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SHORT COMMUNICATIONS

On the Geology of the Weddell Sea, Southern Ocean

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The Weddell Sea belongs to the Atlantic sector of the Southern Ocean. It is located north of the Antarctic rift, between the Antarctic Peninsula and Scotia arc of West Antarctica in the west and Dronning Maud Land of East Antarctica with its submarine continuation, the Maud Ridge, in the east. The rift systems of the American–Antarctic and Southwest Indian ridges serve as the northern boundary of the Weddell Sea. The geology of the Weddell Sea has been poorly studied [1–10], and the existing views on its origin and evolution remain controversial. This paper presents the results of a study of a new set of rock samples (more than 500 kg) collected by N.A. Kurentsova from the material obtained by Agassiz and Sigsbi skate trawls in the course of biological dredging in the Weddell Sea during Leg ANT-XXII/3 of the German R/V *Polarstern* (Fig. 1). The nature of geologic samples dredged with a trawl usually cannot be unequivocally determined. Some geologists suggested that they were transported by floating ice or suspension flows, whereas others argued that they are fragments from basement exposures.

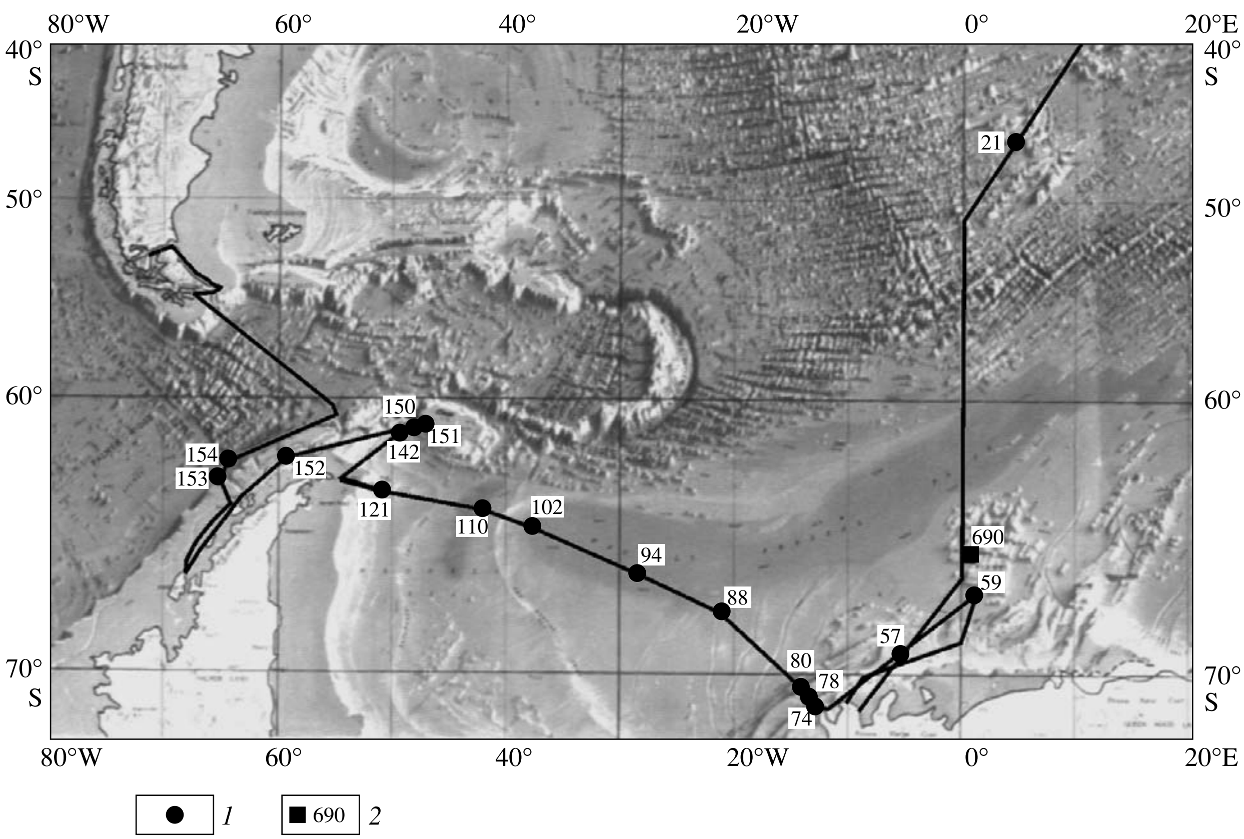


Fig. 1. The route of Leg ANT XXII/3 of the R/V *Polarstern* (22.01–6.04.2005). (1) Geological station and (2) borehole 690 in Maud Rise [8].

Trawling at station 21 was conducted in the Agulhas Basin floor while sailing from Cape Town to the Weddell Sea and Antarctic margin (Fig. 1).

Nine stations were trawled in the Weddell Sea. Five stations were located in the southeastern Weddell Sea. Four of them (57, 74, 78, and 80) occurred in the continental slope of Dronning Maud Land near the Explora Wedge, and station 59 was located in a submarine hill of the ocean floor near the Maud Rise. Four stations (88, 94, 102, and 110) were situated in the middle part of the Weddell Sea floor. Four stations (121, 142, 150, and 151) were explored on the eastern margin of the continental slope of the Antarctic Peninsula and the Southern Ridge of the Scotia arc (Fig. 1).

In addition, samples were trawled outside the Weddell Sea, in the Bransfield Strait of the Antarctic Peninsula (station 152) and in the Bellingshausen Sea, near the South Shetland trench (stations 153 and 154).

During geochemical investigations, rock samples were assigned to the bottom topography using published bathymetric charts [6, 7, 9, 10], materials from borehole 690 drilled on the Maud Rise during Leg 101 of the R/V *Joides Resolution* [8], and publications of Russian geologists on the petrology of the ocean floor [3, 4, 11–16].

The numbering of stations accepted by German researchers (PS67/59 AGT) was simplified by using only the last unique numbers, for example, 57, 58, 59, etc. (Fig. 1).

