Composition, structure and formation conditions of the Arydzhangsky Formation of the Maimecha-Kotuy District of the Siberian Trap Province

R V Shtokalo¹,4, N A Krivolutskaya², A A Konyshev², I T Rass³ and S I Demidova²

¹Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow 119991, Russian Federation
²Vernadsky Institute of Geochemistry and Analytical Chemistry of RAS, building 1, 19, Kosygina Street, Moscow, 119991, Russian Federation
³Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry RAS, 35, Staromonetny Per., Moscow, 119017, Russian Federation

Email: roman.shtokalo.1999@mail.ru

Abstract. We studied 6 sections of the Arydzhangsky lava formation (P₂-T₁) in the Kotuy river valley. The results of petrographic and geochemical studies of the composition of rocks of the Arydzhangsky, Khardaksky and Pravoboyarsky formations are presented. The stratigraphic columns of the sections were built and the composition of the rocks was additionally determined using a scanning electron microscope. In this regard, the relative position of these formations was established, the mantle and crust sources of magmas were confirmed. A geochemical identity of the rocks of the Khardaksky formation with the rocks of the Arydzhangsky formation was established, which suggests a similar age of their formation.

1. Introduction
At the boundary between the Permian and Triassic within the Siberian platform, a vast area of basaltic volcanism and the associated occurrences of intrusive magmatism and unique PGE-Cu-Ni deposits were formed. The problem of the formation of such large volumes of magmatic rocks (Large Igneous Provinces, LIP) has been one of the most controversial in geology over the past thirty years. To solve it, knowledge about the evolution of magmatism in time and space is required. A unified scheme for the development of magmatism at the Permian - Triassic boundary for the Siberian province still does not exist. For its design, the most important are the volcanic rocks of two regions - Norilsk and Maimecha-Kotuy, the relationship between which is not completely clear and is being actively discussed. It is assumed that all the rocks of the latter of these sections were formed after the volcanic rocks of the Norilsk region, or began to form at the same time, partially overlapped with them, and finished forming much later [1].

2. Geological background
The Maimecha-Kotuy region is located in the Northwestern part of the Siberian platform. It is bounded by three main regional structures: from the east by the Anabar uplift, from the southwest by the Tunguska syncline, and from the northwest by the Yenisei-Khatanga trough. The volcanic rocks
of the Maimecha-Kotuy region cover an area of 70,000 km$^2$ and have a maximum thickness of up to 4 km [2]. Basic and ultrabasic rocks of normal, subalkaline and alkaline series are widespread. In this paper, the effusive formations of the Arydzhangsky and Pravoboyarsky Formations of the Upper Permian-Lower Triassic within the river valley Kotuy are considered, having the lowest position in the section. Timeliness in these formations makes it dependent on the specificity of their composition, the area of distribution, and their relationship in the studied region. A distinctive feature of the Arydzhangsky Formation is the presence of alkaline basaltoids, among which limburgites, melanocratic nepheline basalts, melilite basalts, alkaline picrites, as well as interlayers of their tuffs and tuffites are distinguished.

In the lower reaches of the river Kotuy rocks composing the Arydzhangsky Formation are replaced by volcanic rocks and volcanogenic-sedimentary rocks of the Pravoboyarsky Formation, as well as lavas of the overlying Kogotoksky Series. The rocks of the Pravoboyarsky Formation are represented by basic psephitic and agglomerate tuffs, tuffites and rare basalt flows 1.5 to 10 m thick. The section of the effusive formations is completed by the Early Triassic Kogotoksky Series. Within the basin of the river Kotuy, it is represented by the Onkuchaksy Suite. This suite lies on the eroded surface of the Pravoboyarsky and Arydzhangsky Formations and is overlain by sandy-clay deposits of the Boyarkinsky Suite of the Lower Cretaceous in the northwest. The Onkuchak suite is composed almost exclusively of tholeiitic basalts. Interlayers of tuffs, tuffites, and tuff breccias are rare [2].

