Dissolved silica as an indicator of Antarctic Bottom Water penetration, and the variability in the bottom layers of the Norwegian and Iceland Basins

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ABSTRACT

Dissolved silica is used as a quantitative tracer for AABW penetration. At 50°N the bottom water of the Northeast Atlantic contains 29% AABW; this percentage decreases more northward, but AABW can be traced to at least 57°N. Some indications are given that salinity decreased during recent decades in ISOW and that dissolved silica decreased in NSBW.

INTRODUCTION

South of the submarine ridges between Greenland and Scotland, the deep and bottom waters of the North Atlantic are not formed in the area itself; they are mixtures of water masses formed in the Arctic and Antarctic. Cooper (1955) was the first to show the flushing of the deep North Atlantic layers by Arctic water masses, overflowing the ridges between Greenland and Scotland. As shown by Cooper (1955) and by Swift (1984) the propagation of the overflow waters from the Norwegian Sea starts at the sill in the Faroe Bank Channel, continues into the Iceland Basin, after picking up smaller contributions from the intermittent overflow over the Iceland-Faroe Ridge, gradually descends in the Iceland Basin until it enters the western Atlantic basins at the Gibbs Fracture Zone. This water is here referred to as Iceland-Scotland Overflow Water (ISOW). There is some ambiguity in this definition; it has also been called Northeast Atlantic Deep Water by Ellett and Martin (1967), but ISOW is preferred since there are many deep water masses in the Northeast Atlantic. It should be realized, however, that ISOW is the *product* of the overflow, after down-sill mixing. It changes in composition by mixing along its pathway and it is quite different from the bottom waters at the sills. The Arctic components in ISOW are in the first place the waters with temperatures below 0°C, found at the bottom of the Faroe-Shetland Channel (Hermann 1967). These waters fall within the classical definition of Norwegian Sea Deep Water (NSDW), but there is no direct contribution of Norwegian Sea Bottom Water (NSBW). The origin can be traced back to a depth of about 900 m in the Norwegian Sea (Swift 1984). On the other hand, the warmer and fresher Arctic Intermediate and North Icelandic Waters (AIW/NIW), formed in winter at the surface of the Iceland Sea, may contribute in

