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Chronology of Bezymianny Volcano activity, 1956–2010

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ABSTRACT

Bezymianny Volcano is one of the most active volcanoes in the world. In 1955, for the first time in history, Bezymianny started to erupt and after six months produced a catastrophic eruption with a total volume of eruptive products of more than 3 km^3. Following explosive eruption, a lava dome began to grow in the resulting caldera. Lava dome growth continued intermittently for the next 57 years and continues today. During this extended period of lava dome growth, 44 Vulcanian-type strong explosive eruptions occurred between 1965 and 2012. This paper presents a summary of activity at Bezymianny Volcano from 1956 to 2010 with a focus on descriptive details for each event.

1. Introduction

Bezymianny Volcano (summit location 55.9° N, 160.6° E, ~2900 m elevation) is located within the Klyuchevskaya volcanic group on the Kamchatka Peninsula in eastern Russia (Bogoyavlenskaya et al., 1991) (Fig. 1). Bezymianny was initially considered extinct, and was therefore ignored by early studies of the Klyuchevskaya volcanic group (Vlodavets, 1940) (Fig. 2A). However, Piip (1956) recognized the youthful age of volcanic products at Bezymianny and concluded that Bezymianny was, along with Klyuchevskoy, the youngest volcano of the Klyuchevskaya group. He further asserted that Bezymianny Volcano was potentially still active (Piip, 1956).

Bezymianny Volcano is located in the center of the Klyuchevskaya volcanic group. The onset of volcanism at Bezymianny occurred at the end of the Late Pleistocene (10.5–11.0 ka BP; Braitseva et al., 1991). Braitseva et al. (1991) suggest that Bezymianny initially formed as an extrusive dome and later transformed into a stratovolcano more than 5.5 ka BP. Detailed tephrachronology performed on deposits from the last 2500 years showed that periods of heightened activity at Bezymianny typically followed by periods of dormancy (Braitseva and Kiriyanov, 1982). Further, tephra studies suggest that the duration of the previous dormancy period correlates with the length of the following activity period. For example, a period of 1100 years of dormancy was followed by 700 years of activity, and 350 years of dormancy was followed by 350 years of volcanic activity (Braitseva et al., 1991). Renewed volcanic activity following a repose period usually begins with a strong explosive eruption, such as the catastrophic eruption of 1.4 ka BP (Braitseva et al., 1991).

Volcanic products of Bezymianny are mainly andesites, and less frequently basalts, basaltic andesites, and dacites (Gorshkov and Bogoyavlenskaya, 1965). All eruptive products are calk-alkaline. It was noted that discrete periods of volcanic activity lasting centuries or more were characterized by transitions in composition from acidic to more basic, then returning to more acidic (Braitseva et al., 1991).

On October 22, 1955, for the first time in modern history, Bezymianny Volcano started to erupt. The eruption was preceded by gradual buildup of seismic activity, which started on September 29, 1955 and by October 19, 1955 reached the level of hundreds of seismic events per day with hypocenters centered beneath Bezymianny Volcano (Bogoyavlenskaya et al., 1991). The eruption started on October 22, 1955 with strong Vulcanian explosions, which continued throughout November with regular strong ash emissions. The volume of November's tephra was estimated at 0.4–0.5 km^3. From December, 1955 to February, 1956, the explosive activity dropped abruptly. The eastern flank of the volcano began to rise simultaneously with the explosive activity.

On March 30, 1956, the volcano produced a catastrophic directed blast, significantly altering both the volcanic edifice and the surrounding territory. Detailed descriptions of the 1955–1956 eruption were presented by Gorshkov (1957, 1959a, 1959b), Gorshkov and Bogoyavlenskaya (1965), and Bogoyavlenskaya and Braitseva (1990). The summit of the volcano and its eastern flank were destroyed as a result of the directed blast, and a new 1.3 × 2.8-km-wide and 700-m-deep crater was formed. The total area covered by the blast deposits was estimated at 500 km^2. The total volume of eruptive products (blast deposits, Plinian fall, and pyroclastic flows) exceeded 3 km^3 (Gorshkov and Bogoyavlenskaya, 1965; Dubik and Menyailov, 1969; Bogoyavlenskaya and Kirsanov, 1981). The directed blast possessed a kinetic energy of 1.2 × 10^{17} J, with an emission rate of 360–500 m/s (Gorshkov and Bogoyavlenskaya, 1965).

The March 30, 1956 catastrophic eruption was followed by 57 years of intermittent lava dome growth within the crater. The first seismic station near the volcano was installed in September

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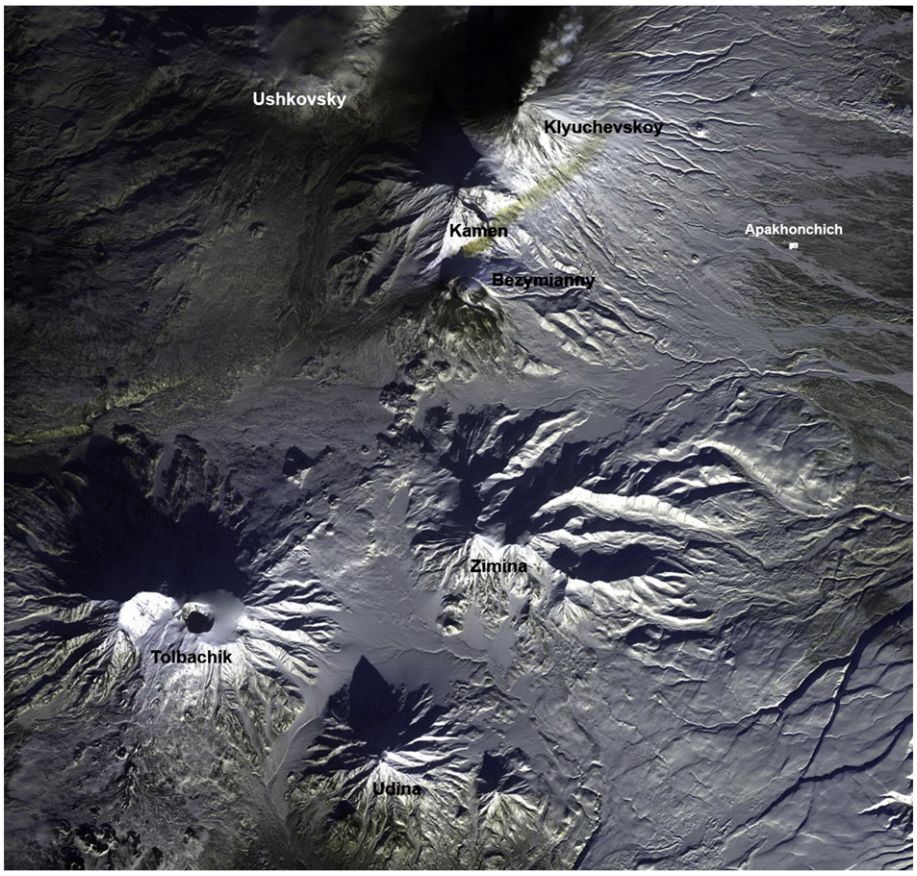

Fig. 1. Location of Bezymianny Volcano at Klyuchevskaya volcanic group, Kamchatka. ASTER satellite image on February 08, 2005 (NASA/GSFC/METI/Japan Space Systems, and U.S./Japan ASTER Science Team).

1960 (Apakhonchich, 16 km northeast of Bezymianny) (Tokarev, 1981) (Fig. 1). The active growth of the lava dome was almost always accompanied by an increase in seismic activity. Following Minakami (1960), Tokarev (1965, 1966, 1981) identified four types (I, II, III, and IV) of volcanic earthquakes and volcanic tremor among seismic events at the Klyuchevskaya volcanic group: three types (II, III, and IV) are typical of Bezymianny. He stated that type II and III earthquakes were associated with lava dome growth and active lava extrusion at the surface. These earthquake swarms also preceded and accompanied explosive eruptions. Type IV earthquakes, as a rule, were associated with explosions from the dome, registered during both weak and strong explosive eruptions and periods of repose (Chubarova et al., 1983). Often type II–IV earthquakes follow one after another and result in volcanic tremor, which can last from minutes to many hours. This tremor usually accompanies the paroxysmal phase of the eruption. The work of Tokarev (1966, 1981), Gorelchik and Stepanov (1976), and Chubarova et al. (1983) present descriptions of the earthquake types and the character of volcanic tremor at Bezymianny. Tokarev predicted Bezymianny explosive eruptions in October 1959, April 1960, and March 1961 (Gorelchik, 2001).

It has been noted (Chubarova et al., 1983; Chubarova, 1985) that the transition from extrusive–explosive to extrusive–explosive–effusive activity at Bezymianny Volcano from 1976 to 1979 resulted in the alteration of the volcano's seismic character. From 1973 to 1975, during periods of very slow extrusion of rigid andesite blocks at the surface, the seismic activity at the volcano was very low. After that less viscous lavas and the effusion of lava flows on the dome flank caused stronger single earthquakes of magnitude (M) $\geq$3, and larger, as well as more energetic earthquake swarms.