3. The geological aspects of the tuff-lava sequences of the Maymecha-Kotuy region
In the Maymecha-Kotuisky area, in the course of geological survey work, the following formations were identified (from bottom to top): Khardakh, Arydzhang, Pravoboyar, Kogotok. The Khardakh Formation was identified by V.N. Egorov [4] in the lower reaches of the Arydzhang Formation. It consists of greenish gray and dark red tuffs with lava fragments of alkaline basaltoids. Previously, it was considered a facies-stratigraphic analogue of the Pravoboyar Formation [4]. The identification of the formation is caused by paleomagnetic data [1], according to which it is an analogue of the Ivakinskaya Formation of the Norilsk region. At the same time, due to the low distribution of rocks and relatively poor exposure, V.A. Fedorenko referred the Khardakhsky Formation to the lower reaches of the Arydzhangsky Formation. The question of the position of the Khardaksky Formation is fundamental for solving the problem of the correlation of volcanism in the Norilsk and Maimecha-Kotuisky regions: did it start simultaneously, or was it separated in time?

During the work, the reference sections for the study of volcanogenic formations in the region were selected with the consideration of the previously obtained data [5, 1] and were also determined directly during field studies (figure 1).

The study of the formation by its predecessors was mainly based on research of the structure and the composition of the section of volcanic rocks 3-4 km below the mouth of the river Bearish along the river Kotuy. We have expanded our studies of the Arydzhangsky Formation and, thus, compiled 6 sections located along the strike of the formation and 2 sections of Onkuchak Formation. In total, we analyzed 85 samples for major (XRF, analyst A.I. Yakushev, Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, RAS) and rare elements (ICP-MS, analyst V.K. Karandashev, Institute of Microelectronics Technology and High-Purity Materials Russian Academy of Sciences (IPTM)).
Figure 1. Stratigraphic columns of formations of the Arydzhangsky (sections 1, 2 the upper part of section 5), the Pravoboyarsky Formations (the lower part of section 5) (compiled by the author).

The volcanic rocks of section 1 belong to the Khardakhsky Formation (tuff-lavas) and the Arydzhangsky Formation, represented by limburgites and augitites. Sections 2 and 3 were studied downstream and are represented by lavas of nephelinites, melanephelinites, and limburgites with interlayers of tuffaceous sandstones and siltstones. Picrites are a characteristic feature of these sections. Section 4 corresponds to the reference section of the Arydzhangsky Formation [5]. The tuff-lavas of the trachybasalts of the Pravoboyarsky Formation is represented at the bottom of Section 5. At the top of that section there are limburgites of the Arydzhangsky Formation as in section 6. Sections 7 and 8 belong to the Onkuchaksky Formation. The correlation of covers from the studied sections is rather complicated, since only the cover of alkaline picrites is the marker horizon, but it is not found everywhere.

4. Petrographical characteristics of volcanic rocks
On the basis of petrographic study of rocks and determination of their composition on a scanning electron microscope, the main varieties of effusive rocks of the region were identified. These are nephelinites, melanephelinites, limburgites, and picrites.
Melanephelinites are porphyry rocks with phenocrysts of olivine (up to 25% of the total amount) and clinopyroxene (30–70%), and the glassy mass consists of pyroxene and olivine. Secondary formations are often well-developed in the ground mass.

Limburgites (olivine melanephelinites) contain phenocrysts of clinopyroxene (70%) and olivine (30%) in a glassy groundmass, consisting of the same minerals, as well as fine magnetite and biotite lath. The structure of the rock is porphyry, the groundmass is microlitic. The single phenocryst of sanidine was identified in the limburgites of section 3.

Nephelinites consist of phenocrysts of nepheline (30–40%), augite (30–50%) and olivine (0–20%), phlogopite and biotite (0–10%), enclosed in a glassy ground mass. A feature of the rock is the presence of prismatic biotite, elongated crystals of apatite with a rim of fluorapatite. Branched phenocrysts of potassium feldspar, represented by sanidine, was also confirmed in the rocks of section 2.

Alkaline picrites form a sustained strike horizon up to 15 m thick. They contain large (up to 3 cm) phenocrysts of olivine (20–70%), clinopyroxene (up to 30%), which are immersed in a glassy groundmass with microliths of the same minerals, phlogopite (up to 5%) and magnetite. In the studied rocks, olivine corresponds in composition to Fo$_{81-83}$, clinopyroxene to En$_{80-84}$, Fs$_{14-16}$, Wo$_{2-4}$.