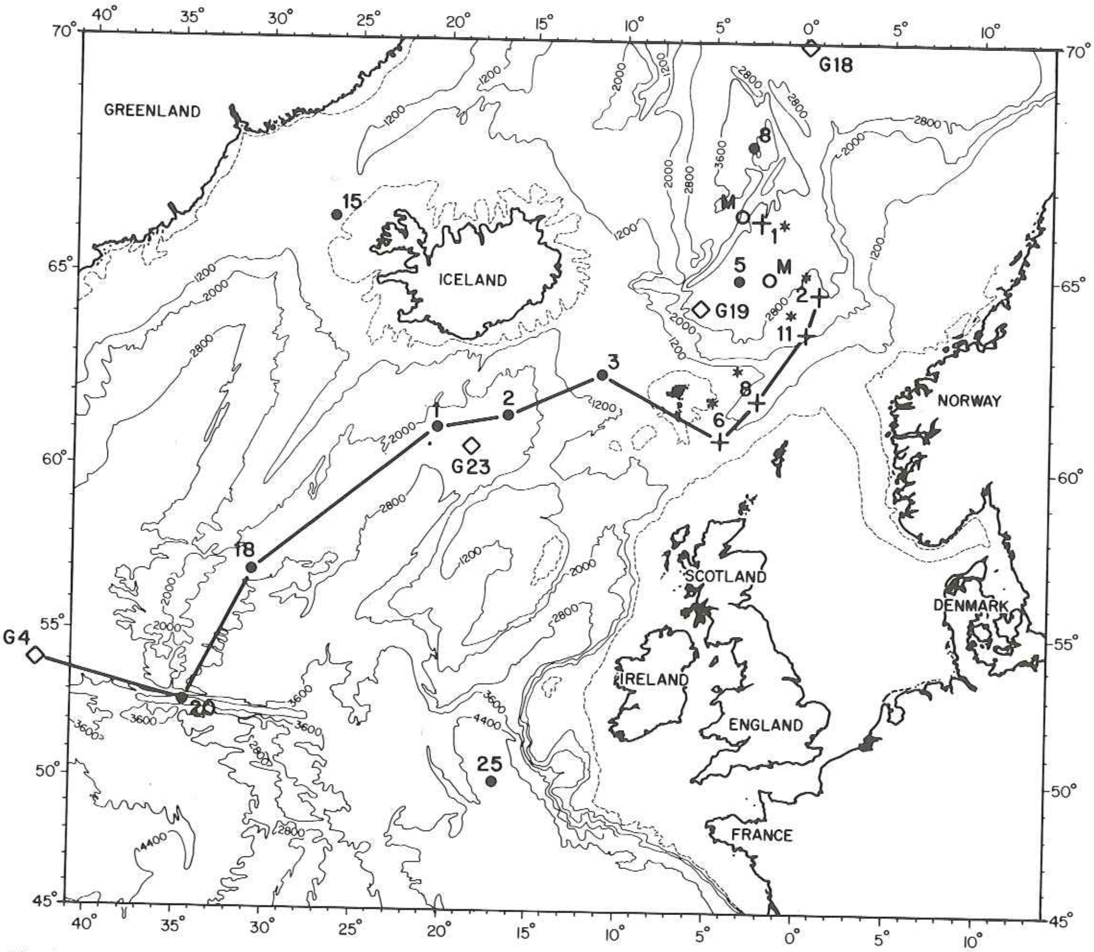

Fig. 1. Positions of stations and station numbers used in the text. GEOSECS 1972 (◇); Tyro 1981 (+; numbers with asterisks); Meteor 1982 (○); Tyro 1983 (●). Sections of salinity and Si along the indicated line are given in Figure 2.

some years to the deep waters of the Faroe-Shetland Channel (Dooley et al. 1984) and to the overflow over the Faroe-Iceland ridge (Hansen and Meincke, 1979). Down-sill mixing with overlying Atlantic waters is responsible for the relatively high salinity of ISOW.

The other bottom water mass involved in flushing of the North Atlantic contains some Antarctic Bottom Water (AABW); the fraction of AABW decreases going northward. Pure AABW, found in the Argentine Basin, contains about 10 times more dissolved silica (hereafter called Si) than the waters of northern origin and the use of Si as a tracer for AABW was first proposed by Cooper (1952) and subsequently demonstrated by Metcalf (1969), Stefánsson and Atkinson (1971), Mann et al. (1973) and Broecker et al. (1976).

The latter authors showed from Si-S correlations that the positive anomalies in Si due to dissolution of particulate silicates are small, less than 4 μmol l^{-1} in the western Atlantic and therefore some of the reserve put forward in the earlier papers is no longer necessary. The purpose of the present paper is to discuss the penetration of AABW in the Northeast Atlantic and to investigate the variability of Si in water masses of northern origin, notably NSBW and ISOW. Si in water masses above the bottom water complex is also briefly discussed.

CRUISE DATA AND METHODS

Sampling was carried out in August 1981 and 1983 with R. V. "Tyro". For comparison data from some GEOSECS stations were used (GEOSECS data reports) and also from two stations in the Norwegian Sea, occupied in May 1982 by R. V. "Meteor" (Van Beusekom 1983). Positions of stations referred to in the text are given in Figure 1. On all Tyro stations salinity and temperature profiles were obtained with a Guildline CTD probe, calibrated by salinity determinations in water samples from a Rosette sampler and with reversing thermometers. Si was determined on board with the manual method of Strickland and Parsons (1968), taking into account the precautions given by Fanning and Pilson (1973).

Analytical precision was 0.015°C for temperature, 0.003 or better for bottle salinities, about 0.01 for CTD salinities, and 0.05 μmol l^{-1} *plus* 0.7% of the measured value for Si.