The submarine Maud Ridge in the eastern part of the Weddell Sea is more than 3 km high and trends nearly N–S, parallel to the Astrid (about 12°E) and Gunnerus (about 31°E) ridges lying east of it in the Indian sector of the Southern Ocean. These three structures are obviously oceanward continuations of structures of the East Antarctic continental margin. The Gunnerus Ridge has a monolithic structure, whereas the Astrid and Maud ridges are obliquely dismembered by the cross-cutting southwestern ends of transform faults accompanying the West Indian mid-ocean ridge. The dismembering is most pronounced in the Maud Ridge [9], the ridge summit of which is cut into a few areas [7]. The northern area with depths of 3500–3600 m is the summit of the Maud Rise. A ridge saddle with depths of up to 4500 m separates the Maud Rise from an area with depths of 2000–1900 m, which is located at the southern base of the ridge and represents a marginal plateau of the continental slope. The ridge slopes are steeply cut by a normal fault. Borehole 690 was drilled in the Maud Rise during Leg 101 of the R/V *Joides Resolution*. It penetrated Recent to Late Cretaceous (Campanian–Maestrichtian) sediments and reached the basalts of the acoustic basement at a depth of 321 m [8].

Two small (about 300 m) hills are shown on the bathymetric chart [9] south of the Maud Rise. The easterly hill was trawled at station 59 (67°30.35S, 0°4.31E, depth of 4622–4306 m). Similar hills and rises are widespread around Antarctica in the Indian Ocean [7] and could be relics of its continental margin, similar to the Elein shoal in the Cooperation Sea. More than 50 kg of samples, including six fragments from 40 × 20 to 15 × 10 cm in size, were recovered at station 59. The samples are fresh porous basaltic porphyrites (sample 59l), massive diabase porphyrites (sample 59k), mineralized dolerites (sample 59n), norites (sample 59d), garnet-bearing granitoids (sample 50a-3) and aplites (sample 59b), garnet–mica schists (sample 59e), amphibolites (samples 59g and 59t), and biotite gneisses (sample 59zh). The most common are garnet-bearing granitoids.

Volcanic rocks from station 59 are fluidal porous basaltic porphyrites with plagioclase xenocrysts. They show elevated content of Ti, Ca, Al, P, and alkalis (especially K), high Fe/(Fe + Mg) ratios, low contents of Si and Mg, and high contents of LILE and LREE (Table 1). In the Th/Yb vs. Ta/Yb diagram, the basaltic porphyrite from station 59 and alkali basalts from borehole 690 in the Maud Rise [8] plot in the field of the enriched mantle (Fig. 2), which also contains some data points of Antarctic seamounts and islands [11, 12, 14, 16]. Porous basalts from station 154 (62°31.46S, 64°39.75W, 3699–3777 m depth, Bellingshausen Sea) occur in the same field.

The volcanic rocks of the Maud Ridge are ascribed to the subalkaline series and resemble the within-plate assemblages of ocean islands. The magmatic rocks of the Maud Ridge were mainly derived from an enriched mantle source [4]. Based on the identical petrochemical and geochemical compositions of volcanic rocks (Table 1, Fig. 2), it can be supposed that the Maud Rise and two relic hills south of it belong to a single geochemical province, which experienced destruction and oceanization. Diverse garnet-bearing intrusive and metamorphic rocks recovered at this station are considered here as relics of the subsided Precambrian continental basement transformed into the secondary oceanic crust.

Marginal plateau of the continental margin in the southern part of the Maud Ridge lies northeast of the German Antarctic station Neumayer, approximately at 5°W. The minimum depth of the plateau is 1745 m, as compared with the maximum depth near the slope foot of up to 4420 m. The plateau has square outlines and is bounded on all sides by steep ledges. The continental slope east and west of it shows a strongly differentiated topography presumably related to the destruction of crust at the intersection of the continental margin and the extension of the transform fault of the Southwest Indian Ridge [9].

The shelf margin along the entire Dronning Maud Land is cut by steep escarpments. One of them is a latitudinal wedge, up to 2000 m high, in the upper continental slope, east of the Neumayer Station. It separates the marginal plateau of the root part of the Maud Ridge from the shelf. Farther to the west along the coast up to the Norway Cape and 18°W, a similarly steep and high

