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Radiogenic helium in Baffin Bay bottom water

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ABSTRACT

[3]He-[4]He ratios, dissolved He and Ne, and tritium have been measured in 87 seawater samples collected at 14 stations in Baffin Bay, Davis Strait, and in the sounds through which Arctic water flows into Baffin Bay. Profiles of δ([3]He), the percent [3]He/[4]He anomaly relative to atmospheric [3]He/[4]He, He, Ne, and tritium can be used to identify and trace water masses. The overall pattern is in good agreement with the three-layer structure and circulation pattern summarized by Muench (1971). For many samples, tritium concentrations and [3]He in excess of solubility equilibrium allow estimation of water mass "ages" which range from near zero to eight years in the upper 500 m. At two stations in central Baffin Bay, there is clear evidence for addition of radiogenic [4]He in the deep water. A time dependent two-box model for the tracers tritium and [3]He gives a renewal time for Baffin Bay deep water in the range 77-455 years, considerably higher than the estimate of 20 years given by Sadler (1976).

1. Introduction

A brief history of expeditions to Baffin Bay, from Baffin's exploratory voyage in 1616 to recent times is given by Muench (1971). According to the oceanographic data the waters of Baffin Bay may be divided into three layers: an upper layer of cold Arctic water which extends from the surface to 100-300 m, an intermediate layer of warm Atlantic water which extends to 1200-1300 m, and a deep layer of relatively cold water which is thought to be of Arctic origin. Baffin Bay receives water from the Arctic Ocean through Smith, Jones and Lancaster Sounds, and Atlantic water which flows northward through the eastern side of Davis Strait. The output from the bay flows southward through the western side of Davis Strait.

The present study of helium isotopes, neon and tritium was undertaken to gain further information on Arctic oceanography and in particular to evaluate the use of the tracers [3]He and tritium for possible future work in this region. The seawater samples were collected during a cruise of the CSS *Hudson* during September-October 1977 and were analyzed by mass spectrometric techniques at McMaster University. Samples for this work were taken at relatively few of the stations occupied during the cruise, the main purpose of which was to obtain precise data on temperatures, salinities, dissolved oxygen, and nutrients (see Jones and Coote,

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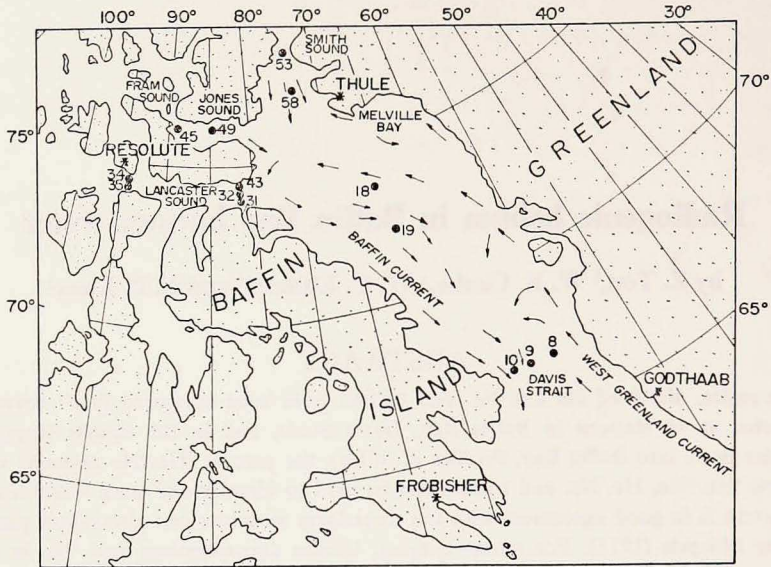
Figure 1. Station locations in Baffin Bay, Davis Strait, and the northern sounds. The surface current pattern is taken from Coachman and Aagard (1974).

1979). Locations of the stations sampled for He, Ne, and tritium are shown in Figure 1.

2. Experimental methods

The seawater samples were transferred from 5-liter Niskin bottles into 40 in. lengths of 3/8 in. annealed copper tubing which were sealed at each end with steel pinch clamps. The initial laboratory procedure consisted of vacuum extraction of the He-Ne fraction of the dissolved gas into break-seal sample tubes made of Corning 1720 glass. The degassed seawater samples were sealed in 1720 glass bulbs and stored for approximately six months prior to mass spectrometric measurement of the ^{3}He generated from tritium (half-life = 12.26 years) decay. More detailed accounts of the techniques used in this laboratory for analysis of He, Ne, and tritium are given by Jenkins and Clarke (1976) and by Clarke et al. (1976). At the end of the gas extraction process, the He-Ne fraction was divided with a precisely calibrated splitter into two sample tubes, one of which was used for ^{3}He/^{4}He measurement in a branch-tube static mass spectrometer designed specifically for ^{3}He/^{4}He measurements on small helium samples. The other sample of He-Ne was "spiked" with precisely known amounts of pure ^{3}He and ^{22}Ne prior to measurement of ^{3}He/^{4}He and ^{20}Ne/^{22}Ne in a separate single-tube mass spectrometer. The standards used for isotope dilution measurements contained known amounts of ^{3}He, ^{4}He, ^{20}Ne and ^{22}Ne. Mass spectrometer discrimination was monitored by frequent analyses of standards interspersed among the "spiked" sample measurements.

3. Results and discussion

The results are given in Table 1 along with potential temperatures and salinities. Profiles for station 18 and station 19 are shown in Figure 2 and profiles for the other stations are shown in Figure 3.

Table 1. Helium, Neon, and Tritium in Baffin Bay 1977.