RESULTS AND DISCUSSION

a) Penetration of AABW

Data on potential temperature, salinity and Si at typical stations are given in Table 1, while Figure 2 shows a cross section of salinity and Si from the Norwegian Sea to west of the Gibbs Fracture Zone, the pathway of ISOW. At the latitudes of this section Si is quite low, but at station 25, Si increases markedly below 2000 m depth (Fig. 3), while the salinity of the bottom waters is lower than that of ISOW (Table 1). This indicates the presence of AABW. At the sills in the Romanche and Chain Fracture Zones, the main entrance of deep waters into the East Atlantic basins, the fraction of AABW in bottom waters has already decreased to less than half by mixing in the South Atlantic (Van Bennekom and Berger 1984). South of station 25, until 24°N, the concentration of Si in bottom waters remains between 45 and 50 μmol l^{-1} (Roemnich and Wunsch 1985). North of station 25 relatively high Si in bottom waters has been found by Ellett and Martin (1973) at 57°N in the Rockall Trough (marked R_2 in Fig. 3), by Lonsdale and Hollister (1979) at about 54°N (marked R_1 in Fig. 3) and in the southern Iceland Basin at 57°N by Mann et al. (1973).

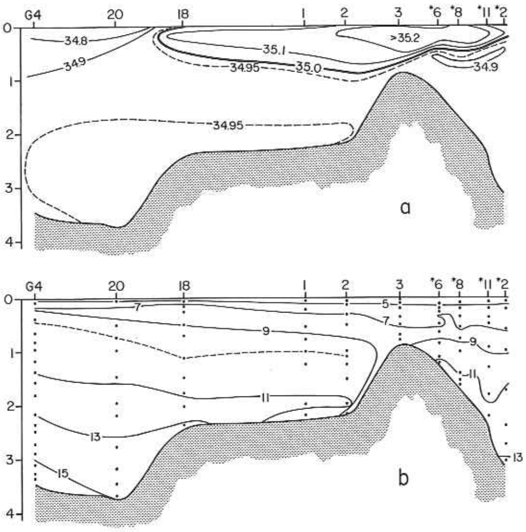

Fig. 2. Section of salinity (upper) and Si (μmol l^{-1}) from west of the Gibbs Fracture Zone through the Iceland Basin and the Faroe-Shetland Channel into the Norwegian Basin. The broken line in b connects intermediate minima.

Depth decreases rather suddenly, going from the Porcupine abyssal plain to the Rockall Trough and the Iceland Basin, and the waters with the highest Si do not penetrate into these corners of the North Atlantic. At R_1 and R_2 Si is higher at the same depth than at station 25, but also potential

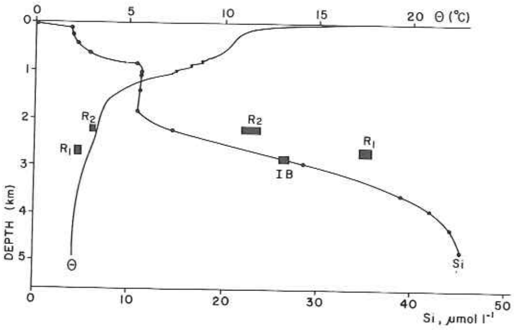

Fig. 3. Profiles of Θ and Si at station 25 on the Porcupine abyssal plain (Fig. 1). Bottom values in the Rockall Trough (R_1, 54°N, Lonsdale and Hollister 1979 and R_2, 57°N, Ellett and Martin 1973) and in the Iceland Basin (IB, 57°N, Mann et al. 1973) are also given.

temperature is lower and the differences might be explained by a slight "upwelling".