As of 2012, intermittent lava dome growth in the crater continues (Girina and Demyanchuk, 2012). Once or twice per year, short-lived strong Vulcanian explosions occur from the dome summit sending ash to heights of 8–15 km above sea level (a.s.l.) and generating pyroclastic flows and surges, which extend about 12–13 km in the different direction of the dome (Figs. 3 and 4). Since 1993 the Kamchatkan Volcanic Eruption Response Team (KVERT, http://www.kscnet.ru/ivs/kvert/index_eng.php) of the Institute of Volcanology and Seismology (IVS, http://www.kscnet.ru/ivs/) Far East Division (FED) Russian Academy of Sciences (RAS) has been responsible for disseminating information about eruptive activity of Kamchatkan volcanoes including Bezymianny. KVERT is a collaborative project of IVS FED RAS, the Kamchatkan Branch of Geophysical Surveys (KB GS, http://www.emsd.ru) RAS, and the Alaska Volcano Observatory (AVO, www.avo.alaska.edu). Remote sensing imagery and analysis of Bezymianny explosive events by AVO and KVERT scientists have resulted in a technique that uses the changing size and temperature of thermal anomalies over Bezymianny to forecast large explosions (Dehn et al., 2000; Schneider et al., 2000; van Manen et al., 2010; Girina, 2012). Volcanological experience and ongoing monitoring and analysis of seismic, video, and satellite data now enable KVERT to forecast explosions at Bezymianny, increasing aviation safety over Kamchatka.

Generally, two distinctive periods of volcanic activity are recognized in the modern eruptive cycle of the volcano: the 1956–1976 extrusive–explosive, and the 1977–present extrusive–explosive–effusive periods (Bogoyavlenskaya and Kirsanov, 1981; Bogoyavlenskaya et al., 1991; Ladygin et al., 2004). The following sections present a short summary of all Bezymianny Volcano eruptions following the catastrophic March 30, 1956 event, focusing on the observational details for each explosive event during 1956–2010.

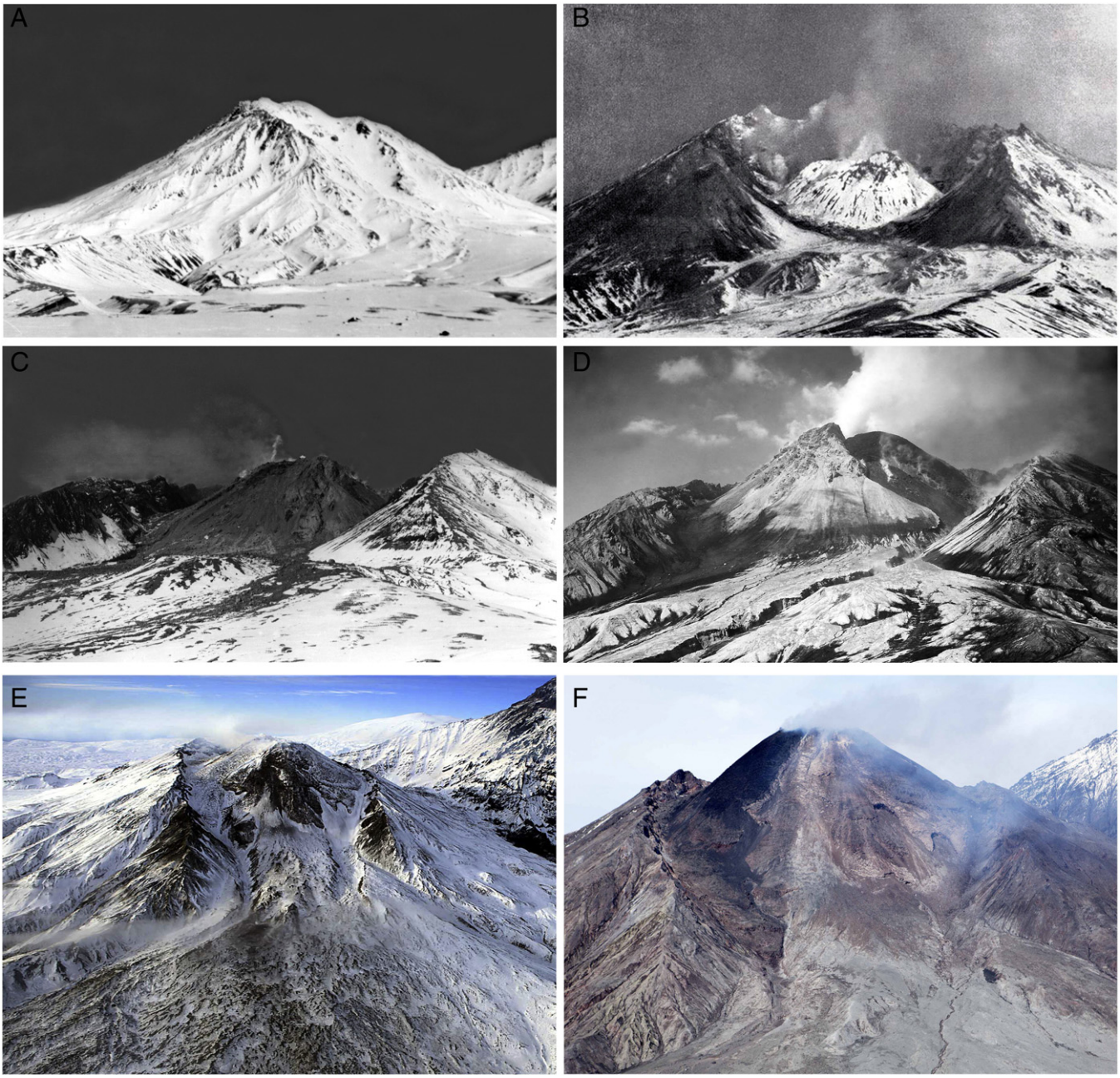

Fig. 2. Bezymianny Volcano: 1946, photo by B. Piip (A); 1957, photo by G. Gorshkov (B); 1965, photo by Yu. Dubik (C); 1982, photo by Yu. Skuridin (D); 2009, photo by Yu. Demyanchuk (E); 2011, photo by Yu. Demyanchuk (F).

2. Paroxysmal explosive eruptions of Bezymianny Volcano associated with lava dome growth

2.1. Extrusive–explosive phase of eruptions

2.1.1. 1956–1965

A quiet extrusion of plastic lava blocks first on the east and northeast, then the south and west, and finally the northwest sectors of the volcanic crater occurred in the first years after the catastrophic 1956 eruption (Fig. 2B). By 1959–1960, lava covered nearly the entire crater floor and had built a dome-shaped monolithic structure (Kirsanov, 1979). By August 3, 1960, the dome was 470 m high with a basal diameter of 900 m and a top diameter of 600 m (Borisova and Borisov, 1962). Later an extrusion of lava blocks was observed throughout the crater accompanied by explosions of varying strength and character. Ash produced by explosive events rose as high as 8–10 km a.s.l. These explosive eruptions were observed in April 1960, March 1961, May 1962, June 1963, July–September 1964, and March–April 1965. The strongest explosive eruption occurred in 1965. The volcano's return to a quiescent state after each eruption took, on average, 1–2 months. With the end of the explosive eruption the fumarolic activity of the volcano gradually weakened (Kirsanov, 1979).

2.1.2. 1965

In March 1965 the seismicity of the volcano became elevated. The first volcanic earthquakes were registered on March 3 at the Apakhonchich seismic station. Nine such earthquakes were recorded from March 3 to 8; in addition volcanic tremor with amplitude (A) 0.1–0.4 μ was noted on March 5 and 7. The number and the energy of seismic events increased on March 8, when the tremor amplitude grew to 0.6–0.7 μ (Dubik and Menyailov, 1969).

Fig. 3. Bezymianny Volcano explosive eruption on May 09, 2006, sending ash to heights of 15 km above sea levels. Photo by Yu. Demyanchuk.

On March 9 at ~04:00 UTC (coordinated Universal Time) observers at the Apakhonchich seismic station heard the first explosive sounds from the volcano. The next explosions occurred at 04:00 and 04:35 UTC. Ash fall began ~05:00 UTC at the Apakhonchich and continued for about 12 h. A strong explosion was noted at 14:10 UTC. Volcanologists aboard the March 10 observation flight over the volcano at 03:30–06:00 UTC, reported a large dense ash column rising up to 10 km a.s.l. and ash plume extending northeast of the volcano. Occasional gas–steam emissions rose to 4.5 km a.s.l. at the background of ash-containing explosions. Three strong earthquakes were recorded on March 10, two on March 11, and one on March 13. On March 10, the volcanic tremor increased from A = 0.2–0.3 μ to A = 1.0 μ, and then returned to A = 0.2–0.3 μ. On March 11 volcanic tremor ceased, but ash-gas plumes for about 4 km a.s.l. continued until April 1.