Depth[s] (m)	Tp (°C)	S (‰)	$\delta(^3He)$ (%)	He $(10^{-8} ccSTP/g)$	Ne	Tritium (T.U.)	^3H-^3He Age (years)
Station 8 66.76N, 57.10W Aug. 30, 1977. Bottom depth = 658m.							
1	5.0 $^\beta$	32.67	−1.5	3.98	17.49	17.4	0.0 ± 0.1
21	5.62	33.02	−1.0	3.99	17.63	18.8	0.2 ± 0.1
51	3.34	33.73	−0.7	4.07	18.02	13.8	0.3 ± 0.1
104	3.62	34.26	0.1	4.01	17.82	9.0	0.8 ± 0.2
256	4.73	34.73	−0.5	3.94ʻ	—	8.1	0.6 ± 0.2
403	3.99	34.72	2.9	4.07	18.18	7.3	2.4 ± 0.2
509	3.62	34.75	3.3	4.06	18.14	6.6	2.8 ± 0.3
Station 9 66.74N, 58.97W Aug. 30, 1977. Bottom depth = 933m.							
1	1.0 $^\beta$	32.09	1.8	4.05	18.46	26.4	0.5 ± 0.1
23	−0.97	32.76	11.4	4.14	18.88	23.3	2.2 ± 0.1
77	−1.57	33.19	15.7	4.19	19.30	—	—
105	−1.61	33.48	21.7	4.12	18.87	—	—
258	0.34	34.01	11.3	4.04	18.27	13.5	3.5 ± 0.2
850	1.05	34.50	4.6	4.15	18.57	—	—
Station 10 66.75N, 60.25W Aug. 30, 1977. Bottom depth = 580m.							
1	0.0 $^\beta$	29.91	−0.1	4.19	19.06	26.9	0.2 ± 0.1
22	−0.92	32.18	12.9	4.24	19.27	26.1	2.2 ± 0.1
53	−1.62	32.99	16.0	4.36	19.71	26.3	2.7 ± 0.1
104	−1.49	33.31	11.3	4.49	19.95	25.1	2.2 ± 0.1
244	−0.63	33.89	17.9	4.18	18.91	17.5	4.1 ± 0.1
393	0.87	34.30	15.8	4.20	18.53	9.2	6.5 ± 0.4
552	1.23	34.46	10.0	4.26	18.59	9.1	4.7 ± 0.4
Station 18 73.46N, 67.29W Sept. 3, 1977. Bottom depth = 2214m.							
12	1.26	32.48	19.3	4.15	19.12	25.5	3.1 ± 0.1
81	−1.63	33.57	15.6	4.16	19.06	19.8	3.4 ± 0.2
153	−1.50	33.78	19.6	4.19	18.93	20.4	3.9 ± 0.2
206A	−0.86	33.91	18.3	4.17	18.77	16.6	4.4 ± 0.2
206B	−0.86	33.91	—	4.20	18.80	15.4	—
300	1.12	34.26	6.8	4.17	18.46	9.6	3.4 ± 0.3
502	1.96	34.55	6.1	4.05	18.08	5.0	5.4 ± 0.6
804	1.08	34.52	0.0	4.16	18.36	3.1	
1201	−0.24	34.48	−2.8	4.19	18.51	2.5	
2044A	−0.45	34.50	−6.3	4.31	18.55	—	
2044B	−0.45	34.50	−4.4	4.26	18.59	0.7	

Table 1. (Continued)

Depth[δ] (m)	Tp (°C)	S (‰)	δ(^{3}He) (%)	He (10^{-8} ccSTP/g)	Ne	Tritium (T.U.)	^{3}H-^{3}He Age (years)
Station 19 72.24N, 65.95W Sept. 4, 1977. Bottom depth = 2323m.							
15	−0.85	32.12	25.4	4.21	19.21	25.3	3.9 ± 0.1
205	−1.21	33.81	21.4	—	—	17.0	4.8 ± 0.2
310	0.15	34.17	15.5	4.16	18.58	12.1	5.0 ± 0.2
514	1.78	34.52	9.6	4.12	18.21	4.1	8.9 ± 1.2
822	1.12	34.53	1.2	4.15	18.31	3.6	
1229	0.13	34.49	−1.2	4.20	18.58	1.0	
2046A	−0.48	34.51	−4.0	4.32	18.92	1.6	
2046B	−0.48	34.51	−4.2	4.28	18.71	—	
Station 31 73.92N, 82.00W Sept. 8, 1977. Bottom depth = 655m.							
14	2.58	31.74	−0.3	4.04	18.01	26.5	0.2 ± 0.1
56	1.24	32.87	13.6	—	—	22.3	2.5 ± 0.2[γ]
107	−0.61	33.52	13.4	4.19	19.03	17.8	3.2 ± 0.1
206	−1.04	33.93	14.6	4.28[ε]	—	16.0	3.8 ± 0.2
410	0.93	34.22	9.2	4.62[α]	20.38[α]	13.2	3.4 ± 0.2[γ]
637	0.68	34.47	9.8	4.18	18.55	5.0	7.6 ± 0.7
Station 32 74.16N, 81.98W Sept. 8, 1977. Bottom depth = 785m.							
14	1.94	32.69	—	4.06	17.97	18.4	—
57	−0.59	33.52	8.1	4.16[β]	18.84[β]	19.7	1.9 ± 0.1[γ]
159	−1.51	33.78	17.1	4.18	19.01	19.6	3.6 ± 0.2
308	0.42	34.05	17.0	4.19	18.83	13.5	4.9 ± 0.2
597	0.50	34.39	13.1	—	—	7.8	6.5 ± 0.3
764	0.70	34.48	7.2	4.22	18.41	3.6	8.0 ± 1.0
Station 34 74.46N, 94.27W Sept. 9, 1977. Bottom depth = 155m.							
11	−0.56	31.47	9.2	4.18	18.99	27.8	1.5 ± 0.1
82	−1.42	32.82	36.6	4.25	19.24	19.4	6.8 ± 0.2
149	−1.38	33.16	31.6	4.26	19.14	18.0	6.4 ± 0.2
Station 35 74.33N, 94.26W Sept. 10, 1977. Bottom depth = 174m.							
8	−0.30	30.61	4.4	4.15	18.83	30.3	0.8 ± 0.1
77	−1.52	32.81	38.9	4.30	19.51	22.4	6.4 ± 0.2
167	−1.45	33.10[β]	34.3	4.26	19.11	20.4	6.2 ± 0.2
Station 43 74.03N, 81.96W Sept. 11, 1977. Bottom depth = 732m.							
24	1.24	31.73	1.0	4.06	18.55	23.2	0.4 ± 0.1
54	−0.68	32.24	11.6	4.09[β]	18.29[β]	22.3	2.3 ± 0.1[γ]
157	−1.11	33.51	20.7	4.21	19.09	17.4	4.7 ± 0.2
308	−0.74	33.99	16.4	4.25	19.04	12.5	5.2 ± 0.2
612	0.36	34.38	14.2	4.15	18.60	8.7	6.2 ± 0.4
714	—	34.46	—	4.31[α]	19.03[α]	5.7	—
Station 45 76.35N, 89.43W Sept. 13, 1977. Bottom depth = 173m.							
12	−1.21	31.62	22.1	4.18	18.97	25.7	3.4 ± 0.1
54	−1.06	32.83	34.7	4.23	19.04	19.7	6.4 ± 0.1
158	−0.81	33.55	27.0	4.20[β]	—	12.7	7.5 ± 0.4[γ]

