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WATER MASS DISTRIBUTION IN THE ICELAND BASIN CALCULATED WITH AN OPTIMAL PARAMETER ANALYSIS

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Abstract

An optimal multiparameter (water mass) analysis was applied upon data collected during the DUTCH-WARP cruises in 1990 and 1991 containing the tracers salinity, potential temperature, oxygen, silicate and nitrate. The method was tested for the influence of measurement errors and the errors in the characteristics. The individual contributions were calculated with a standard deviation of less than 0.05 and the volume percentages with a standard deviation of less than 2.8%. The contributions of the two years were compared. Intermediate Water occupied a larger volume in 1991 than in 1990. In 1990 the IW contribution changed strongly (from 500 to 1000 dbar) in 9 days. It is suggested that this was caused by Sub Polar Mode water (SPMW) brought to this depth.Multiparameter analysis shows that IW is a biochemically determined water mass instead of Antarctic Intermediate Water or Africa Water. Lower deep water (LDW) was found 100 dbar above the bottom at 60°N 20°W in 1990 but not in 1991. LDW seems to recirculate in the Iceland Basin. High Iceland-Scotland Overflow Water was found at the slope of the Hatton Bank.

1. Introduction

In the oceans tracer concentrations are mainly determined by advection and diffusion. The sinks and sources of the tracers are found at the boundaries (land, bottom and surface) and form distinctive source water types. The mixture of source water types that form a water parcel can be used to find the spread, entrainment and diffusion of the source waters and relate these with transport to give insight into the dynamics of the oceans.

Classic water mass analysis is primarily based on a mixing triangle in θ-S space (Mamayev, 1975). A limitation of the method is that maximally 3 source water types can be used to calculate the compositions. In the Iceland basin at least 4 water types are present (Emery and Meinke, 1986, McCartney, 1992), and only with extra assumptions can the mixing triangle be used. Tomzcak (1981), Thompson and Edwards (1981) introduced a method, also based on linear mixing, which allowed more than 3 source water types. They used more tracers than salinity and temperature. A disadvantage of the method was the negative contributions. Menke (1984) and Mackas *et al.* (1987) introduced a method to move a point outside the mixing triangle (causing the negative contribution) to the nearest mixing line or plane. In this paper this method is used to find the distribution of the different source water types. A stability analysis of the method is performed, to get an impression of the influences of measurement errors and errors in the characteristics on the contributions. The variability in and between two years is investigated at 60°N 20°W.

2. Description of the data

Measurements

The data used in this paper were collected by the RV Tyro in the Iceland Basin, during the DUTCH WARP programme (Deep and Upper Transport, Circulation and Hydrography WOCE Atlantic Research Programme) carried out in 1990 and 1991. The CTD measurements were calibrated, averaged and interpolated to give results at 1 dbar pressure intervals. This gave a precision of 0.0015 for salinity (PSS 1978) and 1.7 mK for temperature and 3 μMol/kg for the oxygen. In this paper the potential temperature (ITS 1990) is used, for shortness it is called temperature. From the samples taken with the bottles in the rosette sampler, the

nutrients NO_3, PO_4 and SiO_4 were measured giving a precision of 0.1, 0.06, 0.08 μ Mol/kg, respectively. The PO_4 concentration was not used because it is highly linear correlated with NO_3 (Redfield *et al.*, 1963).
For the calculations from the 1990 data no oxygen values were used because the oxygen sensor failed during that cruise and very few oxygen determinations from the samples were obtained. The bottle data were interpolated to give samples every 25 meters. Only data east of 30°W and below 500 dbar were used. For a more detailed description of the data see Van Aken (1992).
Figure 1 shows the topography of the Iceland Basin together with the stations occupied in 1990 and 1991. The sections in 1990 and 1991 are at the same positions, except the AR7 sections. The names are the same for both years. The distance between stations was 15 miles on sections A, B, C, E, F (1990) and A to J (1991) and 30 mile on section D and the AR7 sections. Section D was only measured in 1990. Sections B and E are put together to give section BE. Section BE is oriented East West and section F is oriented North South. In figure 6 stations 46 and 47 are both measured at 60°N 20°W.

3. Optimal parameter analysis

If it is assumed that a water sample i is formed by linear mixing, this means for sample i defined by:

$$x_i = (\, S_i \;\; \theta_i \;\; O_{2i} \;\; SiO_{4i} \;\; NO_{3_i}) \quad i = 1,\ldots,n \tag{1a}$$

with S_i is the salinity, θ_i the temperature, O_{2i} the oxygen, SiO_{4i} the silicate, NO_{3i} the nitrate concentration of sample i and n the number of samples, and using the following definitions

$$b_i = (b_{i,1}, b_{i,2}, \ldots, b_{i,p}) \tag{1b}$$

$$k_j = (S_{swt_j} \;\; \theta_{swt_j} \;\; O_{2swt_j} \;\; SiO_{4swt_j} \;\; NO_{3swt_j}) \quad j = 1,\ldots,p \tag{1c}$$

$$K = (k_1 \;\; k_2 \ldots k_p)' \tag{1d}$$

that

$$x_i = b_i K \quad (2)$$

b_i is the composition of sample i with $b_{i,j}$ the contribution of source water type j to sample i. k_j the characteristic tracer vector of source water type j, S_{swt_j} the characteristic salinity of source water type j, etc. and K the characteristic matrix. p is the total number of source water types. The implementation of mass conservation is easily done, by adding an extra column with value 1 to the characteristic vector k_j and to the data vector x_j. This is a multiparameter extension of the classic mixing triangle (Tomzcak, (1981)).
Figure 2 shows various property-property plots, and the characteristic values of the source water types are indicated. The few oxygen values of 1990 are used to obtain the characteristic values. The characteristic values of Intermediate Water (IW) are determined on the base of the nitrate maximum instead of on the oxygen minimum. In this paper 5 source water types are used (p=5). If oxygen is used then 5 tracers are used (m=5), otherwise 4 tracers are used (m=4). The following source water types are present: Sub Polar Mode Water (SPMW), Intermediate Water (IW), Labrador Sea Water (LSW), Lower Deep Water (LDW) and Iceland Scotland Overflow Water (ISOW). For more details see section 5.

If $m+1 < p$, there are more unknowns than equations (m+1 because of mass conservation), and the system is underdetermined. When $m+1 > p$ the system is overdetermined. In this case the method minimizes the square residual. The residual for sample i is defined by:

$$R_i = x_i - b_i K \quad (3)$$

and gives the difference between the calculated and the measured tracer value. The residual will be zero when there is exact linear mixing, no measurement errors occur, the tracers behave conservatively and the characteristics of the source water types are correct.
The different tracers used to calculate the contributions have different ranges; therefore the data are standardized. In this paper a standardization is used that gives every tracer range 1.

$$x^{*}_{i,l} = \frac{[x_{i,l} - min_i(x_{i,l})]}{[max_i(x_{i,l}) - min_i(x_{i,l})]} \quad l = 1, \ldots, m \quad (4a)$$

$$k^{*}_{j,l} = \frac{[k_{j,l} - min_i(x_{i,l})]}{[max_i(x_{i,l}) - min_i(x_{i,l})]} \quad l = 1,\ldots,m \tag{4b}$$

$$K^{*} = (\ k_1^{*}\ \ k_2^{*}\ \ldots k_p^{*})' \tag{4c}$$

with $x_{i,l}$, $k_{j,l}$ the value of tracer l of sample i or source water type j , $x^{*}_{i,l}$, $k^{*}_{j,l}$ the standardized value of tracer l of sample i or source water type j and $max_i(x_{i,l})$ and $min_i(x_{i,l})$ are respectively the maximum and minimum value of tracer l over all the i samples. The contributions are now calculated while minimizing the residuals of the standardized data and characteristics. The calculated distributions can be negative and due to the mass conservation other contributions can become greater than 100 %. This is physically unrealistic and is caused by points outside the mixing triangle. Menke (1984) and Mackas *et. al.* (1987) introduced a method that always calculates positive contributions, and by virtue of the mass conservation also contributions smaller or equal to 1. The method moves a sample outside the mixing triangle to the nearest mixing line or mixing plane, giving a zero contribution instead of a negative contribution, but giving larger residuals than without the moving. For a detailed description of the procedure see Mackas *et al.* (1987) and Maamaatuaiahutapu *et al.* (1992).
If errors in the measurement of salinity are less possible than for example in temperature, then, by the calculation of the residuals, salinity must gain a higher weight, resulting in a lower difference between measured and calculated salinity. This is achieved if equation 2 is solved while minimizing the square residual while the residual is defined by:

$$R_i = [x^{*}_i - b_i K^{*}]\ W \tag{5}$$

with W a diagonal matrix with $W_{i,i}$ the weight for tracer i. This means that, with the highest weight on salinity, a point outside the mixing triangle is moved more or less isohaline to the nearest mixing line or plane. In figure 3 this is demonstrated with 3 source water types, and the tracers temperature and salinity. Point 1 is calculated with a 10 times higher weight on salinity than on temperature, point 2 the other way round. Mass conservation always gets the same weight as the highest weight. Point 2 is moved along isotherms to the mixing line in contrast of point 1 which is moved along isohalines. The weighting influences the calculated contributions; point 1 contains 48% SPMW and 52% ISOW while point 2 contains 30% SPMW and 70% ISOW, but both are the results of 1 data point. A weighting matrix can be defined as:

$$W_{l,q} = \frac{\sigma_l}{\Delta swt_l} \delta_{l,q} \qquad (6)$$

with σ_l the standard deviation of tracer l and Δswt_l the highest uncertainty of tracer l in the determination of the characteristic values of the source water types (in standardized units) and $\delta_{l,q}$ the kronecker delta (1 if l=q else 0) This weighting matrix gives a higher weight to tracers with a high standard deviation (= high ability to discriminate between water types) and a low uncertainty in the characteristic tracer values. This weighting is based on Tomzcak and Large (1989). This gives for my data set 23.6, 4.2, 1.0, 17.0, and 10.0 for salinity and the mass conservation, temperature, oxygen, silicate and nitrate respectively. There are other definitions possible; instead of the uncertainty in the characteristics the measurement precision, or the expected non conservative behaviour of a tracer can be used. Mackas *et al.* (1987) used a non diagonal matrix W to take into account the covariance in the tracer characteristics.

4. Stability of the method

The contributions calculated by this method will be influenced by measurement errors and errors in the determination of the characteristic tracer values of the different source water types. The influences were investigated with stability tests. For this stability test only section A of 1991 was used.

