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GEOCHEMISTRY OF LATE CENOZOIC BASALTS FROM EAST KAMCHATKA AND IMPLICATIONS FOR GEODYNAMIC EVOLUTION OF MAGMA GENERATION

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The study of the East Kamchatka basalts contemporary with the origin of the northern branch of the Kuril-Kamchatka trench has shown that they are markedly different from the basalts composing the late Pliocene-Quaternary East Kamchatka volcanic belt. The older basalts are of late Miocene age and resemble intraplate alkali and subalkali basalts (Zr/Nb=6-9, La/Ta=12-23, La/Yb_N=7-32). The younger basalts are similar to moderately alkali and subalkali basalts from rifts of continental margins, such as Rio Grande (Zr/Nb=18-25, La/Ta=20-23, La/Yb_N=2.3-2.9). The late Pliocene basalts composing the belt itself are comparable with typical island-arc rocks (Zr/Nb=30-120, La/Ta=35-75, La/Yb_N=0.7-1.9). This study has revealed that magmatic evolution in the East Kamchatka volcanic belt was greatly different from the generally acknowledged island-arc model.

INTRODUCTION

In Miocene time East Kamchatka was a non-volcanic area where a linear depresssion, known as the Tyushevka trough, was subsiding as it received terrigenous sediments [6]. It became an area of volcanic activity after the Kuril-Kamchatka trench had been formed in the late Miocene [6]. Since then it evolved as the East Kamchatka volcanic belt, a segment of the Kuril-Kamchatka island arc.

The late Pliocene-Quaternary volcanics of the belt have been adequately studied and are well known from many publications [1], [2], [8], to name but a few. Much less is known about the older volcanic rocks which were emplaced there during the time of trench formation, the period of early volcanic activity. It is known that they outcrop as a discontinuous band along the western border of the belt in the eastern spurs of the Valanghinsky Range and in the Tumrok Range, and that subalkali basalts and trachybasalts of unknown series occur there in contradistinction to the moderately potassic and low-K lavas of the East Kamchatka belt [3], [51, [11]. Alkali basalt sills have been encountered by drill holes at the base of the Neogene strata at the junction of the Tyushevka trough with the Kronotskiy Peninsula structure in the eastern fringe of the volcanic belt.

In 1986-1988 the geologic position and geochemistry of the older volcanic rocks emplaced during the early period of the belt history were studied in the course of 1:50000 mapping by a team headed by three writers of this paper, M.G. Patoka, V.S. Uspensky, and M.G. Valov. The study area was a locality at the western border of the belt. The results of that work and a revision of the literature [3], [5], [10] provided a new insight into the Cenozoic tectonic and magmatic evolution of the East Kamchatka belt.

GEOLOGY AND STRATIGRAPHY

The study area is situated in the eastern spurs of the Valaghinsky Range in the Levaya Zhupanova River drainage area (Figure 1, inset). Volcanic activity occurred there during the closing stage of the Neogene history of the Tyushevka trough when the trough was filled with a continental volcaniclastic molasse [11]. Like the previous investigators, we assign the top of the local stratigraphic sequence, which includes volcanic rocks, to the Shchapina Formation which has been dated Pliocene [5], [11]. The new evidence contradicts this dating. We will consider the age of this formation in more detail since it is important for determining the age of the volcanic rocks, especially those erupted at the very beginning of volcanic activity.

We examined the rocks of the said formation in geologic sections from the Levaya Zhupanova River, its right tributaries, Khrustalnyi and Kholodnyi Creeks, and from the Stol Mountain (sections 1 to 4 in Figure 1). The underlying rocks were examined in the first three localities and the overlying in the last. The upper and lower boundaries were poorly eroded and showed no signs of structural unconformity. The fossils we collected were studied by L.N. Konova, paleontologist, R.M. Myasnikova, micropaleontologist, G.B. Chigaeva, paleobotanist, Z.Sh. Sokolova, palynologist, and R.I. Remizovsky, magnetic stratigrapher, all from PGO Kamchatgeologiya.

The Shchapina rocks lie, in all localities, on a 230-meter sequence of fossiliferous sandstone strata including a few siltstone beds. They contain pelecypods and gastropods of 30 species. The characteristic species which have not been found in the older rocks are *Nucula tenuis* (Montagu), *Yoldia* cf. *epilongrissima* Glad., *Y. ermanensis* Glad, *Tellina* cf. *pulchra* Slod., *Siliqua costata* (Say), *Mactra coalingensis* Arnold, *M. selbyensis* Packard, *Mya ex gr. producta* Conrad, *Sinum* cf. *scopulosus* Conrad, and *Neptunea despecta* L. Foraminifers are scarce and few in number. Determined as species were *Buccella* cf. *pseudo-grigida* Seonenko, *Cribroelphidium* cf. *vulgare* (Volosh.), *Elphidiella* cf. *nutovoensis* (Borovl.), *E. oregonensis* (Cushm. et Grant), *Pseudoelphi-diella* cf. *hannai* (Cushm. et Grant), P. cf. *problematica* (Volosh.), *Globobulumina pacifica* Cushm., and *Islandiella* cf. *miocenica* (Volosh. et Borovl.). The macrofossil and microfossil assemblages belong

