

Siberian Traps in the Norilsk Area: A Corrected Scheme of Magmatism Evolution

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Abstract. To understand the origin of the Siberian Traps it is necessary to know the evolution of magmatism in space and time inside the Siberian Platform. It was suggested that volcanic rocks were formed in three stages: rift (OIB), intermediate and trap (WPB). It was studied rocks of the Tuklonsky, Nadezhdinsky and Morongovsky suits in the western part of the Norilsk area and found that they have no intermediate geochemical characteristics (major components and rare elements, especially La/Sm ratios) between OIB and WPB. Therefore, there are only two main stages in the magmatism evolution as the actual trapping stage began from Tuklonsky time.

1. Introduction

To understand the origin of Large Igneous Provinces (LIP), the history of magmatism evolution in space and time has to be known. The Siberian Traps represent the most important object for such study due to their huge volume and the presence of unique PGE-Cu-Ni deposits in the Norilsk area. This region is characterized by a strong contrast sequence of tuff-lava rocks (3.5 km) formed during a short period [1]. Much geological and geochemical data have been obtained since 1960s [2-7] that allowed reconstructing the history of trap volcanism [8-11]. The most widespread model [12] includes three stages of the volcanic rocks' formation: oceanic islands (OIB), 'transit series' (intermediate between OIB and WPB) and intraplate (WPB). The so-called 'transit series of rocks' comprises of rocks with different geochemical parameters close to the latter type (Khakanchansky, Tuklonsky, Nadezhdinsky and Lower Morongovsky suites) but with varying contents of alkalis and LILE. In particular, it is typical of the Upper Nadezhdinsky and the Lower Morongovsky suites. In this regard, the beginning of the actual trap stage was referred to as the middle Morongovsky period.

Tuff-lava rocks around the Norilsk area have studied and found that the subdivision into three groups is not typical for this region. There are only two groups of rocks that have significant differences in both their widespread location and composition. It was shown previously of the Khakanchansky, Tuklonsky and Lower Nadezhdinsky suites [11]. In this paper the question of the relationship between rocks of the Upper Nadezhdinsky and the Lower Morongovsky suites is considering.



2. Geological background and methods of the study

The Norilsk area consists of carbonate-clastic (interbedded with anhydrite and salt) rocks of the Silurian-Devonian and sediments of the Tunguska Group (C₂-P₁). They are overlapped by volcanic rocks of trap formation (P₃-T₁). Ultrabasic-basic intrusions are mainly located in the Devonian rocks or in the lower basalt suits. The main tectonic structures are shown in Figure 1a. Volcanic rocks (basalt and tuffs) are subdivided into 11 suites [13], including the high-Ti (TiO₂ > 2-3 wt%) sub-alkaline basalts and picrites - Ivakinsky (iv), Syverminsky (sv), Gudchikhinsky (gd) and low-Ti (TiO₂ ≤ 1 wt%) tholeiitic basalts - Khakanchansky (hk), Tuklonsky (tk), Nadezhdinsky (nd), Morongovsky (mr), Mokulaevsky (mk), Kharayelakhsky (hr), Kumginsky (km) and Samoyedsky (sm). Tholeiitic basalts dominate in this sequence; they are very similar in terms of their texture and major components (especially hk, tk and nd suites). The boundaries between suites are fixed by trace elements contents and isotopic characteristics of rocks.

3. Objects and Methods of the study

For a detailed study of the 'transit series', volcanic rocks in the eastern part of the Norilsk region (Lake Glubokoe, Figure 1a) were selected. This area represents the junction of the Tunguska Syncline with Khantaysko-Rybninsky Swell developed on a different crystalline basement [14]. Determination of the concentrations of major and trace elements in volcanic rocks were carried out in two ways. The first one consists of definition of the major components with the help of X-ray fluorescence method at the Vernadsky Institute of Geochemistry and Analytical Chemistry RAS, and the distributions of trace elements in the samples were obtained using mass spectrometry with inductively coupled plasma (ICP-MS) in Geochemistry Institute of Mineralogy and Crystal Chemistry of Rare Elements (methodical bases are given in [15]). The second method was comprised of sintering rock powders for glass where the major components and trace elements were measured by EPMA and LA-ICP-MS [7].