On March 30 volcanic activity intensified, and the number of avalanches increased from March 30 to April 2. On April 2 at 15:50 UTC a strong explosive event occurred at the volcano. A volcanic tremor began registering starting at ~16:00 UTC on April 2. Ash fall was observed for several hours at the northeastern flank of Klyuchevskoy Volcano. Hot avalanches continued to collapse from the lava dome. Pyroclastic flow deposits at the Vostochnaya valley were 5-km-long, with a volume (V) of 0.021 km^3 (Table 1). The volcano returned to the background (no explosive but possible extrusive) activity in summer 1965 (Fig. 2C) (Dubik and Menyailov, 1969).

2.1.3. 1966–1976

After the eruption in 1965, plastic lava continued to be extruded between the hard lava blocks at the lava dome. The author thinks it is likely that an extrusion of plastic lava continued all year because observers reported that the volcano was quiet for almost one year (Kirsanov and Studenikin, 1971; Kirsanov et al., 1971; Kirsanov, 1979). In 1966, an extrusion of plastic lava blocks was noted in the 1965 explosive crater. Later almost the entire western and southern parts of the dome summit were involved in the extrusive process. In 1967 an extrusion of plastic lava (named the Nautilus dome) was observed in the central and northern parts of the dome; this activity continued until March 1969. By this time, plastic lava occupied about half of the main lava dome. Starting in March 1969, the formation of numerous cracks in the southern and southeastern parts of the lava dome was noted. By October 1969, a new extrusion (named the October dome) occupied almost all of this area. In May 1970 the eastern part of the October dome had been extruded as a monolithic block, while the western part was represented by a heap of large lava fragments and some spines. The October dome continued to grow until October 1973; its extrusion was accompanied by occasional moderate explosions. By the end of 1973, the lava dome was divided into four blocks, amongst which the western block was stable, while the southeastern, central, and northeastern blocks were actively extruding. An extrusion from the central part of the dome continued from 1974 to 1976. Plastic lava in the central part of the lava dome top reappeared in 1976 (Kirsanov, 1979; Bogoyavlenskaya and Kirsanov, 1981).

2.2. Extrusive–explosive–effusive phase of eruptions

2.2.1. 1977

Seismic buildup prior to a new explosive eruption started in the middle of January 1977. The foci of type II–III earthquakes were located in the edifice of the volcano to the south and southeast of the dome at 0–5 km depth (H) below sea level. The strongest earthquake of this series, M = 2.27 at H ~ 3 km, occurred in the southern part of the epicentral area (Chubarova et al., 1983). In January and February the number of seismic events increased; from February 24 to 27 the earthquakes occurred at a rate of 20–50 per day and numerous hot avalanches were observed, followed by a long period of seismic repose from the end of February to March 25. On March 25, at 00:50 UTC, an M = 1.6 earthquake occurred, the focus of which was above sea level in the volcanic edifice.

An explosive phase of the eruption started on March 25, at 01:05 UTC. Continuous spasmodic volcanic tremor lasted 2 h with A = 0.2–0.5 μm, sometimes spiking sharply to 10 μm at a period (T) of 0.8 s; A/T = 12.5 μm/s (Chubarova et al., 1983). During this Vulcanian-type eruption, a 30 × 60 m crater formed at the dome summit. Ash emission occurred simultaneously with pyroclastic flows formation, and the deposits covered 7–8 km of the dome. The maximum flow width was 300 m, the thickness was 3–5 m, and the temperature of deposits was ca. 300 °C (Bogoyavlenskaya et al., 1979). Deposits were typical of block-and-ash pyroclastic flows. Their area (S) comprised 3.34 km^2 and V = 0.014 km^3 (Seleznev et al., 1984) (Table 1). After the cessation of volcanic tremor, single type II and III earthquakes were recorded for a few hours, after which seismic activity at the volcano ceased.

The effusion of a viscous lava flow on the north-northeast flank of the dome was initially recorded after the end of the explosive phase of the eruption (Bogoyavlenskaya et al., 1979). The flow width was 200 m, the length was 250–300 m, and the thickness was 10–15 m.

The total volume of erupted material from the March 25, 1977 comprised 0.01 km^3 (Bogoyavlenskaya et al., 1979), (Table 1) (Fig. 4).

2.2.2. 1978

The volcano produced fumarolic activity throughout the year, but individual weak Vulcanian-type single explosions were observed only in July and August. Single episodic earthquakes were registered from April to September, and from September 10 to 30 four significant seismic events occurred. On September 30 spasmodic volcanic tremor with A = 0.3 μm (rarely 4 μm) and T = 0.7–0.8 s, with A/T = 5 μm/s, was registered. The two tremor events lasted for 1 and 3 h, with a 10-hour period of repose in between. In the middle phase of the 1977 eruption a series of explosions occurred, resulting in a 3.0-km-long pyroclastic flow at the bottom of the dome (Ivanov et al., 1979). When seismic activity ceased, a new portion of the lava flow appeared (Chubarova et al., 1983).

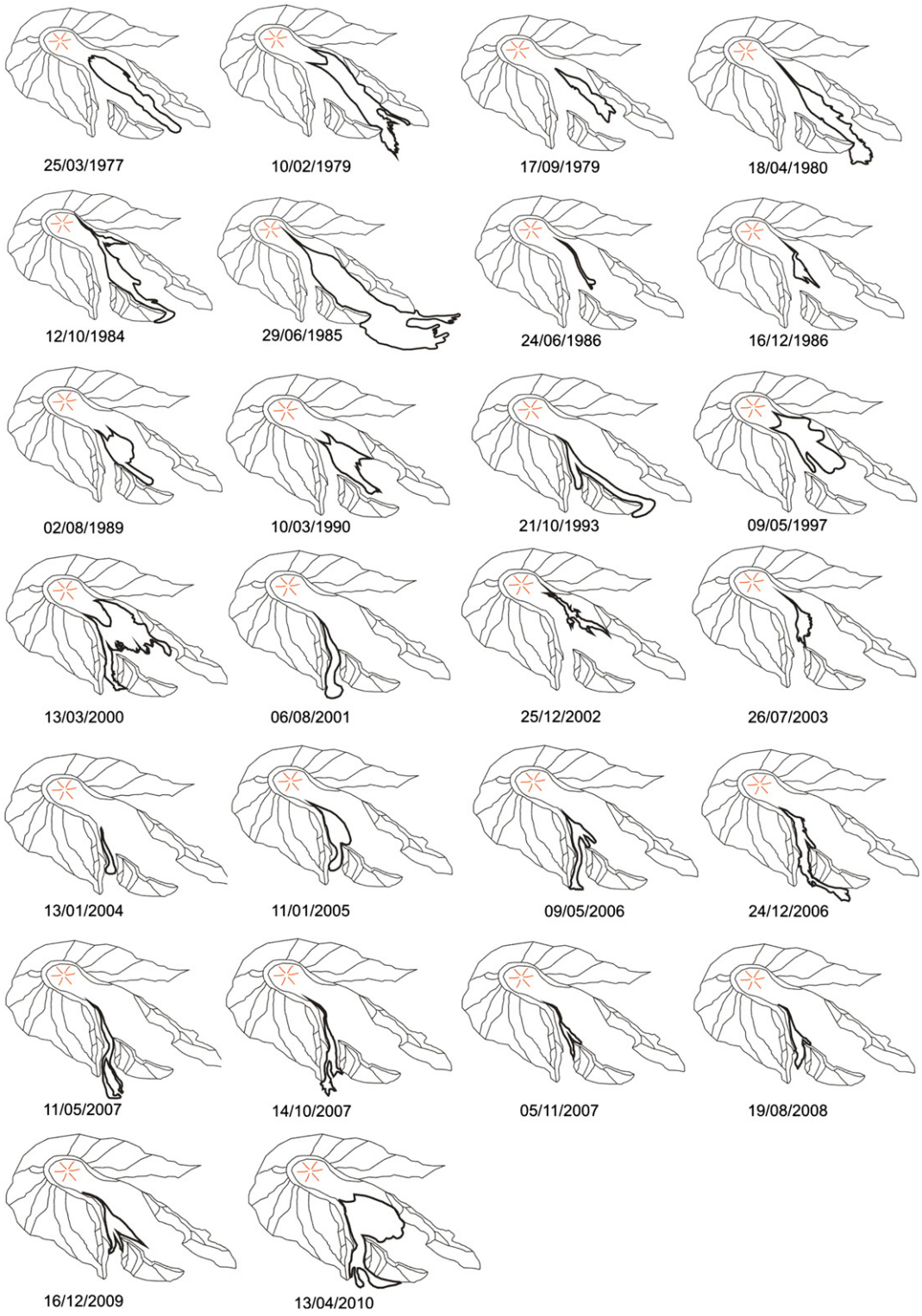

Fig. 4. Pyroclastic flow deposits of Bezymianny Volcano in 1977–2010. Outline by S.O. Borovkov and O.A. Girina.