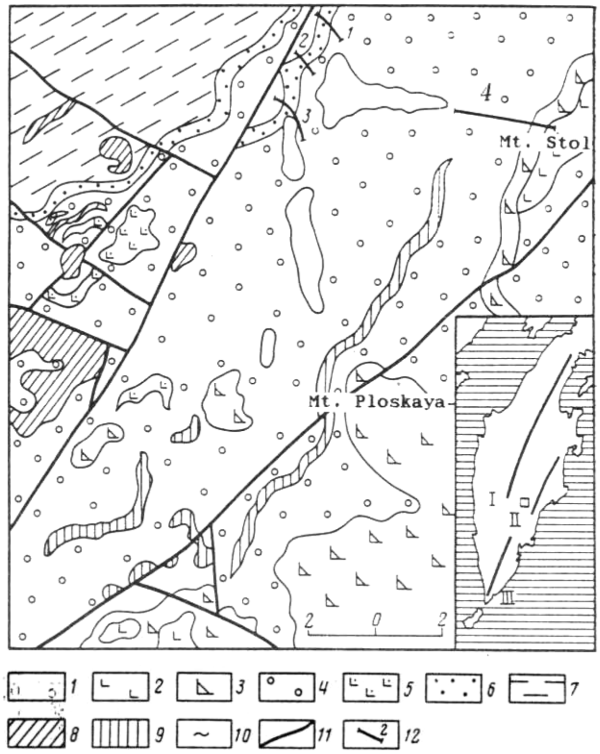

Figure 1 Schematic geologic map of the Levaya Zhupanova River area: 1 – Quaternary; 2 – early Quaternary basalts; 3, 4, 5 – Shchapina Formation, late Miocene–Pliocene: 3 – basalts of the upper sequence, 4 – molasse, 5 – alkali basalts of the lower sequence; 6 – sandstone, late Miocene; 7 – siltstone, Miocene; 8, 9, 10 – subvolcanic bodies: 8 – dacite, 9 – basalt, 10 – alkali basalt; 11 – faults; 12 – geologic sections and their numbers. The inset shows location of volcanic belts: I – Sredinnyi Range, II – East Kamchatka belt, III – South Kamchatka belt. The study area is marked by a square.

undoubtely to the top of the Etolonian regional horizon which was dated middle-late Miocene [4]. The evidence in support of this view is that the sediments older than the sandstones also contain Etolonian fossils, and according to paleomagnetic data the sandstones accumulated 7.4 to 5.8 million years ago.

The rocks of the Shchapina Formation contain abundant flora remains. Those collected from the lower beds, largely in the Khrustalnyi Creek locality, and determined as species are *Equisetum parlatorii* (Heer) Shimper, *Matteuccia septentrionalis* For., *Salix vimenoides* Cheleb., *S. preobrajenskyi* Cheleb., *S. ovalis* Vczer., *S. itelmensis* Cheleb., *S.* cf. *samylinae* Iljinsk. et Pheva, *S.* cf. *uglensis* Cheleb., *S. kenaiana* Wolfe, *S.* cf. *brachipoda* (Trautv. et Mey) Kom., and *S.*

triandroides Cheleb. G.B. Chigaeva has concluded that this floral assemblage "bears a close resemblance to the Klassicheskaya Formation of East Kamchatka and the Ermanovskaya Formation of West Kamchatka, whose age was ascertained to be late Miocene". Having studied fifteen pollen spectra from that level of the geologic section, Z.Sh. Sokolova concluded: "... the dominant assemblage comprises spruce, alder, birch, and hemlock; common but scanty are heat-loving broad-leaved plants and yew trees. At the same time, a perceptible amount of grasses and up to 60 percent frequency of bayberry suggest that the rocks assigned to the Shchapina Formation are of late Miocene age".

Table 1 Compositions of olivines and spinellids from Shchapina basalts.

№	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Σ	f. at. %
1	40,38	0,00	0,00	0,00	0,00	14,92	0,24	43,60	0,13	99,31	16,1
2	38,41	0,00	0,00	0,00	0,00	20,72	0,33	39,98	0,09	99,53	22,5
3	38,42	0,00	0,00	0,00	0,00	20,51	0,36	39,54	0,15	98,68	22,5
4	37,84	0,00	0,00	0,00	0,00	24,18	0,48	37,15	0,22	99,88	26,8
5	35,63	0,00	0,00	0,00	0,00	39,02	0,86	24 12	0,30	99,93	47,6
6	34,77	0,00	0,00	0,00	0,00	42,49	0,90	22, 17	0,25	100,58	51,8
7	0,00	0,65	41,88	15,22	12,19	14,50	0,18	16,08	0,00	100,71	33,6
8	0,00	1,07	38,82	18,26	10,10	18,86	0,26	13,09	0,00	100,48	44,7
9	0,00	9,38	11,00	4,97	36,15	33,46	0,52	4,88	0,42	100,79	79,4
10	0,00	6,52	6,69	3,39	46,85	31,61	0,35	4,02	0,00	99,42	81,5
11	0,00	17,36	1,58	0,44	35,43	39,56	0,89	4,28	0,30	99,84	83,8
12	0,34	19,94	0,80	0,00	27,09	45,64	1,00	1,37	0,27	96,44	94,9
13	0,00	15,50	2,38	0,00	36,14	42,85	0,59	1,32	0,00	98,78	94,8

Note. 1 thru 6 — olivines: 1, 2, 3 — sample 112; 4, 5, 6 — sample 3227; 1, 4 — cores of phenocrysts; 2, 5 — margins; 3, 6 — microlites. 7, 8 — spinels: sample 112, inclusions in olivine phenocrysts. 9, 10 — Cr-bearing titanomagnetites: 9 — sample 112, inclusion in a clinopyroxene phenocryst, 10 — sample 3227, inclusion in a phenocryst of olivine. 11, 12, 13 — titanomagnetites (microlites): 11 — sample 112, 12 — sample 4078/2, 13 — sample 3227. Here and in Tables 2 and 3: sample 112 is olivine-clinopyroxene basalt from lower sequence (an. 4, Table 4); samples 4078/2 and 2141 are subaphyric basalts from lower sequence (an. 7 and 6, Table 4); sample 3227 is megaplagiophyric basalt from upper sequence (an. 19, Table 4).

In the upper Shchapina rocks from the Stol Mountain the Salix flora is represented by new forms: *Salix glaucafolia* Cheleb., *S. udensis* (Trautv. et Mey) Kom., *S. abskondita* Laksh., *S. preobrajenskyi* Cheleb., *Alnus tumrokensis* Cheleb., and *Alnaster pseudokamtchaticum* Baik.

Proceeding from the appearance of willows that resembled the present-day species, G.B. Chigaeva concluded that the host rocks could be dated Pliocene. Z.Sh. Sokolova came to the same conclusion, even though she did not rule out that the rocks might be of Eopleistocene age. Earlier [3], diatoms have been determined from that part of the geologic section; on their basis the rocks can be placed within a Pliocene - Eopleistocene age range.

