Deep-Sea Research, Vol. 35, No. 12, pp. 1919–1935, 1988
Printed in Great Britain.

0198-0149/88 $3.00 + 0.00

^{3}He in the Bransfield Strait waters: indication for local injection from back-arc rifting

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(*Received* 4 *November* 1987; *in revised form* 27 *June* 1988; *accepted* 11 *July* 1988)

Abstract—Helium data from the waters of the Bransfield Strait, the southern Drake Passage and the northwestern shelf of the Weddell Sea are presented. The ^{3}He profiles from the eastern and central basins of the Bransfield Strait show maxima (δ^3He ≈ 7%) below the sill depths that separate the strait from the surrounding open ocean. The ^{3}He excess is interpreted as a local injection of a ^{3}He-rich helium component into the deep waters of the Bransfield Strait from back-arc rifting. Tritiogenic ^{3}He and excess ^{3}He from mixing with Circumpolar Deep Water are excluded as possible sources. The estimated ^{3}He/^{4}He ratio of the injected helium component ($2.4–5.0 \times 10^{-6}$) is less than that of pure mantle helium and may contain radiogenic helium from continental crustal material which underlies the Bransfield Strait.

1. INTRODUCTION

THE Bransfield Strait, the northernmost extremity of Antarctica, is essentially a 100 km wide trough trending southwest to northeast between the Antarctic Peninsula and the South Shetland Islands (Fig. 1a). The Strait extends for about 460 km between Low Island and Clarence Island. The axial depth of the trough varies from 1100 m in the southwest to 2800 m in the northeast, south of Elephant Island (BARKER and GRIFFITH, 1972); it consists of three major basins separated from each other by sills of less than 1500 m in depth. Following GORDON and NOWLIN (1978), we refer to these basins as the western, the central, and the eastern basins. The deepest connections between the Bransfield Strait and the surrounding open ocean are channels near Clarence Island (≈ 1000 m) at the eastern end and between Smith and Snow Islands (≈ 500 m) at the western end of the Strait. Thus, no direct water exchange is apparent between the deep Bransfield Strait and the open ocean at depths much below 1000 m.

The Bransfield Strait is thought to be an active marginal basin either in a back-arc tectonic setting (BARKER and DALZIEL, 1983) or along a transform fault (CRADDOCK, 1983). Submarine volcanism and hydrothermal activity were recently observed (WHITICAR *et al.*, 1985; SUESS *et al.*, 1988). Rifting is known to supply mantle helium to the deep ocean which is characterized by a ^{3}He/^{4}He ratio higher by about a factor of 10 compared to the atmospheric helium isotope ratio of 1.384×10^{-6} (CLARKE *et al.*, 1969; CRAIG and

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LUPTON, 1981). The purpose of this paper is to present helium data from stations located in the Bransfield Strait, the southern Drake Passage, and the northern Weddell Sea and to demonstrate that these data are consistent with a local injection of ^3He into the deep water of the Bransfield Strait. This interpretation is based on data from two separate cruises and supports the more detailed investigation of thermal interaction between back-arc volcanism and basin sediments presently underway (SUESS *et al.*, 1988; in preparation).

2. SAMPLE COLLECTION AND MEASUREMENT

Water samples for helium isotope measurement were obtained on Legs 2 and 3 of the Third Antarctic Expedition of the German Polar R. V. *Polarstern* (ANT III, November 1984–January 1985) at nine stations located in the central and eastern basins of the Bransfield Strait, the southern Drake Passage, and on the shelf of the northern Weddell

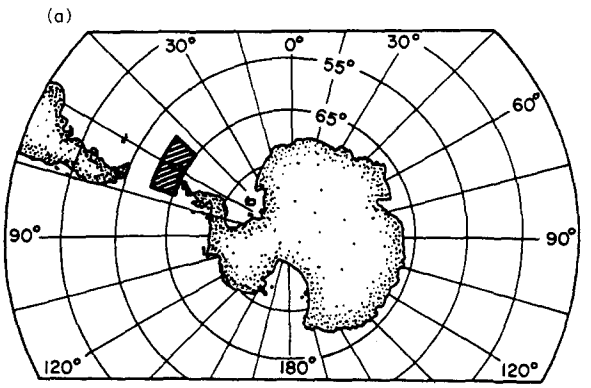

Fig. 1a.

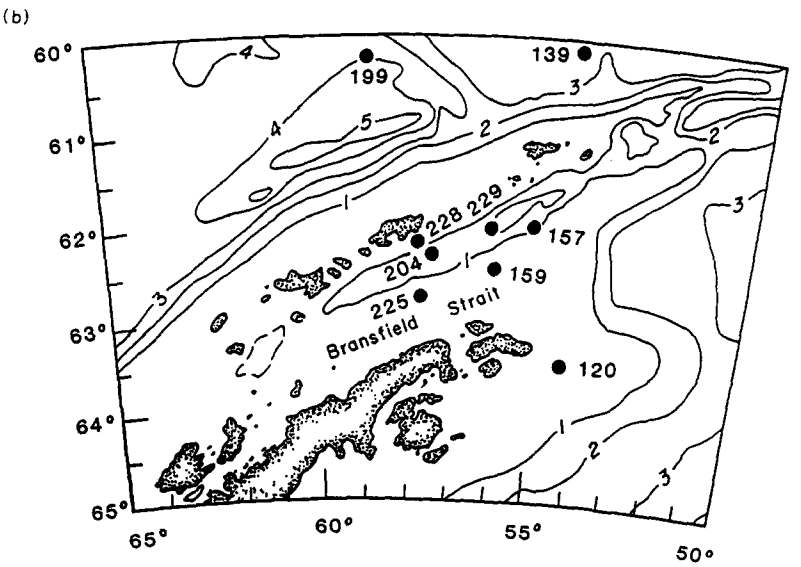

Fig. 1b.