2.2.3. 1979

Type II and III volcanic earthquakes were recorded at the beginning of February, suggesting a preparation for a new explosive eruption of the volcano. An explosive phase of eruption began on February 10 at 22:23 UTC, and lasted until February 11 (Chubarova et al., 1983). Within 2 h of commencing, it was accompanied by volcanic tremor (A_{max} = 8 μm, T = 0.8 s, A/T = 10 μm/s). An eruptive column reached a height of 7–10 km a.s.l. As a result of this paroxysmal phase, most of the northeast sector of the dome was destroyed by directed blast, along with lava flows from the 1977 to the 1978 eruptions. A vigorous, 8-km-long, 2-km-wide and 5–7-m-thick pyroclastic flow formed in the Vostochnaya valley (Fig. 4). The pyroclastic flow S = 4.81 km^2 and V = 0.017 km^3 (Seleznev et al., 1984). On February 15, the temperature of flow deposits was 500–600 °C. The total eruptive products V = 0.01–0.02 km^3 (Ivanov et al., 1979), (Table 1). When the explosive phase ceased, the viscous lava flow started to effuse into a large depression. Seismic activity at the volcano decreased, although from February through April over 100 weak seismic events were registered (Ivanov et al., 1979).

An explosive volcanic eruption began on September 17 without any buildup of seismicity. On this day, spasmodic tremor (A_{max} = 1.2 μm, T = 0.8 s, A/T = 1.5 μm/s) was registered during ~6 h from the onset of the eruption (Chubarova et al., 1983). An ash column reached a height of 8 km a.s.l., accompanied by a 5.5-km-long pyroclastic flow (Fig. 4) (Ivanov et al., 1980). The pyroclastic flow S = 1.26 km^2 and V = 0.0065 km^3 (Seleznev et al., 1984). On September 18 a new lava flow was observed from the Apakhonchich seismic station, and ~8 h a volcanic tremor (A_{max} = 1.5 μm, T = 0.7 s; A/T = 2.1 μm/s) was registered with 5–10 minute periods of repose. This tremor continued for five days after the paroxysm (Chubarova et al., 1983). On September 20, scientists observed a pyroclastic flow traveling down the slope of the volcano (Ivanov et al., 1980). The velocity of the pyroclastic flow in the proximity of the dome exceeded 150 km/h, whereas it was 50–60 km/h at a distance of 3 km from the dome. Gas and ash plumes reached a height of 4 km a.s.l. At night, numerous hot, incandescent blocks of various sizes were observed on the flow surface. Starting on September 23 hot avalanches were no longer observed, but small collapses continued to the end of October. Light ashfalls were rarely registered at the Apakhonchich seismic station. Starting in November 1979, only moderate fumarole activity at the volcano was observed (Malyshev, 2000).

2.2.4. 1980

Heightened volcanic activity was registered on April 18 at 06:00 UTC. Ash emissions to 8–9 km a.s.l. and a series of pyroclastic flows up to 8-km-long were observed during the afternoon of April 18. The pyroclastic flow S = 3.58 km^2 and V = 0.019 km^3 (Fig. 4) (Seleznev et al., 1984). The explosive phase of the eruption was

Table 1
Data for 1965–2010 explosive eruptions of Bezymianny Volcano.

	Data of eruption beginning			Eruption column, height, (km a.s.l.)	Distance of ash plumes, (km)	Direction of ash plumes from the volcano	Magnitude of volcanic tremor, (μm/s)	Deposits of pyroclastic flow		
	Year	Day/month	UTC					Length, (km)	Area, (km^2)	Volume, (km^3)
1	1965	9 March	04:00	10		NE		5		0.021
2	1977	25 March	01:05	10		ESE	12.5	8	3.34	0.014
3	1978	30 September					5	3		
4	1979	11 February	22:23	10			10	8	4.81	0.017
5	1979	17 September		8			1.5	5.5	1.29	0.006
6	1980	18 April		9				8	3.58	0.019
7	1981	13 June	02:00	12		NE		6.5		
8	1981	20 December	16:30	5		N		5		
9	1982	10 June	20:00	8		E		5		
10	1983	22 May	05:00	8				4		
11	1984	15 February	02:30	6			1.5			
12	1984	12 October	23:00	8		NE	4.5	7	2.7	0.012
13	1985	30 June	05:15	10–15		E, NE		12.5	12.25	0.05
14	1986	24 June		6				4	0.25	0.001
15	1986	16 December	19:07	7			10.8	4	0.62	0.001
16	1989	2 August	04:00	8		SW		5.5	0.45	0.001
17	1990	9 March		10				5	1.12	0.005
18	1992	12 March		6		W				
19	1993	21 October	04:00	12	600	SE		8	2.31	0.009
20	1995	5 October	21:00	8	5000	NE	3.3		0.05	
21	1997	9 May	01:12	13.5	700	ENE		5	3.75	0.015
22	1997	5 December	00:15	10	200	NE				
23	1999	24 February	19:15	8	1500	SE				
24	2000	13 March	16:25	8	2000	W, NW		5	4.75	0.02
25	2000	1 November	15:20	6.5	300	SW				
26	2001	6 August	22:28	10	400	S	11.7	5.5	1.31	0.005
27	2001	16 December	00:00	6 ?		W	1.92			
28	2002	25 December	19:20	6 ?		W	0.88	4.5	0.62	0.003
29	2003	26 July	08:45	11	300	W, SW		3	0.81	0.001
30	2004	13 January	22:50	8	300	NNE	3.81	3.5	0.37	0.001
31	2004	18 June	19:40	10	1000	NE	0.43			
32	2005	11 January	08:02	10	400	WSW	0.48	5	0.53	0.003
33	2005	30 November	12:00	6	450	WSW	0.14			
34	2006	9 May	08:21	15	1500	E, NE	1.01	4.5	1.25	0.005
35	2006	24 December	09:17	15	900	NE	0.77			
36	2007	11 May	14:45	8	200	N, NE		6	1.12	0.004
37	2007	14 October	14:27	10	1000	SE	1.08	5.5	1.31	0.005
38	2007	5 November	08:43	8	100	W	0.36	4	0.43	0.001
39	2008	19 August	10:30	9	1300	W, SW	0.4	4.5	0.68	0.003
40	2009	16 December	21:45	10	500	W, NW	1.1	3.5	1.06	0.002
41	2010	31 May	12:34	10	1000	W		6	5.75	0.023

Footnote. The data of 2001–2009 magnitude of volcanic tremor from KBGS RAS: http://www.emsd.ru/~ssl/monitoring/main.htm.

followed by effusion of viscous lava flow, which length approached 1.5 km (Bogoyavlenskaya and Kirsanov, 1981). From September to December, the volcano produced moderate fumarolic activity.

2.2.5. 1981

From January to May, moderate fumarolic activity was registered at Bezymianny. On June 12 at 17:03 UTC the first seismic events of this year were registered within the volcano. Spasmodic volcanic tremor was detected at 17:58 and 18:10 UTC. A dark ash column reaching 5 km a.s.l. was observed from the Apakhonchich seismic station at 18:25 UTC (Malyshev, 2000). At about 18:40 UTC, a 3.5-km-long pyroclastic flow formed; the ash cloud from this pyroclastic flow prevented further visual observations of the edifice. At about 21:00 UTC, ash started to fall in the area of the Apakhonchich seismic station. Volcanic activity began to decline rapidly, and by 20:00 UTC the volcano appeared to have quieted. However, on June 13 at 02:00 UTC the eruptive activity suddenly resumed and produced the largest pyroclastic flow of this eruption, reaching 6.0–6.5 km in length (Ivanov et al., 1982). At 02:30 UTC an ash column reached a height of 12 km a.s.l., accompanied by intense ash fall in the area of the Apakhonchich seismic station. A 4.5-km-long pyroclastic flow formed at 04:10 UTC. Later, volcanic activity decreased. At 23:30 UTC a large hot avalanche was observed, leaving deposits which stretched for 2.5 km from the dome. The volcano produced only moderate fumarolic activity, but rare hot avalanches were observed up to July 10, and the extrusion of a viscous lava flow on the dome flank suggested that juvenile magma was still actively being emplaced.

Malyshev (2000) reported that starting in mid-July deformation of the dome summit's eastern block became noticeable, followed by the appearance of a spine at the beginning of August. According to the data from Seleznev et al. (1984), the height of the spine above the surface of the lava flow was 27 m on July 31; by mid-August it had grown to 80 m with a basal diameter of 60 m. According to the data of Malyshev (1990, 2000), while the extrusion grew, the number and volume of avalanches increased as the summit section of the lava flow gradually collapsed. The extrusive spine also began to gradually collapse. Starting in the second half of August, continuous sporadic incandescence was visible at night, while hot avalanches suggested that the more plastic lava had begun to extrude along the perimeter of the spine base.

