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Eruptions in the Northern Group of Volcanoes, in Kamchatka, during the Early 21st Century

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Abstract—The early 21st century saw increased eruption activity of major volcanoes in the Northern Group of Kamchatka, namely, Sheveluch, Klyuchevskoy, Bezymianny, and the Tolbachik Fissure Zone. The growth of an extrusive dome on Sheveluch andesitic volcano has occurred, with the dome reaching a height of 600 m after 38 years of nearly uninterrupted eruption activity. An 8-year period of relative quiet was followed by ten summit eruptions and two lateral vent openings on the Klyuchevskoy basaltic volcano. Explosive–effusive eruptions were observed nearly every year on the Bezymianny andesitic volcano. A 36-year quiet period gave way to a new eruption in the Tolbachik regional fissure zone.

Keywords: volcano, eruption, Sheveluch, Klyuchevskoy, Bezymianny, Tolbachik fissure zone, Kamchatka

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INTRODUCTION

The volcanoes in the Northern Group of Kamchatka (NGK) are situated in the junction zone between the Kuril–Kamchatka and Aleutian Island arcs, the Emperor Ridge, and the Emperor volcanic area. The interaction of these structures at depth results in high levels of seismic and volcanic activity in the region, and discordance between dynamic processes at different levels in the lithosphere (Gontovaya et al., 2004, 2010; Fedotov et al., 2010). The group includes five volcanoes: the Sheveluch andesitic volcano, the basaltic Klyuchevskoy, andesitic Bezymianny, basaltic Plosky Tolbachik with a summit caldera of the Hawaiian type and two fissure zones of cinder cones (northeastern and the southern, or the Tolbachik zone), and the andesitic Ushkovsky volcano (Figs. 1, 2).

The detailed investigations of the NGK volcanoes and eruptions started in 1935 as the F.Yu. Levinson-Lessing Kamchatka Volcanological Station was set up in the village of Klyuchi and have been continued by researchers at the Institute of Volcanology and Seismology (IV&S), Far East Branch, Russian Academy of Sciences (FEB RAS) (http://www.kscnet.ru/ivs/) until the present. The seismic monitoring of the NGK volcanoes started in 1946 at the Kamchatka Volcanological Station and has been continued until the present by the Kamchatka Branch of the Geophysical Survey (KB GS) RAS (http://www.emsd.ru/). From 2000 on continuous video observations of the NGK volcanoes have been conducted, from 2014 an analysis of the state of volcanoes has been carried out using the Remote Monitoring of Kamchatka and Kuril Islands Volcanic Activity information system (IS) (VolSatView, http://volcanoes.smislab.ru)" (Girina et al., 2017, 2018b, 2019a; Gordeev et al., 2016).

SHEVELUCH VOLCANO

Sheveluch is the northernmost volcano in Kamchatka, as well as being the most dangerous among them (Melekestsev et al., 1991) (Fig. 3). It typically exhibits two types of eruption, namely, catastrophic events that hurl eruption clouds to heights as great as 25 km above sea level (a. s. l.) and discharging volumes of pyroclastic material over 1 km^3 in volume and paroxysmal eruptions related to the growth of the extrusive dome (the ascent of ash clouds up to 15 km a. s. l., with volumes of pyroclastic material below 0.7 km^3) (Gorshkov and Dubik, 1969; Melekestsev et al., 1991). There have been two catastrophic eruptions as far as we know, in 1854 and in 1964 (Gorshkov and Dubik, 1969).

A new extrusive dome began to grow in the crater of the volcano from August 1980. The growth has continued until the present and was accompanied by explosive eruptions (Figs. 4, 5). Three stages have been identified in the growth of the dome: I, the dome began to grow from August 1980 until the end of 1981; II, from April 1993 to January 1995; and III, from

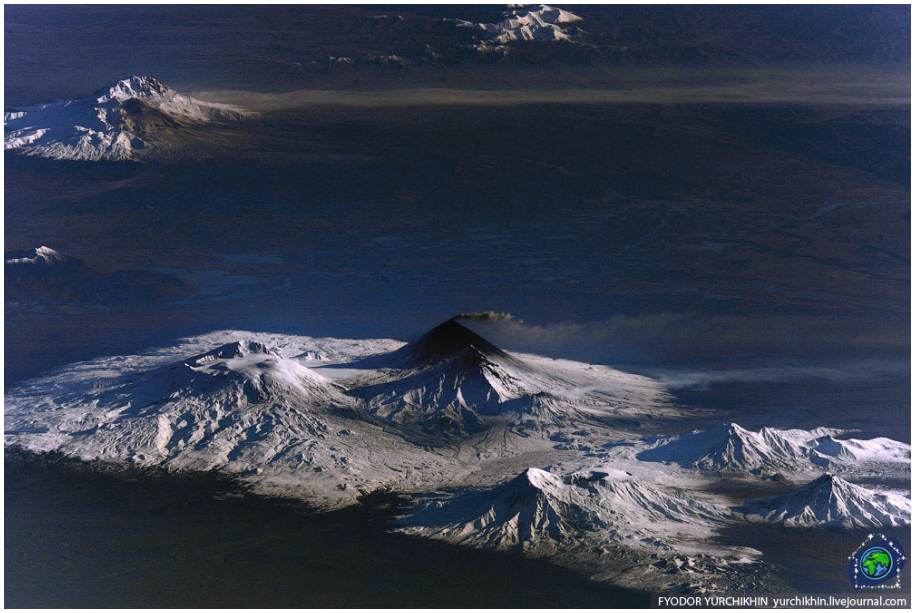


Fig. 1. The Northern Volcanic Group, Kamchatka. Photographed by the cosmonaut F. Yurchikhin from the international space station on September 28, 2010.

Fig. 2. Volcanoes of the Northern Volcanic Group, Kamchatka: In the foreground is Bezymianny, in the center Kamen, Klyuchevskoy is behind it; on the left are Ushkovsky and Krestovsky volcanoes. Photographed by Yu.V. Demyanchuk on September 16, 2014.

2001 until the present (Zharinov and Demyanchuk, 2008; Fedotov et al., 2001, 2004) (see Figs. 4, 5). The start of the volcano's activity and the extrusive eruption during stage I were not preceded or accompanied by any appreciable seismic events (Gorelchik et al., 1996). Stages II and III involved explosive and explosive–effusive types of eruption that replaced the extrusive type. The rate of earthquakes reached 250–300 per day (24 hours) with energy classes reaching 7.0 during the precursory period before the 1993 eruption

Fig. 3. Sheveluch Volcano, photographed by Yu. Demyanchuk on February 21, 2019.

and during the dome growth (stage II). Stage III showed a higher seismicity rate, reaching 300–400 events per day, with the maximum energy class reaching 9.5 (Fedotov et al., 2004). Some changes in the eruption behavior took place after the paroxysmal eruption of May 9, 2004, with a viscous lava flow being noticed for the first time on the extrusive dome (Gorbach, 2006; Girina et al., 2004). The discharge was at a minimum when the extrusive dome first began to develop in 1980–1981, that is, below 0.1–0.2 million m^3 per day; it then reached 1.2 million m^3 during stage II and 0.6 at the beginning of stage II (2001 and 2005) (Zharinov and Demyanchuk, 2008; Fedotov et al., 2001, 2004).