Volcanic rocks were found in the lower and upper sequences of the Shchapina rocks. Single lava flows of subaphyric olivine basalt ranging between 10 and 50 m in thickness were encountered in the

Table 2 Compositions of clinopyroxenes from Shchapina basalts.

№	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Σ	Wo	En	Fs
1	41,39	3,44	11,49	9,37	0,14	9,94	22,58	0,33	0,00	98,68	51,7	31,6	16,7
2	48,90	1,16	4,78	6,83	0,12	13,60	22,98	0,28	0,00	98,64	48,7	40,0	11,3
3	44,03	2,82	9,96	9,50	0,13	10,50	21,95	0,64	0,00	99,51	49,9	33,2	16,9
4	49,60	1,20	4,43	7,17	0,15	13,51	22,71	0,24	0,00	99,00	48,2	39,9	11,9
5	44,82	2,79	9,46	8,86	0,14	10,85	23,06	0,34	0,00	100,32	51,2	33,5	15,3
6	45,17	2,38	7,70	8,60	0,17	11,43	22,56	0,32	0,00	98,34	49,9	35,2	14,9
7	49,80	1,25	4,02	7,55	0,17	13,66	22,44	0,31	0,00	99,20	47,4	40,1	12,5
8	42,97	4,02	8,79	8,31	0,19	10,35	22,81	0,71	0,00	98,12	52,2	33,0	14,8
9	47,34	2,43	4,75	7,73	0,18	12,49	22,61	0,40	0,00	97,94	49,1	37,8	13,1
10	43,60	3,74	8,33	7,70	0,11	10,82	23,21	0,59	0,00	98,11	52,4	34,0	13,6
11	47,82	2,25	4,86	7,19	0,16	12,52	22,10	0,54	0,00	98,44	50,1	37,7	12,2
12	48,64	0,95	3,19	11,74	0,35	13,76	18,56	0,20	0,00	97,41	39,6	40,8	19,6
13	48,51	1,22	2,18	17,38	0,58	11,75	15,76	0,23	0,00	97,59	34,5	35,8	29,7
14	48,13	1,38	2,73	17,15	0,58	11,75	16,33	0,26	0,00	98,33	35,5	35,5	29,0

Note. 1 thru 7 — sample 112; 8, 9 — sample 4078/2; 10, 11 — sample 2141; 12, 13, 14 — sample 3227. 1 thru 4 and 12 — cores of phenocrysts; 5, 13 — margins; 6 thru 11 and 14 — microlites. 1 thru 4 — different sectors of sandglass phenocrysts. Cr_2O_3 is < 0.01 %.

lower Shchapina rocks which outcrop along Khrustalnyi and Stepanov Creeks, the right tributaries of the Levaya Zhupanova River, in a locality 5-6 km southeast of Mt. Kornilovskaya. The lava flows lie between conglomerates or less rudaceous sediments and seem to be fragments of a small paleovolcanic cone. Dikes of clinopyroxene-olivine basalt were mapped in the area between Khrustalnyi and Stepanov Creeks and along Stepanov and Kholodnyi Creeks. As olivine basalts have only been found in the lower sequence, they are likely to be of late Miocene age.

A complex of subaphyric olivine basalts, metaplagiophyric basalts, and subordinate andesite-basalts was mapped in the rocks of the upper sequence on the right and left banks of the Levaya Zhupanova River and in the areas of Mt. Stol and Mt. Ploskaya. The rocks occur as 5- to 15-meter thick lava flows interbedded with basaltic pyroclastic material and occasional lenses of terrigenous and organic (diatomite) rocks, or as thick (up to 30 m) and extensive (up to 15 km) sills and scarce dikes. They seem to be produced by multivent eruptions which resulted in the formation of extensive lava plateaus. The lavas are of Pliocene age as are the rocks of the upper Shchapina sequence.

PETROGRAPHY AND MINERALOGY

The porphyritic basalts contain up to 20-30 percent of olivine and clinopyroxene phenocrysts and have a fully crystallized groundmass. The subaphyric basalts contain single olivine phenocrysts and

Table 3 Compositions of feldspars, analcites, groundmasses, and glasses from Shchapina basalts.

№	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Σ	An	Ab	Or
1	48,70	0,00	32,61	0,71	0,00	0,07	14,60	2,76	0,17	99,63	73,8	25,2	1,0
2	50,11	0,00	31,69	1,01	0,00	0,05	13,69	3,48	0,26	100,29	67,5	31,0	1,5
3	58,10	0,00	26,18	0,61	0,00	0,00	7,00	0,47	0,93	99,29	35,3	59,1	5,6
4	62,56	0,00	23,28	0,56	0,00	0,00	3,57	7,20	3,13	100,30	17,5	64,1	18,4
5	51,28	0,00	29,18	1,13	0,00	0,15	12,65	3,77	0,30	98,46	63,8	34,4	1,8
6	57,56	0,00	25,75	0,85	0,00	0,00	8,64	5,85	0,78	99,44	42,9	52,5	4,6
7	51,81	0,00	28,70	1,28	0,00	0,15	12,61	3,83	0,35	98,74	63,2	34,7	2,1
8	53,67	0,00	23,91	0,25	0,00	0,00	0,23	12,44	0,00	90,51	—	—	—
9	53,12	0,00	24,21	0,55	0,00	0,39	0,16	12,09	0,00	90,51	—	—	—
10	50,80	1,50	19,35	8,59	0,15	4,47	9,32	4,13	1,54	99,86	—	—	—
11	56,34	0,69	19,80	6,50	0,00	3,55	2,40	4,16	5,14	98,59	—	—	—
12	46,24	2,57	18,00	8,65	0,24	4,14	5,42	8,05	0,89	94,19	—	—	—
13	65,62	0,90	13,71	4,81	0,13	0,58	2,45	3,61	6,22	98,03	—	—	—
14	70,26	0,44	15,43	1,43	0,00	0,00	0,86	3,81	6,71	98,94	—	—	—

Note. 1 thru 7 — feldspars, 1 thru 4 — sample 112: 1 — subphenocryst, core; 2 — microlite, 3 — plagioclase, 4 — ternary feldspar from mesostasis; 5, 6, 7 — sample 3227: 5 — megacryst, core, 6 — megacryst, margin, 7 — subphenocryst, core. 8, 9 — analcite: 8 — sample 112, 9 — sample 2141. 10, 12 — bulk composition of groundmass: 10 — sample 112 (averaged over 5 determinations), 12 — sample 4078/2 (averaged over 3 determinations). 11, 13, 14 — glass from groundmass: 11 — sample 112, 13 and 14 — sample 3227.

clinopyroxene subphenocrysts and microlites included in the essentially glassy mesostasis. The porphyritic basalts are comparatively fresh rocks, whereas the subaphyric types are considerably altered.