The percentage of AABW may be calculated from salinity and from Si by linear interpolation between the end-member values of pure AABW (S = 34.67; Si = 130 μmol l^{-1}; Broecker et al. 1976) and pure ISOW. The latter water mass changes in composition along its pathway (Fig. 2) and possibly also with time (see below). From GEOSECS station 23 and data from Mann et al. (1973) salinity in ISOW was taken to be 35.00 and Si = 11μmol l^{-1}. From salinity AABW is found to be 27.5% and from Si 29% in the bottom waters of station 25. Taking salinity as conservative and the end-member composition as stationary, a Si excess of 1.4 μmol l^{-1} is found. This small excess indicates the nearly conservative behaviour of Si in the deep eastern Atlantic Basins and its potential as a tracer for the quantitative composition of deep waters. The low excess is compatible with the very low fluxes of Si (0.1 to 0.7 μmol cm^{-2}y^{-1}, equivalent to 0.1–0.7 μmol l^{-1} in a bottom layer of 1000 m thickness during a residence time of 100 y.) from pore waters in sediments poor in biogenic silica, found by Van Bennekom and Berger (1984).

From Si at positions north of station 25,

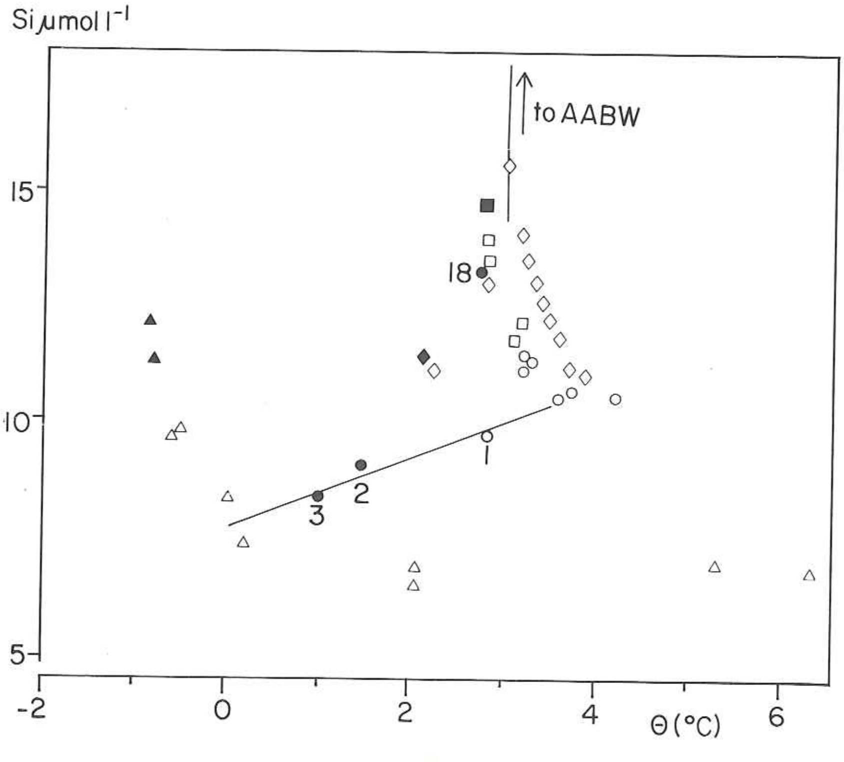

Fig. 4. Relationship between θ and Si in deep (open symbols) and bottom waters (closed symbols) of the Faroe-Shetland Channel (stations *6 and *8, △▲; along the pathway of ISOW in the Iceland Basin (stations 1, 2, 3 and 18, ○● and G23 ◇◆) and in the Gibbs Fracture Zone (station 20, ■□).

TABLE 1

Potential temperature, salinity and dissolved silica in bottom water samples from typical water masses. Sample depth: 10 m above the bottom for ISOW, except at station 1 where the deepest sample was lost, and station 25; 10–20 m above the bottom for NSBW, except for station G18 where the depth range is 400–135 m above the bottom. The deepest sample at station G18 is discussed in section (d).