Table 1. Chemical composition of basalts from the Weddell Sea, South Atlantic

Oxide, element	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	45.39	49.70	50.00	49.72	50.05	40.62	55.48	48.68	47.95	48.08	47.02	45.73	47.78	47.91
TiO_2	3.42	2.63	3.13	2.77	1.98	0.62	2.33	3.70	1.18	1.25	1.90	1.60	0.78	3.02
Al_2O_3	15.44	12.28	13.12	13.30	13.92	21.82	12.92	12.47	17.72	20.07	16.06	15.13	14.70	13.81
FeO	12.62	10.54	12.14	13.90	12.41	14.03	11.75	13.40	8.33	8.02	11.14	10.65	8.77	11.04
MnO	0.21	0.14	0.16	0.22	0.22	0.90	0.17	0.17	0.17	0.13	0.17	0.15	0.16	0.15
MgO	4.24	7.00	6.48	2.75	6.00	1.80	1.68	4.69	5.57	6.16	7.93	8.55	13.53	7.43
CaO	10.88	8.06	7.94	7.84	10.62	0.64	5.70	5.55	8.77	10.97	9.23	6.79	10.32	9.78
Na_2O	3.66	3.16	3.14	4.32	2.19	0.05	1.97	3.58	3.17	3.36	3.21	3.57	2.40	3.31
K_2O	1.53	1.53	1.60	1.48	0.83	5.01	3.88	1.55	1.31	0.54	0.94	1.25	0.37	1.47
P_2O_5	0.67	0.36	0.40	1.12	0.20	0.24	0.73	0.42	0.26	0.26	0.31	0.35	0.14	0.64
L.O.I.	1.54	3.40	2.14	1.56	0.72	14.62	2.16	4.96	4.82	0.26	1.74	6.40	0.00	0.48
Total	99.61	98.85	100.30	98.98	99.15	100.36	98.77	99.18	99.26	99.11	99.69	100.21	99.06	99.07
Rb	29	40	34	32	25	229	111	22	32	7	13	15	13	28
Ba	395	515	618	484	278	532	1923	493	336	96	119	123	183	296
Sr	565	556	684	254	310	65	298	282	657	660	427	415	329	650
La	44	41	41	61	17	57	119	37	16	11	15	15	9	39
Ce	90	91	89	141	39	125	240	87	35	26	31	32	21	83
Nd	43	51	51	83	21	48	109	50	20	15	17	16	12	43
Sm	8.80	10.61	10.90	17.87	5.17	9.48	20.29	10.54	4.46	3.37	4.20	3.91	2.86	9.26
Eu	2.93	3.29	3.42	5.37	1.70	1.72	4.12	3.11	1.45	1.26	1.50	1.49	0.97	3.06
Tb	1.18	1.27	1.31	2.39	0.86	1.28	2.56	1.44	0.62	0.58	0.75	0.69	0.46	1.20
Yb	2.65	2.42	2.53	4.98	2.14	4.66	7.06	3.38	1.96	1.94	2.13	2.06	1.48	1.88
Y	37	35	38	72.34	30.20	49.33	87.52	44.77	22.72	21.63	25.58	24.32	17.06	30.70
Zr	256	323	323	514	148	92	619	341	133	112	130	132	75	342
Nb	63.70	17.77	16.28	39.25	8.41	12.28	31.55	29.62	6.16	6.90	18.75	16.95	2.04	46.94
Hf	5.75	8.40	8.27	12.15	3.88	2.60	15.76	8.68	3.34	2.72	3.13	3.13	2.33	8.15
Th	5.28	4.69	3.77	6.17	3.05	20.10	18.85	4.27	3.61	1.28	1.79	1.67	2.07	5.07
U	1.25	0.92	0.68	1.38	0.47	8.29	1.99	0.88	0.87	0.32	0.72	0.56	0.45	1.39
Ta	4.17	1.27	1.17	2.55	0.57	0.99	1.86	2.13	0.42	0.52	1.26	1.08	0.12	3.33
Cr	4.27	297.14	153.82	16.66	141.89	101.22	4.12	56.65	43.90	75.59	252	326	709	264
Ni	10.17	110.48	72.92	13.65	116.38	88.36	28.84	65.19	61.43	106.6	112	224	149	177
Zn	133	127	134	156	109	81.66	161	152	91	74	97	91	67	140

Note: (1–10) Basalts of the Weddell Sea: (1–5) basaltic porphyrites, samples 59l, 57-1, 74l, 78a, and 80n; (6) volcanic tuff, sample 88e; (7) trachyandesite, sample 94b; (8) aphyric porous basalt, sample 102m; (9, 10) porous olivine–plagioclase basaltic porphyrites, samples 110a and 121a; (11, 12) subalkaline olivine basalts of the Powell Basin, samples 142u and 151-13; (13, 14) porous olivine–plagioclase basaltic porphyrites of the Bellingshausen Sea, samples 153-1 and 154-14. Total Fe is reported as FeO.

wedge is observed in the upper part of the continental slope southwest of the Neumayer Station. The perfectly straight Explora wedge is situated in the middle part of the continental slope. It is located approximately 45 miles from the upper wedge and trends parallel to it (Fig. 1). These steep tectonic wedges reflect the intense dismembering of the continental margin during destruction [7, 9].

Five kilograms of rock samples (including three blocks, up to 10 × 8 cm in size) were trawled up at station 57 (Fig. 1; 69°23.75S, 05°17.33W, 1765 m depth) on the marginal plateau of the southern Maud Ridge. The samples are porous basaltic porphyrites with pyroxenite xenoliths (sample 57-1, Table 1), mineralized dolerites (sample 57-2, Table 2), arcose sandstones (samples 57-14 and 57-16), plagiogranites (sample 57-30), garnet–mica schists (sample 57-4), and garnet amphibolites (sample 57-23). The most common are basalts. As compared with the basalts from station 59, these volcanics are higher in Si and Mg but lower in Ti, Mn, Ca, P, Na, and Fe. The contents of LILE, K, and LREE are similarly high (Table 1, Fig. 3a). In the Th/Yb–Ta/Yb diagram, the basaltic porphyries plot in the field of Andean-type active continental margins (Table 1, Fig. 2).

The volcanic rocks of the marginal plateau belong to the subalkaline series. The recovered angular fragments of granitoids, garnet–mica schists, and garnet amphib-

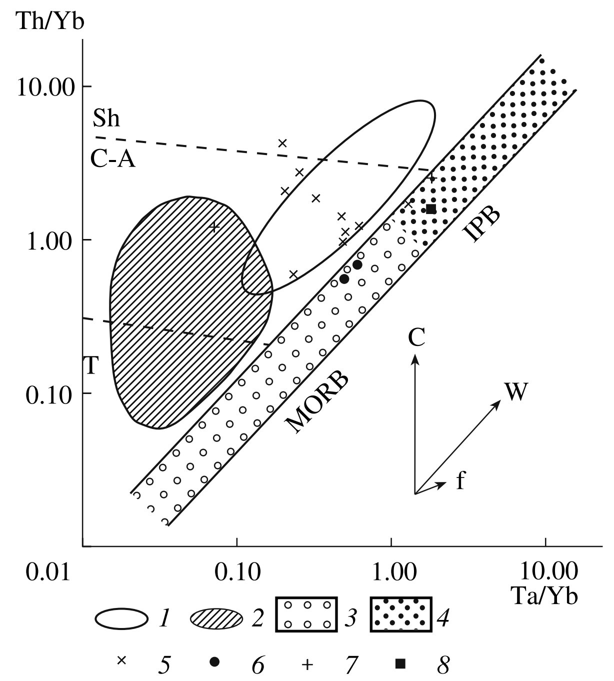


Fig. 2. Diagram of Th/Yb vs. Ta/Yb for the volcanic rocks of the Weddell Sea (Table 1). (*1*) Active continental margins [13]; (*2*) island arcs; (*3*) depleted mantle; (*4*) enriched mantle; (*5*) volcanic rocks of the Weddell Sea, stations 57, 59, 74, 78, 80, 88, 94, 102, 110, and 121 (Fig. 1); (*6*) volcanic rocks of the tholeiite series from the Powell Basin, stations 142 and 151; (*7*) volcanic rocks of the Bellingshausen Sea, stations 153 and 154; (*8*) alkali basalts of Maud Rise, Weddell Sea, borehole 690 [8]; (MORB) mid-ocean ridge basalts, depleted mantle; and (IPB) intraplate basalts, enriched mantle. The vectors show the influence of the following factors: (W) within-plate enrichment by lithophile elements, (C) crustal contamination, and (f) fractional crystallization. The dashed lines separate the fields of tholeiitic (T), calc-alkaline (CA), and shoshonitic (Sh) rocks.