The mineral phases have been studied using a Camebax electron microprobe at the Institute of Volcanology (analyst V. V. Ananiev). Examples of the analyses are presented in Tables 1, 2 and 3.

The olivine phenocrysts from the porphyritic basalt are zoned crystals with broad high-Mg cores (Fo_{84-86}) and very narrow and more ferriferous margins (Fo_{76-83}). Olivine contains euhedral crystals of high-Al spinel (Al_2O_3=34-45 wt.% with Cr_2O_3=15-23 wt.% and f=33-45 at.%). The clinopyroxene phenocrysts are tinted pink and often have a sandglass texture with one sector consisting of high-Ti fassaite (TiO_2=2-3.6 wt.% and Al_2O_3=8.5-12.5 wt.%) and the other of high-Ti and high-Al salite (TiO_2=1.2-1.8 wt.% and Al_2O_3=4.5-6 wt.%). Fassaites are higher in Na_2O than salites and contain more iron which is more oxidized than iron in salites. Clinopyroxene phenocrysts contain inclusions of Cr-rich (up to 6% Cr_2O_3) and aluminous (up to 11% Al_2O_3) titanomagnetite with 74-84 at,% of iron. Common among the subphenocrysts are laths of bytownite An_{69-75} (see Tables 1, 2 and 3).

The groundmass of the porphyritic basalt consists of microlites of clinopyroxene, plagioclase, titanomagnetite, and analcite and a mesostasis of sodic plagioclase, ternary feldspar, and glass. Clinopyroxene microlites consist of salite (more abundant) or fassaite which are compositionally similar to the salite and fassaite of the phenocrysts (Figure 2 and Table 2). Plagioclase from the microlites is calcium labradorite An_{65-67} and plagioclase from the mesostasis is

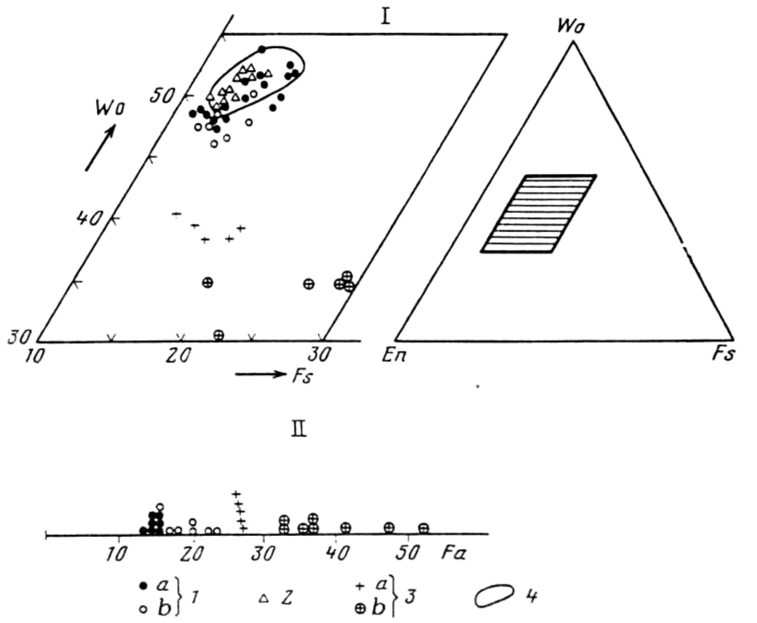

Figure 2 Compositions of pyroxenes (I) and olivines (II) from the basalt of the Shchapina Formation: 1 — olivine-clinopyroxe basalt from the lower sequence: a — cores of phenocrysts, b — microlites and margins of phenocrysts (analyses 5 and 6 in Table 4); 3 — megaplagiophyric basalt from the upper sequence: a and b — same as in 1 (analysis 19 in Table 4); 4 — region of pyroxenes from alkali lavas of Eastern Australia [20].

andesine An_{35-43} (Figure 3 and Table 3). The composition of ternary feldspar from the mesostasis is An_{17-24} Ab_{61-64} Or_{14-25}. Titanomagnetite contains 17-17.5% TiO_2, <2% Al_2O_3, and 83-85 at.% iron. Analcite occurs as small crystals with regularly developed faces. The bulk composition of the groundmass corresponds to aluminiferous K-Na subalkali basalt (see Table 3).

Olivine of the phenocrysts from the subaphyric basalts is totally replaced by chlorite. Like in the porphyritic basalt, clinopyroxene in subphenocrysts and microlites may be represented by Ti-bearing fassaite or salite, which occur in approximately equal proportion (see Figure 2 and Table 2). They are similar to the pyroxenes from the porphyritic basalt except for a somewhat higher TiO_2 and Na_2O percentages. Titanomagnetite is also more titaniferous (TiO_2=20-22 wt.%) and more ferriferous (95-100 at,%). There are microlites of sphene. Spots and amygdules of analcite are common in the glassy groundmass. Spots and veinlets of albite were observed. The bulk composition of the groundmass corresponds to alkali basalt containing a considerable amount of water (5-6 %) as evidenced by the sum deficiencies (see Table 3).

Basalts from the upper sequence are more abundant in plagioclase.

