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Structure and Composition of the Nadayansky Lava Flow: an Example of the Homogeneity of Lava Flows of the Siberian Trap Province[1]

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Abstract—The Nadayansky Flow is one of the main markers of the volcanic pile of the Siberian Trap Province and covers an area of approximately 48 000 km^2 at an average thickness of 30 to 50 m. The paper is the first to present data demonstrating the constancy of the major- and trace-element composition of the Nadayansky Flow, typifying basalt lava flows in the province. The flow makes up the bottom part of the Mokulaevsky Formation in the Norilsk area and the bottom of the Khonnamansky Formation at the Putorana Plateau and, correspondingly, overlies the Morongovsky and Ayansky formations (the names of these formations differ because they are used in different schemes for the stratigraphic subdivision of the volcanic rock sequence). The rocks show an obvious glomerophyric texture, which makes this flow clearly distinguishable from the under- and overlying rock units. The composition of the Nadayansky Flow was studied throughout its length of a few hundred kilometers and shows very little varying concentrations of major components (48.31 SiO_2, 1.26 TiO_2, 15.8 Al_2O_3, 12.71 Fe_2O_3, 0.19 MnO, 6.89 MgO, 11.1 CaO, 2.25 Na_2O, 0.37 K_2O, 0.14 P_2O_5, 0.02 Cr_2O_3) and trace elements (2.44 La/Sm and 1.56 Gd/Yb), whose variations are within the analytical uncertainties (XRF and ICP-MS analyses). The basalt of the flow crystallized from tholeiitic melt, whose composition was analogous to those of melts that produced all other flows of the Mokulaevsky Formation. For comparison, the paper displays the inner structures of the underlying Morongovsky and Mokulaevsky formations in the basin of the Mikchangda River in the eastern part of the Norilsk area. The composition of the basalts of these formations also varies insignificantly. The main difference is an increase in TiO_2 concentration from 1.19 to 1.3 wt % with the transition from the lower formation to the upper one. In spite of the insignificant difference between the concentrations, it is of principal importance and makes it possible to distinguish between the basalts of these formations. The detected constancy of the compositions of the formations as a whole and the Nadayansky Flow in particular are principally important for studying continental flood basalt provinces and demonstrates the compositional homogeneity of the erupted magmas and their sources. These results are important as an example how geochemical data can be used to correlate widely spaced sequences of volcanic rocks.

Keywords: Siberian traps, basalts, geochemistry, Norilsk area, Putorana Plateau

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INTRODUCTION

In attempts to understand how large magmatic provinces (LIPs) are formed, it is principally important to know their inner structure to be able to reproduce the spatiotemporal evolution of the magmatism. This is even more important for the world's largest Siberian Trap Province (whose estimated volume amounts to 1.5 million km^3, according to Zolotukhin et al., 1978). Researchers studying this province face the problem of correlations between individual vertical sections of the tuff–lava sequence that occur at great distances from one another. It is often pretty difficult to correlate these sections because their rocks have similar structures and textures, and the stratigraphic section at the plateau are strongly disturbed by tectonics, which has vertically displaced some rock units for tens of meters. Some researchers believe that the composition of rocks that make up individual formations and even individual lava flows significantly vary along the strakes of these units, and this is why geochemical data are practically not used in the paleomagnetic reconstructions (Pavlov et al., 2011, 2019; Fetisova et al., 2014). Indeed, the composition of some formations in

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the Norilsk area laterally vary, as is the case with, for example, the Gudchikhinsky (Sobolev et al., 2009) and Nadezhdinsky (Krivolutskaya et al., 2016) formations. However, this pertains only to rocks in the Norilsk–Igarka ancient rift zone (Krivolutskaya et al., 2019), and it is still uncertain as to how much the chemical composition of individual basalt lava flows of the trap association on the platform varies (or does not vary), because no such data are currently available from the literature.

This problem can be elucidated only by studying the volcanic rocks, which are characterized by certain structural–textural features and extend over significant areas, and which can be reliably identified in the field. There are only a few such markers currently distinguished in the Siberian Platform (Mezhvilk, 1962; Starosel'tsev, 1989). One of the most interesting of them is the Nadayansky Flow, which covers an area of 48000 km^2 (Starosel'tsev, 1989) in the north of the Siberian Platform (in the Putorana Plateau and the northern Norilsk area; Fig. 2). The flow overlies the bottom part of the Mokulaevsky Formation in the Norilsk area (Fig. 2a) and correspondingly, the Khonnamakitsky Formation in the Putorana Plateau (these units are complete analogues of each other and were named differently when surveyed and mapped on different 1 : 1000000 sheets of the geological map: sheets R-45 and R-46). The flow overlies, correspondingly, the Morongovsky and Ayansky formations, and was named correspondingly (the name of the flow translates as *overlying the Ayansky Formation*). The rocks of the flow differ from the under- and overlying ones in having a glomerophyric texture, in contrast to the aphyric and oligoglomerophyric under- and overlying rock varieties. Thanks to this, this flow well serves as a marker for surveying volcanics rocks in the northern Siberian Platform, where the flow rests on erosion surfaces and contrastingly differs from the underlying rocks in being more resistant to weathering and in showing clearly discernible columnar parting. The unit occurs on progressively lower elevations from north to south because of postmagmatic tectonic motions (Starosel'tsev, 1991).

It has been determined that the composition of the rocks of the unit varies very insignificantly over distances of hundreds of kilometers, as also does the composition of the rocks of the formation, and this is important for the use and interpretations of geochemical data on the Siberian Platform.

MATERIALS AND METHODS

We studied the composition and structure of the Nadayansky Fow in outcrops in the Norilsk area and in samples provided for us by courtesy of G.N. Nesterenko, which were collected on the Putorana Plateau in 1981–1985 (Fig. 1). This study is based on data on 27 samples. We also examined representative geologic sections of the Morongovsky and Mokulaevsky formations in the Mikchangdinsky area to be able to compare them with one another and with rocks of the Nadayansky Flow. Twenty-one samples were taken from the central portions of lava flows least altered by secondary processes.

Rocks of the Nadayansky Flow were analyzed for eleven major oxides by XRF on an AXIOS mAX (PANalytical) spectrometer with a scanning channel at the Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM), Russian Academy of Sciences (analyst A.I. Yakushev), according to methods of quantitative analysis (III-category accuracy), which were designed and development at the Fedorovskii All-Russia Institute of Mineral Resources (VIMS) (*Methods...,* 2011). The excitation source of the characteristic radiation of atoms was an X-ray tube with an Rh anode (output power up to 4 kW, accelerating voltage 60 kV, current 160 Ma). Concentrations of major components in rocks of the Morongovsky and Mokulaevsky formations were determined by the same techniques at the Vernadsky Institute of Geochemistry and Analytical Chemistry (GEOKhI), Russian Academy of Sciences (analysts I.A. Roshchina and T.V. Romashova). The methodical foundations of the analytical procedures are described in (Krivolutskaya et al., 2018). Concentrations of trace elements were analyzed by ICP-MS at the Institute of Problems of Microelectronics and Ultrapure Materials (IPTM), Russian Academy of Sciences (analyst V.K. Karandashev). The relative standard deviations (calculated based on data of numerous independent measurements of the BHVO-1, BCR-2, and DTS-2 standards of the United States Geological Survey), which were prepared analogously to the analyzed samples, are presented in Table 3 in the Supplement.