Influence of errors in the characteristic values

The largest uncertainties for tracer characteristics were 0.01 for salinity, 1 °C for temperature, 5 µmol/kg for oxygen, 1 µmol/kg for silicate and nitrate both. To test the influence each characteristic tracer value was changed with the uncertainty of that tracer. The characteristic salinity of SPMW is normally 34.640 (table 1), now the contributions were calculated once with a value of 34.630 and once with 34.650. The other tracer values remain unaltered. For each tracer and each source water type this was done giving 50 sets of contributions. The difference between the normal contributions and the "disturbed" contributions were calculated and summarized in table 2. The overall influence can be calculated with the volume percentages occupied by the 5 water masses. These results are listed in test A in table 3. The difference between the normal percentages and the mean percentages indicates that decreasing a value does not have the opposite effect of increasing the value. The highest differences are caused when the characteristics of LSW are changed. The used uncertainties are uncertainties in the determination of the SPMW characteristics, and these are much larger than the uncertainties in the determination of the characteristics of for example LSW. Therefore these results can be considered as "worst case" results. If for every source water type its own uncertainty in its tracer characteristic was used, the influence is much less (test B). When these uncertainties were used to disturb the characteristics all together randomly (with a random number for every tracer and every source water type, with a standard deviation equal to the tracer uncertainty of that specific tracer of that source water type) the influence increased (test C). Summarizing the table shows that the individual contributions are estimated with a standard deviation of 0.01, 0.03, 0.05, 0.004 and 0.04 for respectively SPMW, IW, LSW, LDW and ISOW and the volume percentages are calculated with a standard deviation of 0.4 %, 2.3 %, 2.8 %, 0.3 %, and 2.7 %.

Influence of measurement errors

Besides the uncertainty in the characteristic values, also the measurement errors influence the calculated contributions. The influence of the measurement errors was tested by disturbing the normal data with random noise of a standard deviation equal to measurement precision (see section 2, for the nutrients 0.1 μ mol/kg was used) and zero mean. All tracers were disturbed at the same time, but the disturbance for each tracer in a sample was uncorrelated. This was done 25 times. Table 4 summarizes the differences between the contributions calculated with the disturbed and undisturbed data. The standard deviations of the differences indicate that the overall influence is small (<0.03). The volume calculations were only slightly influenced (table 5).

Influence of oxygen

For the calculations of the 1990 data no oxygen was used. To find the influence of oxygen on the calculations, the contributions of 1991 were calculated with and without oxygen. The volume percentages of the different sections are listed in table 6. The maximal difference between the calculated volume percentages is 1.4%. The small influence of oxygen is due to its low weight (1 vs. 23.6). Differences between the years 1990 and 1991 larger than 1.4% are significant and not due to the absence of oxygen in the calculations.

5. Water masses in the Iceland Basin

Tracer distributions

Figures 4a, 5a, 6a, 7a show the spatial distribution of the different tracers at section F and BE. Figures 4a and 6a show the data of 1990 on section F and BE. No Oxygen is shown here. Figures 5a and 7a show the data on the sections F and BE in 1991.

The salinity distribution (I in the figures 4a, 5a, 6a and 7a) shows a salinity minimum with values below 34.92 and oxygen values above 275 µmol/kg indicating Labrador Sea Water (LSW) (Talley and McCartney, 1982). Sub Polar Mode Water (SPMW), formed by winter time convection in the North Atlantic Ocean (McCartney and Talley, 1982) can be found above 750 meters. Between this layer and LSW there was an oxygen minimum (subfigure III in the figures) and an NO_3 maximum (subfigure V). These extremes were not on the same depths. To obtain a characteristic values, the nitrate maximum is used. The water mass responsible for these extreme values is tentatively called Intermediate Water (IW) (Van Aken en De Boer, 1993). Its origin is not quite clear. Tsuchiya *et al.* (1992) suggest that it is Antarctic Intermediate Water (AAIW), although they did not find a continuous core so far north. Kawase and Sarmiento (1986) found a layer with corresponding characteristics which they call Africa Water (AW). McCartney (1992) suggests that the oxygen minimum is caused by an oxygen flux to the sediments of the Rockall Hatton Plateau, but in my data the oxygen minimum at the Rockall Hatton Plateau appears to be 200 dbar above the bottom (AR7 section 1991, not shown in this paper). IW can also be determined biochemically. Near the bottom below the layer of LSW, two cold water masses were found. In figure 2d Lower Deep Water (LDW) is apparent with its high silicate concentrations

(Bennekom, 1985, De Boer *et al.*, 1991). This water mass is influenced by Antarctic Bottom water which give it its high silicate concentrations. LDW is transported by the Deep Northern Boundary Current (DNBC) westward looping through the Rockall Through, west across the south flank of the Rockall Plateau, north along the Hatton Bank into the Iceland Basin, where it turned westward with the ISOW along the Reykjanes Ridge. In the subfigures II and III Iceland Scotland Overflow Water (ISOW) with its low temperature and high oxygen concentration (Lee and Ellet, 1965) is apparent. This water flows to the south-west, along the Icelandic slope and the Reykjanes Ridge.

Water mass distributions

With the characteristics from table 1 the contributions of the source water types were calculated. Figures 4b-7b show the distributions of the contributions. Subfigure I shows SPMW. On the section BE a lower concentration of SPMW was found in 1991 than in the 1990 and than on other sections. SPMW is found near the surface. On sections BE and F a relative SPMW maximum was found at 1800 dbar. It was brought to this depth by entrainment in ISOW at the Iceland Faroe Ridge (Van Aken and De Boer, 1993). In subfigure II the IW distribution is shown and it appears that IW does not reach the Icelandic shelf at section F. Between 1990 and 1991 great differences occurred in the IW distributions. In 1991 it reached almost to the bottom at the sections A, B, E, F and AR7, this was not the case in 1990 (except at section AR7).

High LSW contributions are found at 500 dbar, due to the high temperature and salinity characteristics of the SPMW. The minimum of the LSW and the maximum of the IW contribution at 1000 dbar (also shown in figure 8c) suggests that IW divides the water mass formed by mixing of SPMW and LSW into two parts. Looking to the characteristics of IW and compare them with the characteristics of AAIW as found by Tsuchiya et al. (1992) and use them in a mixing triangle containing LSW, AAIW and SPMW, it is not possible to obtain the characteristics of IW without negative contributions. This means that with the available water masses to modify AAIW it is not possible to obtain IW, and therefore it is not likely that IW is diluted AAIW. The same reasoning holds for Africa Water (AW). This water is suggested to be the source of IW by Kawase and Sarmiento (1986). With SPMW, LSW, AW and MOW (Mediterranean Outflow water) it is again not possible to obtain the characteristics of IW without negative contributions (personal communication M.H.C. Stoll). This leads to the conclusion that IW is a biochemical water mass. The highest contributions of LSW are found at 1700 dbar.

Subfigure IV presents the LDW distribution. There was a clear difference between 1990 and 1991 and between the sections. In 1991 on section F the LDW distribution showed 2 cores. This supports the recirculation pattern of LDW as suggested by McCartney (1992). In 1991 the LDW had equal in- and outflow surfaces (nothing is said about transports), while in 1990 the inflow seems to be much more confined to the Hatton Bank while the outflow is much broader. In the latter case the density suggests that the inflow velocity is much higher than the outflow velocity. At section BE only 1 core was found 1990.

The ISOW distribution is shown in subfigure V with the highest values near the bottom. High ISOW contributions at 1000 dbar depth are found on the Icelandic shelf. ISOW is found over the whole section, also in the south (F) and east (BE). With the DNBC flowing along the Hatton Bank to the north, this means that part of the ISOW is recirculated into the Iceland Basin (Harvey and Theodorou, 1986). On the BE section ISOW was found on the whole section. Although the highest values were found near the Reykjanes Ridge, values over 50% were found at the Hatton Bank.

6. Variability in water mass compositions in the Iceland Basin

Variability at 60°N 20°W

In 1990 and 1991 60°N 20°W was visited 5 times. In figure 8 the contributions from the different source water types are plotted against the depth. The +++ and xxx lines are the results from 1991. The contribution of SPMW and ISOW appears to be similar in the two years. In IW, LSW and LDW contributions there were larger differences within a year (see ooo,□□□, and ◊◊◊ all measured in 1990) and between the years. The IW maximum dropped, i.e. the oxygen minimum and nitrate maximum became less extreme. This can be seen in figure 6b V. Stations 46 and 47 are both on 60° N 20° W, only 9 days apart (47 was done first!). Station 46 corresponds with the ◊◊◊ in figure 8 and 47 corresponds with ooo. The squares were done 4 days after station 47. The maximum nitrate concentration was lower at station 46 than at 47, while the temperature and salinity were higher at station 46. In figure 8a it appears that the SPMW contribution is higher at station 46. This suggests that SPMW is brought to this depth.

The LSW contribution also changed. In 1990 the maximum contribution of LSW was higher than in 1991 (10% more), and shallower (1700 dbar vs. 1800 dbar). The difference was caused by IW: in 1991 the nitrate maximum was larger and thicker than in 1990, and this caused LSW contribution to be smaller in 1991 than in 1990. This means that biochemical processes (e.g. remineralisation) were higher in 1991. In figure d the contribution of LDW is plotted. In 1991 (+++ and xxx) there was a minimum at 2700 dbar while in 1990 there was a maximum. This means that LDW is sometimes present at this position and sometimes not. This could also be seen in silica plots (De Boer and Van Aken, 1991) of that position. LDW was not found near the bottom, but about 100 dbar above the bottom. Below the core of LDW, ISOW is found.

Variability between the sections and the years

Table 6 summarizes the volume percentages of the water masses of the different sections. It is not possible to compare the section because the depth influences the percentages. If the largest depth of a section is only 750 dbar, no LDW and ISOW are available, and therefore the other percentages increase. On all sections LSW was the most dominant water mass and LDW the least. The percentage SPMW did not change much (less then ±3%). The IW volume increased by 1.2%-6.7% except on section C, where it vanished. On section C ISOW increased (found at the surface), due to significantly lower nutrient concentration in 1991 than in 1990. This caused the nitrate maximum to be lower and the IW volume to be smaller. The decrease in nutrients on section C is in contrast with the measurements at 60°N 20°W. The LSW volume percentages changes about ±7% at sections E and F.

The LDW volume stayed the same in both years, although the distribution differed. Although a large amount of LDW was found only at section AR7 in 1990, LDW can be found at section H and I, so LDW reached far into the Iceland Basin. From the AR7 section to these sections LDW is much diluted. The ISOW volume percentage decreased at the south-west part of the basin, and increased in the north-east part.

7. Conclusions

The optimal parameter analysis is a useful tool for water mass analysis. According to the stability tests the results are not much influenced by measurement errors or errors in the characteristics. The individual contributions are estimated with a standard deviation of less than 0.05 and the volume percentages are calculated with a standard deviation of less than 2.8%. The effect of not using oxygen is very small due to the low weight of oxygen gained from the weighting matrix. A disadvantage of the method is the dependency of the results on the weighting matrix. The weighting can change the contributions significantly when only salinity and temperature are used. If other tracers are used this influence becomes less.

IW was much stronger in 1991 than in 1990, while LSW was weaker. LDW was not found near the bottom but 100 dbar above (60°N 20°W). From the multiparameter analysis it appeared that IW is a biochemically obtained water mass. In 1990 a maximum of LDW was found, in 1991 it was absent. LDW reaches far into the Iceland Basin. On the F section two cores were present suggesting recirculation of LDW. High contributions of ISOW were found at the slope of the Hatton Bank.