olites are presumably relics of the subsided Precambrian basement of the continental crust.

A terrace near the Explora wedge is located at the Antarctic continental slope, northwest of Cape Norway [9]. It is 60 miles wide and about 200 miles long. The wedge near Cape Norway is 1500 m high, and the Explora wedge is 2500 m high. The terrace surface is complicated by numerous suspension flows and canyons, whose channels occasionally coincide with small transverse faults and fissures, which can be exemplified by the Wegener Canyon (near station 80) formed during the destruction of the continental margin.

Three successful trawlings were conducted during the cruise in this area at stations 74 (71°18.47S, 13°58.48W, 1362–946 m depth, about 20 kg of rock samples), 78 (71°09.37S, 13°59.11W, 2162–2039 m depth, about 40 kg of samples), and 80 (70°40.19S, 14°43.77W, 2890–3005 m depth, about 50 kg of samples).

The samples from **station 74** are dominated by porous basaltic porphyrites with amygdaloidal structures (sample 74l, Table 1); there are also picrites (sample 74a), mineralized dolerites (sample 74-2, Table 2), olivine gabbro (sample 74s), and occasional biotite schists (sample 74n). The volcanic rocks show high contents of Ti, Mg, alkalis, LILE, and LREE (Fig. 3a, Table 1). In the Th/Yb–Ta/Yb diagram, the porous basaltic porphyrites plot in the field of Andean-type active continental margins, near the points of basalts from stations 57, 78, and 80 (Fig. 2). The volcanic rocks are ascribed to the subalkaline series.

The samples from **station 78** are porous basaltic porphyrites (sample 78a), mineralized massive basaltic porphyrites (samples 78l, 78e, 78m, 78d, and 78b; Tables 1, 2), mineralized dolerites (samples 78s, 78v, and 78sh), granosyenites with garnet (sample 78i), biotite plagiogneisses (sample 78z-2), quartz–plagioclase paragneisses (sample 78u), garnet–hypersthene quartzites (sample 78z), mica schists (sample 78shch), and quartz-bearing amphibolites (samples 78t, 78yu, 78r, and 78zh). Station 78 is located at a greater depth and closer to the Explora wedge than station 74. Higher amounts of metamorphic relict of continental crustal rocks and mineralized dolerites were recovered at station 78 (Table 2). The garnet of quartzites is almandine (Table 3). The volcanic rocks have high contents of Fe, Ti, alkalis, P, LILE, and LREE (Table 1, Figs. 2, 3a) and belong to the subalkaline series.

The samples from **station 80** are mineralized massive basaltic porphyrites, dolerites, diabases (samples 80n, 80sh, 80t, and 80p), tuffs (samples 80l and 80t-2), sandstones (sample 80s), pyroxenites (sample 80-2), gabbros (samples 80i and 80kh), garnet–mica schists (sample 80e), amphibolites (sample 80ch), garnet granulites (samples 80a and 80z; Tables 1, 2), and silicified garnet gneisses of granulite facies (samples 80k and 80b). Light pink almandine is abundant in the granulites and mica schists (Table 3). The volcanic rocks are more magnesian and have lower contents of alkalis (especially K), P, and Ti compared with the basalts from stations 74 and 78 (Table 1). In the Th/Yb–Ta/Yb diagram, basalt sample 80n plots in the field of active continental margins but away from the points of stations 57, 74, and 78 (Fig. 2).

The volcanic rocks from station 80 belong to the calc-alkaline series.

The Explora wedge area presumably contains widespread relics of the subsided Precambrian continental basement of East Antarctica in the form of amphibolites, garnet granulites, and gneisses cut by pyroxenites. Similar metamorphic complexes with charnockites are abundant in East Antarctica.

The floor of the Weddell Sea was trawled at four stations (Fig. 1): 88 (68°03.56S, 20°24.23W, 4777–4848 m depth, 5 kg of rock samples), 94 (66°38.10S, 27°05.29W, 4701–4839 m depth, 15 kg of samples), 102 (65°35.33S, 36°29.10W, 4581–4801 m depth,