The first paroxysmal eruption during stage III occurred May 19–22, 2001. The eruption column rose to reach 15 km a.s.l. (or 12.5 km above the lava dome), with pyroclastic and mud flows extending along the Baidarnaya River for a distance of 18 km as measured from the volcano (Fedotov et al., 2001, 2004) (Table 1). The extrusive dome began to grow rapidly, with the diameter of its base being 1350 m in May 2004, the diameter of its crown being 240–270 m, and the height from the crater top being 520 m; the volume reached 0.30 million km^3 (Fedotov et al., 2004) (see Figs. 4, 5). The violent explosive eruption of May 9, 2004, which hurled an eruption column to heights of 11 km a.s.l. (or 8.5 km above the dome) destroyed part of the dome, leaving deposits of block-and-ash pyroclastic flow overlain by juvenile material due to pyroclastic flows of porous andesite, which were first accompanied by the formation of pyroclastic surges (Girina et al., 2007b; Ozerov and Demyanchuk, 2004). This eruption was followed by the discharge of lava of higher plasticity, which made viscous lava flows to armor the agglomerate mantle of the extrusive dome that had formed by that time. The average lava discharge was 0.15–0.23 m^3/s in May–July 2004 (Gorbach, 2006). Lava flows continue to be forced upward and have been accompanied by ash explosions hurling ash to heights as great as 7–12 km a.s.l. (or 4.5–9.5 km above the dome) and by collapsing incandescent avalanches with ash rising to 5–6 km a.s.l. (or 2.5–3.5 km above the dome). This has continued until the present time with some intermissions.

The largest paroxysmal explosive eruption of the volcano related to the growth of the lava dome since 1980 occurred on February 27, 2005. A large eruption column rose from the central part of the lava dome to heights of 10 km a.s.l. (or 7.5 km above the dome) and collapsed onto the southwestern slope of the volcano. As an example, the Baidarnaya River canyon, whose

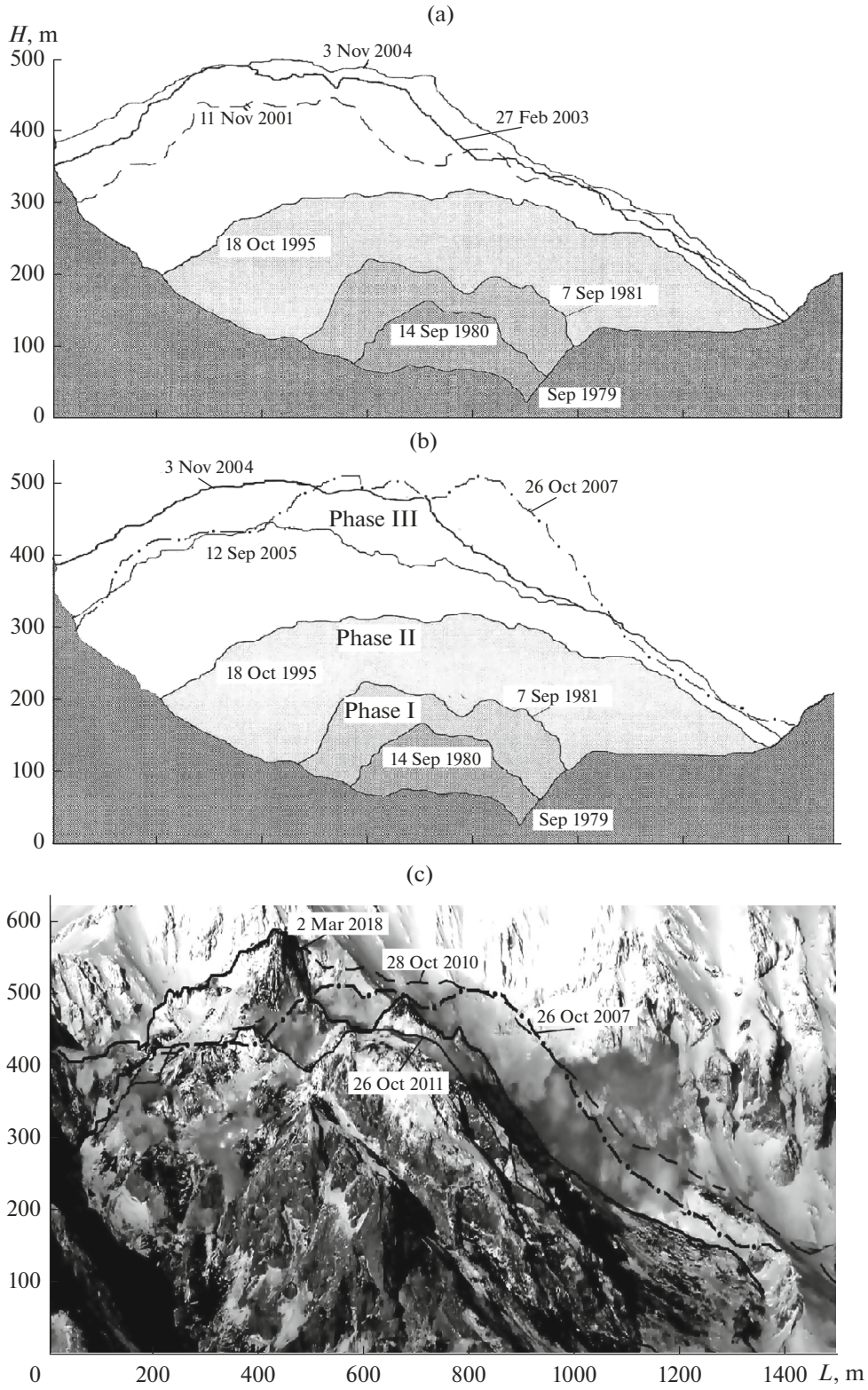


Fig. 4. Profiles of the lava dome during different phases of its growth: the initial phase and the growth of the western sector prior to the February 27, 2005 eruption (a); the formation of the dome in the eastern sector between September 12, 2005 and October 26, 2007 (b); the growth (October 26, 2007 to October 28, 2010) after the collapse of October 27, 2010, the growth of the western sector between October 26, 2011 and March 2, 2018 (c).