OVERVIEW OF THE COMPOSITION OF ROCKS OF THE SIBERIAN PLATFORM

The Siberian Trap Province covers the Siberian Platform and the southern part of the Taimyr Peninsula. Typical traps (*Geological Dictionary,* 2014) are tholeiite basalts flooding extensive areas on the platform in the northern and central parts of the province: in the Norilsk area, Putorana Plateau, and the Tunguska syneclise. Data on the Taimyr rocks are still too scarce to compare these rocks with volcanics on the Siberian Platform. The volcanic rocks were initially subdivided into formations in the 1960s, when geological survey of the territory was carried out, and their geochemistry is described in numerous publications (Fedorenko, 1981; Zolotukhin et al., 1986; Nesterenko et al., 1990, 1991; Lightfoot et al., 1990, 1993; Ryabov et al., 2000; Al'mukhamedov et al., 2004; Krivolutskaya, 2014; and others). The most comprehensive sequence of the Late Permian–Early Triassic volcanics occurs in the Norilsk area and has a total thickness of 3.5 km. The sequence comprises eleven

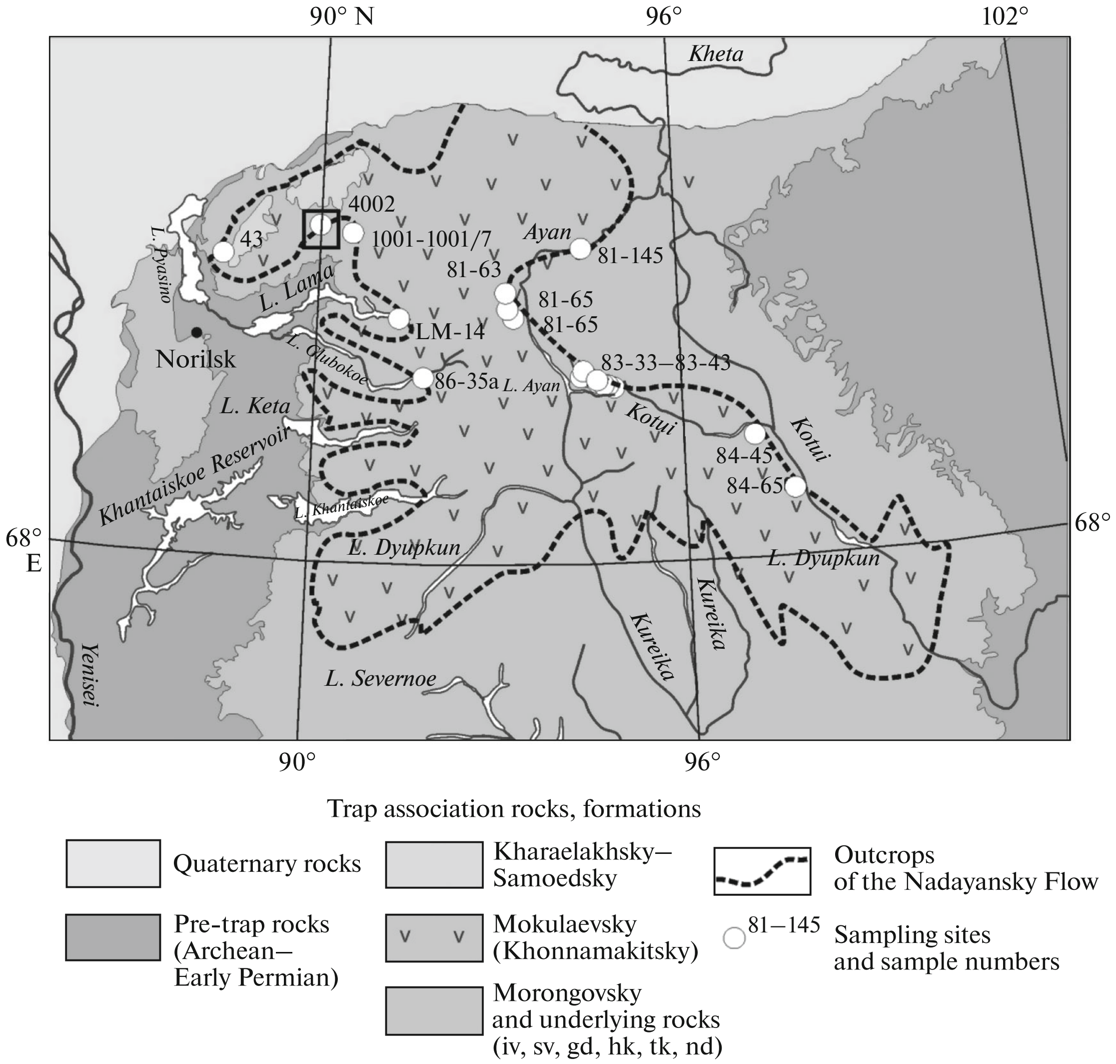

Fig. 1. Schematic geological map of the northern Siberian Trap Province showing the Nadayansky Flow and our sampling sites.

formations (listed upsection from its bottom part): Ivakinsky, Syverminsky, Gudchikhinsky, Khakanchansky, Tuklonsky, Nadezhdinsky, Morongovsky, Mokulaevsky, Kharaelakhsky, Kumginsky, and Samoedsky. The lowermost three formations are made up of subalkaline and picrite basalts with elevated TiO_2 concentrations (>1.5 wt %) and are spatially constrained to the Norilsk–Igarka ancient rift zone. The uppermost Kharaelakhsky, Kumginsky, and Samoedsky formations are preserved only in the Kharaelakhsky and Kumginsky depressions (Table 1). The most widely spread formations are Morongovsky and Mokulaevsky, with the average thicknesses of each of them amounting to 500 m. As was mentioned above, these formations at the Putorana Plateau are named Ayansky and Khonnamakitsky, respectively (Nesterenko et al., 1991; Sharma, 1996). In the Tunguska syneclise, volcanics of this level are grouped into the Nidymsky and Kochechumsky formations. These formations make up much (close to 70% by volume) of the preserved lava rocks on the Siberian Platform. The geological setting of the Nadayansky unit in the lava sequence is shown in Fig. 2a.

RESULTS AND DISCUSSION

Structure of the Morongovsky and Mokulaevsky Formations

In the Norilsk area and Putorana Plateau, rocks of the Morongovsky and Mokulaevsky formations are well exposed at the surface and are also drilled through by holes in the former area. The petrology and geochemistry of the rocks are described in (Dodin, 1964; Zolotukhin et al., 1978, 1986; Lightfoot et al., 1990, 1993; Fedorenko et al., 1996; Krivolutskaya and Rudakova, 2009; Sluzhenikin et al., 2014). We have studied in much detail the vertical sections of these formations and the Nadayansky Flow in the basin of the Mikchangda River (Fig. 2b), in the valley of the Southern Iken River, a right-hand tributary of the

Mikchangda River, and along Kotogor and Poteryannyi streams, which are tributaries of the former river.

The whole vertical section of the Morongovsky Formation crops out in the valley of Kotogor Stream and comprises 21 lava flows (samples 126–4031, Figs. 2b, 2c). The thicknesses of the individual lava sheets (which are sometimes referred to as lava flows, which is not fully warranted as not reflecting their areal extent) varies from 10 to 37 m, and the total thickness of the formation is 320 m. The rocks are aphyric (73% of the overall rock volume) or plagiophyric, occasionally glomerophyric massive basalts. The lowest amygdaloidal zones are 20–30 cm thick, whereas the upper ones are as thick as a few meters (Figs. 2c, 2d). Two psammite tuff units were found in the course of fieldwork. It is quite probable that the number of the thin tuff units is actually greater, but these rocks only poorly crop out. The pyroclastic rocks make up no more than 10% of the total volume of the formation.

The volcanic rocks of the Morongovsky Formation consist of plagioclase, pyroxenes, and more rare olivine; and the minor minerals are ilmenite, titanomagnetite, chalcopyrite, pyrrhotite, and occasional pentlandite and pyrite. The phenocrysts of the porphyritic basalts are rare plagioclase crystals or their aggregates (glomerophyric varieties of the rocks), and the groundmass is doleritic, as is also typical of aphyric basalts.

