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NEW EVIDENCE ON BACKARC VOLCANISM IN THE EASTERN ALEUTIANS

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New evidence is presented on the types of volcanic formations and the chemical composition of volcanic rocks in the backarc area of the Islands of the Four Mountains and Umnak Island Eastern Aleutians. The evidence was obtained during cruise 38 of the R/V *Vulkanolog*. Three types of formations were distinguished: (1) volcanic peaks sitting on the sediments, (2) eroded volcanic edifices, and (3) scarps on the edges of fault blocks and depressions. The first two represent a young volcanic rock complex, the third, the rocks of the basement complex. The alkali content in the rocks is notably higher than in the lavas of the Islands of the Four Mountains. This indicates the presence of a transverse geochemical zoning, normal for island arcs. Both complexes were found to contain lavas with an island-arc normal and an elevated TiO_2 content (up to 1.9%) over a wide variation of the silica content. This suggests an independent origin of each group of rocks.

INTRODUCTION

The Aleutian island arc does not have volcanoes in its backarc region, except for the eastern segment (Cold Bay and the Islands of the Four Mountains), where there is a backarc volcanic zone, similar to that of the Kuril island arc [3]. This zone includes several volcanic islands (Amak, Bogoslof, Uliaga, Kagamil, and Carlisle) and a few submarine volcanoes [5]. Only two of the volcanic islands were studied previously, Amak and Bogoslof [2], [5], [7]. No evidence has been available in the literature on the other volcanoes, including submarine volcanoes in the backarc zone.

In 1990 joint Soviet-American geological and geophysical investigations were carried out during cruise 38 of the R/V *Vulkanolog* in the backarc zone of the Island of the Four Mountains and Umbak Island. They consisted in continuous seismic profiling (CSP), echo sounding, marine magnetic survey, and dredging. The evidence on the character of volcanic occurrences and the chemical composition of the volcanic rocks, obtained as a result of these investigations is the subject of this paper[a].

GEOLOGY OF THE BACKARC ZONE AND THE DESCRIPTION OF DREDGING SITES

As agreed upon with the US Navy, the study area was limited by 172°W and 164°W and, in the south, by the territorial waters boundary 12 miles from the islands (Figure 1). The geophysical investigations that were intended to improve the knowledge of the structure and geomorphology of the area and locate sites suitable for dredging (including young volcanoes) were arranged along a system of tracks oriented largely parallel to the island arc trend. The interval between the tracks was 5-10 miles in a regional survey and smaller than that in area where anomalous objects were discovered.

According to previous investigations [9], the area is underlain by volcanogenic-sedimentary rocks of three series: the lower (early? - late Eocene) series, the middle (Oligocene-Miocene) series, and the upper, Pliocene-Quaternary series (younger than 5.3 m.y.).

The sea floor of the study area has a block structure and varies from 500 to 2000 m in depth. The blocks are separated by depressions, possibly grabens, with asymmetric sides of varying slope. Numerous island-arc morphological features (steep scarps, small mounts, ridge, and valleys) complicate the sea-floor topography. The submarine valleys seem to be parts of the giant Bering and Umnak submarine canyons. Most of them are deep, narrow, V-shaped depressions, incised to a depth of hundreds of meters into the bottom sediments, some of them being as wide as 2-3 km. The largest valleys cut throughout the upper sedimentary sequence but have a distinct U shape because the sediments of the middle sequence or some unit of the upper were more resistant to erosion because of a higher degree of consolidation.

The cross-sections plotted from our seismic records show stratified volcanogenic-sedimentary formations to a depth of 1 km. The base of the section shows fragments of an interface that can be interpreted as the top of the middle sequence.

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[a] In this paper we consider the petrochemical and some of the mineralogical features of the rocks. The mineralogy, trace element abundances, and isotopic composition will be discussed in detail elsewhere.

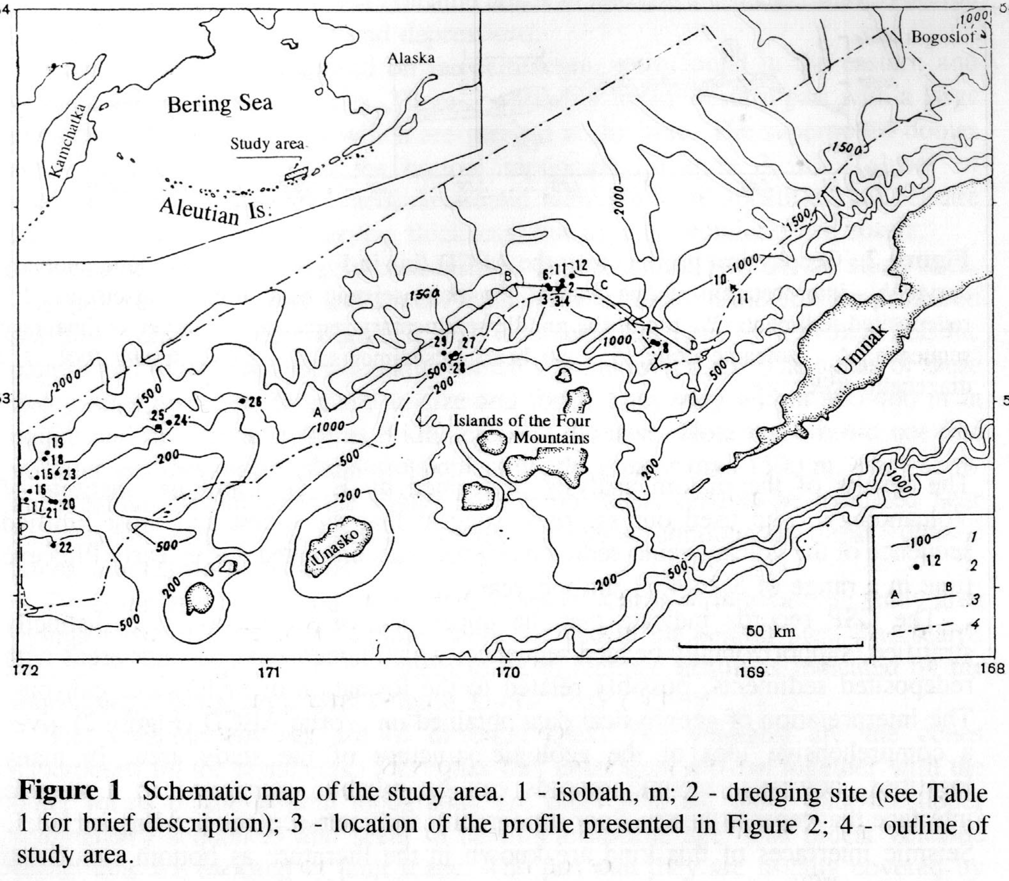


Figure 1 Schematic map of the study area. 1 - isobath, m; 2 - dredging site (see Table 1 for brief description); 3 - location of the profile presented in Figure 2; 4 - outline of study area.