On August 31, while obscured by low cloud cover, distinct rumbling noises were heard sporadically from the volcano. Hot avalanches (sometimes as many as 30–40 per hour) coming from the east, originating near the summit of the dome, resulted in incandescence during the night of September 1–4 (Malyshev, 2000). By September 5, lava effusion had gradually replaced the spine growth. A new lava flow traveled at about 1 m/h through the first half of September. During the second half of September, the lava flow continued to be active, while a new extrusive spine appeared in the northeast part of the dome summit. By November 16, the flow was 360-m-long. By the middle of November, the flow rate decreased to 3–4 cm/h. Seismic activity of the volcano was very weak, despite continuous lava effusion. Starting on November 15, the number of earthquakes slightly increased, and effusive activity of the volcano increased sharply; the lava began flowing at 0.8 m/h and gradually decreased in speed. By the middle of December, the lava flow was 500-m-long and the average flow rate had decreased to 3.5 cm/h (Malyshev, 1990, 2000).

Type II–III earthquakes were recorded near the volcano in the second half of December. An explosive eruption began on December 20 at 16:30 UTC, producing an ash column that reached a height of 5 km a.s.l. The 2.5-km-thick ash plume stretched to the north (Malyshev, 2000). The volcano produced several large pyroclastic flows at 16:20, 18:20, 19:11, and 20:37 UTC, which reached 5 km from the summit of the volcano. On December 22, gas and steam activity was observed. On the night of December 23 a bright glow from nearly constant hot avalanches was observed, indicating that a new lava flow was extruding over the surface of the old lava flow. By December 25 the lava flow was 200-m-long, 40-m-thick, and traveling at an average flow rate of 2 m/h. By January 4, the flow rate had decreased to 0.2 m/h, and the number of hot avalanches had also decreased. For example, from January 1 to 3 only 1–2 avalanches were recorded per hour (Malyshev, 2000).

2.2.6. 1982

By mid-January the lava flow front had almost stopped moving, but the avalanches numbers increased, particularly during the period from January 9 to 16. For example, on January 11 avalanches occurred nearly continuously, while the volcanic tremor did not exceed 0.1 μm/s. The lava flow front was about 50–60 m thick.

In late January, a 30–35-m-high lava bulge with a 120 m basal diameter started to grow at the summit of the dome. By the end of the month, the base had developed into an extrusive block (Malyshev, 1990, 2000), with a smooth transition from effusive to extrusive activity. Beginning on June 5, incandescent lava was observed at the Apakhonchich seismic station. By June 10 both avalanches numbers and incandescence intensity on the dome had increased considerably.

On June 10, the volcano produced another explosive eruption. Starting at roughly 16:00 UTC, seismic activity increased due to extensive hot avalanches at the volcano (Malyshev, 2000). At 18:00 UTC, weak gas-and-ash emissions were observed. On June 10 at about 20:00 UTC an ash column rose to 7–8 km a.s.l. Seismic data showed the times at which volcanic activity increased: 18:46, 20:07, 20:27 and 21:10 UTC, which apparently corresponded to the formation of portions of a 2.5-km-long pyroclastic flow. This was followed by a 4–5-km-long pyroclastic flow at 21:20 UTC. The explosive phase then began to wane, though on June 10 at 24:45 and 22:30 UTC, and June 11 at 00:05 UTC, large avalanches were observed. The volcano returned to moderate fumarolic activity (Fig. 2D) and by the autumn, the lava flow had cooled (Malyshev, 2000).

2.2.7. 1983

The first evidence of renewed volcanic unrest was detected in January, with slight deformations at the dome summit. Processing of the aerial photography survey data from January 26 revealed cracks on the dome summit, possibly related to the emplacement of new lava into the edifice of the dome (Ivanov et al., 1988). On February 22, an 80 × 100 m deformation zone was detected, with one block as high as 5 m. Destruction of the lava flow surface and small avalanches occurred in the deformation zone. By April 30, a 50–70-m-high extrusive block had formed in the deformation zone, accompanied by avalanches.

On May 22 a white steam-and-gas column rose to a height of about 500 m, but starting at 02:00 UTC the volcano was obscured by clouds. Gradually the color of the clouds turned gray, indicating the presence of ash in plumes. On May 22 at 05:00 UTC rumbling was heard from the volcano; by 09:00 UTC the amount of ash in the plumes had significantly increased, and the clouds turned almost black (Malyshev, 2000). Seismic data revealed two periods of volcanic tremor, from 05:00 to 08:10 and from 15:00 to 19:00 UTC on May 22. The tremor averaged A = 2.0 μm. Later, ash fall drifted 30 km east from the volcano. Near the Apakhonchich seismic station, ash was as thick as 1.5 mm. Rumbling was heard from the volcano until 00:23 UTC on May 23, but cloudiness prevented any observations. When the sky cleared on May 25, a new lava flow was detected on the dome and a white gas-and-steam column rose 1.5 km above the volcano. Moderate fumarolic activity at the volcano continued until early 1984. Fieldwork revealed that the eruption had produced pyroclastic flow deposits ~4-km-long, 50–200-m-wide, and 1–12-m-thick (Malyshev, 2000).

2.2.8. 1984

Sporadic earthquakes recorded during the second half of January were precursors of this eruption. Aerial surveys of the volcano on January 21 and February 2 revealed evidence of new activity (Fedotov et al., 1985). As had occurred previously, deformations on the dome summit produced a new block, followed by a subsequent transition to a lava flow. In January, a dome-like bulge occurred on the dome summit, and then gradually transformed into an extrusive block 40–60 m high. On February 4 at about 23:00 UTC an ash column above the volcano was observed from Kozyrevsk village, followed by gray ash fall later in the day. From February 5 to 11 a blizzard in the Kamchatka River valley prevented any observations. On February 10 the earthquake (M = 1.3) was recorded. On February 13 the number of events started to increase (Fedotov et al., 1985). From February 12 through 13, the volcano produced small ash emissions possibly related to hot avalanches. On February 14 ash from avalanches rose to a height of 6 km a.s.l., and ash plumes drifted 50 km from the volcano.

On February 15 at 02:30 UTC the climactic stage of the explosive eruption was reached. Volcanic tremor at this time was 1.5 μm/s. After a short decrease, volcanic activity began to increase slightly, producing a new lava flow at the eastern slope of the dome estimated to be about 600-m-long (Malyshev, 2000). On February 16 seismic activity began to decrease. On February 17 lava flow extrusion ceased, and fumarolic activity at the volcano decreased to a moderate level.

New avalanches from the dome were observed in early September (Malyshev, 2000). Starting on September 20 white gas clouds were observed above the volcano summit at a height of 4 km a.s.l. Beginning on September 23, sporadic type II and III earthquakes were recorded, while both the power and the number of avalanches increased. Ash from avalanches rose to heights of 4.5–6 km a.s.l. The most vigorous avalanches were observed on October 1, 5, and 10–11. Rumbling from the avalanches was heard 16 km away from the volcano at the Apakhonchich seismic station. The extrusive stage of the eruption was accompanied by avalanches, which exposed a solid, 80-m-high andesitic block. On October 5 two to three events per hour were recorded, accompanied by continuous rumbling; on October 12 the number of events increased to ten to fifteen per hour (Fedotov et al., 1985).

On October 12 at 19:00 UTC a dark-gray gas-and-ash plume was observed above the volcano at a height of about 5 km a.s.l., stretching 40 km east-southeast. At 21:00 UTC weak ashfalls near the Apakhonchich seismic station resulted in pinkish and pale-gray ash deposits. On October 12 at 23:00 UTC the eruption of the volcano entered an explosive phase. At this time the directed ash burst to the northeast from the volcano was observed, with the ash column reaching a height of 5 km a.s.l. By October 12 at 23:05 UTC another directed burst was noted at the volcano, and later vertical explosions began at 3–8 minute intervals, producing cauliflower-like clouds (Fedotov et al., 1985). The largest number of earthquakes was recorded on October 13 from 00:00 to 02:00 UTC and from 10:00 to 12:00 UTC, when pyroclastic flows were being produced nearly continuously and were accompanied by ash clouds. The clouds from the eruption reached 10 km a.s.l. The explosive activity at the volcano lasted until October 14 at 05:00 UTC. During the periods of vigorous explosive activity, the volcanic tremor A = 5 μm. The eruption was accompanied by pyroclastic flows which were observed on October 13 at 00:11, 00:24, 01:42, and 04:05 UTC, reaching up to 7 km from the volcano (Fig. 4) (Girina, 1991). The Apakhonchich seismic station recorded A = 3–5 μm seismic events concurrent with the volcano's pyroclastic flows production. High-level volcanic activity led to increased ashfalls near the station. The highest ash fall intensity was reported on October 13 from 00:00 to 02:00 UTC, at which time the fallout mass reached 1.5 kg/m^2. From 05:00 to 09:00 UTC the volcano was relatively inactive, though it continued to produce hot avalanches. Starting at 08:45 UTC activity began to increase, and on October 13 from 09:00 to 12:00 UTC activity was very intense, though volcanic tremor was relatively homogeneous and did not exceed 3 μm/s. The volcano was producing pyroclastic flows during this period. On October 14 from 22:00 to 23:00 UTC, when the volcanic tremor increased to 3.5–4.5 μm/s, scientists in a house at the Plotina observed stronger bursts of pyroclastic material. In addition, the eruption of pyroclastic flows on October 14 at 05:20, 07:10, 07:25, and 07:40 UTC coincided with increased tremor (up to 2.0–2.8 μm/s) (Malyshev, 2000).