The composition of the plagioclase phenocrysts varies from An_{63} to An_{75}, whereas the groundmass plagioclase ranges from An_{44} to An_{77} (mostly from An_{55} to An_{65}, Table 1 in the Supplement). Pyroxenes occur in the intergranular space between plagioclase laths, and Mg# of the clinopyroxene broadly varies from 51 to 87, and Mg# of the orthopyroxene is 57 to 63 (Table 2 in the Supplement). Olivine was found only in three flows (whose rocks contain 1–3 vol % of this mineral). The olivine is iron-rich and contains 43 to 47 mol % forsterite.

The *Mokulaevsky Formation* consists in this area of 19 lava sheets, whose total thickness is close to 400 m and which crop out in the valley of Poteryannyi Stream (Figs. 2b, 2d). The thicknesses of individual basalt flows vary more significantly than in the Morongovsky Formation: from 10 to 50 m. The formation is dominated by aphyric basalts (47%) and contains poikilophitic (27%) and glomerophyric (26%) basalts. No tuff beds were found in this formation. The plagioclase phenocrysts have the composition $An_{50.3}$ to $An_{84.4}$ (mostly An_{80-82}). The groundmass plagioclase occurs as laths and broad-tabular crystals, whose composition is principally as in the phenocrysts (Table 1 in the Supplement). The pyroxene is mostly clinopyroxene, Mg# = 59–83. The orthopyroxene has Mg# = 53–81 (Table 2 in the Supplement).

The compositions of rock-forming minerals in rocks of the Morongovsky and Mokulaevsky formations are practically exactly identical. This is most obvious for the plagioclase phenocrysts (Figs. 3a, 3b), which are strongly dominated by labradorite An_{67-70}. The groundmass plagioclase has a closely similar composition (Figs. 3a, 3d), although data on the Morongovsky Formation are scarcer than on the Mokulaevsky Formation. Pyroxenes of the Mokulaevsky Formation are slightly more magnesian, with most common values of Mg# = 77–83 (Figs. 3e, 3f), whereas these values for the Morongovsky Formation are Mg = 77–79.

General Characteristics of the Nadayansky Flow

The Nadayansky Flow in the bottom part of the Mokulaevsky Formation is a lava sheet of tholeiites 20–30 m thick in the Norilsk area and up to 100 m in the eastern Putorana Plateau (Starosel'tsev, 1989), shows obvious columnar parting (Krivolutskaya, 2014), and consists of glomerophyric rocks (Figs. 4a, 4b), which make it different from the under- and overlying rock units. The glomerophyric plagioclase aggregates are as large as 5–8 mm and account for up to 20% of the rock by volume (Figs. 4a, 4d). It is the size and content of these aggregates that make these rocks different from the other glomerophyric varieties in the Mokulaevsky Formation, in which these aggregates are no larger than 2–3 mm and make up no more than 3% of the rocks by volume (the rocks with single glomerophyric aggregates are referred to as oligoglomerophyric; Fig. 2). The groundmass has a plane-parallel, ophitic, or sometimes poikilophitic texture (Figs. 4e, 4f). The flow sometimes includes a thin (15–20 cm) tuff bed in the bottom part and is overlain by fine-crystalline massive and rare-porphyritic basalts of the Mokulaevsky Formation (single plagioclase crystals 1–2 mm and make up 1–3 vol % of the rock).

The major rock-forming minerals are the same as in the Mokulaevsky Formation: plagioclase, clinopyroxene, and orthopyroxene; the minor minerals are ilmenite and titanomagnetite; and the rare minerals are sulfides (pyrrhotite and chalcopyrite). The plagioclase is often saussuritized, and the pyroxenes are usually fresh. The only phenocrysts are large tabular plagioclase crystals up to 5–6 mm long, which often form aggregates of three to four grains with clearly seen twins (Figs. 4c, 4d). The crystals are unzoned. Their composition is analogous to that of phenocrysts in other basalts of the Mokulaevsky Formation (Table 1 in the Supplement). The groundmass consists of plagioclase laths (An_{55-81}), anhedral clinopyroxene (Mg# = 61–78), whose composition varies from $Wo_{12}En_{34}Fs_{54}$ to $Wo_{37}En_{14}Fs_{49}$ (Table 2 in the Supplement), and platy or dendritic ilmenite crystals. The sulfides are constrained to fractures in rock-forming minerals or to intergranular space in between.

Chemical Composition of Rocks of the Morongovsky and Mokulaevsky Formations

The chemical compositions of rocks in the examined vertical sections of the formations (Figs. 2c, 2d) and the composition of the Nadayansky Flow are pre-

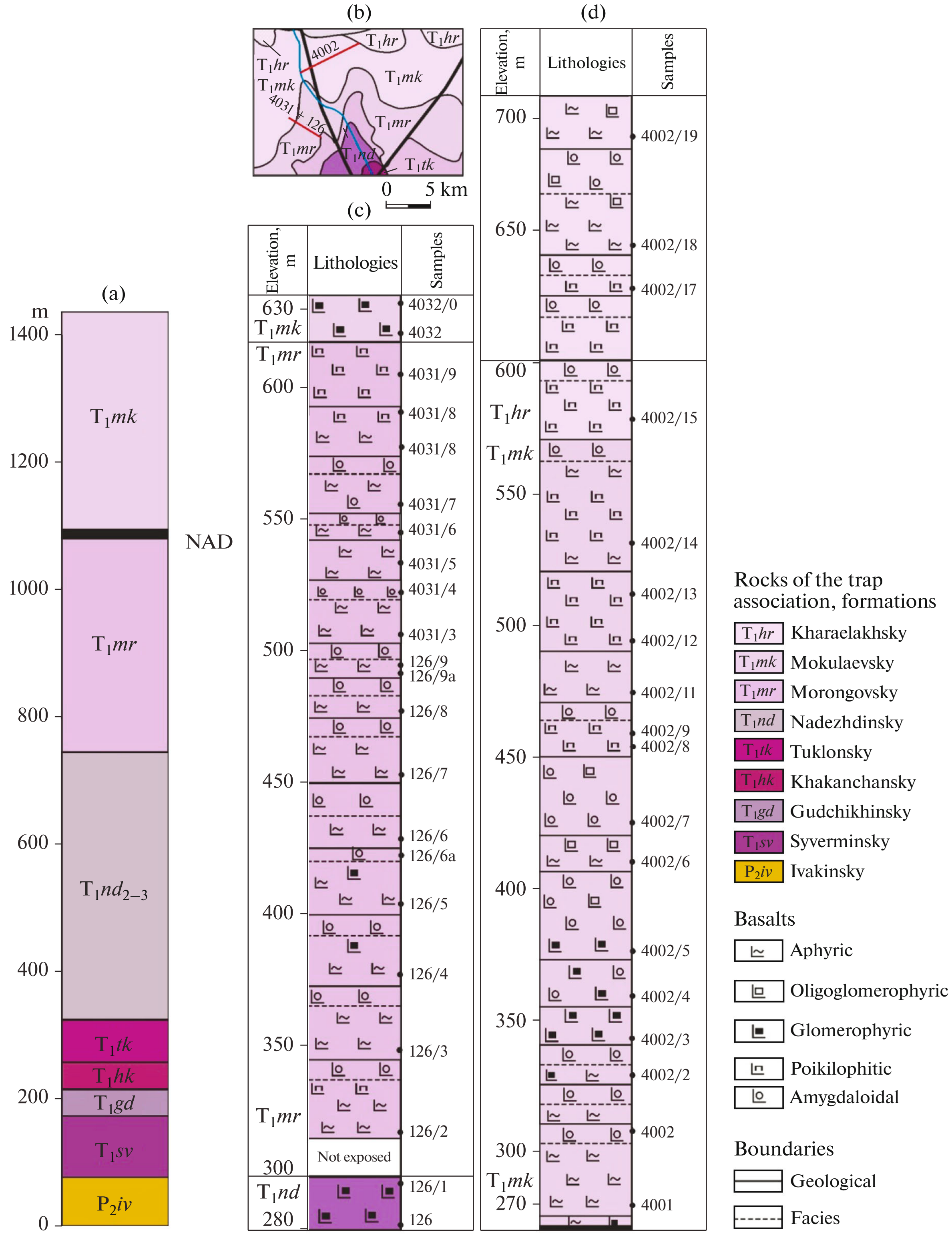

Fig. 2. (a) Geological sections showing the Nadayansky Flow (NAD) in the bottom portion of the Mokulaevsky Formation (NAD is shown as a heavy black line); (b) schematic map showing the location of the studied geological sections in the valley of the Iken River; (c, d) geological sections of the Morongovsky and Mokulaevsky formations.