Water mass	*Stations*	*Sample depth*	*Θ (°C)*	*S*	*Si (μmol l^{-1})*
NSBW, 1972	G18	2880–3150	–1.042 to –1.052	34.909–34.913	14.0–14.1
ibid	G19	2800–3460	–1.042 to –1.043	34.909–34.914	14.1–14.7
NSBW, 1981–83	*1, 8, M	2800–3730	–1.046 to –1.052	34.912–34.914	13.3–13.6
Iceland-Scotland Overflow water	3	760	+1	34.920	8.1
ibid	2	2150	1.52	34.968	8.9
ibid	1	2310	2.12	34.97	—
ibid	1	2170	2.80	34.980	9.7
ibid	18	2325	2.66	34.97	13.2
ibid	20	3690	2.675	34.98	14.8
Northeast Atlantic Bottom Water rich in AABW	25	4820	2.11	34.909	45.2

given in Figure 3, AABW is found to be 20% at R_1, 13% at IB and 9–11% at R_2. The sharp decrease in the percentage of AABW in northward direction is primarily a matter of depth, but there is also a "hydrographic" boundary between the northward flowing AABW-containing bottom waters and the southward flowing products of ISOW. These waters meet near the Gibbs Fracture Zone, where 14.8 μmol l^{-1} were found near the bottom (3700 m depth) at station 20 (Table 1). Shor et al. (1980) gave about 16 μmol l^{-1} for the same position, while Broecker et al. (1976) gave 13–14.5 μmol l^{-1}. The latter values may be slightly too low to characterize the waters at the bottom of the Gibbs Fracture Zone, because they were taken from less than 2700 m depth.

Figure 4 shows the relationship between Θ and Si in ISOW. In the northern Iceland Basin (stations 1, 2 and 3) this relationship is approximately linear for the waters between the bottom and about 1200 m depth. Along the eastern slope of the Reykjanes Ridge (stations 18 and 20), Si is markedly higher in bottom waters and the same is found for the waters at station G23 from 2100–2400 m depth (435–135 m above the bottom). As appears from Figure 4, this is compatible with the presence of minor amounts of AABW. The 15–16 μmol l^{-1} of Si, found in the bottom waters of the Gibbs Fracture Zone suggest the presence of 3–4% AABW. For a number of reasons these percentages are very uncertain. Diffusion from pore waters and dissolution of particulate silica of biogenic origin in the water column may cause a slight increase in dissolved silicate, while also the end-member value of 11 μmol l^{-1} has an uncertainty of at least 1 μmol l^{-1}, as appears from Figure 4. The markedly lower values at stations 2 and 3 were not taken into account, because these may be associated with a recent decrease in temperature in bottom waters in that area (see section c).

Nevertheless, it seems not impossible that the Gibbs Fracture Zone is an outlet of AABW, present in small admixtures in ISOW, to the western Atlantic Basins.

TABLE 2

Salinities in bottom waters of the northern Iceland Basin, along the pathway of ISOW. Stations referred to are divided into two groups: Area A, south of Iceland 60°30′–63°N; 16–18°W and area B, along the eastern slope of the Reykjanes Ridge, 54–59°N; 31–23°W.

Year of obs.	*Area*	*Sample depth*	*Salinity*	*Reference*
1960	A	>1200	35.03	Hermann (1969)
1960	A	1400–1700	35.02–35.04	Steele et al. (1962)
1972	A	1800–2500	34.98–34.99	Bainbridge (1976, p. 44)
1973	A	1900	34.98	Malmberg (1974)
1983	A	2150–2300	34.95–34.97	this work
1958	B	1900–2800	35.00–35.03	Fuglister (1960)
1967	B	1900–2700	34.99–35.01	Mann et al. (1973)
1972	B	2700	35.00	Bainbridge (1976, p. 91)
1983	B	2300	34.98	this work

It may be safely concluded that AABW penetrates at least to 57°N in the Northeast Atlantic. This is much farther north than in the Northwest Atlantic, where it can be concluded from Broecker et al. (1976) that AABW does not penetrate north of 45°N. Farther south a thin layer of AABW-containing bottom water is found (e.g. Stefánsson and Atkinson 1971). Comparing the sections given by the latter authors with Figure 3 shows that in the western basins a very steep gradient in Si is found below 4500 m depth, whereas in the eastern basins the steepest gradient is found at about 2500 m depth and a small gradient is found near the bottom.

