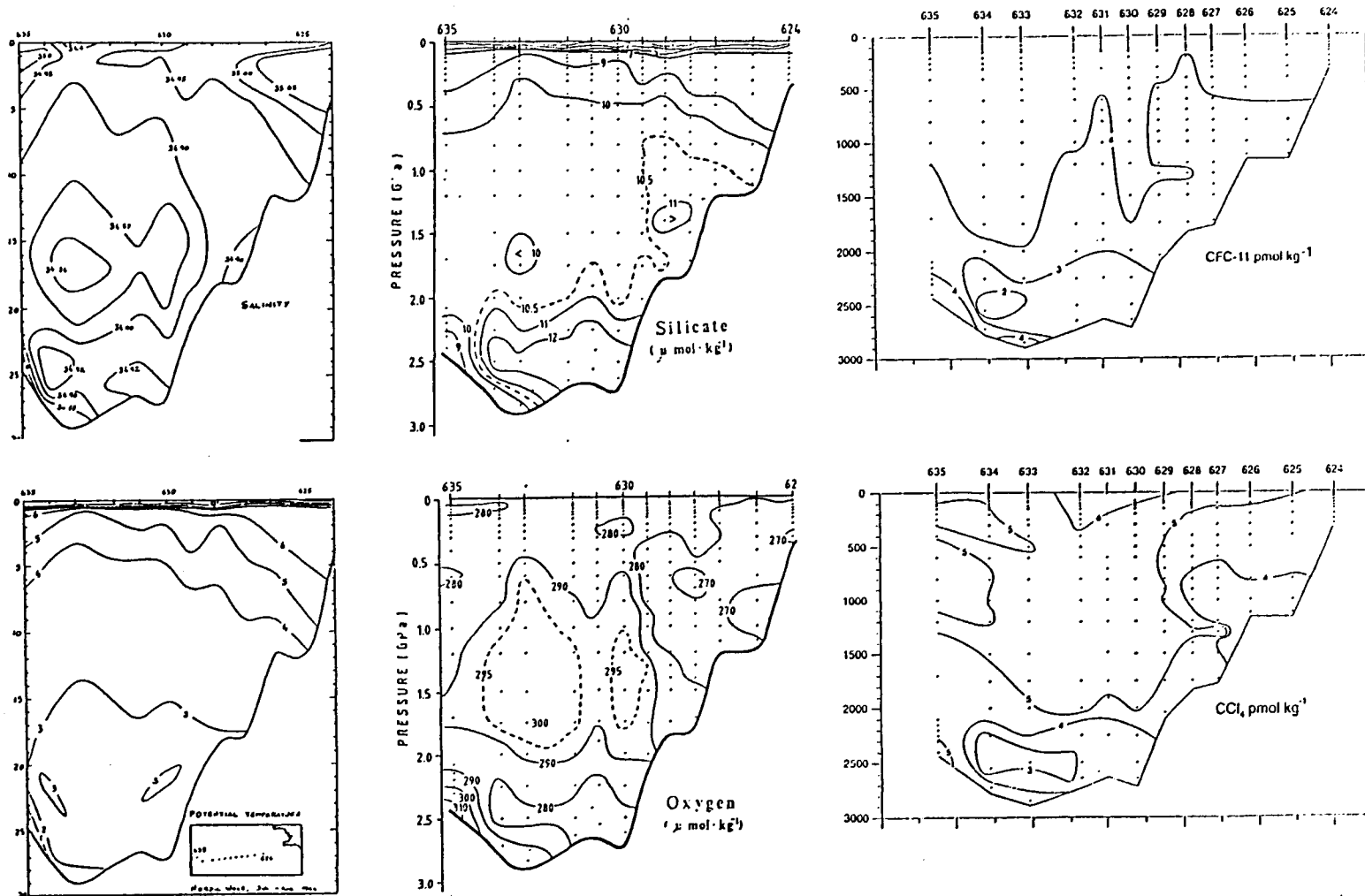
Figure 7.
Section V across the Irminger Basin from the Reykjanes ridge (station 624) to the continental shelf east of Greenland (station 635) showing the same parameters as in Figure 3.