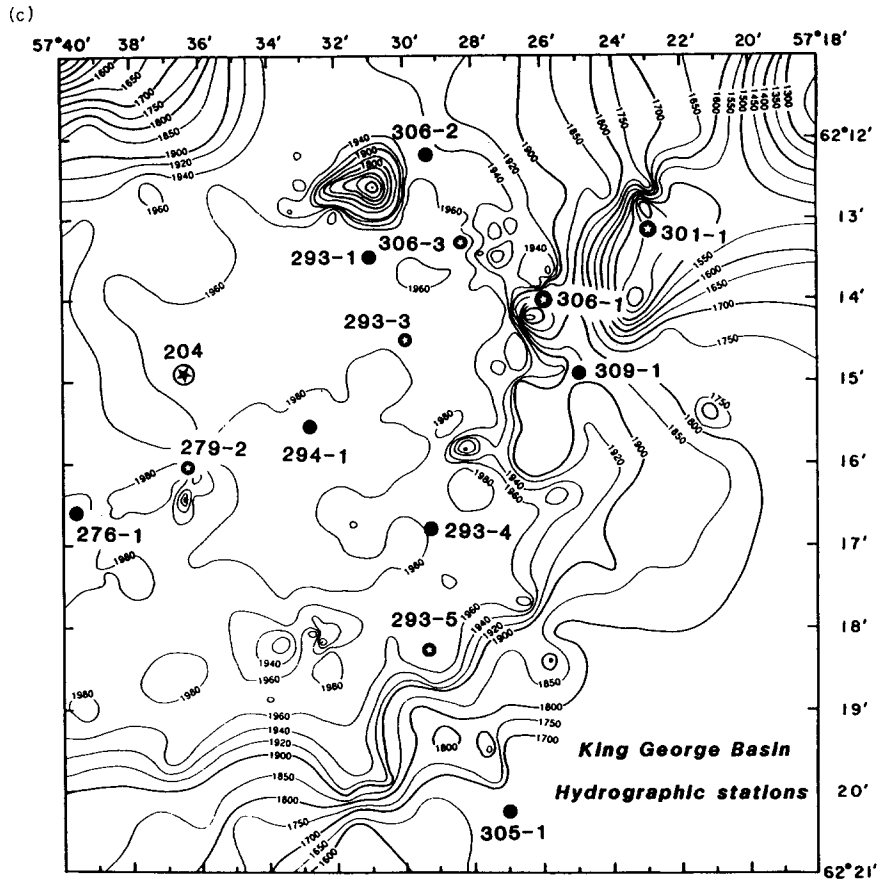

Fig. 1. (a) Map showing the geographical position of the Bransfield Strait. (b) Geographical position of the ANT III helium stations. (c) Geographical position of the ANT IV helium stations.

Sea (Fig. 1b). Additional samples were collected at four stations during Leg 2 of the Fourth Antarctic Expedition of *Polarstern* (ANT IV, November 1985) in the central basin of the Bransfield Strait (Fig. 1d). The sampling during ANT IV was concentrated in the deep and bottom waters and only at Sta. 306 were samples from depths shallower than 1000 m taken.

The water was subsampled from a rosette/CTD system equipped with a Neil Brown Mark III CTD profiler and 12 Niskin bottles (volume: 12 l) and stored in pinched-off copper tubing. In the laboratory, the water samples were degassed in a vacuum extraction system and, after separating other gases including neon, the helium isotopes were measured using a dedicated mass spectrometer (LYNCH and KAY, 1981). ^{3}He results are reported as deviations of the measured helium isotope ratio R ($R = [^3He]/[^4He]$) from that of atmospheric air, i.e. $\delta^3He = ((R_{sample}-R_{air})/R_{air}) \times 100\%$. ^{4}He results are given in units of 10^{-8}cc STP/g H_2O, or as deviations from the solubility equilibrium, Δ^4He, where $\Delta^4He = (([^4He_{sample} - {}^4He_{eq})/{}^4He_{eq}) \times 100\%$ and $^4He_{eq}$ is the ^{4}He concentration of water in solubility equilibrium with the atmosphere (WEISS, 1971). The overall

precision of the ^{3}He data is ±0.2% or better, and that of the ^{4}He data is estimated to be about ±0.5%. The accuracy of the ^{4}He data is about ±1%. The ^{3}He data are not corrected for tritium decay during storage of the samples prior to measurement. However, the maximum tritium concentration was measured in samples from the Bransfield Strait to be about 0.5 TR, which leads to a negligible increase of δ^3He, of at most 0.06%, in the storage time of ≤6 months.

3. HYDROGRAPHY

The basic hydrographic features of the Bransfield Strait have been described by CLOWES (1934). The relatively warm and low-salinity surface waters which are prominent in the northern and western part of the Bransfield Strait are advected from the Bellingshausen Sea into the Strait. The same holds for the subsurface temperature and salinity maximum. The southeastern Bransfield Strait is influenced by Weddell Sea waters entering the Strait over the continental shelf near d'Urville and Joinville Islands. This water is colder and more saline than the Bellingshausen Sea water. The waters below 1000 m in the Bransfield Strait are colder and less saline than the waters of the surrounding open ocean at comparable depths. From this discrepancy Clowes concluded that the bottom water of the Bransfield Strait is essentially formed within the Strait and that it is winter thermohaline alteration of the waters situated over the continental shelf of the Antarctic Peninsula bounding the Bransfield Strait which contributes to the renewal of bottom water. GORDON and NOWLIN (1978) concluded from T–S data that one mixing component of near-surface water in the convective renewal of the Bransfield Strait bottom water is the same as that involved in the Weddell Sea bottom water formation. This water mass is found on the shelves of the northwestern Weddell Sea and the southeastern Bransfield Strait.

The T–S diagram for the ANT III stations (Fig. 2a) supports the idea of deep water renewal from the southern shelf of the Bransfield Strait bordering the Antarctic Peninsula; the deep water T–S characteristics are very similar to those of the stations located on the shelves of the northern Weddell Sea (Sta. 120) and the southern Bransfield Strait (Sta. 225). The small differences may be caused by admixture of water with higher temperatures and salinities or by modification of the shelf water in the winter, when most of the deep water should be formed. The different T–S characteristics for the deep water of the eastern and central basins described by GORDON and NOWLIN (1978) are reflected in the T–S plot. Station 204 in the central basin shows lower temperatures and slightly higher salinities in the deep water in comparison to values at Stas 229 and 157 located in the eastern basin. The influence of the Circumpolar Deep Water (Stas 199 and 139) on the deep water of the Bransfield Strait is only of minor importance. The ANT IV T–S data of the Bransfield Strait deep water (Fig. 2b) are very similar to the ANT III data.