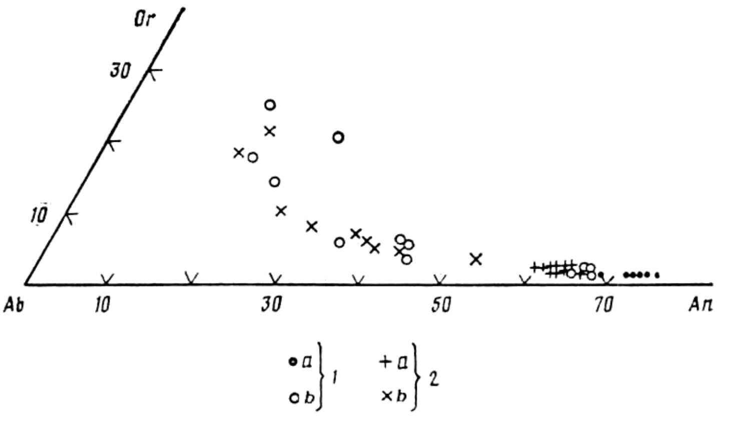

Figure 3 Compositions of feldspars from the Shchapina basalts: 1 — olivine—pyroxene basalt from the lower sequence: a — cores of phenocrysts and subphenocrysts, b — margins, microlites, and mesostasis (analysis 4 in Table 4); 3 — megaplagiophyric basalt from the upper sequence: a and b same as in 1 (analysis 19 in Table 4).

The megaplagiophyric types contain large elongate crystals (megacrysts), reaching 10-15 mm in length, of labradorite An_{62-66} which often occur in aggregates and contain rounded grains of olivine. The narrow margins of the plagioclase megacrysts consist of potassium oligoclase or andesine An_{26-43}. The cores of the olivine phenocrysts and the olivine grains from the megacrysts consist of chrysolite Fo_{72-73} and the margins of hyalosiderite Fo_{52-67}. The olivine phenocrysts contain crystals of titanomagnetite (6-9% Al_2O_3 and 3-4% Cr_2O_3). The subphenocrysts are plagioclases similar to the plagioclase megacrysts (An_{60-65} in cores and An_{36-39} in margins) or augites. The augite grains are chemically zoned too (see Table 2 and Figure 2): the iron and TiO_2 percentages increase and those of calcium and Al_2O_3 decrease from cores to margins.

The groundmass of the megaplagiophyric basalts consists of microlites of andesine-labradorite, hyalosiderite, augite (similar to that of the phenocryst margins), and titanomagnetite and a small amount of brown oxidized glass whose composition ranges between Fe-bearing potassic trachite and potassic trachyrhyodacite (see Table 3).

The subaphyric basalts contain single small phenocrysts of olivine (less frequently of plagioclase) in a well crystallized groundmass similar to the groundmass of the megaplagiophyric basalts.

The mineral composition of basalts from the lower sequence bears a close resemblance to that of alkali olivine basalts from the Sredinnyi Range of Kamchatka, except that the pyroxenes are higher in Ti and Na. The mineral composition of basalts from the upper sequence is similar to that of megaplagiophyric subalkali basalts from the

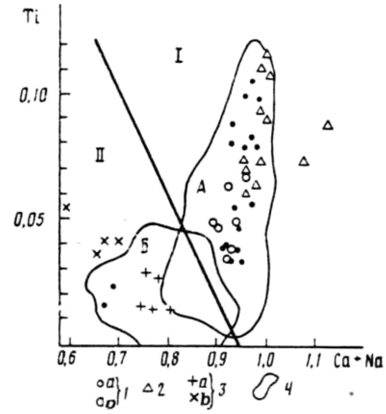

Figure 4 Ti/(Ca+Na) diagram for alkali (I) and nonalkali (II) clinopyroxene basalts after [16]: 1, 2, 3 — see 1, 2, 3 in Figure 1; 4 — regions of most common compositions of pyroxenes from alkali (A) and nonalkali (B) basalts after [16]. Ti and (Ca+Na) have been calculated.

Tolbachik zone of cinder cones [2].

At the same time, a Ti and Al enrichment and a high calcium content of the pyroxenes from the basalts of the lower sequence make them similar to the pyroxenes of alkali basalts from oceanic islands [14] and continental rifts [9], [18], [20]. Considerable Ti and Al variations in sandglass phenocryst sectors have been reported in basalts from continental rifts [18], [20], as well as the presence of microlites in the groundmass that show similar variations [20]. The last important point is that the diagram offered by Letterrier *et al.* [16] (Figure 4) to separate clinopyroxenes from alkali (field I) and nonalkali (field II) basalts shows that pyroxenes from the basalts of the lower sequence fall within field I and those from the upper within field II.

PETROCHEMISTRY AND GEOCHEMISTRY

Chemical analyses of the basalts were made at the Central Chemical Laboratory of PGO Kamchatgeologiya. Trace elements and rare earths were determined at the Institute of Geology and Geophysics, Siberian Division, USSR Academy of Sciences: REE, Ba, Th, U, Sc, Hf and Ta by instrumental neutron activation analysis and Rb, Sr, Y, Zr and Nb by X-ray fluorescence analysis (analyst Yu.G. Shipitsin) and V, Cr, Co, Ni, Cu and Zn by atomic absorption spectrophotometry (analysts F.M. Zaporoshenko and T.A. Kirilenko). The same samples were analyzed for the same elements at the Institute of Geology of Ore Deposits, Geochemistry and Mineralogy, USSR Academy of Sciences. The results

Table 4 Chemical analyses of Shchapina basalts.