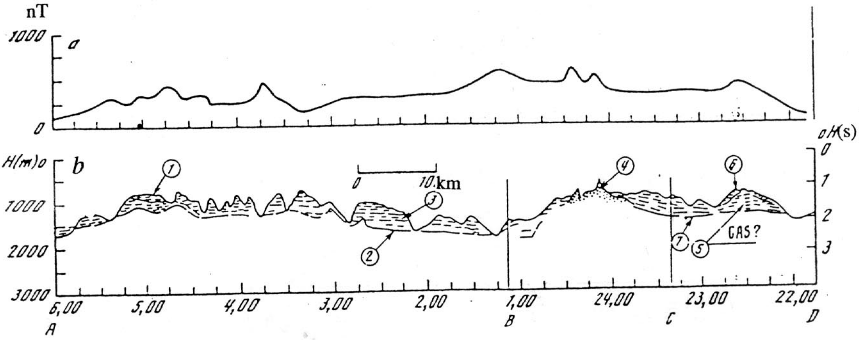


Figure 2 Geophysical profile along the ABCD line in Figure 1. *a* - magnetic anomaly curve; *b* - interpretation of one-channel (Sparker) seismic data. Figures in circles: 1 - redeposited sediments; 2 - top of the middle sedimentary sequence; 3 - upper sedimentary sequence; 4 - volcanic cone; 5 - gas-bearing sediments; 6 - gas-hydrated *BSR*; 7 - diagenetic *BSR*.

The results of the diatom analysis performed by E. G. Lupikina, Institute of Volcanology, who used our samples, suggest that the oldest and most lithified sequence of the volcanogenic-sedimentary rocks accumulated during early Pliocene time in a range of 5.26-4.71 million years.

The CSP records indicate that the upper part of the section is a distinctly stratified, subhorizontally bedded sequence, which nonetheless contains areas with redeposited sediments, possibly related to the formation of underwater canyons. The interpretation of geophysical data obtained on profile ABCD (Figure 2) gives a comprehensive idea of the geologic structure of the study area. In many localities, however, seismic records can be reliable interpreted to a seismic interface that repeats the sea-floor topography and intersects the bedding surfaces. Seismic interfaces of this kind are known in the literature as bottom simulating reflectors (*BSR*) of gas-hydrate or diagenetic origin [6]. Because in our case this interface occurs at 600-650 m depth below the sea floor, it must be of diagenetic origin. Another important point is that the seismic records display anomalous zones or high-amplitude reflectors (bright sports) in the sediments, possibly produced by gas accumulations. Locally, bottom simulating reflectors of gas-hydrate origin were observed.

The main feature of the anomalous magnetic field is a high-intensity long-period anomaly, oriented along the island-arc slope, which is usually observed in continent-ocean transition zones. Magnetic anomalies were also observed above some small positive topographic features within the island-arc slope. Because high values of remanent magnetization are typical of volcanic rocks, the occurrence of a short-period magnetic anomaly served as another indication of volcanic bodies in the interpretation of seismic data.

Three types of objects, suitable for dredging the bedrock, were found in the study area (Table 1): (1) volcanic peaks (cones or extrusive bodies) sitting on the sediments, (2) volcanic structures on the slopes of submarine valleys that were partly or totally eroded (buried volcanic cones or extrusive bodies), and (3) scarps on the edges of fault blocks and depressions.

Volcanic cones, superposed on the sediments, were found in the eastern and western parts of the study area. There is a locality in the western part with a large number of domes, some of which are merged at the base. The superposed domes are easily recognizable in the bottom topography (Figure 3, *a*). Taluses of volcaniclastic material are traceable around them. In some localities, taluses are covered by sediments of varying thickness, but usually sediments are absent.

Volcanic cones are largely concentrated in the central part of the study area. They are severely eroded and almost indistinguishable from the erosion-produced sea-floor relief features (Figure 3, *b*). We identified them by a typical seismic pattern and local magnetic anomalies which amount to 400 nT. The cones of these two groups do not differ much in size and form. They vary within 300-400 m in height and may be as large as 3 km across at the base. Note that we did not find volcanic edifices on the island-arc slope at depths greater than 1500 m. They show an irregular distribution (see Figure 1) and obviously tend to be localized near contacts between various types of tectonic features or continue the linear volcanic zones situated on the islands.

Dredging was carried out on various kinds of scarps throughout the study area though most of the dredge samples were derived in the central part. The scarps may be as steep as 20-30° and seem to be of tectonic origin as indicated by the morphology and seismic data (Figure 3, *c*).

The volcanic edifices are of different ages. The youngest are the cones superposed on the sediments. The cones that underwent erosion together with the other forms of the bottom topography are older (but not older than the upper sedimentary sequence) and seem to be of Pleistocene age. The oldest volcanic formations are exposed in fault scape. The fact that they are usually covered by sediments indicates that they were produced during earlier volcanic events and can be considered as a basement for the edifices of the two former groups.

So, we can conclude that dredge samples were collected from two stratigraphically individual rocks complexes.

In the backarc zone of the Islands of the Four Mountains, dredging was performed at 27 sites, 24 of which were successful (see Table 1).

A large amount of angular blocks and smaller fragments of compositionally uniform extrusive rocks, definitely of local origin, was raised from 12 sites (V38-2, -4, -6, -7, -10, -16, -18, -22, -24, -28, and -29). Three sites (V38-17, -25, and -26) yielded materials of considerable more diverse composition. Fragments of local lavas cannot be distinguished with certainty from exotic fragments of ice-rafted or turbidity-current origin. The dredge samples raised from nine sites (V38-5, -8, -11,

Table 1 Location and material of dredging sites on Eastern Aleutian submarine volcanoes,

Dredging site number	*Coordinates (start - end)*		*Dredging interval, m*	*Location*	*Morphology*
	Lat. N	*Long. W*			
1	2	3	4	5	6
V38-2	53°17.8′ 53°17.2′	169°46.1′ 169°47.0′	820-730	14 miles N of Uliaga	YVP
V38-3	53°17.6′ 53°17.5′	169°46.25′ 169°46.1′	850-560	Same	"
V38-4	53°17.6′ 53°17.8′	169°46.4′ 169°46.0′	800-750	"	"
V38-5	53°17.25′ 53°17.1′	169°49.0′ 169°47.6′	900-830	15 miles N of Uliaga	"
V38-6	53°17.25′ 53°17.1′	169°49.5′ 169°48.6′	820-750	13 miles N of Uliaga	"
V38-7	53°08.9′ 53°08.7′	169°22.5′ 169°21.3′	1050-980	13 miles NE of Kagamil	EVE ?
V38-8	53°08.8′ 53°09.0′	169°23.3′ 169°23.4′	1150-970	Same	EVE ?
V38-9	53°16.9′ 53°17.1′	169°04.2′ 169°04.1′	570-400	16.5 miles NW of Vsevidov peak, Umnak	ES
V38-10	53°17.5′ 53°17.5′	169°04.25′ 169°04.25′	500-400	Same	"
V38-11	53°18.3′ 53°17.0′	169°44.0′ 169°43.6′	1040-840	28 miles of Uliaga peak	EVE

cruise 38, R/V *Vulkanolog*.

