Petrology and geochemistry of the Tolbachik stratovolcano

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Introduction. The numerous of national and international publications were dedicated to Plosky Tolbachik volcano eruptions and adjacent monogenetic cones, which were erupted repeatedly during Holocene, including historical time [i.e. Vlodavets, 1937; Popkov, 1946; Peep, 1946, 1954; Menyailov, 1953; Sirin and Farberov, 1963; Kirsanov et al., 1974; Ivanov and Khrenov, 1979; Fedotov, 1984; Krivenko, 1990; Kersting, 1995; Tatsumi et al., 1995; Hochstaedter et al., 1996; Kepezhinskas et al., 1997; Turner et al., 1998; Pineau et al., 1999; Volynets et al., 2000; Churikova et al., 2001; Münker et al., 2004; Portnyagin et al., 2007; Volynets et al., 2013]. However, all these data mainly relates to monogenetic cones, but the information on stratovolcanoes itself practically absent. There are only few papers on Ostry and Plosky Tolbachik stratovolcanoes focusing on geology [Ermakov and Vazheevskaya, 1973], petrography and some petrochemistry of the rocks [Ermakov, 1977; Flerov and Melekestsev, 2013]. The modern geochemical and isotope studies of the stratovolcanoes were never achieved. In this report we present geological, petrographical, petrochemical, geochemical and some K-Ar data on the rocks of Tolbachik massif. The present report based on representative collection of 154 samples from stratovolcanoes, dikes, monogenetic cones of different ages, including last 2012-2013 eruption. Additionally our study included samples separately standing edifice of Povorotnaya mount, which age according to K-Ar dating is 0,306±0,01 Ma.

The geological history of Tolbachik massif consists of four consecutive periods of volcano activity: basement formation, growth of two sub-simultaneous stratovolcanoes, development of dike complex and formation of numerous cinder and cinder-lava monogenetic cones.

The basement of volcano with diameter more than 20 km and angle of inclination not exceeding 5° is exposed in northern, north-western and south-western sectors of volcano and represented by single blocks, outliers, necks and spurs. A single definition of age of these rocks by K-Ar method shows 0,086±0,016 Ma. The presence of augite-porphyric rocks with large (up to 2 cm) augite phenocrysts is typical of volcano basement [Ermakov and Vazheevskaya, 1973].

Ostry and Plosky Tolbachik stratovolcanoes are different from the basement morphologically with higher angles of inclination up to 20-30º. The thickness of the lava flows normally less than 5-7 meters. The main rock forming minerals are Ol, Cpx, Pl, Mt, less Opx.

Dike complex was developing during both first stages of volcano activity. The numerous dikes that crosscut the older edifices form a radial pattern as well as ring structures in all sectors of both edifices. Their thickness ranges from 1 to 10 m and they reach up to 2 km in length. The large variations in chemical composition of dikes suggest several stages of their intrusions.

Subsequent geological processes led to the destruction of the Plosky Tolbachik summit with caldera formation 3 km in size. Ostry Tolbachik stratovolcano was influenced by series of landslides, with largest of them directed to SE.

Final and continuing to the present time stage of activity at Tolbachik massif started about 10 Ka ago by formation of monogenetic cones zone along the fissure from S-SW to NE. These cones are composed mainly of cinder but often produced lava flows as long as 10 km. During 10-2 Ka ago only subalkaline mainly mega-plagiophyric basalts were erupted. Since 2 Ka ago started so-called “contrast” period with the eruptions of both subalkaline and high-Mg basalts [Flerov and Melekestsev, 2013].

Based on petrographical features, Tolbachik massif rocks can be divided into three groups. There are Ol-bearing rocks (Ol–Cpx-Pl, Ol–Pl, Ol-Cpx, and Ol-Opx-Pl), Ol-free lavas (2Px–Pl, Cpx–Pl, and Pl), and subaphyric samples. About 80% of rocks are represented by Ol-bearing rocks. The samples of the Povorotnaya mount are similar to the basement rocks and belong to Ol–Cpx-Pl association, including the existence of augite-porphyric rocks.