4. Results and discussions

4.1. The structure of the tuff-lava sequences in the eastern part of the Norilsk area

The studied section of volcanic rocks (Figure 1) located in the eastern part of area (Lake Glubolcoe) begins from the rocks the Tuklonsky suit overlapping the Khakanchansky tuffs. The Tuklonsky suite consists of 8 poikilophytic, picritic and tholeiitic basalts. The thickness of this suite is 75 m. The Nadezhdinsky suite (156 m thick) is located on the Tuklonsky one and is subdivided into three subsuites (according textural features of the rocks): lower, middle and upper [13]. Lower subsuite in this section is not established (it appears only in the west of the territory). Middle subsuite is mainly composed of aphyric and porphyritic basalts. Upper member consists of three flows of glomeroporphyritic basalts (Figure 1b). The Morongovsky suite (> 400 m) completes the studied section (only its lower part is shown in Figure 1b). It is represented by plagioporphyritic basalts with fluidal texture.

4.2. The geochemical features of the volcanic rocks

The chemical composition of the studied volcanic rocks varies from basalts to andesite's (Table 1, only representative analyses are given), SiO₂ changes from 49.17 up to 53.46 wt.%. The total amount of alkalines ranges from 2.14 to 4.87 wt.% (Na₂O > K₂O). Significant differences between the suites are in the MgO content varying from 5.89 to 8.67 wt.%. Consequently, elevated SiO₂ and low TiO₂ (> 52 wt.% and < 1 wt.%) contents are typical of the Nadezhdinsky suit, whereas in the Morongovsky one, they are < 50 wt.% and > 1.1 wt.%. Trace elements patterns for the studied rocks (Figure 2a) indicate on the one hand their similarity ((low Ti content and Gd/Yb ratio, enrichment in incompatible elements, the presence of negative Ta-Nb, Eu and Ti anomalies), and on the other hand on their differences. The spectrum of distribution of rare elements in the Tuklonsky suite is located slightly below the spectra of overlying suits (partly due to elevated MgO content) but its topology is close to each one.

