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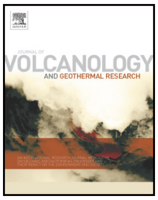

Magmatic plumbing systems of the monogenetic volcanic fields: A case study of Tolbachinsky Dol, Kamchatka

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ABSTRACT

Clusters of small-volume volcanoes that individually may be defined as monogenetic, but have interlinked and interconnected plumbing systems, are used to be categorized as monogenetic volcanic fields (MVF). We argue that such volcanic clusters should be distinguished as separate type of volcanism, intermediate between monogenetic and polygenetic. The magma plumbing system structure of the MVF (its complexity and polymagmatic character) is the key argument for the potential separation of them in a classification. To avoid confusion caused by genetic meaning of the used words we suggest using a term "areal volcanism" or "areal volcanic fields" (AVF instead of MVF) as defining this special type of volcanic activity. Here we provide a review of the main characteristic features of one of the largest Holocene AVF, which is active now – the Tolbachik field of cinder cones in the southern part of Klyuchevskaya volcano group (Kamchatka), known in the literature as Tolbachinsky Dol. This paper is focused on the research of magma plumbing system. We consider structural, morphological, geological, geochemical and petrological data on the erupted basalts and their genesis. Specially planned seismic experiments made in 2010–2015 (seismic tomography and microseismic sounding) allowed modeling of the principal elements of the magma plumbing system of Tolbachik AVF. Analysis of the investigations made in this area shows that Tolbachik AVF has a complex, dynamic, variable magmatic feeding system, which can be visualized as a superposition of subvertical and sublateral magma conduits. The contrast composition of the erupted rocks is caused by their different, although genetically connected, magma sources and mixing processes. One of the long-lived eruptive centers of Tolbachik AVF is Plosky Tolbachik stratovolcano, which lost its independent activity and was captured by Tolbachik AVF in Holocene. The AVF formed rejuvenated volcanism using the feeding system of the stratovolcano like an "old anthill". The magma plumbing system characteristics of Tolbachinsky Dol strongly support the idea of separation of AVF from monogenetic volcanism type in the classification.

1. Introduction

The interest of the research community to the enigma of monogenetic volcanism constantly increases during the last years. To some extent this is caused by the fact that small eruptive centers are less studied in comparison with the large and long-lived stratovolcanoes. But probably the main reason of this attention is the wide manifestation of this type of volcanism in the world: monogenetic volcanoes and fields of monogenetic volcanism (MVF) are described in all geodynamic environments and span practically all chemical compositions (although basaltic spectrum prevails (Connor and Conway, 2000)).

Definitions of MVF which were available from the literature up to the beginning of 2000th are not quite up to date and do not meet the modern understanding of this phenomenon among the main types of volcanism. One of the first papers defining MVF appeared at the beginning of XXth century, but its subject was limited to the rhyolite plateaus (Daly, 1911). The term changed its meaning with time and gained accents on the small size, large areas of distribution, absence of polygenetic edifices, clustering of the vents, similar composition of volcanic products in same area, short activity times, type of magmatic feeding, etc. (Geological dictionary, 1973; Vlodavets, 1971; Vazheevskaya, 1966, 1979; Tarakanovsky, 1978; Williams, 1950; Macdonald, 1972; Nakamura, 1977; Williams and McBirney, 1979; Greeley, 1982; Walker, 1993; Hasenaka, 1994; Takada, 1994; and many, many others). The information and data sets accumulated with time, but the idea of MVFs as clusters of monogenetic short-lived volcanoes, concentrated along the fracture zones, with primitive plumbing systems that allow quick magma supply from the upper mantle to the surface (subvertical conduits, sometimes complicated by small magma chambers) prevailed.

In XXIst century, IAVCEI initiated a Commission on Monogenetic Volcanism. Due to its activity and personal efforts of many researches, during the last decade a series of papers appeared which are dedicated to the systematization of the existing ideas of monogenetic volcanism,

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with quantitative assessments for classification of the eruptive centers. A thorough and detailed summary of the published works on volcanology, geochemistry, structural and tectonic controls, morphology and genetic relationships of the monogenetic edifices and volcanic fields is provided in Smith and Nemeth, 2017; Nemeth and Kereszturi, 2015; Canon-Tapia, 2016; etc. We address the readers to the mentioned works and references therein for the most contemporary review of research in this area of study. Probably the main achievement of the work undertaken is a new classification suggested by (Nemeth and Kereszturi, 2015), which takes into account the following parameters of the monogenetic eruptive centers: morphology of the edifice, history of the eruptive activity (amount of eruptive episodes and time spans between them), type of eruptive activity, amount of magma batches involved, volume of the single events and a total volume of the edifice and products. A very important conclusion of this work is that MVFs can't be classified either as monogenetic or polygenetic volcanism and must be considered as a transitional type between sensu stricto monogenetic and polygenetic volcanoes. Nemeth and Kereszturi (2015) emphasize several main characteristic features that distinguish MVFs. First, it is polymagmatic origin of the eruptive centers (which may be manifested by the eruption of the magmas with contrast chemical composition (within single event or as separate eruptive episodes in the same MVF) or documented in volcanic rocks geochemistry, for example as different isotopic composition of separate magma batches (McGee et al., 2015, etc.). Other frequent features of MVFs are large volume of some edifices and clustering of monogenetic edifices. It is proposed that there are long-lived and complicated magmatic plumbing systems under MVFs. The role of sublateral magma supplying structures in feeding and evolution of MVFs is still not clear. Lateral migration of magma before or during the eruptions is documented in a series of papers (Ishizuka et al., 2008; Grandin et al., 2011, González et al., 2013, Caudron et al., 2015, McGee et al., 2015, etc.). Most well-known examples of such migration are recorded for Iceland volcanoes (Einarsson and Brandsdottir, 1980; Sigmarsson et al., 2000; Sigmundsson et al., 2015), during volcanic unrest stage before submarine eruption near El Hierro island (Martí et al., 2013; González et al., 2013; García-Yeguas et al., 2014; Ibanez et al., 2012), during Manda-Hararo-Dabbahu rift activity in Ethiopia in 2005–2011 (Grandin et al., 2011; Passarelli et al., 2014) and in Lunayyir MVF in 2009 in Saudi Arabia (Pallister et al., 2010; Zobin et al., 2013; Koulakov et al., 2014, 2015). Another, fundamental, difference between MVF and polygenetic type of activity is the absence of the focused central feeding vent. Nevertheless, in some cases it is possible that the plumbing system of MVF may be focused in one channel within an expected time that is probably less than a million of years. The next stage in that case would be a growth of the polygenetic volcano. The reverse development is also possible: when a monogenetic volcanic field is superimposed to the stratovolcano, and captures the remnants of its feeding system (f. ex., Flerov and Melekestsev, 2013). For example, in Klyuchevskaya volcanic group in Kamchatka, there are two volcanic massifs composed by stratovolcanoes with superimposed fissure zones of monogenetic volcanism: Late Pleistocene - Holocene Ostry & Plosky Tolbachik massif and Late Pleistocene – Early Holocene Krestovsky & Ushkovsky massif (Melekestsev et al., 1991; Flerov and Ovsyannikov, 1991; Flerov et al., 2017) (Fig. 1). The latter is less studied then Tolbachinsky Dol probably due to its inactive character, but it is supposed that this massif represents the extinct analog for Tolbachik (Flerov et al., 2017). Clearly, in such complicated cases only a detailed study of the petrology, geochemistry of eruptive products integrated with the geophysical research of the feeding systems may shed light on the situation and help to distinguish an extinct stratovolcano captured by monogenetic zone from the active polygenetic volcano associated with flank parasitic vents.

In this paper, we investigate Tolbachinsky Dol in Kamchatka, Russia (Figs. 1, 2) as an example to demonstrate some features of the magmatic feeding system that are not characteristic for the sensu stricto monogenetic volcanic field (sensu Nemeth and Kereszturi, 2015) or typical polygenetic volcanoes, but may be crucial to segregate monogenetic volcanic fields as a special type of volcanic activity, which we suggest to call areal volcanic fields (AVF). We review the results achieved by various methods of research which were published during the last decade and compare them with our own investigations made in this area to highlight the features that distinguish Tolbachinsky Dol as a true representative of AVF type of volcanic activity.