Major and trace elements were analyzed in analytical laboratories of Japan. All rocks of Tolbachik massif belong to a medium-K and high-K calc-alkaline basalt–basaltic–andesitic series. In detail, however, there are some differences in the trends for major and trace elements. On all variation diagrams (Fig. 1) all samples split for three groups with formation of two different trends and one separate area. The first trend consists of medium-K basalts and basaltic andesites (Fig. 1, trend 1). It includes all samples of Tolbachik massif basement, the lower parts of stratovolcanoes up to the elevation 2100 m, as well as all samples of Povorotnaya mount. This trend shows increasing K_2O and Na_2O and decreasing Al_2O_3, TiO_2,CaO, FeO, and MgO from basalts to basaltic andesites. The SiO_2 variation is the largest compared to other groups of samples.

The second medium-high-K trend includes the upper parts of stratovolcanoes higher than 2100-2500 m and the lavas of majority of cinder and cinder-lava cones. This trend is very steep and at SiO_2 variations only by 2,5% shows the sharp increase of alkalies, P_2O_5 and TiO_2 and sharp decrease in MgO, MnO, Fe_2O_3 and CaO (Fig. 1, trend 2). Trend 2 is quite unusual for the volcanic rocks which were formed only by fractional crystallization.

High-Mg basalts of 1975-1976 eruption are located where two trends intersect and probably could represent a high-Mg end-member for both of them (Fig. 1). There are no differences between Ostry and Plosky Tolbachik stratovolcanoes. The samples of dike complex are located in both trends.

The third group of rocks, which forms a separate area on all variation diagrams represented by basaltic andesites with SiO_2 54-55%, high alkalies, P_2O_5, TiO_2 and Fe_2O_3 at relatively low MgO and CaO. This group includes only the rocks of the first three days of 2012 eruption (so-called Menyailov Vent).

Trace element patterns for all studied rocks have typical arc signatures with strong but variable LILE and LREE enrichment and low HFSE, which testify fluid influences. The samples of trend 1 have systematically lower values for REE, Nb and Ta compared to samples of trend 2. On trace element and trace element ratios binary diagrams the samples of two trends are also systematically different. The rocks of third group are mostly enriched in all incompatible elements not only inside the Tolbachik massif lavas, but also inside all rocks of Klyuchevskaya group of volcanoes. At the same time high-Mg basalts of 1975 eruption show the lowest patterns in all incompatible elements at Tolbachik massif. The samples from trend 1 and high-Mg basalts of 1975 are systematically depleted in Nb, Ta and REE compare to NMORB while the rocks of trend 2 and group 3 are systematically enriched.

Conclusions: (1) Volcanic activity at the area of Tolbachik massif started with formation of large basement, which was represented by middle-K Ol-bearing basalts and basaltic andesites including the augite-porphyric associations. Mantle source of these melts was depleted compare to N-MORB. This magma chamber was active also during first stages of stratovolcanoes formation. (2) Younger, upper parts both stratovolcanoes were influenced by different high-K mantle source, which was enriched in alkalies, TiO_2, P_2O_5, and all incompatible trace elements. The rocks of this series are systematically enriched compared to N-MORB. The Holocene lavas of monogenetic cones also belong to this rock series. (3) The rocks of the Povorotnaya mount similar in petrography and chemical composition to the Tolbachik massif basement. Taking into account these data and data of K-Ar dating, we conclude that the Povorotnaya mount is the block of Tolbachik massif basement.