Weight, kg	*Type of raised material*	*Lithology*
7	8	9
60-80	Angular blocks and fragments, minor boulders	Angular blocks of Cpx-Am-Pl basalt; boulders of gabbro-diorite, altered andesite, mudstone
80-90	Dozen of small angular blocks, one large subrounded block, one boulder	Angular blocks of fresh Cpx-Am-Pl basalt; large block of fresh 2Px-Pl andesite; boulder of dark red jasper
>300	Angular blocks and fragments, a few boulders and ~60 kg of medium and large pebbles	Angular blocks of Cpx-Am-Pl basalt; boulders of paleotypal basalt, Bt granite
~50	A few angular fragments and boulders	One fragment of Pl basalt, other fragments and boulders of metasediments, one boulder of Bt gneissic granite
~150	One large angular block, many small angular blocks, fragments and rubble	Fresh Ol-Cpx basalt, minor Cpx-Pl basaltic andesite
~40	One large block, a few fragments, a dozen of large pebbles	Block and fragments of Ol-Cpx basalt; some siltstone fragments
150	Boulders, pebbles (domin.), blocks, angular fragments, rubble	Angular fragments and rubble of 2Px-Pl andesite; blocks and some fragments of siltstone; boulders and pebbles of mudstone, siltstone, black shale, diorite, monzonite, gabbro
~0.5	Small pebbles	2Px-Pl basaltic andesite and andesite
~20	Angular fragments, minor large pebbles	Fragments of 2Px-Am-Pl basaltic andesite, minor Am-Pl acid adesite
30-40	Two angular fragments, pebbles	Fragments of altered andesite and basaltic andesite; pebbles of mudstone, phyllite, siliceous schist, Am-gabbro, Bt-Am granodiorite and plagiogranite

Table 1 (continued).

1	2	3	4	5	6
V38-12	53°19.2′ 53°19.25′	169°43.4′ 169°44.3′	1140-1000	Same	EVE
V38-15	52°47.8′ 52°46.9′	171°55.1′ 171°55.7′	1200-1060	30 miles NW of 1052-m peak on Amuhta I.	YVP
V38-16	52°46.0′ 52°46.2′	171°57.4′ 171°56.8′	1100	30.5 miles NW of 1052-m peak on Amuhta I.	"
V38-17	52°44.6′ 52°43.9′	171°58.0′ 171°58.4′	830-310	30 miles NW of 1052-m peak on Amuhta I.	"
V38-18	52°51.0′ 52°51.6′	171°53.5′ 171°53.3′	1300-1150	31.5 miles NW of 1052-m peak on Amuhta I.	"
V38-19	52°51.9′ 52°51.5′	171°52.9′ 171°52.2′	1300-1150	Same	"
V38-20	52°44.1′ 52°45.0′	171°51.2′ 171°50.5′	950-560	24 miles NW of Amuhta I.	"
V38-21	52°44.4′ 52°44.9′	171°51.8′ 171°51.9′	950-580	Same	"
V38-22	52°37.7′ 52°38.4′	171°51.2′ 171°51.5′	1060-680	20 miles NW of Amuhta I.	ES
V38-23	52°48.7′ 52°48.7′	171°54.4′ 171°54.4′	1000-710	25 miles NW of Amuhta I.	YVP

7	8	9
~30	Angular small blocks and fragments, some with Fe-Mn crusts	Sandstone; one block of coquina, one of Cpx-Am-Pl basaltic andesite, and one of Cpx-Am-Pl andesite
~100	40% of angular blocks with Fe-Mn crusts, 60% of pebbles	Blocks of poorly lithified siltstone; pebbles of mudstone, sandstone, and minor basalt, andesite, two-mica schist, and gabbro
~300	Angular blocks, fragments, rubble	Uniform Cpx-Ol basalt with small xenocrysts of pyroxenite
~300	Angular blocks, fragments, ~20% of pebbles	Blocks and fragments of Ol-Cpx-Pl basalt, minor Px-Pl ± Ol basaltic andesite and Am andesite; pebbles of sandstone, gravelstone, andesite, gabbro, granodiorite, gneiss
~30	One large and one small blocks, four angular fragments	Large block and fragments of Ol-Cpx-Pl basalt, small block of medium-grained sandstone
~80	Pebbles and boulders	42% lavas, 26% sedimentary rocks, 16% phyllite, 7% intrusive rocks, 9% exotic rocks
10-15	Angular fragments and pebbles	Fragments of gravelstone and sed. breccia; pebbles of andesite and dacite
60	Blocks, fragments, rubble	Blocks and fragments of gravelstone and sed. breccia; minor rubble of andesite
≥300	Angular, fragments and blocks, a few large subrounded fragments	Angular fragments at blocks of fresh subaphiric Cpx-Ol-Pl basalt and minor breccias and basaltic andesite; a few blocks of sandstone; subrounded blocks of Px-Pl andesite
≥150	Angular blocks, fragments, and boulders	Large blocks of Ol-Cpx-Pl basalt; small blocks and fragments of poorly cemented mudstone and minor 2Px-Pl andesite; boulders of altered lava, phyllite, schist, and minor gabbro and granite

Table 1 (continued).

1	2	3	4	5	6
V38-24	52°56.8′ 52°57.0′	171°23.0′ 171°23.1′	750-570	26 miles NW of 1143-m peak on Chuginadah I.	EVE (YVP ?)
V38-25	52°56.0′ 52°56.2′	171°25.9′ 171°26.2′	1100-900	24 miles NW of 1143-m peak on Chuginadah I.	"
V38-26	52°58.9′ 52°58.7′	171°04.0′ 171°04.1′	725-570	24.7 miles N of 1143-m peak on Chuginadah I.	ES
V38-27	53°07.2′ 53°07.2′	170°12.6′ 170°12.0′	780-670	15 miles NW of 1609-m peak on Carlisle I.	EVE ?
V38-28	53°07.0′ 53°07.0′	170°12.6′ 170°12.5′	890-600	14.5 miles NW of 1609-m peak on Carlisle I.	EVE ?
V38-29	53°07.6′ 53°07.5′	170°15.3′ 170°16.2′	1150-850	15.7 miles N of 1609-m peak on Carlisle I.	EVE ?