2. Geological setting

Kamchatka subduction system is located at the north-western part of the Pacific at the convergent boundary of the Okhotsk and Pacific plates. The latter is presently subducting under Kamchatka at the rate of 8–9 cm/year (DeMets et al., 1990, Scholl, 2007, and others). Quaternary volcanism in Kamchatka occurs in three zones, parallel to the trench: Eastern Volcanic Front, graben-like Central Kamchatka Depression (CKD), and Sredinny Range in the back-arc.

Kamchatka is one of the most active volcanic arcs in the world. Besides 30 active stratovolcanoes, it hosts about 20 MVFs, which are situated in the frontal, central and rear-arc parts of the arc. For example, >250 monogenetic edifices are situated in the Southern Kamchatka (which is geodynamically considered as a continuation of the Kurile arc), with the estimated volume of erupted products about 140 km^3 (Laverov, 2005). Sredinny Range, representing the back-arc part, hosts >1000 monogenetic cones and lava fields, and many of them were active through Holocene despite their location about 400 km behind the arc front. The nature of voluminous monogenetic volcanism in Sredinny Range provokes sharp discussions, but it is poorly understood because of the remoteness of the objects. Detailed integrated studies of more accessible MVFs in CKD may provide invaluable keys for solving many of the problems with magma genesis in the back arc.

Tolbachik monogenetic volcanic field, or Tolbachinsky Dol (TD), as its southern part is usually referred to in the literature, is situated in CKD. According to the last studies, CKD is extending with a rate of 17 ± 3 mm/yr over mid-late Quaternary time (Kozhurin and Zelenin, 2017). The total area of the lava plain is 875 km^2 (Braitseva et al., 1984). It adjoins two stratovolcanoes (Ostry and Plosky Tolbachik) and consists of two flanks, located at the SSW and NE slopes of Plosky Tolbachik edifice. Cinder cones, formed here during the last 10 Ka, are located along the SW-NE fissure and tend to cluster (Fig. 1c): 80% of the cones are concentrated in the narrow band 3–4 km wide (Braitseva et al., 1984; Churikova et al., 2015b). TD is an ideal object for testing of the integrated models of magma plumbing systems: due to the two big eruptions happened here during the last 50 years (Great Fissure Tolbachik Eruption in 1975–76 and Tolbachik fissure eruption in 2012–2013) this area is very well studied by a variety of methods.

There are >120 cinder cones up to 300 m high (a.g.l.) in TD. They have contrast composition from high-Mg medium-K basalts to high-Al sub-alkaline basalts and basaltic andesites; there are as well basalts of transitional (intermediate) compositions (Fedotov and Markhinin, 1983; Fedotov et al., 1984; Volynets et al., 1983). During the last eruption (2012—2013) about 0.67 km^3 of basaltic trachyandesite with high K_2O and TiO_2 content were erupted for the first time in the geological history of this volcanic massif (Volynets et al., 2015). Tolbachinsky Dol crosses a stratovolcano (Plosky Tolbachik) with the similar (high-Mg and high-Al) composition of its products (Churikova et al., 2015a). Plosky Tolbachik was formed at the beginning of Holocene and to the time of fissure eruptions of 1975 and 2012 already lost its activity (Fedotov and Markhinin, 1983; Fedotov et al., 1984; Flerov et al., 2015). There were no eruptions at the northern end of the monogenetic field during the last 2000 years (to the north from the stratovolcano edifice).

During the complex geophysical studies of the GFTE in the seventieth of the last century some features of the deep structure, the boundaries location, depths of the supposed zones of the magmatic feeding

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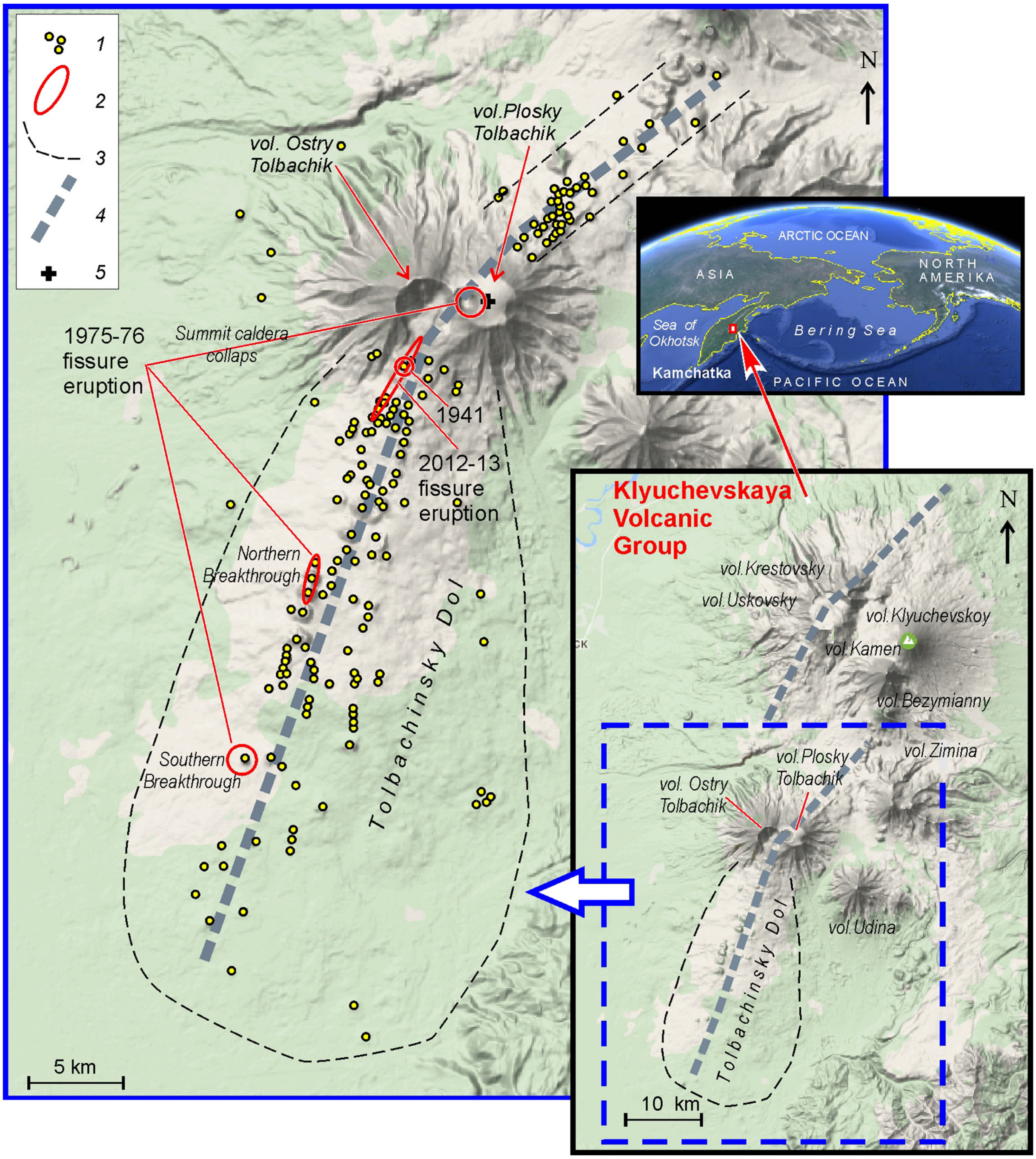

Fig. 1. The Tolbachik volcanic field. Cinder cones are plotted on the map accordingly to the data base of the Institute of volcanology and seismology FEB RAS "Holocene Kamchatka volcanoes", http://geoportal.kscnet.ru/volcanoes/geoservices/hvolc.php. Sites of the last eruptions (1941, GFTE 1975–76, 2012–2013) are outlined. Legend: 1 – cinder cones; 2 – historical fissure eruptions; 3 – nominal boundary of the Tolbachik areal zone; 4 – deep fault; 5 – location of the old crater of Plosky Tolbachik stratovolcano.

and magma reservoirs were determined (Fedotov and Markhinin, 1983; Fedotov et al., 1984; Anosov et al., 1978; Balesta et al., 1977; Balesta, 1991; Zubin and Tarakanovski, 1976; Smirnov, 1979; Fedorchenko et al., 1980; and many others). The research accomplished at the beginning of the 2012–2013 eruption involved seismological, GPS and InSAR data, and resulted in the visualization of the possible location of the magmatic chamber in 2012 during the unrest stage (Ermakov et al., 2014; Fedotov et al., 2015; Kugaenko et al., 2015b; Belousov et al., 2015; Lundgren et al., 2015). (Dobretsov et al., 2016) provides the results of mineral chemistry and melt inclusion studies with the new data on the crystallization conditions in the magmatic chambers (temperature, pressure and depth) for the Tolbachik area. The 2012–2013 eruption also revived the debate on the nature of contrast composition of rocks and resulted in series of publications with new geochemical data for the products of stratovolcanoes and monogenetic activity and new models of magma generation process here (Churikova et al., 2015a; Flerov et al., 2015; Koloskov et al., 2017; Portnyagin et al., 2015; Volynets et al., 2015; etc.). Table 1 provides a summary of the characteristics of TD.