№	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Σ	K_{Mg}
Basalts of lower sequence														
1	45,31	1,80	15,16	4,82	4,66	0,15	9,90	8,00	3,63	1,57	0,60	3,08	99,58	69,8
2	45,50	2,17	13,26	4,29	6,22	0,17	10,44	8,30	2,56	1,10	0,46	5,57	100,14	68,5
3	46,29	1,81	14,60	1,59	6,67	0,18	10,95	8,27	3,11	1,49	0,51	3,98	99,45	73,9
4	47,68	1,75	17,30	1,62	6,71	0,18	10,26	7,36	2,60	1,37	0,38	2,92	100,18	72,5
5	44,80	2,88	15,87	3,57	5,16	0,24	7,71	7,22	2,59	2,70	1,09	5,51	99,35	65,9
6	44,84	2,75	15,00	6,19	2,70	0,17	6,68	6,45	4,96	1,33	1,30	7,33	99,70	62,9
7	46,01	2,50	15,01	4,59	2,90	0,17	7,14	6,45	4,69	1,81	1,28	6,54	99,09	68,0
8	47,55	2,17	13,45	5,65	3,35	0,18	7,15	7,10	4,50	1,58	1,39	7,65	99,89	64,0
Basalts of upper sequence														
9	51,21	2,25	16,20	3,94	7,31	0,23	4,38	8,03	3,57	1,52	0,58	0,48	99,70	45,8
10	51,21	2,25	16,05	3,65	7,57	0,23	4,33	7,85	3,21	1,57	0,59	1,20	99,71	45,6
11	51,29	2,13	16,38	2,48	7,91	0,22	4,88	8,20	2,80	1,74	0,60	1,42	100,07	50,2
12	51,40	2,13	16,50	3,72	7,40	0,23	4,21	7,85	3,14	1,57	0,62	1,06	99,89	45,1
13	51,46	2,06	14,97	2,59	8,65	0,23	5,09	8,41	2,87	1,61	0,52	1,40	99,86	51,2
14	52,00	2,25	15,81	3,76	7,14	0,21	4,17	7,71	3,48	1,60	0,60	1,21	99,92	45,4
15	50,52	1,75	17,02	3,69	7,38	0,20	4,72	8,76	3,17	1,15	0,33	1,14	99,83	48,1
16	50,68	1,94	16,22	5,09	7,11	0,21	3,67	9,18	2,93	1,36	0,29	1,32	100,00	39,7
17	50,78	1,81	18,60	3,91	6,49	0,19	3,40	8,63	3,44	1,36	0,33	1,27	100,41	41,6
18	51,17	1,84	15,14	5,07	8,26	0,24	5,01	7,95	2,75	1,54	0,40	1,01	100,38	45,1
19	51,25	2,00	17,48	4,07	7,14	0,22	4,00	8,45	3,57	1,31	0,40	0,57	100,46	43,7
20	51,35	1,78	15,73	4,40	8,48	0,24	5,09	8,41	2,75	1,60	0,40	0,93	101,16	46,2
21	51,90	1,69	17,89	2,85	6,77	0,20	4,26	8,69	2,98	1,54	0,40	1,18	100,35	48,9
Analogs of lower Shchapina basalts from neighboring areas														
22	45,78	1,27	14,41	5,81	4,62	0,13	11,59	6,73	3,03	1,43	0,52	5,35	100,07	71,2
23	46,40	2,56	16,42	1,51	8,54	0,22	7,67	7,87	3,75	1,80	0,85	0,67	98,27	61,9
24	50,12	1,89	14,84	1,28	6,75	0,14	10,40	8,13	3,51	1,41	0,30	1,18	99,95	73,4
25	46,30	1,94	17,21	2,51	4,47	0,07	5,38	5,94	4,24	3,19	0,75	7,80	97,80	62,7
Average compositions of East Kamchatka basalts														
26	49,75	0,79	18,71	3,82	6,25	0,18	6,18	10,81	2,33	0,43	0,16	0,51	99,92	57,2
27	51,11	1,05	18,04	4,10	5,96	0,19	5,25	9,52	2,90	0,84	0,23	0,67	99,86	53,3

Note. 1 thru 4 — olivine-clinopyroxene basalts: 1 — sample 8105/2, Kholodnyi Cr., dike; 2 — s. 2175/3, Stepanov Cr., dike; 3 — s. 3166, locality between Khrustalnyi and Stepanov Creeks, dike; 4 — s. 112, Zverievyi Cr., dike. 5 thru 8 — subaphyric basalts: 5 — s. 1135, Stepanov Cr., lava flow; 6 — s. 2141, Khrustalnyi Cr., lava flow; 7 — s. 4078/2, same; 8 — s. 2138/2, same. 9 thru 14 — subaphyric basalts: 9 — s. 3225, Levaya Zhupanova R., lava flow; 10 — s. 4096/1, L. Zhupanova R., lava flow; 11 — s. 4090/2, Mt. Ploakaya, lava flow; 12 — s. 2201, same; 13 — s. 4104, Maltseva B., lava flow; 14 — s. 4096, L. Zhupanova R., lava flow. 15 thru 21 — megaplagiophyric basalts: 15 — s. 2201, Ht. Ploskaya, lava flow; 16 — s. 4105, Maltseva R., lava flow; 17 — s. 2214, L. Zhupanova R., lava flow; 18 — s. S-19, Mt. Stol, lava flow; 19 — s. 3227, L. Zhupanova R., lava flow; 20 — s. S-22, Mt. Stol, lava flow; 21 — s. 2217, L. Zhupanova R., lava flow. 22 thru 25 — late Cenozoic subalkali and alkali basalts from neighboring areas: 22 — olivine basalt, Mt. Kolyuchaya, lava flow, after A. Tsikunov (private communication); 23 — trachybasalt, Bivuachnyi Cr., after [5]; 24 — olivine basalt, P. Shchapina R., lava flow; 25 — alkali basalt, Konusnyi Hill, sill, average of 4 analyses [10]. 26, 27 — average basalt compositions, East Kamchatka volcanic belt [2], [8]: 26 — low-K basalt, average of 82; 27 — moderately alkali basalt, average of 90.

showed good agreement.

As regards the alkalis (Table 4), the porphyritic basalts from the lower sequence correspond with subalkali basalts and the subaphyric types with alkali basalts. The basalts from the upper sequence tend to group about the boundary between subalkali and moderately alkali rocks. The Na_2O/K_2O ratio ranks the basalts of both sequences as K-Na types. All basalts show elevated TiO_2 and P_2O_5 contents, the concentrations of these oxides in the subaphyric types being higher than in the porphyritic basalts, both from the lower and upper sequences, and reaching the peak values in the subaphiric alkali basalts of the lower sequence.

Table 5 Trace element concentrations in East Kamchatka basalts.