4. ^{3}He DATA

The ^{3}He data are plotted in Fig. 3 and listed in Tables 1 and 2. The ANT III profiles from the eastern and central basins of the Bransfield Strait (Fig. 3a) show surface ^{3}He values near the solubility equilibrium of –2% (FUCHS *et al.*, 1987). The ^{3}He values increase with depth to reach a maximum of about 4.5% in the deep water (depth

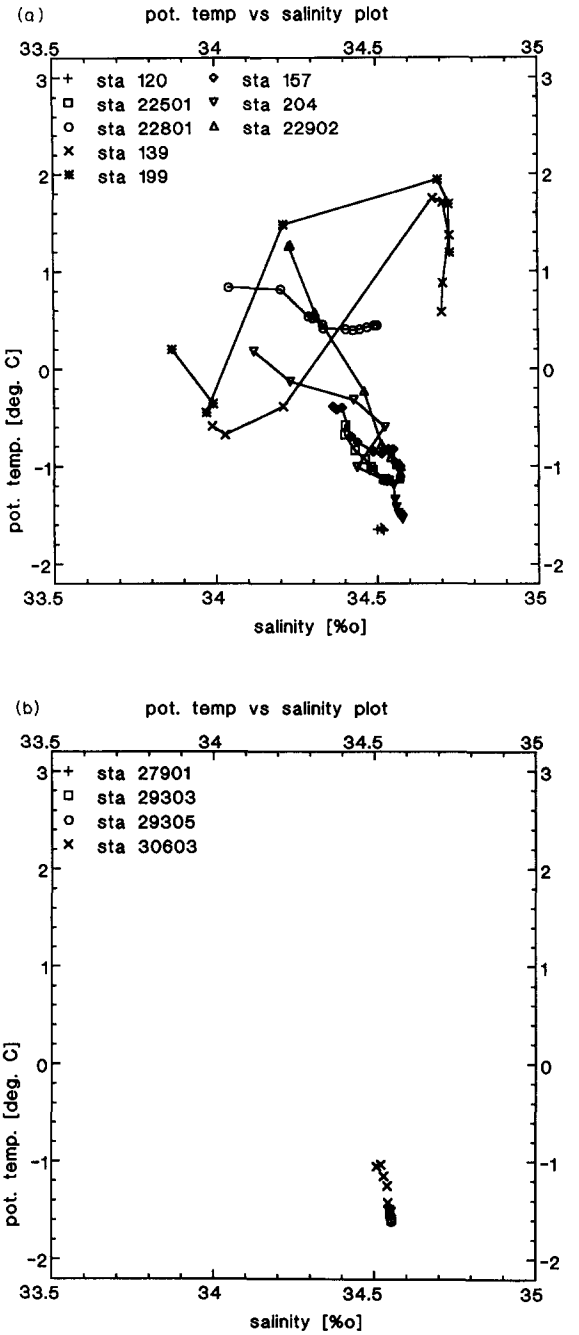

Fig. 2. θ–S plots. (a) ANT III stations located in the southern Drake Passage (139, 199), the eastern basin of the Bransfield Strait (157, 22902), the central basin of the Bransfield Strait (204), the shelf of the Bransfield Strait (22801, 22501), and the shelf of the northern Weddell Sea (120). (b) ANT IV stations located in the central basin of the Bransfield Strait.

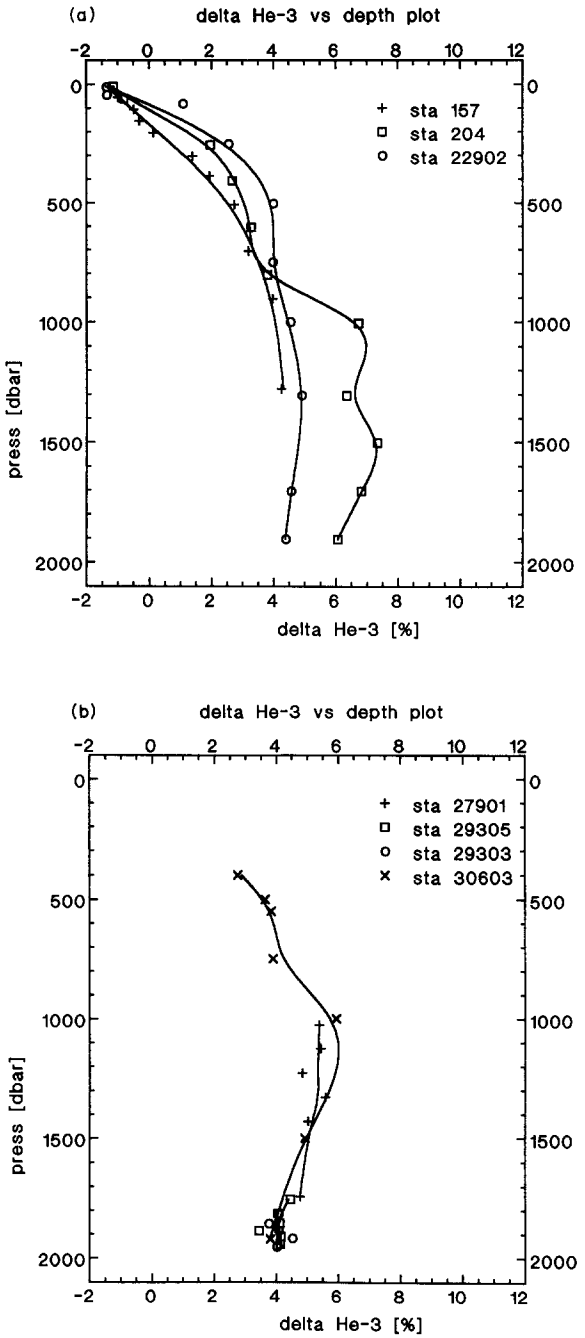
(a)
delta He-3 vs depth plot
sta 157
sta 204
sta 22902
press [dbar]
delta He-3 [%]
(b)
delta He-3 vs depth plot
sta 27901
sta 29305
sta 29303
sta 30603
press [dbar]
delta He-3 [%]

Fig. 3a, b.