3. The distinctive features of Tolbachinsky Dol: Review and discussion

3.1. Contrast composition of TD basalts and their genesis

Tolbachinsky Dol is composed by the lavas of contrasting composition – high-Mg, medium-K basalts (hereafter high-Mg basalts), high-Al, high-

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Fig. 2. The Tolbachik volcanic field. (a): a chain of cinder cones 40 km long (photo by M. Zelensky). (b): Gas and ash eruptive column above the Northern Breakthrough, GFTE, 1975 (photo by N. Smelov). (c): Clusters of cinder cones in the central part of TD (photo by D. Melnikov). D–F: 2012–2013 Tolbachik fissure eruption. (d): Lava fountain above the new cinder cone on January 5th 2013 (photo by A. Poletaev). (e): Lava river (basaltic trachyandesite) flows from under the new cone (photo by D. Melnikov). (f): Edge of toothpaste lava flow (basaltic trachyandesite) in ~6 km from the eruptive center (photo by D. Melnikov). (g): Panoramic view in the southern part of the Klyuchevskaya volcanic group. On the foreground: ash-and-cinder plain and cones of Tolbachinsky Dol. On the background, volcanoes: 1 – Ostry Tolbachik, 2 – Plosky Tolbachik, 3 – Zimina, 4 – Udina (photo by Yu. Kugaenko).

K basalts and basaltic andesites (hereafter high-Al basalts), and the transitional varieties (hereafter intermediate basalts, K-rich high-Mg basalts – K-high-Mg basalts), divided by their MgO/Al_2O_3 (>0.6, 0.4–0.6 and < 0.4) ratio and K_2O content (>1% and < 1%) (after (Flerov and Bogayavlenskaya, 1983), subdivision by K_2O content – after (Portnyagin et al., 2015)) (Fig. 3). The last eruption brought to the surface products with composition unique for TD – basaltic trachyandesites with high titanium and alkali content. Historical eruptions produced rocks of all mentioned types.

In 1941, during a short event at the SW slope of Plosky Tolbachik, intermediate and K-rich high-Mg basalts were erupted.

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Table 1
Basic information about Tolbachinsky Dol.

Parameter	Description	References
Geographic location	Kamchatka peninsula Klyuchevskaya volcanic group, south-western part	
Tectonic position	Central Kamchatka depression SW-NE fault zone	
Age	Holocene	Braitseva et al., 1984
Amount of eruptive centers	>120	Braitseva et al., 1984
Size of the MVF	S ~ 875 km^2, L ~ 40 km	Braitseva et al., 1984
Size of eruptive centers (for historical eruptions only)	**GFTE 1975–1976** Northern Breakthrough: Cone I: 299 m, volume 0.133 km^3 Cone II: 278 m, volume 0.099 km^3 Cone III: 108 m, volume 0.022 km^3 Lava flows 8.86 km^2, volume 0.22 km^3 Southern breakthrough: Cone I: 165 m, volume 0.016 km^3 Lava flows 35.87 km^2, volume 0.97 km^3 **2012–2013 eruption**: Naboko vents: up to 123 m, volume 0.02 km^3 Lava flows >35 km^2, volume 0.55–0.65 km^3	Inbar et al., 2011 Dvigalo et al., 2014
Historical eruptions	Fissure eruptions: 1739–1740 1941 1975–1976 (GFTE) 2012–2013 Plosky Tolbachik eruptive episodes: Sparse data. Hawaiian type terminal activity, weak explosive events, fumarole activity, and periodic presence of lava lakes inside the caldera. 1728, 1739–1740, 1769, 1788–1790, 1793, 1904, 1927, 1931, 1937, 1939–41, 1975–76. According to Gushchenko (1979) – 18 eruptive episodes during 1700 years.	Braitseva et al., 1984 Churikova et al., 2015b Gushchenko, 1979 Bykasov, 2014 Fedotov et al., 1991
Duration of historical eruptions	1739–1740 no data 1941 1 week GFTE ~17 months 2012–2013–9 months	
Duration of volcanic unrest prior to eruptions	GFTE – 9 days (seismic data) 2012–13 eruption – up to 7 months (trustful seismic and GPS data for 4–5 months)	Fedotov and Markhinin, 1983. Kugaenko et al., 2015a
Volcanic products	Lava, cinder, ash and bombs Composition: High-Mg basalts High-Al basalts Intermediate basalts K-rich high-Mg basalts Basaltic trachyandesites	Volynets et al., 1983 Churikova et al., 2015a, 2015b Portnyagin et al., 2015 Volynets et al., 2015
Morphology of eruptive centers	Cinder cones Lava fields Eruptive fissures During historical time, the Plosky Tolbachik stratovolcano is one of the eruptive centers	Fedotov et al., 1991 Flerov and Melekestsev, 2013 Flerov et al., 2015
Magma batches involved	(1) high-Mg basalt, fractionation of primary mantle melts (2) high-Al basalt to basaltic andesites and basaltic trachyandesites produced by fractionation of (1), but can serve as independent magma batch, feeding the eruption(s) or mixing with high-Mg melts to form intermediate basalts	Portnyagin et al., 2015
Volume of historical eruptions	1941 0.1 km^3 1975–1976 GFTE: 2.18 km^3 2012–2013: 0.65 km^3	Braitseva et al., 1984 Dvigalo et al., 2014 Belousov et al., 2015
Total volume of erupted products	>80 km^3	Braitseva et al., 1984

During the 1975–76 Great Fissure Tolbachik eruption, three types of rocks were observed. Eruption started from the massive explosions of high-Mg basalts at the Northern Breakthrough, which lasted for ~2 month; then the center of eruption activity migrated to the south and it continued with the effusions of high-Al basalts at the Southern Breakthrough. Intermediate basalts appeared at the end of activity at the Northern Breakthrough and at its beginning at the Southern Breakthrough (Volynets et al., 1983; Fedotov and Markhinin, 1983; Fedotov et al., 1984).

In 2012–13 basaltic trachyandesites with high titanium and alkali content were erupted. Besides, during this event the migration of the activity center from the north to the south was again observed at the initial stage of the eruption. Unlike in 1975, this time composition of lavas changed mainly in terms of silica content and accompanying macro- and microelement changes: together with relocation of the activity center from the Menyailov vent to the Naboko vent, SiO_2 and K_2O decreased, MgO, FeO and TiO_2 increased (Volynets et al., 2015). Also, the distance between the vents was much smaller in 2012 than in 1975–76 (~10 km in 1975 vs. ~2.5 km in 2012).

There are two principal ideas of high-Mg and high-Al basalts genetic relationship, when they appear within the same volcanic structure. The first hypothesis implies that parental magmas are independent and generated at different depths, while transitional basalts are the result of their mixing at the lower levels prior to the eruption (Volynets et al., 1983; Fedotov and Markhinin, 1983; Fedotov et al., 1984; etc.) The other approach substantiates high-Mg and high-Al basalts genetic relationship as a result of the fractionation of the single high-Mg parent, producing high-Al daughter melts (as it has been shown for Klyuchevskoy volcano in (Ozerov et al., 1996; Ariskin et al., 1995; Kersting and Arculus, 1994, etc.)). Incompatible elements patterns provide arguments for both points of view (Fig. 4). From one side, the degree of fractionation between most incompatible elements (Nb, Ta, HREE) is rather high and hard to explain within the frames of simple fractionation processes. On the other hand, high-Mg basalts, high-Al