Table 2. Chemical composition of rocks from the Weddell Sea, South Atlantic

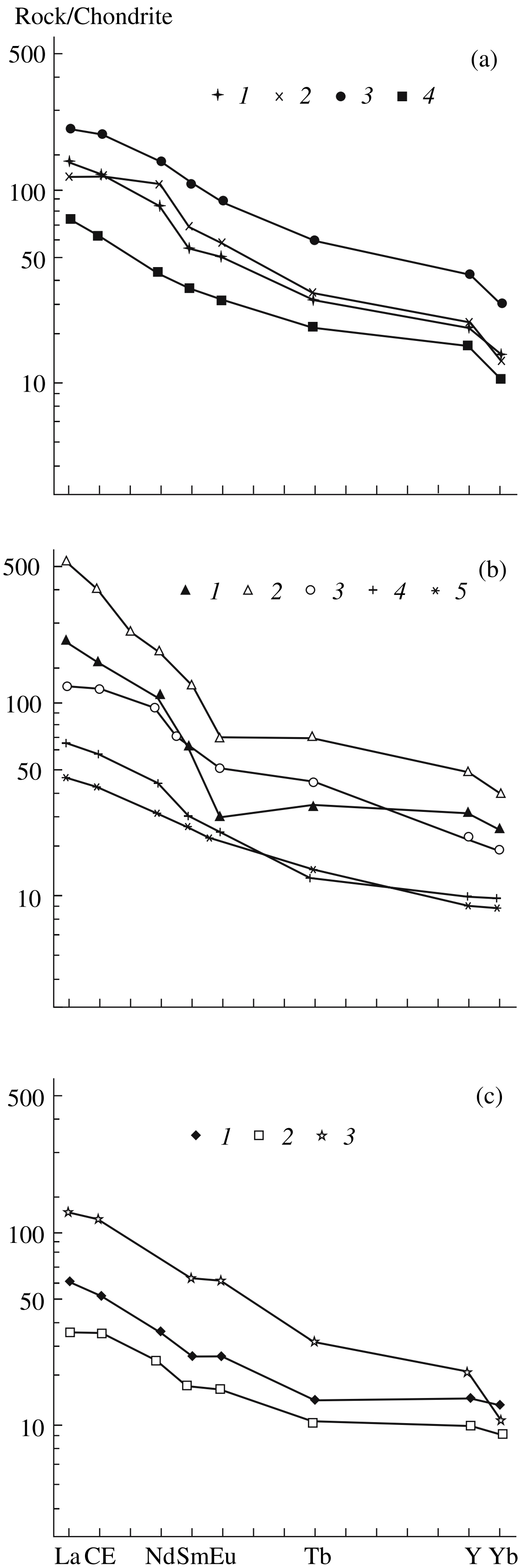
Oxide, element	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	53.35	47.48	49.25	44.08	49.92	40.32	50.37	58.51	45.95	45.74	47.83	49.55	49.74	47.87
TiO_2	1.29	3.07	2.80	3.01	2.97	5.52	0.58	1.51	1.17	0.37	2.65	2.80	2.56	2.24
Al_2O_3	14.56	13.10	10.46	7.40	10.20	10.65	2.78	16.10	12.18	10.95	14.62	12.50	14.10	13.48
FeO	9.98	13.12	10.66	13.16	10.33	21.62	14.68	9.42	11.21	9.46	12.86	15.70	15.95	14.66
MnO	0.15	0.21	0.15	0.20	0.17	0.30	0.27	0.18	0.23	0.17	0.20	0.29	0.22	0.24
MgO	3.65	5.86	8.44	10.31	9.13	5.70	17.66	4.92	10.40	18.16	5.57	3.14	3.38	5.62
CaO	7.13	9.38	11.55	11.92	9.04	14.35	11.35	3.66	12.74	7.98	11.43	7.55	9.10	10.95
Na_2O	3.21	2.45	1.90	2.55	1.70	0.64	0.61	1.60	2.22	0.90	2.53	3.84	2.88	2.45
K_2O	2.27	2.39	1.47	2.86	1.81	0.27	0.46	1.09	1.12	0.21	0.57	0.82	0.71	0.54
P_2O_5	0.38	0.30	0.36	0.86	0.40	0.99	0.07	0.17	0.78	0.11	0.26	1.31	0.45	0.24
L.O.I.	3.14	1.70	2.20	2.52	3.22	0.00	0.06	1.74	0.72	5.48	0.58	1.54	0.00	0.80
Total	99.11	99.07	99.31	98.94	98.98	100.37	99.20	98.92	98.80	99.71	99.11	99.04	99.10	99.11
Rb	58	59	29	108	35	–	17	83	7	16	12	22	14	10
Ba	1080	350	650	1380	660	260	90	330	430	–	240	390	320	230
Sr	518	396	933	1463	771	51	147	162	1040	59	283	182	172	237
Y	40	44	32	40	37	80	18	55	29	17	33	88	51	40
Zr	238	180	312	318	354	272	43	219	269	40	150	352	132	120
Nb	7	10	14	114	9	11	6	19	14	2	9	24	9	1
Cr	35	62	303	257	360	69	1700	84	317	869	79	39	56	86
Ni	32	78	144	143	215	56	707	63	145	491	76	34	59	71
Zn	164	192	169	183	172	266	152	131	227	122	192	239	244	173
Pb	12	6	–	16	7	–	4	6	10	10	–	6	2	0
Cu	23	114	57	145	73	49	31	109	20	52	121	29	93	155
V	221	257	207	248	158	214	156	227	173	147	220	79	231	264
Co	35	43	41	59	43	48	93	31	38	77	43	29	39	57
S	420	400	130	250	150	410	100	840	120	70	340	750	760	1070
As	–	–	–	–	–	–	–	11	–	6	–	2	–	–

Note: (1–8) Rocks from the Explora Wedge and Maud Rise, eastern part of the Weddell Sea: (1–5) mineralized dolerites, samples 59n, 57-2, 74t, 78l, and 80sh; (6) garnet pyroxenite, sample 80a; (7) diallagite, sample 80-2; (8) garnet granulite, sample 80b; (9–14) rocks from the floor of the Weddell Sea: (9) hornblendite, sample 88g; (10) mineralized olivine gabbro, sample 88i; (11, 14) mineralized dolerites, samples 94u and 110kh; (12) mineralized gabbro, sample 102g; and (13) pyroxenite, sample 110s (Fig. 1). Total iron is reported as FeO.

25 kg of samples), and 110 (65°00.85S, 43°00.13W, 4629–4653 m depth, more than 100 kg of samples).