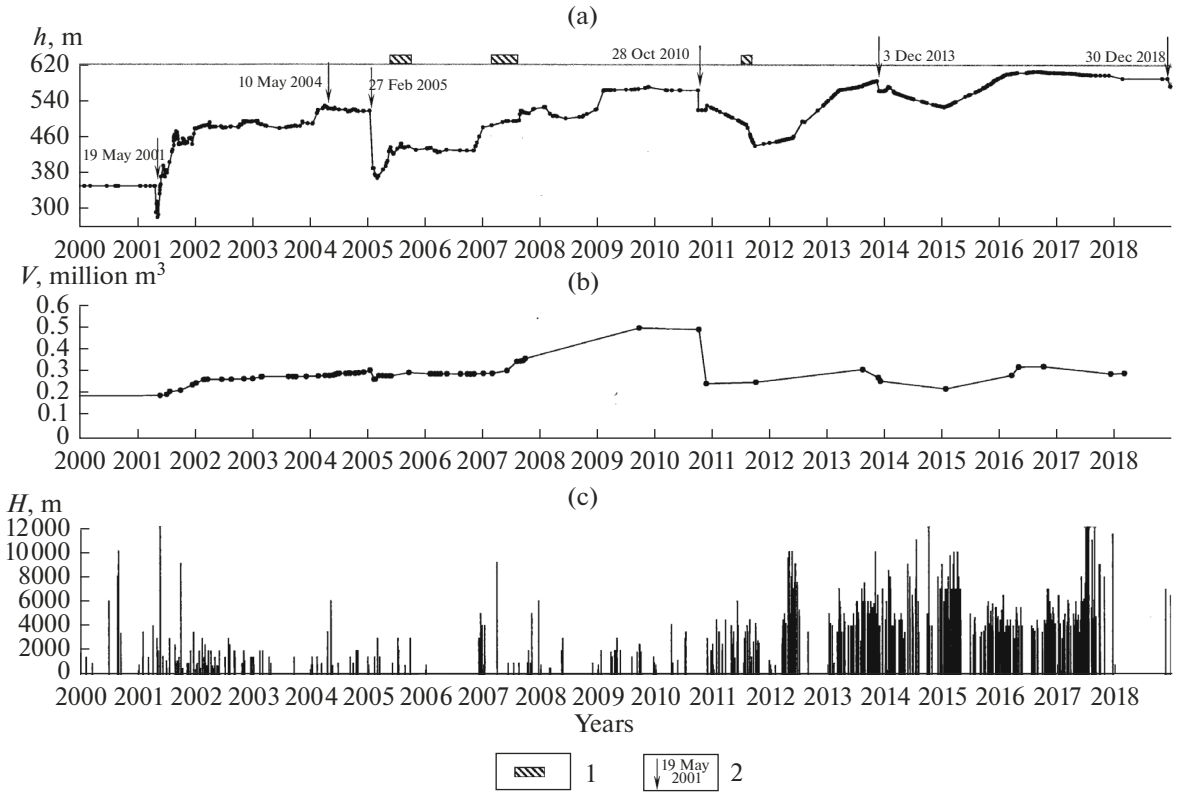


Fig. 5. The 2000–2018 eruptions of Sheveluch Volcano: changes in the maximum height of the lava dome as determined from theodolite measurements (a): (1) periods when lava flows were discharged onto the dome slopes, (2) powerful explosive eruptions; changes in lava dome volume (b); height of ash ejections (c).

depth reaches 40 m, was completely filled with deposits of pyroclastic flows (Girina et al., 2006; Nuzhdaev et al., 2005). The deposits of the pyroclastic flows over an area of 31.5 km^2 were 10–15 m on average, while the average thickness of the material deposited by the pyroclastic surges was approximately 1 m. The volume of the pyroclastic deposits due to the eruption was estimated to be 0.5 km^3 (Girina et al., 2006) (see Table 1).

The eruption of October 27, 2010 was very violent as well, with an ash column rising to 9 km a.s.l. (or 6.5 km above the dome) and the deposits of the pyroclastic flows lying over an area of approximately 20 km^2 (Girina et al., 2011; Ovsyannikov and Manevich, 2010) (see Table 1).

The explosive–extrusive–effusive eruption continued. The dome growth was due to intense explosive activity of the volcano, with discrete explosive events hurling ash to heights of 15 km a.s.l. (or 12.5 km above the dome) and occurring occasionally at a level of as many as 25 in a year or sometimes 22 per day. As an example, an explosive event occurred on July 26, 2013: the ascent of the ash column to heights of 10 km a.s.l. (or 7.5 km above the dome) was accompanied by the collapse of a pyroclastic flow that went for approximately 5 km along the Baidarnaya River valley. Lightning discharges could be observed in the ash cloud. According to satellite observations, the ash plume propagated for 520 km southeast of the volcano. The volcano exhibited vigorous activity on October 18, 2013, as follows: 22 explosions hurled ash to heights of 7–10 km a.s.l. (or 4.5–7.5 km above the dome), deposits of pyroclastic flows were formed on the southwestern slope of the volcano; according to satellite observations, the ash plumes extended as far as 200 km southeast of the volcano (Girina et al., 2014a). An extraordinary explosive event, although moderate in vigor, occurred on September 18, 2016. Explosions produced the collapse of large lava blocks in the southwestern part of the dome and generated pyroclastic flows 12 km in length along the Baidarnaya riverbed (Gorbach et al., 2017).

According to (Zharinov and Demyanchuk, 2008), the lava dome had a volume of 360 million m^3 by the end of October 2007.

KLYUCHEVSKOY VOLCANO

Klyuchevskoy Volcano stands 4750 m a.s.l.; its crater is 700 m across. It is one of the more vigorous active volcanoes in the world, discharging an average of 60 million tons per year (Khrenov et al., 1991) (see Figs. 1, 2). Its slopes and base contain tens of cinder

Table 1. Paroxysmal eruptions of Sheveluch Volcano

Time of paroxysmal eruption	Maximum height of eruption column, km a.s.l.	Maximum length of ash plume, km	Direction of ash plume movement	Maximum magnitude of volcanic tremor, μm/s	Eruption features
May 19–22, 2001	15	500	NE		First event since 1993
May 9, 2004	11	600	E–SE	14.8	Area of pyroclastic flow deposits is 5.3 km^2, volume of ejecta is 0.06 km^3 (Girina et al., 2007a)
February 27, 2005	10	800	W–SW		Area of tephra deposits is 25000 km^2; area of pyroclastic flow deposits is 31.5 km^2, volume of ejecta is 0.5 km^3 (Girina et al., 2006)
September 22, 2005	7.5	500	SE	4.5	Area of pyroclastic flow deposits is 1.9 km^2, volume of ejecta is 0.01 km^3 (Nuzhdaev et al., 2005)
October 27, 2010	9	2500	E	18.4	Area of pyroclastic flow deposits is 20 km^2 (Girina et al., 2011)

and cinder-and-lava cones, in addition to numerous lava flows due to summit and parasitic eruptions. The high eruption activity of the volcano results in a cinder cone that arises in its crater at times (hence, the volcano became higher), and the cone was destroyed by later eruptions. Information on Klyuchevskoy eruptions is available from 1697, while the 20th century saw 26 summit eruptions and 19 flank eruptions (Girina et al., 2018b; Piip, 1956; Khrenov et al., 1991). The last powerful terminal eruption of Klyuchevskoy to occur in the 20th century took place in 1994 (Ozerov et al., 1997). Outflow of magma along the central conduit was observed in 1995–1999, with the process being occasionally accompanied by bursts of activity, as those which occurred, e.g., during the period from March 5 to September 7, 1997 when the ash column rose to 9 km a.s.l. (or 4.2 km above the volcano's crater).