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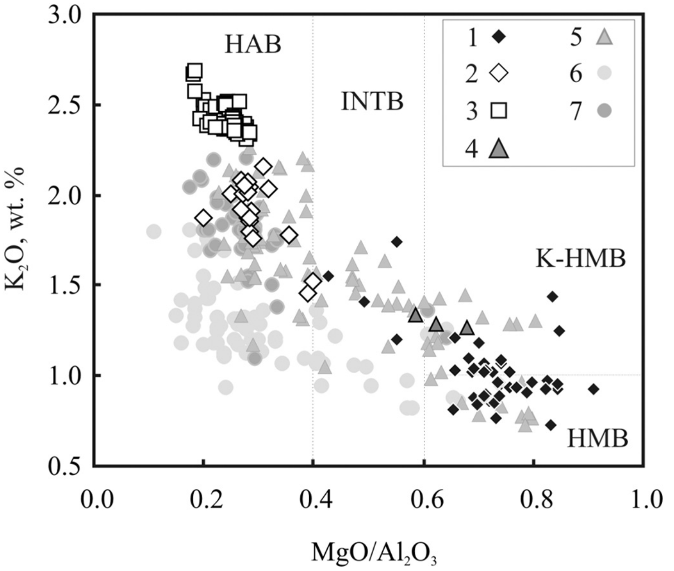

Fig. 3. Classification diagram for the Tolbachik volcanic field rocks, compared to Plosky and Ostry Tolbachik massif rocks. Boundaries and the idea of classification after (Flerov and Bogayavlenskaya, 1983), subdivision of high-Mg basalts to K-rich – after (Portnyagin et al., 2015). HMB – high-Mg basalts; K-HMB – K-rich high-Mg basalts; INTB – intermediate basalts; HAB – high-Al basalts and basaltic andesites, including TBA (basaltic trachyandesites of 2012–2013 eruption). Legend: 1 – 1975 Northern Breakthrough basalts; 2 – 1975–1976 Southern Breakthrough basalts and basaltic andesites; 3 –basaltic trachyandesites of the 2012–2013 eruption; 4 – basalts of the 1941 eruption; 5 – volcanic rocks of the Tolbachik volcanic field, prior to the 1941, 1975–76 and 2012–2013 eruptions; 6 – volcanic rocks forming trend 1 after (Churikova et al., 2015a) – Plosky and Ostry Tolbachik stratovolcanoes (lower parts), dikes, Plosky Tolbachik pedestal, Povorotnaya mt.; 7 – volcanic rocks forming trend 2 after (Churikova et al., 2015a) – Plosky and Ostry Tolbachik stratovolcanoes (upper parts), dikes, cinder cones. Compositions of 1975–76 and 1941 volcanic rocks are from Churikova et al. (2001), Fedotov and Markhinin (1983), Fedotov et al. (1984), Portnyagin et al. (2007), (2015), Volynets et al. (1978), Volynets et al. (2000), and Tatsumi et al. (1995). Compositions of 2012–2013 rocks are from Volynets et al. (2015).

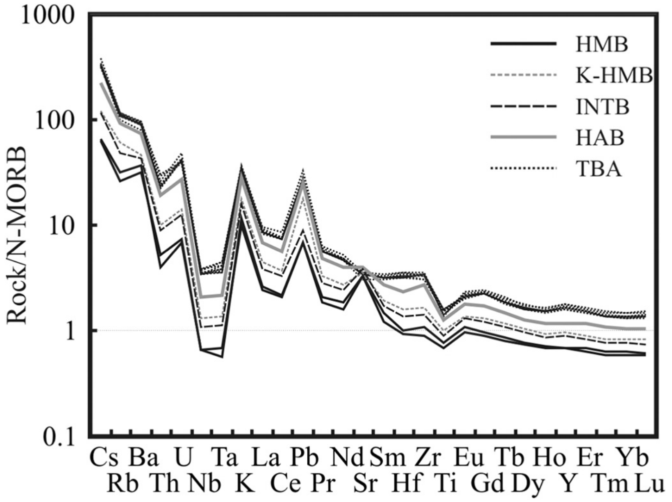

Fig. 4. N-MORB normalized incompatible trace elements patterns for the representative samples of the Tolbachik volcanic field. HMB – high-Mg basalts after Churikova et al. (2001) (sample 655–1975 Northern Breakthrough, MgO = 9.77 wt%) and Portnyagin et al. (2015) (sample K01-25 - Peschanye Gorki, MgO = 10.6 wt%); K-HMB – K-rich high-Mg basalts after Portnyagin et al. (2015) (sample K01-30 – 1004 Cone, MgO = 10.3 wt%); INTB – intermediate basalts after Portnyagin et al. (2015) (sample K01-54 – Pelmen Cone, MgO = 8.1 wt%); HAB – high-Al basalts after Churikova et al. (2001) (sample 22-8 - 1976 Southern Breakthrough, MgO = 4.41 wt%); TBA – 2012–2013 basaltic trachyandesites after Volynets et al. (2015) (MgO = 3.02–4.42 wt%). Normalization values after (Sun and McDonough, 1989).

basalts and basaltic trachyandesites' patterns are practically parallel (with the exception in substantial drops of Sr and Eu concentrations, caused by plagioclase crystallization) and thus do not require additional sources to explain their origin and genetic relationship.

The 2012–2013 eruption provided new material for justifying the second point of view. (Volynets et al., 2015) proposed that variations in compositions of 1975–76 and 2012–13 rocks are consistent with a high degree of low pressure (100–300 MPa), nominally anhydrous fractionation of a parent melt compositionally similar to the 1975 Northern Breakthrough basalt. Geochemistry, petrological observations and modeling are in agreement with the newly erupted material being derived from remnant high-Al magma from the 1975–76 eruption with only slight amounts of cooling (<1 °C per year) during the intervening 36 years. The authors describe processes that caused chemical changes within the course of the 2012–2013 eruption, but do not explain in details the microelement differences between 1975 high-Mg basalt and 2012–13 basaltic trachyandesite.

Churikova et al. (2015a) provided a first detailed investigation of the petrology, geochemistry and geochronology of Plosky and Ostry Tolbachik stratovolcanoes, compared them to the monogenetic field and argued that appearance of the two geochemical trends that exist at Tolbachik massif (medium- and high-K, Fig. 3) is caused by the different activity of water at crystallization: from H_2O-saturated crystallization of high-Mg basalt to unhydrous of the sub-alkaline. According to this work, the difference in microelement concentrations in the rocks of two trends is a result of various enrichment/depletion of the same mantle source due to the upwelling.

Flerov et al. (2015) describe mineralogy and chemistry of high-Al basalts produced by Ostry and Plosky Tolbachik stratovolcanoes (upper Pleistocene – 15–20 Ka), eruptions of the first stage of Holocene TD activity (10–2 Ka) and historical eruptions. They emphasize principal differences in rocks' characteristics of these three associations. Using their observations and thermobarogeochemical estimates they assume that it is impossible to produce basaltic and trachybasaltic rocks by differentiation of the same parent melt. They propose the existence of the large magma reservoir at 20–35 km depth and a series of smaller chambers at 0–15 km depth; evolution of this large reservoir at constant supply of alkaline melts from the deeper horizons provided time-spaced eruptions of high-Al, intermediate basalts and basaltic trachyandesites; they also presume the possibility of the existence of the layered mantle-crust chamber, where trachybasaltic magma assimilated basic crust material.

Koloskov et al. (2015, 2017) analyze petrology and isotopic composition of GFTE and 2012–13 eruption; they suggest that the main processes that influence the composition of the erupted products are (1) the melting degree of the asthenospheric mantle reservoir, and (2) mixing of melts produced by lithospheric and asthenospheric mantle sources. They do not agree with the idea of genetic relationship of the high-Al basalts of the 1975–1976 Southern Breakthrough and 2012–2013 basaltic trachyandesites. According to their opinion, the asthenospheric diapir under Central Kamchatka is one of the feeding sources for the GFTE.

A thorough analysis of the chemistry of the TD rocks is provided in (Portnyagin et al., 2015). They show that REFC processes (recharge-evacuation-fractional crystallization, after (Lee et al., 2014)) can explain all the particular characteristics of volcanic rocks in this area. According to this point of view, primary magmas, formed at ~60 km depth, are fractionating at depths <35 km in the open system with periodical replenishment by the primitive melts, followed by mixing of magmas of both types, further fractionation and, finally, eruption (s). Therefore, high-Mg basalts are the result of fractionation of the primary mantle melts. High-K high-Al basalts, which are the dominant type in TD, and basaltic trachyandesites of the last eruption are described as steady-state compositions – the products of the long-term evolution of this long-lived system and fractionation in situ. (Portnyagin et al., 2015) argue that Tolbachik geochemical characteristics meet the main criteria allowing to apply REFC processes to their genesis (which are listed as

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(1) existence of steady-state compositions and (2) their similarity to the compositions of the equilibrium crystallization; (3) dependence of REFC cycles, needed to achieve the steady-state composition, on the element distribution coefficient, and (4) potential high fractionation between the incompatible element). Transitional basalts are the result of mixing of the evolved (high-Al basalt) and primitive (high-Mg basalt) magmas. An advantage of this hypothesis is that it explains fractionation between incompatible microelements in high-Mg and high-Al basalts, which is interpreted with difficulties in the frames of the simple fractionation in the closed system. Conclusions made by (Volynets et al., 2015) do not contradict with this work – they explain part of the REFC cycle. So, here we see a conception which at certain parameters combines the models of genetic relationships, fractionation and mixing of magmas.