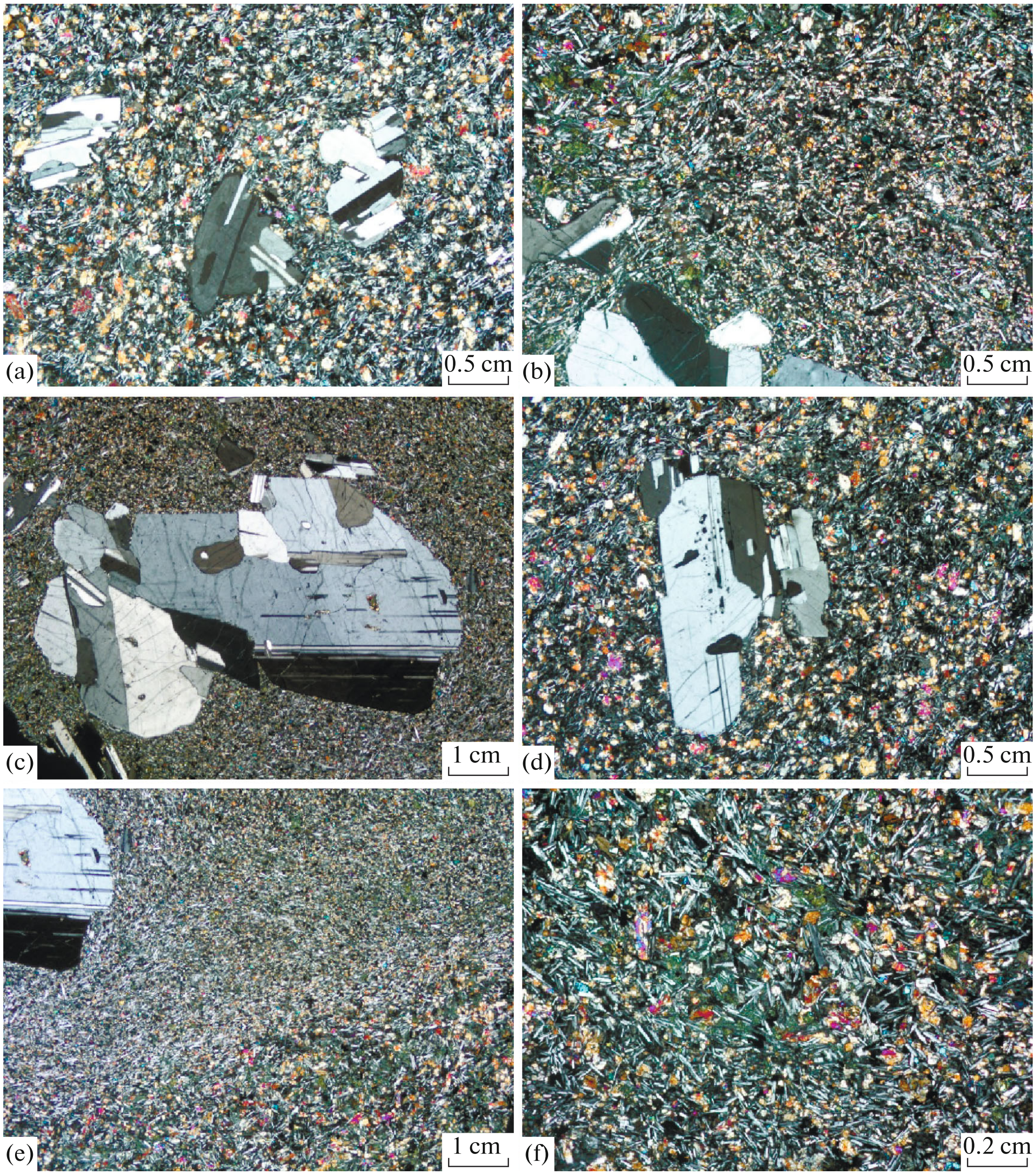

Fig. 3. Micrographs of basalts from the Nadayansky Flow: (a, b) porphyritic textures of the rocks; (c, d) glomerophyric plagioclase aggregates; (e, f) plane-parallel groundmass structure.

sented in Table 1. The minimum and maximum values and the standard deviations (*RSD*, %) of the compositions of the stratigraphic units are reported in Table 3 in the Supplement, which also lists oxide concentrations normalized to 100 wt %. The rocks are typical tholeiites of normal alkalinity, with Na dominating over K (Na_2O/K_2O = 4.96–11.88), as is typical of the central part of the Siberian Trap Province. The main reason for the significant variations in the concentrations of alkalis is secondary alterations of the rocks. The major-component concentrations vary as follows (wt %): 46.18–49.97 SiO_2, 0.92–1.38 TiO_2, 14.54–15.98 l_2O_3, 10.34–13.19 Fe_2O_3, 0.16–0.23 MnO, 5.97–7.73 MgO, 10.62–11.86 CaO, 1.96–2.38 Na_2O, 0.17–0.53 K_2O, 0.12–0.16 P_2O_5.

The Nadayansky Flow is characterized by a very little varying composition throughout its whole length and in vertical section. The variations in the concentrations of most major components are smaller than the relative inaccuracies of XRF analysis (Table 3 in the Supplement). The only exceptions are iron and potassium, for which RSD are 4.1 and 27 relative %, respectively (the values for the standard reference samples are 2.1 and 16 relative %). The composition of the flow also varies very insignificantly in its vertical section, as seen from the concentrations of major com-

Table 1. Composition of volcanic rocks from the Morongovsky and Mokulaevsky formations