Nine summit eruptions occurred during 19 years, with two of these involving flank discharges: March 22, 2003 to March 3, 2004; January 15 to April 10, 2005; February 15 to July 26, 2007; October 8, 2008 to January 28, 2009; September 16, 2009 to December 12, 2010; September 1, 2012 to January 10, 2013; August 15 to December 15, 2013; January 1 to March 24, 2015; and April 3 to November 6, 2016 (see Table 1) (Girina et al., 2014b, 2018b, 2019b; Zharinov and Demyanchuk, 2009, 2016). That of 2009–2010 was the longest event (1 year and 3 months), while the 2015 eruption was the shortest (less than 3 months) (Table 2).

The first appreciable increase in Klyuchevskoy activity to occur in the present century was observed in late January 2000 (a steam–gas column rose to 10 km a.s.l., or 5.3 km above the crater). A thermal anomaly began to be recorded occasionally from December 25, 2002. The volcano began to show Strombolian activity from March 22, 2003 and Vulcanian activity from July 2 (ash flew to heights of 6.0–8.5 km a.s.l., or 1.3–3.8 km above the crater), with ash plumes extending for as long as 300 km in different directions from the volcano (see Table 2).

Each of the nine eruptions began by fresh lava filling the crater, producing incandescence during nighttime (as the thermal anomaly was recorded on satellite images above the crater) and by Strombolian activity, with lava spouting in the crater and volcanic bombs being ejected to 300–500 m above the crater rim. Two eruptions exhibited eruptive activity alone, namely, March 22, 2003 to March 3, 2004 and September 1, 2012 to January 10, 2013. The other eruptions discharged (from the central vent) long lava flows in several different streams along the Krestovsky, Apakhonchich, and Kozyrevsky chutes and adjacent slopes of the volcano (see Table 2).

Flank vents were formed in the southwestern and eastern slopes of the volcano on October 11, 2013 and April 26, 2016, respectively (see Table 2) (Girina et al., 2014b, 2019b; Zharinov and Demyanchuk, 2018). These eruptions produced extensive lava fields; as an example, the area of the field due to the 2013 eruption was 0.95–1.0 km^2 (Girina et al., 2014b).

The largest explosive events on Klyuchevskoy were recorded in 2007 and in 2013, with the ash columns rising to 12 km a.s.l. (or 7.3 km above the crater); the longest ash clouds and plumes were observed in 2007 (5500 km), in 2010 (2300 km), and in 2013 (2500 km) (see Table 2) (Girina et al., 2009, 2011, 2017). As an example, the culmination of the eruption of August 15 to December 15, 2013 lasted uninterruptedly during

Table 2. Eruptions of Klyuchevskoy Volcano

Eruption duration	Maximum height of eruption column, km a.s.l.	Maximum length of ash plume, km	Direction of ash plume movement	Maximum magnitude of volcanic tremor, μm/s	Eruption features
March 22, 2003 to March 3, 2004	8.5	300	E, NE, NW, SE	20.5 January 12, 2004	Strombolian activity since May 11, 2003; Vulcanian activity since July 2, 2003
January 15, 2005 to April 10, 2005	9	600	N, NW	39.5 March 11, 2005	Strombolian activity since January 15; Vulcanian activity since January 21; January 31: lava flow began to be discharged into the Krestovsky chute
February 15 to July 26, 2007	12	5500	N	83.8 June 19, 2007	Strombolian activity since February 15; March 28: lava flow began to be discharged into the Krestovsky chute; Vulcanian activity since February 24
October 8, 2008 to January 28, 2009	8	700	E	53.9 December 10, 2008	Strombolian activity since October 13, 2008; November 21, 2008: lava flow began to be discharged into the Krestovsky chute; Vulcanian activity since November 30, 2008
September 16, 2009 to December 12, 2010	9	2300	E	65.0 October 18, 2010	Strombolian activity since September 16, 2009; November 13: lava flow began to be discharged into the Apakhonchich chute, and afterwards into the Krestovsky and Kozyrevsky chutes; Vulcanian activity since February 22, 2010; April 9, 2010: a steaming fissure on the SW slope of volcano
September 1, 2012 to January 10, 2013				0.6 January 9, 2013	Strombolian activity
August 15, 2013 to December 15, 2013	12	2500	E, SE	312.4 October 18, 2013	Strombolian activity since August 15; August 26: lava flow began to be discharged into the Krestovsky chute and afterwards into the Apakhonchich chute; Vulcanian activity since October 9; October 11, 2013 08:16–08:24 UTC: a flank vent breaking out the SW slope of volcano
January 1, 2015 to March 24, 2015	8	1000	NW	6.6 March 25, 2015	Strombolian activity since January 1; January 8–9: lava flow began to be discharged into the Apakhonchich chute; Vulcanian activity since January 10
April 3 to November 6, 2016	8	500	SW, E, SE	52.2 April 15, 2016	Strombolian activity since April 3; Vulcanian activity since April 23; April 23: lava flow began to be discharged into the Apakhonchich chute; April 26: a flank vent breaking out in the Apakhonchich chute; around August 15: lava flow began to be discharged into the Krestovsky chute

Table 2. (Contd.)

Eruption duration	Maximum height of eruption column, km a.s.l.	Maximum length of ash plume, km	Direction of ash plume movement	Maximum magnitude of volcanic tremor, μm/s	Eruption features
March 2 to August 25, 2017	8	600	SE–SW	2.9 April 1, 2017	Vulcanian episodes
December 5, 2017 to January 18, 2018	7	220	E, W, N, S	0.5 December 29, 2017	
May 7–14, 2018	10.5 May 14, 2018	350	E, SW	0.4 May 26, 2018	
April 21–22, 2019	7	100	E, W, N, S	0.4 April 22, 2019	
June 12 to July 1, 2019	6	180		0.8 June 10, 2019	

October 15–20, and the ash column rose to 9–10 km a.s.l. (or to 4.3–5.3 km above the crater). The vigor of volcanic tremors reached 312.4 μm on October 18 (http://www.emsd.ru). Visual observations provided evidence of powerful Strombolian activity on Klyuchevskoy (lava was spouting to heights of 800 m in the summit crater) and of Vulcanian activity (the ash column rose to 8–10 km a.s.l., or 3.3–5.3 km above the crater), and several lava flows continued descending down the Klyuchevskoy western and southeastern slopes. Strong explosions ejected volcanic bombs that fell on the middle of the slope, at heights of 2.5 km a.s.l., and rolled downwards. The summit was shrouded in flames and the roar of the discharges was heard some tens of kilometers from the volcano. According to satellite observations, the ash plumes propagated for distances reaching 2500 km, mostly southeastward and eastward from the volcano, with aerosol clouds being also observed, apart from ash clouds. We note that simultaneously with the Klyuchevskoy eruption, 22 explosive events occurred on Sheveluch on October 18 (http://www.ksc-net.ru/ivs/kvert/van/index.php?n=2013-17), with the ash plumes floating southeastward from the volcano (Girina et al., 2014a).