Therefore, the analysis of the existing petrological models shows ambiguity in the interpretation of the nature of processes which lead to the observed chemical diversity of magmas. There is also no agreement on the depth of Mg and Al magma reservoirs. At the same time, the position of most authors is more or less consistent with the concept of magma mixing processes, though they do not reach a consensus on the origin of mixing components from one or more sources.

3.2. Uneven temporal and spatial distribution of eruptive centers with different magma compositions. Superposition of AVF to the Plosky Tolbachik stratovolcano

One of the main TD features is its superposition to the Plosky Tolbachik stratovolcano. The formation of TD started at Late Pleistocene – Holocene boundary with opening of the large fissure zone. According to the petrological studies of (Churikova et al., 2015a) since that time rocks of high-K series, forming the lava plain of TD, also prevail in composition of the stratovolcano, while its lower part and basement are built by middle-K high-Mg basalts and their derivatives. Upper parts of PT (summit lavas and pyroclastics) are chemically identical to high-Al basalts of TD. (Flerov and Melekestsev, 2013; Flerov et al., 2015) propose that PT already lost its activity at the beginning of Holocene and was captured by the fissure zone of monogenetic volcanism, which inherited its feeding conduits. If this indeed was the case then during the last two thousand years the stratovolcano worked as a subordinate structure – one of the eruptive centers of the regional zone of cinder cones.[1] From this point of view, all eruptions happened in Holocene at the slopes of PT, including the 2012–13 eruption, are as a matter of fact the manifestation of the fissure volcanism, typical for MVF, i.e. they can't be considered as parasitical vents of the stratovolcano (Flerov and Melekestsev, 2013; Flerov et al., 2015, etc.)

The volcanic activity in Tolbachinsky Dol continues throughout Holocene. Once in several hundred years large fissure eruptions happen here, producing >1 km^3 of lava and pyroclastic deposits. The history of this area is described in details in (Braitseva et al., 1984; Churikova et al., 2015a, 2015b). It is divided to two main stages: ~10–2 Ka and last ~2 Ka. At the beginning of Holocene this volcanic fields was about 60 km long and 13–15 km wide, and the basalts were erupted around its whole area. Effusive eruptions with exclusively high-Al basaltic composition prevailed during the first stage. The second stage (2 Ka – now) is principally different. The spatial distribution of the eruptive centers changed. The active area decreased in size, the northern part of the TD (to the north from PT) lost its activity. The volcanic activity was now concentrated in the narrow band only 3–4 km wide. Besides high-Al basalts, magmas with high-Mg basaltic composition appeared on the surface. Large cinder cones up to 300 m high a.g.l. were formed in the central part of TD, the explosivity index of the eruptions increased (sometimes up to 30–70%). The reason of such abrupt change in the composition, style, volume and distribution of eruptions at ~2 Ka is still under debate. The wider area involved in the eruptive process at the beginning of Holocene can be explained by the end of glaciation period which enhanced the decompression effect. Activation of the deep fault, in turn, caused the appearance of more primitive high-Mg magma on the surface and grouping of the eruptive centers along the fissure zone. Studies of Churikova et al. (2015a) confirm that high-Mg middle-K magmas existed below Tolbachik zone since Pleistocene times. Therefore, observations on the evolution of the volcanic activity in TD throughout Holocene may serve as a key for understanding the changes in geodynamic environment on a larger scale.

The interesting feature of TD at the second stage of its evolution (including our time) is the uneven spatial distribution of the eruptive centers with contrast composition of magmas (Fig. 5). High-Al basalts are located in the northern part of TD and Plosky Tolbachik stratovolcano, high-Mg basalts were erupted mainly in the middle part of TD, while intermediate basalts dominate in its southern part.

So, Tolbachik VF substantially changed during Holocene both in terms of area and composition of erupted rocks.

The temporal variability of Tolbachik VF is revealed both in smaller time spans (e.g., within the last 100 years). This is shown using the examples of the historical eruptions in (Kugaenko et al., 2015b). All known historical fissure eruptions at TD were preceded and sometimes accompanied by the activation of Plosky Tolbachik stratovolcano (Fedotov and Markhinin, 1983; Fedotov et al., 1984; Kugaenko et al., 2015a,b) and increased seismic activity under it, which was interpreted as a result of magma movement in one or two peripheral magmatic reservoirs (Fedotov et al., 2011; Ermakov et al., 2014; Belousov et al., 2015)). For the last three eruptions (1941, GFTE and 2012–13) the accompanying activity of the stratovolcano decreased with each next event. These changes may confirm the assumption of the degradation of the PT feeding system under the influence of AVF.

Therefore, Tolbachik AVF is complicated by the PT edifice, which represents one of the eruptive centers of AVF during at least Late Holocene. The evolution of AVF was accompanied by the change in composition of volcanic rocks. The uneven spatial distribution of the basalts with contrast composition bears testimony on the lateral differences in the magmatic plumbing system of the AVF, while stratovolcano's feeding system is gradually degrading.

3.3. About the structure of the magmatic plumbing system

A SW-NE fissure zone that crosses Tolbachinsky Dol and Plosky Tolbachik edifice is concerned as the main structural element of the tectono-magmatic model of TD (Fig. 1). This structure was revealed and described by Ermakov et al. (1974) and Ermakov and Vazheevskaya (1973) as a deep fault. It was assumed that the roots of this fault lie at crust – upper mantle boundary (not <30–35 km) (Fedotov and Markhinin, 1983; Fedotov et al., 1984). Later Ermakov et al. (2014) and Ermakov and Ermakov (2006) argued for shallower depth of this fault (10–15 km) and supposed that the plane of the fault falls to the east (with the angle of incidence 75–80°). They considered this fault as a main magma conduit feeding TD.

The first model of TD plumbing system was suggested right after GFTE (Fedotov and Markhinin, 1983; Fedotov et al., 1984; Volynets et al., 1983). The eruption was accompanied by the formation of caldera at the summit of Plosky Tolbachik stratovolcano; it was supposed that the basaltic magma migration from the chamber under PT to the Southern Breakthrough area caused this event. The earthquakes swarms stretched for 50 km to the south from PT, indicating hidden dikes propagation and illustrating the scale of the ongoing events. The model of the magmatic feeding of GFTE eruptive centers, spatially separated along the fault, was based on the hypothesis of mixing of the melts coming from different depths and assumed that there are sublateral magma conduits (Volynets et al., 1983). The depths of magma generation and conduits locations remained controversial. The authors of this model also proposed that during the geological history of TD, strong eruptions

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[1] As we see it, Plosky Tolbachik can be figuratively visualized as an old abandoned anthill: its internal structure permits magmas of the areal zone easily reach surface.