The samples from **station 88** include (Tables 1, 2) lapilli tuffs (sample 88e), porous basaltic porphyrites (sample 88d), dolerites (samples 88l and 88k), diabases (sample 88s), sandstones (samples 88n and 88p), tuffites (sample 88f), gabbrosyenites (sample 88b), mineralized olivine gabbroids (sample 88i), granosyenites (sample 88v), granodiorites (samples 88m and 88zh), biotite granites (sample 88p), hornblendites (sample 88g), and plagioclase pyroxenites–hypersthenites (samples 88a and 88zh). The tuffs are strongly porous and show high gas contents and fluidal structures. They have high contents of Al, Fe, Mn, and, especially, K (in volcanic glass) and low contents of Ti, Mg, Ca, and Na (Table 1). In the Th/Yb–Ta/Yb diagram, the tuff composition plots in the field of shoshonites (Fig. 2). The volcanic tuffs have extremely high contents of LILE, K, and LREE (Fig. 3b). Their negative Ta–Nb anomaly is related to crustal contamination (vector C, Fig. 2). As compared with the East Antarctic continental slope, this station shows an increasing role of basic–ultrabasic rocks: gabbrosyenites, diorites, hornblendites, and pyroxenites. The granitoids are presumably relics of the continental crust, but some geologists argued that they were transported by floating ice.

The samples from **station 94** are trachyandesites with K-feldspar phenocrysts (sample 94b, Table 1), mineralized diabases (sample 94u, Table 2), mineralized gabbroids (sample 94r), garnet-bearing granitoids (sample 94yu), charnockites (sample 94k), garnet-bearing biotite paragneisses (sample 94z), biotite schists (sample 94ts), and olivine–plagioclase pyroxenites (sample 94m). The trachyandesites have elevated con-



tents of Ti, Fe, K, P, LILE, K, and, especially, LREE and exhibit a negative Ta–Nb anomaly (Fig. 3b, Table 1). In the Th/Yb–Ta/Yb diagram, they plot near the point of tuff (sample 88e) and the field of shoshonitic rocks (Fig. 2, Table 1). The trachyandesites are ascribed to the subalkaline (shoshonitic) series.

The granitoids, charnockites, schists, and gneisses are presumably relics of the Precambrian crustal basement.

The samples from **station 102** are represented by aphyric porous basalts (samples 102m, 102d, 102-2, and 102-10), mineralized dolerites, diabases (samples 102ts and 102n), mineralized diorites (sample 102g), tuffs (sample 102k), sandstones (sample 102t, 102u), plagiogranites (sample 102zh), metamorphosed alkaline schists with superimposed metasomatic hastingsite (sample 102z), garnet–mica schists (sample 102a), and amphibolites (sample 102b). The contents of Ti, Fe, total alkalis, LILE, and LREE in the volcanic rocks are high but lower than those in the flood basalts from station 94 (Table 1, Fig. 3). In the Th/Yb–Ta/Yb diagram, the basalts from this station plot in the field of Andean-type active continental margins, near the compositions of volcanic rocks from stations 57, 74, and 78 (Fig. 2, Table 1). The basalts correspond to the subalkaline series.

The samples from **station 110** are represented by porous basaltic porphyrties (sample 110a), tuffs (sample 110v), mineralized dolerites (samples 110m and 110u), mineralized melanocratic diorites (sample 110s), plagiogranites (sample 110-3), hornfelsed peralkaline granitoids (sample 110 shch), metasomatites (sample 110zh), plagiogneisses (sample 110k), amphibolites (sample 110i), silicified mineralized amphibolites (sample 110sh), and garnet amphibolites (sample 110-1). The metasomatic rocks recovered at station 110 probably indicate the activity of deep-seated transmagmatic fluids. In the Th/Yb–Ta/Yb diagram (Fig. 2), the composition of basaltic porphyrite

Fig. 3. Chondrite-normalized REE distribution patterns for the rocks of the Weddell Sea (Table 1). (a) Volcanic rocks from the eastern part of the Weddell Sea: (*1*) porous basaltic porphyrite of the subalkaline series, sample 59l, Maud Rise, station 59 (Fig. 1); (*2*) porous basaltic porphyrite of the subalkaline series, sample 57-1, Marginal plateau, station 57 and sample 74l, terrace near the Explora Wedge; (*3*) porous basaltic porphyrite of the subalkaline series, sample 78a, terrace near the Explora Wedge; and (*4*) calc-alkaline basaltic porphyrite, sample 80n, Wegener Canyon, Explora Wedge (Fig. 1). (b) Volcanic rocks from the (*1*–*4*) floor and (*5*) western part of the Weddell Sea: (*1*) porous volcanic tuff, sample 88e; (*2*) trachyandesite, sample 94b; (*3*) porous aphyric basalt of the subalkaline series, sample 102m; (*4*) porous basaltic porphyrite of the calc-alkaline series, sample 110a; and (*5*) porous basaltic porphyrite of the calc-alkaline series, sample 121a. (c) Volcanic rocks of the (*1*) Powell Basin and (*2, 3*) Bellingshausen Sea: (*1*) olivine basalts of the tholeiite series, samples 142u and 151-13 (Table 1); (*2, 3*) porous basaltic porphyrites, samples 153-1 and 154-14.

from station 110 falls beyond the field of active continental margins, near the points of stations 88 and 94. The basaltic porphyrites of station 110 are enriched in Al, Mg, and Ca but depleted in Ti, Fe, LILE, and LREE relative to the basalts from stations 102 and 94 (Tables 1, 2; Fig. 3b). The volcanic rocks are ascribed to the calc-alkaline series.

Judging from the petrographic characteristics of the obtained rock samples, the floor of the Weddell Sea contains abundant relics of the continental crust, whereas ice-transported fragments are rare. The rocks are granitoids, mica schists, amphibolites, and gneisses, which were affected by extensive metasomatism and silicification. Ultrabasic rocks, plagioclase pyroxenites, were found at stations 88 and 94, and hornblendite was documented only at station 88. Ore-bearing dolerite dikes occur at all the stations.

Northeastern continental slope of the Antarctic Peninsula. The southeastern slope of Joinville Island was trawled only at **station 121** at a depth of 2495–2561 m (63°37.32S, 50°45.03W; Fig. 1). Forty kilograms of rocks samples were uplifted there. The samples are strongly porous olivine–plagioclase basaltic porphyrites (samples 121a, 121r, and 121d), massive olivine–plagioclase basalts (sample 121g), sandstones (samples 121m and 121v), tuffs (sample 121z), plagiogranites (samples 121i, 121zh, and 121e), and quartzites (samples 121l and 121b). In the Th/Yb–Ta/Yb diagram (Fig. 2), the composition of basalt sample 121a falls in the lower part of the field of Andean-type active continental margins. Compared with the basalts from stations 102 and 110 in the floor of the Weddell Sea, these basalts are higher in Al, Ca, Na, and Mg but lower in Ti, Fe, K, P, LILE, and LREE (Table 1, Fig. 3b). The volcanic rocks are ascribed to the calc-alkaline series.