When lava flows hit glaciers on the volcano's slopes, the result was to produce secondary (phreatic) explosions, with steam and ash occasionally rising up to 8 km a.s.l. Intensive melting of glaciers and snow patches by moving lava flows produced mudflows during the eruptions of 2005 and 2008 (traveling for 27 km along the Krutenkaya River in 2005), in 2007 (up to 35 km along the Kirgurich River as far as the Klyuchi airport), in 2013 (70 km along the Studenaya River), and other similar occurrences (Girina et al., 2007, 2009, 2014a; Fedotov and Zharinov, 2007, 2016).

An extraordinary phenomenon was observed during the eruption of September 16, 2009 to December 12, 2010: the volcanologists Ya.D. Muraviev, A.A. Ovsyannikov, and Yu.V. Demyanchuk saw the formation of a radial fissure on April 8 (Greenwich time), 2010, with the fissure extending for 1200 m on the Klyuchevskoy southwestern slope at altitudes of 3900–4600. Later, a lava flow began to be discharged from it (Muraviev et al., 2010).

One result of the eruptive activity of Klyuchevskoy in the 20th and 21st centuries was to completely fill the deep Krestovsky chute that was created during the 1944–1945 eruption with lava material by May 2011, so that the bulk of the lava flows began to move along the Apakhonchich chute (Girina et al., 2016, 2019b; Piip, 1956).

The large cinder cone that was built by the above eruptions on the volcano's summit filled the crater completely. As withdrawal of magma occurred, the crater of the cinder cone, which had become the crater of Klyuchevskoy volcano proper, expanded and deepened, with cinder and lava outliers being exposed on the crater slopes. To provide an example, the mountaineer A. Gorchakov made GPS measurements on August 6, 2011 to find that the crater was an oval 300 × 200 m in size, and the volcano had an absolute altitude of 4845 m a.s.l., i.e., the cinder cone stood 96 m above the rim of the older crater (Girina et al., 2012).

The explosive–effusive eruptions were followed by a withdrawal of magma along the magma conduit. Considerable movements of the cinder and lava mass that filled the conduit produced large collapses of pyroclastic material from the inner slopes of the crater, and ash clouds appeared above the summit. As an example, five episodes of such activity were observed after the 2016 eruption during the period between March 2017 and July 2019: an ash column rose to 10.5 km a.s.l. (or 5.3 km above the crater) and ash plumes extended for 600 km from the volcano (see Table 2). No Strombolian activity was observed on the volcano during these periods of time, no thermal anomaly

above the crater was recorded on satellite images, so that we can infer that no fresh magmatic material was supplied onto the ground surface.

BEZYMIANNY VOLCANO

Bezymianny is one of the most active volcanoes in the world. It is situated in the middle of the Klyuchevskoy Volcanic Group in Kamchatka (Girina et al., 2018b) (see Figs. 1, 2). The first historical eruption of the Bezymianny andesitic volcano began on October 22, 1955 and continued until its catastrophic eruption of March 30, 1956, which produced an explosive crater 700 m deep and 1.3 × 2.8 km in diameter; over 3 km^3 pyroclastic material was discharged and moved as tephra, as deposits of the directed blast and pyroclastic flows (Gorshkov, 1957; Gorshkov and Bogoyavlenskaya, 1965). The disaster was at once followed by the growth of an extrusive dome in the crater that is still continuing (Bogoyavlenskaya and Kirsanov, 1981; Dubik and Menyailov, 1969; Kirsanov et al., 1971; Malyshev, 2015; Girina, 2013, among others).

The volcano continued its cyclic extrusive–explosive–effusive activity in 2000–2012 as it was first seen during the 1977 eruption (Bogoyavlenskaya and Kirsanov, 1981):

—A new cycle of activity on Bezymianny began as the growth of an extrusive block in the crater or on the summit of the lava dome;

—This was followed by an explosive phase lasting between 20–30 min and 36 hours;

—The next phase was a long-continued (between a few months and half a year) extrusion of viscous lava flows onto the dome slopes;

—A quiet fumarolic activity (a quiescence in its activity) occurred until the start of the new cycle.

A total of 27 explosive eruptions due to the growth of the extrusive dome have occurred on Bezymianny from 2000 until June 2019 (Table 3).

The eruption cloud that rose above the volcano varied in height between 4 and 15 km a.s.l., i.e., between 1.2 and 12.2 km above the summit (Fig. 6).

A total of 21 explosive eruptions have occurred on Bezymianny for 12 years, between 2000 and October 2012: one in each of the years 2002, 2003, 2008, 2009, 2010, and 2011, three in 2007, and two in each of the remaining years (see Table 3). The inter-eruption intervals varied between 22 (in 2007) and 485 days (between the eruption of 2008 and that of 2009).

The volcano had been in a relatively quiet period during 2012–2016, probably because of the high effusive activity exhibited by the Tolbachik Fissure Eruption of 2012–2013 and of the four eruptions of Klyuchevskoy in 2012–2013, 2013, 2015, and 2016 (Girina, 2016; Girina et al., 2018b).

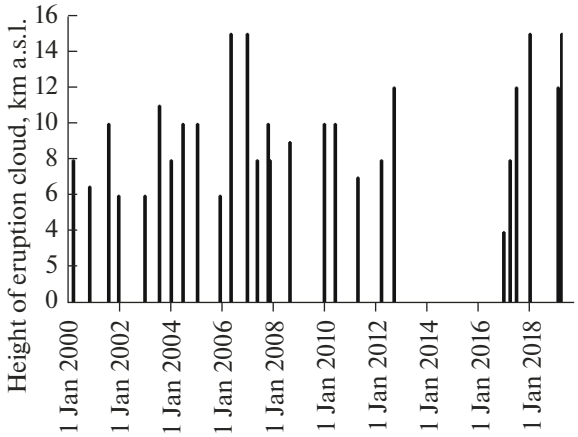


Fig. 6. The height of eruption clouds above Bezymianny during the explosive eruptions of 2000–2019.

A total of six explosive eruptions have occurred on Bezymianny in the 2.5 years between December 2016 and June 2019: one in 2016, three in 2017, and two in 2019. We will dwell on the more recent activity of Bezymianny in more detail.

The period between December 2016 until mid-2018 saw the extrusion of viscous lava flows onto the western and southern slopes of the volcano's lava dome with four accompanying explosive eruptions that ejected ash as high as 15 km a.s.l. (up to 12 km above the crater): December 15, 2016, and March 9, June 16, and December 20 in 2017. There were two eruptions in 2019, on January 20 and on March 15. The most violent paroxysmal eruptions of Bezymianny in 2016–2019 occurred on December 20, 2017 and on March 15, 2019.