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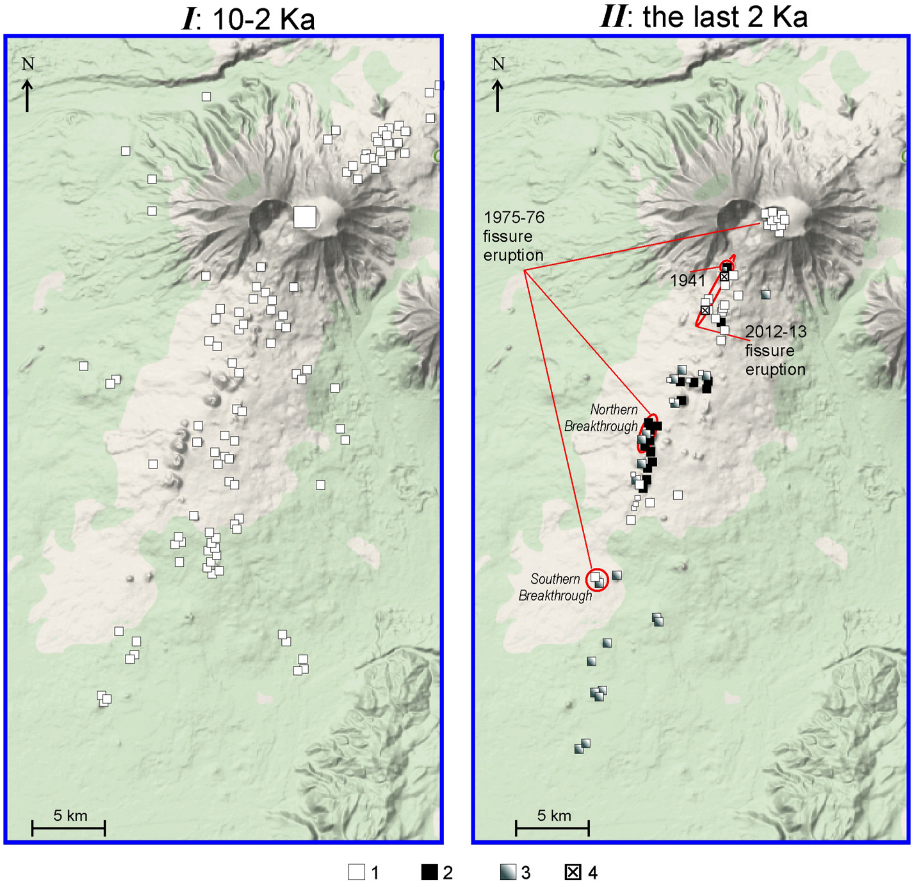

Fig. 5. Evolution of the Tolbachik VF in Holocene: change of the activity area and composition of erupted rocks. Legend: 1 - high-Al, high-K basalts and basaltic andesites (HAB), 2 - high-Mg, medium-K basalts (HMB); 3 - the transitional varieties (intermediate basalts – INTB); 4 - basaltic trachyandesites (TBA).

of deeply originated high-Mg basaltic magmas triggered the eruptions of high-Al basalts stored at lower crustal levels.

The development of the seismic network in Kamchatka allowed receiving better and more detailed data on the earthquakes in Klyuchevskaya volcanic group. Seismic observations in Klyuchevskaya volcanic group area started in 1946 from the installation of the seismic station in Klyuchi village (~50 km from Klyuchevskoy volcano). In 1975, at the beginning of the 1975–76 eruption, three seismic stations worked in Klyuchevskaya volcanic group area (Fedotov et al., 1984), and in 2006 there were already 12 permanent radiotelemetric seismic stations. These stations generally are equipped with short-period ($T = 1.2$ s) 3-component seismometers SM-3 (spectral range: 0.5–20 Hz, dynamic range: ~54 dB). Detailed review of seismological observation in Kamchatka is presented in (Gordeev et al., 2013; Chebrov et al., 2013). Therefore, at the beginning of the twenty first century, it became possible to use seismic tomography for the studies of the internal structure of this area.

Using seismic tomography results, geological and geophysical data, Fedotov et al. (2010) provided complex model of the deep structure of Klyuchevskaya volcanic group (Fig. 1). This model is based on the assumption that the magmatic sources and magmatic reservoirs of all volcanoes of Klyuchevskaya group are interrelated. Magma supply to the peripheral chambers and craters of the active volcanoes is carried out by long vertical channels, while monogenetic centers feeding is implemented through the fissures, which solidify after the eruptions. But the magmatic feeding of TD in this model is in accordance with the views formed in 1970–80 during GFTE research.

A tectono-magmatic model of Tolbachik areal zone was proposed by Ermakov et al. (2014). They took into account geological data, seismic tomography and the spatial distribution of the earthquakes. According to this model, the intrusions are formed in the upper wing of the inclined deep fault. This process is accompanied by the seismicity concentrated to the east from the fault axis. The magmatic sources of the monogenetic volcanism are proposed at 10–15 km depth b.s.l. to the north from Plosky Tolbachik and under its edifice (anomaly G-1 at Fig. 6). The model also includes the peripheral magma chambers under PT at ~0 and ~3 km depth b.s.l.

Nevertheless, due to the weak local seismicity and remoteness from the main regional group of the seismic stations, Tolbachinsky Dol was on the periphery or even outside the area of the trustworthy modeling in the first series of the published works on the tomography of Klyuchevskaya volcanic group. Therefore, at the initial period of seismic tomography in Kamchatka this method did not bring any new data on the internal structure of TD.

After 2012–2013 eruption a new model was proposed for the magmatic system of PT and TD by Belousov et al. (2015). This model took into account the new data received during the eruption and was to some extent in agreement to the above mentioned ideas. It includes 4 magmatic reservoirs of different size and depth, which are connected by channels (Fig. 6). The existence of magmas of contrast composition is interpreted in accordance with (Portnyagin et al., 2015). This model also provides the possibility for the lateral deep migration of basalts along the rift.

However, all above hypotheses are heuristic – they are not supported by quantitative estimates.

A new stage in the investigations of the crustal structure in TD area was opened by the specially planned seismic research, as a result of which the quantitative values were received, i.e. parametric estimates of anomalies that can be related to the elements of magmatic feeding system.

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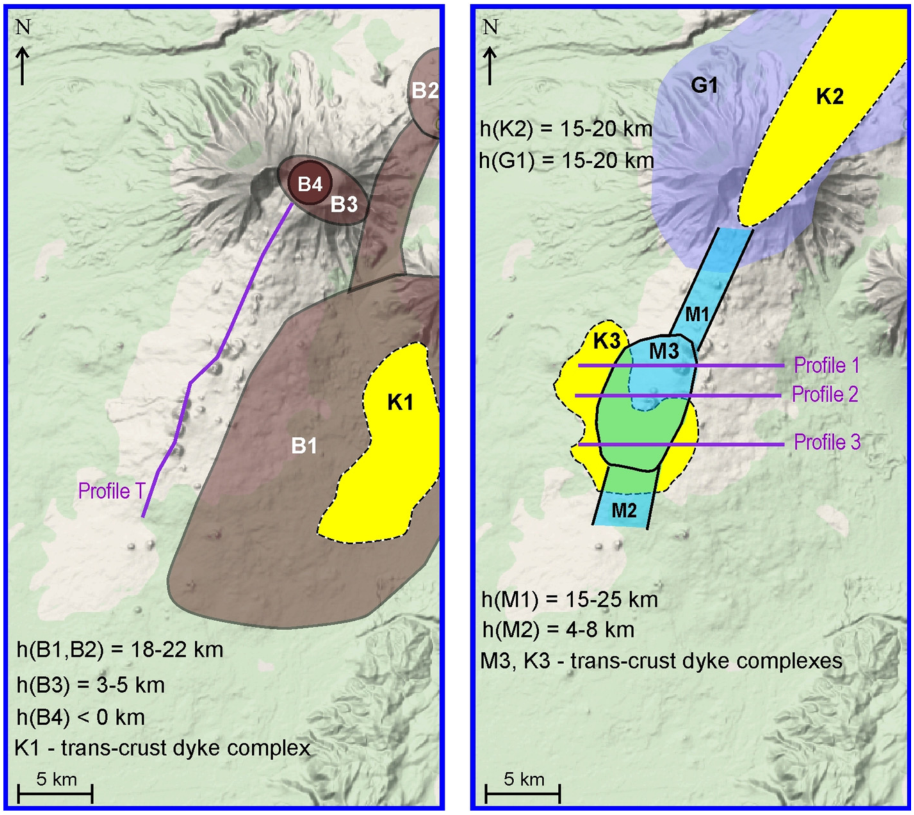

Fig. 6. Elements of the magma plumbing system of the Tolbachik VF according to the results of different authors. B – elements of model by (Belousov et al., 2015): B1 – high-Mg magma storage zone under Tolud seismic cluster; B2 – high-Mg magma storage zone under north-eastern part of Tolbachik VF; B3 – high-Al magma storage zone under Plosky Tolbachik at 5 km b.s.l. depth; B4 – shallow high-Al magma storage zone under Plosky Tolbachik that was emptied and destroyed during 1975–76 eruption. K and G are determined by seismic tomography data, M – by MSM. The boundaries of the parametric anomalies that are interpreted as the elements of magma plumbing system of Tolbachik volcanic zone and their depths are shown on the figure. K1, K2, K3 - possible magma storage (dyke complexes) by (Koulakov et al., 2017): K1 – magma storage, found to the east from VF; K2 – part of magma plumbing system common for Plosky Tolbachik and northerner volcanoes of the Klyuchevskaya group (Bezymianny, Klyuchevskoy); K3 – magma storage, under the central part of Tolbachik VF. G1 - magma storage by (Ermakov et al., 2014). M1, M2, M3 – elements of magma plumbing system under central part of Tolbachik VF according to MSM results (Kugaenko et al., 2013, 2018): M1 – sublateral magma conduit at 15–25 km b.s.l. depth, going under PT; M2 – sublateral magma conduit at 4–8 km b.s.l. depth, going along the fault from the central to the southern part of VF; M3 – trans-crust area of magma conductivity (dyke complex) under the central part of VF, under the chain of the highest cinder cones. The cross sections along the three parallel profiles across M3 are shown at Fig. 7.