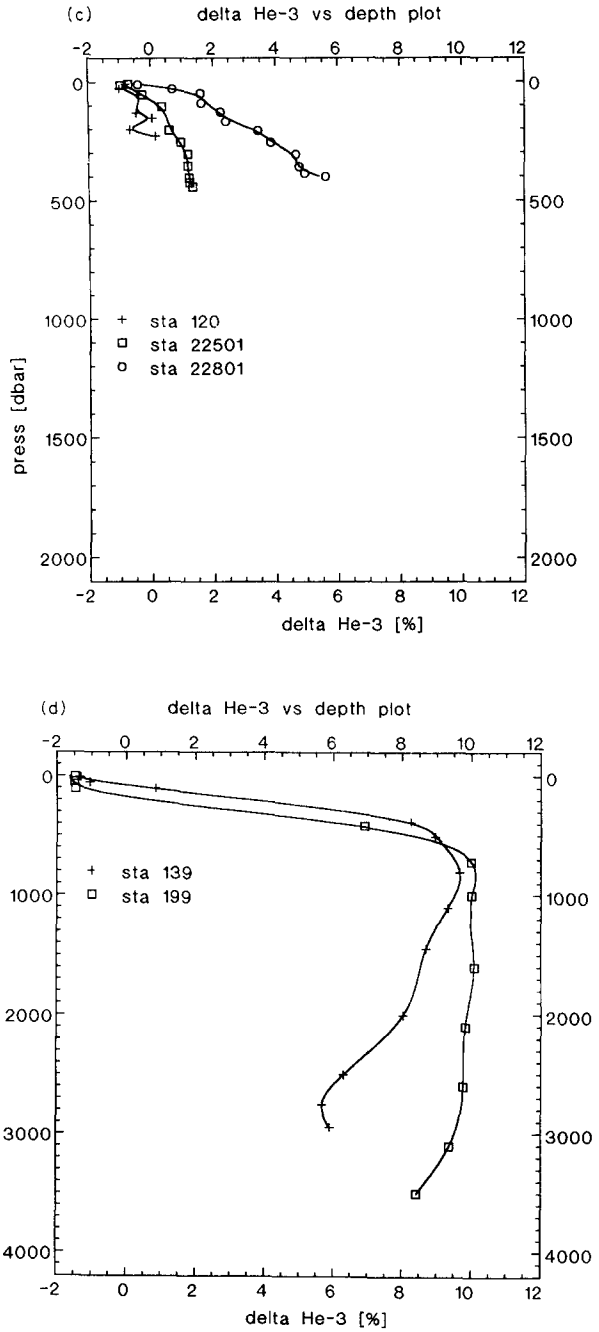

Fig. 3. ^{3}He depth profiles. (a) ANT III stations, eastern (22902, 157) and central (204) basin of the Bransfield Strait. (b) ANT IV stations, central basin of the Bransfield Strait. (c) ANT III stations, shelves of the Bransfield Strait (22501, 22801) and the northern Weddell Sea (120). (d) ANT III stations, southern Drake Passage.

Table 1. *Helium isotope and hydrographic data,* Polarstern *cruise ANT III, Legs* 2 *and* 3, *November* 1984–*March* 1985

Pressure (dbar)	θ (°C)	Salinity (‰)	δ^3He (%)	c^4He (10^{-8}cc STP/g H_2O)	Δ^4He (%)
Station: 120					
Position: 63.50°S, 54.25°W					
Date: 21 November 1984					
9	−1.65*	34.50†	−0.80, 0.11	4.09	
27	−1.65*	34.50†	−1.00, 0.11	4.10	
55	−1.65*	34.50†	−0.40, 0.11	4.08	
75	−1.63	34.511			
104	−1.64	34.511			
133	−1.64	34.515	−0.47, 0.11	4.12	2.7
154	−1.65	34.519	0.03, 0.09	4.20	4.7
180	−1.66	34.519			
203	−1.66	34.519	−0.68, 0.09	4.03	0.5
229	−1.66	34.519	0.14, 0.11	4.19	4.4
Station: 139					
Position: 60.00°S, 54.00°W					
Date: 24 November 1984					
13	−0.59	33.988	−1.32, 0.11	4.03	0.7
55	−0.68	34.028	−1.05, 0.16	4.13	3.2
105	−0.39	34.210	0.84, 0.16	4.11	2.9
387	1.75	34.674	8.24, 0.11	4.18	6.0
507	1.71	34.707	8.94, 0.11	4.21	6.8
806	1.37	34.727	9.66, 0.11	4.22	6.9
1105	0.88	34.706	9.31, 0.11	4.24	7.2
1446	0.58	34.702	8.69, 0.11	4.23	6.8
2005	0.16	34.684	8.02, 0.11	4.24	6.8
2503	−0.16	34.663	6.30, 0.11	4.24	6.6
2755	−0.26	34.660	5.67, 0.11	4.24	6.5
2946	−0.28	34.659	5.90, 0.11	4.26	7.0
Station: 157					
Position: 62.00°S, 55.00°W					
Date: 26 November 1984					
10	−0.39	34.363	−1.26, 0.09	4.06	1.8
55	−0.42	34.375	−1.00, 0.07	4.07	2.0
105	−0.40	34.391	−0.49, 0.16	4.07	2.0
154	−0.70	34.419	−0.32, 0.15	4.00	0.1
204	−0.76	34.439	0.13, 0.16	4.13	3.4
303	−0.85	34.488	1.38, 0.18	4.13	3.4
384	−0.87	34.514	1.93, 0.16	4.17	4.4
507	−0.83	34.534	2.73, 0.16	4.17	4.4
705	−0.83	34.549	3.18, 0.16	4.20	5.2
905	−0.96	34.555	3.97, 0.16	4.22	5.6
1057	−0.99	34.564			
1277	−1.00	34.571	4.25, 0.16	4.24	6.1
Station: 199					
Position: 60.34°S, 58.93°W					
Date: 2 December 1984					
5	0.20	33.864	−1.48, 0.12	4.07	2.0
50	−0.36	33.991	−1.50, 0.12	4.07	1.8
110	−0.45	33.970	−1.47, 0.12	4.09	2.2
420	1.48	34.212	6.90, 0.12	4.12	4.1
720	1.94	34.690	9.99, 0.12	4.21	6.9
1000	1.69	34.725	10.00, 0.12	4.22	7.1
1600	1.19	34.728	10.08, 0.12	4.25	7.6
2100	0.80	34.717	9.82, 0.12	4.26	7.6
2600	0.49	34.711	9.77, 0.12	4.27	7.7
3100	0.29	34.706	9.37, 0.12	4.27	7.6
3300	0.27	34.704			
3500	0.17	34.689	8.42, 0.12	4.28	7.8