Table 1. (Continued)

Depth[δ] (m)	Tp (°C)	S (‰)	δ(^{3}He) (%)	He (10^{-8} ccSTP/g)	Ne	Tritium (T.U.)	^{3}H-^{3}He Age (years)
Station 49 76.08N, 83.83W Sept. 13, 1977. Bottom depth = 585m.							
95	−0.93	33.19	25.9	4.17	18.86	16.3	5.8 ± 0.2
198	−1.30	33.71	11.9	4.14	18.93	16.6	3.1 ± 0.2
403	−0.20	34.23	20.1	4.17	18.86	10.0[β]	7.2 ± 1.2[γ]
562	−0.13	34.30	19.4	4.25	18.66	8.5	8.2 ± 0.3
Station 53 78.32N, 74.27W Sept. 15, 1977. Bottom depth = 534m.							
27	−0.87	32.71	1.5	4.12	18.96	18.5	0.7 ± 0.1
105	−1.17	33.61	19.2	4.20[ε]	—	12.7	5.7 ± 0.3
263	−0.75	33.99	—	4.19	19.08	13.1	—
312	−0.70	34.09	18.2	4.19	18.90	13.2	5.3 ± 0.3
514A	−0.56	34.23	15.4	4.26	18.91	10.9	5.6 ± 0.3
514B	−0.56	34.23	13.9	4.25	18.89	10.0	5.6 ± 0.4
Station 58 77.33N, 74.50W Sept. 16, 1977. Bottom depth = 724m.							
72	−1.32	33.72	14.8	4.18	19.13	15.9	3.8 ± 0.2
103	−1.03	33.79	15.4	4.17	19.04	17.3	3.7 ± 0.2
154	−0.74	33.91	—	—	—	15.1	—
200	−0.34	33.91	15.8	4.20	18.84	12.0	5.2 ± 0.3
255	0.05	34.14	10.1	4.16	18.83	12.0	3.6 ± 0.2
307	−0.09	34.19	12.4	5.40[α]	23.15[α]	10.0	5.0 ± 0.2[γ]
408	−0.28	34.26	16.1	4.14	18.76	8.5	7.0 ± 0.4
512	−0.34	34.31	16.5	4.18	18.81	8.2	7.3 ± 0.5
613	−0.33	34.35	16.3	4.17	18.79	9.3	6.6 ± 0.4
719	−0.32	34.37	15.0	4.27	19.05	9.4	6.2 ± 0.5

[α] Air contamination during sampling or in subsequent processing is suspected. For these samples, δ(^{3}He) values have been corrected, and interpolated He concentrations used to calculate ^{3}H-^{3}He ages.
[β] Interpolated or extrapolated value.
[γ] ^{3}H-^{3}He age calculated using interpolated values for He and/or tritium, or corrected values for δ(^{3}He).
[δ] Depths labelled A or B are duplicate samples taken from the same Niskin bottle.
[ε] He concentration determined by peak height comparison with air standards during ^{3}He/^{4}He analysis. Experimental error is ∼±2% compared to a typical error of ±0.5% for isotope dilution analysis.

^{3}He/^{4}He data is expressed in terms of δ(^{3}He) values where

$$\delta(^3\text{He}) = \left[\frac{(^3\text{He}/^4\text{He})_{\text{sample}}}{(^3\text{He}/^4\text{He})_{\text{atm.}}*} - 1 \right] \times 100\%$$

The average uncertainty in δ(^{3}He) was 0.3% (1σ) for this series of analyses as determined from the scatter of results for identical samples prepared from aliquots of air.