In 2014–2015, a temporal network of 30 additional seismic stations was installed in Tolbachinsky Dol area. It allowed creation of the first seismotomographic model for the southern part of Klyuchevskaya volcanic group and TD (Koulakov et al., 2017). The tomographic inversion was performed using the LOTOS code (Koulakov, 2009), which enables simultaneous inversion of the velocities of P and S waves and source parameters. For TD area, three spatially separated feeding sources were revealed (K-1, K-2 and K-3, Fig. 6). They are interpreted as systems of magma supplying fissures – dyke complexes. One of the sources is visualized under the central part of TD. Dyke complex responsible for PT feeding is subvertical up to 10–15 km b.s.l. depth, while in deeper horizons this system of fissures obliquely continues to the north and joins the feeding zone of the volcanoes of the central part of Klyuchevskoy group. This is fundamentally different from the classical views to the subvertical channels (Fedotov et al., 2010).

Starting from 2010, the investigation of the internal structure of the crust in Tolbachinsky Dol area was done by microseismic sounding method (MSM) (Gorbatikov et al., 2008, 2013, Gorbatikov and Stepanova, 2008; Gorbatikov and Tsukanov, 2011; Tsukanov and Gorbatikov, 2015; for more detailed methodology review, the readers are referred to the Supplementary materials for this paper). This method uses low-frequency (f < 1 Hz) microseismic fluctuations as probing signals. They are registered step-by-step at the given points of the polygon. The survey was accomplished in 2010–2015 at >450 points with 500 m step. It includes the central part of TD, 2012–2013 eruption area and Plosky Tolbachik edifice up to the edge of the summit caldera. With MSM, the following elements of the magmatic feeding system of TD were revealed: (1) sub-lateral structure at 15–25 km b.s.l. depth that continues under PT (M1 at Fig. 6); (2) sub-lateral magma conduit at 4–8 km b.s.l. depth, going along the fault from the central to the southern part of TD (M2); large (~15–20 km along the fault zone and ~9–10 in the transverse direction) trans-crust magma conduction zone under central part of TD, under the chain of the highest cinder cones (M3). More detailed research of the latter heterogeneity revealed alternate magma reservoirs and feeding conduits as well as regular patterns in their location and configuration (Kugaenko et al., 2011, 2013). Fig. 7 demonstrates three vertical profiles of M3 zone, which goes through different Holocene fissures. There are relatively low speed anomalies, which can be interpreted as magma conduits or magma-containing areas. The comparative analysis shows that the profiles are similar, with similar heterogeneities on them.

The anomalies, identified under Tolbachinsky Dol by two independent methods, are in general agreement. The anomaly under the central part of TD, where the largest cinder cones were formed, is clearly seen both in seismotomographic and MSM-profiles (K-3 and M3, Fig. 6). This may mean that in this part of Klyuchevskaya volcanic group there is a trans-crust zone where magma, most likely, exists even during the periods of prolonged absence of the eruptions. In its upper parts it may be envisaged as dyke complex. Microseismic sounding provides more detailed information on anomalies configuration and allows complementing the tomographic model with sublateral elements. Both methods of research do not reveal any substantial shallow

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magma reservoirs under Plosky Tolbachik stratovolcano, described in (Ermakov et al., 2014; Fedotov et al., 2011; Belousov et al., 2015).

Therefore most recent seismic investigations on a base of quantitative estimates show that Tolbachinsky Dol has a complicated magma plumbing system, which is a superposition of subvertical and sublateral elements, including magmatic reservoirs and feeding conduits. This system allows various ways of magma supply to the surface (Figs. 7, 8) (Kugaenko et al., 2018; Volynets and Kugaenko, 2015). Elements of the magma plumbing system differ in various segments of TD. The configuration of the magmatic system allows magma migration along monogenetic field zone and do not contradict the magma mixing model, which is a base for some of the petrogenetic models for basalts of TD.

4. Conclusions

The understanding of the nature of monogenetic volcanic fields is in constant progress.

Tolbachinsky Dol, one of the well-studied monogenetic volcanic fields, has several distinctive features, which are not typical for separate monogenetic edifices or polygenetic volcanoes. First and most important, TD has a complicated, dynamic, variable magmatic plumbing system. It is worth to list here the main features of TD and its magmatic plumbing system:

(1) Spatial concentration of the eruptive centers along the elongated zone of the deep fault and clustering of the monogenetic edifices;
(2) Polymagmatic genesis of separate eruptive centers (eruption of the magmas with contrast composition and/or multiple sources involved in magma generation). High-Mg basalts are produced by fractionation of the primary mantle melts; high-K high-Al basalts and basaltic trachyandesites of 2012–2013 eruption are the result of the long-term evolution of this magmatic system, with fractionation of Mg basaltic magmas in situ, while basalts with intermediate composition are produced by mixing between high-Al and high-Mg basalts.
(3) Uneven spatial distribution of eruptive centers of different composition.
(4) Temporal variability of volcanic activity in Tolbachinsky Dol.
(5) Tolbachinsky Dol is superimposed to Plosky Tolbachik stratovolcano. Most likely, in Holocene PT serves as one of the eruptive centers of the areal volcanic field. Geophysical data confirm its subordinate role with respect to the superimposed areal volcanic field.
(6) New instrumental seismic data allow us to complement and detail the model of Tolbachinsky Dol magma plumbing system, on a base of quantitative estimates. The results of the microseismic sounding (2010–2015) and detailed seismic tomography experiment (2014–2015) revealed parametric anomalies which can be interpreted as elements of the magma plumbing system. Tolbachinsky Dol has a complicated magma plumbing system, which can be visualized as a superposition of subvertical and sublateral magma conduits. Our research reveals a system of independent magma conduits and magmatic reservoirs. Finally, there are no pronounced subvertical channels above the crystalline basement level. This conclusion contradicts the existing ideas of simple subvertical magma supplying channels, feeding the monogenetic centers. Petrological data confirm the existence of the complicated magmatic system with mantle feeding and open fractionation in the crustal reservoirs.
(7) Characteristics of Tolbachik volcanic field strongly support the separation of MVFs from monogenetic and polygenetic

