Structure and Geochemical Features of the Volcanic Rocks in the Tunguska Syneclise (Siberian Trap Province)

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Abstract. To understand the origin of the Siberian trap province, it is necessary to know its internal structure in detail. Only two areas were described, the Noril’sk and Maimecha-Kotuy, while the main part of the province, the Tunguska syneclise, is still poorly characterized. The main goal of our study is an investigation of the structure and geochemistry of volcanic rocks located in the central part of the province. We have studied basalts and tuffs and compared them with the rocks of the Noril’sk area. All studied rocks belong to three formations: Korvunchansky, Nidymsky and Kochechumsky. The whole thickness of this cross-section is around 1,000 m. Our geochemical data demonstrate that the lower part of the cross-section comprises basalts with TiO₂ = 1 wt% while the upper part consists of the basalts with the average TiO₂ content 1.4-1.5 wt%. Based on this data, these rocks can be correlated with Morongovsky and Mokulaevsky formations located in the Noril’sk area. Despite many similarities between the volcanic rocks of these two areas, the basalts and tuffs of the Tunguska syneclise have their specific features, i.e. many tuff horizons, small thickness of flows and their poikiloophitic structure that reflect the rock formation near the boundary of the Tunguska syneclise.

1. Introduction
The Siberian trap province is the largest continental province of flood basalts in the world [1-3]. Its origin is under discussion for several decades and many models of its formation were suggested [4-6]. Almost all constructions do not take into account the real geological structure of magmatic rocks and their relationships within the province, they are based only on data from the Noril’sk [7-9] and Maymecha-Kotuy [10, 11] areas. Meanwhile, the central part of the province, the Tunguska syneclise, remains outside the scope of research (figure 1). We have studied basalts and tuffs from this area and compare them with very well studied rocks of the northern part of the province. The volcanic rocks of the Tunguska syneclise have their specific features and similarities with other formations of the Siberian platform.
2. Objects and methods

We have studied magmatic rocks in the Lower Tunguska river valley near village Tura (figure 1, 2). 67 samples were taken from outcrops and open pits exposed the Korvunchamsky, Nidymsky and Kochechumsky formations. The representative cross-section of the two last formations is located near Tura village. Major elements in rocks were determined by XRF at the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry RAS, using WD spectrometer (model Axios mAX, PANalytical, Netherlands). Trace elements in rocks were analysed by ICP-MS at the Institute of Microelectronics Technology and High Purity Materials RAS (analyst V.K. Karandashev). Mass-spectral determination of elements was performed with an X-7 quadrupole mass spectrometer (Thermo Scientific, USA) at the following parameters: plasma power of 1300 W, argon plasma flow rate – 13 l/min.
3. Brief geology

The Siberian trap province (251 Ma, [1]) consists of tuffs and tholeitic basalts covering the square of 1,500,000 km². It includes numerous intrusive bodies as well. Cross-section of volcanic rocks has the maximal thickness (3.5 km) in the northern part of the province, in the Noril’sk area. 11 formations were recognized there, they are following (from the bottom to the top): Ivakinsky, Syverminsky, Khakanchansky, Tuklonsky, Morongovsky, Mokulaevsky, Kharaelakhsky, Kumginsky and Samoedsky [1, 7, 8]. The manes of formations in other areas of the province are
different because they were studied by other geological organizations at another time. These variable subdivisions of rocks put the question on a correlation of basalts flows and tuff horizons around the province. Modern geological data help to solve this problem but they characterize only northern part of the province, including the Noril’sk and Maymecha-Kotuy areas, while the central part of the province was not studied jet.

4. Results and discussions

4.1. Geology of the volcanic rocks in the Lower Tunguska river valley

Basalts and tuffs of the Nidymsky and Kochechumsky formations are exposed on the surface in the studied area while tuffs of the Kolvunchansky formation were penetrated by boreholes drilled by Ltd. Quartssamotsvety (figure 2). We have studied rocks of the last formation in outcrops near the west boundary of the area. The well-studied cross-section includes three formations mentioned above (figure 3). It consists of alternating basalt flows and tuffs horizons that dominate in the lower part of the cross-section (figure 4).