After the explosive activity ceased, seismic activity began to decline. A lava flow started to effuse from the crater to the lava dome flank and it continued until November 7. White and partially gray gas was observed above the dome, while sporadic hot avalanches traveled down the flanks.

The autumn paroxysm resulted in the formation of a small crater at the dome summit, and an abrasive trench on the eastern slope (Fedotov et al., 1985). There were two pyroclastic flow deposits in the Vostochnaya valley. The northern deposits were 4-km-long, up to 50-m-wide, and from 1.5 to 5 m thick, with S = 0.075 km^2 and V = 0.002 km^3, and were located higher, at the entry to the trench. The southern deposits were as long as 7 km, while their width and thickness varied from 50 to 500 m and from 0.3 to 8 m respectively; deposits S = 2.7 km^2 and V = 0.012 km^3 (Fedotov et al., 1985; Girina, 1991) (Table 1). The eruption also produced a large amount of ash. Ash plumes drifted to the east over the middle of the Kumroch Ridge, to the northeast over Kamaki village, and to the north-northeast near Kharchinsky Volcano. Ash deposits covered about 5000 km^2. Distribution of ash varied from 5000 to 6000 g/m^2 near the volcano to 300 g/m^2 at the Podkova seismic station (25 km from the volcano), 30 g/m^2 in Klyuchi village and about 1 g/m^2 in Kamaki village (65 km from the volcano) (Kirsanov et al., 1985).

2.2.9. 1985

The first signs of renewed volcanic unrest (first avalanches) related to the beginning of the extrusive stage were detected on June 12 (Malyshev, 2000). The growing extrusion block was initially 20–30 m tall and stretched along the explosive vent axis. Later, the growth rate of the extrusive block at the crater bottom increased, and on June 24 a large hot avalanche caused by the collapse of a portion of the extrusion (Malyshev, 2000). Another two avalanches were observed on June 25. It was reported (Malyshev, 2000) that the extrusion of the block was irregular, and it was noted on June 18 and 24–25 that the extrusive process had intensified. By the end of June the extrusive block had reached a height of up to 100 m. On June 29 at 07:10 UTC a low sporadic rumble from the volcano started to grow louder and eventually became continuous. Meanwhile, an A = 14 μm tremor was recorded at the Apakhonchich seismic station. During the next hour, the rumbling noise decreased. After 10–12 h, when fog allowed observation into the Vostochnaya valley, a new 5-km-long pyroclastic flow was observed.

The main explosive eruption phase began on June 30 at 05:15 UTC. At this time, volcanologists working on the flanks of Zimina Volcano (8.5 km south of Bezymianny) heard a rumbling noise, and from 06:30 UTC they noted loud thunderous sounds (Alidibirov et al., 1990). At 08:00 UTC radio communication was interrupted, possibly due to electrical discharge during the eruption. At 08:20 UTC, a series of loud rumblings were followed by 10 km long pyroclastic flows and ash clouds with lighting observed 200–400 m above the flows. Based on the duration of lightning activity, some pyroclastic flows continued until 13:00 UTC, June 30. Pyroclastic flows as long as 8 km were observed on June 30 at 09:40 UTC (volcanic tremor A = 3.2 μm at 09:32 UTC), at 10:05 UTC (A = 3.3 μm at 10:05 UTC), at 10:50 UTC (A = 2.3 μm at 10:42 UTC), and at 11:25 UTC (A = 2.9 μm at 11:18 UTC). Starting at 12:00 UTC on June 30, a new rumbling noise from avalanches was reported, and at 12:35 and 13:08 UTC two more pyroclastic flows traveled 10 km from of the volcano, accompanied by tremor A = 13 μm at 12:31 UTC (Alidibirov et al., 1990; Malyshev, 2000). Starting at 13:20 UTC a low-frequency jet-like noise, accompanied by the sounds of discrete explosions, was heard over a period of an hour. The noise intensity varied: at 13:50 and

14:00 UTC it peaked at an interval of 30–40 s, while at 14:17 UTC it was continuous for nearly 140 s. At 14:20 UTC, a wide, glowing pyroclastic flow extended for about 12.5 km. The flow temperature was about 600–700 °C. Later, pyroclastic material erupted nearly continuously, accompanied by extensive lightning; lightning activity then decreased and had ceased by ~17:00 UTC. Possibly during the period of the highest intensity noise, a direct blast may have destroyed two wooden houses 3.5 km from the dome and produced pyroclastic surge deposits (Alidibirov et al., 1990; Girina, 1994, 1997). Seismic data showed that the maximum tremor A = 21 μm was recorded at 14:24 UTC, at the moment when the glowing pyroclastic flow was produced. Ash rose to a probable height of 10–15 km a.s.l. Gradually decreasing activity at the volcano continued for the next 29.5 h (Malyshev, 2000). Seismic data revealed pyroclastic flows on June 30 at 16:30 UTC (tremor A = 5.6 μm) and on July 1 at 01:59 UTC (A = 3.1 μm). On July 1 at 19:40 UTC collapse of the remaining blocks in the explosive–erosive funnel caused a pyroclastic flow, which traveled about 4 km from the volcano. At the time tremor A = 3.1 μm. Flows deposits S = 10.5 km^2 (S = 12.25 km^2 according to our more precise definition (Fig. 4) (Borovkov, 2011)) with V = 0.05 km^3 (Alidibirov et al., 1990) (Table 1).

On July 1, lava flow effusion from the crater into the explosive–erosive funnel began, appearing as two incandescent flows. Numerous hot avalanches were noted at the flow front. By July 14, sector inflation had been detected inside the explosive–erosive funnel, which had filled with the lava flow. In late July an extrusive block formed at the most inflated point, accompanied by hot avalanches and high seismic activity at the volcano. It was reported (Malyshev, 2000) that on July 30 the lower part of the block collapsed, resulted in renewed effusion of lava down the dome. On August 4 the lava flow was moving at its highest rate (1.7 m/h). By mid-September the lava flow had filled most of the explosive–erosive funnel. The volcano showed no activity until October 15. Following this period of quiescence, hot avalanches traveled down the flow front followed by renewed lava extrusion. By early November the extrusion of a new block at the dome had given way to lava inflation. That process was accompanied by numerous hot avalanches, which on November 5 were produced at a rate of one per minute (Malyshev, 2000). By November 7 lava inflation had transformed into a lava flow; flow movement continued until December 14, accompanied by hot avalanches. By December 20, the upper part of the flow was covered with snow.

2.2.10. 1986

The first signs of renewed volcanic activity were recorded at the end of March; an onset of avalanches was associated with the renewal of the extrusive phase of the eruption (Malyshev, 1995, 2000). Later, a 50 m high dome-like bulge with a 150-m-diameter base formed at the top of the lava flow; its growth was accompanied by avalanches. By the beginning of June, the extrusive block had risen above the level of the lava flow, while the number of avalanches had decreased. In mid-June the growth of the dome resumed, and avalanches became more frequent. By June 20 the growing extrusion was 100 m high and 200 m in diameter. Within the next two days, the increasingly plastic material had been fully extruded, and the extrusion began to shrink; by June 23 only a small spine remained, while the remaining material transformed into a new lava bulge. New pyroclastic flows were occurring, producing cauliflower-type ash clouds. Ash plumes were directed 30–40 km south of the volcano leaving small ash falls along the eastern slopes of Zimina volcanoes. By this time the spine had been totally destroyed and its former site was covered by a 120-m-long lava flow moving at a rate of 5 m/h.

On June 24 the culmination of the explosive eruption occurred: during strong explosive activity at Bezymianny, two 4-km-long small pyroclastic flows formed, covering S = 0.25 km^2 (Fig. 4) (S = 0.31 km^2 (Borovkov, 2011)) with V = 0.001 km^3 (Maksimov et al., 1992) (Table 1). On the morning of June 26 the lava flow was 40–50 m thick and 400–450 m long with an average flow rate of ~10 m/h. By June 29, when the lava flow stopped moving, it was 500–550 m long. By July 1 hot avalanches coming from the flow front had almost stopped (Malyshev, 1995, 2000). Explosive episodes gave way to moderate fumarolic activity.