Perhaps it is possible to relate the residuals of the samples at the surface to surface cooling or precipitation and the residuals near the bottom to fluxes from the bottom. This paper does not consider residuals. Further research is needed to address the question. Linear mixing is assumed in this method. There is no specific model behind this linear mixing; nothing is said about processes such as advection, diffusion etc.. Therefore care must be taken when physical processes are deduced from the contributions calculated in this way.

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Table 1. **Characteristic values of the source water types**

Source water type	Salinity	Pot. Temp. (^{o}C)	Oxygen μmol/kg	SiO4 μmol/kg	NO3 μmol/kg
SPMW	35.640	12.0	270	3.6	12.0
IW	34.976	4.8	246	11.2	20.1
LSW	34.887	3.4	280	10.6	17.2
LDW	34.905	2.1	239	45.5	22.2
ISOW	34.985	2.0	280	10.0	15.2

Table 2. **Difference between contributions calculated with changed and unchanged characteristics.**

test	Water mass	max(|ΔB|)	mean(ΔB)	std(ΔB)
A	SPMW	0.06	-0.001	0.007
	IW	0.29	0.002	0.033
	LSW	0.40	-0.006	0.047
	LDW	0.03	0.000	0.004
	ISOW	0.34	0.004	0.040
B	SPMW	0.02	0	0.002
	IW	0.04	0	0.005
	LSW	0.11	0	0.010
-	LDW	0	0	0.001
	ISOW	0.09	0	0.008
C	SPMW	0.04	-0.004	0.007
	IW	0.11	0.011	0.025
	LSW	0.23	-0.021	0.049
	LDW	0.09	0	0.002
	ISOW	0.25	0.014	0.039

ΔB means the difference between the contributions calculated with changed and unchanged characteristics. $B_{i,j}$ is between 0 and 1.
The results obtained in test A are calculated with the maximal uncertainty for a tracer, and each tracer of each source water type is changed separately. The results of test B are obtained with the uncertainties of each tracer belonging to the source water type (separately), and the results of test C are obtained while using the uncertainties of B but every tracer is changed simultaneously. See text for more details.

Table 3. **Volume percentages calculated from the contributions which are calculated with the changed characteristics.**

test	water mass	unchanged	min	max	mean	std
		%	%	%	%	%
A	SPMW	11.4	10.0	12.5	11.4	0.4
	IW	14.0	5.9	25.0	14.4	2.3
	LSW	55.7	45.3	60.3	54.9	2.8
	LDW	1.9	1.0	3.3	1.9	0.3
	ISOW	17.0	11.1	27.3	17.3	2.7
B	SPMW	11.4	11.2	11.7	11.5	0.09
	IW	14.0	13.0	15.3	14.2	0.32
	LSW	55.7	53.7	56.9	55.5	0.58
	LDW	1.9	1.7	2.0	1.9	0.03
	ISOW	17.0	15.4	18.7	16.9	0.46
C	SPMW	11.4	10.4	12.0	11.2	0.44
	IW	14.0	11.5	17.2	14.7	1.6
	LSW	55.7	48.7	58.2	54.2	2.7
	LDW	1.9	1.6	2.1	1.8	0.14
	ISOW	17.0	14.4	22.4	18.0	2.1

For the explanations of the tests A, B, and C see table 2.

Table 4. **Difference between contributions calculated with disturbed and undisturbed data.**

Water mass	max(|ΔB|)	mean(ΔB)	std(ΔB)
SPMW	0.20	-0.0003	0.0039
IW	0.13	-0.0011	0.0253
LSW	0.16	-0.0019	0.0284
LDW	0.01	0.0000	0.0028
ISOW	0.17	0.0011	0.0187

ΔB means the difference between the contributions calculated with disturbed and undisturbed data. $B_{i,j}$ is between 0 and 1.

Table 5. **Volume percentages calculated from the contributions which are calculated with the disturbed data sets.**

water mass	undisturbed %	min %	max %	mean %	std %
SPMW	11.4	11.5	11.5	11.5	0.02
IW	14.0	14.0	14.5	14.3	0.10
LSW	55.7	55.1	55.6	55.3	0.10
LDW	1.9	1.8	1.9	1.9	0.01
ISOW	17.0	16.9	17.1	17.0	0.01

Table 6. **Volume percentages calculated with (1991) and without oxygen (1990, 1991).**

	1990 Water mass					1991 (incl. O_2) Water mass					1991 (excl. O_2) Water mass				
section	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
A	10.7	12.8	54.9	2.6	19.1	11.4	14.0	55.7	1.9	17.0	11.5	13.4	56.5	1.9	17.0
B	8.7	9.1	59.3	3.3	19.6	7.2	13.9	56.7	3.5	18.6	7.3	13.3	57.5	3.5	18.4
C	25.0	8.1	65.7	1.1	0.1	27.8	0.6	67.6	0.0	3.9	27.8	0.5	67.8	0.0	3.9
D	11.2	11.0	57.4	1.9	18.6										
E	11.0	13.0	60.0	3.6	12.4	9.3	19.7	53.9	3.9	13.2	9.4	18.9	54.7	3.9	13.0
F*	11.1	13.3	59.9	2.8	13.0	10.8	19.4	52.6	2.2	15.0	10.9	18.8	53.4	2.3	14.7
G						18.4	14.6	49.7	0.7	16.5	18.5	14.2	50.3	1.3	14.9
H						16.0	17.9	49.6	1.3	15.3	16.1	17.2	50.5	1.3	14.9
I						24.9	19.3	39.9	1.3	14.6	25.0	18.4	41.3	1.3	14.0
J						37.0	15.3	43.4	0.8	3.5	37.1	14.4	44.5	0.8	3.2
AR7**	5.7	11.6	48.0	17.5	17.2	12.1	20.4	45.5	5.7	16.4	12.2	19.5	46.8	5.6	15.9

* Section F in 1990 was 1 station (15 mile) less to the north

** AR7 section had different positions in 1990 and 1991.

Water mass 1 = SPMW
2 = IW
3 = LSW
4 = LDW
5 = ISOW

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Figure captions

Figure 1

A subset of the hydrographic stations occupied during the DUTCH-WARP cruises in 1990 and 1991. The sections in 1990 and 1991 had the same names. Sections A, B, C, E and F were done in both years; section D was only done in 1990 (station distance 30 nautical miles), and sections G, H, I and J were only done in 1991. For all these section the station distance was 15 nmiles. The AR7 sections were different in 1990 an 1991 (station distance was 30 nmiles). The western boundary of the Iceland Basin is formed by the Reykjanes Ridge, while the eastern boundary is formed by the Rockall-Hatton Plateau and the Iceland-Faeroe Ridge.

Figure 2 (positioned after figure 3)

Property-property plots. All the samples measured in 1990 and 1991 are plotted. a: salinity-potential temperature; b: salinity-oxygen; c: salinity-silicate; d: nitrate-silicate. The silicate, nitrate and oxygen units are µ mol/kg.

Figure 3 (positioned before figure 2)

A hypothetical mixing triangle, with only SPMW, LSW and ISOW to show the influence of the weighting matrix. P is the original data point, point 1 is the resulting data point when a 10 times higher weight on salinity is used than on temperature, and point 2 is resulting data point if a 10 times higher weight is used on temperature. In table 2 the calculated contributions are listed.

Figure 4

Figure 4a shows the tracer distributions on section F in 1990. Subfigure I shows the salinity distribution, subfigure II the (potential) temperature distribution, subfigure III the oxygen distribution (not in 1990), subfigure IV the silicate distribution, subfigure V the nitrate distribution and subfigure VI the sigma theta distribution. The silicate, nitrate and oxygen units are µmol/kg.

Figure 4b shows the distribution of the contributions of the different source water types. Subfigure I shows the SPMW contribution, subfigure II the IW contribution, subfigure III the LSW contribution, subfigure IV the LDW contribution and subfigure V the ISOW contribution.

Figure 5

As figure 4 with the data on section F in 1991.

Figure 6

As figure 4 with the data on section BE in 1990.

Figure 7

As figure 4 with the data on section BE in 1991.

Figure 8

The contributions of the source water types on 60°N 20°W. Figure a shows the SPMW contribution, figure b the IW contribution, figure c the LSW contribution, figure d the LDW contribution and figure e the ISOW contribution. The +++ and xxx belong to the measurements in 1991. Station 88 in figure 5 and 7 corresponds with the +++. The ooo, ◊◊◊ and □□□ are measured in 1990. The ooo corresponds with station 47 of figure 4 and 6, the ◊◊◊ correspond with station 46 figure 4 and 6. □□□ were measured 4 days after station 47 and 5 days before station 46.

47(90) was measured 7/17/1990; 83(90) was measured 7/21/1990; 46(90) was measured 7/26/1990; 60(91) was measured 4/29/1991 and 88(91) was measured 5/6/1991.