The analytical precision of He and Ne concentrations was ± 0.5% and ± 0.3%,

* $(^3\text{He}/^4\text{He})_{\text{atm.}} = 1.384 \times 10^{-6}$—Clarke *et al.* (1976).
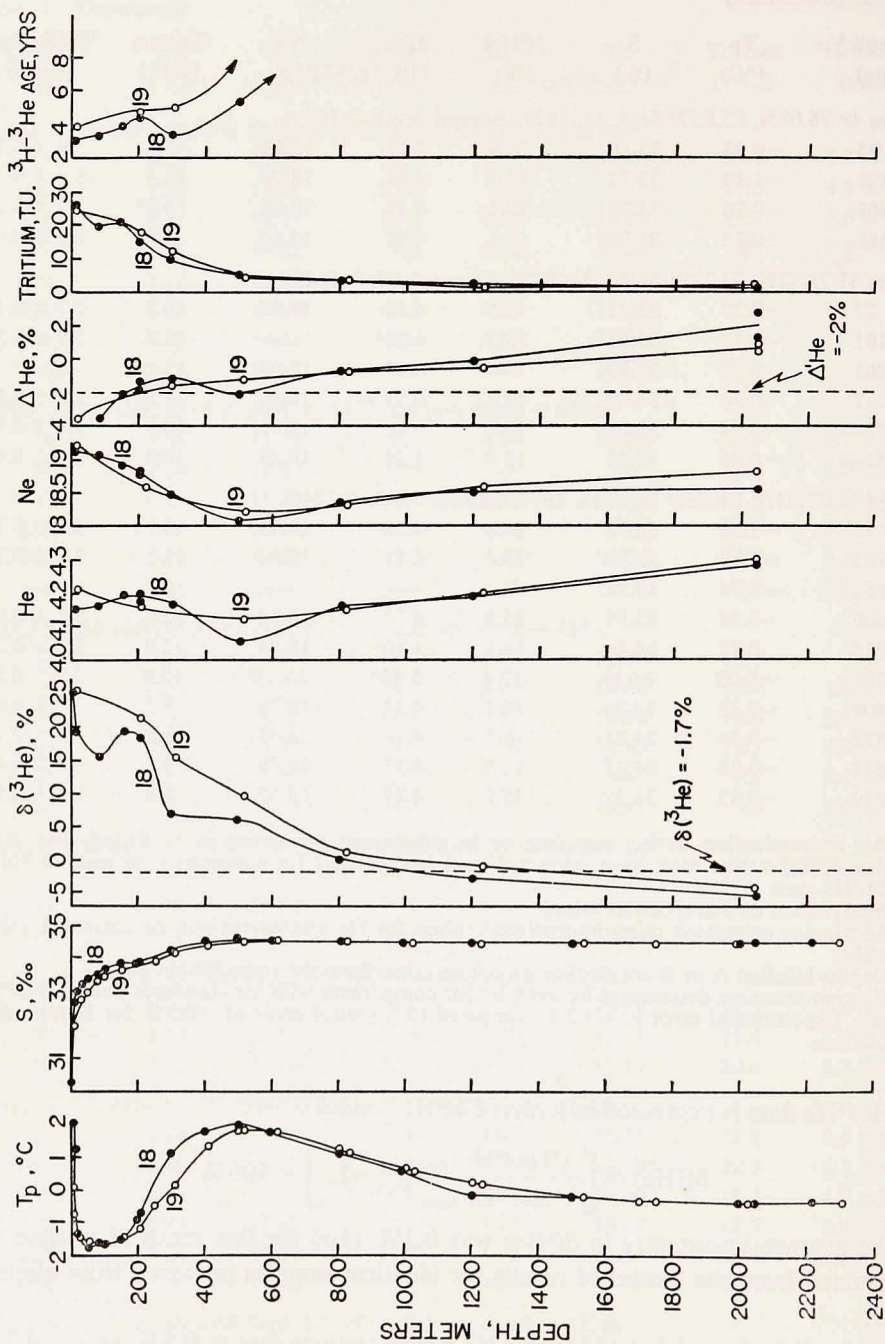
Figure 2. Vertical profiles at station 18 and station 19 in Baffin Bay. Locations are shown in Figure 1. He-Ne concentrations are in units of 10^{-8} cc STP g^{-1}.
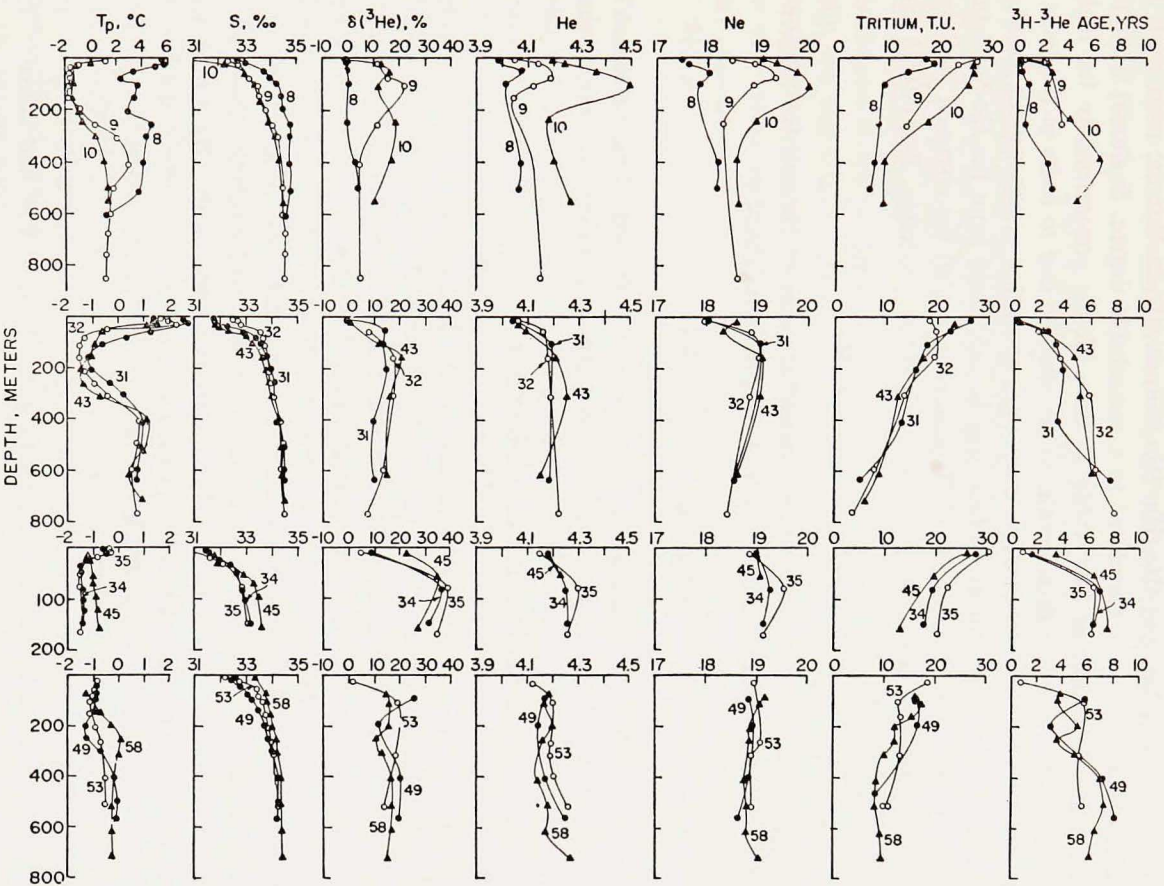
Figure 3. Vertical profiles at stations in Davis Strait and northern sounds. Locations are shown in Figure 1. He-Ne concentrations are in units of 10^{-8} cc STP g^{-1}.

respectively. These errors include 1σ measurement errors determined from the scatter of results for standards as well as estimates of volumetric errors in preparation of $^3\text{He-}^{22}\text{Ne}$ spikes and $^3\text{He-}^4\text{He-}^{20}\text{Ne-}^{22}\text{Ne}$ standards. For the most part, He and Ne concentrations are correlated to a remarkable degree. It should be noted, however, that five samples (see Table 1) have He-Ne concentrations far higher than normal. We attribute these results to air addition due to leaks in the seals of the samplers, or to air contamination during gas extraction or subsequent handling.