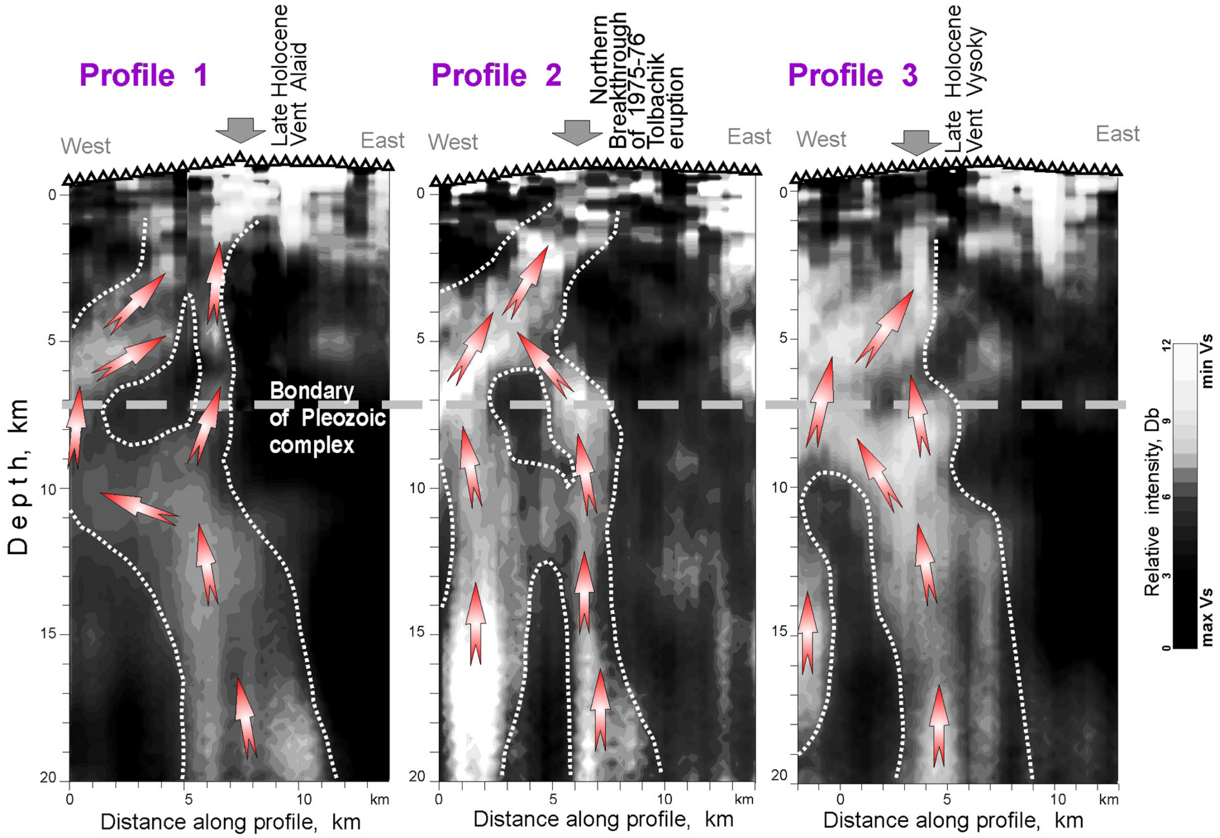

Fig. 7. Vertical cross sections along microseismic profiles 1–3 (Fig. 5) showing deep distributions of relative seismic velocity, modified after (Kugaenko et al., 2013, 2018). In this view the low velocity heterogeneities are light-colored. Dotted lines show the boundaries of the low velocity structures, which are considered as the elements of the magma plumbing system in M3 zone at Fig. 5. Most light-colored areas are interpreted as magma storage zones. Arrows show probable paths for basaltic magma movement to the surface.

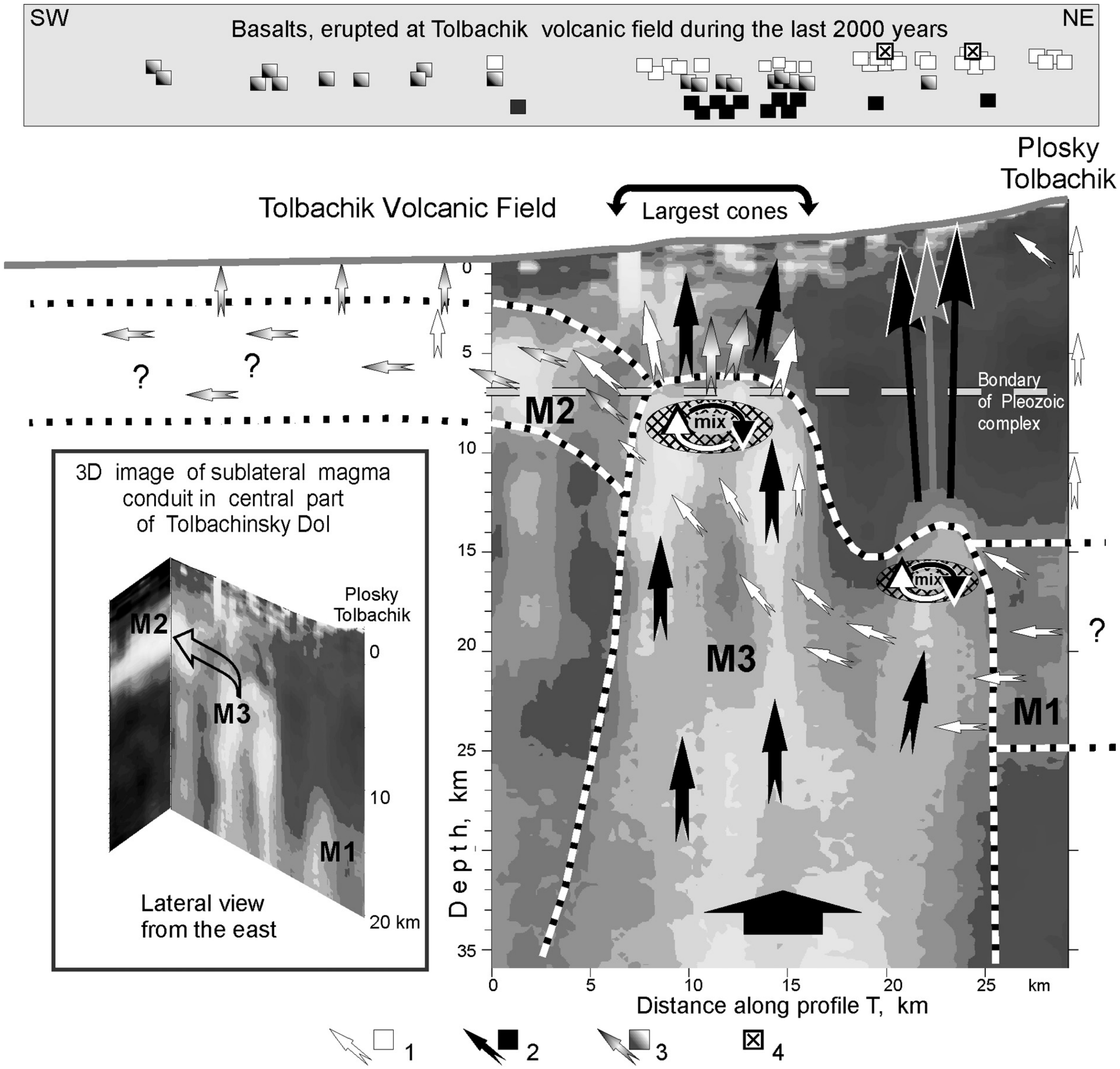

Fig. 8. The conceptual scheme of magma plumbing of Tolbachik VF on a base of vertical cross section along the microseismic profile T (Fig. 7), modified after (Volynets and Kugaenko, 2015; Kugaenko et al., 2018). Arrows indicate possible pathways for basaltic magmas of different composition according to the model of magma fractionation and mixing (Portnyagin et al., 2015). The scheme provides possible explanation for the uneven spatial distribution of the basalts of different composition in Tolbachik VF. Legend as at Fig. 5.

volcanoes in classification suggested by (Nemeth and Kereszturi, 2015) (Table 2). In Russian (mainly, but not exclusively) literature there is a special term for this type of volcanic activity – “areal volcanism” (for example, Vlodavets, 1971; Vazheevskaya, 1966, 1979; Tarakanovsky, 1978, etc.). Taking into account all the facts stated above, which come into conflict with the definition of the monogenetic volcanism sensu stricto, we believe it might be prudent to accept term “areal volcanism” or “areal volcanic fields” (AVF instead of MVF) as defining this special type of volcanic activity, because it allows eliminating confusion caused by genetic meaning of the used words. The term “areal” emphasizes the spatial distribution of a phenomenon of a certain type on the earth surface. That allows applying it to clusters of small-volume volcanoes, where each volcano is formed as a result of a single eruptive episode, but the geochemical features of the erupted lavas indicate their genetic affinity, caused by the interlinked and interconnected plumbing systems of these eruptive centers.

Table 2
Principal reasons for classification of AVF as a special type of volcanism based on Tolbachinsky Dol example.

	Composition of magma	Type of volcanic edifices in the field	Areal distribution of eruptive centers	Polygenetic volcanic edifices	Magmatic plumbing system
Monogenetic volcanic fields in the old classification	Constant	Monogenetic	Separate eruptive centers	Absent	Primitive
Tolbachinsky Dol – a possible example of the **areal volcanic field**	Contrast	Monogenetic and polygenetic	Clustering of eruptive centers	Present and captured by AVF	Complex system of subvertical and sublateral magma conduits

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Therefore, integration of various methods in volcanic fields' studies allows avoiding ambiguity in the interpretation of the results. While the investigations of Tolbachik AVF continue, we would like to emphasize the importance of the multidisciplinary approach as the main instrument to create trustful models of the processes hidden in the depths.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jvolgeores.2018.03.015.

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