A new period of activity began near the end of October with an extrusive process. On November 7, a dome-like body 50 m high with a diameter of about 100 m at the dome summit, cut by a vertical northwest-trending crack (Malyshev, 2000). By November 25 this formation had increased in size: its height and diameter reached 80 m and 120 m, respectively, while the crack had also widened significantly. In early December avalanches from the dome were registered. By December 8 an extrusive block had appeared at the lava dome surface. On the night of 9/10 December hot avalanches began, signaling the emergence of new material at the surface. Effusion of fresh lava and the formation of the lava bulge at the dome summit led to destruction of the rigid extrusive block. On December 14 the block height was about 100 m with a diameter of 80 m, while the lava bulge height was about 60 m with a diameter of 150–200 m. On December 14 and 15, in addition to hot avalanches, a white gas–steam plume mixed with a small amount of ash produced by avalanches rose above the dome to a height of 4.5 m a.s.l. Vigorous hot avalanches accompanied by cauliflower-type ash clouds were registered on December 15 at 21:20 UTC and on December 16 at 00:30 UTC. Later, hot avalanches began to come down almost continuously. Shallow volcanic earthquakes that occurred during the collapse of the hot avalanches were recorded at the Apakhonchich seismic station (Malyshev, 2000). The effusion of juvenile material started on December 9, and it was reported that on December 16 and 17 the collapse of the avalanche from the lava bulge produced not only large fragments but an intensively curling, purple ash cloud rising above the avalanche (Malyshev, 2000). By 12:32 UTC on December 16 the extrusive block had been totally destroyed. The lava bulge had changed into the lava flow, which reached a length of 200–220 m and a thickness of 20–25 m (Malyshev, 2000).

Based on seismic data, a culminating explosive phase of the eruption occurred on December 16 at 19:07 UTC and lasted 2.5 h. At that time the tremor A = 6.5 μm at T = 0.6 s and A/T = 10.8 μm/s (during the eruption A_{ave} = 0.6 μm, T = 0.7 s and A/T = 0.86 μm/s) (Zharinov et al., 1991; Malyshev, 2000). This likely produced the eruptive column which rose to 6–7 km a.s.l, accompanied by a 4.5-km-long pyroclastic flow. On December 17 at 00:20 UTC an ash plume rose to 5 km a.s.l. Hot avalanches occurred continuously. At 00:49 on December 17, a new pyroclastic flow was formed (Malyshev, 2000). The maximum volcanic tremor at this time reached A = 5.8 μm. The length of the pyroclastic flow was 4 km, with S = 0.62 km^2, and V = 0.001 km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

2.2.11. 1987–1988

Deformation of the lava flow on the dome top began in December 1986 and continued through January 1987 (Malyshev, 1995, 2000). Over a two-month period, the lava flow top at the dome began to slowly bulge. However, only in early February did small avalanches begin, associated with more rapid extrusion of the lava block. By the end of February the block was 100 m high, with a 250-m-diameter base and a 150-m-diameter summit (Malyshev, 2000). The extrusive block at the surface had been gradually destroyed, and in April a lava bulge was observed at its former location. On April 15 hot avalanches were observed, a less viscous lava flow originated at the dome slope. The effusive stage continued with periodic increases and decreases in activity until the summer of 1989 (Malyshev, 2000).

2.2.12. 1989

In July weak fumarolic activity and small avalanches were observed, mainly at the boundary between the last lava flow and the stable southwest portion of the dome. Occasional ash plumes were

observed above the volcano at 17:00 UTC on August 1 apparently associated with hot avalanches on the northeast flank of the lave dome (Girina et al., 1993). On the southern dome flank, at the boundary between the latest lava flow and the previously stable part of the dome (just below the crater), a hot block was observed from which hot avalanches occasionally originated. Starting at 18:00 UTC on August 1 volcanic activity began to increase rapidly: at 18:30 UTC an ash plume reached 3.8 km a.s.l., and by 18:35 UTC it had risen to 4.5 km a.s.l. Between 19:00 and 20:35 UTC a vigorous steam and gas plume rose to 4.5 km a.s.l. During this event, observers noted persistent increasing roaring and hot avalanches (Girina et al., 1993).

At 20:40 UTC a dark spot of fresh extruded lava at the dome was noted. From 21:40 to 22:00 UTC a vigorous steam and gas plume was again observed above the volcano. Extruding lava was seen through the clouds. Beginning at 23:30 UTC, short hot avalanches were observed falling down the northern trench. The oval spot of fresh lava broadened. From 00:50 to 04:00 UTC on August 2 the number of avalanches gradually decreased.

On August 2 at 04:00 UTC the first pyroclastic flow, 3-km-long, formed after the explosion; a second 4-km-long flow formed at 04:12 UTC and at 04:20 UTC the longest flow reached 5.5 km. Continuing until 07:00 UTC small 2–3-km-long pyroclastic flows formed persistently. At this point, volcanic activity gradually diminished. From 16:30 to 23:00 UTC small hot avalanches were again observed, now associated with the effusion of a new lava flow at the dome flank. At 19:10 UTC (after the clouds had cleared) a steaming crack opened in the southern dome flank, at the boundary between the latest lava flows and the stable part of the dome. Below this crack were an erosive cavity and a small chute which had formed during the movement of the pyroclastic flows. Girina et al. (1993) determined that the 5.5-km-long pyroclastic flow deposits covered $S = 0.45$ km^2 and contained $V = 0.001$ km^3 (Fig. 4) (Table 1).

2.2.13. 1990

At the end of January the first signs of volcanic unrest began, with small avalanches from the southeast flank of the dome (Belousov et al., 1996). In mid-February new extrusive blocks were noted at the top of the dome. On March 9 large avalanches were recorded, generating ash clouds up to 5 km a.s.l. On March 10 this activity culminated in an explosive eruption that produced an ash cloud rising up to 10 km a.s.l. The block-and-ash pyroclastic flow stretched for 5 km along the Vostochnaya valley. The flow contained $S = 1.12$ km^2 and $V = 0.005$ km^3 (Fig. 4) (Borovkov, 2011) (Table 1). Additional slowly effusing lava continued to flow along the eastern flank of the dome.

2.2.14. 1992

From March 12 to 13 a weak explosive volcanic eruption occurred producing an ash cloud that rose to heights of 5–6 km a.s.l. and stretched west from the volcano (Belousov et al., 1996). In Kozyrevsk village ash deposits reached 4 g/m^2. The brief extrusion of a viscous lava flow was observed afterwards.

2.2.15. 1993

The first eruptive cloud above the volcano was reported on October 21 at 04:00 UTC (Belousov et al., 1999). At 11:00 UTC an ash fall that lasted 6 h began in Nikolskoye village in the Komandorskie Islands, 515 km from the volcano. Three ash plumes drifting 300 km to the southeast were detected in a satellite image at 03:25 UTC on October 21. During the climactic phase, the estimated height of the explosive bursts was 13 km a.s.l. On October 22–23, sporadic ash emissions rose to heights of 8–12 km a.s.l., and were reported in the Gidrometeopost at the Khapitsa River, 30 km east of the volcano. It is likely that the eruption continued for next four days because weak ashfalls were noted in Klyuchi village on October 27 and 28. By mid-November activity had decreased considerably. Fieldwork at the volcano on November 12 revealed the partial destruction of the southeastern part of the dome, and the effusion of the lava flow.

The volcano formed three pyroclastic flow deposits at its eastern foot, directed to the east (2-km-long, $S = 0.25$ km^2, $V = 0.002$ km^3), southeast (8-km-long, $S = 3.5$ km^2, $V = 0.01$ km^3), and south (4-km-long, $S = 0.75$ km^2, $V = 0.008$ km^3). Estimated total pyroclastic flow deposits $V = 0.02$ km^3 (Belousov et al., 1999). Our data showed that total flow $S = 2.31$ km^2 and $V = 0.009$ km^3 (Fig. 4) (Borovkov, 2011) (Table 1).

2.2.16. 1994

From late August to early October, small ash clouds above the volcano were observed from Kozyrevsk village. From September 2 to 8 hot avalanches at the volcano were noted, generating ash plumes that rose to 4 km a.s.l. In early September a new lava flow appeared on the dome flank which filled the destroyed northeastern part of the dome and traveled 700 m down the slope, covering part of the agglomerate mantle of the dome (KVERT Report, 1994).