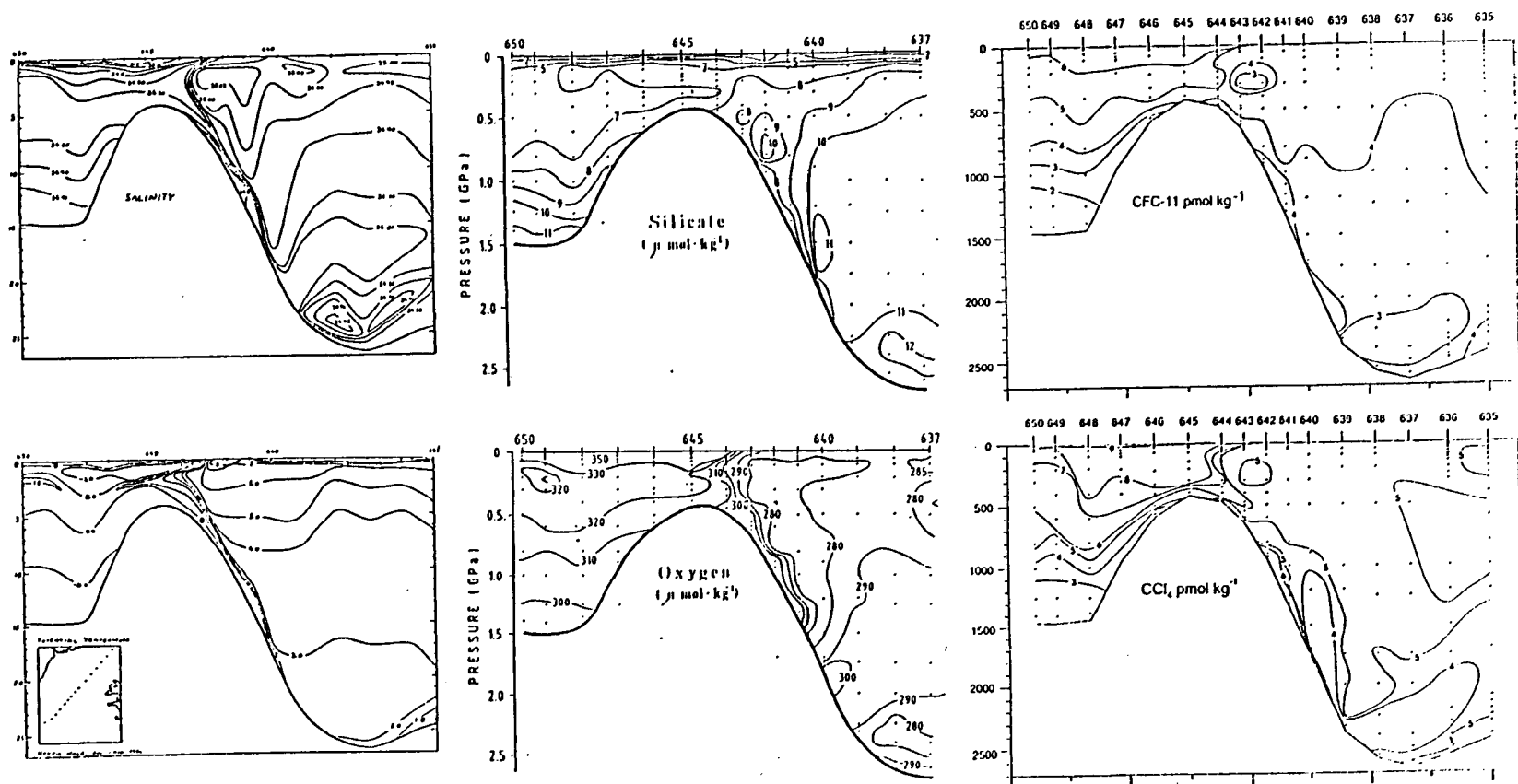
Figure 8.
