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A BONINITE TREND IN THE SUBMARINE LAVAS OF PIIP VOLCANO AND ITS SURROUNDINGS, WESTERN ALEUTIAN ARC

1. GEOLOGY, PETROCHEMISTRY, MINERALOGY

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New data are presented on the geology, petrochemistry, and petrography of three volcanic complexes in the area of Piip Volcano and its surroundings. The rocks are attributed to an island-arc moderately potassic calc-alkalic series. A high Mg content of the rocks and dark colored minerals (boninite trend) reflects a specific character of volcanism and its development on the margin of the Komandorsky basin in connection with the processes of diffuse back-arc spreading.

INTRODUCTION

The recent discovery of an active submarine volcano, Piip, [9], [10], [11] at the back of the Komandorskie Islands attracted the attention of investigators because of the unusual geologic position of the volcanic center. In the first place, it is localized within the structures that border the western Aleutian arc where volcanic activity was believed [15] to cease as far back as the Pliocene. Secondly, the subduction of the Pacific plate under the East Asian plate occurs there tangentially so that this subduction zone is actually degenerating to become a transform fault. Thirdly, this volcanic center is located in the Komandorsky Basin bordering the Komandorsky segment of the Aleutian arc where volcanic activity may be influenced by both back-arc spreading and subduction.

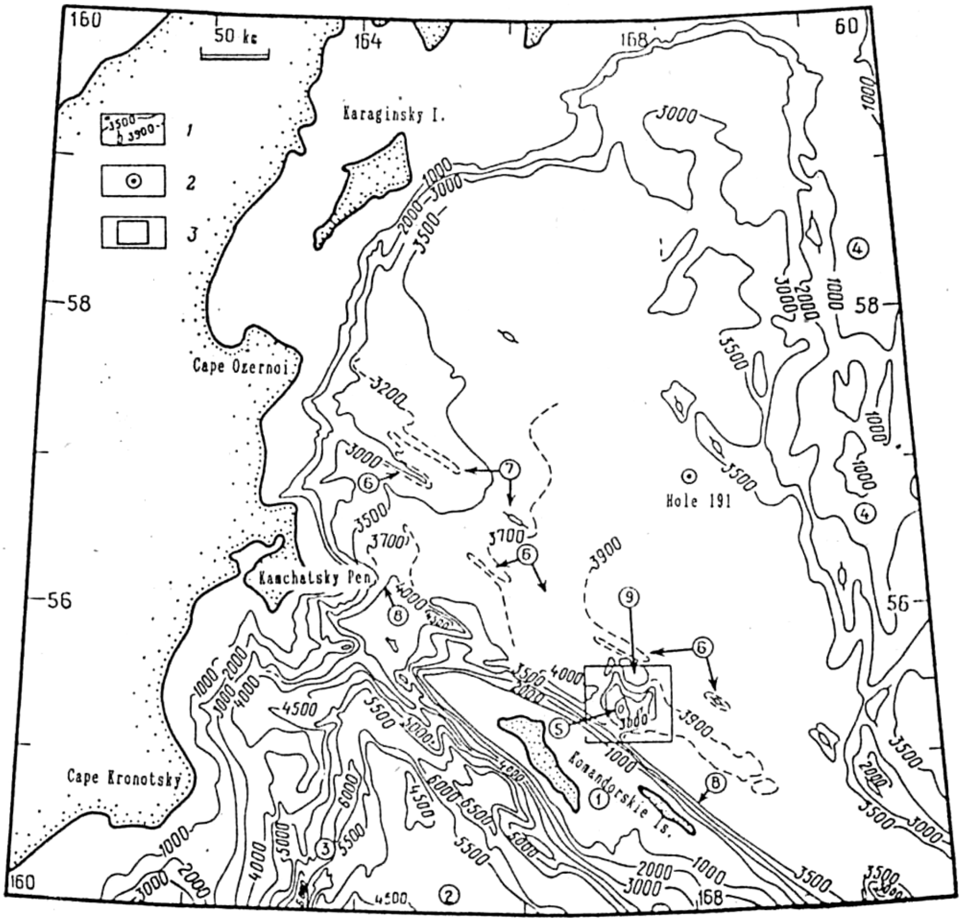


Figure 1 Morphostructural map of the Komandorsky Basin. 1 – isobath, m: *a* – basic, *b* – subsidiary; 2 – DSDP hole 191 [19]; 3 – location of study area mapped in Figure 3. Figures in circles denote morphostructures: 1 – Komandorsky segment of Aleutian arc; 2 – western end of Aleutian trench; 3 – northern end of Kuril-Kamchatkan trench; 4 – Shirshov Ridge; 5 – submarine Piip Volcano; 6 – Alpha fracture zone; 7 – Beta rise; 8 – Bering fracture zone; 9 – Komandorsky graben.

The objective of this study was to determine the type of the Piip activity in terms of geodynamic models based on the plate tectonic concept and attempt to find specific compositional features of the erupted lavas that might be related to the peculiar geologic position of this new volcanic center. For lack of space, in this paper we consider the geological, petrochemical and mineralogical aspects of the problem. Results on trace element distribution and isotopic composition will be presented in part 2.

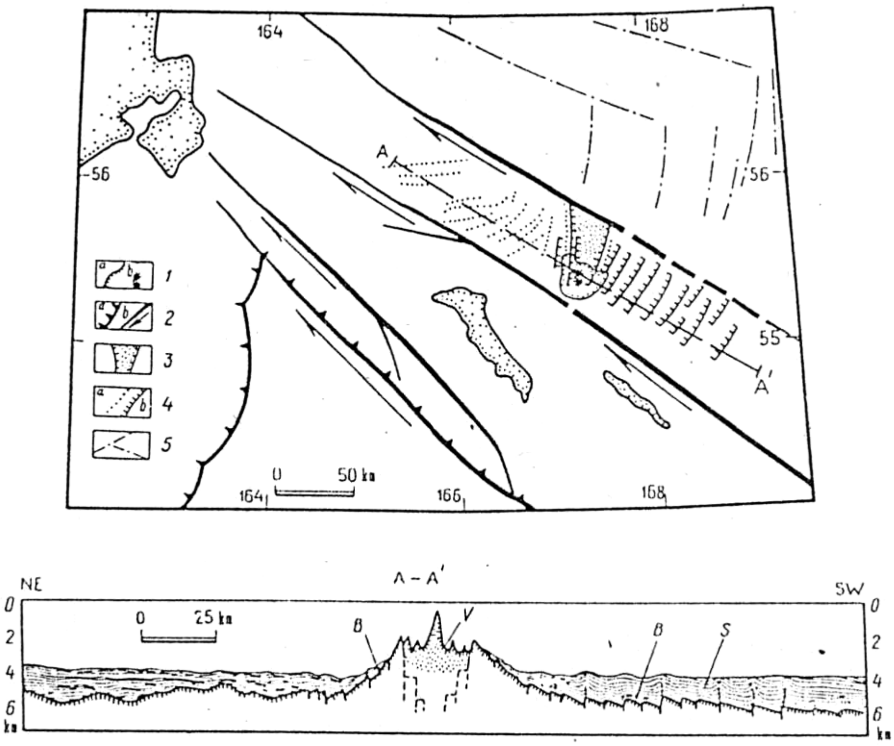


Figure 2 Schematic tectonic map of the southern Komandorsky Basin and cross-section along line A-A′. 1 — elements of volcanic mass: *a* — limits of volcanic mass, *b* — Piip Volcano; 2 — lithospheric faults: *a* — related to trenches, *b* — strike-slip faults; 3 — Komandorsky graben; 4 — normal faults in acoustic basement and in Komandorsky back-arc basin (*a*), trends of acoustic basement ridges NW of the Vulkanologov Massif (*b*); 5 — structural trends in the central Komandorsky Basin. Notation in A-A' cross-section: B — acoustic basement, S — sediments, V - volcanic mass with Piip Volcano.