A potentially useful parameter which may be calculated from the He-Ne data is $\Delta'\text{He}$, the corrected percent excess of He assuming that all the observed Ne excess relative to solubility equilibrium is due to air injection processes. Beg (1971) gives the following relation:

$$\Delta'\text{He} = \Delta\text{He} - f\,\Delta\text{Ne}$$

where ΔHe and ΔNe are the apparent percent excesses of He and Ne relative to the equilibrium solubility values of Weiss (1971), and f is defined by

$$f(T_p,S) = \frac{(\text{Ne/He})_{\text{seawater}}}{(\text{Ne/He})_{\text{air}}}$$

Most of the $\Delta'\text{He}$ values are negative by up to 4%. We would expect that $\Delta'\text{He}$ values should be close to zero in near surface samples, perhaps increasing above zero in deep samples due to addition of radiogenic ^4He. The negative $\Delta'\text{He}$ values are probably due to the fact that the air-injection model is an oversimplification. When He and Ne are considered in this way, no account can be taken of atmospheric pressure changes, or of temperature changes which occur after gas equilibration. In addition, the effects on He and Ne concentrations due to ice formation and ice melting are unknown. It appears that He-Ne concentrations measured in this work show distinctly different characteristics than He-Ne patterns in Atlantic or Pacific samples. The problem however is complicated, and we reserve discussion for a future paper. In the meantime we will use the $\Delta'\text{He}$ values in a comparative sense at station 18 and station 19 for the deep samples and for samples above 500 m.

Tritium concentrations given in Table 1 were measured by the ^3He growth technique. Analytical precision for tritium varied with the tritium content, the time the degassed water sample was stored before analysis, and other factors. For a discussion of analytical errors in this method for tritium measurement see Clarke *et al.* (1976). For high concentration samples of 10-30 T.U.* errors were about $\pm$ 3%, for samples between 2 and 10 T.U., errors were about $\pm$ 8% and below 2 T.U. errors were about $\pm$ 0.5 T.U.

A tritium-^3He age determination is a specific application of radioactive dating using a parent-daughter pair. The method was first outlined for natural waters by Tolstikhin and Kamenskiy (1969). Suppose a parcel of water is initially in equilib-

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* 1 T.U. $= 1^3\text{H}/10^{18}\text{H}$.

rium with the atmosphere at the sea surface, and then sinks and accumulates ³He from tritium decay. Assuming a closed system, i.e. no mixing with other water parcels of different tritium and ³He content, the relationship between tritium and excess ³He is given by

$$\tau = 17.69 \ln \left[1 + 0.0571 \, (\delta - \delta_{eq.}) \, \frac{(He)}{(^3H)} \right]$$

where τ is the interval (in years) between equilibration at the surface and the time of sampling, δ is the observed value of $\delta(^3He)$, corrected back to the time of sampling and $\delta_{eq.}$ is the helium isotope equilibrium solubility effect at the temperature of the seawater sample. We have used the unpublished $\delta_{eq.}$ data of Top and Clarke in preference to the published data of Weiss (1970) because of two considerations. Firstly, the Top-Clarke data seem more relevant to natural conditions because mass spectrometric measurements of ³He/⁴He were made for air and seawater in equilibrium with the air at closely spaced temperature intervals from −2°C to 20°C. The Weiss measurements were made with microgasometric techniques using pure ³He and ⁴He at approximately 1 atm. pressure, and at three temperatures, 0.07°C, 20.13°C, and 40.46°C. Secondly, the mass spectrometric data is more precise than the microgasometric data. In the equation above, (He) is the He concentration in units of 10^{-8} cc STP g^{-1} and (³H) is the tritium concentration in T.U. The precision of ³H-³He dates given in Table 1 varies from ± 0.1 to ± 1.2 years.

a. Baffin Bay—Stations 18 and 19. Temperature and salinity data (see Figure 2) outline the relatively warm and saline Atlantic water core ($T_p = 1.9$°C, $S = 34.6$‰) at a depth of approximately 500 m. This water mass is discernible in the $\delta(^3He)$ values at station 18 but not at station 19, probably because of mixing of the Baffin current with the Western Greenland current at the latter location. At station 18 the shallow Baffin Bay water is clearly identified at 150-200 m by well defined maxima in $\delta(^3He)$, He, and tritium-³He age. A less prominent tritium maximum indicates an Arctic origin for some of the water, which is in agreement with the considerations of Muench (1971). This feature cannot be seen at station 19 due perhaps to sparsity of sampling in the upper 200 m.

At both stations, $\delta(^3He)$ is extraordinarily high near the surface, gradually decreasing with increasing depth. The usual pattern observed for $\delta(^3He)$ in the upper 1 km in the world oceans is one of values close to zero in surface samples with a shallow $\delta(^3He)$ maximum at a depth which depends on the depth of the main thermocline, the tritium concentration and other factors—see for example the GEOSECS Atlantic profiles described by Jenkins and Clarke (1976). In that study only one Atlantic Station (station 74, 55S 50W) showed a near-surface $\delta(^3He)$ pattern similar to the patterns observed at stations 18 and 19. These high values of $\delta(^3He)$ near the surface coupled with unusually high tritium-³He ages demonstrate the effect of the shallow pycnocline which is common to regions where seasonal melting of

ice occurs. At stations 18 and 19, a thin, low-density surface layer (σ_t varies from 24.23 to 26.54 in the top 20 m) acts as a "lid" on the underlying water and greatly decreases the rate of exchange of helium with the atmosphere. These observations show that the thickness of the mixed layer is less than 10 m in these locations.

Another unusual feature of the Baffin Bay profiles is that $\delta(^3He)$ decreases to values significantly below zero in the deep water. In Figure 2 the dashed line drawn at $\delta(^3He) = -1.7\%$ represents the helium isotope equilibrium solubility effect for seawater at 0°C (Top and Clarke; unpublished). The $\delta(^3He)$ values below -1.7% observed at 1201 m and 2044 m (station 18) and at 2046 m (station 19) must be due to addition of radiogenic ^4He which has a greater effect on $^3He/^4He$ than any addition of ^3He either from tritium decay or of primordial origin from the mantle. Because addition of ^3He cannot be dismissed *a priori*, the deep $\delta(^3He)$ values merely set lower limits on the percentage of radiogenic ^4He. The average $\delta(^3He)$ for the deepest samples at stations 18 and 19 is -4.7%. Thus a *minimum* radiogenic ^4He component of 3% is needed to account for the observed decrease in $\delta(^3He)$ from the equilibrium solubility value of -1.7%. An independent estimate of radiogenic ^4He input can be obtained from the He-Ne concentration data. Plots of $\Delta'He$, the percent He excess relative to solubility after correction for air injection are shown in Figure 2. Both profiles clearly show an increasing trend of $\Delta'He$ with depth which we interpret as being due to the presence of radiogenic ^4He in the deep water. The dashed line drawn in the $\Delta'He$ diagram represents an average value of -2.0% in the upper 600 m at station 18 (excluding the surface $\Delta'He$ value of -6.0%). The bottom sample at this station has a $\Delta'He$ value of $+ 2.0\%$, indicating 4.0% excess of radiogenic ^4He. A similar comparison for station 19 gives a value of 2.7% radiogenic ^4He. The average for both stations is 3.4%. This value is approximate, with an assigned uncertainty of $\pm 1.5\%$ because the $\Delta'He$ calculation involves only two conservative gases, and the effects of atmospheric pressure variations and possible temperature changes after gas equilibration cannot be evaluated—for a detailed account of these effects see Craig and Weiss (1971). Nevertheless, the close agreement between the radiogenic ^4He percentage obtained from $\Delta'He$ data and the lower limit obtained from $\delta(^3He)$ data indicates a relatively small addition of ^3He of radiogenic and, or, primordial origin to the bottom water, somewhere between zero and 1.9% of the dissolved ^3He.