Element	4	7	3	6	11	9	17	26	27
Rb	9	25	16,5	11,5	25,7	28,8	15,8	5,8	10,8
Cs	0,43	0,30	3,0	—	0,05	—	0,75	0,35	0,55
Sr	648	721	1720	580	349	347	476	316	387
Ba	225	445	1282	746	262	225	302	132	275
Cu	168	43	90	—	338	325	396	—	—
Zn	107	107	113	—	131	137	166	—	—
Sc	35	16,5	35,5	18	32,5	37	30	38	36
V	219	151	187	145	438	430	378	260	226
Cr	241	186	145	188	96	110	96	140	183
Co	36	38,4	35	31	32,5	37,1	30,5	35	32,6
Ni	160	140	87	111	23	33	23	45	49
Y	22,2	24,4	23	25	41,4	46,5	40	16,1	23,7
Zr	160	364	473	507	199	213	173	46	93
Hf	4,0	10,6	11,2	9,6	4,8	5,7	3,3	1,3	2,1
Nb	17,9	57	67	76	8,0	11,5	7,4	—	1,0
Ta	1,4	5,1	5,4	4,65	0,82	0,85	0,58	0,056	0,11
Th	2,2	9,3	9,5	8,7	1,7	1,9	2,0	0,45	0,79
U	0,65	2,9	2,9	2,9	1,1	—	0,75	0,25	0,47
La	18,2	60,6	66,9	109	13,9	16,6	13,4	3,0	5,7
Ce	34,8	107	118	234	35,5	41,4	27,1	7,1	13,2
Nd	19,6	44,4	46,2	88,2	23,4	22,8	16,6	6,5	10,2
Sm	4,9	9,6	12,5	16,2	7,0	7,2	5,0	2,05	3,00
Eu	1,65	3,2	3,7	4,66	2,2	2,2	1,75	0,78	0,99
Gd	5,4	7,4	9,6	9,6	6,1	6,4	6,0	2,6	3,55
Tb	0,87	1,03	1,3	1,2	1,0	1,1	0,95	0,48	0,60
Tm	—	—	—	0,4	0,68	0,68	0,55	0,29	0,34
Yb	2,0	2,2	2,5	2,3	4,0	4,2	3,1	1,98	2,24
Lu	0,30	0,25	0,41	0,35	0,7	0,71	0,4	0,29	0,33

Note. Sample numbers are given as in Table 4. 26 — average of 9 analyses, 27 — average of 10 analyses.

The lower basalts are considerably higher in Mg than the upper. The Mg ratio, $K_{Mg}=Mg/Fe^{2+}+Mg$, at.%, where Fe^{2+} has been computed from the total iron using the known relation $Fe_2O_3/FeO=0.15$, averages 71.3% (n=5) for the porphyritic basalts and 64.5% (n=5) for the subaphyric types from the lower sequence and 44.0% (n=9) for the megaplagiophyric types and 47.7% (n=10) for the subaphyric basalts from the upper sequence. On the K_{Mg} basis, only the lower porphyritic basalts can be equated with mantle lherzolite [7].

In general, the basalts of the lower sequence are characterized by high concentrations of both coherent (Cr, Ni) and many of incoherent elements (Sr, Th, Nb, Ta, light REE) and by moderate concentrations of Rb, Y, heavy REE, Yb, Cu, Zn and Ba (Table 5). All of them show small Zr/Nb (6-9) and La/Ta (12-23) and large Ni/Co (2.5-4.4) and Cr/V (0.8-1.2) values. In accordance with a variable Mg content (different degree of fractionation), the porphyritic basalts are higher in Ni and Cr and lower in lithophile trace elements than the subaphyric types. The compositions of rare earth elements in the lower basalts show a high degree of differentiation (La/Yb_N=7-32) and the curves of REE distribution normalized to chondrite slope rapidly from left to right falling within the region of Cenozoic subalkali and alkali K-Na basalts from Mongolia and the Transbaikal area (Figure 5).

The basalts of the lower sequence are less magnesian, less alkalic, show lower concentrations of both Cr and Ni and Sr, Th, Nb, Ta and light REE and higher concentrations of Rb, Y, heavy REE, Cu and V with larger Zr/Nb (18-25) and La/Ta (20-23) ratios and smaller Ni/Co (0.7-0.9) and Cr/V (0.21-0.26) ratios. The compositions of rare earth elements in them are less differented (La/Yb_N=2.3-2.9) and the curves of REE distribution normalized to chondrite are considerably flatter and intersect the REE curves for the lower basalts.

At the same time, the basalts of the lower and upper sequences of the Shchapina Formation are markedly different from the late Pliocene-Quaternary basalts of the East Kamchatka volcanic belt: they are higher in alkalis, in Ti, P, Nb, Ta, Zr, Hf, Th, U and in light REE (Figure 6 and Table 5) and show smaller Zr/Nb and La/Ta values. Besides, the lower basalts are higher in Sr, Ni and Cr and the upper in Rb, Y and heavy REE. Finally, the Shchapina basalts show a larger degree of REE fractionation (see Figure 5): the La/Yb_N value of the late Pliocene - Quaternary basalts ranges between 0.7 and 1.9.

DISCUSSION OF RESULTS

The alkali and subalkali basalts surveyed have been studied in a small area but similar rocks have been reported in the literature from many areas of East Kamchatka.

Ermakov et *al,* [5] described the petrochemical analogs of the basalts from the lower Shchapina sequence from the Mt. Kolyuchaya area and from the mouth of Bivuachnyi Creek in the upper course of the Levaya Zhupanova River, the localities situated at a distance of 10 km and 45-50 km, respectively, from the study area (see analyses 22 and 23 in Table 4). The rocks they described are lava flows from the Shchapina Formation and associated dikes in the first locality and dikes from the Tyushevka Formation of Neogene age. One of the writers of this paper discovered Ti-rich subalkali basalts in the lower beds of the Shchapina Formation outcropping farther northward in the middle course of the Pravaya Shchapina River (see analysis 24 in Table 4). Suprunenko and Markovsky [10] described sills of Ti-rich alkali basalt containing titanaugite from a Neogene interval in a borehole drilled in the Tyushevka trough bordering the volcanic belt