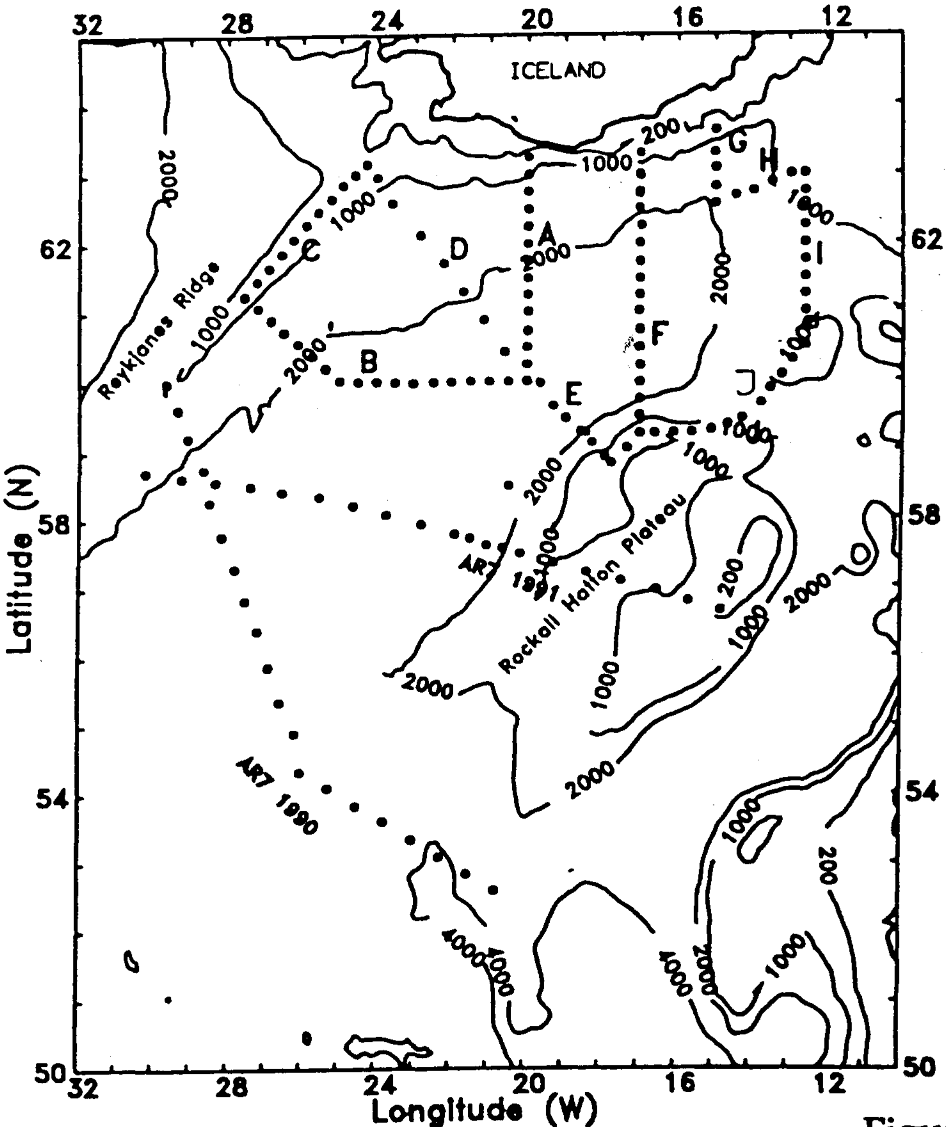


Figure 1

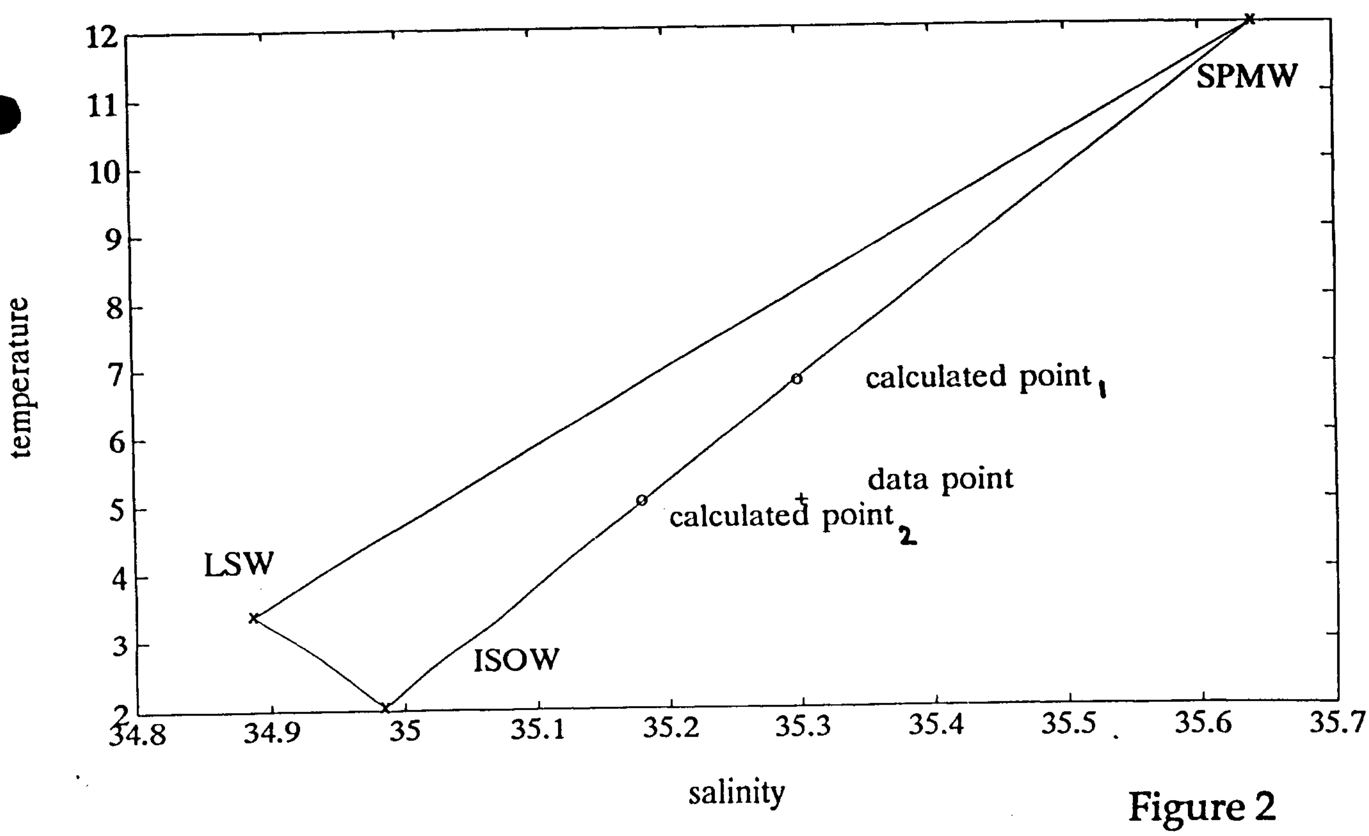


Figure 2

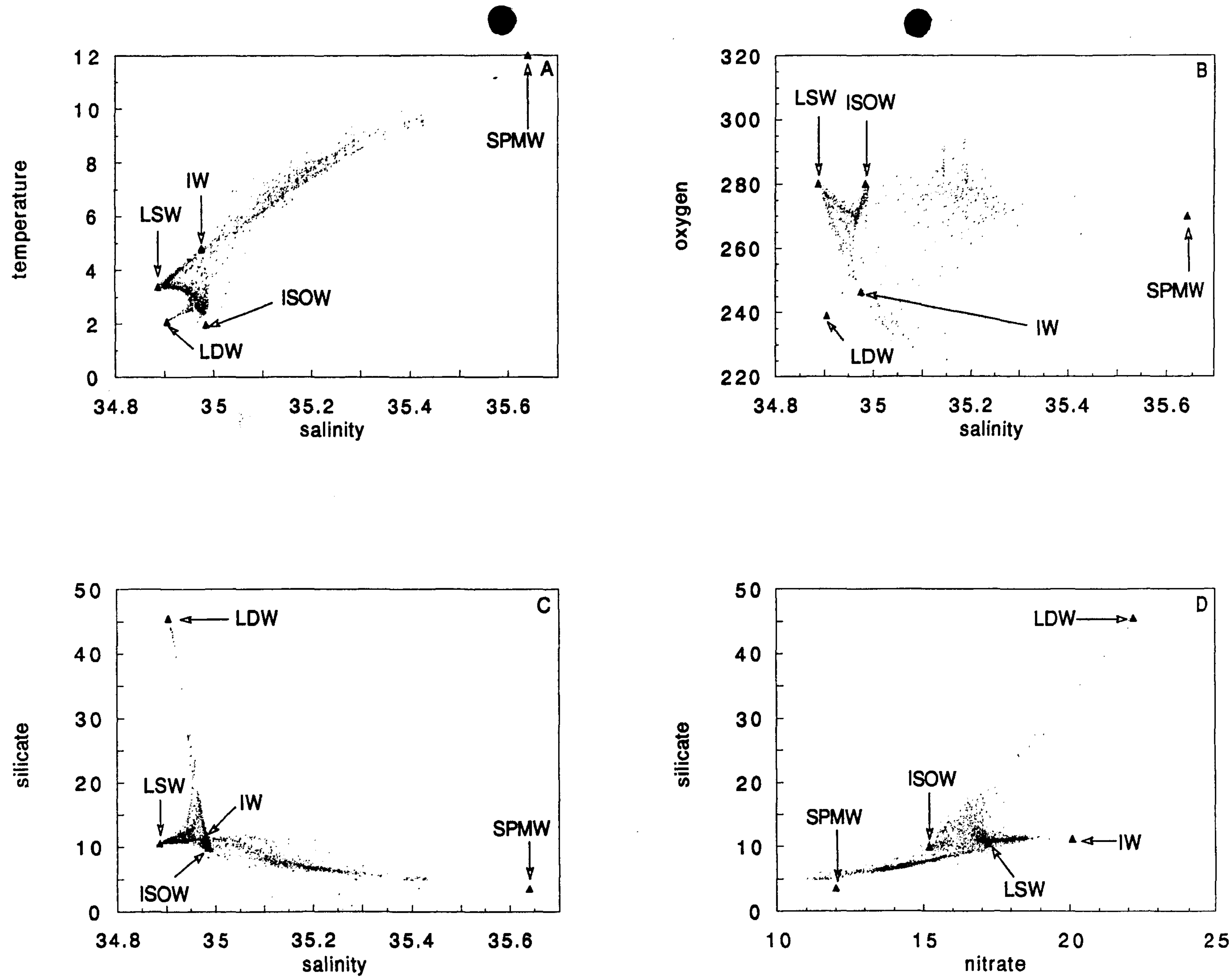

A
temperature
salinity
SPMW
IW
LSW
ISOW
LDW
B
oxygen
salinity
LSW
ISOW
SPMW
IW
LDW
C
silicate
salinity
LDW
LSW
IW
ISOW
SPMW
D
silicate
nitrate
LDW
ISOW
SPMW
IW
LSW