A systematic difference between ages in the upper 500 m is apparent: the average age for this layer is 4 years at station 18 and 5.5 years at station 19. Measurements of dissolved oxygen utilization are consistent with this observation: $\Delta O_2 = -1.19$ ml l^{-1} at station 19 and $\Delta O_2 = -1.03$ ml l^{-1} at station 18 where $\Delta O_2 = (O_2)_{measured} - (O_2)_{equilibrium}$ using the equilibrium solubility values of Green and Carritt (1967). The age difference in the upper 500 m can be explained by considering the low tritium-^3He ages determined for Atlantic water entering Baffin Bay (see data for station 8 in Figure 3) and the circulation pattern in Baffin Bay shown in

Figure 1. The Baffin current carries a mixture of Arctic water and Baffin Bay water along the western side of the bay north of Lancaster Sound. The current swings eastward south of Lancaster Sound, influencing station 19 to a greater extent than station 18. Although station 19 must be influenced to some extent by Atlantic water carried by the West Greenland current, the effect on station 18 must be more important in order to produce the observed age difference.

While the ^{3}H-^{3}He ages may be taken at face value in the top several hundred meters where the main mode of transport is advection, at greater depths the effect of diffusive exchange must be taken into account. In order to obtain an estimate of the exchange time between the upper and the deep layers a simple one-dimensional two-box model was considered (see Fig. 4). The upper box is assumed to extend from the surface to 1200 m, and the bottom box includes depths below 1200 m, where very small gradients are observed for potential temperature—see Figure 2. The choice of the upper 1200 m as a well mixed box is certainly not ideal because the upper box is in communication with the Labrador Sea at depths above 800 m. However, the results obtained using integral-averaged tracer concentrations for the upper box should be similar to results using a more realistic two-box model for the upper 1200 m. The two tracers are radioactive tritium and its stable daughter ^{3}He. Using the method described by Peterson and Rooth (1976), the model equations are:

$$\frac{dC_1}{dt} + \lambda C_1 = \mu(C_1' - C_1) + J_1 \tag{1}$$

$$\frac{dC_2}{dt} - \lambda C_1 = \mu(C_2' - C_2) + J_2 \tag{2}$$

where

C_1 = tritium concentration in the deep box, in atoms g^{-1}
C_2 = ^{3}He concentration in the deep box, in atoms g^{-1}
C_1' = tritium concentration in the upper box, in atoms g^{-1}
C_2' = ^{3}He concentration in the upper box, in atoms g^{-1}
J_1 = tritium source term in the deep box, in atoms g^{-1} y^{-1}
J_2 = ^{3}He source term in the deep box, in atoms g^{-1} y^{-1}
λ = decay constant for tritium = 0.0566 y^{-1}
μ = exchange coefficient in y^{-1}

Before attempting the solutions the time dependency of the average concentrations of tritium and ^{3}He must be established. We would expect the average concentration of tritium in the upper box to follow a similar form to that of the surface tritium with some time lag. Such a function has been calculated by Dreisigacker and Roether (1978), however the actual form of the function is too complex to allow for a simple solution for the above equations. Two alternatives were considered: 1) Approximation with a form $C_1'(t) = ae^{-kt}$ with time zero shifted to 1969 and

2) Approximation with a form $C_1'(t) = z(1 - e^{-\bullet t})$ with time zero at 1962. Both choices were found to lead to comparable exchange times, however, a finite range for the values of μ could only be obtained using the latter form. Adjusting the Dreisigacker and Roether function for present measurements, the parameters z and x were calculated to be 9 T.U. and 0.64 y^{-1}, respectively. The time variation of average ³He is due to the radioactive decay of tritium and can be represented by

$$C_1'(t) = b + c(1 - e^{-\alpha t}) \tag{3}$$

The assumption made to calculate the numerical value of the parameter α is that the ³He concentration in 1977 in the upper box (C_2') had reached 98% of its asymptotic value, $b + c$. Further, ³He concentration at time zero (b) was chosen to be 4% above solubility equilibrium to allow for an air-injected component in accordance with the observations. These assumptions led to the value of $\alpha = 0.03$ y^{-1}.

Time dependent solutions of the simultaneous equations (1) and (2) can be found by taking the Laplace transforms with $C_1'(t)$ having the form of $z(1 - e^{-\bullet t})$ and no source terms $(J_1 = J_2 = 0)$. Solving for the transformed equations and inverting yields:

$$C_1 = C_1 (O).A + (\mu z/DE) (E(1-A) + D(G-A)) \tag{4}$$

$$C_2 = C_2 (O).B + (b+c) (1-B) + \mu c(K-B)/L + C_1 (O) (B-A) \\ + z(\lambda/D-B) + (z\mu/DEF) (AEF-ADF+BDE-\lambda DG) \tag{5}$$

where

$$A = e^{-(\lambda+\mu)t} \qquad\qquad F = \mu-x$$
$$B = e^{-\mu t} \qquad\qquad\quad G = e^{-\bullet t}$$
$$D = \lambda+\mu \qquad\qquad\quad K = e^{-\alpha t}$$
$$E = \lambda+\mu-x \qquad\qquad L = \alpha-\mu$$

The observed values of tritium and ³He concentrations to be matched by these equations are 0.7 ± 0.5 T.U. and $1.525 \pm .015 \times 10^6$ atoms/g, respectively. The tritium measurement of 1.6 ± 0.5 T.U. at 2046 m (station 19) was ignored because of our suspicion that this sample had been contaminated. The limits of the range for values of μ which simultaneously satisfy the observed concentrations in the deep box were graphically determined to be 0.0022 and 0.013 y^{-1}. The best value of μ in this interval which fits the actual measurements is 0.0074 y^{-1}. These figures correspond to an exchange time of $135 \pm \begin{smallmatrix}320\\58\end{smallmatrix}$ y.