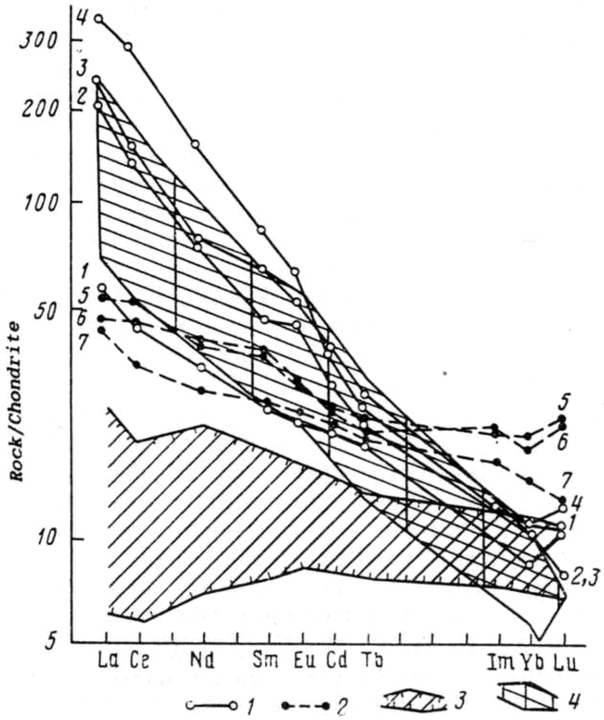

Figure 5 Trace element distribution in late Cenozoic basalts of East Kamchatka: 1, 2 — basalts of the Shchapina Formation: 1 — from lower sequence, 2 — from upper sequence (figures at the curves are numbers of analyses in Table 5); 3 — region of late Pliocene-Quaternary basalts from the East Kamchatka volcanic belt [1], [2]; 4 — region of Cenozoic subalkali and alkali K-Na basalts from Mongolia and the Transbaikal region, USSR [7].

on the east (see analysis 25 in Table 4). Shantser and Kraevaya [11] reported megaplagiophyric and subaphyric basalts, similar to the upper Shchapina basalts, from the Tumrok Range. Regrettably, the alkali and subalkali basalts reported have not been characterized in terms of trace and rare earth element variation which provides important evidence for the understanding of the geotectonic origin of volcanism.

For example, the lower Shchapina basalts fall within the region of intraplate volcanics on ternary trace element diagrams (see Figure 6 as an example). They bear a close resemblance to Cenozoic subalkali and alkali basalts from continental plates (Mongolia and Transbaikal region [7], Eastern Australia [17], etc) and from spreading-type marginal seas (Oki I., Sea of Japan [19], North Phillipine Sea [22]). They have the same trace element percentages, similar Zr/Nb, La/Nb [15], La/Ta [22] and other values, and are comparable in mineral composition, e.g., both contain high-calcium Al-rich and Ti-rich pyroxene. The subalkali basalts of the lower Shchapina sequence are

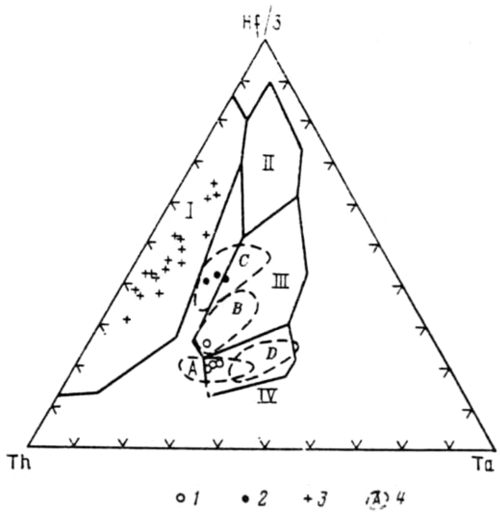

Figure 6 Th-Hf-Ta diagram for basalts from various geodynamic environments after [21]: 1, 2 — see 1 and 2 in Figure 5; 3 — late Pliocene-Quaternary basalts from East Kamchatka volcanic belt after [1] and [2]; 4 — regions of basalts from: A — Oki-Dogo I., Japan [22], B — intraplate basalts from Sredinnyi Range, Kamchatka [1], [2]; C — Rio Grande rift [12], [13]; D — Mongolia and Transbaikal region, USSR [7]; I to IV — regions of basalts from different geodynamic environments [21]: I — island arcs, II — mid-oceanic ridges, III — mid-oceanic ridge and intraplate basalts, IV — intraplate basalts.

similar to the late Cenozoic rift-type basalts of the Sredinnyi Range of Kamchatka [1], [2] in the Nb, Ta, Zr, Th and REE percentages, whereas the alkali types show higher concentrations of these elements.

The diagram of Figure 6 indicates that the basalts of the upper Shchapina sequence fall within the region of basalts from rifts of continental margins, such as the Rio Grande rift [12], [13]: they have the same concentrations of incoherent trace elements as the Rio Grande subalkali basalts.

At the same time, the late Pliocene-Quaternary basalts of the East Kamchatka volcanic belt have many geochemical features in common with island-arc basalts, such as low Ti, Nb, Ta and Zr concentrations along with large Zr/Nb (30-120) and La/Ta (35-75) values [1], [2]. Figure 6 shows that they lie in the field of island - arc rocks.

Proceeding from the evidence presented above we can conclude that progressive changes occurred in the geochemistry of the rocks from intraplate to island-arc basalts during the volcanic history of the East Kamchatka volcanic belt. They might be related to changes in the magma generation environment and depth. Obviously, during the early period of volcanic activity, in late Miocene, magma was generated in the extensional environment and at a large depth in a region of undepleted mantle at a spinel or garnet spinel facies level (basalts from the lower Shchapina sequence). Later, in early Pliocene, the region of magma generation rose slightly (spinel facies), but the extensional environment remained (basalts from the upper Shchapina sequence). Finally, in late Pliocene-Quaternary time, when an island arc had formed, the magma generation region shifted into the upper mantle to a plagioclase facies level and magma was generated under conditions of compression caused by subduction.

We conclude by noting that as far as we know no examples of similar changes in the geochemistry of volcanic rocks have been reported from island-arc histories.

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