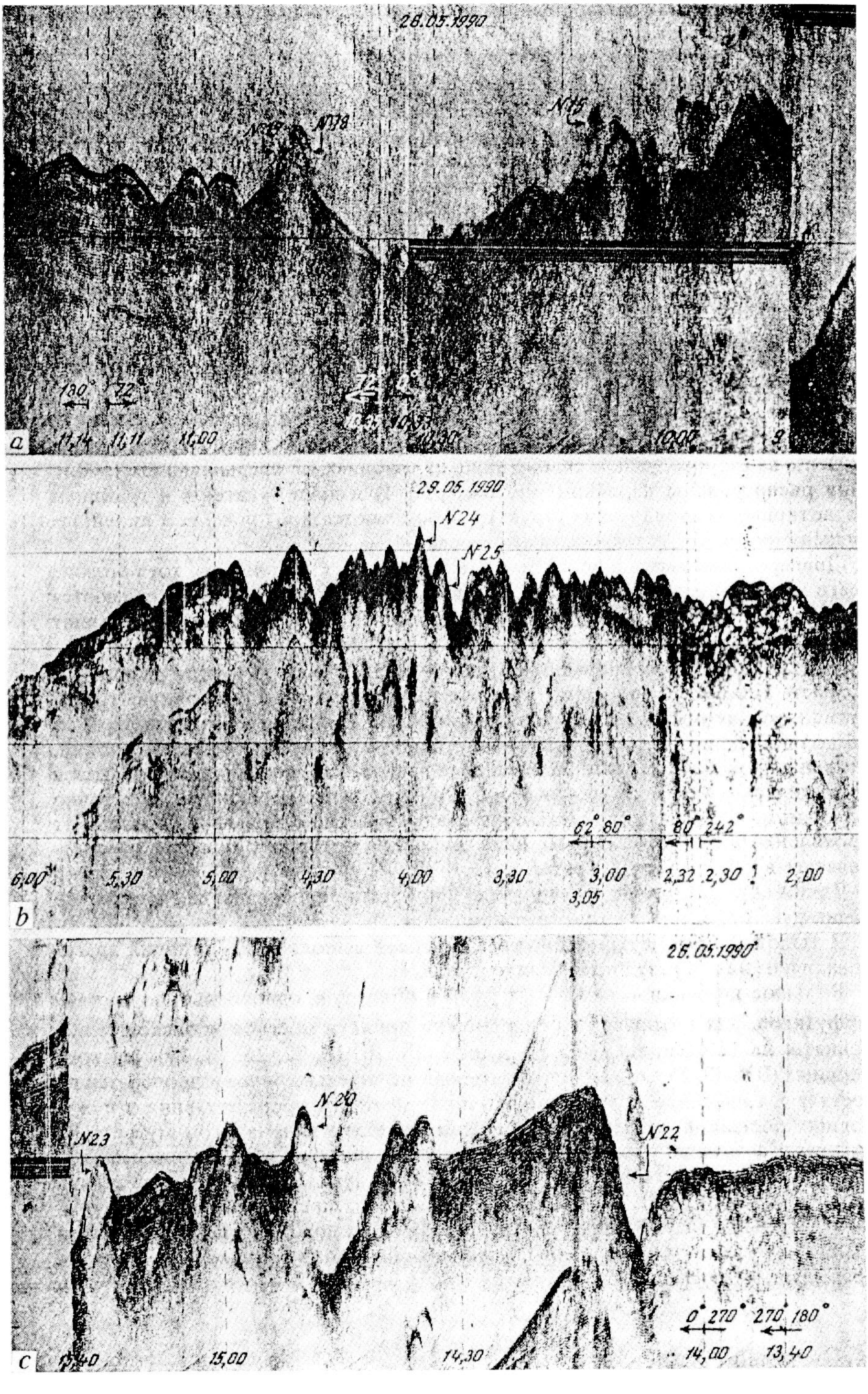
Note. YVP - young volcanic peak; EVE - eroded volcanic edifice; ES - erosion scarp, canyon side; Pl - plagioclase, Ol - olivine, Cpx - clinopyroxene, Am - amphibole, Bt - biotite, 2Px - clinopyroxene + orthopyroxene.

-12, -15, -19, -20, -21, and -23) yielded predominantly boulders, pebbles, or blocks of poorly cemented sedimentary rocks with scarce lava fragments, the source of which is unknown, as in the previous case.

7	8	9
~300	Angular blocks and fragments with Fe-Mn crusts, rare boulders and pebbles	Blocks and fragments of fresh Ol-Cpx basalt with microxenoliths of ultrabasic rocks; one block of 2Px-Pl basaltic andesite; boulders and pebbles of basaltic andesite, tuff, and gabbro
~150	Subrounded blocks and fragments with Fe-Mn crusts, some pebbles, and a few boulders	Blocks of fresh Ol-Cpx-Pl basalt, gravelstone, and minor 2Px-Pl basaltic andesite, andesite, gabbro; pebbles and boulders of sandstone, mica schist, paleotypal volcanics
50-60	Subrounded blocks, boulders and pebbles	Blocks of subaphyric fresh Ol-Cpx-Pl basalt, paleotypal dolerite, sandstone, mudstone, Bt gneiss; boulders and pebbles of tuff, greenstone lava, phyllite, sandstone, Bt granite, pegmatite
0.5-1.0	Pebbles and organic detritus	Pebbles of paleotypal lava and phyllite
~70	One large angular block, many small blocks and fragments, well-rounded pebbles	Small blocks of fresh Ol-Cpx-Pl subaphyric basalt and basaltic andesite; large block of greenschist; fragments of jasper, diorite, paleotypal lava, and poorly cemented sediments; pebbles of paleotypal lava, metasediments
30-40	Angular blocks and fragments	Fresh subaphyric Cpx-Pl basaltic andesite

CHEMISTRY OF VOLCANIC ROCKS

The chemical and mineral compositions of rocks were determined using angular fragments alone. Generally, the rocks vary from low-silica basalts to acid andesites (Table 2). The dominant rock type in the two groups of different age is basalt with minor amounts of basaltic andesite and andesite. Most of the fragments are fresh, though some of the lava fragments had vesicles filled with zeolites or smectite (basalt samples V38-5/1, -7/4, -17/3, -22/2, -22/5, -23/1, -24, and -24/1) and some


28.05.1990
N15
N18
180°
72°
a
11,14
11,11
11,00
10,30
10,00
9
29.05.1990
N24
N25
62° 80°
80° 242°
6,00
5,30
5,00
4,30
4,00
3,30
3,00
3,05
2,32
2,30
2,00
b
28.05.1990
N20
N23
N22
0° 270°
270° 180°
c
15,00
14,30
14,00
13,40

showed oxidation on the surface or in cracks (sites V38-16, -17, and -24). A few samples showed chloritization (V38-25/3, -26/1, -28/2, and -28/3) or carbonatization (V38-25/6 and -25/7).

According to the total alkali content, most of the lavas recovered from the backarc zone of the Islands of the Four Mountains tend toward the boundary between the rocks of normal and elevated alkalinity, and according to the K_2O content, toward the top of the field of the moderately potassic series or toward the field of the high-K series. Moreover, some of the basalts are even more alkalic and resemble absarokites of the shoshonite-latite series (Figure 4). The lavas of volcanic islands from the backarc zone of the Eastern Aleutians, Bogoslof and Amak, have similar positions. Generally, volcanic rocks from the backarc zone of the Eastern Aleutians resemble the volcanics of the backarc volcanic zone of the Kuril Islands in terms of alkalinity [3].

However, there is a difference between them: the lavas of the Kuril backarc zone are dominated, according to Miashiro's classification, by calc-alkalic varieties, whereas basalts and basaltic andesites from the Aleutian backarc zone are mostly lavas of the tholeiitic series, except for some calc-alkalic varieties that appear among the andesites and some of the high-magnesian basalts (see Figure 4). The lavas of the lower and upper complexes do not differ much in alkalinity and in the FeO^{-}/MgO ratio, except that absarokites were found in the upper complex alone.

At the same time some of the lava samples are notably less alkalic and tend toward the bottom of the field of moderately potassic rocks in a K_2O-SiO_2 diagram and toward the field of the calc-alkalic series in a Miashiro diagram. They are usually found in dredge hauls with compositionally different fragments (sites V38-17 and V38-25) or in hauls where the other samples are more alkalic and compositionally identical rocks (sites V38-6 and V38-24). In terms of the total and potassic alkalinity, these rocks correspond to the lavas of volcanic islands from the forearc zone of the Aleutian arc segment concerned and also to the lavas of Umnak Island, situated in the forearc zone, west of the Islands of the Four Mountains (see Figure 4). The occurrence of these rocks in the dredge hauls, as well as of the boulders and pebbles of paleotypal lavas, intrusive, metamorphosed sedimentary, and other exotic rocks, is related to ice-rafting, turbidity currents, or other transportation mechanisms. On this basis, most of the basalts can be considered to be of local origin, whereas a fairly large amount of basaltic andesite and andesite fragments are likely to be exotic.