b) Intermediate water layers

Figure 3 indicates a slight minimum in Si at about 1900 m depth, while in the section of Figure 2 weak minima in Si are found at 1000 to 1300 m depth in the Iceland Basin. These minima (Si = 11 μmol l^{-1}) coincide with minima in salinity (S = 34.93 – 34.94) at potential temperatures between 3.4 and 3.8°C. These characteristics are according to Lee and Ellett (1965) and Harvey and Glynn (1985) due to the influence of Labrador Sea Water (LSW). It is noteworthy that Si in ISOW and in LSW is the same, which means that in the quantitative calculations of section (a) the percentages of AABW, based on Si, are completely independent of assumptions regarding the dominant mixing process: either horizontal mixing along the bottom with ISOW or vertical mixing with LSW.

The slight inversions of temperature between 800 and 1100 m depth in Figure 3 are presumably due to a minor influence of water from the Mediterranean Sea. The differences in Si between 1000 and 2000 m are <0.5 μmol l^{-1}. It is impossible to relate such small variations to different water masses; also dissolution of particulate silica of biogenic origin could play a role.

c) Variability in ISOW

At station 2, in the northernmost part of the Iceland Basin, salinity, potential temperature and Si decreased markedly in the deepest 100 m. At 2150 m depth (10 m above the bottom), Θ and S were respectively 1.48°C and 34.95. Such low values have to my knowledge not been reported previously from that region and depth. The recent review by Swift (1984) gives a range of 1.8 to 3°C and salinities very close to 35.00. It is difficult to distinguish between short term variations and long term trends, but observations listed in Table 2 suggest a decrease of ISOW salinities in the period 1958–1983 of 0.03–0.07.

It is difficult to draw pertinent conclusions from a few stations: the layer of ISOW is often narrow and thin, while meandering may also occur. For example $S = 34.968$ and $\Theta = 1.52°C$ were given for the bottom water at station 2 in Table 1, but a second cast at the same depth (2150 m), only 2 nautical miles to the west, gave $S = 34.95$ and $\Theta = 1.48°C$, while a third one, another 2 miles to the west, gave $S = 34.97$ and $\Theta = 2.12°C$.

In spite of this variability, the whole pattern of salinity distribution has changed in the northeastern part of the Iceland Basin. In 1960 the cold product of ISOW was recognizable as a bottom layer of relatively high salinity (Steele et al. 1962), whereas in 1983 this layer showed a lower salinity than the waters above (Fig. 2). The data of Malmberg (1974), obtained in 1973, also indicate a decrease of salinity near the bottom in this area.

Brewer et al. (1983) suggested that the freshening trend in the deep North Atlantic is associated with LSW; the above data show that ISOW may also be involved.

Figure 2 shows that in 1981 an intermediate salinity minimum (34.89–34.90) was found at 550 to 650 m depth in the Faroe-Shetland Channel. At this minimum, potential temperatures ranged from 0.3 to 0.6°C; these temperatures are 2°C lower than during the mid-seventies (Dooley et al. 1984).

It is not certain when and from what depth in the Faroe-Shetland Channel the bottom waters in the Northeast Iceland Basin originated. The linear Θ-Si relationship at stations 1, 2 and 3 in Figure 4 suggest a Si value of 7.5–8 μmol l^{-1} at $0.3° < \Theta < 0.6°C$. In 1981 at stations *6 and *8 in the Faroe-Shetland Channel 7.2–8 μmol l^{-1} of Si were indeed found over this range of Θ at depths of 500–700 m. More stations, occupied in the same year and analyzed at more depth levels are needed to draw more definite conclusions about e.g. the role of down-sill mixing and the role of cold waters overflowing the Iceland-Faroe Ridge (Hansen and Meincke 1979) and to answer the question if Si decreases with the decreasing salinities.