Table 1. Continued

Pressure (dbar)	θ (°C)	Salinity (‰)	δ^3He (%)	c^4He (10^{-8}cc STP/g H_2O)	Δ^4He (%)
Station: 204					
Position: 62.25°S, 57.55°W					
Date: 3 December 1984					
10	0.18	34.119	−1.15, 0.12	4.09	2.7
60	−0.13	34.231	−0.81, 0.16	4.07	2.1
110	−0.32	34.428			
255	−0.60	34.524	1.96, 0.16	4.10	2.8
406	−1.01	34.537	2.66, 0.16	4.20	5.1
605	−1.19	34.552	3.27, 0.09	4.21	5.2
805	−1.34	34.556	3.80, 0.09	4.23	5.6
1006	−1.42	34.560	6.72, 0.09	4.33	8.1
1305	−1.48	34.566	6.35, 0.16	4.23	5.6
1502	−1.50	34.571	7.34, 0.09	4.56	13.8
1705	−1.52	34.576	6.82, 0.09	4.28	6.8
1905	−1.54	34.579	6.06, 0.09	4.29	7.0
Station: 22501					
Position: 62.99°S, 57.99°W					
Date: 6 January 1985					
9	−0.58	34.401	−0.71, 0.08	4.23	6.0
14	−0.68	34.399	−0.96, 0.08	4.20	5.2
54	−0.84	34.430	−0.27, 0.09	4.19	4.8
105	−0.93	34.462	0.36, 0.09	4.19	4.8
155	−1.01	34.480			
205	−1.04	34.486	0.58, 0.09	4.16	4.0
256	−1.13	34.519	0.95, 0.09	4.20	5.0
305	−1.14	34.525	1.16, 0.15	4.21	5.2
355	−1.13	34.523	1.18, 0.09	4.19	4.7
405	−1.15	34.534	1.22, 0.09	4.18	4.5
425	−1.15	34.535	1.24, 0.09	4.25	6.2
442	−1.15	34.535	1.33, 0.09	4.20	5.0
Station: 22801					
Position: 62.13°S, 58.00°W					
Date: 8 January 1985					
10	0.84	34.040	−0.41, 0.07	4.12	3.7
29	0.82	34.202	0.69, 0.08	4.14	4.3
48	0.54	34.287	1.59, 0.08	4.41	11.0
89	0.52	34.300	1.61, 0.08	4.19	5.5
127	0.46	34.331	2.22, 0.08	4.15	4.4
168	0.42	34.333	2.39, 0.11	4.18	5.2
207	0.41	34.403	3.41, 0.07	4.26	7.2
257	0.40	34.425	3.81, 0.08	4.27	7.5
307	0.41	34.446	4.61, 0.08	4.19	5.5
358	0.43	34.469	4.74, 0.07	4.20	5.8
386	0.45	34.491	4.91, 0.08	4.17	5.0
399	0.45	34.500	5.59, 0.08	4.19	5.5
Station: 22902					
Position: 61.98°S, 56.07°W					
Date: 8 January 1985					
11	1.27	34.234	−1.36, 0.12	4.41	11.3
43	1.26	34.229	−1.35, 0.12	4.14	4.5
80	0.58	34.308	1.08, 0.17	4.28	7.8
151	−0.23	34.460			
250	−0.78	34.513	2.54, 0.15	4.17	4.4
502	−0.91	34.542	3.99, 0.17	4.23	5.9
751	−0.98	34.559	3.97, 0.07	4.22	5.6
999	−0.98	34.568	4.54, 0.17	4.28	7.1
1302	−1.00	34.572	4.90, 0.07	4.25	6.3
1500	−1.07	34.571			
1703	−1.11	34.570	4.56, 0.11	4.21	5.3
1902	−1.13	34.569	4.38, 0.07	4.23	5.8

*Data taken from CTD plot; estimated precision: ±0.1°C.
†Data taken from CTD plot; estimated precision: ±0.05‰.

Table 2. Helium isotope and hydrographic data, Polarstern *cruise ANT IV, Leg 2, November–December* 1985

Pressure (dbar)	θ (°C)	Salinity (‰)	δ^3He (%)	c^4He (10^{-8}cc STP/g H_2O)	Δ^4He (%)
Station: 27901					
Position: 62.27°S, 57.61°W					
Date: 15 November 1985					
1026	−1.45	34.547	5.39, 0.13	4.36	8.8
1125	−1.48	34.548	5.43, 0.23	4.34	8.3
1227	−1.52	34.549	4.84, 0.23	4.21	5.0
1328	−1.54	34.550	5.59, 0.13	4.19	4.5
1429	−1.55	34.551	5.03, 0.13	4.20	4.8
1742	−1.58	34.554	4.78, 0.13	4.19	4.5
Station: 29305					
Position: 62.30°S, 57.49°W					
Date: 23 November 1985					
1754	−1.59	34.551	4.46, 0.08	4.21	5.0
1814	−1.59	34.552	4.05, 0.13	4.28	6.8
1855	−1.60	34.553	4.11, 0.23	4.27	6.5
1886	−1.60	34.553	3.44, 0.23	4.26	6.2
1911	−1.60	34.553	4.16, 0.13	4.21	5.0
1943	−1.61	34.553	4.14, 0.13	4.22	5.2
Station: 29303					
Position: 62.24°S, 57.49°W					
Date: 23 November 1985					
1815	−1.59	34.552	4.07, 0.13	4.30	7.2
1855	−1.59	34.552	3.76, 0.23	4.42	10.2
1885	−1.59	34.553	4.08, 0.13	4.26	6.3
1917	−1.60	34.553	4.53, 0.23	4.24	5.8
1952	−1.60	34.553	4.02, 0.23	4.34	8.2
Station: 30603					
Position: 62,23°S, 57.45°W					
Date: 26 November 1985					
399	−1.05	34.508	2.75, 0.13	4.31	7.8
500	−1.03	34.521	3.64, 0.13	4.27	6.8
550	−1.15	34.530	3.83, 0.08	4.19	4.7
749	−1.25	34.541	3.90, 0.15	4.32	7.9
999	−1.42	34.543	5.94, 0.15	4.29	7.1
1499	−1.53	34.549	4.92, 0.15	4.28	6.8
1921	−1.51	34.552	3.81, 0.15	4.38	9.2

≥ 100 m) of the eastern basin (Stas 157 and 229) and 7.5% in the deep water of the central basin (Sta. 204). The highest ^{3}He concentrations are found in the northern part of the central basin (Sta. 204) in the depth range between 1000 and 1500 m. The ANT IV data (Fig. 3b) show a similar distribution with maximum ^{3}He concentration (≈ 5.75%) at Sta. 306 occurring at about 1000 m depth. It is lower by about 2% than the maximum ^{3}He concentration at Sta. 204 (ANT III) as is the ^{3}He concentration of the bottom water between the two stations in the central basin. Locally, the ^{3}He concentrations can be considerably higher [up to about 20% at Stas 301 and 306 (for location see Fig. 1c); data from Zafer Top, Miami] than the values presented in this study as shown by SUESS *et al.* (1988).

The ^{3}He profiles from the stations located on the shelf of the Bransfield Strait (Stas 225 and 228; see Fig. 1b) and the northern Weddell Sea (Sta. 120) show surface ^{3}He concentrations (≈ −1%) significantly above the solubility equilibrium with the

atmosphere (Fig. 3). At the stations from the southern shelf of the Bransfield Strait (Sta. 225) and from the shelf of the northern Weddell Sea (Sta. 120) ^{3}He concentrations increase with depth to a maximum value of ≈1.25% at a depth of ≈250 m (Sta. 225). In contrast, the ^{3}He concentration at Sta. 228, which is located on the shelf of the northern Bransfield Strait, increases to relatively high values of ≈5.5% near the bottom at ≈400 m.