Figure 3

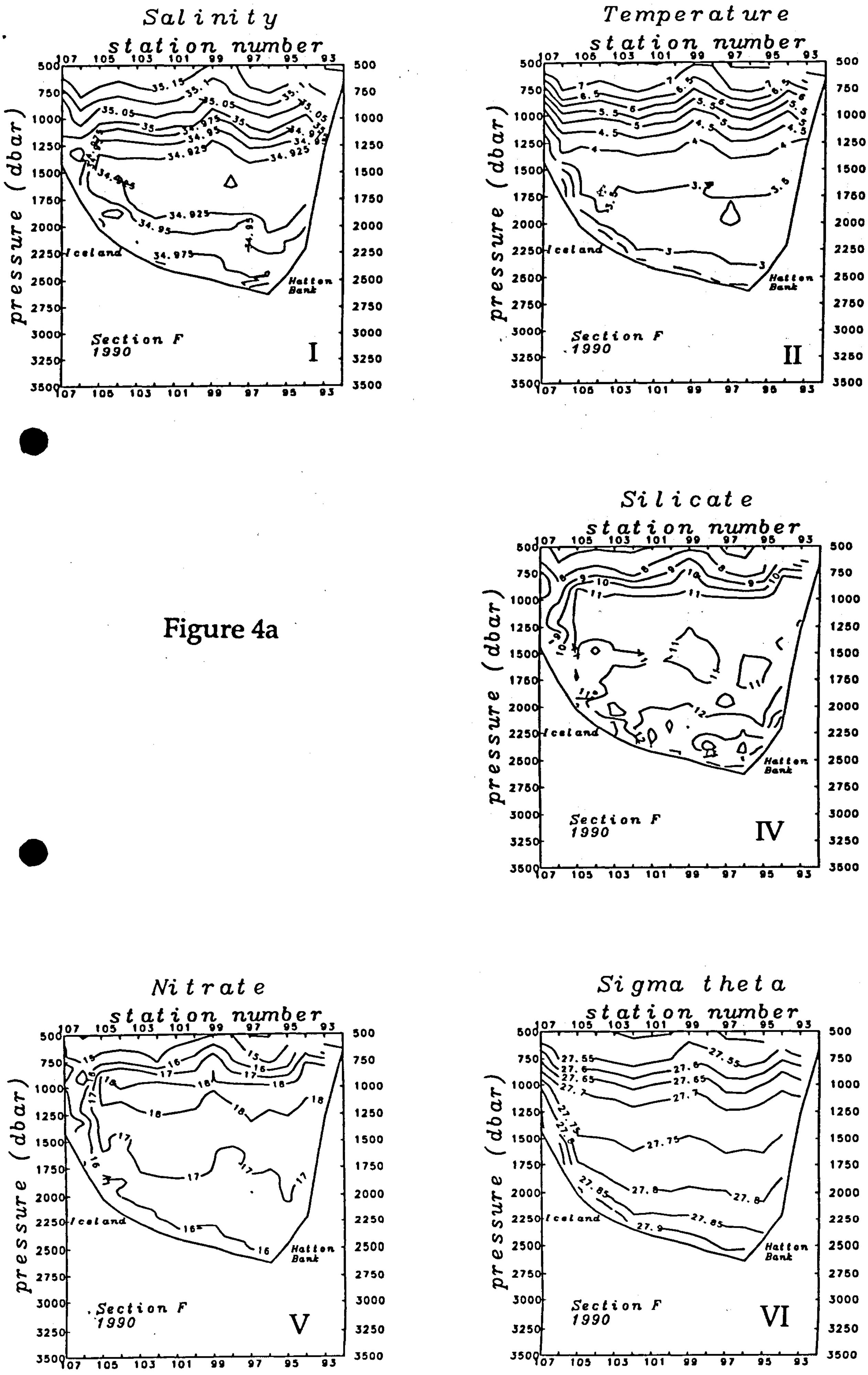
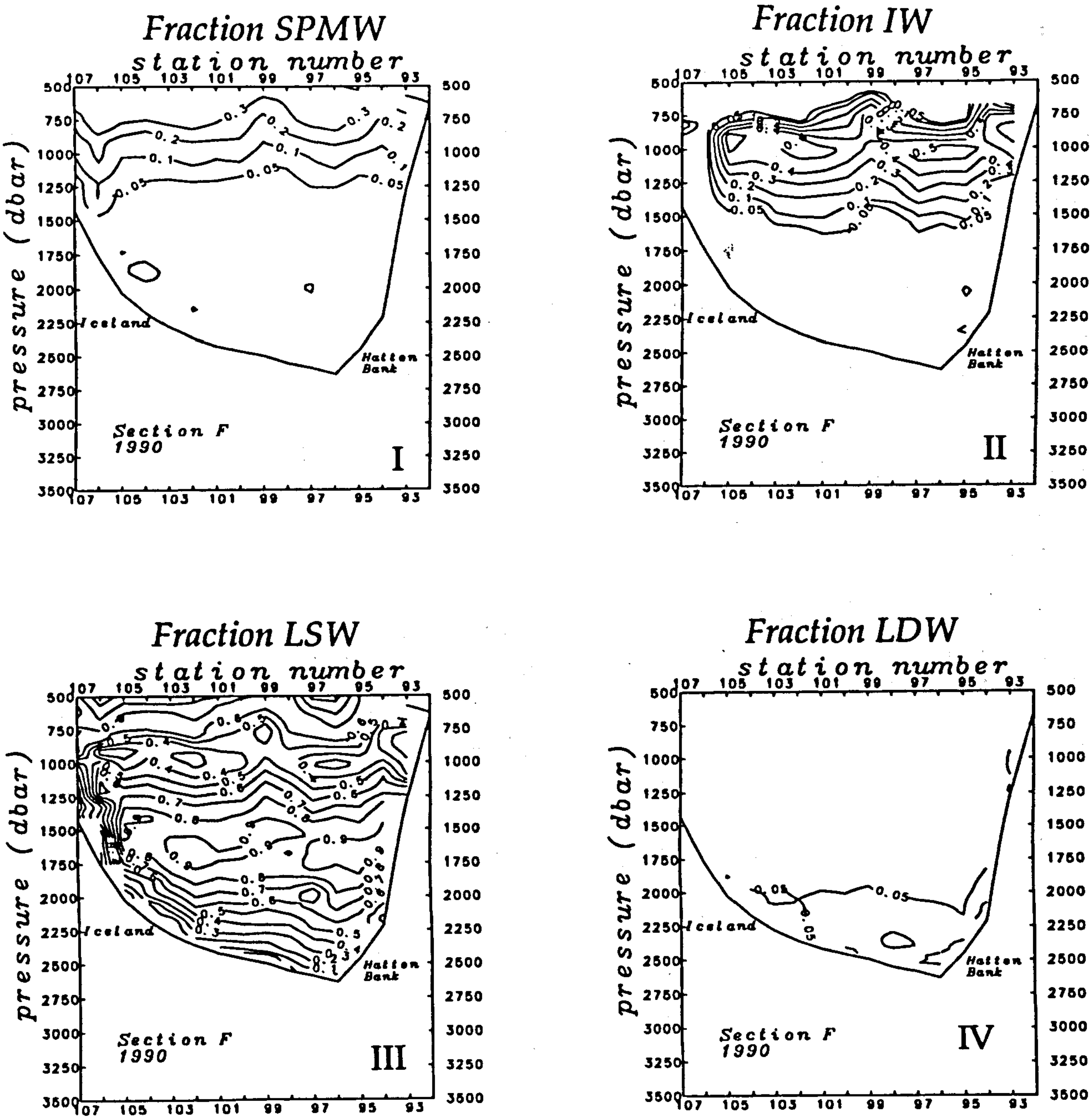
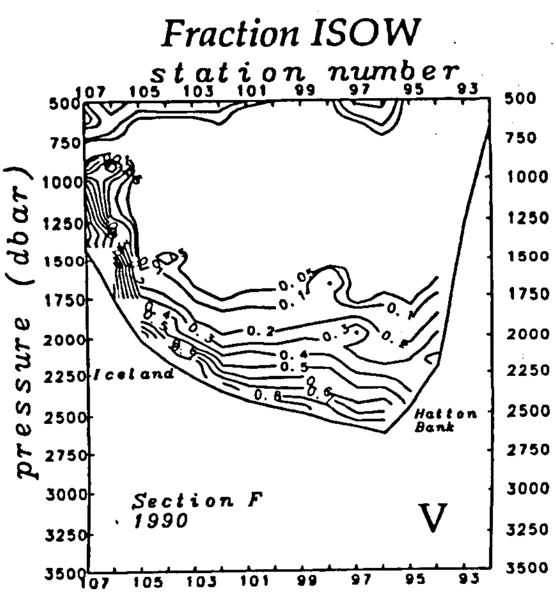

Salinity
Temperature
Silicate
Nitrate
Sigma theta
station number
pressure (dbar)
Iceland
Hatton Bank
Section F 1990
I
II
IV
V
VI

Figure 4a



Fraction SPMW
station number
pressure (dbar)
Iceland
Hatten Bank
Section F
1990
I
Fraction IW
station number
pressure (dbar)
Iceland
Hatten Bank
Section F
1990
II
Fraction LSW
station number
pressure (dbar)
Iceland
Hatten Bank
Section F
1990
III
Fraction LDW
station number
pressure (dbar)
Iceland
Hatten Bank
Section F
1990
IV



Fraction ISOW
station number
pressure (dbar)
Iceland
Hatten Bank
Section F
1990
V