d) Variability in NSBW and NSDW

Profiles of Si against depth for various stations in the Norwegian Sea are given in Figure 5. The bottom layers of the Norwegian Basin (below about 3000 m depth) had in 1981, 1982 and 1983 dissolved silica concentrations of 13.3 to 13.6 μmol l^{-1}. This is about 1 μmol l^{-1} less than in 1972 during the GEOSECS expedition, a difference well above the analytical precision of 0.1–0.2 μmol l^{-1}. This alone is not sufficient to conclude that Si in NSBW decreased. The positions were not exactly the same (Fig. 1) and analytical procedures were not intercalibrated. Nevertheless, both data sets show that NSBW is very homogenous horizontally below 2800 m and from 1000 to 2000 m depth the differences in Si between 1981–83 and 1972 were less than 0.2 μmol l^{-1}.

Temperature and salinity did not change significantly between 1972 and 1981–83 in NSBW (Table 1) but tritium concentrations increased: In 1972 less than 0.15 T. U. were found below 2000 m at G19, while in 1983 0.3–0.5 T. U. were present below 2000 m at stations 5 and 8 (W. G. Mook, personal communication). Also in 1981 during the TTO–NAS cruise (Transient Tracers in the Ocean–North Atlantic Survey), 0.3 T. U. were found in the bottom waters of the Norwegian Basin (H. G. Östlund, personal communication). A detectable amount of tritium (0.3 T. U.) was found in 1972 in the deepest sample of station G18. Peterson and Rooth (1976) concluded that below sill depth, the waters of the Norwegian Basin were in 1972 essentially free of tritium. They apparently neglected the deepest sample of station G18. This sample had in 1972 a concentration of Si, comparable to the values found in 1981–83 in the bottom

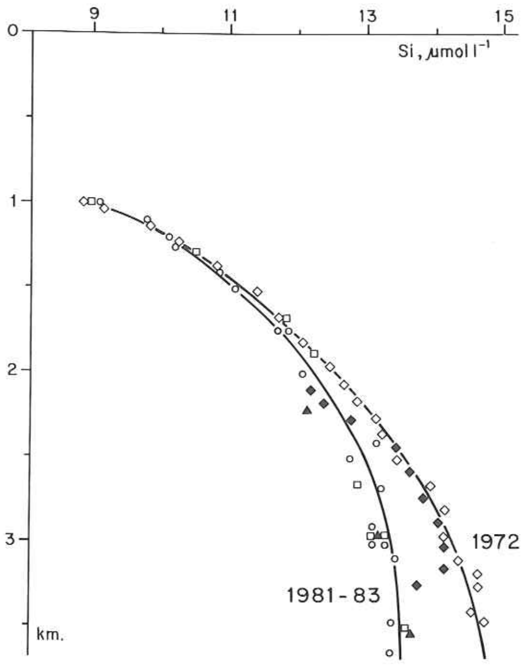

Fig. 5. Profiles of Si in the Norwegian Sea. Northern part: GEOSECS 18 (◆), 1983–8 (▲). Southern part: GEOSECS 19 (◇), 1983 (○) and 1981 (□). The μmol kg^{-1} in the GEOSECS data reports were converted into μmol l^{-1}.

waters of the entire Norwegian Basin (Fig. 5).

The increase in tritium between 1972 and 1981 is not compatible with the time scale of more than 100 years for the exchange between the deep Greenland and Norwegian Basins, estimated by Peterson and Rooth (1976). A tentative conclusion is that the transport of bottom waters from the Greenland Basin into the Norwegian Basin is not stationary, but was accelerated since 1972 or shortly before that year in view of the bottom sample at G18. This would decrease Si and increase tritium, because in 1972 the Greenland Basin bottom waters had Si = 9.7–10.1 μmol l^{-1} (Bainbridge 1976) and tritium concentrations of 1–2 T. U. (Peterson and Rooth 1976).

Changes in NSBW do not influence Si in the deep Faroe-Shetland Channel. On the contrary, Figure 5 shows that over the relevant depth range of 1000–1500 m Si has remained constant.

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