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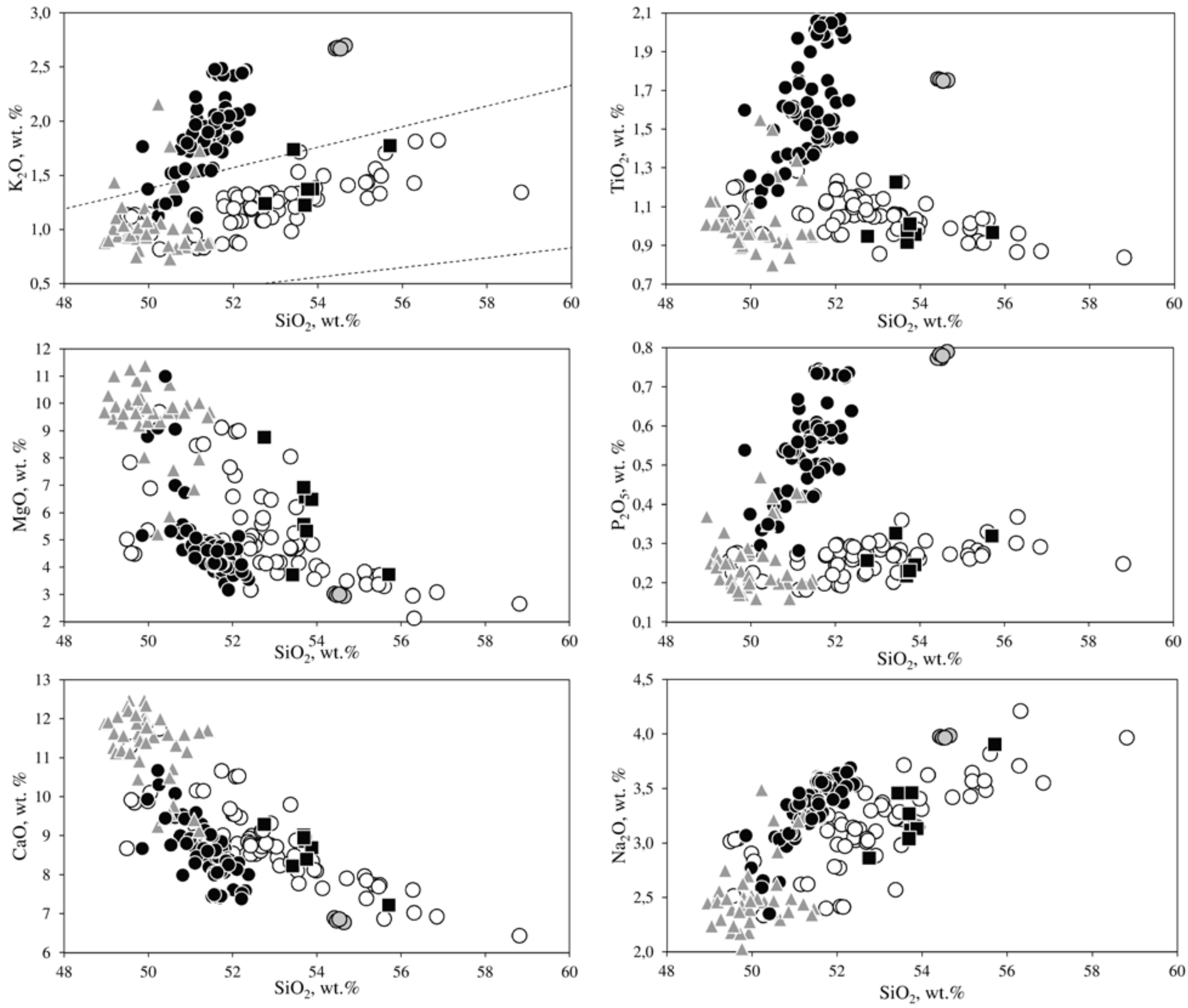

Fig. 1: SiO_2 vs. major elements diagrams for Tolbachik massif rocks and Povorotnaya mount. Open circles – trend 1, black circles – trend 2, grey circles - Menyailov Vent, triangles – high-Mg basalts of 1975 eruption; squares – Povorotnaya mount.