Figure 4b

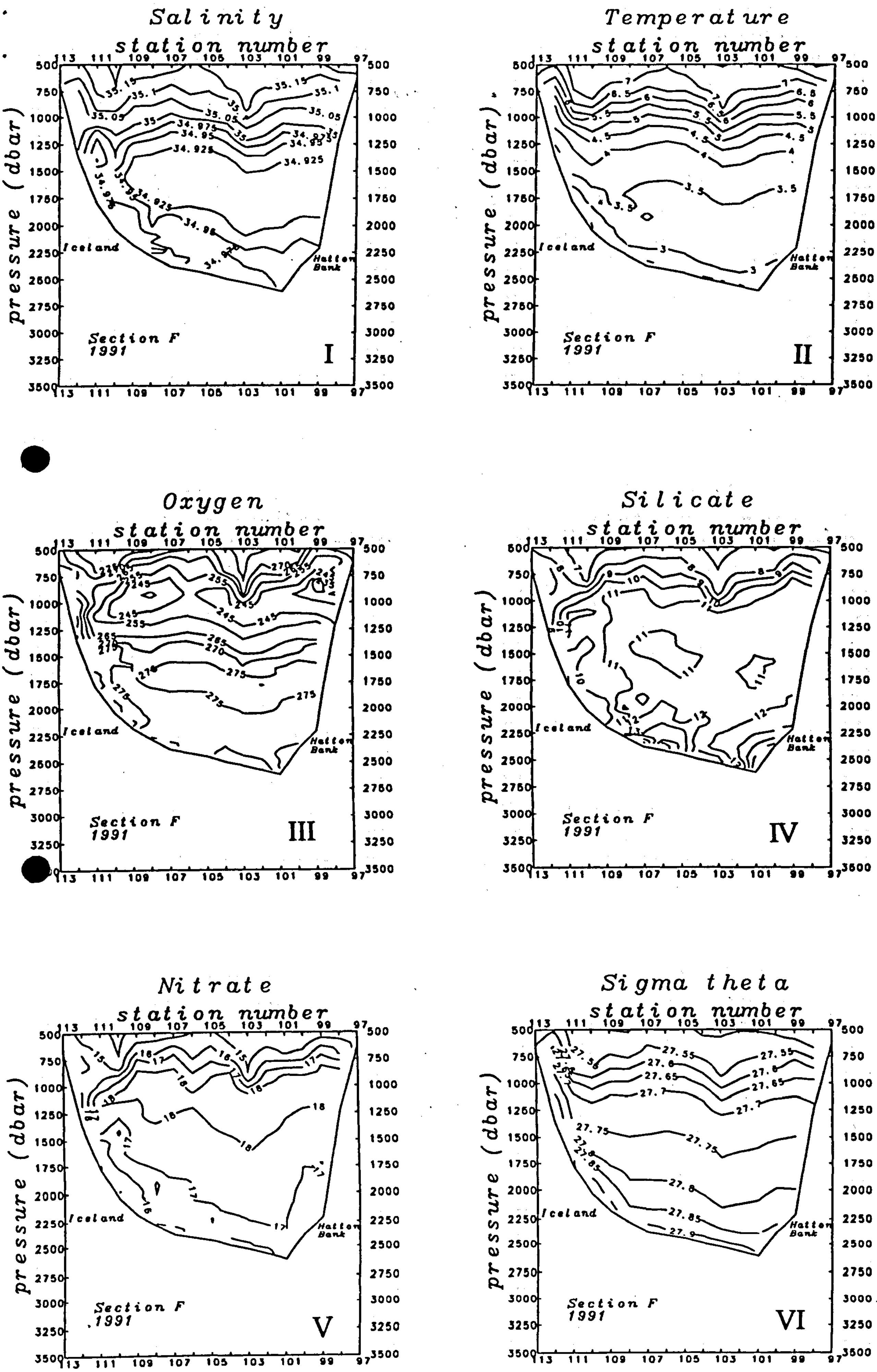
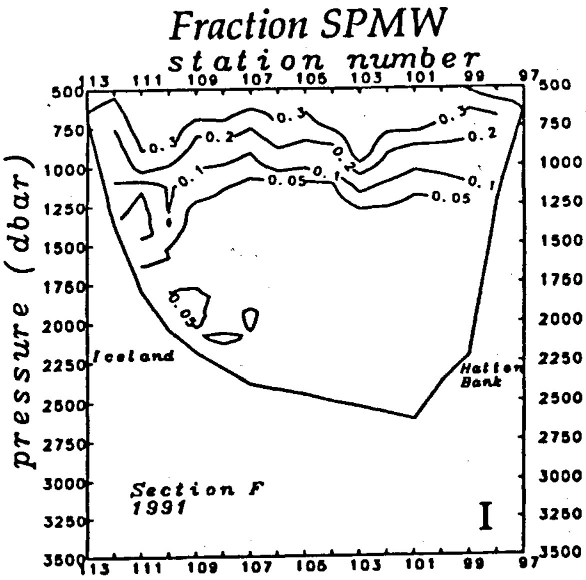
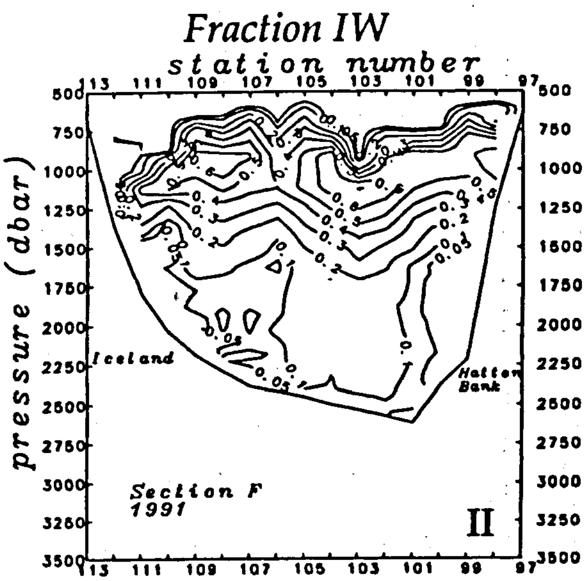
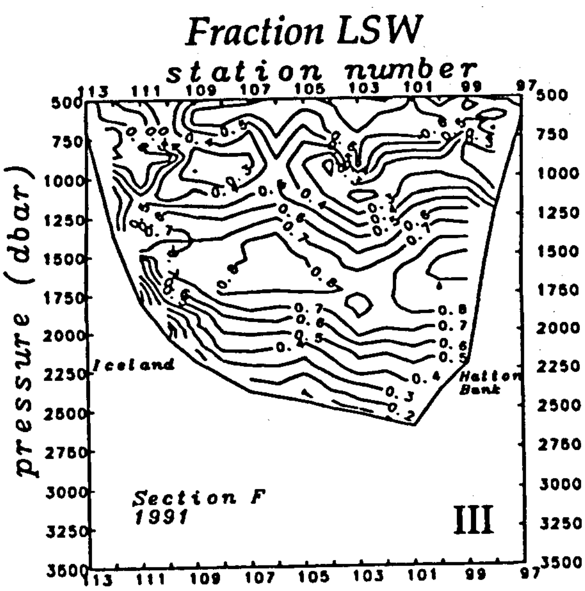
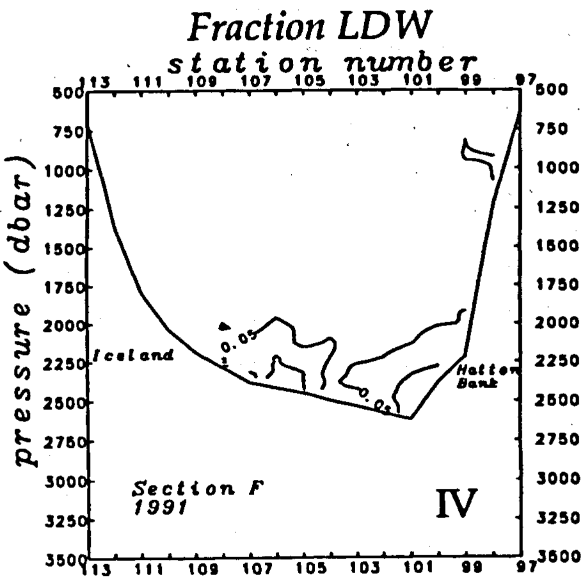

Salinity
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
I
Temperature
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
II
Oxygen
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
III
Silicate
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
IV
Nitrate
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
V
Sigma theta
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
VI

Figure 5a


Fraction SPMW
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
I


Fraction IW
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
II


Fraction LSW
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
III


Fraction LDW
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
IV

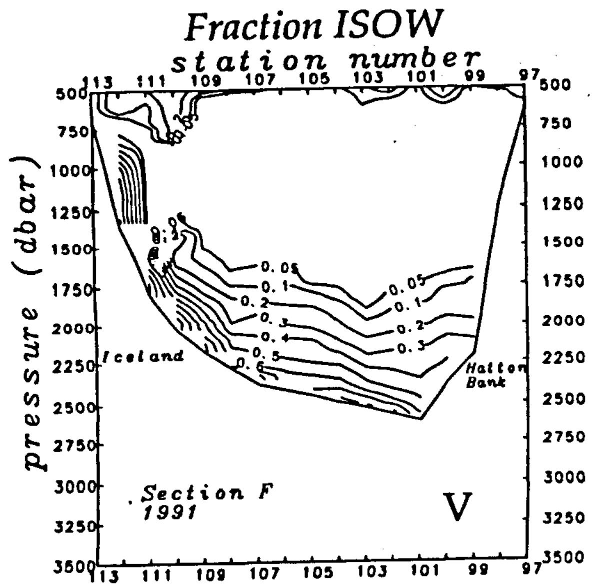
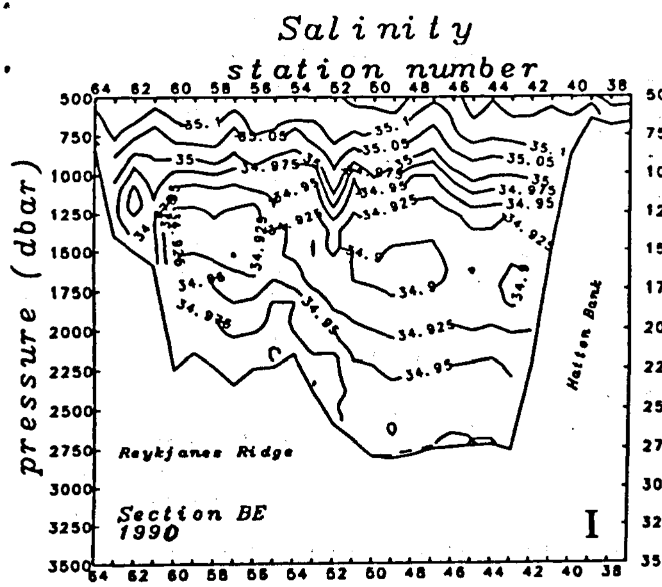

Fraction ISOW
station number
pressure (dbar)
Iceland
Hatton Bank
Section F
1991
V

Figure 5b


Salinity
station number
pressure (dbar)
Reykjanes Ridge
Section BE
1990
I

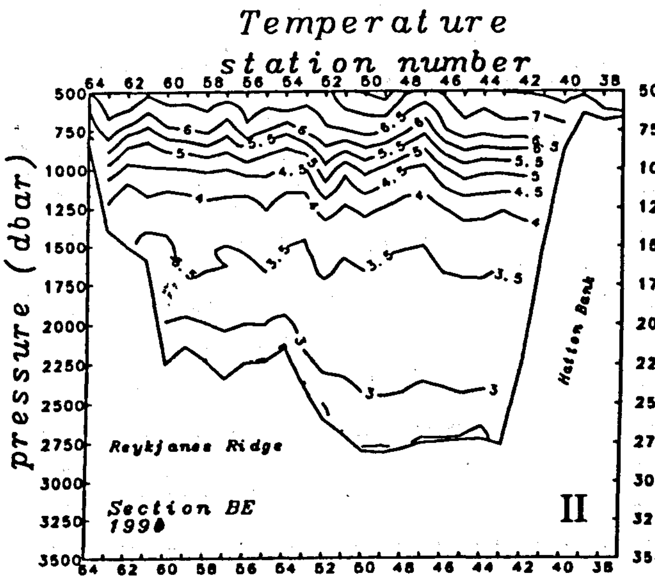
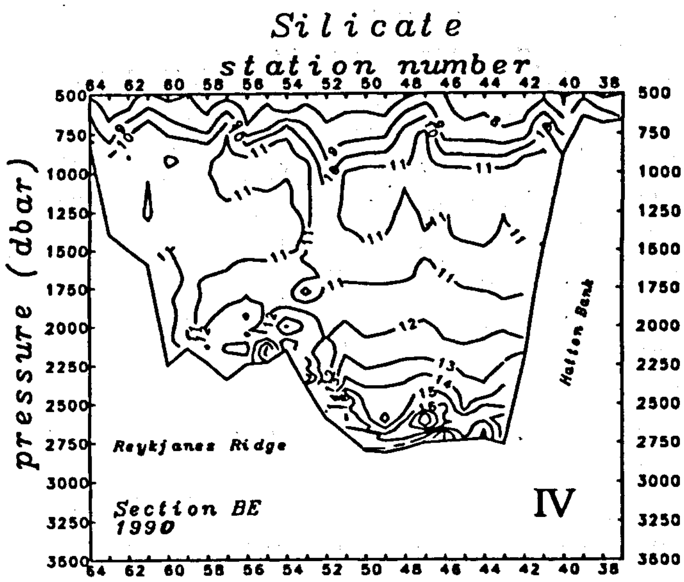
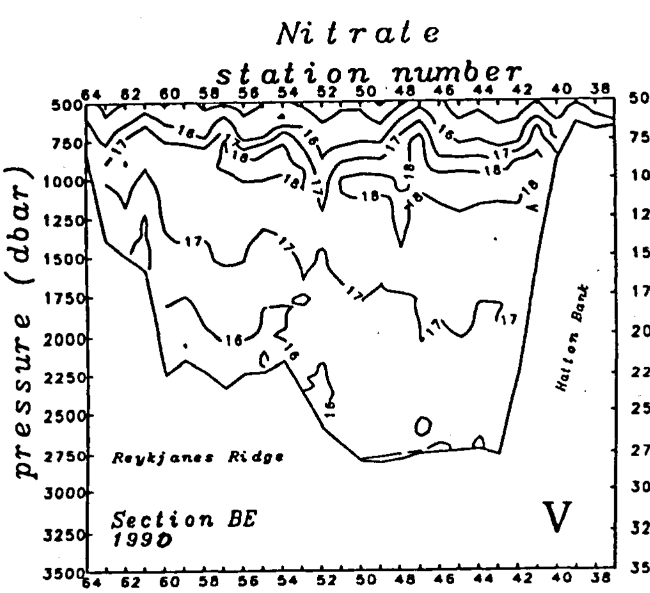
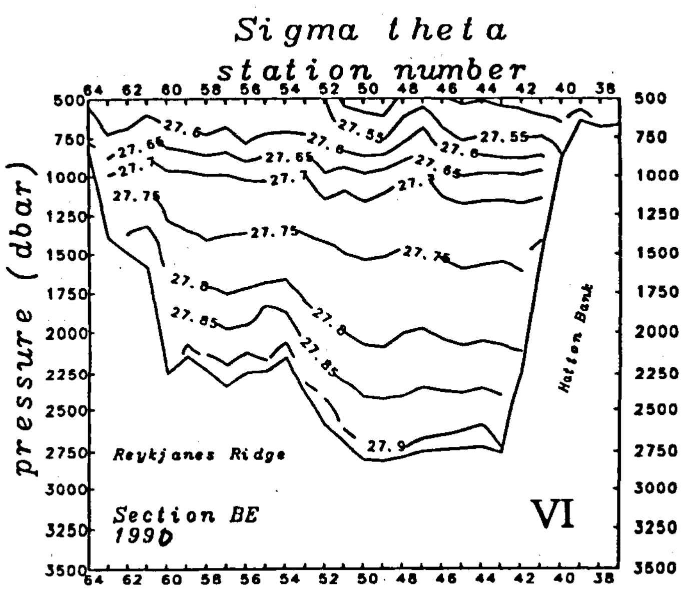
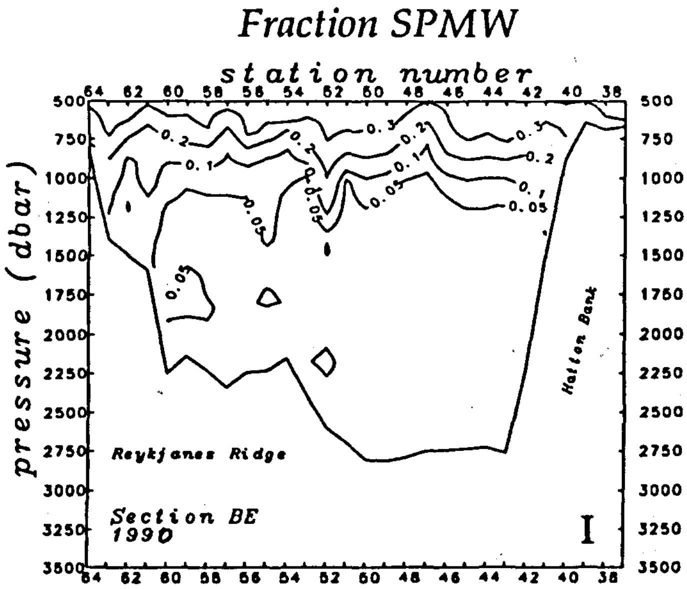