The Powell Basin is located in the northwestern part of the Weddell Sea, between the Antarctic Peninsula margin and the South Orkney Islands. Samples were obtained at three stations (Fig. 1): 142 (62°09.78S, 49°30.59W, 3304–3345 m depth, basin floor, 5 kg of rock samples), 150 (61°48.20S, 47°28.69W, 1738–2256 m depth, steep western slope of the South Orkney Islands, 80 kg of samples, including 16 fragments 15 × 20 and 20 × 30 cm in size), and 151 (61°45.40S, 47°07.54W, 1151–1168m depth, slope of the South Orkney Islands, 10 kg of samples; Fig. 1).

The samples from **station 142** are (Table 1) abundant fresh porous olivine–plagioclase basaltic porphyrites with a fluidal structure (samples 142-3, 142-4, 142-5, 142-6, 142u, 142ts, 142e, and 142ya), compact massive plagioclase basaltic porphyrites with an amygdaloidal structure (samples 142i, 142m, and 142d), tuffobreccias (samples 142b and 142l), sandstones (samples 142-2, 142-7, 142-sh, and 142-yu), fine-grained mineralized dolerites (samples 142-2, 142-k, 142-kh, and 142-f), mineralized diorites (sample 142v), plagiogranites (samples 142p, 142r, 142zh, 142z, and

Table 3. Microprobe analyses of selected minerals from the rocks of the Explora Wedge, Weddell Sea

Garnets

Oxide	1	2	3	4	5
MgO	8.11	4.63	5.83	3.46	5.85
SiO_2	41.55	37.46	37.61	37.42	38.46
Al_2O_3	11.35	20.56	20.22	20.45	20.37
CaO	11.33	4.77	1.11	4.06	5.32
TiO_2	1.90	0.03	0.02	0.04	0.02
FeO	20.67	31.66	34.10	32.88	29.56
Cr_2O_3	0.07	0.06	0.03	0.00	0.02
MnO	0.08	0.43	0.56	2.04	0.66
Total	95.06	99.60	99.48	100.35	100.26

Note: (1, 3) Garnet granulites, samples 80a and 80z; (4) garnet quartzite, sample 78z; and (2, 5) garnet gneisses, samples 80b and 94z (Table 2).

Clinopyroxenes

Oxide	1	2	3	4
SiO_2	51.28	52.71	52.22	41.34
Al_2O_3	2.46	2.62	1.88	12.39
Fe_2O_3	13.32	7.44	11.36	18.56
MgO	11.34	14.94	12.39	9.64
CaO	21.24	20.74	21.50	11.32
TiO_2	0.16	0.30	0.21	2.50
Na_2O	0.61	1.29	0.50	1.60
K_2O	0.01	0.01	0.00	1.96
Cr_2O_3	0.03	0.35	0.00	0.05
MnO	0.11	0.19	0.73	0.25
Total	100.56	100.59	100.79	99.61

Note: (1) Garnet granulite, sample 80a; (2) pyroxenite, sample 80-2; (3) charnockite, sample 94k; and (4) plagiogneiss, sample 110k (Table 2, Fig. 1).

Orthopyroxenes

Oxide	1	2	3	4
SiO_2	51.28	52.71	52.22	41.34
Al_2O_3	2.46	2.62	1.88	12.39
Fe_2O_3	13.32	7.44	11.36	18.56
MgO	11.34	14.94	12.39	9.64
CaO	21.24	20.74	21.50	11.32
TiO_2	0.16	0.30	0.21	2.50
Na_2O	0.61	1.29	0.50	1.60
K_2O	0.01	0.01	0.00	1.96
Cr_2O_3	0.03	0.35	0.00	0.05
MnO	0.11	0.19	0.73	0.25
Total	100.56	100.59	100.79	99.61

Note: (1) Garnet quartzite, sample 78z; (2) garnet granulite, sample 80z; and (3) garnet paragneiss, sample 94z (Table 2, Fig. 1).

142a), one sample of garnet-bearing plagiogranite (142), and mineralized quartzites (samples 142g, 142n, and 142t). The volcanic rocks have higher contents of Mg, Ca, and Al but lower Fe, alkalis, LILE, and LREE than the alkali basalts from the floor of the Weddle Sea (Figs. 1, 2, 3c). In the Th/Yb–Ta/Yb diagram (Fig. 2), the composition of sample 142 plots in the field of weakly enriched mantle sources. The points of volcanic rocks from the Jones Mountains, Hubert Miller Seamount, and Marie Byrd Seamounts in West Antarctica plot in the same field [12, 14]. These volcanics are ascribed to the tholeiite series.

The samples from **station 150** are unaltered porous olivine–plagioclase basaltic porphyrites (samples 150-5 and 150-2), massive plagioclase basaltic porphyrites (sample 150a), tuffs (sample 150z), abundant fresh fine-grained mineralized dolerites (samples 150-2, 150-4, 150l, 150t, 150d, 150p, 150r, 150b, and 150g), plagiogranites (samples 150kh, 150n, 150m, and 150f), and quartzites (samples 150e, 150v, 150u, 150ts, and 150sh).

The samples from **station 151** are porous olivine–plagioclase basalts (samples 151-9, 151-8, 151-13, 151-11, and 151-10), plagioclase basaltic porphyrites (sample 151-14), plagiogranites (samples 151-12, 151-6, 151-3, and 151-4), and quartzitic schists (samples 151-2, 151-7, 151-1, and 151-5). Compared with the rocks from station 142, the basalts are depleted in Si, Ca, and Fe but have similar contents of LILE and LREE and Th/Yb and Ta/Yb ratios (Figs. 2, 3c; Table 1). The volcanic rocks from station 151 are ascribed to the tholeiite series.