Figure 3 Fragments of seismoacoustic sections illustrating various types of dredging sites. *a* - volcanic cone superimposed upon sediments; *b* - eroded volcanic edifices; *c* - fault scarp. N15, N18, N19, etc., are dredging sites.

Table 2 Chemical composition of volcanic rocks from the backarc zone of the Islands of the Four Mountains.

Component	V38-2			V38-3			V38-4			V38-5	V38-6	
	2/2	2/1	2G/2	3/2	3/1*	3G/1*	4/1	4/2	4G/1	5/1**	6/5	6/3
SiO_2	52,06	52,28	52,30	52,14	58,68	60,79	52,44	52,44	52,70	49,56	47,82	47,82
TiO_2	0,86	0,85	1,09	0,85	0,68	0,78	0,82	0,90	1,09	1,94	1,12	1,09
Al_2O_3	19,88	19,61	19,67	19,77	17,10	17,56	19,58	19,28	19,06	14,68	17,18	17,03
Fe_2O_3	3,22	2,95	3,74	3,02	1,63	1,64	3,22	4,06	3,75	5,08	3,54	3,53
FeO	4,94	5,21	4,39	5,05	4,42	4,57	4,98	4,32	4,34	6,48	5,70	6,19
MnO	0,22	0,20	0,27	0,12	0,18	0,17	0,21	0,21	0,22	0,18	0,18	0,22
MgO	2,94	3,28	2,62	3,28	2,76	2,30	3,18	3,16	2,38	7,12	7,64	7,90
CaO	9,82	10,32	9,16	10,64	8,74	5,68	10,58	10,23	9,86	9,52	12,18	11,58
Na_2O	3,58	3,70	3,53	3,58	4,29	3,89	3,46	3,52	3,48	3,58	2,94	2,76
K_2O	1,42	1,42	1,38	1,38	1,46	1,48	1,38	1,42	1,38	1,08	1,24	1,08
P_2O_5	0,59	0,57	0,58	0,54	0,26	0,21	0,56	0,50	0,57	0,35	0,28	0,26
H_2O^-	n.f.	n.f.	0,12	n.f.	n.f.	0,08	n.f.	n.f.	0,12	n.f.	n.f.	0,10
LOI (H_2O^+)	0,12	"	(1,16)	"	0,20	0,76	"	0,20	0,88	0,38	0,50	0,26
Σ	99,65	100,39	100,01	100,37	100,40	99,91	100,41	100,24	99,83	99,95	100,32	99,82

Component	V38-6				V38-7		V38-8		V38-10			V38-12
	6/4	6/2	6G/3	6/1*	7G/1	7/1	8/1*	8G/1*	10/1	10/2	10/3	12G/1
SiO_2	47,90	48,04	48,10	53,20	51,08	52,56	59,06	60,12	53,94	54,28	60,82	56,58
TiO_2	1,08	1,12	1,31	0,97	0,86	0,74	0,73	0,84	0,88	0,96	0,69	1,00
Al_2O_3	16,96	17,28	17,55	16,21	17,65	16,89	17,60	17,39	19,26	19,08	19,25	18,94
Fe_2O_3	3,32	3,97	3,65	3,38	3,39	3,16	2,81	1,62	4,92	5,11	2,35	3,02
FeO	6,57	5,93	5,28	7,92	5,60	6,25	4,15	4,82	2,30	2,30	2,16	3,85
MnO	0,23	0,17	0,15	0,20	0,15	0,18	0,17	0,14	0,11	0,08	0,18	0,22
MgO	8,02	7,64	6,18	5,08	5,38	5,06	3,38	3,18	3,06	2,86	2,20	1,98
CaO	11,58	11,58	12,94	9,32	10,12	9,86	6,88	6,52	7,94	8,22	4,98	7,66
Na_2O	2,65	2,76	2,86	2,93	2,49	2,64	3,74	3,43	4,25	4,43	4,64	3,79
K_2O	1,08	1,14	1,09	0,72	1,10	1,33	1,29	1,25	2,06	2,06	2,31	1,57
P_2O_5	0,24	0,24	0,25	0,13	0,22	0,23	0,11	0,12	0,34	0,38	0,14	0,42
H_2O^-	0,12	0,10	0,16	n.f.	0,20	0,20	n.f.	0,04	0,10	n.f.	n.f.	0,12
LOI (H_2O^+)	0,42	0,32	0,40	0,30	1,32	0,62	0,30	(0,52)	0,42	0,44	0,56	0,80
Σ	100,17	100,29	99,92	100,36	99,56	99,92	100,22	99,99	99,58	100,20	100,28	99,95

Table 2 (continued).

Compo-nent	V38-12		V38-16			V38-17					V38-18	
	12/i	12/2	16G/2	16G/3	16	17/2	17G/3	17G/2	17/5*	17/12*	18/1	18G/1
SiO_2	56,68	60,04	47,54	47,90	47,98	46,88	47,74	47,98	53,90	57,68	47,82	48,60
TiO_2	0,81	0,68	0,97	0,99	0,47	0,92	0,99	0,99	0,62	0,57	0,77	0,84
Al_2O_3	19,10	18,28	16,17	16,05	16,23	17,52	17,36	17,56	20,38	18,27	17,87	17,94
Fe_2O_3	3,18	2,25	2,93	2,80	n.f.	2,89	2,88	3,08	4,04	3,02	2,88	2,87
FeO	4,12	3,09	5,86	5,92	6,68	7,04	6,55	5,77	4,17	3,76	6,41	6,00
MnO	0,19	0,18	0,17	0,17	0,18	0,11	0,18	0,16	0,14	0,14	0,14	0,18
MgO	2,42	2,94	11,20	11,20	13,96	9,44	8,80	8,32	2,33	3,10	6,96	7,06
CaO	7,52	6,19	11,60	11,04	9,70	10,98	11,38	11,96	9,10	7,84	13,17	12,94
Na_2O	3,93	4,30	2,28	2,34	2,45	2,49	2,44	2,54	3,49	3,52	2,27	2,18
K_2O	1,56	1,78	0,87	0,87	1,02	0,99	0,95	0,94	0,99	1,16	0,87	0,84
P_2O_5	0,40	0,26	0,14	0,15	0,25	0,18	0,18	0,16	0,18	0,15	0,16	0,15
H_2O^-	0,12	n.f.	0,12	0,08	0,12	0,04	0,12	0,14	0,10	0,12	0,10	0,12
LOI (H_2O^+)	0,41	0,36	0,52	0,20	0,62	0,08	0,04	0,32	0,26	0,30	0,44	0,52
Σ	100,44	100,35	100,23	99,71	99,61	99,56	99,61	99,92	99,70	99,63	99,86	99,99