GEOLOGIC SETTING

Evidence of the geologic structure of the study area was largely collected during several cruises of the R/V *Vulkanolog* in 1981-1988 and borrowed from [21], [22], [23] and [24]. According to this evidence, the Komandorsky Basin is bounded on the south by the Bering fracture zone (Figure 1) which has been identified as one of the seismically active lithospheric faults in the system of right-lateral strike-slip faults in the western end of the Aleutian arc [8]. The sea floor traces of this fault are a scarp on the NE slope of the Komandorsky segment of the Aleutian arc and a deep depression and a scarp that extend in the NW direction as far as the continental slope of eastern Kamchatka, north of the submarine continuation of Cape Africa. The Alpha fracture zone extends parallel to and 60-80 km northeast from the Bering fracture zone; it is distinct in the bottom topography, magnetic pattern, and sedimentary sequence [12]. This fracture zone extends as far as the southern end of Shirshov Ridge in the east and Cape Ozernoi of Kamchatka in the west. Its western, probably more active segment has a better topographic expression.

The crustal block bounded by the Bering and Alpha fracture zones is geophysically different from the other areas of the Komandorsky Basin and hence can be considered as an independent structure. It is characterized by a specific magnetic pattern and its acoustic basement is broken into many blocks by numerous faults of approximately N-S and NNE trends. Some of these faults extend into the sediments up to the topmost layers. Tectonic movements were most active in the area NE of Bering Island where the Komandorsky graben was formed with the upthrown sides and the downthrown central block. The schematic tectonic map presented in Figure 2 shows that normal faulting there was related to the right-lateral faults of the western Aleutian arc. Apparently, the opening of the Komandorsky graben was caused by a right-lateral slip along the western segment of the Alpha fracture. This conclusion is consistent with the data on the focal mechanisms of earthquakes from that area [5].

The northern part of the Komandorsky graben is not covered by sediments and has a distinct topographic expression. The southern part of the graben is filled with volcanic material. Volcanic rocks also outcrop on its flanks. In the middle of the graben's southern part stands a large young volcanic cone – Piip Volcano. A large number of lava domes, particularly numerous to the northwest from the cone, occur at the foot of the volcano and on the graben flanks (Figure 3). These volcanic formations, including those on the graben flanks, have been recognized as parts of one volcanic mass which was called "Vulkanologov Massif" [9], [10]. In this paper, by "Vulkanologov Massif" we mean the volcanic structure on which Piip Volcano was formed.

The results of the previous geological, geophysical and petrological studies [1], [9], [10], [11] were used to prepare a morphostructural map of the volcano and its surroundings. These studies provided evidence of the present-day volcanic activity and of the rocks that compose the summit portion of the cone. The work done during cruise 35 of the R/V *Vulkanolog* in 1989 added new information on the types of the Piip volcanic rocks, among which acid andesites were identified in addition to the previously known dacites and rhyodacites. Besides, the chemical composition of the lavas composing the Vulkanologov Massif was determined for the first time. The sites of the dredging stations of that cruise are shown in Figure 1; their coordinates and the description of the dredged material are given in Table 1.

The summit portion of the massif (2100-2500 m below sea level) is made up of andesites and basaltic andesites. Fragments of magnesian andesite were recovered at station V35-5 from a lava dome in the northwestern part of the massif. Xenoliths in the dacite of a lava dome at the foot of the Piip cone (st. V35-4) showed a similar

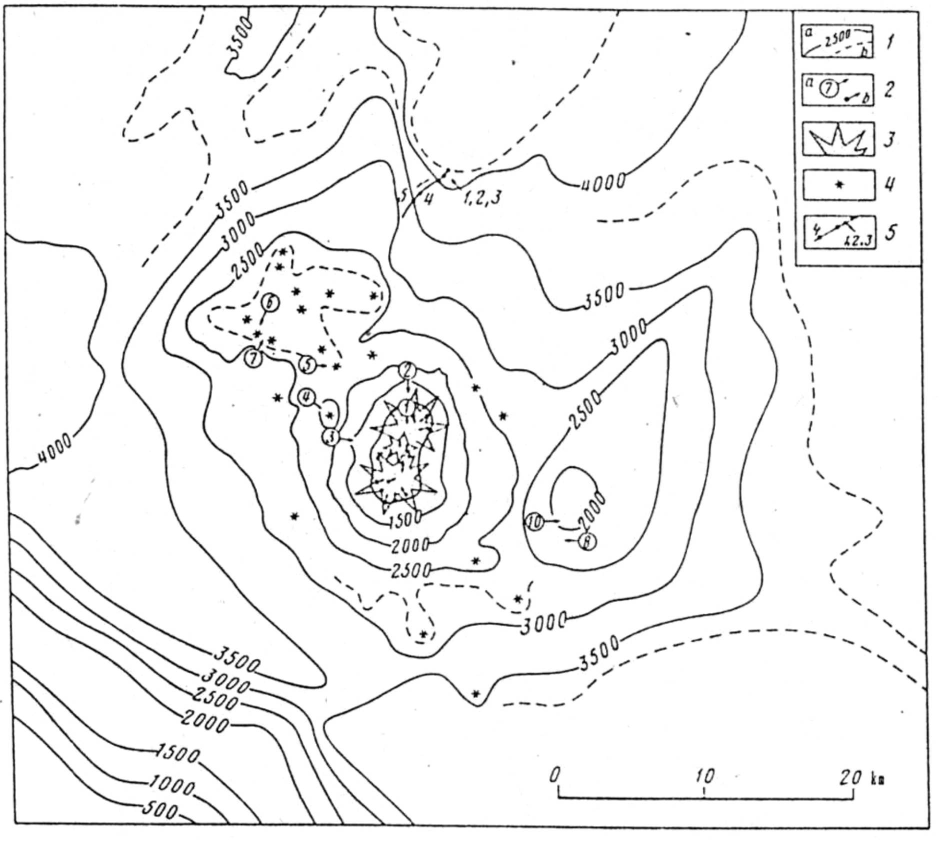


Figure 3 Location map of the study area. 1 — isobath, m: *a* — basic, *b* — subsidiary; 2 — dredging sites: *a* — cruise 35, R/V *Vulkanolog, b* — cruises 21 and 26, R/V *Vulkanolog* [9], [10]; 3 — Piip volcanic cones; 4 — lava domes; 5 — sampling sites of MIR-1 submersible.

composition. One of the dredges raised fragments of volcanic rocks and poorly cemented sediments in the same part of the massif (st. V35-7); some fragments of andesitic lava are coated with aleuropelite and show distinct chill borders. These relations between the lava and sediments suggest that the andesitic lava had flowed under water, the process being synchronous with the deposition of sediments.