Temperature
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1990
II

Figure 6a

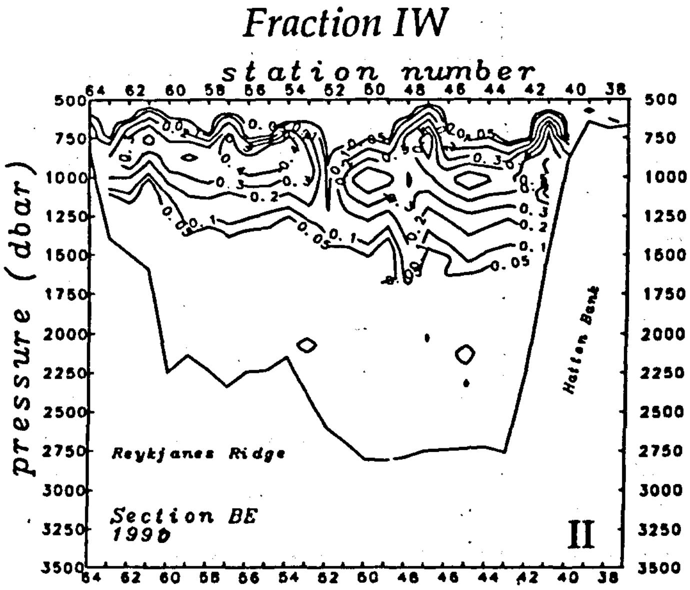

Silicate
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1990
IV


Nitrate
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1990
V

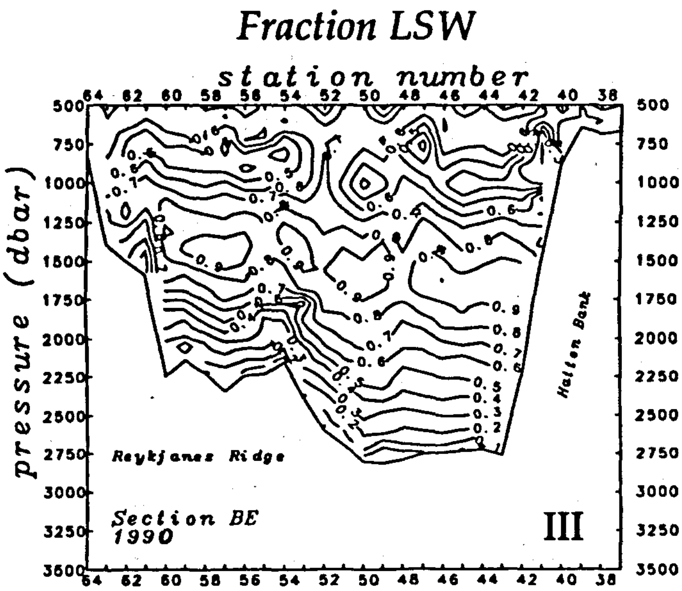

Sigma theta
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1990
VI



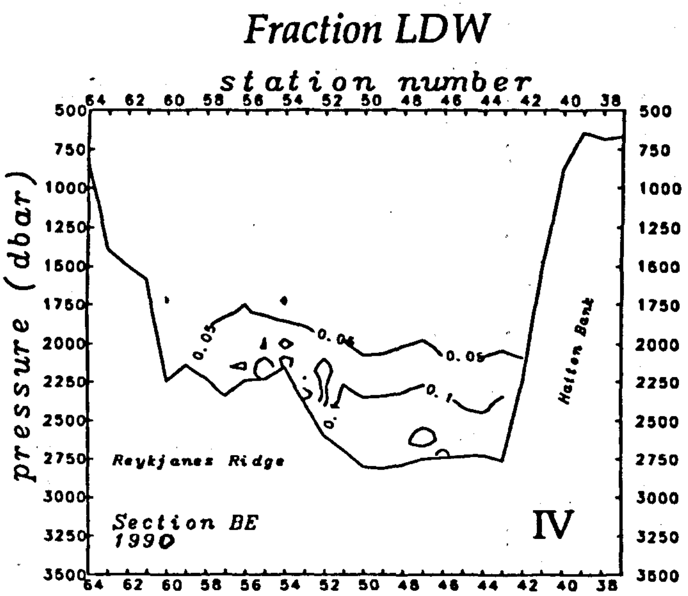
Fraction SPMW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1990
I



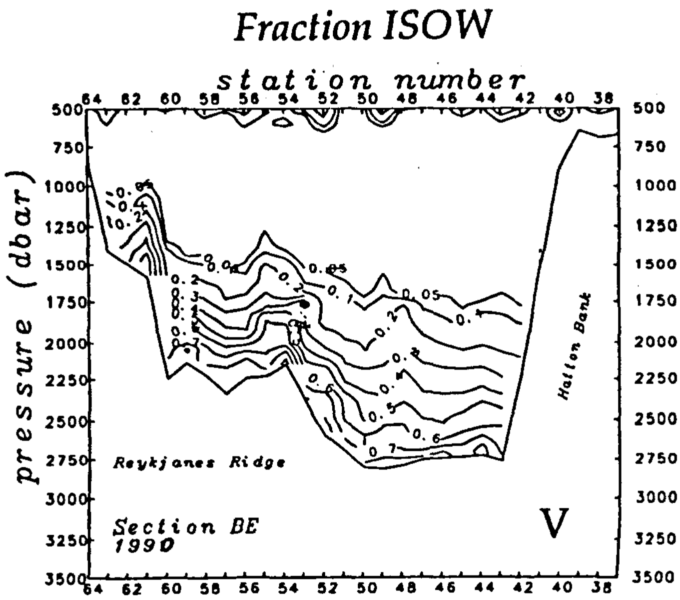
Fraction IW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1990
II