For the present we will assume that the excess ⁴He in the deep water is radiogenic, originating from U and Th decay in the solid earth, most probably in the bottom sediments of Baffin Bay. The average radiogenic ⁴He excess below 1200 m as determined from consideration of Δ'He data is 2.5%—see Figure 2. Thus, using the exchange time determined above, we obtain a ⁴He flux $\phi(4) = 5.2 \begin{smallmatrix}+3.9\\-3.7\end{smallmatrix} \times 10^5$
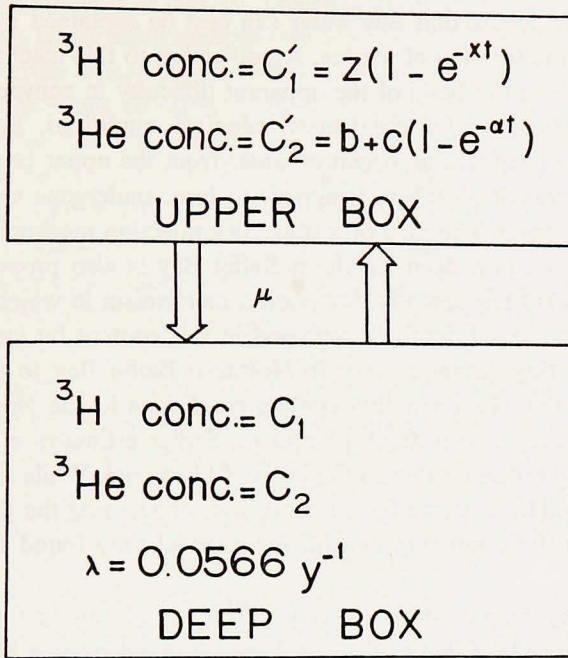
Figure 4. Two-box model for vertical exchange of tritium and ^{3}He.

atoms cm^{-2} sec^{-1}. This value can be compared with the mean world ocean average of $3 \pm 1.5 \times 10^5$ atoms cm^{-2} sec^{-1} given by Craig *et al.* (1975).

The condition for the existence of solutions to equations (4) and (5) which satisfy the observed concentrations of ^{3}He and tritium in the bottom box severely restricts the amount of excess ^{3}He of primordial origin. We estimate that no more than 1% of observed ^{3}He could be from this source. The upper limit of primordial ^{3}He flux is given by $\dfrac{\phi(3)}{\phi(4)} = \dfrac{1}{2.5} \times R_s$, where $R_s = 1.35 \times 10^{-6}$ is the ^{3}He/^{4}He ratio in Baffin Bay bottom water, and $\phi(4) = 9.1 \times 10^5$ atoms cm^{-2} sec^{-1}. The upper limit of $\phi(3)$ is 0.5 atoms cm^{-2} sec^{-1} which is significantly smaller than the estimated world ocean primordial ^{3}He flux of 4 ± 1 atoms cm^{-2} sec^{-1} given by Craig *et al.* (1975). This observation suggests a relative lack of tectonic activity on the deep floor of Baffin Bay, or that the mantle underneath is lower than average in primordial ^{3}He.

The origin of the Baffin Bay Bottom water is uncertain. Sverdrup *et al.* (1942) suggested a mixture of Labrador Sea deep water and Baffin Bay surface water, the salinity of which had been increased by ice formation, to form the bottom water. In this connection, Redfield and Friedman (1969) measured deuterium contents of the surface and deep waters in the polar regions and concluded that the deuterium-

salinity relations in deep Baffin Bay water can best be explained by the addition of brine liberated in the freezing of sea-ice. An objection to this mechanism was raised by Muench (1971) on the basis of the apparent difficulty in convecting the mixture to depths below 200 m under usual meteorological conditions. Bailey (1956) and Collin (1965) have proposed an origin of water from the upper layers of the Arctic Ocean through Nares Strait where it appear to have undergone some modification by the addition of brine. The idea of a transitory injection mechanism of this water through Smith Sound into deep Northern Baffin Bay is also proposed by Muench (1971). Sadler (1976) has recently described a mechanism in which water from the Nares Strait above the sill depth is increased in salt content by ice formation, and mixes with Baffin Bay Atlantic water in Northern Baffin Bay to form the bottom water. He argues that the prevailing cooling conditions in the North water region should allow convection to a depth of 500 m. Sadler estimates a renewal time of 20 y for Baffin Bay bottom water on the basis of his model. While the above mechanism seems reasonable to us, we have reservations concerning the time scale on two counts apart from the disagreement with the renewal time found from tritium-^{3}He data.

Firstly, using the deep Atlantic oxygen utilization rate upper limit of 2×10^{-3} ml l^{-1} y^{-1} estimated by Riley (1951), and the observed oxygen utilization of $\Delta O_2 = -3$ ml l^{-1} at 2044 m, station 18, we obtain a renewal age of at least 1500 y. Alternatively, using the range of values of $2.7 - 5.3 \times 10^{-3}$ ml l^{-1} y^{-1} estimated by Munk (1966) for the deep North Pacific, the renewal time is somewhere between 1100 y and 570 y. Even though caution should be exercised when different regions are compared, it does not seem reasonable to suppose that the oxygen utilization rate in deep Baffin Bay is 50 times greater than the above estimates. Secondly, the expected tritium concentration in the bottom water can be calculated using the two-box model for tritium alone. If the initial conditions and boundary values are adjusted to fit the observed properties in the North Water region, and an exchange time of 20 y is assumed, we obtain a predicted 1977 tritium value of 4 T.U. in the bottom water. The observed tritium concentration in the bottom water is about 1 T.U., which requires a higher exchange time than 20 y.