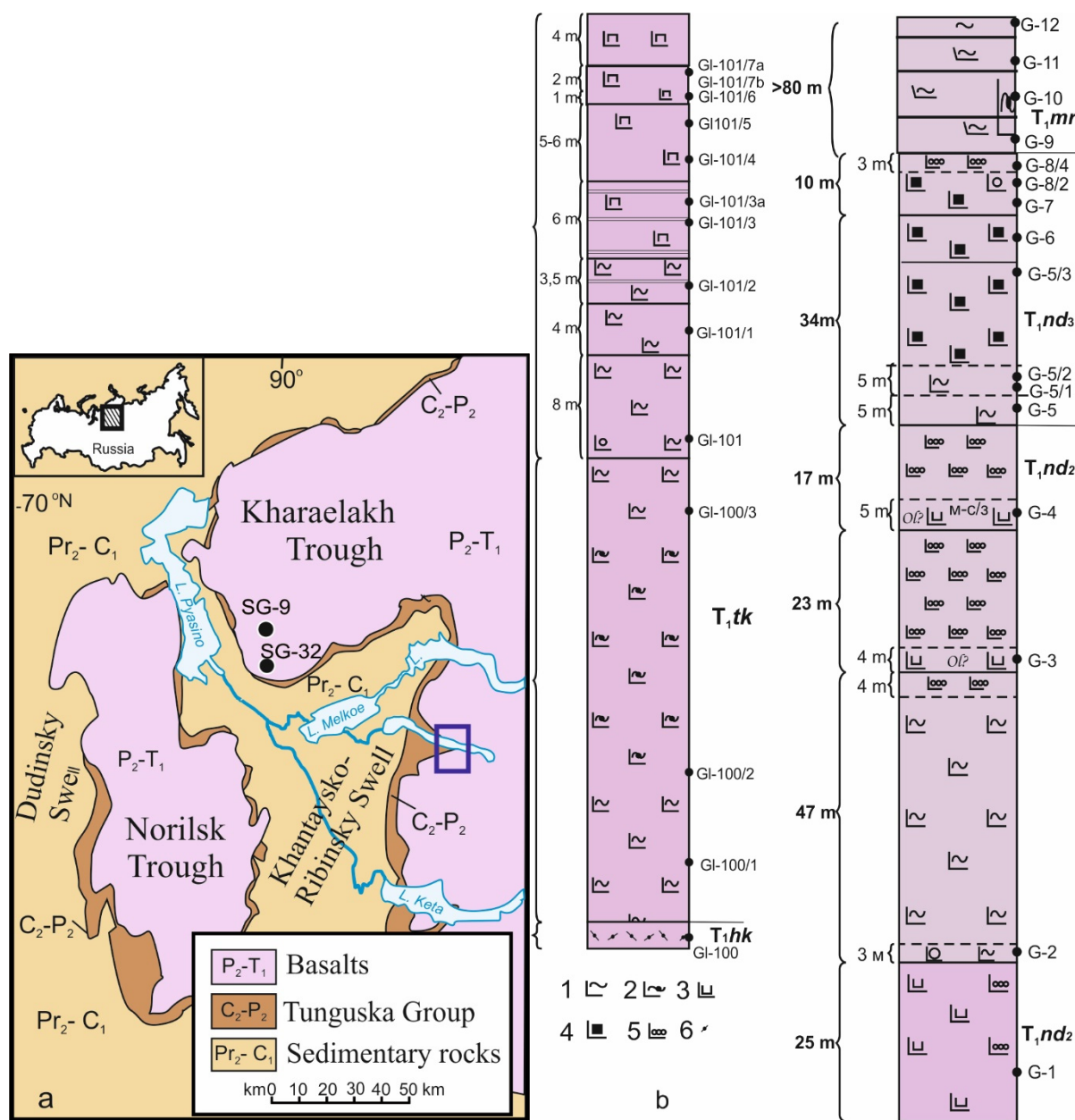


Figure 1. Geological schema of the Norilsk area (a) and sections of the studied basalts (b)

- a: SG-9, SG-32 – boreholes, blue rectangle shows studied area with sections of basalts in Figure 1b;
 b: 1-5- basalts: 1- aphyric, 2 - porphyric, 3-poikilophitic, 4-glomeroporphyric, 5-amigdable; 6 -tuffs,
 G-1- sample number

‘Transit’ series, comprising the upper Nadezhdinsky and lower Morongovsky suits [12], were formed between them at an intermediate stage and have transitional characteristics (Figure 2b). But this conclusion was made on the basis of geochemistry only from the boreholes SG-9 and SG-32 (Figure 1a) in the western part of the area. Nevertheless, the thickness and composition of basalts (especially for gd, nd and tk suits) vary significantly around the area [7, 10]. Usually, the Nadezhdinsky (as middle so upper subsuits, Figure 2a) and Morongovsky basalts have absolutely different compositions. They belong to the different stage of magmatism development – rift and trap (not both to trap, as was suggested by [9] – and their thicknesses increase in opposite directions, to west and east

correspondingly. Therefore, they do not characterize specific regime of an evolutionary intermediate stage.

Table 1. Chemical composition of the volcanic rocks (Lake Glubokoe)