At Sta. 199, located in the southern Drake Passage (Fig. 1), ^{3}He concentrations increase from values near the solubility equilibrium with the atmosphere in the surface water to maximum values of ≈10% between 700 and 2600 m (Fig. 3d). Towards the bottom (≈3500 m depth) the ^{3}He values decrease to 8.5%. At Sta. 139 the ^{3}He distribution in the upper water column (depth ≤700 m) is very similar to that found at Sta. 119. Below a depth of about 700 m the ^{3}He concentrations decrease steadily with depth to values of ≈6% near the bottom (≈3000 m depth).

5. DISCUSSION

The highest ^{3}He concentrations in the eastern and central basins of the Bransfield Strait are found in the deep water below about 1000 m, i.e. below the depth of the sills that separate the Bransfield Strait from the adjacent oceans. Generally, three processes could be responsible for this ^{3}He excess: tritium decay, renewal of the Bransfield Strait deep water from ^{3}He-rich water masses found between about 300 and 1000 m in the Drake Passage and in the northwestern Weddell Sea, or injection of a ^{3}He-rich helium component into the deep waters of the Bransfield Strait. In the following we discuss each process separately.

Tritiogenic ^{3}He

^{3}He is the decay product of tritium [^{3}H, half life: 12.43 years (UNTERWEGER *et al.*, 1980)] and has a natural concentration in ocean surface water of about 0.2 TR [DREISSIGACKER and ROETHER, 1978: TR (Tritium Ratio) is a synonym of TU and means a [T]/[H] ratio of 10^{-18} (TAYLOR and ROETHER, 1982)]. The natural tritium in the ocean is masked by an anthropogenic component which has been brought into the atmosphere by the nuclear weapon tests, mainly in the 1960s; it is introduced to the ocean surface water via water vapor exchange with the atmosphere and by precipitation (WEISS *et al.*, 1979). As the Bransfield Strait is an area of deep-reaching convection, tritium can be found throughout the water column (GORDON and NOWLIN, 1978).

To estimate the contribution of tritium decay to the ^{3}He balance in the deep water, a simple time-dependent 1-box model has been calculated (model concept: Fig. 4a). In the model the deep water below 1000 m depth is assumed to be a well-mixed water mass renewed from the surface water which has a prescribed time-dependent tritium concentration calculated from the data by WEISS and ROETHER (1980) using the procedure described by DREISSIGACKER and ROETHER (1978). The tritium input function calculated in this way (Fig. 4b) is higher by about 20% compared to the input function given by JENKINS *et al.* (1983) for the Weddell Sea. This deviation is within the error of such calculations and means that the tritium boundary condition used in the surface box of the model might be taken as an upper limit.

The tritium concentration in the deep water depends on the exchange rate between the deep and the surface water and the decay of tritium. The tritium concentration for the

deep water ($c_1(t)$) is calculated by fitting $c_1(t)$ to the observed tritium values with the exchange rate k as a free parameter ($k = 1/\tau$, where τ is the mean residence time of the water in the deep box). With an exchange rate k calculated in this way, the model can be run for ^{3}He. Assuming a constant surface water ^{3}He concentration of –2% and taking a mean residence time, τ, of 30 years (obtained from a best fit of the calculated tritium values to the observed tritium concentrations in the deep water, see Fig. 4c), a tritiogenic ^{3}He concentration of about 1.35% is calculated (Fig. 4d). Comparing this value to the observed ^{3}He excess above solubility equilibrium with the atmosphere in the deep water of the Bransfield Strait (≈4–6%), only about 1/4 of the excess can be explained by tritiogenic ^{3}He.

As the tritium data available from the deep Bransfield Strait waters are sparse and the error of the mean values is considerably high (data for 1975 from GORDON and NOWLIN, 1978; data for 1985, unpublished tritium measurements from the Heidelberg tritium laboratory), sensitivity runs were performed in order to estimate the effect of changes in τ on the calculated tritiogenic ^{3}He excess. These runs were done with values for τ ranging from 10 to 100 years to fit the highest and lowest observed tritium values. As can be seen in Fig. 4c the variation of τ does not have a big effect on the calculated tritiogenic ^{3}He

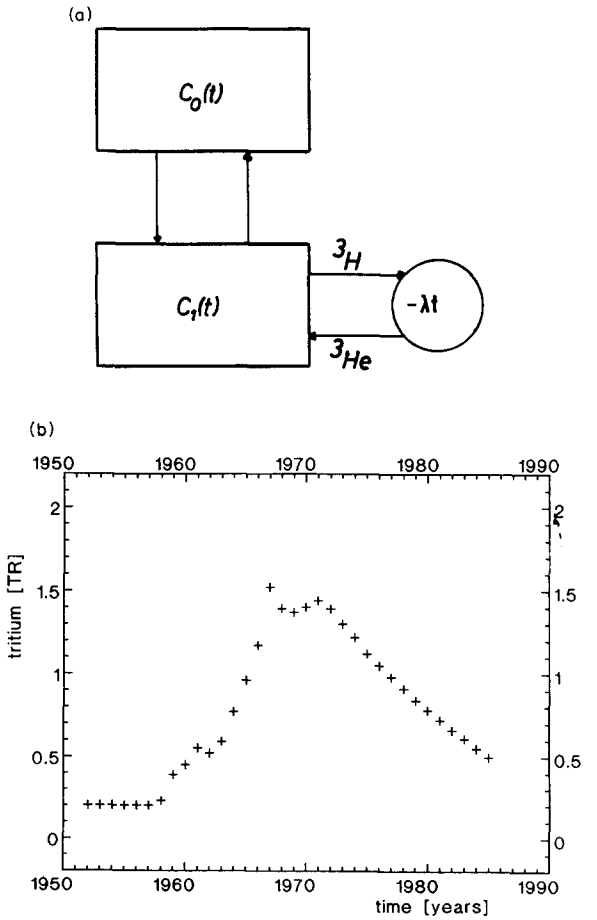

Fig. 4a, 4b.