The volcanic rocks of the Powell Basin are closely similar to typical MORB, in particular, to young tholeiites from the Bransfield Strait [15, 16], which is probably related to the westward propagation of the American–Antarctic Ridge along the South Ridge of the Scotia Arc [12]. The uniform composition of rocks from the three stations (142, 150, and 151) in the Powell Basin suggests their bedrock occurrence.

Thus, the volcanic rocks of the Weddle Sea represent four series: early subalkaline (shoshonitic, station 94, seafloor), calc-alkaline (stations 80, 110, and 121) related to the destruction of the continental crust, late subalkaline (stations 59, 57, 74, and 78), and tholeiitic (stations 142, 150, and 151). The appearance of the tholeiitic series (E-MORB) in the Powell Basin is probably related to the upwelling of a buoyant hot mantle diapir beneath the rift system of the American–Antarctic Ridge and its southwestward movement to the Bransfield Strait. Two volcanic complexes of different age and composition probably occur in the Weddell Sea: (1) older shoshonitic and (2) a younger complex related to the oceanic crust in the area of continental crust destruction. The latter is confined to the presently active area of the young rift.

CONCLUSIONS

1. Regular distribution of identical rocks was observed in different stations in the Weddell Sea. This suggests that these samples represent bedrock occurrences rather than products of transportation by floating ice.

2. Two regions were distinguished: the East Antarctic margin (submarine Maud Ridge), which is characterized by the intense destruction and oceanization of the continental crust, and the northwestern part of the Weddell Sea (Powell Basin), where spreading processes are superimposed on the weakly destructed continental crust.

3. The volcanic rocks of the Maud Ridge were derived from an enriched mantle source. The fact that the same porous basalts were found at station 59 and compose the top of the Maud Rise in borehole 690 indicates a 4-km subsidence of the seafloor in the region of station 59.

4. The following geologic section was observed at various stations: young fresh porous basaltic porphyrites underlain by older massive basaltic porphyrites metamorphosed under greenschist-facies conditions. The presence of granulite-facies rocks suggests a continental origin for these rocks.

5. The mineralogical and geochemical features of magmatic rocks collected from various areas of the floor of the Weddell Sea may indicate a contribution of deep fluids.

6. We believe that the magmatic replacement of the Precambrian granite–metamorphic complex of the continental basement by basic–ultrabasic mantle material played the main role in the transformation of the continental crust into the secondary oceanic crust. This process occurred under a significant contribution of fluid flows and uneven activity of geologic processes, in contrast to the formation of the primary oceanic crust under the influence of seafloor spreading.

7. Our results suggest that the basement of the Weddell Sea had a continental origin and experienced extensive destruction.

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REFERENCES

1. M. M. Kavun and O. S. Vinnikovskaya, "Geological Structure of the Northwestern Weddell Sea, Antarctica," Byull. Mosk. O-va Ispyt. Prir., Otd. Geol. **68** (6), 83–95 (1993).
2. F. Coren, G. Ceccone, E. Lodolo, et al., "Morphology, Seismic Structure and Tectonic Development of the

Powell Basin, Antarctica," J. Geol. Soc. **154**, 849–862 (1997).

3. A. A. Marakushev, "Geological Structure and Petrological Models for the Formation of the Earth's Crust," Tikhookean. Geol. **23** (5), 3–24 (2004).
4. T. I. Frolova, "Role of Magmatic Processes in the Transformation of the Continental Crust," Byull. Mosk. O-va Ispyt. Prir., Otd. Geol. **76** (2), 7–24 (2001).
5. P. F. Barker, "Geophysical Profiles, Scotia Sea; Scotia Sea Bottom Topography; Scotia Sea Magnetic Lineations, Seismicity," in *International Geological–Geophysical Atlas of the Atlantic Ocean*, Ed. by G. B. Udintsev (IOC, Moscow, 1990), pp. 58–61 [in Russian].
6. GEBCO// IHO / IOC / CHS. 1984. 2003.
7. B. C. Heezen and M. Tharp, *World Ocean Floor* (New York, 1977, 1994).
8. E. S. Schandl, M. P. Gordon, and F. J. Wieks, "Mineralogy and Geochemistry of Alkali Basalts from Maud Rise, Weddell Sea, Antarctica," Proc. Ocean Dril. Prog., Sci. Res. **113**, 5–11 (1990).
9. H. W. Schenke, S. Dijkstra, F. Niederjasper, and T. Schone, *AWI Bathymetric Chart of the Weddell Sea* (1998).
10. W. Smith and D. Sandwell, "Global Sea Floor Topography from Satellite Altimetry and Depth Sounding," Science **277**, 1956–1962 (1997).
11. G. B. Udintsev, R. Gerzonde, D. E. Teterin, et al., "Geology of Peter I Island and the Probable Dynamics of the Evolution of West Antarctica in the Bellingshausen Sea," Tikhookean. Geol. **21** (6), 31–45 (2002).
12. G. B. Udintsev and H. W. Schenke, *Sketches on the Geodynamics of West Antarctica* (GEOS, Moscow, 2004) [in Russian].
13. T. I. Frolova and I. A. Burikova, *Magmatic Associations of Modern Geotectonic Settings* (Mosk. Gos. Univ., Moscow, 1997) [in Russian].
14. S. R. Hart, J. Blusztajn, and C. Craddock, "Cenozoic Volcanism in Antarctica: Jones Mountains and Peter 1 Island," Geochim. Cosmochim. Acta **59**, 3379–3388 (1995).
15. N. M. Sushchevskaya, G. B. Udintsev, B. V. Belyatskii, et al., "Magmatism in the Central Part of the Bransfield Strait Spreading Zone, Southern Ocean," Geokhimiya, No. 6, 612–625 (2002) [Geochem. Int. **40**, 551–563 (2002)].
16. N. A. Kurentsova and G. B. Udintsev, "Main Features in the Structure and Evolution of the South Scotia Sea, West Antarctica," Tikhookean. Geol. **23** (5), 25–39 (2004).