Section VI through the Denmark Strait from the Irminger Basin (station 635) to the Iceland
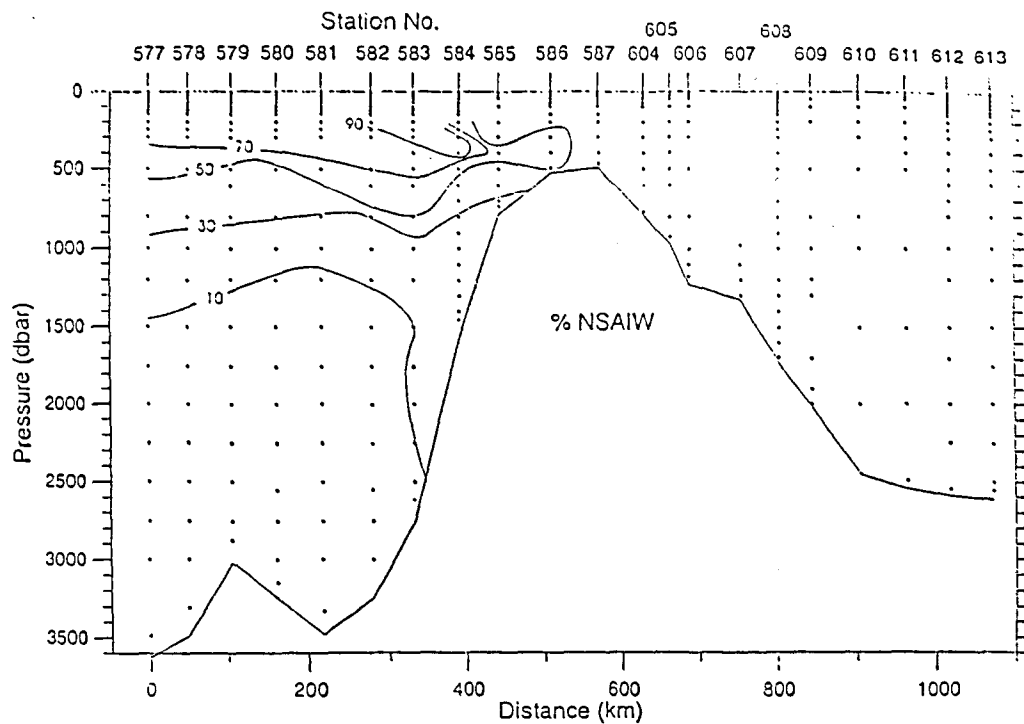Sea (station 650). The same parameters as in Figure 3.
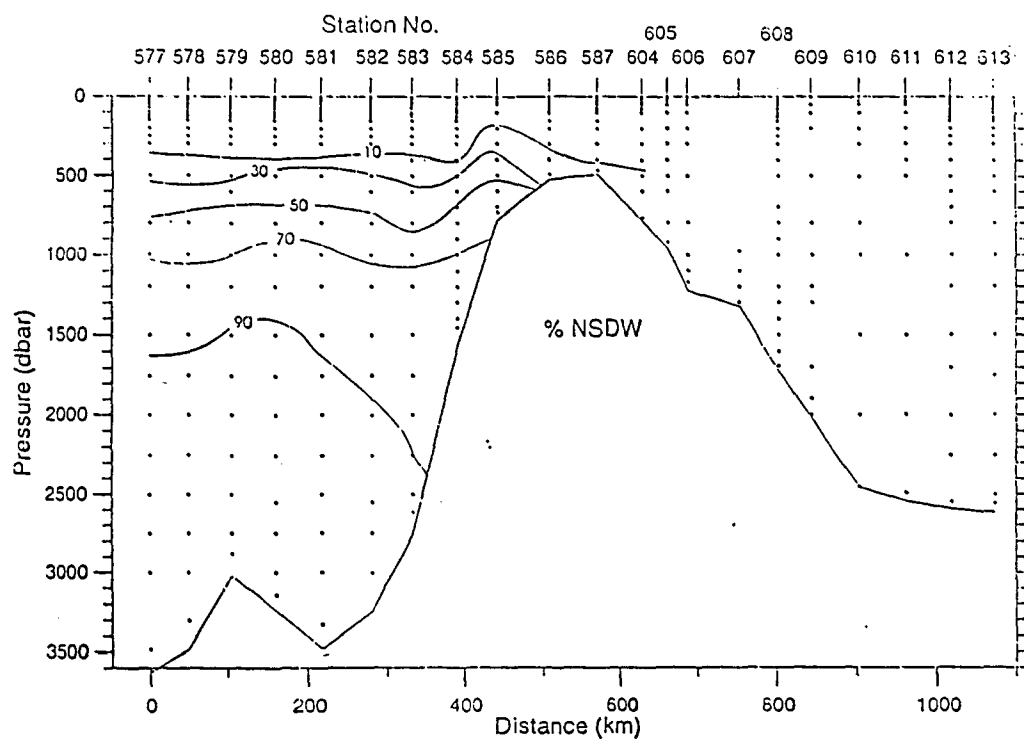
Fig 9.