![Figure 3. Volcanic rocks of the Tunguska synclise (a-contact of the Kolvunchansky tuffs and Nidymsky basalts, b-pillow lava from the lower subformation of the Nidymsky formation, c- vein of Iceland spar in the Nidymsky basalts, d-basalts of the upper subformation of the Nidymsky formation)
consists of thin (3-5 m) pillow lavas and amygdales separated by tuffs horizons 3-7 m of thick. The basalt/tuff ratio is around 3:2 for this subformation. The thickness of lower subformation variables from 30-40 m to 270 m due to the roof undulation of the Korvunchansky formation. These lavas are of important economic value because they contain piezo-optical calcite which was explored for a long time. The upper subformation of the Nidymsky formation comprises mostly lavas with a subordinate amount of tuffs (basalts/tuffs=4:1). It is represented by poikiloophytic basalts with massive texture and thin amygdales zones that are constant in their structure and texture around the area. Lava flows have a thickness of 5-10 m (figure 4).

![Figure 4. Spider-diagram for rocks of the Tunguska synclise (normalized after [12])](image)

The Kochechumsky formation overlaps the Nidymsky one. It consists of lava flows (8-10 m of thick) with rare tuff horizons, its thickness changes from 200 to 250 m. Basalts have a massive texture and poikiloophytic structure that are very similar to the texture and structure of the Nidymsky rocks.

4.2. Geochemistry of the volcanic rocks in the Lower Tunguska river valley
The composition of representative samples from the Korvunchansky, Nidymsky and Kochechumsky formations are given in Table 1. Analyses No 1 and 5 correspond to tuffs of the Korvunchansky and

