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Petrological and geochemical evolution of the Tolbachik volcanic massif, Kamchatka, Russia

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ABSTRACT

Data on the geology, petrography, and geochemistry of Middle–Late-Pleistocene rocks from the Tolbachik volcanic massif (Kamchatka, Klyuchevskaya group of volcanoes) are presented and compared with rocks from the neighboring Mount Povorotnaya, Klyuchevskaya group basement, and Holocene–historical Tolbachik monogenetic cones. Two volcanic series of lavas, middle-K and high-K, are found in the Tolbachik massif. The results of our data analysis and computer modeling of crystallization at different P–T–H_2O–fO_2 conditions allow us to reconstruct the geochemical history of the massif. The Tolbachik volcanic massif started to form earlier than 86 ka based on K–Ar dating. During the formation of the pedestal and the lower parts of the stratovolcanoes, the middle-K melts, depleted relative to NMORB, fractionated in water-rich conditions (about 3% of H_2O). At the Late Pleistocene–Holocene boundary, a large fissure zone was initiated and the geodynamical regime changed. Upwelling associated with intra-arc rifting generated melting from the same mantle source that produced magmas more enriched in incompatible trace elements and subduction components; these magmas are high-K, not depleted relative to N-MORB melts with island arc signatures and rift-like characteristics. The fissure opening caused degassing during magma ascent, and the high-K melts fractionated at anhydrous conditions. These high-K rocks contributed to the formation of the upper parts of stratovolcanoes. At the beginning of Holocene, the high-K rocks became prevalent and formed cinder cones and associated lava fields along the fissure zone. However, some features, including 1975–1976 Northern Breakthrough, are represented by middle-K high-Mg rocks, suggesting that both middle-K and high-K melts still exist in the Tolbachik system. Our results show that fractional crystallization at different water conditions and a variably depleted upper mantle source are responsible for all observed variations in rocks within the Tolbachik volcanic massif. Sr–Nd isotopes are consistent with 2–4% crustal assimilation during formation of the pedestal and stratovolcanoes, while the young lava fields do not show evidence of crustal assimilation. Major and trace element data coupled with K–Ar dating provide strong evidence that Mount Povorotnaya, located in 8 km northeast of Plosky Tolbachik, is an old block of the Tolbachik massif pedestal and for the moment it is the oldest (306 ka) known object in Klyuchevskaya group of volcanoes.

1. Introduction

Most Holocene volcanic activity on the Kamchatka peninsula has occurred within the Klyuchevskaya group of volcanoes (KGV), located in the northern part of the Central Kamchatka Depression (CKD). The tectonic setting of this area is dominated by a triple junction of lithospheric plates: Pacific, Bering, and Okhotsk. Presently, the origin of the geochemical diversity of the volcanic rocks in this area is the most discussed and critical one among the issues of magma origin at the Kamchatka subduction zone. Although a number of published papers have provided data on KGV volcanoes (Khrenov et al., 1991; Kersting and Arculus, 1994, 1995; Pineau et al., 1999; Dorendorf et al., 2000; Ozerov, 2000; Churikova et al., 2001, 2007, 2013; Mironov et al., 2001; Portnyagin et al., 2007a,b; Turner et al., 2007), most of them address only the products of recent and historical eruptions. And yet, it is impossible to understand the time-spatial evolution of the KGV without considering the pre-historical volcanism of each individual volcano and the

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entire area in question. Systematic studies of many KGV volcanoes were not conducted until recently and their geochemical and age correlation remains poorly constrained.

These unstudied volcanoes include not only such presently extinct volcanoes as Udina, Zimina, and Gorny Zub, but also Ostry Tolbachik and Plosky Tolbachik stratovolcanoes, on the slopes of which new monogenic cones were actively developing during the last 10 ka, erupting lavas of different compositions (Fig. 1). Numerous national and international publications were dedicated to Plosky Tolbachik volcano eruptions and adjacent monogenetic cones, which erupted repeatedly during the Holocene, including historical times (i.e. Vlodavets, 1937; Popkov, 1946; Piip, 1946, 1954; Menyailov, 1953; Sirin and Farberov, 1963; Kirsanov and Ponomarev, 1974; Ivanov and Khrenov, 1979; Fedotov and Markhinin, 1983; 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., 2007a; Volynets et al., 2013; see also Churikova et al., 2015). However, the referenced data mainly relate to monogenetic cones, whereas the information specifically on stratovolcanoes is practically nonexistent. Tolbachik massif was studied on a reconnaissance basis only in the 1970s. During that time, a geological map of this volcano was developed and the first petrographical and mineralogical data were obtained from its rocks (Ermakov, 1977). Presently, only a few papers have been published on the geology and petrography of Ostry and Plosky Tolbachik stratovolcanoes (Ermakov and Vazheevskaya, 1973) together with a few papers addressing to a limited extent the petrochemistry of the rocks, and mineral compositions (Ermakov, 1977; Flerov and Melekestsev, 2013; Flerov et al., 2015). Even though the data published in the 20th century showed that the cinder cones of the Tolbachik volcanic massif erupted distinct magmas ranging from high-Mg basalts to high-K trachybasalts, modern geochemical and isotope studies of the stratovolcanoes were not conducted, therefore, the evolution of those rocks was not clearly understood.