Component	Consecutive number									
	1	2	3	4	5	6	7	8	9	10
	Sample									
	81-63	81-64	81-65	81-145	83-33	83-35	86-35a	83-36	83-37	83-38
SiO_2	48.08	48.08	47.99	47.4	48.44	48.83	47.92	48.95	48.49	48.67
TiO_2	1.38	1.32	1.34	1.3	1.31	1.3	1.22	1.28	1.34	1.28
Al_2O_3	14.96	14.89	14.8	15.13	15.27	15.35	15.06	15.37	14.94	15.26
Fe_2O_3	13.06	13.19	13.1	12.75	13.01	12.95	12.52	12.79	13.18	12.99
MnO	0.20	0.20	0.19	0.20	0.20	0.19	0.18	0.19	0.19	0.20
MgO	6.78	7.07	7.14	6.41	6.81	6.85	6.91	6.72	6.83	6.89
CaO	10.94	11.01	10.82	11.27	11.24	11.08	11.24	10.99	11.01	11.1
Na_2O	2.29	2.31	2.16	2.12	2.38	2.3	2.22	2.32	2.38	2.34
K_2O	0.33	0.34	0.31	0.26	0.32	0.4	0.27	0.45	0.47	0.37
P_2O_5	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.14
LOI	1.72	1.29	1.99	3	0.76	0.49	2.21	0.66	0.93	0.65
V	226	242	239	246	250	246	243	224	225	225
Cr	101	139	155	134	120	133	96	102	101	111
Ni	93	115	115	94	96	104	105	83	79	89
Cu	122	144	134	126	132	129	118	116	112	114
Zn	77	234	91	79	95	84	80	77	74	72
Rb	2.90	4.60	4.55	1.77	5.83	10.04	6.37	6.42	8.69	7.97
Sr	172	194	177	191	200	197	196	185	176	181
Y	20	21	21	21	21	21	21	20	20	19
Zr	78	80	81	80	81	82	86	78	75	75
Nb	3.25	3.34	3.22	3.46	3.56	3.48	3.90	3.25	3.14	3.18
Ba	122	198	186	119	150	225	144	189	141	120
La	6.99	7.48	6.89	7.16	7.33	7.40	8.53	7.01	6.95	6.89
Ce	17	17	16	17	17	17	20	17	16	16
Pr	2.40	2.47	2.37	2.37	2.50	2.42	2.72	2.40	2.37	2.34
Nd	10.8	11.1	10.8	10.8	11.2	11.0	11.7	10.8	10.5	10.5
Sm	3.22	3.11	3.04	3.16	3.26	3.21	3.32	3.08	3.04	3.06
Eu	1.14	1.14	1.13	1.15	1.17	1.16	1.13	1.17	1.12	1.08
Gd	3.85	3.85	3.78	3.76	3.90	3.91	3.92	3.88	3.74	3.65
Tb	0.64	0.63	0.65	0.63	0.66	0.64	0.62	0.62	0.64	0.63
Dy	4.31	4.26	4.11	4.19	4.36	4.28	4.23	4.35	4.29	4.24
Ho	0.89	0.87	0.87	0.89	0.90	0.90	0.88	0.92	0.90	0.86
Er	2.49	2.45	2.41	2.45	2.46	2.45	2.48	2.48	2.44	2.43
Tm	0.36	0.36	0.35	0.37	0.37	0.37	0.36	0.36	0.37	0.36
Yb	2.39	2.33	2.37	2.42	2.42	2.43	2.32	2.46	2.41	2.43
Lu	0.36	0.35	0.34	0.36	0.38	0.35	0.35	0.37	0.36	0.36
Hf	2.25	2.17	2.20	2.26	2.26	2.18	2.31	2.30	2.15	2.15
Ta	0.23	0.24	0.24	0.26	0.27	0.24	0.28	0.23	0.23	0.25
Pb	1.69	16.86	2.17	1.69	2.67	1.91	1.98	2.96	1.59	1.78
Th	1.05	1.16	1.02	1.09	1.09	1.13	1.37	1.13	1.10	1.12
U	0.38	0.40	0.33	0.44	0.46	0.45	0.54	0.47	0.46	0.45

Table 1. (Contd.)

Component	Consecutive number									
	11	12	13	14	15	16	17	18	19	20
	Sample									
	83-39	83-40	83-41	83-42	83-43	84-45	84-65	1001	1001/1	1001/2
SiO_2	48.62	48.5	48.11	48.71	48.32	48.35	48.57	48	47.9	47.86
TiO_2	1.31	1.29	1.32	1.22	1.19	1.27	1.28	1.3	1.3	1.29
Al_2O_3	15.36	15.12	14.8	14.61	14.54	15.06	15.16	15	15.01	15.23
Fe_2O_3	12.93	12.93	13.13	12.35	12.22	12.86	13.03	12.8	12.83	12.71
MnO	0.19	0.19	0.19	0.19	0.18	0.19	0.20	0.19	0.19	0.19
MgO	6.65	6.88	6.81	7.16	7.16	6.91	6.98	7.1	6.97	6.9
CaO	11.14	11.09	11.11	11.58	11.85	10.94	11.07	10.7	10.79	10.82
Na_2O	2.35	2.33	2.23	2.11	2.02	2.33	2.36	2.15	2.18	2.19
K_2O	0.33	0.24	0.33	0.19	0.17	0.44	0.42	0.44	0.44	0.43
P_2O_5	0.14	0.14	0.14	0.13	0.13	0.14	0.14	0.14	0.15	0.14
LOI	0.86	1.18	1.54	1.59	2.01	1.39	0.63	2.13	2.12	2.13
V	235	242	221	231	213	237	234	220	227	222
Cr	103	115	105	121	108	115	136	110	117	113
Ni	85	92	87	100	90	91	91	85	91	87
Cu	119	118	121	111	98	120	115	108	111	110
Zn	79	88	80	92	67	80	79	71	82	79
Rb	2.77	4.18	4.04	6.55	4.91	7.68	6.65	8.76	8.89	8.67
Sr	184	193	177	190	171	182	181	165	170	170
Y	20	20.2	19.4	19.2	18.1	20.2	19.8	19.0	19.2	18.9
Zr	78	77.9	74.9	73.4	69.2	77.6	75.2	72.1	73.6	71.6
Nb	3.30	3.34	3.15	3.09	3.00	3.37	3.20	3.05	3.27	3.10
Ba	123	160	117	175	113	166	156	176	147	112
La	11.70	7.13	6.90	7.09	6.57	7.04	6.95	6.67	6.78	6.62
Ce	26	17	16.2	16.3	15.3	16.6	16.3	15.8	15.9	15.6
Pr	3.33	2.40	2.36	2.31	2.17	2.36	2.32	2.25	2.30	2.26
Nd	13.8	10.7	10.5	10.3	9.7	10.5	10.5	10.2	10.2	10.4
Sm	3.53	3.14	3.06	2.75	2.85	3.05	3.07	3.02	2.97	2.98
Eu	1.21	1.12	1.06	1.06	1.01	1.12	1.10	1.08	1.08	1.09
Gd	4.09	3.71	3.72	3.63	3.29	3.62	3.70	3.63	3.70	3.75
Tb	0.66	0.63	0.61	0.59	0.58	0.63	0.61	0.61	0.62	0.62
Dy	4.38	4.18	4.16	4.03	3.78	4.18	4.14	4.09	4.19	4.08
Ho	0.89	0.88	0.86	0.83	0.81	0.87	0.86	0.85	0.87	0.88
Er	2.46	2.50	2.40	2.35	2.25	2.40	2.41	2.36	2.43	2.46
Tm	0.36	0.37	0.36	0.34	0.34	0.36	0.36	0.36	0.36	0.36
Yb	2.40	2.39	2.34	2.28	2.21	2.38	2.35	2.36	2.39	2.42
Lu	0.35	0.37	0.35	0.35	0.33	0.34	0.35	0.37	0.35	0.36
Hf	2.13	2.23	2.18	2.06	2.04	2.17	2.18	2.17	2.21	2.21
Ta	0.24	0.26	0.23	0.23	0.23	0.26	0.24	0.24	0.24	0.23
Pb	1.89	2.45	1.84	4.47	1.88	1.77	1.65	1.55	2.91	2.32
Th	1.10	1.09	1.09	1.13	1.06	1.09	1.09	1.06	1.07	1.04
U	0.45	0.48	0.44	0.45	0.43	0.44	0.44	0.46	0.46	0.44

Table 1. (Contd.)