| No | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|----|-----|-----|-----|-----|-----|-----|-----|-----|
| No sample | HT-0 | HT-2 | HT-4 | HT-7-1.2 | HT-7-1.4 | HT-9 | HT-10 | HT-12/1 |
| SiO₂      | 48.65 | 45.46 | 45.98 | 45.81 | 52.61 | 47.64 | 46.7 | 47.08 |
| TiO₂      | 0.96  | 1.28  | 1.37  | 1.36  | 1.13  | 1.44  | 1.68 | 1.52  |
| Al₂O₃     | 13.53 | 13.81 | 14.26 | 16.21 | 14.17 | 14.99 | 12.86 | 13.82 |
| Fe₂O₃     | 9.52  | 12.9  | 12.98 | 13.47 | 9.92  | 13.47 | 15.24 | 13.96 |
| MnO       | 0.20  | 0.171 | 0.189 | 0.249 | 0.114 | 0.199 | 0.163 | 0.194 |
| MgO       | 5.73  | 7.27  | 6.96  | 4.29  | 4.5   | 7.62  | 5.69 | 6.72  |
| CaO       | 5.3   | 8.17  | 8.21  | 11.58 | 5.06  | 10.62 | 9.71 | 10.09 |
| Na₂O      | 4.13  | 2.59  | 3.66  | 2.36  | 1.86  | 2.42  | 1.72 | 2.27  |
| Element | K<sub>2</sub>O | P<sub>2</sub>O<sub>5</sub> | LOI | Si | Total | Li | Be | Rb | Sr | Y | Cs | Cd | Ba | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu | Pb | Th | U | Sc |
|---------|----------------|----------------|-----|----|-------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
|         | 1.05           | 0.94           | 0.34 | 0.15 | 2.49  | 0.25 | 0.14 | 0.34 | 0.12 | 0.12 | 0.13 | 0.19 | 0.12 | 0.16 | 0.13 | 0.16 | 10.61 | 6.86 | 5.68 | 3.94 | 7.92 | 1.06 | 5.87 | 3.73 | 0.07 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | 99.87 | 99.57 | 99.76 | 99.61 | 99.89 | 99.90 | 99.90 | 99.88 |
|         | 18.5           | 10.85          | 9.37 | 7.87 | 9.00  | 6.89 | 7.44 | 7.01 | 31.9 | 24.6 | 8.66 | 2.81 | 160 | 16.06 | 4.61 | 6.76 | 176 | 303 | 305 | 207 | 906 | 184 | 183 | 190 | 22.2 | 24.9 | 25.4 | 32.4 | 24.7 | 27.0 | 29.7 | 27.3 |
|         | 143            | 27.2           | 1.35 | 8.62 | 2.45  | 0.83 | 4.01 | 3.73 | 195 | 303 | 296 | 110 | 340 | 110 | 340 | 110 | 340 | 110 | 340 | 110 | 340 | 110 | 340 | 110 | 340 | 110 | 340 | 110 | 340 | 110 | 340 |
|         | 249            | 422            | 202  | 91  | 339  | 107 | 94  | 134 |
|         | 14.3           | 6.41           | 6.62 | 11.77 | 16.42 | 7.96 | 9.21 | 8.09 |
|         | 31.3           | 16.4           | 16.6 | 27.8 | 37.1 | 19.9 | 22.8 | 20.2 |
|         | 3.73           | 2.31           | 2.29 | 3.70 | 4.25 | 2.63 | 3.10 | 2.72 |
|         | 15.9           | 11.6           | 11.4 | 17.7 | 18.0 | 12.9 | 14.8 | 13.1 |
|         | 3.68           | 3.41           | 3.41 | 4.95 | 4.14 | 3.77 | 4.31 | 3.76 |
|         | 1.08           | 1.18           | 1.20 | 1.59 | 1.9 | 1.26 | 1.44 | 1.31 |
|         | 4.13           | 4.15           | 4.35 | 5.95 | 4.46 | 4.63 | 5.35 | 4.64 |
|         | 0.65           | 0.71           | 0.72 | 0.99 | 0.78 | 0.88 | 0.77 |
|         | 4.01           | 4.70           | 4.87 | 6.53 | 4.57 | 4.92 | 5.75 | 5.07 |
|         | 0.83           | 1.00           | 1.00 | 1.37 | 0.93 | 1.04 | 1.22 | 1.07 |
|         | 2.54           | 2.83           | 2.95 | 3.96 | 2.77 | 3.03 | 3.48 | 3.04 |
|         | 0.36           | 0.42           | 0.42 | 0.56 | 0.40 | 0.44 | 0.50 | 0.44 |
|         | 2.45           | 2.66           | 2.70 | 3.61 | 2.54 | 2.76 | 3.21 | 2.79 |
|         | 0.36           | 0.40           | 0.40 | 0.55 | 0.37 | 0.41 | 0.46 | 0.41 |
|         | 8.62           | 1.99           | 1.75 | 2.94 | 3.99 | 2.29 | 2.30 | 2.15 |
|         | 3.56           | 0.92           | 0.94 | 1.61 | 3.91 | 1.11 | 1.17 | 1.06 |
|         | 1.35           | 0.34           | 0.38 | 0.89 | 1.06 | 0.54 | 0.51 | 0.46 |
|         | 27.2           | 37.0           | 37.5 | 39.1 | 26.3 | 35.0 | 37.2 | 36.5 |

End of Table 1

| Element | Ti | V | Cr | Co | Ni | Cu | Zn | Ga | Zr | Nb | Hf |
|---------|----|---|----|----|----|----|----|----|----|----|----|
|         | 5470 | 211 | 161 | 34 | 79 | 89 | 87 | 15.7 | 96 | 5.87 | 2.66 |
|         | 7962 | 290 | 150 | 51 | 126 | 162 | 101 | 17.6 | 93 | 3.68 | 2.37 |
|         | 8521 | 288 | 144 | 49 | 112 | 164 | 101 | 17.7 | 93 | 3.72 | 2.40 |
|         | 9703 | 319 | 119 | 54 | 91 | 165 | 105 | 22.9 | 131 | 6.29 | 3.23 |
|         | 7215 | 189 | 95 | 34 | 71 | 118 | 107 | 17.4 | 119 | 6.99 | 2.90 |
|         | 8957 | 293 | 177 | 34 | 136 | 156 | 101 | 19.8 | 106 | 4.71 | 2.63 |
|         | 10450 | 316 | 136 | 51 | 90 | 180 | 101 | 20.3 | 118 | 4.88 | 2.88 |
|         | 9454 | 319 | 198 | 51 | 107 | 189 | 111 | 19.0 | 108 | 4.56 | 2.58 |
Note. No analyses, formation: 1-Korvunchansky, 2-6 – Nidymsky, 7-8 – Kochechumsky.