E. G. Lupikina and L. M. Dolmatova, the micropaleontologists from Kamchatka, determined the diatom-based age of the aleuropelite that cements the lava fragments to be late Miocene to early Pliocene. Somewhat older ages were reported by Scholl *et al.* [26] for submarine lavas from the western end of the Komandorsky segment: 8.8 m.y., K-Ar dating; the sediments were dated by foraminifers as mid-middle Miocene. In 1990, during cruise 22 of the R/V *Akademik Mstislav Keldysh,* the scarp of the NW slope of the massif was examined by

Table 1 Location of dredging sites and results of dredging and sampling with a MIR-1 submersible.

Site	Location	Coordinates		Depth interval, a	Quantity of recovered material, kg	Character of material	Rock types
		lat. N	lon. E				
V 35–1	Piip, summit of N cone	55°25,6' 55°25,2'	167°16,1' 167°16,1'	400—600	≥ 500	Blocks, large fragments, and < 5% debris	Massive, sometimes vesicular andesite, scarce dacite
V35–2	Piip, N slope	55°27' 55°26,4'	167° 2' 167°16,2'	1200—1620	~6	One block coated with Fe-Mn oxide	Massive andesite
V35–3	Piip, W slope	55°24,7' 55°24,6'	167° 11,5' 167°12,7'	1460—1840	40—50	White pumice, fragments and pebbles	Dacitic pumice, fragments of massive dacite
V35–4	Lava dome at W foot of Piip	55°26' 55°25,8'	167° 9,8' 167°10,4'	1300—1940	~150	Blocks, fragments	Massive dacite with xenolyths of basaltic andesite and andesite
V35–5	Vulkanologov Massif, peak in the west	55°27,3' 55°27,3'	167° 10' 167° 10,1'	2100—2400	20—25	Fragments and pebbles with Fe-Mn coating	Massive magnesian andesite with scarce round vesicles
V 35–6	Vulkanologov Massif, peak in the west	55°29,3' 55°28,7'	167°6,7' 167°6,4'	2140—2300	2	Fragments with 2-3 cm Fe-Mn crust, pebbles	Slightly vesicular andesite
V35–7	Vulkanologov Massif, west	55°27,9' 55°28,4'	167°6,2' 167°6,8'	2200—2350	300	Blocks, fragments, single pebbles	Vesicular andesite, coated with aleuropelite aleuropelite debris

Table 1 (continued)

V35–8	Vulkanologov Massif, east	55°20,6' 55°20,6'	167°27,5' 167°26,5'	2100—2400	150	Blocks, fragments	Moderately vesicular andesite
V35–10	Vulkanologov Massif, east	55°21,2 55°21,2'	167°26,2' 167°26,6'	2100—2500	150	Blocks, rubble with Fe-Mn crust	Massive basaltic andesite and andesite
2316/1	Vulkanologov Massif, lower N slope; wall of several flows (top flow)	55°33,7'	167°19,1'	4024	—	Pillow lava flow	Aluminous basalt
2316/2	Same, flattened flow	55°33,6'	167°19,0'	4000	—	Flow with ropy surface covered with slightly lithified clay	Aluminous basalt
2316/3	Same, flow on western edge of local fissure	55°32,3'	167°17,2'	3488	—	Large-block flow	Andesite, similar to Piip lavas
2316/4	Same, flat portion of slope	55°33'	167°17,4'	3648	—	Flow with thin mud cover	Magnesian andesite
2316/5	Vulkanologov Massif, basement, N side (basin floor)	55°38,8'	167°19,1'	4243	—	Fragments of pillow lava with thin Fe-Mn crust	High-Ti basalt

Note. Coordinates of dredging sites are given for the beginning and end of dredging.

Table 2 Chemical compositions of lavas from the Vulkanologov Massif and its foundation.

Oxide	1	2	3	4	5	6	7	8
SiO_2	47,46	51,08	50,86	53,30	56,36	56,88	56,13	57,02
TiO_2	1,41	0,98	0,96	1,02	0,65	0,68	0,78	0,73
Al_2O_3	16,54	18,73	18,75	16,91	18,20	18,36	18,30	17,88
Fe_2O_3	1,77	1,62	1,65	2,80	1,63	1,63	1,92	1,00
FeO	6,38	4,60	4,48	4,18	3,23	3,25	3,46	3,97
MnO	0,11	0,14	0,14	0,11	0,08	0,10	0,12	0,08
MgO	7,89	5,66	5,20	4,76	4,38	4,04	4,22	3,84
CaO	9,18	10,69	11,09	8,74	7,20	7,48	7,64	7,16
Na_2O	2,70	3,58	3,58	3,89	4,05	4,05	3,90	4,05
K_2O	1,20	0,82	0,82	1,04	1,40	1,30	1,35	1,35
P_2O_5	0,24	0,22	0,22	0,13	0,11	0,11	0,11	0,12
H_2O^+	3,48	1,26	1,18	1,14	1,66	1,66	1,93	1,38
H_2O^-	1,24	0,56	0,68	1,28	0,68	0,60	0,62	1,00
Σ	99,60	99,94	99,61	99,38	99,63	100,14	100,48	99,58
FeO*/MgO	1,01	1,07	1,15	1,41	1,07	1,17	1,23	1,27
K_{Mg}, at. %	63,8	62,5	60,9	55,9	62,5	60,4	59,2	58,4

Note. 1 – basalt of the foundation; 2 through 10, 16, 17 – lavas of the massif; 11 through 14 – dome on the NW slope of the massif; 15 – xenolyth in dacite from a parasitic cone on Piip, Sample numbers: 1 – 2316/5; 2 – 2316/2; 3 – 2316/1; 4 – V35-10/5; 5 – V35-10/3; 7 – V35-6/1; 8 – V35-8; 9, 10– V35-7/2; 11 thru 14 – V35-5/5, 3, 2, 1; 15, 16 – V35-4d, 4e; 17 – 2316/4. Sample 11 yielded 0.44% CO_2. For location of dredging sites see Table 1 and Figure 3.

V. V. Matveenko from a manned submersible MIR-1. Fragments of T_i-bearing basalt displaying a pillow structure were collected at the foot of the scarp on the floor of the graben. The lower part of the scarp consists of aluminous pillow basalt which is overlain by a sequence of thin flows of the same basalt with ropy surfaces. Above follows a flow of magnesian andesitic lava and finally, on the scarp bench, a block lava flow of andesitic composition resembling the Piip andesitic lavas (see Table 1).

ANALYTICAL METHODS

23 samples dredged from nine sites and five samples collected with the MIR-1 submersible were analyzed at the Chemical Laboratory of the Institute of Volcanology by the analysts A. M. Okrugina, G. V. Lets, and G. P. Novoseltskaya. Mineral phases were determined at the Mineralogical Laboratory of the same institute with the Camebax electron microprobe (analysts V. V. Ananiev, G. P. Ponomarev, and V. M. Chubarov).