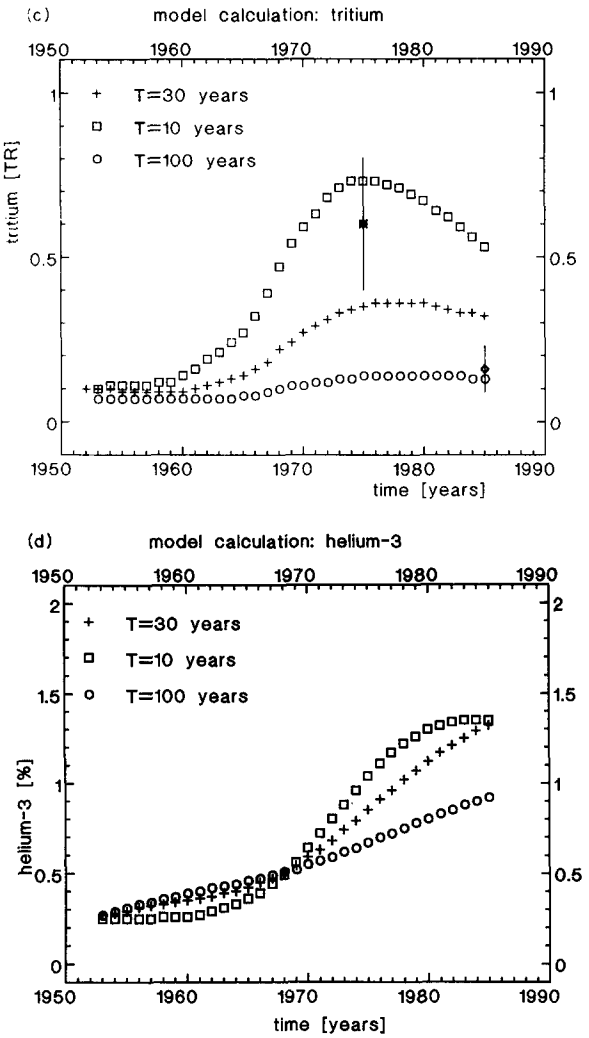

Fig. 4. (a) Schematic picture of the box model used for the estimate of the tritiogenic ^{3}He component in the deep water of the Bransfield Strait. (b) Tritium input function $c_0(t)$ prescribed for the surface water box. For explanation see text. (c) Tritium concentration of the deep water calculated by use of the box model ($c_1(t)$). Experimental data from GORDON and NOWLIN (1975) and unpublished Heidelberg tritium laboratory data (1985). For explanation see text. (d) Calculated tritiogenic ^{3}He concentration of the deep water. For explanation see text.

excess. The reason for this behaviour is that in the case of a lower mean residence time, which results in higher tritum concentrations of the deep water, the ^{3}He produced by tritium decay escapes more rapidly to the atmosphere. On the other hand for higher τ values the tritium concentrations in the deep water are lower, resulting in a lower tritiogenic ^{3}He production. On the basis of the sensitivity runs we estimate that the tritiogenic ^{3}He signal should range from 1 to 1.5%; i.e. 1/4 to at most 1/3 of the ^{3}He excess observed in the deep water of the Bransfield Strait is related to tritium decay.

Mixing

If the ^{3}He excess were caused by deep water formation via mixing, one of the end-members involved in the mixing process must have a high ^{3}He concentration. According to GORDON and NOWLIN (1978), the deep water in the Bransfield Strait is renewed by deep convection of water masses with temperatures near freezing and salinities of about 34.62% normally found on the shelf of the northern tip of the Antarctic Peninsula. This water mass is exposed to exchange with the atmosphere and therefore exhibits low ^{3}He concentrations (–1 to 1%, see Fig. 3c). The fact that the ^{3}He concentrations of –1% to +1% are above the solubility equilibrium with the atmosphere by about 1–3% is due to the partial ice cover in this area which suppresses gas exchange.

The Circumpolar Deep Water (CDW) and the Warm Deep Water found in the southern Drake Passage and the northern Weddell Sea are both characterized by high ^{3}He concentrations between 7 and 10% (see Fig. 3d and SCHLOSSER *et al.*, 1987), but both are either absent from the Bransfield Strait or only of minor importance (GORDON and NOWLIN, 1978). The upper water column (depth $\leq$1000 m) is made up of water masses that are relatively cold and low in ^{3}He ($\leq$4%, Fig. 3a, b). The water found on the shelf of the northern Bransfield Strait is strongly influenced by the CDW, and from the T–S plot (Fig. 2a) it is evident that CDW does not contribute significantly to the deep water.

Therefore, the deep water in the Bransfield Strait should have ^{3}He concentrations similar to that of the water masses found on the shelves of the northern Weddell Sea and the southern Bransfield Strait, respectively, i.e. $\leq$1%. This, however, is not the case as the deep water has similar temperatures as the shelf water component but the ^{3}He concentrations are higher by about 6% (Fig. 5). A hypothetical mixing line between shelf water and CDW, the water mass with the highest ^{3}He concentration (broken line in

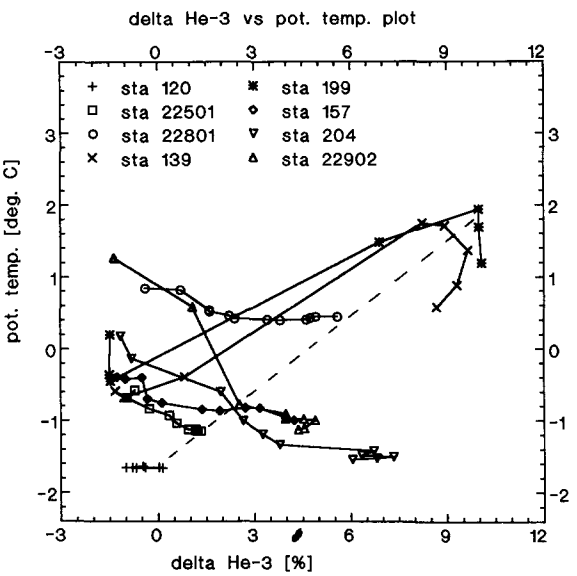

Fig. 5. θ–^{3}He plot for the ANT III stations. The broken line is a hypothetical mixing line between the shelf water component and the Circumpolar Deep Water found in the southern Drake Passage. For explanation see text.

Fig. 5), evidently suggests that the ^{3}He excess in the deep waters of the Bransfield Strait cannot be produced by mixing processes.