Results from multivariate analysis of data in Section I from the Norwegian Sea to the Iceland-Faroe Island ridge. The fractional composition (in %) of NSDW in the upper figure and NSAIW in the lower figure as deduced from PCA/PLS analysis of data. Three sources of water were used, except NSDW and NSAIW also one source close to the surface, NEAW.
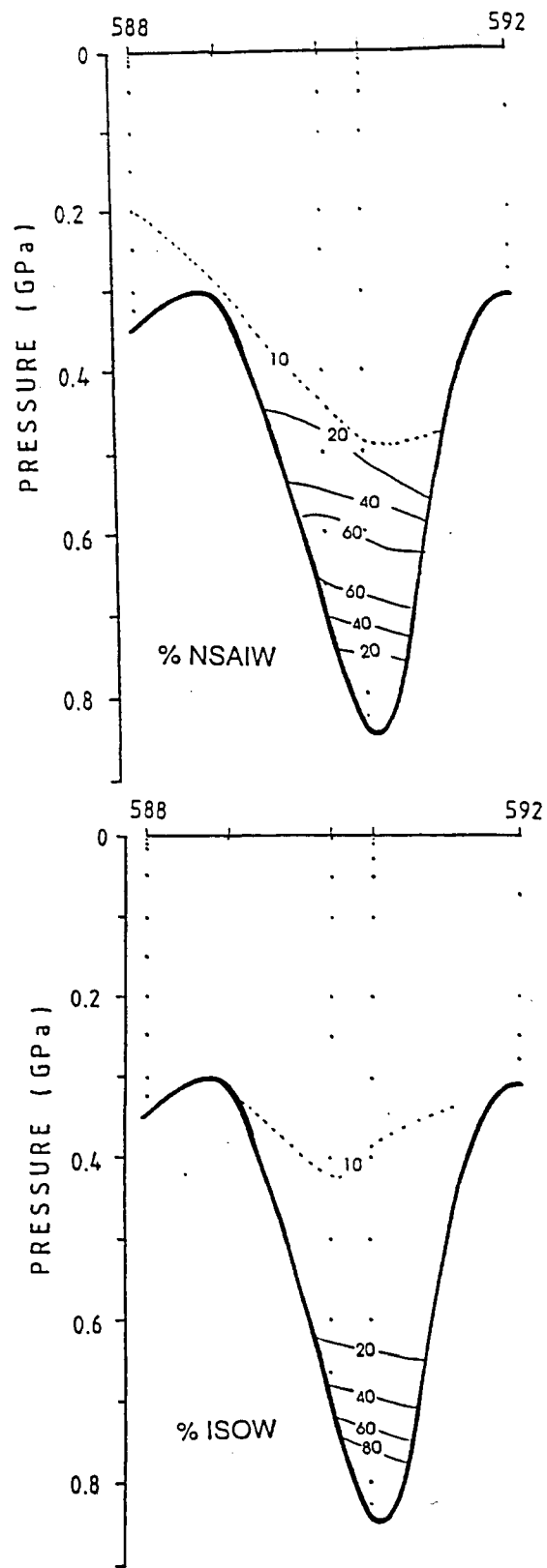
Figure 10.
Multivariate analysis of data from the Faroe Bank Channel, Section II. Four source waters were used for the PCA/PLS treatment, ISOW, NSAIW, NEAW and an additional surface water, which stabilised the model.