Component	Consecutive number									
	21	22	23	24	25	26	27	28	29	30
	Sample									
	1001/3	1001/4	1001/6	1001/7	LM-14	4002	43	4002/2	4002/3	4002/4
SiO_2	48.27	48.1	47.96	47.77	48.58	49.71	48.50	49.71	49.48	48.65
TiO_2	1.23	1.27	1.25	1.31	1.22	1.22	1.27	1.22	1.22	1.29
Al_2O_3	15.22	15.06	15.05	15.08	15.16	15.98	15.10	15.98	15.73	15.24
Fe_2O_3	11.57	12.82	12.92	12.68	12.33	10.84	12.10	10.84	11.27	12.12
MnO	0.16	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.20	0.21
MgO	6.51	7.02	7.05	6.84	6.84	6.81	7.18	6.81	6.56	6.58
CaO	11.29	10.64	10.62	10.82	11.61	11.97	11.30	11.97	12.16	12.70
Na_2O	2.26	2.17	2.18	2.25	2.2	2.11	2.12	2.11	2.23	2.08
K_2O	0.53	0.44	0.44	0.44	0.28	0.23	0.53	0.23	0.32	0.24
P_2O_5	0.17	0.15	0.14	0.14	0.13	0.12	0.14	0.12	0.12	0.12
LOI	2.89	2.02	2.07	2.37	1.34	2.01	1.16	2.01	2.07	1.91
V	182	225	222	223	219	289	268	289.1	258.8	274.2
Cr	108	115	111	113	138	107	115	107	115	118
Ni	71	88	87	86	80	97	122	97.4	76.3	75.3
Cu	54	109	109	109	101	77.9	148.0	78	100	96
Zn	67	73	75	75	66	81	100	81	198	170
Rb	5.71	8.84	8.68	8.79	3.13	2.24	9.48	2.24	3.68	2.37
Sr	222	166	164	168	171	217	181	217	214	213
Y	19.8	19.2	19.0	19.2	18.3	25.6	23.8	25.6	25.2	24.6
Zr	81.1	74.5	72	74	68	87	86	87	84	83
Nb	4.26	3.56	3.05	3.1	2.92	4.68	5.06	4.68	4.32	4.39
Ba	203	143	133	123	93	126	127	126	124	136
La	10.60	6.90	6.62	6.65	6.30	7.03	7.96	7.03	6.63	7.12
Ce	23.1	16.2	15.7	15.7	14.9	17.1	17.8	17.1	16.0	16.9
Pr	3.07	2.33	2.26	2.28	2.17	2.33	2.52	2.33	2.20	2.31
Nd	12.6	10.4	10.2	10	9.9	10.7	11.8	10.7	10.4	10.5
Sm	3.16	3.03	2.96	3.11	2.92	2.99	3.26	2.99	2.87	2.89
Eu	1.06	1.08	1.08	1.06	1.04	1.00	1.05	1.00	0.97	0.98
Gd	3.71	3.71	3.60	3.69	3.57	3.37	3.43	3.37	3.41	3.39
Tb	0.62	0.62	0.61	0.61	0.61	0.58	0.68	0.58	0.58	0.58
Dy	4.20	4.10	4.11	4.17	4.09	3.86	4.16	3.86	3.87	3.82
Ho	0.89	0.88	0.84	0.88	0.87	0.87	0.84	0.87	0.88	0.86
Er	2.51	2.44	2.38	2.47	2.34	2.31	2.52	2.31	2.28	2.23
Tm	0.38	0.36	0.36	0.36	0.34	0.34	0.37	0.34	0.34	0.33
Yb	2.58	2.44	2.37	2.44	2.28	2.18	2.35	2.18	2.16	2.11
Lu	0.39	0.35	0.35	0.36	0.33	0.32	0.35	0.32	0.32	0.31
Hf	2.29	2.22	2.11	2.21	2.03	2.13	2.48	2.13	2.13	2.08
Ta	0.28	0.26	0.22	0.23	0.21	0.26	0.28	0.26	0.25	0.24
Pb	2.43	1.68	2.42	1.59	1.39	0.01		2.42	2.10	2.09
Th	1.73	1.11	1.05	1.09	1.00	0.01	1.17	1.12	1.02	1.04
U	0.87	0.50	0.44	0.46	0.40	1.12		0.39	0.37	0.49

Table 1. (Contd.)

Component	Consecutive number									
	31	32	33	34	35	36	37	38	39	40
	Sample									
	4002/5	4002/6	4002/7	4002/8	4002/11	4002/14	4002/15	126/2	126/3	126/4
SiO_2	49.20	48.82	49.24	47.71	48.97	49.46	49.46	47.3	48.12	48.35
TiO_2	1.25	1.258	1.28	1.30	1.31	1.34	1.38	1.19	1.11	1.13
Al_2O_3	15.83	15.43	15.56	15.33	15.44	15.7	15.75	15.7	15.29	15.25
Fe_2O_3	11.56	11.65	11.66	11.62	11.66	11.9	11.6	12.5	11.69	12.37
MnO	0.21	0.192	0.196	0.182	0.212	0.208	0.2	0.2	0.19	0.21
MgO	6.56	6.71	6.9	6.65	6.97	7.02	6.81	7.2	7.31	7.72
CaO	12.36	11.61	11.41	11.23	11.46	11.15	11	11.4	11.87	11.77
Na_2O	2.06	2.15	2.14	2.13	2.17	2.16	2.18	2.2	2.00	2.00
K_2O	0.17	0.34	0.38	0.22	0.21	0.34	0.41	0.4	0.23	0.42
P_2O_5	0.12	0.125	0.12	0.12	0.129	0.126	0.135	0.15	0.13	0.13
LOI	1.60	2.23	1.75	4.2	2.26	1.34	2.09	2.00	2.15	1.30
V	272.5	287	291	285	267	277	259	269	266	262
Cr	101	115	111	110	129	127	93	169	157	116
Ni	78	91	89	100	91	102	90	154	151	169
Cu	89	81	106	95	104	116	94	102	92	95
Zn	76	81	81	84	125	85	80	79.6	77.4	79.8
Rb	1.96	3.38	8.17	1.57	1.50	4.74	6.80	10.1	3.7	10.5
Sr	210	199	193	197	198	205	194	182.5	182.8	165.6
Y	23.8	25.1	25.2	26.4	25.5	26.6	26.9	24.3	22.9	23.4
Zr	80	84	84.1	90.2	86.6	90.0	93.2	85.0	83.6	80.3
Nb	4.23	3.94	4.14	4.63	4.60	4.36	2.68	5.01	4.96	4.62
Ba	108	130	130	113	135	131	136	139.2	123.8	113.6
La	6.39	6.72	6.73	6.88	6.67	7.01	7.28	7.1	7.6	6.9
Ce	15.4	16.5	16.5	16.8	16.4	17.0	17.9	16.8	17.7	16.2
Pr	2.10	2.22	2.26	2.34	2.28	2.37	2.43	2.3	2.3	2.2
Nd	9.82	10.4	10.3	10.9	10.9	11.0	11.5	10.6	10.4	9.9
Sm	2.74	3.02	3.04	3.07	3.01	3.08	3.22	2.89	2.68	2.76
Eu	0.93	0.98	0.99	1.05	1.02	1.05	1.08	0.98	0.89	0.93
Gd	3.14	3.42	3.35	3.63	3.41	3.55	3.63	3.28	3.08	3.21
Tb	0.54	0.58	0.59	0.62	0.60	0.61	0.63	0.58	0.53	0.56
Dy	3.54	3.93	3.93	4.11	3.87	4.02	4.10	3.76	3.45	3.61
Ho	0.82	0.86	0.88	0.93	0.88	0.93	0.93	0.86	0.79	0.84
Er	2.16	2.29	2.31	2.41	2.28	2.36	2.43	2.30	2.08	2.24
Tm	0.32	0.34	0.34	0.36	0.35	0.35	0.36	0.33	0.31	0.33
Yb	1.99	2.11	2.14	2.30	2.16	2.25	2.29	2.15	1.93	2.08
Lu	0.30	0.32	0.31	0.34	0.32	0.33	0.33	0.32	0.29	0.31
Hf	1.95	2.13	2.14	2.35	2.13	2.26	2.33	2.15	2.04	2.05
Ta	0.23	0.19	0.20	0.27	0.25	0.23	0.09	0.28	0.27	0.26
Pb	2.03	2.32	2.40	1.84	9.80	2.00	2.07	1.86	2.30	1.86
Th	0.94	0.97	0.98	1.02	0.97	1.05	1.08	1.13	1.34	1.15
U	0.37	0.34	0.33	0.36	0.49	0.36	0.33	0.38	0.47	0.43

Table 1. (Contd.)