Injection of primordial helium

Tritium decay and admixture of CDW can not explain the ^{3}He excess observed in the deep waters of the Bransfield Strait. Thus, we conclude that injection of primordial helium is the source of the ^{3}He excess. This hypothesis can be validated by the ^{3}He/^{4}He characteristics. Figure 6a shows ^{3}He vs ^{4}He for the ANT III stations from the eastern and central basins of the Bransfield Strait (Stas 157, 204 and 229) and from the shelves of the northern Weddell Sea and the southern Bransfield Strait, respectively (Stas 120 and 225). The ^{3}He/^{4}He values of the deep basins of the Bransfield Strait fall along a mixing line between surface water with ^{3}He/^{4}He values close to the solubility equilibrium with the atmosphere (indicated by point A in Fig. 6a) and the bottom water. The slope of ^{3}He/^{4}He of the deep Bransfield Strait waters falls between those for atmospheric helium and primordial helium. The mean values of the ^{3}He and ^{4}He values of the deep water (below 1000 m depth) are 6.16×10^{-14} cc STP/g H_2O and 4.24×10^{-8} cc STP/g H_2O (Fig. 6a, B) for the eastern basin and 6.32×10^{-14} cc STP/g H_2O and 4.28×10^{-8} cc STP/g H_2O (Fig. 6a, C) for the central basin. If, as we assume, the deep Bransfield Strait water is formed from shelf water, the ^{3}He/^{4}He ratio of the injected helium is given by the slopes of the lines DB and DC, respectively, for the eastern and central basin. Thereby D represents the mean ^{3}He/^{4}He characteristic of the shelf water.

The ^{3}He/^{4}He ratios of the injected helium component estimated are about 6×10^{-6} for the eastern basin and 8×10^{-6} for the central basin. They are 4.3–5.8 times the atmospheric helium isotope ratio. Similar values are obtained for the ANT IV stations (Fig. 6b). Because no data from shelf stations are available from this cruise, the initial helium content of the shelf water component is taken to be the same as from the ANT III stations (Stas 120 and 225). The ANT IV ^{3}He/^{4}He data show a considerable scatter in the deep water, leading to a variation in the ^{3}He/^{4}He ratio of the added helium component for the single stations ($4–7.1 \times 10^{-6}$). The origin of this scatter and the low ^{3}He/^{4}He ratio of the added helium component may be due to an atmospheric helium fraction brought into the Bransfield Strait water by addition of a small amount of glacial melt water (SCHLOSSER, 1986) during the deep water formation or due to inclusion of small air bubbles into the copper tube during water sampling. An alternative explanation is the addition of radiogenic helium that is produced in the sediments by the decay of the natural uranium and thorium decay series (^{3}He/^{4}He ratio: 10^{-7}–10^{-8}). Radiogenic helium also can be contributed by rifting of continental crust underlying the Bransfield Strait. The air helium component can be eliminated if neon is measured in parallel to helium, because neon has no known source in the ocean other than air. Because no neon data are available, it is not possible to determine the extent to which the ^{3}He/^{4}He ratios are influenced by air helium. Further studies of the helium distribution in the Bransfield Strait therefore should include neon measurements.

The ^{3}He/^{4}He ratio of the added helium component has to be corrected for the tritiogenic ^{3}He as estimated above. If a maximum tritiogenic ^{3}He concentration of 2% is assumed, the corrected ^{3}He/^{4}He ratios range from $2.4–5.0 \times 10^{-6}$ (1.7–3.6 times the atmospheric ^{3}He/^{4}He ratio). These ratios are much below that obtained for pure mantle helium, which is about eight times the atmospheric ^{3}He/^{4}He ratio, but are identical to the ratios indicating escape of mantle volatiles through continental crust undergoing exten-

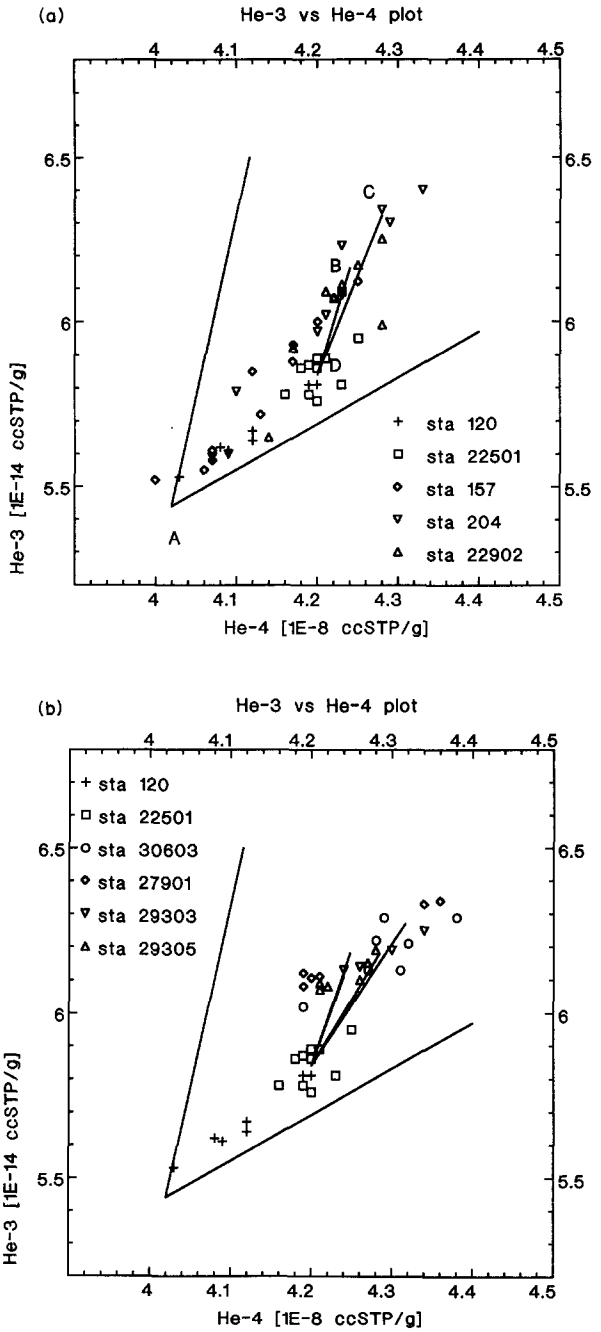

Fig. 6. $^3He/^4He$ plot for the stations located in the Bransfield Strait. (a) ANT III data. (b) ANT IV data except Stas 120 and 22501 (ANT III shelf stations).

sion (OXBURGH and O'NIONS, 1987). Interestingly, helium from the Mariana back-arc spreading centre shows also these ^{3}He/^{4}He ratios (3.2 times atmospheric; HORIBE *et al.*, 1986). If the low ^{3}He/^{4}He ratios observed in back-arc basins are a general feature or are indeed related to a continental component can not be decided on the basis of the few available helium data.

Acknowledgements—We are grateful to the officers and crew of PFS *Polarstern* for the technical assistance during ANT III and ANT IV. G. Flenner and G. Rohardt operated the CTD/rosette system and provided the hydrographic data for ANT III as did R. Wittstock for ANT IV. G. Zimmek performed most of the helium measurements. This work was supported by the Deutsche Forschungsgemeinschaft and by the National Science Foundation grant DPP-8512395 (E.S.).

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