Fraction LSW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1990
III



Fraction LDW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1990
IV



Fraction ISOW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1990
V

Figure 6b

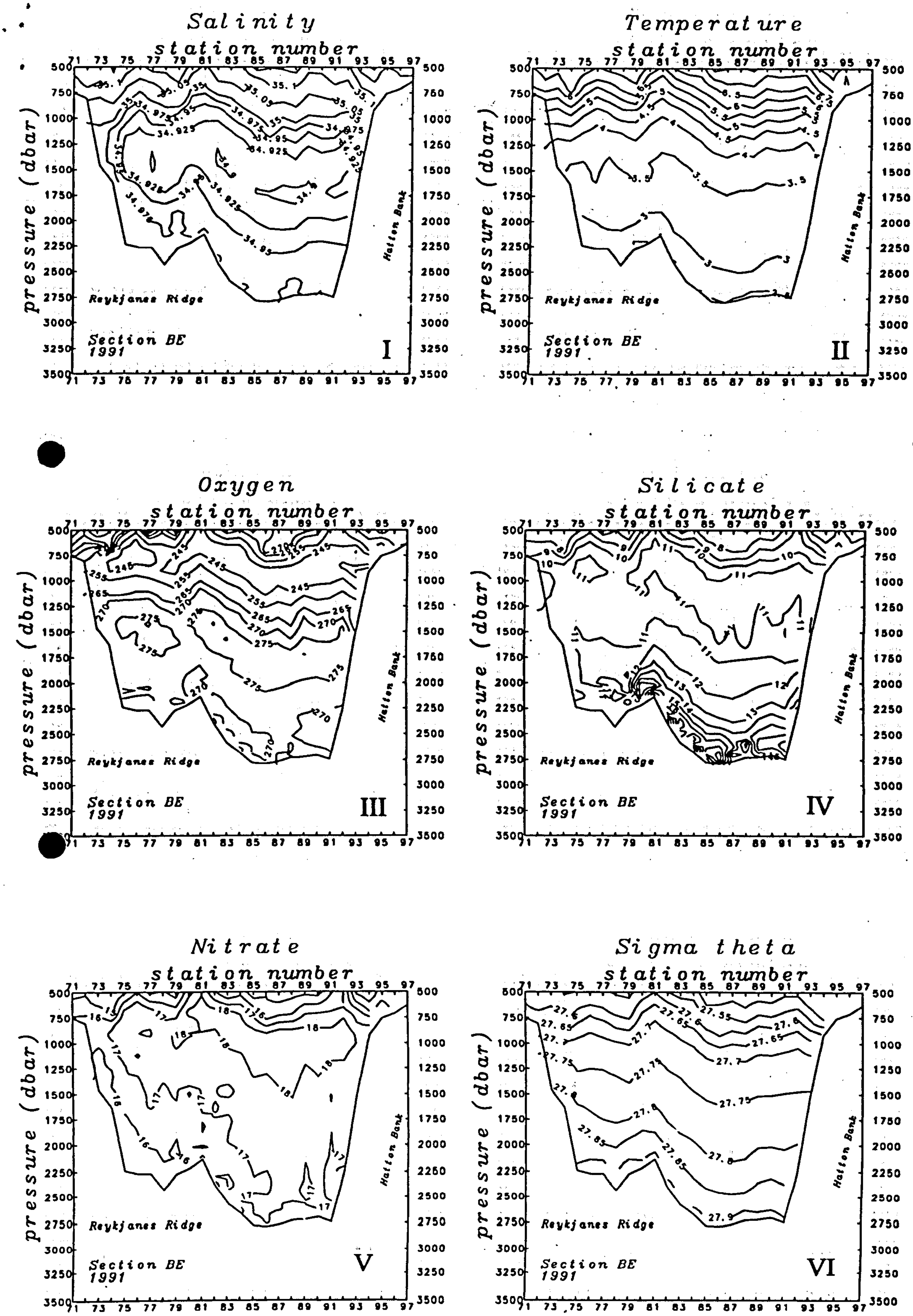
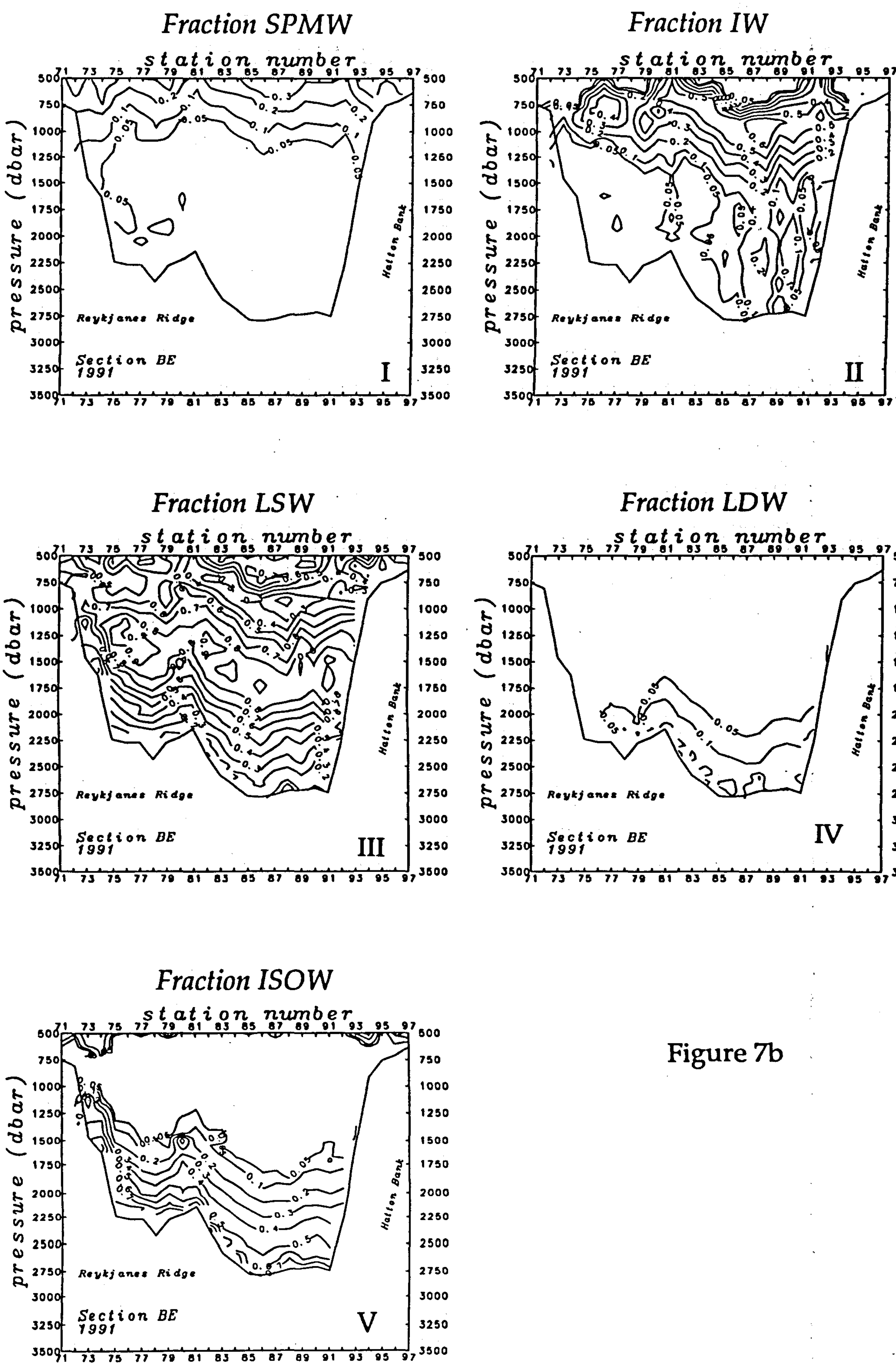

Salinity
station number
pressure (dbar)
Reykjanes Ridge
Section BE
1991
I
Hatton Bank
Temperature
station number
pressure (dbar)
Reykjanes Ridge
Section BE
1991
II
Hatton Bank
Oxygen
station number
pressure (dbar)
Reykjanes Ridge
Section BE
1991
III
Hatton Bank
Silicate
station number
pressure (dbar)
Reykjanes Ridge
Section BE
1991
IV
Hatton Bank
Nitrate
station number
pressure (dbar)
Reykjanes Ridge
Section BE
1991
V
Hatton Bank
Sigma theta
station number
pressure (dbar)
Reykjanes Ridge
Section BE
1991
VI
Hatton Bank

Figure 7a



Fraction SPMW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1991
I
Fraction IW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1991
II
Fraction LSW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1991
III
Fraction LDW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1991
IV
Fraction ISOW
station number
pressure (dbar)
Reykjanes Ridge
Hatton Bank
Section BE
1991
V

Figure 7b

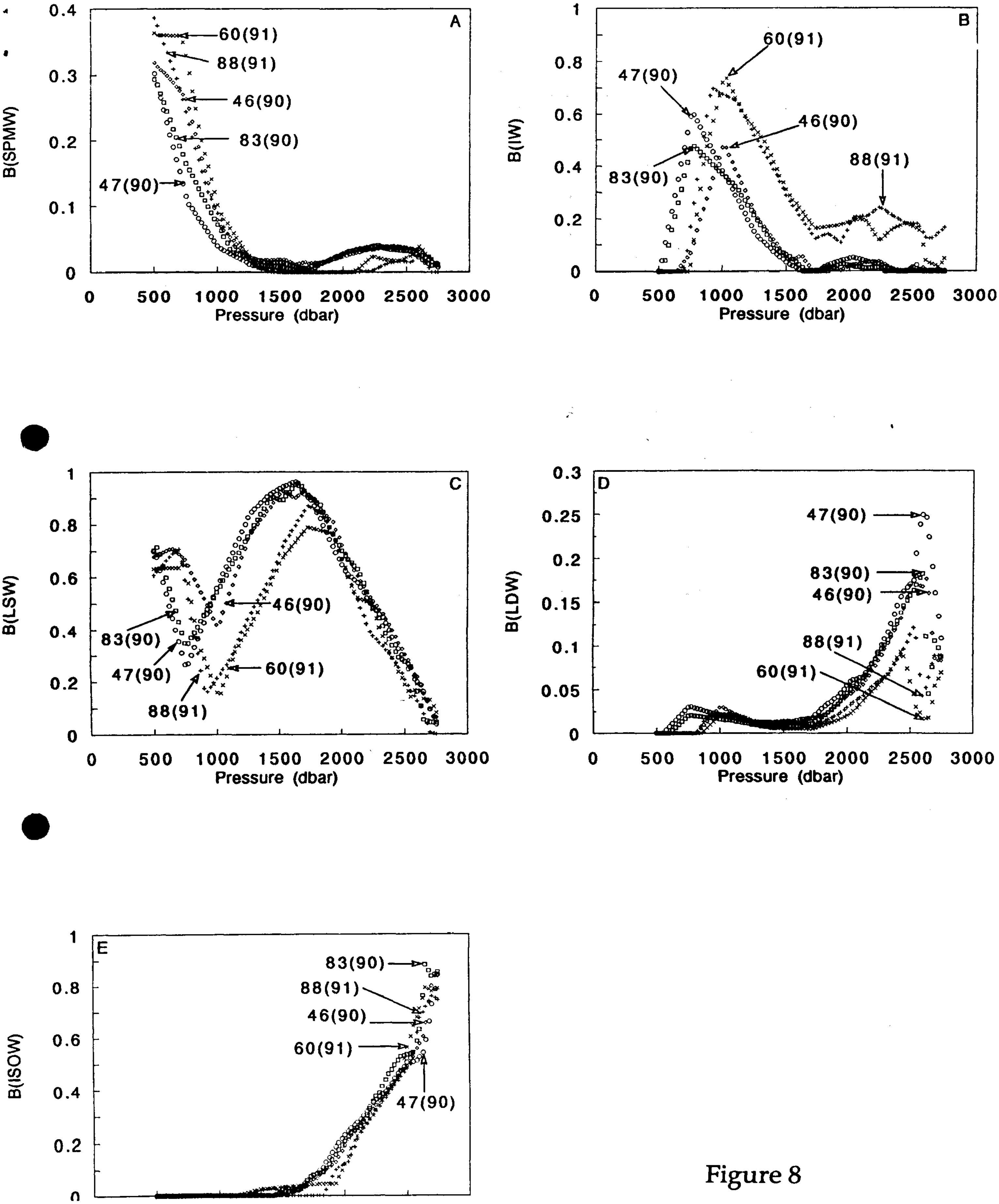

A
B(SPMW)
60(91)
88(91)
46(90)
83(90)
47(90)
Pressure (dbar)
B
B(IW)
60(91)
47(90)
46(90)
83(90)
88(91)
Pressure (dbar)
C
B(LSW)
46(90)
83(90)
47(90)
60(91)
88(91)
Pressure (dbar)
D
B(LDW)
47(90)
83(90)
46(90)
88(91)
60(91)
Pressure (dbar)
E
B(ISOW)
83(90)
88(91)
46(90)
60(91)
47(90)

Figure 8