Sample	Gl-100/1	G-1	G-5/1	G-7	G-8/2	G-9	G-10	G-11
SiO ₂	50.43	52.75	52.07	53.23	52.70	48.1	48.33	48.86
TiO ₂	1.02	0.97	0.97	1.05	0.96	1.12	1.13	1.25
Al ₂ O ₃	16.40	15.05	16.06	15.10	15.39	15.28	15.25	15.54
FeO	9.77	9.41	9.54	10.08	9.49	11.71	12.36	12.12
MnO	0.19	0.17	0.22	0.16	0.16	0.19	0.21	0.22
MgO	7.25	7.62	7.53	5.89	6.70	7.34	7.73	7.01
CaO	12.65	9.17	8.94	8.91	11.49	11.86	11.76	11.42
Na ₂ O	1.96	3.72	2.31	2.77	1.81	1.24	0.95	1.04
K ₂ O	0.25	0.42	1.68	1.94	0.46	0.19	0.44	0.57
P ₂ O ₅	0.09	0.11	0.12	0.11	0.10	0.13	0.13	0.15
Cr ₂ O ₃	-	-	-	-	-	0.012	0.009	0.022
Rb	2.9	11.1	50.9	72.3	6.9	7.24	4.42	4.02
Ba	144	280	639	495	324	154	156	144
Th	0.88	3.16	3.60	3.61	3.53	1.19	1.15	1.09
U	0.21	0.72	1.01	0.92	0.93	0.50	0.47	0.44
Nb	3.48	8.15	8.31	8.87	8.20	4.76	4.32	4.23
Ta	0.21	0.54	0.53	0.55	0.52	0.29	0.27	0.26
La	8.13	18.1	19.0	19.2	18.1	8.12	7.87	7.60
Ce	17.1	37.1	39.4	39.4	37.1	17.5	17.2	16.6
Pb	4.74	10.83	7.59	7.23	9.76	3.14	2.51	3.62
Pr	2.20	4.52	4.66	4.75	4.44	2.39	2.37	2.29
Nd	10.02	18.6	19.0	19.3	18.4	11.32	11.06	10.83
Sr	314	287	323	394	285	192	198	200
Sm	2.68	3.99	4.24	4.22	4.02	3.16	3.01	2.91
Zr	73.7	132	136	142	135	85.2	77.3	75.7
Hf	1.97	3.27	3.54	3.61	3.43	2.13	1.98	1.92
Eu	1.09	1.16	1.17	1.13	1.09	1.15	1.11	1.10
Gd	3.20	4.19	4.37	4.47	4.29	3.68	3.44	3.33
Tb	0.53	0.66	0.70	0.72	0.67	0.61	0.59	0.57
Dy	3.51	4.36	4.52	4.51	4.44	4.18	3.94	3.89
Ho	0.71	0.86	0.92	0.90	0.90	0.84	0.83	0.79
Y	19.3	23.7	25.1	24.8	24.7	21.9	21.1	20.4
Er	2.06	2.53	2.71	2.56	2.63	2.40	2.34	2.22
Tm	0.30	0.36	0.38	0.37	0.37	0.35	0.32	0.32
Yb	1.98	2.42	2.57	2.56	2.45	2.45	2.38	2.34
Lu	0.28	0.35	0.38	0.38	0.39	0.36	0.34	0.34

Note. Oxides are given in wt.%, elements – in ppm. No sample is in Figure 1b.

4.3. Discussion

The repeating in the development of magmatism in the Norilsk region was emphasized by many researchers [2, 5]. The most popular model includes two main stages of basalt origin: the oceanic islands

OIB (high Ti content and Gd/Yb ratio, Ivakinsky-Gudchihinsky suites) and intraplate WPB including ‘transit series of rocks’. Indeed Nadezhdinsky suit differs by enrichment in incompatible elements (in particular, the high (La/Sm)_n ratio, fluctuating from 2.59 to 2.88) and positive Sr anomaly. Morongovsky suite is characterized by lower enrichment in rare elements ((La/Sm)_n = 1.62-1.70).

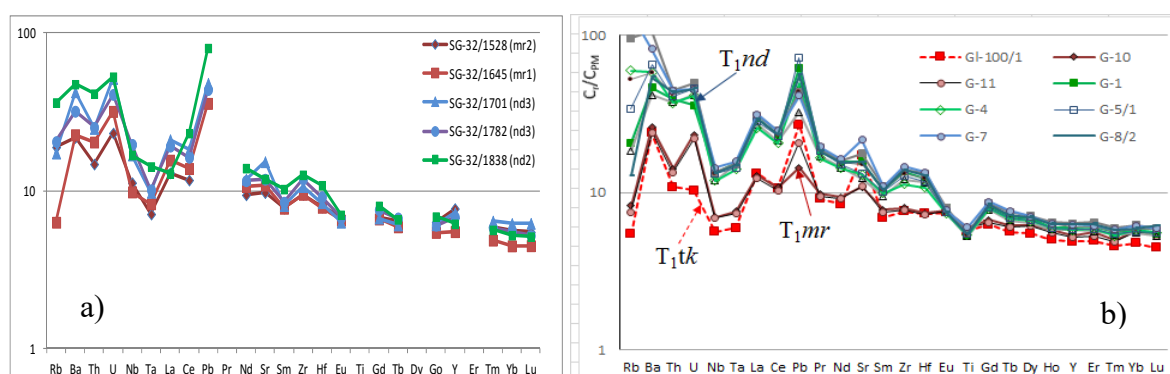


Figure 2. Patterns for rocks of different suits (normalized to primitive mantle [16]): a) after [12], b) studied rocks; lines, suites: red – tk, green - nd₂, blue – nd₃, brown – mr.