5. Chemical characteristics of the Arydzhang Formation

5.1. Major components
A detailed analysis of geochemical data indicates that the rocks of Aryzhangsky Formation are predominantly tephrites, basanites, picrites, and trachybasalts (figure 2). Figurative points of rock compositions for the Khardakh Formation are similar to those for the Aryzhangsky Formation. The tuff-lavas of the Pravoboyarsky Formation have a heterogeneous composition.

![Figure 2](image)

**Figure 2.** Classification petrochemical diagram SiO$_2$ - (Na$_2$O + K$_2$O) (TAS diagram) for rocks of the Arydzhang, Pravoboyar and Onkuchak Formations.
The Harker diagrams clearly show the trends of crystallization differentiation of the parental melt - sequential separation of olivine, pyroxene, and feldspars. Most of points of Onkuchaksky Formation fell in the field of basalts of normal alkalinity basalts.

Alkaline basaltoids of the Arydzhangsky Formation have high values of oxides of titanium (3–5 wt %) and iron (10–16 wt %). Pravoboyarsky Formation is characterized by the lower concentrations of TiO$_2$ (1 wt %), CaO (3.5–5.5 wt %) and P$_2$O$_5$ (0.13 wt %), but higher Al$_2$O$_3$. The increase in alumina content can be explained by the appearance of plagioclase. The rocks of the Onkuchaksky Formation have lower concentrations of TiO$_2$ (1.5 wt %) and P$_2$O$_5$ (0.13–0.2 wt %) compared to the rocks of the Arydzhangsky Formation.

The alkalinity of rocks is determined by nepheline (Na$_2$O) and sanidine (K$_2$O). CaO and P$_2$O$_5$ are controlled by apatite. The tuffaceous sandstones of the Arydzhangsky Formation are high-potassium (7–9 wt %) due to the presence of sanidine.

5.2. Interpretation of analysis results for trace elements

The distribution of trace elements in rocks from studied formations is shown on the spider diagram. There are two types of spectra (figure 3).

The first one (solid lines) corresponds to the rocks of the Arydzhangsky and Khardakhsky Formations, as well as the basalts of the Onkuchaksky one. This type is characterized by high concentrations of light impurity elements and low concentrations of heavy ones, which may indicate the presence of garnet in restite. Distinct positive Sr and negative U anomalies indicate an enriched mantle source of material for alkaline rocks of the Arydzhangsky Formation.

The second type (dotted lines) is related to tuff sandstones of the Arydzhangsky Formation and tuff-lavas of trachybasalts of the Pravoboyarsky Formation, respectively. They are characterized by a positive Pb anomaly, Ta-Nb, Sr and Ti minimum, which indicates the participation of the crust in the formation of rocks. The obtained data are evidence of the formation of rocks in the setting of epiplatform rifts.

6. Conclusions
The formations of sections 1–3 and the tops of section 5 and section 6 belong to the Arydzhangsky Formation. The bottom of section 5 is defined as tuff-lava of the trachybasalts of the Pravoboyarsky Formation. Sections 7 and 8 are represented by basalts of the Onkuchaksky Formation.

Rocks of section 1, assigned to the Khardakhsky Formation, have identical trace element distribution spectra as the rocks of the Arydzhangsky Formation. Samples of section 1 are characterized by the same compositions of petrogenic oxides as other rocks of the Arydzhangsky Formation.

The tuffaceous formations of the Pravoboyarsky Formation in section 5 are distinguished by the distribution spectra of trace elements typical of crustal source. Their magmatic source differs sharply from the source of the volcanic rocks of the Arydzhangsky suite. Within section 5, the tuff-lavas of the Pravoboyarsky Formation are faciesly replaced by the limburgites of the Arydzhangsky Formation. The alternation of such rocks of different genesis may indicate the simultaneous action of different cauldrons of magmatism.

Thus, the petrographic composition of the Arydzhangsky Formation is specific and changes throughout its entire length in the valley of the river Kotuy. The rocks of this Formation and the Pravoboyar Formation are in sharp contrast. Khardakhsky Formation is compatible with the Arydzhang Formation by petrographic and geochemical features. According to these criteria, its identification is not substantiated, and by us the Khardakhsky Formation belongs to the lower reaches of the Arydzhangsky Formation.

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