Component	V38-18	V38-22				V38-23		V38-24				
	18/2	22/1**	22/5**	22/2**	22G/2**	23/1	23/2**	24/1	24G/2	24G/4	24/3	24/2
SiO_2	48,85	51,92	52,80	52,90	54,32	47,82	63,00	46,92	48,10	48,12	48,26	48,50
TiO_2	0,80	1,70	1,70	1,57	1,69	0,85	1,30	1,06	1,14	1,09	1,10	1,08
Al_2O_3	17,05	16,52	15,30	16,20	15,90	15,98	14,30	17,38	17,37	16,96	15,90	15,32
Fe_2O_3	2,96	3,01	5,73	3,83	3,80	3,16	1,83	3,95	3,70	4,12	4,03	3,33
FeO	6,64	7,74	5,74	6,75	7,15	5,95	5,55	4,91	4,94	4,71	5,82	6,70
MnO	0,18	0,15	0,18	0,17	0,20	0,07	0,16	0,08	0,13	0,14	0,17	0,16
MgO	7,56	3,58	3,36	3,40	3,18	10,06	2,30	6,82	6,60	6,90	8,14	9,20
CaO	11,24	7,92	7,84	7,88	7,32	11,25	5,42	12,37	12,76	12,44	11,62	10,02
Na_2O	3,43	3,46	3,66	3,77	3,43	2,48	4,05	2,27	2,18	2,13	2,44	3,82
K_2O	0,92	1,89	1,58	1,54	1,84	1,09	1,75	1,85	1,89	1,89	1,54	1,62
P_2O_5	0,18	0,26	0,53	0,30	0,35	0,23	0,25	0,35	0,41	0,43	0,37	0,35
H_2O^-	0,20	0,22	0,77	0,54	0,20	0,24	0,13	0,46	0,36	0,28	0,08	0,14
LOI (H_2O^+)	0,45	0,64	0,25	1,04	0,96	0,48	0,25	1,30	0,80	0,78	0,00	0,20
Σ	100,46	99,62	99,44	99,89	100,34	99,66	100,29	99,82	100,38	99,99	99,47	100,44

Table 2 (continued).

Compo-nent	V38-24	V38-25					
	24/10*	25/2	25/1*	25/3*	25/7*	25/5*	25/6*
SiO_2	54,32	50,60	52,70	55,68	58,82	60,98	61,90
TiO_2	1,01	0,98	0,76	1,08	0,62	0,71	0,58
Al_2O_3	15,70	17,88	17,80	17,61	18,10	17,65	17,12
Fe_2O_3	3,64	2,00	1,80	0,63	2,60	3,00	1,92
FeO	5,32	6,75	5,46	6,18	3,31	3,39	2,87
MnO	0,18	0,17	0,17	0,18	0,09	0,35	0,11
MgO	5,74	5,50	6,26	3,68	2,71	2,50	2,74
CaO	9,57	10,70	10,00	8,70	6,72	6,40	6,88
Na_2O	2,98	2,70	2,62	3,29	3,34	3,11	3,40
K_2O	0,60	1,07	0,73	0,56	1,62	1,62	1,20
P_2O_5	0,18	0,16	0,23	0,21	0,17	0,29	0,13
H_2O^-	0,72	0,16	0,26	0,00	0,16	0,08	0,55
LOI (H_2O^+)	0,48	0,70	0,61	1,58	1,42	0,12	0,69
Σ	100,44	99,47	99,40	99,38	99,68	99,60	100,09

Component	V38-26	V38-28		V38-29		
	26/1*	28/3**	28/2**	29/2**	29/1**	29G/3**
SiO_2	49,92	47,42	54,36	54,76	54,92	56,78
TiO_2	0,87	1,54	1,55	1,52	1,60	1,64
Al_2O_3	18,81	15,55	18,05	16,98	16,89	16,79
Fe_2O_3	4,19	2,67	2,46	2,66	2,84	2,54
FeO	4,80	10,95	6,21	6,06	5,86	5,14
MnO	0,13	0,28	0,11	0,11	0,12	0,15
MgO	5,82	6,23	3,45	2,60	2,88	2,70
CaO	10,64	10,32	7,44	7,36	7,26	6,52
Na_2O	2,85	2,80	3,29	3,70	3,89	3,79
K_2O	0,61	0,70	1,62	1,96	1,75	1,98
P_2O_5	0,22	0,22	0,17	0,38	0,21	0,36
H_2O^-	0,52	0,16	0,06	0,38	0,24	0,26
LOI (H_2O^+)	1,00	0,86	0,82	1,14	1,16	1,22
Σ	100,38	99,70	99,59	99,61	99,72	99,91

Note. Analyses were performed at the Institute of Volcanology. Analysts, V. V. Dunin-Barkovskaya, G. V. Knyazeva, G. P. Novoseletskaya, and A. V. Solovieva. V38-2 to V38-29 - site numbers; 2/2 to 29G/3 - sample numbers.

* Possibly ice-rafted or turbidity-current material

** Hih-Ti rocks

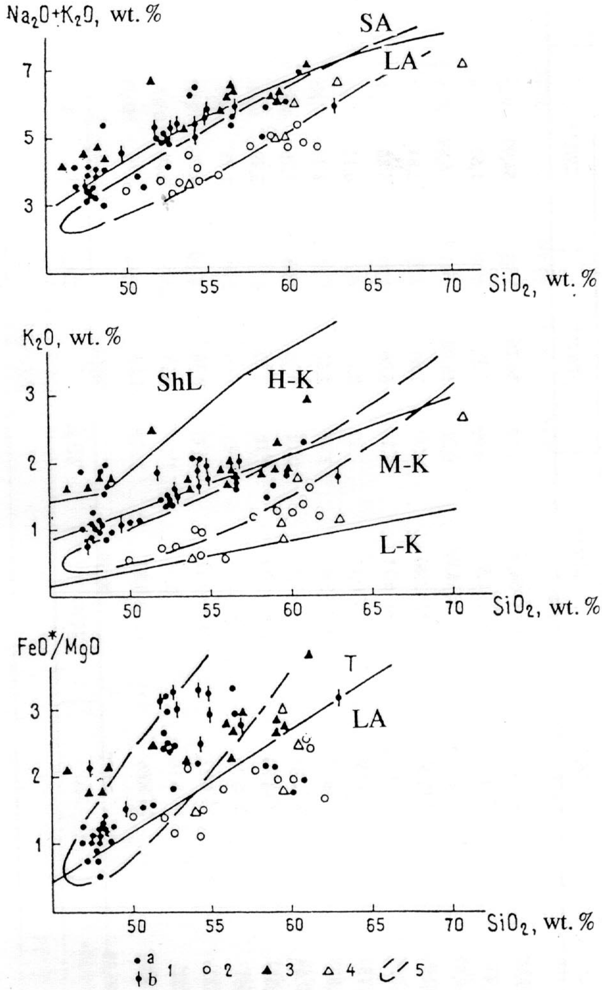


Figure 4 Petrochemical diagrams for lavas from the Eastern Aleutian backarc zone. 1, 2 - lavas dredged in the backarc zone of the Islands of the Four Mountains: 1 - local lavas of the medium-Ti (*a*) and high-Ti (*b*) groups, 2 - exotic (?) lavas; 3 - lavas of Amak and Bogoslof Is., Eastern Aleutian backarc zone; 4, 5 - forearc lavas, Eastern Aleutians: 4 - lavas of the Islands of the Four Mountains, 5 - lavas of Umnak I. (4 and 5 after [2], [4], [5], [7], and [8]). SA - slightly alkalic, LA - low-alkalic, ShL - shoshonite-latite, H-K - high-K, M-K - medium-K, L-K - low-K, T - tholeiitic.