5. Conclusions

This study shows that the rocks form the upper Nadezhdinsky and the lower Morongovsky suites are very different from each other, without intermediate compositions between them. Consequently, the allocation of ‘transit suites’, appears to be unsupported. The trap stage did not start from the upper Morongovsky suit, as previously believed, but from Tuklonsky whose geochemical features and area of distribution correspond to WPB.

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References

- [1] Kamo S, Czamanske G, Amelin Y, et al. Rapid eruption of Siberian flood-volcanic rocks and evidence for coincidence with the Permian-Triassic boundary and mass extinction at 251 Ma. *Earth Planet Sci Lett* 2003; 214:75-91.
- [2] Godlevsky M. *Traps and ore-bearing intrusions of the Noril'sk district*. Moscow: Gosgeoltekhizdat; 1959.
- [3] Zolotukhin V, Vilensky A, Dyuzhikov O. *Basalts of the Siberian platform*. Novosibirsk: Nauka; 1986.
- [4] Lightfoot P, Naldrett A, Gorbachev N. Geochemistry of the Siberian trap of the Noril'sk area, USSR, with application for the relative contributions of crust and mantle to flood basalt magmatism. *Contr Mineral Petrol* 1990; 104:631-644.
- [5] Lightfoot P, Howkesworth C, Hergt J. et al. Remobilisation of the continental lithosphere by mantle plumes: major, - trace-element and Sr-, Nd-, and Pb-isotope evidence from picritic and tholeiitic lavas of the Noril'sk District, Siberian Trap, Russia. *Contr. Mineral. Petrol* 1993; 114: 171-188.
- [6] Fedorenko V, Lightfoot P, Naldrett A, et al. Petrogenesis of the Flood-Basalt Sequence at

- Noril'sk, North Central Siberia. *International Geology Review* 1996; 38: 99-135.
- [7] Sobolev A, Krivolutskaya N, Kuzmin D. Petrology of the parental melts and mantle sources of Siberian trap magmatism. *Petrology* 2009; 17: 253-286.
- [8] Arndt N, Chauvel C, Czamanske G, et al. Two mantle sources, two plumbing systems: tholeiitic and alkaline magmatism of the Maymecha River basin, Siberian flood volcanic province. *Contr Mineral Petrol* 1998; 133: 279-313.
- [9] Al'mukhamedov A, Medvedev A, Zolotukhin V. Evolutions of Permo-Triassic basalts of the Siberian Platform in time and space. *Petrology* 2004; 12: 339-353.
- [10] Krivolutskaya N. The problem of subdivision of volcanic rocks of the trap formation of the Noril'sk region. *Doklady Earth Sciences* 2011; 439: 1088–1092.
- [11] Peat, I., Elkins-Tanton, L., Large igneous provinces and explosive basaltic volcanism. In: *Volcanism and global Enviromental Change*. Cambridge Univ. Press. 2015, 3-15.
- [12] Wooden J, Czamanske G, Fedorenko V, et al.. Isotopic and trace element constraints on mantle and crustal contributions to Siberian continental flood basalts, Noril'sk area, Siberia. *Geochim Cosmochim Acta* 1993; 57: 3677-3704.
- [13] *Geology and ore deposits of the Noril'sk region*. Guidebook of the VII I PS, Moscow-Noril'sk: Moskovsky Contact Press 1994.
- [14] Dolgal' A. Realization of V.N. Strakhov ideas in interpretation of geopotential fields. In: *Academician V.N. Strakhov as geophysics and mathematic*. Moscow: Nauka, 2012; 55–78.
- [15] Krivolutskaya N, Rudakova A. Structure and geochemical characteristics of trap rocks from the Noril'sk Trough, Siberian craton. *Geochemistry International* 2009; 47: 635-656.
- [16] Hofmann A. Chemical differentiation of the Earth: the relationship between mantle, continental crust and oceanic crust. *Earth Planet Sci Lett* 1988; 90: 297-314.