Component	Consecutive number							
	41	42	43	44	45	46	47	48
	Sample							
	126/5	126/7	126/8	126/9a	4031	4031/3	4031/6	4031/17
SiO_2	48.67	48.87	48.1	46.18	49.66	46.86	49.09	49.97
TiO_2	1.17	1.16	1.04	0.928	1.25	1.186	1.162	1.133
Al_2O_3	15.38	15.51	15.6	15.29	15.76	15.06	15.6	15.74
Fe_2O_3	12.13	12.09	11.5	10.34	11.62	11.87	11.34	11
MnO	0.21	0.22	0.2	0.164	0.205	0.203	0.196	0.194
MgO	7.33	7.01	6.0	7.52	6.93	7.3	6.88	6.94
CaO	11.10	11.44	11.8	11.68	11.36	11.82	11.78	11.54
Na_2O	2.18	1.98	2.03	1.93	1.16	2.10	2.04	2.12
K_2O	0.49	0.29	0.29	0.29	0.36	0.39	0.17	0.39
P_2O_5	0.16	0.15	0.19	0.098	0.127	0.143	0.126	0.13
LOI	1.68	1.74	2.34	5.42	1.57	2.95	2.31	2.69
V	281	272	211	228	262	270	288	283
Cr	194	118	75	273	113	83	90	90
Ni	152	128	75.3	104	87	92	107	100
Cu	106	114	44.3	55	61	80	98	89
Zn	84.2	91.6	85.8	67	138	73	146	81
Rb	9.8	12.4	22.0	2.44	8.39	5.26	2.72	7.10
Sr	171.2	200.6	279.0	382	193	171	212	210
Y	25.4	27.8	30.2	16.0	25.8	25.2	26.0	25.5
Zr	86.8	95.5	116.8	55.7	87.9	82.9	91	88
Nb	5.00	5.55	8.59	3.12	4.90	4.68	5.53	5.41
Ba	122.6	163.9	316.7	57	155	119	105	85
La	7.2	8.4	15.3	5.80	7.54	7.20	7.63	7.58
Ce	17.3	19.9	32.7	13.0	17.9	16.9	17.8	17.8
Pr	2.3	2.7	4.0	1.69	2.42	2.30	2.38	2.38
Nd	10.9	12.2	16.6	7.7	11.0	10.4	10.9	10.7
Sm	2.98	3.31	3.70	2.08	2.98	2.85	2.92	2.97
Eu	0.98	1.13	1.10	0.80	1.00	0.95	0.98	0.97
Gd	3.43	3.94	4.11	2.36	3.33	3.33	3.41	3.39
Tb	0.61	0.68	0.70	0.40	0.59	0.57	0.59	0.59
Dy	3.96	4.44	4.73	2.67	3.80	3.82	4.04	3.82
Ho	0.92	1.01	1.07	0.61	0.86	0.87	0.92	0.88
Er	2.46	2.73	2.98	1.60	2.33	2.31	2.38	2.36
Tm	0.35	0.39	0.45	0.23	0.34	0.34	0.36	0.35
Yb	2.26	2.56	2.91	1.52	2.22	2.18	2.29	2.23
Lu	0.33	0.38	0.44	0.21	0.32	0.32	0.34	0.33
Hf	2.22	2.54	2.85	1.56	2.14	2.10	2.21	2.15
Ta	0.29	0.34	0.47	0.18	0.25	0.22	0.32	0.29
Pb	1.94	2.06	3.97	1.35	9.47	1.24	12	1.99
Th	1.21	1.28	2.58	0.70	1.16	1.11	1.27	1.19
U	0.49	0.49	1.14	0.17	0.43	0.37	0.51	0.49

Concentrations of major oxides are in wt %, elements are in ppm. Rocks: (1–27) Nadayansky Flow, (28–37) Mokulaevsky Formation, (38–48) Morongovsky Formation.

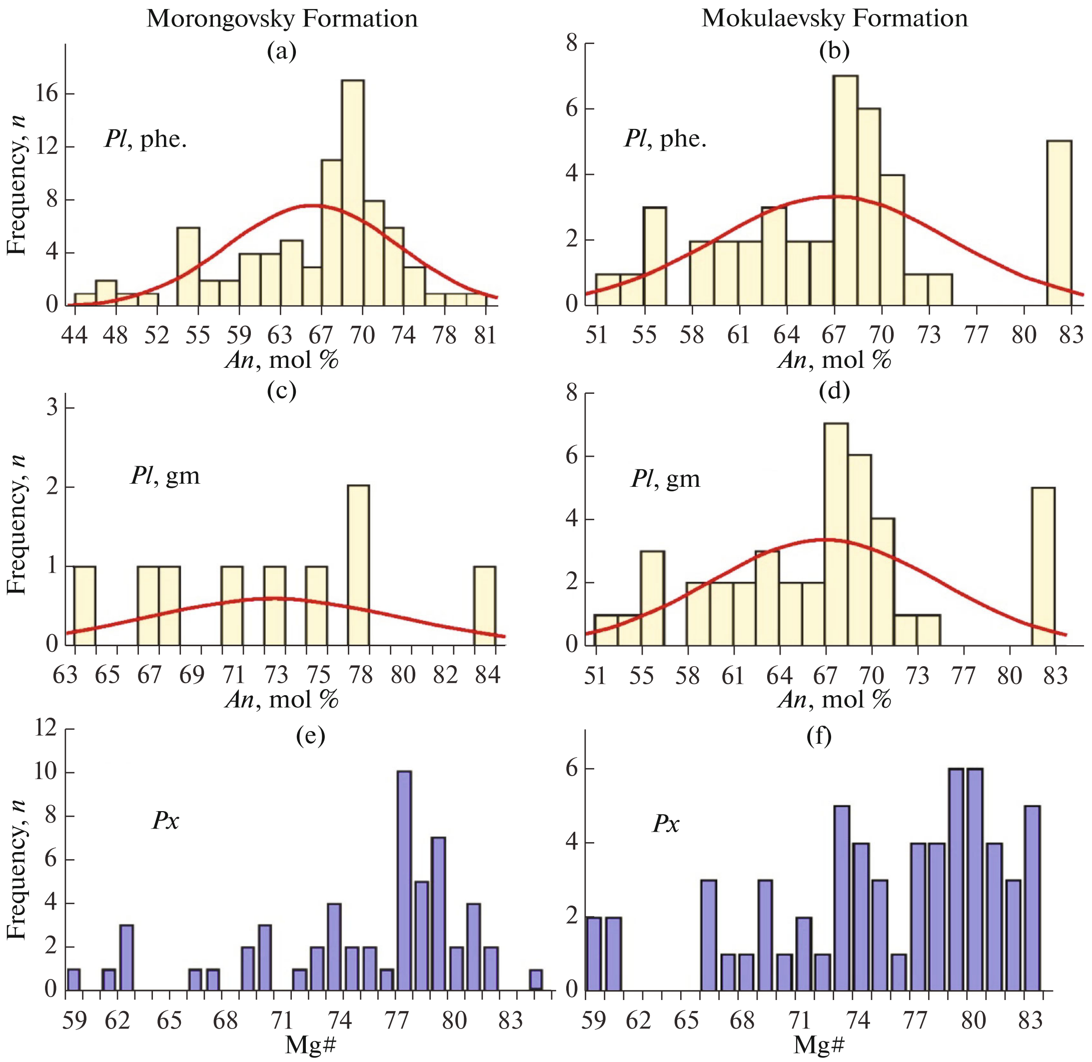

Fig. 4. Histograms of the compositions of minerals in basalt of (a)–(c) the Morongovsky Formation and (d)–(f) Mokulaevsky Formation; *Pl* phe—*Pl* phenocrysts, *Pl* gm—groundmass plagioclase, *Px*—pyroxenes, *An*, mol %—anorthite mole fraction in plagioclase, Mg#—Mg mole fraction of pyroxene (100 × MgO/(MgO + FeO).

ponents in samples from the bottom and top parts of this flow (Table 1, samples 1001, 1001/1, and 1001/2).