To determine the rock variations within the Tolbachik volcanic massif and to investigate the petrogenetic relationships between the rocks of Plosky and Ostry Tolbachik stratovolcanoes, dike complex, lavas of the adjacent zone of lava fields, and adjacent centers of the KGV, in this paper we present geological, petrographical, petrochemical, geochemical, isotopic and some K–Ar data on the rocks of Tolbachik volcanic massif. The present paper is based on the study of a representative collection of 155 samples from stratovolcanoes, dikes and monogenetic cones of different ages, including the 2012–2013 eruption (Fig. 2). Additionally, our study included samples from the separate edifice of Mount Povorotnaya and the KGV basement located

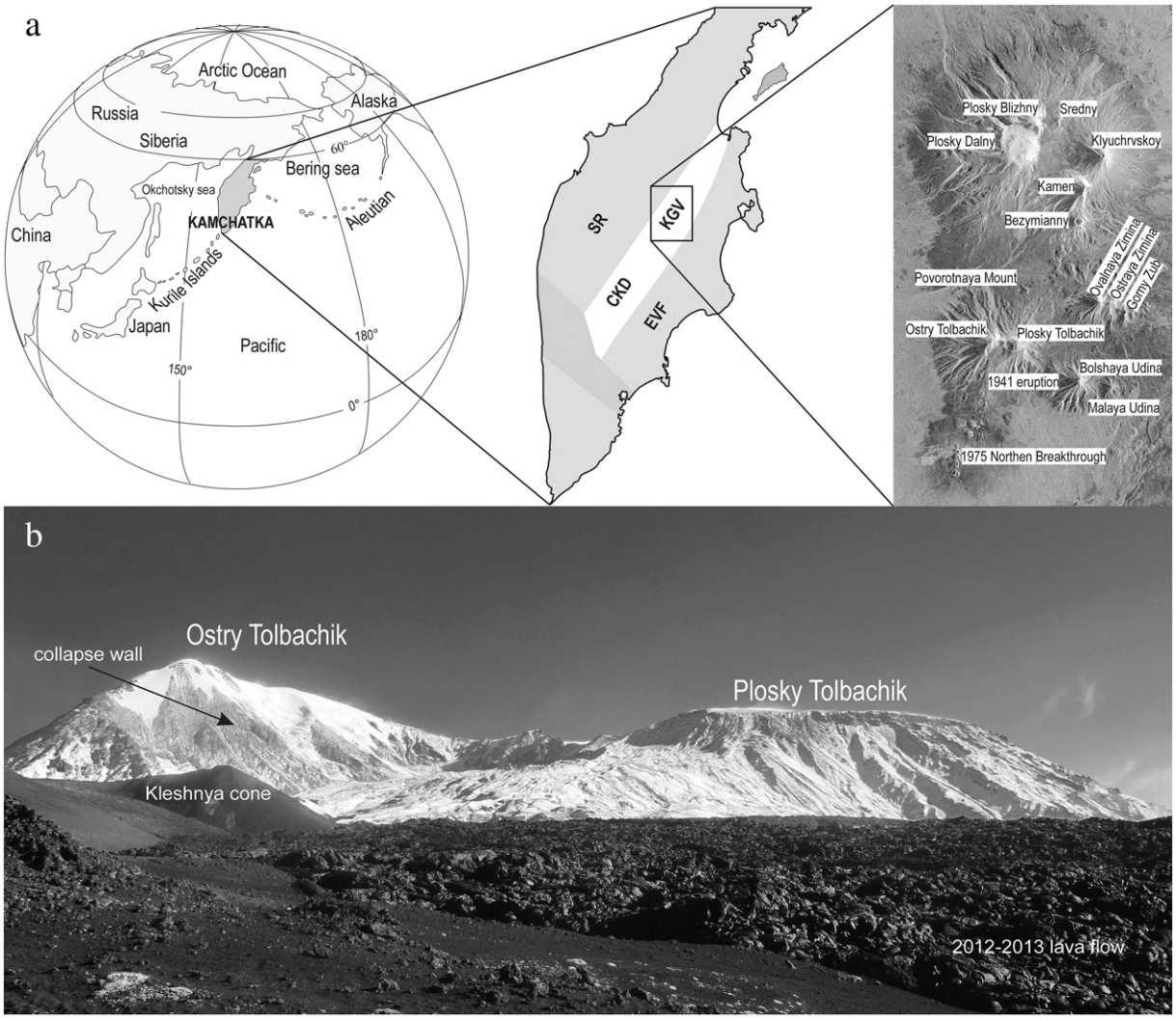

Fig. 1. Overview of the study area. (a) Location of the Tolbachik volcanic massif within Kamchatka and the Central Kamchatka Depression (CKD). Tectonic sketch of Kamchatka after Erlich and Gorshkov (1979) and map of the Klyuchevskaya group of volcanoes with labels of some objects at Tolbachik volcanic massif: EVF — Eastern Volcanic Front; CKD — Central Kamchatka Depression; SR — Sredinny Range; KGV — Klyuchevskaya group of volcanoes. (b) View of Tolbachik volcano from the south. Ostry Tolbachik with collapse wall is on the left, and Plosky Tolbachik is on the right. The lava flow of 2012–2013 eruption is in the foreground.