As an example: the explosive eruption of December 15, 2016, which ejected a small amount of ash to heights of up to 4 km a.s.l., took place 111 days after the detection of a new extrusive body in the volcano's crater on August 26 and 10 days after the obvious resumption of activity on the volcano on December 5 involving a starting extrusion of viscous lava flows onto the western slope of the lava dome (Girina et al., 2018a). The March 9, 2017 eruption (when ash rose to heights of 7–8 km a.s.l.) was observed 94 days after the starting effusive activity of the volcano and 84 days after the first explosive eruption (Girina et al., 2018a). The July 16 eruption (the ash cloud rose to reach 12 km a.s.l., an area of over 108750 km^2 was exposed to ashfalls) (Fig. 7) occurred 99 days after the second eruption, while the December 20 eruption (the eruption cloud rose to 15 km a.s.l., the main ashfall area was approximately 78000 km^2, including 42600 km^2 onshore) took place 188 days after the third eruption. In other words, the occurrence of a large explosive eruption required nearly twice as long a time to accumulate the needed energy compared with each of the two preceding ones. It should also be noted that while the first three erup-

Table 3. The eruptions of Bezymianny Volcano

Start of explosive eruption	UTC	Height of eruption column, km a.s.l.	Length of ash plume, km	Direction of ash plume movement	Maximum magnitude of volcanic tremor, μm/s	Duration of volcanic tremor, hours
13 Mar 2000	16:25	8	2000	W–NW		
1 Nov 2000	15:20	6.5	300	SW		
6 Aug 2001	22:28	10	400	S	11.7	
16 Dec 2001	0:00	6		W	1.92	24
25 Dec 2002	19:20	6	200	W	0.88	6
26 Jul 2003	8:45	11	300	W–SW		
13 Jan 2004	22:50	8	300	N–NE	3.81	0.5
18 Jun 2004	19:40	10	1000	NE	0.43	0.7
11 Jan 2005	8:02	10	400	W–SW	0.48	11
30 Nov 2005	12:00	6	450	W–SW	0.14	1
9 May 2006	8:21	15	1500	E–NE	1.01	3.3
24 Dec 2006	9:17	15	900	NE	0.77	6.5
11 May 2007	14:45	8	200	N–NE		
14 Oct 2007	14:27	10	1000	NE	1.08	11
5 Nov 2007	8:43	8	100	W	0.36	1
19 Aug 2008	10:30	9	1300	W–SW	0.4	1
16 Dec 2009	21:45	10	500	W–NW	1.1	1.5
31 May 2010	12:34	10	1000	W		
13 Apr 2011	20:20	7	100	N–NW	0.23	3
8 Mar 2012	21:40	8	200	NE	0.68	17.5
1 Sep 2012	19:30	12	500	SE	0.88	2
15 Dec 2016	6:00	4	120	W	0.1	2.36
9 Mar 2017	3:10	8	600	NE, N–NW	0.34	6.34
16 Jun 2017	4:53	12	700	NE, E	0.4	2
20 Dec 2017	3:40	15	2000	NE	0.4	5.25
20 Jan 2019	16:10	12	600	NW	0.22	2
15 Mar 2019	17:30	15	900	E–NE	0.12	4

tions occurred on the background of active effusions of lava flows onto the slope of the Bezymianny dome, the last occurred on the background of decreasing or decaying effusive activity.

The volcano was comparatively quiet in 2018 and the thermal anomaly in the area of the volcano had a considerably lower temperature by mid-February; this probably indicated the termination of the extrusion of the viscous lava flow onto the dome slope after the explosive eruption of December 20, 2017. The anomaly had a higher temperature also between March 24 and November 5 (occasionally reaching 27–28°C), probably because of the growth and existence of a new small lava dome that was detected in the crater of the volcano during a helicopter overflight on July 9, 2018 (http://geoportal.kscnet.ru/volcanoes/imgs/2373.jpg).

The video at (https://www.youtube.com/watch?v=Fhbfzd9l2fI) and satellite observations provides evidence that the next explosive eruption of the volcano occurred on January 20, 2019, that is, 394 days since the preceding eruption. The explosions sent ash to heights of 10–12 km a.s.l. (or 7–9 km above the dome), the ash plume was moving northwest from the volcano (see http://geoportal.kscnet.ru/volcanoes/imgs/2409.gif where the propagation of the ash plume is based on data from the Himawari-8 satellite at the VolSatView IS). The ashfalls involved Kamchatka, Magadan Region, and parts of the Sea of Okhotsk with a total area of 200000 km^2 (see Table 3) (Girina et al., 2019c).

Continuous observations of the Bezymianny activity helped to identify some patterns in its precursory periods before explosive eruptions (Tokarev, 1966; Girina, 2012). An integrated (video, visual, and satellite observations) monitoring of the volcano during the period from 2002 to 2019 by the KVERT (Kam-

Fig. 7. A VolSatView IS visualization of ash cloud moving from Bezymianny during the June 16, 2017 eruption between 04:53 and 21:20 UTC based on data from the Himawari-8 satellite (Girina et al., 2017).

chatkan Volcanic Eruption Response Team) scientists at the IVS FEB RAS enabled the researchers to predict 14 explosive eruptions at Bezymianny (December 16, 2001, December 25, 2002, January 11, 2005, May 9, 2006, May 11, 2007, October 14–15, 2007, August 19, 2008, May 31, 2010, March 8, 2012, September 1, 2012, March 9, 2017, July 16, 2017, December 20, 2017, and March 15, 2019). Warnings for large explosive eruptions of the volcano were published at the IVS FEB RAS site (KVERT, http://www.kscnet.ru/ivs/kvert) with advance times of 0.5–24 h before eruption onsets (Girina et al., 2017, 2018a; Girina, 2012).

THE 2012–2013 TOLBACHIK FISSURE ERUPTION

The bulk of the data on the eruption dynamics was acquired during field work of the Tolbachik Expedition sent by the IVS FEB RAS, as well as by overflights of the volcano and from aerial photographic surveys and thermal surveys of the lava flows conducted on November 29, December 13, and December 27, 2012, as well as on February 15 and June 5, 2013 (Droznin et al., 2013; Dvigalo et al., 2014).

The eruption was preceded by 5 months of higher seismicity and ground deformation that were at the maximum 1 day before the onset of the November 27, 2012 eruption, which lasted 9 months. This can be provisionally divided into three phases, with the first and the third lasting approximately 10 days, while the main phase was over 8 months long.

The initial phase. The eruption area was first surveyed in the evening of November 28. The newly formed eruption fissure on the southwestern slope of Plosky Tolbachik Volcano discharged ash and incandescent bombs accompanied by intense lava effusion. An ash cloud rose as high as 3 km above the fissure. Two groups of vents, the most active among all, were determined from on board a helicopter during the overflight of the eruption area on November 29. One was in the middle of the eruption fissure at an altitude of 1850 m a.s.l. (the Menyailov Cone) and the second at an altitude of 1740 m a.s.l. (the Naboko Cone) (Figs. 8, 9). These cones were named after the eminent volcanologists A.A. Menyailov and S.I. Naboko. The uppermost lava vents were in the fissure at an altitude of approximately 2000 m a.s.l. on the southeastern base of the 1941 cone, and the lowermost at an altitude of approximately 1500 m a.s.l. on the western base of Krasnyi Cone. Two large lava flows of the aa type were moving west and southwest at speeds reaching 200 m/h over terrain covered with snow 0.1–0.5 m thick. These first flows subsequently formed two complex-structured lava fields (the Vodopadnoe and Leningradskoe), which were named after the two field bases of the IVS FEB RAS buried by the flows (see Fig. 2). The Vodopadnoe field was formed by lava that came from the upper portion of the eruption fissure, while the Leningradskoe received the bulk of its lava from the lower portion of the fissure.