9	10	11	12	13	14	15	16	17
57,80	57,12	56,96	56,54	56,25	57,12	55,70	57,11	56,64
0,66	0,73	0,77	0,61	0,77	0,73	0,64	0,60	0,62
17,29	17,74	16,02	16,68	16,48	16,21	17,73	17,30	16,95
2,32	1,85	1,04	1,28	0,98	1,00	1,39	1,27	1,25
2,94	3,54	2,72	3,69	4,09	4,05	3,83	3,18	4,02
0,08	0,08	0,09	0,12	0,11	0,05	0,05	0,06	0,11
3,44	3,44	6,64	6,62	6,40	6,22	6,18	5,42	5,74
6,46	6,56	7,66	7,20	7,22	7,20	8,66	8,08	7,18
4,30	3,89	3,57	3,89	3,46	3,56	3,65	3,84	3,58
1,50	1,45	1,20	1,30	1,27	1,30	1,08	1,30	1,35
0,13	0,14	0,17	0,13	0,18	0,14	0,14	0,14	0,15
1,96	1,73	2,08	1,37	1,83	1,43	1,14	1,44	1,86
0,65	1,22	0,23	0,39	0,47	0,86	0,08	0,45	0,62
99,53	99,49	99,59	99,82	99,51	99,87	100,27	100,49	100,07
1,46	1,51	0,55	0,73	0,77	0,80	0,82	0,85	0,90
55,0	54,1	76,4	70,9	69,7	69,1	68,4	67,6	66,7

CHEMICAL COMPOSITION OF VOLCANIC ROCKS

In accordance with the chemical composition (Tables 2 and 3) and geological position of the volcanic rocks, they have been grouped into three complexes:

- lower complex of basement olivine basalts with an elevated TiO_2 percentage;
- middle stratified complex of aluminous basalts, basaltic andesites, and moderately magnesian and high-Mg andesites of the Vulcanologov Massif;
- upper differentiated complex consisting of magnesian andesites of the lava domes, moderately magnesian andesites and dacites of flank Piip eruptions, and andesites and dacite-rhyodacites produced by the summit Piip eruptions.

According to the overall alkalis content, all rocks belong to the normal series. The K_2O concentrations attribute them to the moderately potassic series and the ratio of FeO*/MgO to SiO_2 to the calc-alkaline series. The exception is the olivine basalts which fall within the region of tholeiites. They are higher in TiO_2 and H_2O* than the Massif and Piip lavas. Some features indicate that they are close to oceanic and marginal-sea subalkalic basalts.

A distinctive feature, common to the lavas of the Vulkanologov

Table 3 Chemical compositions of lavas produced by summit and flank Piip eruptions.

Oxide	1	2	3	4	5	6	7	8	9	10
SiO_2	64,02	61,85	64,78	61,23	65,13	60,92	59,34	67,50	67,30	59,58
TiO_2	0,42	0,51	0,44	0,59	0,43	0,67	1,13	0,35	0,47	0,52
Al_2O_3	16,17	16,58	16,21	17,51	16,23	17,46	17,82	15,80	15,61	17,81
Fe_2O_3	0,72	0,88	0,73	0,75	1,69	0,89	2,06	1,04	0,70	1,04
FeO	2,79	3,00	2,74	3,28	2,62	3,08	3,37	2,19	2,16	3,36
MnO	0,06	0,07	0,08	0,08	0,08	0,08	0,07	0,11	0,08	0,12
MgO	3,28	3,44	3,04	2,92	3,38	3,10	3,44	1,54	1,24	4,07
CaO	4,38	5,58	4,50	5,82	4,22	7,10	6,32	3,24	3,14	6,46
Na_2O	4,73	4,52	4,73	4,39	4,79	4,11	4,37	5,16	4,40	4,20
K_2O	1,35	1,25	1,35	1,20	1,35	1,07	0,94	1,82	1,57	1,50
P_2O_5	0,12	0,13	0,11	0,13	0,11	0,18	0,21	0,12	0,09	0,20
H_2O^+	0,92	0,65	0,61	0,63	0,86	0,60	1,13	1,12	1,96	0,50
H_2O^-	0,40	0,30	0,34	0,22	0,36	0,06	0,29	0,51	0,55	0,54
Σ	99,36	99,32	99,66	99,36	100,31	99,50	100,49	100,50	99,82	99,90
FeO*/MgO	1,05	1,10	1,12	1,12	1,22	1,25	1,52	2,03	2,25	1,06
K_{Mg}, at. %	63,0	61,8	61,5	61,3	59,3	58,8	54,0	46,8	44,2	62,8

Note. 1 through 7, 9 – Piip northern cone (1 – 6 and 9 – lavas, 7 – homeogenic inclusions in dacite); 8 – dome at the foot of the volcano; 10 – lava flow on the northern slope of the Massif. Sample Numbers: 1 through 5 – V35-1/4, 2, 6, 1, 5; 6 – V35-2; 7 – V35-1/9; 8 – V35-4/2; 9 – V35-3/1; 10 – 2316/3. Extra determinations: 2 – 0.56 % LOI; 4 – 0.61 % LOI; 9 – 0.55 % CO_2.

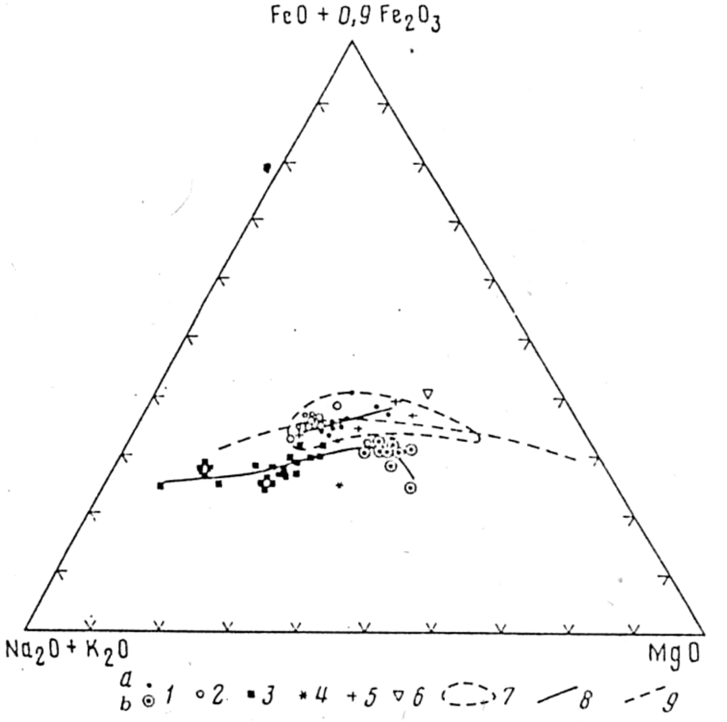


Figure 4 Triangular diagram for lavas under study. 1 — lavas of the Vulkanologov Massif and high-Hg andesite of lava domes (a — moderately magnesian, *b* — high-Hg); 2 — glasses from high-Mg andesites of the Massif; 3 — Piip lavas and andesites from a flow on the Massif (similar to Piip andesites); 4 — submarine magnesian basalts of Komandorsky segment [26]; 5 — magnesian andesites and dacites of Aleutian arc [26]; 6 — olivine basalt of the basement (sample 2316/5); 7 — magnesian series rocks of Shiveluch (O. N. Volynets, private communication); 8 — evolution trends of the Massif and Piip lavas; 9 — trend of boninite series rocks from the Mariana trough [17].

Massif and Piip Volcano is a low Fe concentration, and hence an elevated value of K_{Mg} = Mg/(Mg + ΣFe), at.%, which makes them markedly different from the normal island-arc lavas. Examples of the K_{Mg} values from the Kuril-Kamchatkan rocks are 42-58% in calc-alkalic andesites against 54-63% in the moderately magnesian andesites of the middle stratified complex and 31-47% in calc-alkalic dacites against 43-63%, respectively. The K_{Mg} values of 61-62% observed in the basalts of the Vulkanologov Massif are comparable with those of the calc-alkalic basalts of Kamchatka which contain > 7% MgO instead of 5-6% MgO in the basalts concerned. The K_{Mg} values in the magnesian andesites of the study area range within 66-76%. Only some of the Kuril-Kamchatkan and Aleutian calc-alkalic basalts, containing > 9% MgO, have similar K_{Mg} values: volcanoes Kharchinskiy, Zarechnyi, and the Tolbachik group in Kamchatka and some basalts from Okmok,

Table 4 Representative analyses of glasses in andesites from the Vulkanologov Massif.