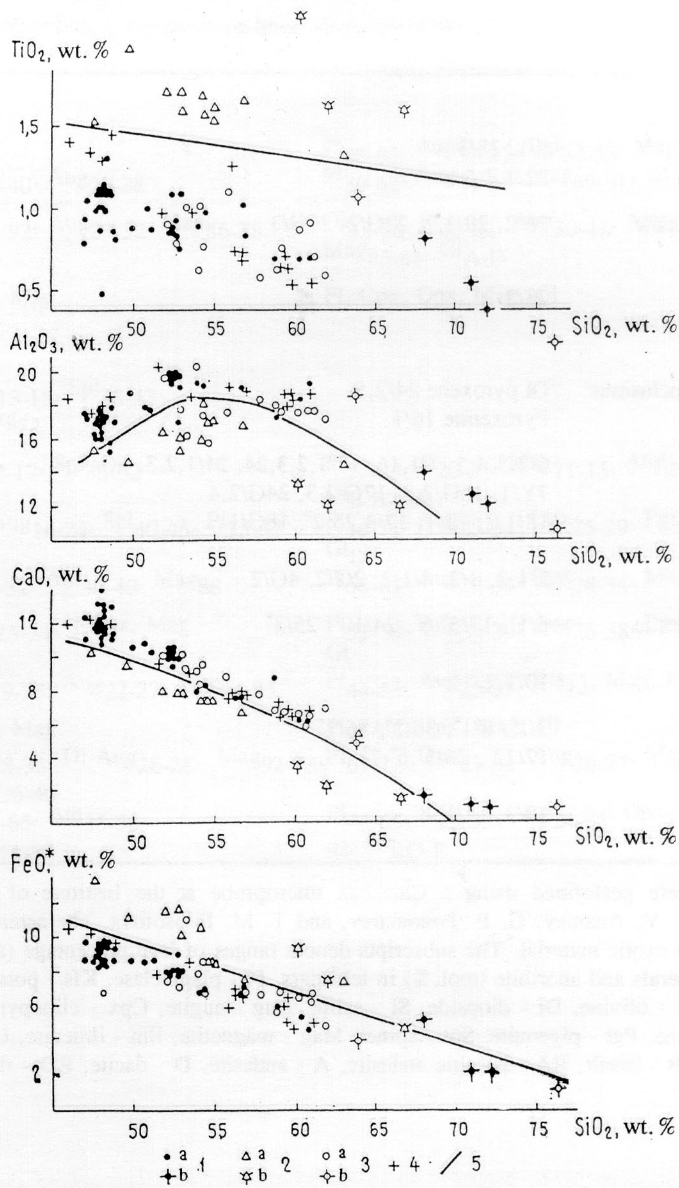


Figure 5 Variation diagrams for the chemical compositions of lavas and interstitial glasses from them. 1, 2 - local lavas: 1 - medium-Ti group, 2 - high-Ti group; 3 - exotic (?) medium-Ti lavas: *a* - bulk composition, *b* - interstitial glasses (average); 4 - Amak and Bogoslof lavas, backarc zone; 5 - boundary between medium- and high-Ti groups.

Table 3 Mineral composition of lavas from the backarc zone of the Islands of the Four

Rock type	*Sample number*	*Phenocrysts, %*
		High-Ti
Basalt	5/1, 28/3	< 3
	22/1,2,5	3-5
Basaltic andesite	28/2, 29/1,2, 22G/2, 29G/3	5-10
Andesite	23/2	5-10
		Medium-Ti
Ultrabasic inclusions in basalts	Ol pyroxene 24/2,5 Pyroxenite 16/1	
Basalt	6/2,3,4,5, 7/1,16, 17/1,2,3,24, 24/1,2,3, 6G/3, 7Y/1, 16G/2,3, 17G/2,3, 24G/2,4	15-25
	18/1,2, 23/1, 17/4,25,2*, 18G/1	15-25
	2/1,2, 3/2, 4/1,2, 2G/2, 4G/2	20-25
Basaltic andesite	6/1*, 17/5*,6*, 24/10*, 25/3*	5-20
	10/1,2	25-30
Andesite	3/1*, 8/1*, 36/1*, 86/1*	15-25
	17/12*, 25/5*,6*,7*	20-30
	10/3, 12/1,2	20-25

Analyses were performed using a Camebax microprobe at the Institute of Volcanology. Analysts, V. V. Ananiev, G. P. Ponomarev, and T. M. Filosofova. The asterisked samples may contain exotic material. The subscripts denote ranges of iron percentage (at. %) in dark-colored minerals and anorthite (mol. %) in feldspars. Pl - plagioclase, Kfs - potassium-sodium feldspar, Ol - olivine, Di - diopside, Sl - salite, Aug - augite, Cpx - clinopyroxene, Opx - orthopyroxene, Pgt - pigeonite, Spl - spinel, Mag - magnetite, Ilm - ilmenite, Gl - glass with subscripts: B - basalt, BA - basaltic andesite, A - andesite, D - dacite, RD - rhyodacite, R - rhyolite.

As regards the TiO_2 content, most of the samples are moderately titaniferous lavas (<1.2% TiO_2), whereas some of them contain up to 1.9% TiO_2 and vary in silica from basalts to acid andesites (see Table 2). The latter are higher in Fe_2O_3 and lower in CaO and Al_2O_3 than the medium-Ti lavas. Microprobe analyses showed the same differences between the glasses from the groundmasses of these

Mountains.

Phenocryst assemblage, composition of cores	*Groundmass assemblage and composition*
series	
Pl_{78-82}, Ol	Pl_{48-65}, Aug_{30-33}, Pgt_{32-33}, Mag_{85-91}, Gl
Pl_{70-94}, Ol_{30-40}, Aug_{29-38}	Pl_{39-62}, Aug_{34-38}, Mag_{89-91}, Gl_A, Ol_{44-54}
Ol_{35-36}, Pl_{74-92}, Aug_{27-32}, Mag_{86-88}	Ol_{35-36}, Pl_{45-62}, Aug_{30-41}, Aug_{36-37}, Pgt_{31-36}, Mag_{85-61}, Gl_{A-D}
Pl, Cpx, Opx, Mag	Pl, Cpx, Opx, Mag, Gl
series	
Ol_{12-18}, Cpx_{13-15}, Spl_{38-43}	
Cpx_{26-30}, Mag_{82}	
Ol_{13-17}, Di_{12-17}, Spl_{38-52}	Pl_{57-85}, Sl_{20-31}, Mag_{71-75}, Aug_{22-47}, Mag_{74-81}, $Gl_{B,BA,A}$
Ol_{13-19}, $Di\text{-}Aug_{14-24}$, Spl_{40-45}, Pl_{75-87}	Pl_{34-71}, Aug_{25-34}, Opx_{25-29}, Pgt_{27-30}, Mag_{94-95}, Gl_D
Pl_{68-84}, Sl_{25-32}, Am_{30-40}, Mag_{88}	Pl_{58-65}, Aug_{26-31}, Opx_{28-34}, Mag, Gl_D
Pl_{61-71}, Aug_{25-34}, ±Opx, Mag	Pl_{53-50}, Aug_{34-39}, Aug_{36-38}, Pgt_{35-38}, Mag_{95-96}, Gl
Pl_{55-66}, Am_{19-28}, Aug_{22-27}, Mag_{84-85}	Pl_{44-53}, Aug_{25-27}, Kfs_{12}, Mag, Gl
Pl, Opx, Cpx, Mag	Pl, Opx, Cpx, Mag, Gl
Pl_{51-60}, Am_{28-36}, $Di\text{-}Aug_{26-28}$, Mag_{92-93}, Ilm_{88-90}, Opx_{36-40}	Pl_{67-77}, Opx_{27-32}, Aug_{26-27}, Mag_{93-95}, Gl_R
Pl_{76-88}, Pl_{53-65}, Am_{35-50} Sl_{26-32}, Mag_{71-89}	Pl_{43-65}, Sl_{25-33}, Aug_{24-33}, Opx_{31}, Pgt_{37-42}, Mag_{89-94}, $Gl_{RD,R}$