According to the aerial survey of November 29, 2012, the lava flows covered an area of 14.46 km^2, the total volume of discharged lava was 0.072 km^3. The average lava discharge during the initial period of the eruption (November 27 through December 1) was 440 m^3/s (Dvigalo et al., 2014). The first lava portions contained 54% SiO_2, with the concentration decreasing to 52% later on (Volynets et al., 2015).

The vents that were situated in the upper portion of the eruption fissure (including the Menyailov crater) stopped erupting by December 1, 2012. Most of the lower vents (except for the Naboko crater) did so by December 8, 2012. The boundary of the Vodopadnoe lava field was at an altitude of 705 m a.s.l., the flows

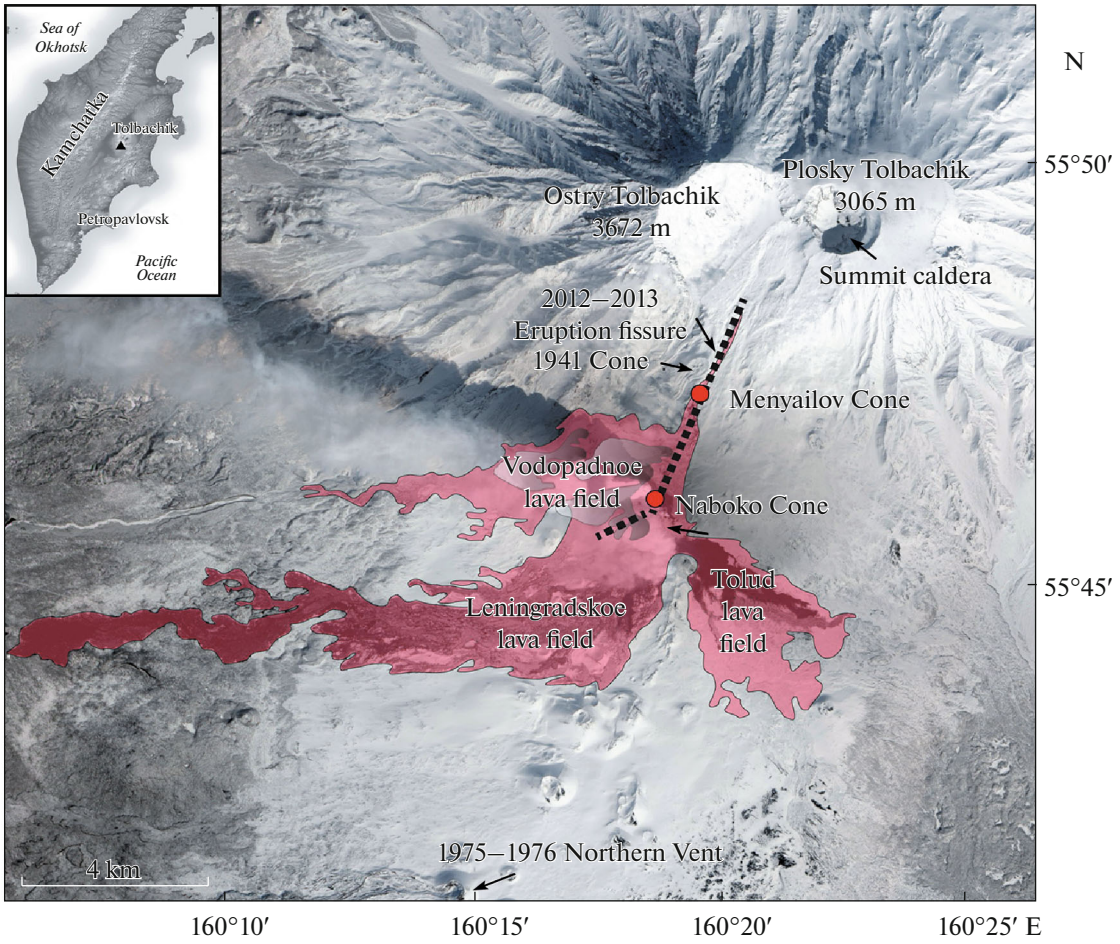


Fig. 8. Eruption fissures (dashed lines) and lava fields due to the 2012–2013 Tolbachik Fissure Eruption (based on data from the NASA EOS-1 ALI satellite as of April 5, 2013).

were as thick as 10 m, had a length of 8.5 km, and a volume of 0.043 km^3 (Dvigalo et al., 2014). The Leningradskoe field received lava from the Naboko Cone and continued expanding, with its length exceeding 10 km by December 8; the frontal part of the lava flow was in forest at an altitude of 700 m a.s.l.

The main phase. Lava continued spouting at the Naboko Cone (1740 m a.s.l.) and lava effusion from the cone continued until the end of the eruption, while the eruption itself gradually changed its character. A small lava lake was formed in the Naboko Cone crater; the lake was continually boiling, ejecting spouts of liquid lava, light volcanic scoria, and Pele's hair. The cone discharged lava through a wide break in the southern slope, and lava was moving in an opened deep narrow (5 to 10 m wide) canyon over agglutinated scoria deposits (Fig. 10). The lava speed in the flow was 2–3 m/s; the temperature was 1060–1080°C.

By the end of December the lava discharge decreased from 140 m^3/s to 18 m^3/s (Dvigalo et al., 2014). The Leningradskoe lava field became 18 km long, and began to get wider and thicker. The Tolud lava field began forming in January, and its length was 4.3 km in late August 2013 (see Fig. 8).

The part of the lava canyon nearest to the Naboko Cone was transformed to become a short lava pipe. Subsequently, the lava was flowing from the lava lake via pipes whose average diameter was approximately 10 m and which were dipping at approximately 3°; it emerged at the ground surface at some distance from the cone.

The lava pipes changed their configuration during the eruption, with lava moving from the Naboko Cone at the terminal phase of the eruption for a few kilometers via a complicated system of lava pipes buried at depths of 1 to 20 m within the lava field. The lava flow could be observed through several gas ventholes in the pipe tops, as well as in the frontal portions of the lava field (Belousov et al., 2015). Plastic lava was observed to be slowly oozing in some areas of the lava field through the top of aa flows, assuming the shape of nearly spherical pillows (see Fig. 9). When the lava discharge diminished to approximately 15 m^3/s by the end of May, pahoehoe lavas became dominant and

Fig. 9. The Naboko cinder cone, view from the south in July 2013. Vertical degassing jets (from right to left): the main crater with the lava lake, the flank vent, and the gas venthole in the top of the lava pipe. Photographed by A.B. Belousov.

formed an extensive sheet in the southern sector of the lava field. The level of lava was gradually lowering in the lava channels during the summer, so that they were entirely empty toward the autumn. This long-continued effusive activity produced a lava field consisting of numerous alternating aa and pahoehoe lava flows with basaltic trachyandesite compositions. The lava field had a total area of 40 km^2 by the end of the main phase, with the maximum thickness of the lava fill being 70 m.