Although the rocks of the Morongovsky and Mokulaevsky formations are very similar (Table 1), their compositions still show certain differences, which are used in surveying. The differences between these formations are particularly significant in their TiO_2 concentrations (Fig. 5a): the basalts of the Morongovsky Formation contain <1.2 wt % TiO_2, whereas the rocks of the Mokulaevsky Formation contain >1.2 wt % TiO_2 (this also pertains to the Nadayansky Flow, whose rocks contain 1.2 wt % TiO_2 on average). The differences in the concentrations of other major components are very small, and those for Al_2O_3 and CaO are shown in Figs. 5b and 5c.

Concentrations of trace elements in the rocks of the Nadayansky Flow vary within the analytical errors for most elements (we have analyzed the rocks for 38 elements). Variations greater than the analytical inaccuracies are typical of the transition metals (Cu, Ni, Zn, V, and Cr), LILE (Cs, Ba, and Rb), and sometimes also of LREE (La, Ce, and Pr), U, Th, and Pb. The base-metal concentrations (first of all, those of Cu) in the basalts are controlled mostly by the concentrations of sulfides, which are unevenly distributed in the rocks. The concentrations of such elements as Ba, Rb, etc. may have been modified by overprinted hydrothermal processes. The Morongovsky and Mokulaevsky formations (including the Nadayansky Flow) differ from one another in the La/Sm ratio (Fig. 5d).

The complete comparison of the three datasets (those on the Nadayansky Flow and on the Mokulaevsky and Morongovsky formations, which are denoted as NAD, MOR, and MOK, respectively, below) was carried out with the application of single-factor variance analysis and using the Statistica 13.3 RUS (TIBCOSoftwareInc., Tulsa, United States)

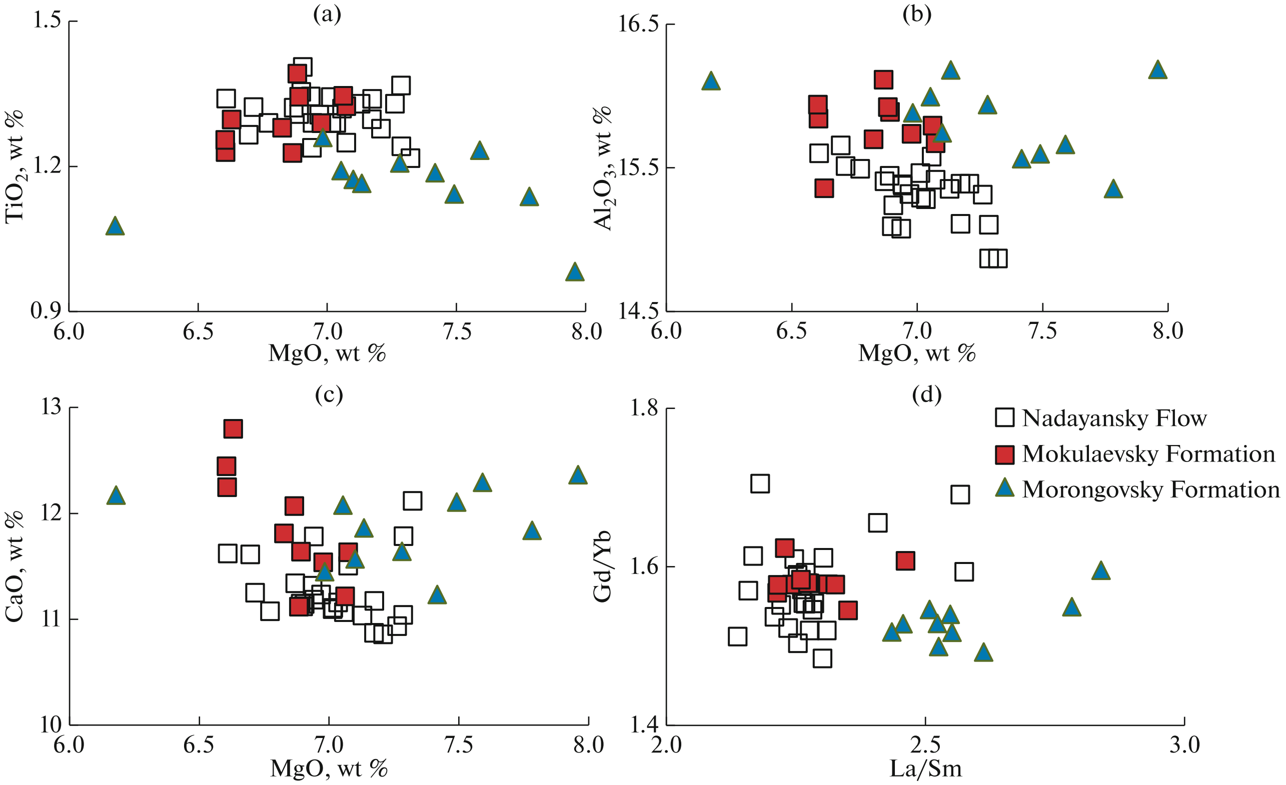

Fig. 5. (a) MgO–TiO_2, (b) MgO–Al_2O_3; (c) MgO–CaO, and (d) La/Sm–Gd/Yb diagrams for rocks of the Nadayansky Flow, Morongovsky Formation, and Mokulaevsky Formation.

software (Table 4 in the Supplement). The Shapiro–Wilk test was used to estimate the normality of the distributions of values for each of the datasets. Because the values were ($p > 0.05$) and indicated that the distributions are not normal, the further analysis was conducted using logarithms of the concentrations.

Samples from each of the sets ($n = 27$ for NAD, 11 for MOK, and 11 for MOR) were regarded as imaginary replications and were used to form the average values. Differences between the average concentrations of major components and trace elements in the datasets were analyzed using the Tukey test. The statistical hypotheses were tested at 0.05p.

The generalized linear models (GLM) reveal significant differences between the datasets depending on concentrations of elements ($p < 0.002$). The maximum differences in concentrations of major oxides were determined (Table 2 in the Supplement) for TiO_2, SiO_2, Fe_2O_3, and CaO. Among trace elements, the greatest differences were determined for Co, V, Nb, REE (Eu, Gd, and Yb), Y, and Th, as is seen in the La/Sm–Gd/Yb diagram, in which the composition points of the rocks of the Morongovsky Formation plot away from the points of the Mokulaevsky Formation (including the Nadayansky Flow).

CONCLUSIONS

Although the Siberian traps have long been studied, their geochemical features are still understood inadequately poorly, particularly at a regional scale. Extensive reviews in which vertical sections of the rocks in different structural zones of the Siberian Trap Province were correlated dealt mostly with the tuff–lava sequence and selectively considered rock compositions from some areas (Zolotukhin et al., 1984, 1986, 1989). Extensive high-precision data have been acquired on rocks in the Norilsk area (Lightfoot et al., 1990, 1993, 1994; Fedorenko et al., 1996). However, no comparison of the chemical compositions of rocks from certain formations, including their individual lava flows and sheets, has ever been conducted.

We were the first to acquire data on the composition of the Nadayansky Flow in studying the compositional homogeneity of the basalts of the trap association. We have demonstrated that the glomerophyric basalts have a very little varying composition: this pertains to the concentrations of practically all major oxides and main trace elements. Our results demonstrate the potentialities of using geochemical data for correlating widely spaced vertical sections of volcanic rocks.

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