It seems fairly certain that the observed properties in the deep water require some process of salt addition, and some scheme such as mixing of Arctic and Baffin Bay Atlantic water as proposed by Sadler (1976). What seems to be crucial is the time scale for the mechanism. Although the North water region appears to be the most likely location for salt addition to occur, convection to 500 m may be a rare event indeed, and bottom water may yet be formed at the rate required by the tritium-^{3}He data. It is also possible that other parts of the Bay could act as source regions for infrequent additions to the bottom water. The implications for proposed monitoring of deep convection during bottom water formation in Baffin Bay are obvious.

b. Davis Strait—Stations 8, 9 and 10. Oceanographic properties are markedly different for the three Davis Strait stations (see Fig. 3). Station 8 is swept by the Western Greenland current which carries relatively warm and saline Atlantic water into Baffin Bay. Stations 9 and 10 intercept the Baffin Bay current travelling southward. In the upper 200 m, the water at station 8 is clearly different from the water at stations 9 and 10 on the basis of T_p and S data, although station 9 can barely be distinguished from station 10. The three stations can easily be distinguished by the distinct maxima in He and Ne at 50 m, 75 m and 100 m (stations 8, 9 and 10 respectively) which closely follow the $\sigma_t = 26.80$ surface across Davis Strait. This feature is most prominent at station 10, and must therefore be a real characteristic of the Baffin current, which spreads laterally as far east as station 8. The origin of the He-Ne maximum is not understood at present. The anomalies (at station 10) seem far too large to be accounted for by temperature changes after gas equilibration, pressure changes, or by mixing of water types equilibrated at different temperatures. Air injection might be considered to be responsible for part of the effect in some *ad hoc* manner—it could be supposed for example that a storm about two years prior to sampling in 1977 caused air bubble injection and the observed supersaturation of He and Ne. However, the He-Ne results do not seem to fit the expected pattern for air injection, and moreover we see no evidence whatsoever for excess oxygen, or oxygen maxima at the appropriate depths at stations 8, 9 and 10. It is also very puzzling that this feature is not seen at other stations which are influenced to varying extent by the Baffin current—Stations 19, 31, 32 and 43, or at stations which intercept the Arctic Ocean water flowing into Baffin Bay—stations 34, 35, 45 and 53. These facts suggest an origin somewhere between a position considerably south of Lancaster Sound, so as to avoid station 19, and the location of station 10. We suspect at present that winter ice-formation may cause supersaturation of He and Ne—further sampling and/or laboratory experiments are needed to resolve this question. However, whatever mechanism is responsible, the large and easily measurable anomalies in He and Ne could provide interesting and useful tracer information in the future.

Distinct differences between stations 8, 9 and 10 are also seen in the profiles of $\delta(^3\text{He})$, tritium, and tritium-^{3}He age (Fig. 3). The tritium data shows the extent to which the Baffin current is influenced by high-tritium Arctic Ocean water (stations 9 and 10) and also how station 8 is influenced by low-tritium Atlantic water. Tritium-^{3}He ages also show distinct differences between the relatively young Atlantic water (about 1 y at 100 m, station 8) and the Baffin current (about 2 y at 100 m, station 10).

c. Lancaster Sound—Stations 31, 32 and 43. The locations of these stations are influenced by Arctic Ocean water and by Baffin Bay Atlantic water according to Muench (1971). Below about 200 m, the presence of the Baffin Bay Atlantic water

is clearly evident from T_p and S data. $\delta(^3He)$ profiles are similar for stations 32 and 43 which are different from the $\delta(^3He)$ profile at station 31. He profiles are similar for stations 31 and 32, and station 43 shows a He maximum at about 300 m. Ne profiles are similar for all three stations. Near-surface samples are high in tritium (18-26 T.U.) at all three stations, with stations 31 and 43 higher than station 32. This observation is due either to an increased influence of high-tritium run-off water on stations 31 and 43 versus station 32, or that the Baffin Bay Atlantic water exerts more influence near the surface on station 32. The latter explanation is in agreement with the salinity data in the upper 50 m. Tritium-^{3}He age profiles are quite similar, ranging from about 0.3 y in near-surface samples to about 7 y at 600 m. A tritium-^{3}He age minimum of 3.4 y at 400 m is seen at station 31—this feature does not appear to be related to other oceanographic properties.

d. Resolute and Fram Sound—Stations 34, 35 and 45. Stations 34 and 35 show closely similar values for T_p and S in the expected range for Arctic Ocean water with no apparent intrusion of Baffin Bay Atlantic water. T_p and S values for station 45 are higher, indicating a small effect from Baffin Bay Atlantic water which enters Jones Sound. Tritium values at all depths are higher for station 35 than for station 34 which is due either to different proportions of high-tritium run-off water, or may reflect a real difference in tritium concentration at the Arctic Ocean sources which are presumably in the Canadian Basin. The relatively low tritium values seen at station 45 in Fram Sound probably also reflect a real difference in source tritium compared to the sources of water which flow past the positions of stations 34 and 35. Tritium-^{3}He ages are very similar for stations 34 and 35, with slightly higher ages found at station 45.

e. Jones Sound and Smith Sound—Stations 49, 53 and 58. All three stations are influenced to some extent by Baffin Bay Atlantic water. Station 53 seems to be affected the most. The low tritium values (about 13 T.U.) seen below 100 m at station 53 probably reflect the tritium concentration in the upper water of the Lincoln Sea which is distinctly lower in tritium than the water at roughly similar depths in the Canadian Basin. In this connection, the source for station 45 appears to be about 15 T.U. (50-150 m) and the source for stations 34 and 35 is about 21 T.U. at similar depths. Thus the source for station 45 is intermediate in tritium concentration between the sources for stations 34 and 35 and station 53, but station 45 appears to be closer in tritium to station 53 than to station 34 or 35.

4. Summary

The He, Ne and tritium results are in general agreement with the structure and circulation pattern proposed by Muench (1971). At some stations, notably stations 8, 9, 10, 18 and 19, the above tracers reveal information which is not obtainable

using conventional oceanographic tracers—T_p, S, O_2 and nutrients. Although we can only speculate at present about the origin of the 100 m maximum in He and Ne seen at station 10, the large size of the anomaly indicates that it might provide a worthwhile tracer for the Baffin current. Perhaps the most striking result was at stations 18 and 19 where clear evidence for radiogenic ^{4}He is found in the deep water. A two-box model calculation using the tracers tritium and ^{3}He gives a deep water renewal time of 77-455 y, which is in fair agreement with estimates based on deep ocean oxygen utilization rates. The ^{4}He flux into the deep water is calculated to be $5.2 \begin{smallmatrix}+3.9\\-3.7\end{smallmatrix} \times 10^5$ atoms cm^{-2} sec^{-1}, which is in good agreement with the world-ocean average. The upper limit for the primordial ^{3}He flux into the deep water is 0.5 atoms cm^{-2} sec^{-1}, which is only about one tenth of the world-ocean estimate, indicating a recent lack of tectonic activity on the floor of Baffin Bay, and/or a depletion in primordial ^{3}He in the mantle underneath Baffin Bay.

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