Oxide	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	59,41	59,89	60,14	60,07	53,23	63,14	61,50	66,11	65,18	68,48	67,42	63,65
TiO_2	0,77	0,76	0,80	0,78	0,72	0,45	2,20	1,06	1,14	1,34	1,02	1,11
Al_2O_3	16,32	15,86	15,91	15,95	18,71	16,68	13,53	15,45	14,80	14,15	13,46	13,56
FeO	5,21	4,68	5,04	4,76	3,87	3,54	4,83	5,13	5,77	3,43	1,95	2,17
MnO	0,12	0,05	0,07	0,06	0,03	0,00	0,13	0,06	0,10	0,08	0,03	0,06
MgO	3,55	3,38	3,49	3,48	4,07	2,53	1,74	0,55	0,88	0,37	0,16	0,14
CaO	6,36	6,08	6,31	6,18	9,69	4,85	3,45	3,83	2,44	1,93	1,40	1,38
Na_2O	4,18	4,10	4,13	3,85	3,26	3,11	3,76	2,50	1,42	2,15	0,72	1,15
K_2O	1,05	1,13	1,18	1,14	0,61	1,51	2,92	2,72	1,96	1,18	4,36	4,67
Σ	96,97	95,94	97,06	96,27	94,19	95,81	94,07	97,41	93,68	93,11	90,52	87,90
K_{Mg}, at. %	54,2	56,3	55,2	56,6	65,2	56,0	39,1	12,4	21,4	16,1	23,1	10,1

Note. 1 through 8 – glasses in high-Mg andesites (1 through 6 – sample V35-5/1; 7, 8 – s. V35-5/3): 1 through 4 – glasses in groundmass; 5, 6, 7 – glasses in melt inclusions (5 – in olivine phenocryst, 6 – in plagioclase phenocryst, 7 – in high-Fe bronzite subphenocryst), 8 – in aggregate of fine plagioclase grains; 9 through 12 – glasses in groundmass of moderately magnesian andesites (9, 10 – s. V35-8/1; 11, 12 – s. V35-10/3). Analyses 5, 6 and 9 were made as single measurements and the others by scanning.

Makushin and Adagdak Volcanoes in the Aleutians. The very presence of magnesian andesites among the rocks under study is an important distinctive feature of the latter. Boninites, as a variety of magnesian andesites, are known to be a rock type typical of the arcward slopes of trenches [13], [16] and are uncommon for island arcs (a known example is setouchite from SW Japan [28]). Single occurrences of magnesian andesites have been located on Moffet Volcano, Adak I. [20], and Sitkin I. (R. W. Kay, private communication) and dredged from the NW end of the Komandorskie segment [26]. Volynets *et al.* [2], [4] described magnesian andesites from Shiveluch and Zarechnyi Volcanoes of Kamchatka, close to the junction of the Kuril-Kamchatkan and Aleutian arcs. Kepezhinskas and coworkers [6], [7] reported them from the Neogene volcanics of the Pakhachi Range in Koryakiya, the northern surroundings of the Komandorsky Basin. However, all Aleutian magnesian andesites of the N and NW surroundings of the Komandorsky Basin have K_{Mg} values lower than those of the magnesian andesites from the Vulkanologov Massif (61-67% in the Aleutians, 56-67% in Kamchatka, 56-62% in the Pakhachi Range), except a comparable value of 71% in the magnesian andesites dredged by D. W. Scholl [26].

On a triangular diagram (Figure 4), the basalts and medium-Mg andesites of the Vulkanologov Massif and the magnesian andesites and dacites of the Aleutian arc lie in the same field which coincides with the field of the Shiveluch lavas and is elongate along the trend of the boninite series of the Mariana trough. The magnesian andesites of the Massif and of the NW underwater extension of the Komandorsky segment are notably shifted from them toward a lower FeO concentration. The Piip lavas also lie aside from the Shiveluch lava field, being not only less alkalic but also less ferriferous. These two latter groups form one trend, subparallel to the boninite trend of the Mariana trough. The olivine basalts of the basement contain less alkalis and their data point lies above the Shiveluch lava field. The residual glasses of the magnesian andesites (Table 4) are somewhat higher in FeO as compared to the bulk composition of the rocks. On the diagram they lie in the field of the moderately magnesian andesites, showing similar concentrations of the other major components. The residual glasses of the medium-Mg andesites have a dacitic composition but are markedly different from the Piip dacites by higher K_2O and TiO_2 percentages and lower Al_2O_3, MgO, CaO and Na_2O concentrations (see Table 4). Obviously, this rules out the generation of these dacites by the fractionation of andesitic magma.

The independent differentiation trends of the two rock associations under study (Piip magnesian andesites — andesites, dacites and Massif Vulkanologov basalts — moderately magnesian andesites) suggest that there were two sources of different parental magmas: magnesian andesitic magma in the former case and aluminous basaltic magma, possibly similar to the basalt of the foundation, in the latter. It is not unlikely that part of the moderately magnesian andesites was derived from the primary magma of the first type.

Table 5 Mineral compositions of lavas from the Vulkanologov Massif and Piip Volcano.

Volcanic complex	location	Rock type	Phenocrysts		Groundmass
			Proportion, vol. %	Composition of cores	
Lower complex	Vulkanologov Massif, foundation	High-Ti basalt	≤ 5	Ol 13 with Sp 86-39 inclusions	Sp 36-39. Altered Gl_b
Middle stratified complex	Vulkanologov Massif	High-Al basalt	5—10	Pl 78-88, Cpx 10-14, Ol 10-12 with Sp 30-35 and Il 35-37 inclusions	Pl 49-69, Cpx 13-28,
		Moderately magnesian andesite	25—35	Pl 66-83, Cpx 13-16, Ol 16	Pl 55-59, Cpx 19-32, Opx 16-22, Pg 18-21, Gl_d
		Magnesian andesite	10—15	Cpx 13-16, Ol 11-13 with Sp 36-49, Pl 65-68	Pl 56-65, Cpx 16-20, Opx 18-22, Ol 14-16, Gl_a
Upper differentiated complex	Vulkanologov Massif, domes	High-Mg andesite	≤ 5	Cpx 10-14, Opx 31-32 with Il 60-68, Ol 8.5-9.5, Pl 39-50, Pl 62-66	Pl 59-66, Cpx 11-17, Opx 11-17, Ol 12-16, $Gl_{a,d}$
	Piip. flank lavas	Andesite	25—35	Pl 37-43, Pl 67-70, Opx 28-32 with Il 86, Am 31-33, Ol 11-13 with Sp 50-75, Cpx 12-13, Cpx 23	Pl 54-68, Cpx 14-23, Opx 13-23, Sp 68-75, CM 83-85, TM 83-91, Il 83-84, $Gl_{r,d}$
		Dacite	25—40	Pl 28-52, Pl 66-84, Opx 33-36 with Il 87-88 and TM 90-93, Am 32-35, Cpx 29	Pl 30-31, Opx 26-35, TM, Tr, Gl_r
	Piip	Acid andesite	25—35	Pl 40-53, Pl 83, Opx 25-31, Am 29-32, Cpx 24-30	Pl 52-60, Opx 15-21, 26-29; Cpx 18-21, TM 89-91, Il 86-99, $Gl_{rd,r}$
		Dacite-rhyodacite	25—45	Pl 36-46, Pl 62-82, Am 28-33, Opx 27-33, Cpx 15-18, Cpx 24, TM 94-97, Il 93-94	Pl 36-51, Opx 14-27, TM 95, 96; Il 95-96, Gl_r