The lava lake in the crater of the Naboko Cone was changing during the eruption, as follows. At first, lava was freely flowing from the lake through a gap in the cone; then it was overflowing from it during explosions; afterwards, when the gap in the cone had been filled with scoria, the lava lake became oval and had a size of 50 × 25 m. In July–August the lake parted into two round lakes, each 10 m across, and then completely disappeared in the later half of August. The small lava lake lying in a flank vent of the Naboko Cone remained nearly unchanged during the main phase of the eruption.

The explosive activity of the Naboko crater also changed in intensity, with the highest activity (lava spouting and ejections of volcanic bombs to heights of 300 m above the crater) occurring during the first 2 months of the eruption, while afterwards the average height of tephra ejections diminished to 100 m.

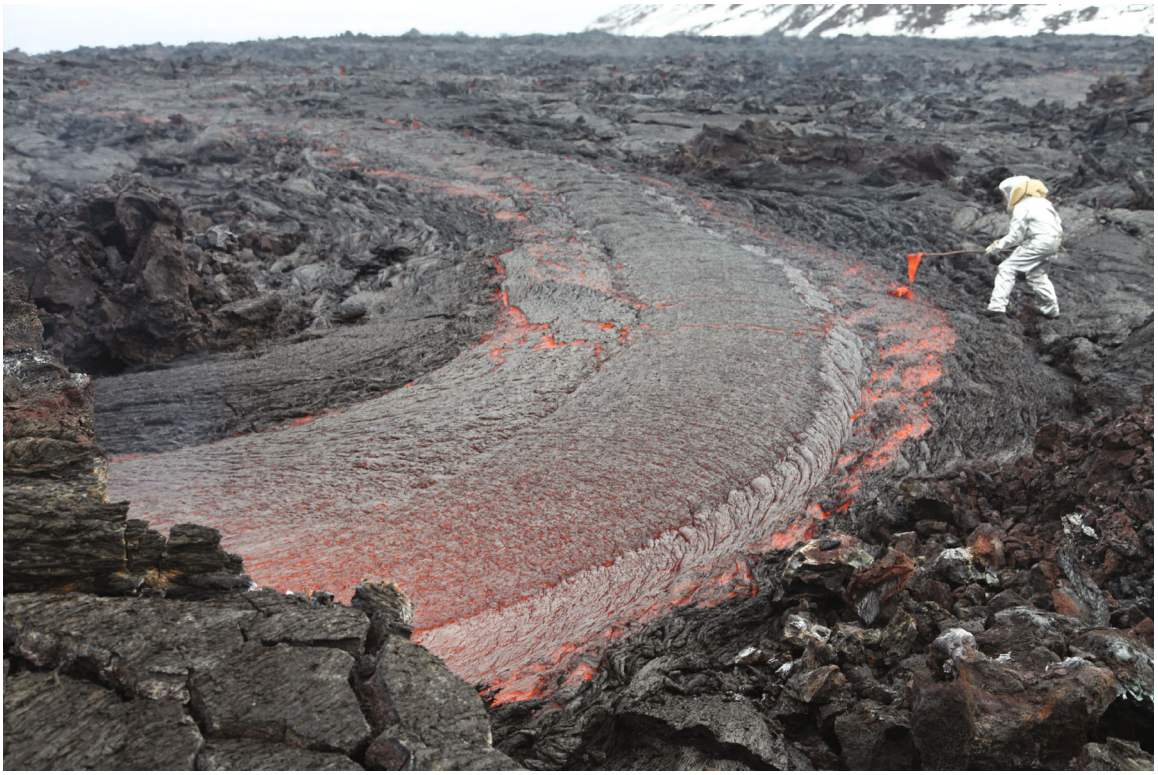
The terminal phase. The lava discharge dropped from 10–20 m^3/s to zero on August 23. The lava lake in the Naboko Cone disappeared and merely some low Strombolian discharges rising to heights of 30 m continued; these were interrupted by pauses that occasionally lasted for as long as 3 days. Toward the end of September the activity had completely ceased.

The Naboko Cone was 125 m high toward the end of the eruption, the main crater had a diameter of 100 m and was 30 m deep. Approximately 0.55 km^3 of basaltic trachyandesite lava was discharged in 9 months.

CONCLUSIONS

The years 2000–2019 saw 42 eruptions on four volcanoes in the Northern Volcanic Group, Kamchatka. The four volcanoes were in eruption simultaneously in 2012–2013: the extrusive–explosive–effusive eruption of Sheveluch that continued from 2001 was joined by eruptions of the following volcanoes: Bezymianny on March 8 and September 1, Klyuchevskoy from September 1, 2012 to January 10, 2013, and the Tolbachik Fissure Eruption from November 27, 2012 to September 15, 2013 (see Tables 1–3). Three volcanoes were frequently active in nearby time intervals during 1 year. As an example, a high level of activity was recorded on Sheveluch, Klyuchevskoy, and Bezymianny in 2005,

(a)



(b)

Fig. 10. The lava flows observed during the 2012–2013 Tolbachik Fissure Eruption: the lava river that exited a lava pipe 1 km of the Naboko Cone, May 2013 (a); pahoehoe flows in the Tolud lava field moving over the 1975–1976 cinder, July 2013 (b). Photographed by A.B. Belousov.

2010, and 2017. In 2005, Bezymianny erupted on January 11, and Klyuchevskoy began erupting on January 15 and continued to do so during 3 months, with the most powerful (since 1964) eruption of Sheveluch occurring during that time on February 27; in addition, Sheveluch and Bezymianny were recorded erupting on September 22 and November 30, respectively (see Tables 1–3). In 2010, two powerful eruptions occurred upon the background of the ongoing eruption of Klyuchevskoy, which lasted from September 16, 2009 to December 12, 2010; these events were due to Bezymianny (May 31) and to Sheveluch (October 27). June 2017 saw a large explosive event on Sheveluch on June 14 and on Bezymianny (a paroxysmal event on June 16), with the eruption activity of Klyuchevskoy still continuing (Girina et al., 2018b).

The volcanoes in the Northern Volcanic Group of Kamchatka are still active. Although we have a long-term continuous series of instrumental observations using several different techniques (geological, geophysical, video, and satellite means) to monitor the volcanoes, many unresolved issues still remain concerning the deep structure of the volcanoes, the zones of magma generation, the generation of magmas of different compositions ranging from basalts to dacites, eruption prediction, and so on. All of these problems require continued study and detailed monitoring of the volcanoes using advanced methods. A joint analysis of all data available on volcanoes will enable us to solve these problems.

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