rocks. Note that the same chemical features distinguish the high-Ti lavas from the rocks of the volcanic islands of the Eastern Aleutian backarc zone, Amak and Bogoslof, whose composition fields coincide with the fields of the dredged medium-Ti lavas (Figure 5). The regular differences in the contents of the above mentioned rock-forming oxides with a similar silica range suggest that the rocks of these two types were derived from different parental magmas.

Compositionally identical high-Ti lava fragments were raised from scarps where the rocks of the older complex are exposed (sites V38-22, -28, and -29). In two cases (sites V38-5 and V-38-23), single blocks of high-Ti lava were discovered in the stone material dredged from the edifices composed of young volcanics. The heterogeneity of the material raised at these sites does not rule out that the high-Ti lava fragments are exotic. On the other hand, medium-Ti lavas were raised both from the slopes of young volcanoes and from older eroded edifices (V38-12, -24, -25), and also from fault scarps (V38-10). Note that medium-Ti and High-Ti lavas of fairly close ages occur on the volcanoes of Umnak Island which is situated in the same tectonic block but in the forearc zone of the arc [5]. It is likely that lavas of different Ti contents coexisted in the forearc and backarc zones of the arc during a long period of time, up to the Holocene. Note for comparison that high-Ti lavas have not been found among the Pliocene-Quaternary volcanics of the Kuril Islands [3].

The high-Ti basalts are low- and medium-Mg rocks with a MgO content of 3.4 to 7.1%, and a Mg/Fe ratio of 35-53% (K_{mg} = MgO/MgO + FeO + 0.9F_2O_3%). Most of the medium-Ti basalts are moderately magnesian rocks (MgO=5.5-8.5%, K_{mg}=53-64%), though the basalts with a high silica content, transitional between basalts and basaltic andesites (SiO_2=52-53%), are usually low-magnesian (MgO=2.5-3.5%, K_{mg}=35-43%), whereas some of the low-silica basalts (SiO_2<48%) are high-magnesian (9.5-14% MgO, K_{mg}=67-80%) and resemble in this respect the magnesian basalts of Okmok Volcano (Umnak I.) from the forearc zone of the arc, which are believed by some investigators to be representative of the primary magmas for the Aleutian lavas [5], [8].

At the same time the magnesian basalts of the backarc zone of the Islands of the Four Mountains differ from the corresponding Okmok basalts by a higher content of alkalies, primarily potassium, and are similar in this respect to the magnesian basalts of the Kuril backarc zone [3].

PETROGRAPHY

As seen in Table 3, the rocks of both age groups, varying in silica and TiO_2, contain phenocrysts of usual island-arc associations. The exception is that some of the medium-Ti basalts (with a high and locally medium K_{mg} value) do not contain phenocrysts of plagioclase, but bear small inclusions (a few millimeters to 1-1.5 cm) of wehrlite and pyroxenite, which seem to be of segregation origin.

Generally, the lavas of the medium-Ti group are highly crystalline rocks, which is evidenced by a large amount of phenocrysts, a high degree of groundmass crystallization with a small amount of residual glass, and the occurrence of segregation inclusions. Many mineralogic features of these lavas, which are especially abundant in the backarc zone of the Islands of the Four Mountains, are similar to the mineralogy of medium- and high-K calc-alkalic lavas from the backarc zone of the Kuril arc [12]. These features are (1) a large amount of amphibole phenocrysts in the andesites, and the occurrence of amphibole as phenocrysts in some basaltic andesites and even in some basalts; (2) the absence of orthopyroxene phenocrysts in the basalts and of pigeonite as microlites in the groundmasses of all rock types; (3) the presence of Cr-Al-spinel in olivine phenocrysts from the basalts; (4) the occurrence of melanocratic, plagioclase-free varieties among the basalts; and (5) an elevated *mg* value in the olivine and clinopyroxene phenocrysts of the basalts and a high Ca content in the clinopyroxenes of all rock types.

The high-Ti lavas differ from the medium-Ti lavas by a smaller amount and smaller size of phenocrysts, the absence of amphibole in the phenocrysts and of Cr-Al-spinel inclusions in the olivine phenocrysts, a higher Fe/Mg ratio in the dark-colored minerals, and by the presence of pigeonite in the groundmass. These features make the high-Ti lavas similar to medium- and high-K tholeiitic rocks that are locally found in the backarc zone of the Kuril arc. Another distinctive feature of these lavas is a fairly common replacement of olivine by smectite.

CONCLUSION

The geological and geophysical investigations carried out during cruise 38 of the R/V *Vulkanolog* in the Bering Sea area of the Islands of the Four Mountains in the eastern segment of the Aleutian arc, confirmed the occurrence of young volcanic edifices, sitting on the sediments or formed simultaneously with the accumulation of the upper sedimentary sequence. Older volcanic formations are exposed by erosion on the slope of submarine canyons or occur in fault scarps, which are covered by sediments. The young structures and the slightly older formations, exposed by erosion, are distinguished as a young volcanic rock association. Along with the known volcanic islands (Amak, Bogoslof, etc.), they composed the backarc volcanic zone of the Eastern Aleutians. The volcanic rocks, exposed in fault scarps, are referred to an older rock complex, which served as a foundation for the younger edifices.

The content of alkalies, primarily K_2O, in the younger and older rocks of the study area is notably higher than in the lavas of the Islands of the Four Mountains and of Umnak I. in the forearc zone of this arc segment. This suggests the presence of a transverse geochemical zoning, typical of island arcs.

Many of the younger volcanics are chemically similar to the lavas of volcanic islands from the backarc zone of the Eastern Aleutians (Amak, Bogoslof) and resemble lavas from the backarc zone of the Kuril Islands. However, in contrast to the Kuril arc, the rocks of the basalt-andesite series include, along with usual medium-Ti lavas, rocks with an elevated TiO_2 content. Although rocks with varying TiO_2 concentrations were found in the upper and lower complexes, high-Ti lavas are more abundant in the latter. The occurrence of lavas with a medium and a high TiO_2 content throughout the silica range (47-63% SiO_2) of the dredge rock samples suggests an independent origin of each group, and their individual mineralogies are indicative of different physicochemical conditions of their parental magma crystallization.

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