Note. Mineral phases: Ol — olivine, Cpx — clinopyroxene, Opx — orthopyroxene, Am — amphibole, Pg — pigeonite, Pl — plagioclase, Sp — spinel, TM — titanomagnetite, CM — chrome magnetite, Il — ilmenite, Tr — tridimite, Gl — glass. Figures near abbreviations indicate at.% iron for dark colored minerals and mol.% An for plagioclases. Subscripts below glasses indicate composition: b — basaltic, a — andesitic, d — dacitic, rd — rhyodacitic, r — rhyolitic.

All volcanics under study, except for the basalts of the foundation, are very fresh rocks containing varying amounts of phenocrysts and a more or less crystallized groundmass, primarily of hyalopilitic texture, in which a smaller or larger amount of pure glass is preserved. Some of the dredged fragments of extrusive magnesian andesite (V35-5), aluminous basalt (2316/1), and moderately magnesian andesite (V35-7) have chilled margins and contain > 50% glass. The fragments of Ti-rich basalt dredged from the foot of the Massif have chilled margins too and are apovitrophyric rocks with wholly devitrified glass. Beneath the chill margins, the glass is wholly replaced by aggregates of secondary minerals (e. g., smectite) which form spherulites. Fresh olivine phenocrysts are preserved in these rocks only in the chill margins and are wholly replaced by carbonate or smectite beneath them.

The mineral composition of the rocks is presented in Table 5 which suggests two important conclusions. One is that all rocks contain smaller or larger amounts of high-Mg dark colored minerals, both in phenocrysts and in microlites. In fact, olivines with the iron content of ≤13%, found in the basalts of the foundation, in the aluminous basalts and magnesian andesites of the Massif, in the magnesian andesites of the lava domes, and in the andesites of the Piip flank eruption, are uncommon for island-arc lavas and have only been found in magnesian basalts. For example, in the Quaternary volcanics of the Kuril-Kamchatkan arc, olivines of such composition have only been found in basalts containing > 9% MgO [3], [4]. Olivines with ≤10% iron have been found only in the magnesian basalt and andesite lavas of Shiveluch Volcano. A similar situation is observed with enstatite-diopside clinopyroxenes containing ≤16% iron, which occur in all rock types of the middle and upper complexes including the moderately magnesian andesites of the Vulkanologov Massif and the Piip dacites (Tables 5 and 6). Magnesian bronzites with ≤20% iron, which are common in the magnesian and moderately magnesian andesites and occasionally found in the dacites and acid andesites of the upper complex, have been reported from the Kuril-Kamchatka region only in the magnesian basalts and andesites of Zarechnyi Volcano, Kamchatka, as relicts in the cores of clinopyroxene phenocrysts. An important feature is the presence of magnesian spinel inclusions in the phenocrysts of dark colored minerals from the basalts of the foundation and the aluminous basalts and magnesian andesites of the middle complex, and the presence of picroilmenite in the aluminous basalts the spinels from the andesites containing more chromium than the spinels from the basalts (Table 7). The occurrence of high-Mg phases of dark colored minerals in the lavas of the middle and upper complexes agrees with the high Mg content of these lavas and makes them similar to the rocks of the boninite series and the magnesian andesites of SW Japan, the rocks whose distinctive feature is the

Table 6 Representative analysis of pyroxenes.

Oxide	1a	2b	3c	4a	5b	6a	7c	8a
SiO_2	53,33	47,18	47,94	56,41	55,24	53,47	50,56	53,61
TiO_2	0,39	1,86	1,90	0,19	0,24	0,30	1,02	0,04
Al_2O_3	3,92	6,62	9,52	1,01	0,82	1,74	3,11	0,66
Cr_2O_3	0,85	0,02	0,03	0,03	0,03	0,30	0,00	0,02
FeO	3,73	7,49	12,17	11,20	11,89	4,85	9,63	21,03
MnO	0,09	0,17	0,29	0,29	0,30	0,18	0,30	0,59
MgO	16,36	13,59	13,78	27,65	24,50	17,67	14,51	24,46
CaO	21,50	20,76	15,47	2,87	5,82	20,11	18,72	0,53
Na_2O	0,29	0,38	0,46	0,00	0,00	0,05	0,29	0,00
Σ	100,46	98,09	101,63	99,65	98,84	98,66	98,14	100,94
f, at.%	11,35	23,63	33,15	18,51	21,40	13,35	27,14	32,54
Wo (mol. %)	45,6	45,6	35,1	5,7	11,8	41,5	40,3	1,0
En (mol. %)	48,2	41,6	43,4	76,8	69,3	50,7	43,5	66,7
Fs (mol. %)	6,2	12,8	21,5	17,5	18,9	7,8	16,2	3,2

Note. Vulkanologov Massif: 1, 2, 3 – from high-Al basalts (1, 2 – sample 2316/2, 3 – sample 2316/1); 4 through 7 – from moderately magnesian andesite (sample V35-8/1); 8 through 12 – from high-Mg andesites (8, 9, 12 – sample V35-5/3; 10, 11 – sample V35-5/1). Piip: 13 through 17 – from andesite (sample V35-2). 1, 2, 3, 6, 7, 11, 12, 16, 17 – clinopyroxenes; 4, 5, 8, 9, 10, 13, 14, 15 – orthopyroxenes and pigeonite. a – core, b – margin, c – microlite, 3c – chill "spinifex" in glass; 12, 13 – large microlites,

presence of magnesian olivine, bronzite, and chrome spinel [13], [17], [18], [27]. However, in contrast to the boninites, the high-Mg dark colored minerals of the microlites and the margins of the phenocrysts in the rocks of the study area are associated with the plagioclases of labradorite composition.

The other important mineralogical feature of the rocks is that the magnesian andesites of the lava domes and the andesites and dacites of Piip and its parasitic cones contain compositionally different mineral phases which could not be in equilibrium (see Table 5). For instance, all rock types of this group, except the magnesian andesites of the lava domes, contain phenocrysts and subphenocrysts of plagioclase with the cores of bytownite-calcium labradorite and andesine-sodium labradorite and the margins of plagioclase of intermediate composition (Figure 5). The plagioclase microlites in the groundmass of the lavas are intermediate too. The cores of calcium plagioclases have a variegated zoning and contain numerous glass inclusions, while the cores of sodium plagioclases contain no inclusions and are poorly or randomly zoned. The magnesian andesites of the lava, domes and the andesites of the Piip flank eruption contain phenocrysts and subphenocrysts of magnesian olivine (forsterite and magnesian chrisolite, respectively) bearing spinel inclusions, and of clinopyroxene (enstatite-diopside) along with phenocrysts of hypersthene and magnesian-ferriferous hornblende. Moreover, the hypersthene cores often have rims of magnesian bronzite which is