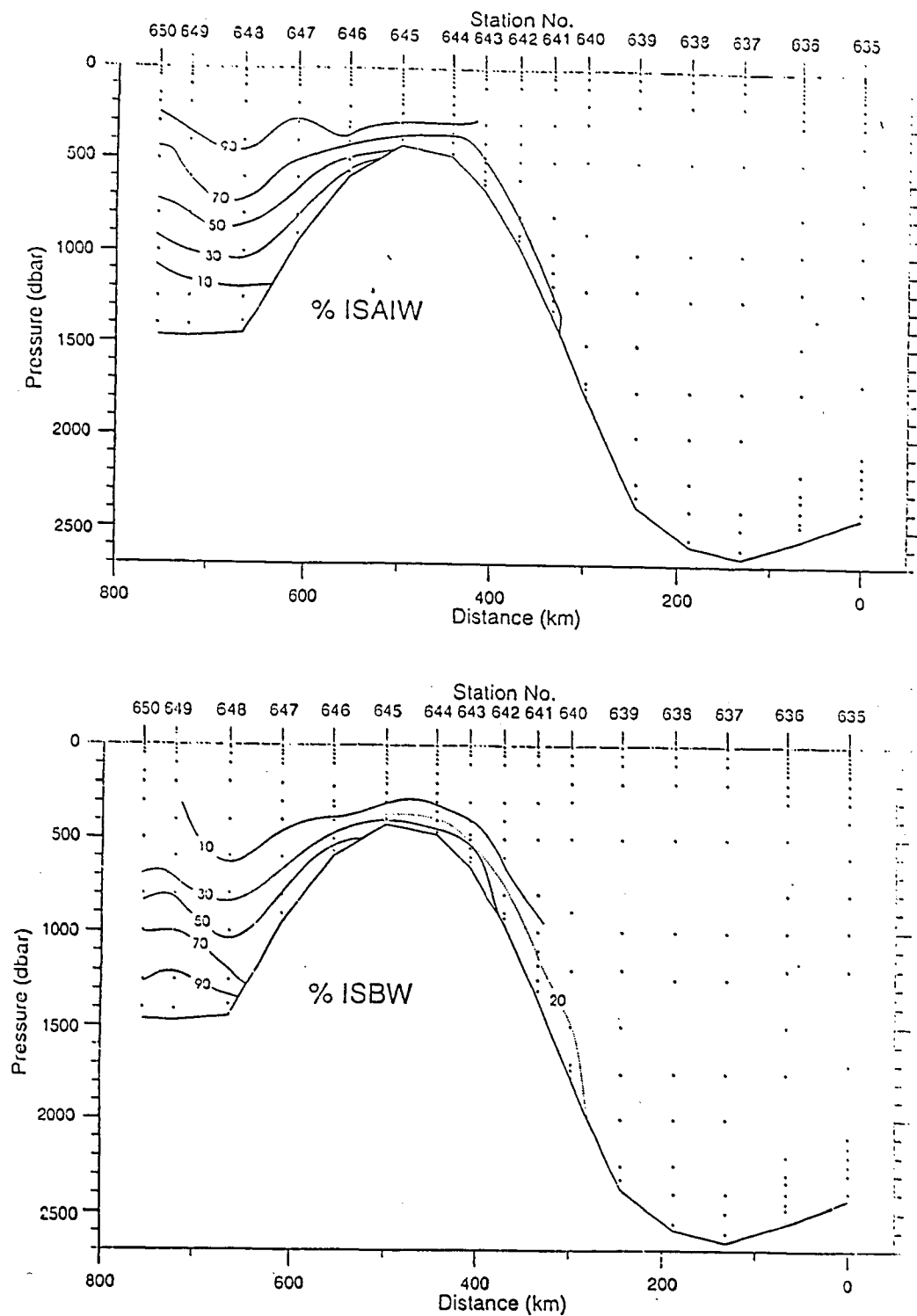
Figure 11.

Multivariate analysis of data from the Denmark Strait and the Iceland Sea, Section VI. The three source waters were ISBW, ISAIW and ISW.