Nidymsky formations, respectively, while the rest ones are basalts. All these rocks belong to basic rocks of normal alkalinity with a predominance of sodium over potassium. The tuffs are characterized by elevated SiO$_2$, K$_2$O, LOI and lower MgO, TiO$_2$ in comparison with the basalts. They have higher contents of Th, U, Pb, Nb, Ce and lower V, Sc as well. The TiO$_2$ concentrations in basalts of the Kochechumsky formation are higher than contents in the Nidymsky formation, thus titanium content smoothly increases from bottom to top of the cross-section.

Distributions of rare elements in studied rocks are very similar and very close to continental crust. All patterns have similar topology; they are characterized by Ta-Nb, Ti negative and Pb, Sr positive anomalies. The tuffs (brawn lines on figure 4) are enriched in LILE and depleted in HREE in comparison with the basalts that could be a result of their alteration and occurrence of sediments.

4.3. Discussion
Correlation of basalt sections located at a great distance from each other is important for reconstruction of basalt plateau structure and magmatism evolution. State geological mapping of 1:200,000 and 1:1,000,000 scales realized in 1960-1980 decided this problem by geological methods based on a correlation of separate volcanic sections. The comparison included a structural analyse of sections (number basaltic flows, their thickness, amount of tuff horizons) and rock textures. A few geochemical data (only major elements in rocks) were obtained for the Siberian platform. New period of the volcanic rocks study beginning from 1990 is characterized by the application of precious geochemical methods (ISP-MS, XRF, isotope study). Obtained data are summarized in GEOROCK database (http://georoc.mpch-mainz.gwdg.de) and they help to correlate volcanic sections. The paleomagnetic study is a very effective method for reproduction of magmatic evolution as well [13, 14].

Geological study of the volcanic rocks in the Tunguska syncline demonstrates their difference from the effusive rocks in the Noril’sk area due to a large volume of pyroclastic rocks and small thickness of flows. These features bring them closer to the part of the Noril’sk area formed by the Khakancheansky and Tuklonsky formations. Despite a larger thickness of flows (20-30 m), Tuklonsky basalts are characterized by similar image due to poikiloophytic texture and crystal size. They overlap the Khakanchansky tuffs in the NW Tunguska syncline. This geological position could be correlated with the position of the Korvunchansy and lower Nidymsky formations despite the conclusion on the coeval formation of the Korvunchansy rocks with the lower part of the Noril’sk section (Syverminsky-Nadezhdinsky formations) [15].

Nevertheless, the geochemical features of the studied rocks are very close to those of the basalts of the Noril’sk region as a whole [16, 17], especially to volcanic rocks of the upper formations, starting with the Morongovsky one. The last formation can be correlated with the Korvunchansky tuffs. Lavas of the Nidymsky formation are similar to the Mokulaevsky rocks while basalts of the Kochechumsky formation correlate with rocks of the Kharaelakhsky formation based on TiO$_2$ content.

5. Conclusions
Structure and composition of the volcanic rocks in the Tunguska syncline have been studied. These rocks were subdivided into three formations, the Korvunchansky, Nidymsky and Kochechumsky, forming a section of 1,000 m in thick. The main features of this section are large volumes of tuffs (20%) and small thickness of basalt flows.
Geochemical data demonstrate that the studied formations could be correlated with the Morongovsky, Mokulaevsky and Kharaelakhsky formations in the Noril’sk area.

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