9b	10c	11a	12c	13a	14b	15c	16a	17c
55,40	55,59	52,67	51,21	54,28	55,23	56,29	52,47	51,23
0,14	0,45	0,23	0,82	0,02	0,14	0,13	0,25	1,24
2,59	2,19	2,61	3,39	0,29	2,32	1,76	1,83	3,47
0,58	0,19	0,17	0,04	0,00	0,07	0,02	0,09	0,00
6,90	8,97	4,45	8,12	18,48	10,17	9,85	5,85	13,12
0,13	0,18	0,09	0,21	0,58	0,17	0,21	0,12	0,31
31,28	30,62	16,67	14,80	25,46	29,59	28,77	15,94	16,97
2,52	1,75	22,11	19,85	0,71	1,92	2,16	22,94	13,31
0,00	0,00	0,18	0,28	0,00	0,02	0,00	0,32	0,38
99,53	99,93	99,19	98,75	99,84	99,63	99,19	99,81	100,06
11,01	14,12	13,03	23,53	28,9	16,2	16,12	17,07	30,25
4,9	3,4	45,3	42,4	1,4	3,8	4,3	46,2	28,2
84,6	83,0	47,6	44,0	70,1	80,7	80,3	44,6	50,1
10,5	13,6	7,1	13,6	28,5	15,5	15,4	9,2	21,7

also found extensively in microlites (Figure 6). Finally, the Piip dacites and andesites, whose dark colored minerals are dominated by Mg-Fe hornblende, hypersthene, and augite, contain a small amount of enstatite-diopside phenocrysts with bronzite prevailing in microlites. Here, too, the hypersthene cores are encased in bronzite rims. The coexistence of these drastically different mineral phases is commonly attributed to magma mixing.

DISCUSSION OF RESULTS

The results of this study were used to deduce the age relations of the volcanic events and the rocks they produced and identify the rock types.

The basalts dredged from the base of the Vulkanologov Massif are greatly different from the lavas composing the massif and the Piip cone in chemistry (higher TiO_2 content), mineralogy (lack of pyroxenes and plagioclases), and texture (apovitrophyric). Chemically, they resemble subalkalic basalts of marginal seas [14] and hence seem to be of the basement type, even though they differ from the sea-floor basalts of the Komandorsky Basin, penetrated by DSDP hole 191, by a considerably higher K_2O content and a lower TiO_2 percentage.

The Vulkanologov Massif is younger than its foundation (possibly a large shield volcano). It is composed largely of aluminous basalts in the lower part and of moderately magnesian andesites in the upper,

Table 7 Representative analyses of spinels and picroilmenite.

Oxide	1	2	3	4	5	6	7	8
TiO_2	1,08	0,89	0,45	52,06	0,37	0,46	0,59	7,57
Al_2O_3	28,00	24,68	30,61	1,10	16,79	16,67	24,03	2,60
Cr_2O_3	32,70	38,24	33,95	2,29	45,20	45,57	34,95	13,22
Fe_2O_3	9,02	7,64	6,81	9,63	9,09	10,37	7,90	38,34
FeO	15,60	15,31	12,34	17,09	16,90	13,97	25,52	32,68
MnO	0,25	0,24	0,25	0,26	0,29	0,30	0,40	0,39
MgO	14,19	14,02	16,29	17,55	11,70	13,97	6,81	3,27
Σ	100,83	101,02	100,73	99,98	100,34	101,30	100,21	98,08
f, at.%	38,15	38,00	29,83	35,32	44,76	35,93	67,77	84,85

Note. 1, 2 – from basalts of the foundation (sample 2316/5), inclusions in olivine with f = 13; Vulkanologov Massif: 3, 4 – from high-Al basalts (sample 2316/2), inclusions in olivine with f = 10-10,5; 5, 6 – from high-Mg andesite (sample 2316/4), inclusions in olivine with f = 11-12; 7, 8 – from Piip: andesite (sample 2316/3); 7 – core and 8 – margin of a 40μ × 40μ grain in groundmass.

which also contains some aluminous basaltic and magnesian andesites. Judging from the relations between the dredged rocks and the sediments, the age of the basement underlying the massif can be placed in the late Miocene-early Pliocene range. It is important to note that the sea floor survey with the manned submersible MIR-1 has revealed that the basal flows of the massif rest on the basement basalts and that there are no sediments of notable thickness between them. Consequently, the formation of the massif and that of the Komandorsky Basin floor, at least between the Bering and Alpha fractures, could not be separated by a large period of time. This supposition is consistent with the absolute age of basalts from Hole 191 — 9.3±0.8 m.y. [25] and with the age of magnesian andesites dredged from the NW end of the Komandorsky segment — 8.8 m.y. [26].

Finally, the youngest rocks overlying the massif — the dacites and andesites of the Piip cone and the lavas composing its parasitic cones and the extrusive domes — all seem to be of Quaternary age and Piip can be recognized on the basis of the evidence presented in [10] to be an active volcano. The magnesian andesites of the extrusive domes, containing, along with Mg-rich mineral phases, hypersthene, hornblende, and andesine, characteristic of the Piip dacites, may include some dacitic material. On the other hand, the occurrence of magnesian olivine, enstatite-diopside, diopside, and bronzite in the Piip andesites may be related to an admixture of magnesian andesite lava. This and a number of common chemical features suggest that the emplacements of the Piip lavas and of the magnesian andesite lavas were not far spaced in time.

When discussing the chemistry of the rocks, we postulated that the Piip andesites and dacites were products of the compositional evolution of the primary magnesian andesite magma, whereas the lavas of the Vulkanologov Massif were products of the primary magma,

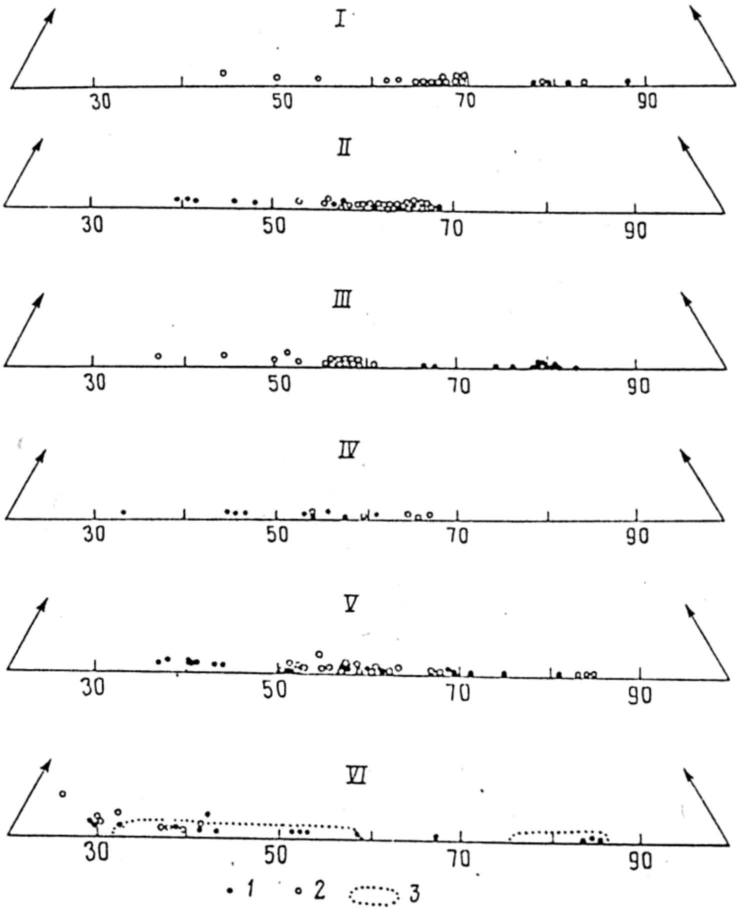
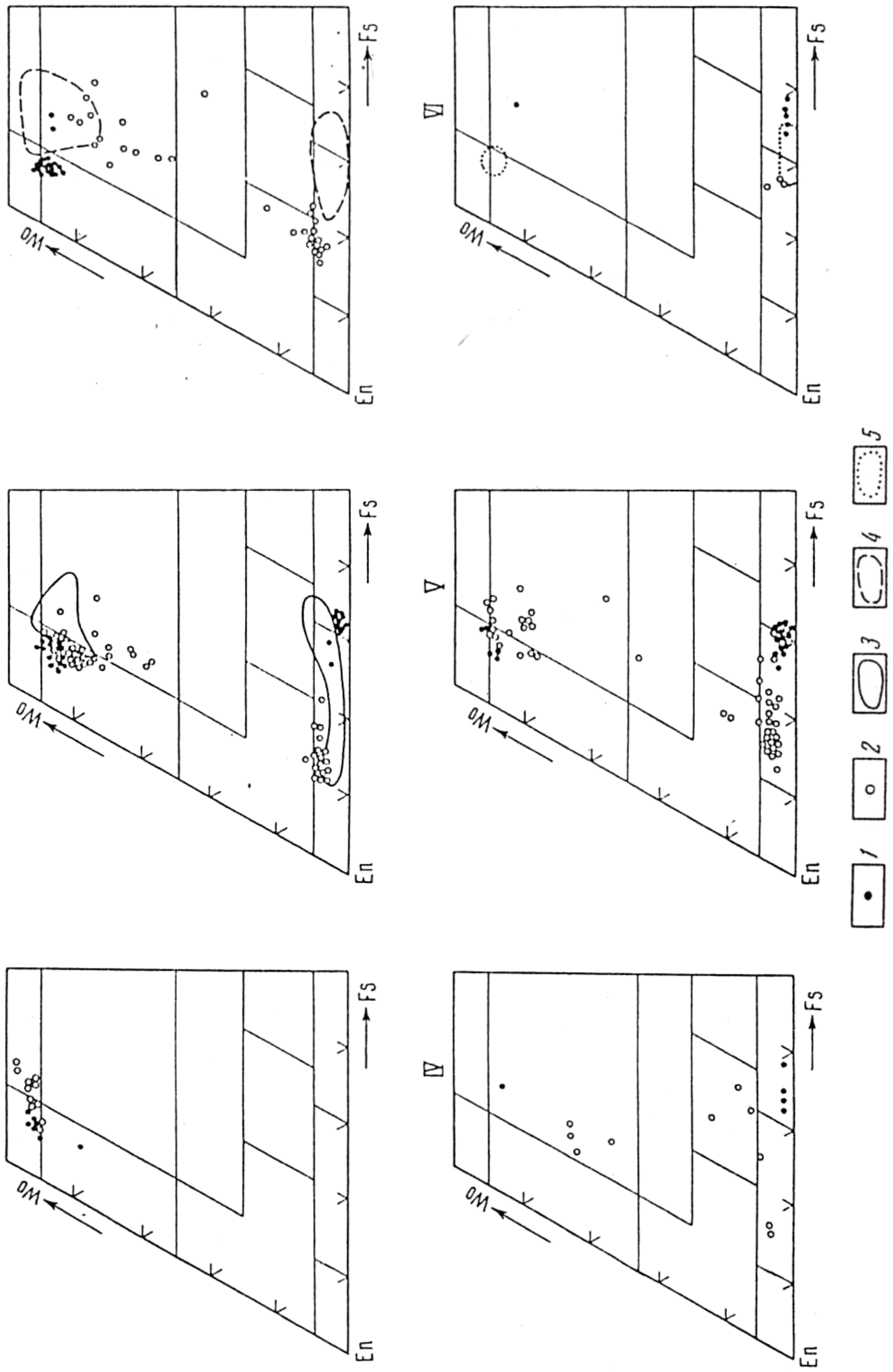


Figure 5 Compositions of plagioclases. *Vulcanologov Massif:* I – high-Al basalts; II – high-Mg andesites; III – medium-Mg andesites; IV – xenolyth of magnesian andesite in dacite from a lava dome. *Piip:* V – andesites; VI – dacites of lava domes at the foot. 1 – core and inner zones; 2 – margins and microlites; 3 – field of plagioclases in Piip dacites and rhyodacites.

possibly close to the basalts of the basement. It is obvious that to understand the origin of the rocks concerned we must test the possibility of different magma sources. As this can be done more efficiently with due allowance for the geochemistry of the rocks, we intend to discuss this point in the next paper.

As follows from the evidence presented here, all the volcanics (except the basement basalts) can be attributed to the island-arc moderately potassic calc-alkalic series. At the same time, they posses a number of individual features, the most important being a high Mg content of the rocks and a related high Mg content of the early



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phases of dark colored minerals. This feature, which can be called a boninite trend, is particularly distinct in the magnesian andesites. We mentioned above and want to emphasize here that late Cenozoic magnesian andesites (lavas) featuring a boninite trend were reported from many areas of the N and NE surroundings of the Komandorsky Basin and were also found in the Aleutians. Admittedly, the magnesian andesites concerned (and the corresponding rocks from the other sites around the Komandorsky Basin) are different from the typical boninites by a lower MgO and a higher K_2O content, the absence of phenocrysts of magnesian bronzite and clinoenstatite, a less chromic spinel (excluding the Shiveluch lavas), and by the presence of plagioclase and ferriferous dark colored minerals, occasionally including amphibole. Whereas the content of andesine, hypersthene, and amphibole in the magnesian andesites may be related, as mentioned above, to an admixture of dacitic material, the subphenocrysts and microlites of labradorite have obviously crystallized from a magnesian andesite melt.

Recently, more and more investigators have been inclined to relate the origin of boninitic magma to back-arc spreading [16].

In this connection, if the type of volcanism in the study area - the island-arc moderately potassic calc-alkalic series — was controlled largely by subduction, then its individual feature — a high Mg content of the rocks and dark colored minerals (boninite trend) — was related to a specific character of its development at the periphery of the Komandorsky Basin in connection with the processes of diffuse back-arc spreading. These processes obviously played the decisive role in the localization of volcanic centers in the southern part of the Komandorsky Basin: they provided structures favorable for channeling magmatic melts into the upper layers of the crust.

In conclusion, it should be emphasized that the boninite trend of the volcanic rocks is obviously a unique petrologic evidence of the contribution of spreading into their origin.

Figure 6 Compositions of pyroxenes. *Vulkanologov Massif:* I — aluminous basalts; II — high-Mg andesites; III — medium-Mg andesites; IV — xenolyth of magnesian andesite in dacite, *Piip:* V — andesites; VI — lava dome dacites, 1 – cores; 2 – margins and microlites; 3 – field of pyroxenes in magnesian basaltic andesites and andesites from Shiveluch and Zarechnyi Volcanoes, Kamchatka [3]; 4 – field of pyroxenes in calc-alkalic basaltic andesites and andesites of the Kuril Is, [3]; 5 – field of pyroxenes from Piip dacites.

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