2.2.17. 1995

Late in September 1995 the 1994 lava flow was seen to have been overlaid with a new flow that was covered by snow. Starting on October 1 type II–III volcanic earthquakes (after the Tokarev classification scheme; Tokarev, 1966, 1981) were registered in the area of the volcano. From October 1 to 5 about 50 earthquakes were recorded (Ozerov et al., 1996). Starting at 17:00 UTC on October 5, a series of explosive earthquakes occurred at 10–30 second intervals. After about 10 min, surface earthquakes waves formed a continuous volcanic tremor with $T = 0.9$–1.0 s. Tremor intensity grew rapidly, and by 17:21 UTC on October 5 the average $A = 1.5$ μm, with a maximum $A = 3.3$ μm (A/T = 1.5 and 3.3 μm/s respectively). Ozerov et al. (1996) distinguished four Bezymianny activity periods on October 5–6 by the character of volcanic tremor: 17:10–18:20 UTC and 19:45–20:25 UTC on October 5, from 21:59 UTC on October 5 to 00:30 UTC on October 6, and 08:00–10:45 UTC on October 6. Between the activity peaks numerous volcanic earthquakes continued to be recorded; for example, from 00:30 to 08:00 UTC on October 6 about 100 explosive earthquakes were detected. At 20:25 UTC on October 5 a light-gray gas–ash column was observed above the volcano.

On October 5 at about 21:00 UTC ash rose to 8 km a.s.l., and after 30 min ash fall was observed in Klyuchi village. The peak ash fall intensity occurred from 00:00 to 02:20 UTC on October 6. Several hours of ash fall resulted in 0.2 cm of light-gray ash with a weight of 700 g/m^2. Weak ash fall continued until October 7 (Ozerov et al., 1996). The ash cloud from this eruption was detected by satellite at a distance of 5000 km from the volcano, near Unalashka Island in the Aleutian chain (Kirianov et al., 2001).

A thermal anomaly at the volcano remained from October 8 till December 17, 1995. Analysis of the thermal anomaly in National Oceanic and Atmospheric Administration (NOAA) satellite images after the eruption made it possible to estimate the pyroclastic flow deposits $S = 0.05$ km^2 (Table 1). The temperature of flow deposits was estimated to be 166–186 °C, and cooled gradually over two months (Abdurakhmanov et al., 2001).

2.2.18. 1997

Weak gas–steam activity was observed at Bezymianny in early April. Between April 19 and 23, very weak volcanic tremor was recorded. At 17:45 UTC on May 8 an ash plume was noted above the volcano that drifted 40 km southeast at a height of about 4 km a.s.l. During the next 2 h volcanic activity decreased slightly. On May 9 at 01:12 UTC the volcano sending an eruptive column to heights of 12–13.5 km a.s.l. (KVERT Report, 1998). At 04:30 UTC on May 9 ash fall began in Klyuchi. After 2 h the weight of the ash was 180 g/m^2. At 06:30 UTC on May 9 an ash plume drifting 420 km east-northeast from the volcano was noted in satellite images. At

about 03:00 UTC on May 10 an ash plume rose to 6 km a.s.l. Seismic activity was slightly less than on May 9. An ash plume extending about 700 km east-northeast of the volcano was detected in a satellite image at 18:00 UTC on May 10. Pilots reported an ash cloud over the volcano at 08:15 UTC on May 15, though no further ash plumes were observed in satellite images. The pyroclastic flow deposits were 5-km-long, with S = 3.75 km^2 and V = 0.015 km^3 (Fig. 4) (Borovkov, 2011) (Table 1).

On December 3–4 a thermal anomaly over the volcano appeared in satellite images, indicating effusive activity at the lava dome. Moderate gas–steam activity was observed during this period.

New explosive eruption of the volcano started at about 18:30 UTC on December 4. No preliminary seismicity increase was recorded. At 20:30 UTC on December 4 an ash cloud rose to 6 km a.s.l. and drifted northeast from the volcano. At 00:00 UTC on December 5 an intensity of the eruption increased. On December 5 at 00:15 UTC an ash column raised to 9–10 km a.s.l. (KVERT Report, 1998). High levels of seismicity at the volcano continued. At 13:32 UTC on December 5 an ash plume drifted 211 km northeast from the volcano, at a height of 9–10 km a.s.l. Pilots in the area reported that an ash column rose to 12–13 km a.s.l. on December 5. At 20:00 UTC on December 5 only fumarolic activity of the volcano was observed, but a gas–steam plume reached about 4 km a.s.l. The explosive phase of the eruption was over, but active lava effusion likely continued. Bezymianny seismic activity was obscured by intense aftershocks from seismic events recorded after the M = 7.8 December 6 earthquake on the east coast of Kamchatka, but by December 9 seismicity had decreased to low level. Moderate fumarolic activity of the volcano continued until the end of the year (KVERT Report, 1998).

2.2.19. 1998

From January to May the volcano was relatively quiet: only moderate fumarole activity was observed, and seismicity was low. On June 1, for the first time in a long time, a thermal anomaly was observed in satellite imagery. The size of the anomaly gradually grew to 5 pixels by June 10, but no seismic events were recorded at the volcano. The thermal anomaly gave evidence for renewed extrusive-effusive volcanic activity. Gas–steam plumes rose to 100–800 m above the volcano and drifted about 10 km in different directions. On June 22–23 an incandescence was observed from the dome and hot avalanches were seen from its southeastern flank indicating a viscous lava flow effusion. From June 22 to 29 weak shallow seismic events were recorded in the Bezymianny area. Dense clouds prevented any visual or satellite observations, so there were no data recorded to confirm the explosive activity, though the thermal anomaly was detected in satellite imagery until late June. Moderate fumarolic activity was observed until the end of the year (KVERT Report, 1999a; McGimsey et al., 2003).

2.2.20. 1999

Moderate gas and steam volcanic activity was observed in January. From January 26 to 28 five weak volcanic earthquakes in the volcano area were registered, and starting on February 9 a seismic activity of the volcano began to increase. On February 13 a thermal anomaly was detected in satellite images, probably it associated with extrusive activity on the dome. During the week beginning on February 15, twenty to forty weak volcanic earthquakes were registered daily; moderate fumarolic activity continued as well. On February 17–18 ash plumes containing small amount of ash and stretching 40–50 km from the volcano were noted in satellite images. At 10:00 UTC on February 24 a gas–steam plume rose to 6.5 km a.s.l., and extended for 100 km from the volcano. Starting at 14:30 UTC the volcanic tremor intensity grew sharply. On February 24 at 19:15 UTC an ash column rising to 8 km a.s.l. was observed from Kozyrevsk village. On February 24 a plume saturated with ash was detected in satellite imagery, stretching for several hundred kilometers southeast of the volcano. During February 24–25 the ash cloud was traced for 1500 km southeast of the volcano. Seismic activity gradually decreased towards the end of February. Moderate fumarolic activity continued to the end of the year (KVERT Report, 1999b; McGimsey et al., 2004a).

2.2.21. 2000

From January to the middle of February Bezymianny produced only moderate gas–steam activity and low seismicity. From February 11 to 17 seven weak volcanic earthquakes were registered in the volcano area. Starting on March 10 the seismic activity of the volcano began to increase sharply. An explosive phase of the eruption began on March 13 at 16:25 UTC (KVERT Report, 2000). A strong spasmodic volcanic tremor was noted at a seismic station located 100 km away. On March 13 at 16:44 UTC a satellite image showed a thermal anomaly 18 pixels in size, and a small ash cloud 10 km west of the volcano. At 19:42 UTC the ash cloud had drifted west at an approximate height of 8 km a.s.l., and at 20:15 UTC ash fell in Kozyrevsk village. At 23:00 UTC the ash plume stretched for 225 km from the volcano to the Sredinny Ridge. The strongest explosive event occurred at 21:31 UTC on March 13 (Senyukov et al., 2004). On March 14 a 50 °C thermal anomaly and a small ash cloud were noted in satellite images. Between March 14 at 21:32 UTC and March 15 at 08:32 UTC Geostationary Meteorological Satellites (GMS) (Tokyo) images showed the ash cloud drifting across the Shelekhov Bay northwest of the volcano at an approximate height of 7 km a.s.l. (KVERT Report, 2000).

After 22:00 UTC on March 13 seismic activity began to decrease, and was low on March 14. However, on March 15 starting at 10:00 UTC the number of volcanic earthquakes again increased sharply and starting at 12:22 UTC a volcanic tremor lasted for 1.5 h. The levels of volcanic tremor suggested possible ash emissions at an approximate height of 5 km a.s.l. (Senyukov et al., 2004). At 17:30 UTC on March 15 a thermal anomaly 8 pixels in size, and a 60 × 100 km ash cloud 140 km west of the volcano were noted in satellite images. From 11:50 to 21:30 UTC on March 16 strong seismic activity of the volcano continued. On March 18 at 09:06 UTC a dark, dense column of volcanic ash rose over Bezymianny summit to a height of 8 km a.s.l.; the ash plume drifted southeast from the volcano. Seismicity returned to background levels after March 19. Weak avalanches continued, but volcanic tremor was not detected. The explosive eruptions produced 5-km-long pyroclastic flow deposits (S = 4.75 km^2, V = 0.02 km^3) at the foot of the volcano (Borovkov, 2011) (Fig. 4) (Table 1).

From March to August a moderate fumarolic activity of the volcano was observing. The lava flow continued to effuse at the flank of the dome, and combined with the cooling pyroclastic flow deposits resulted in a thermal anomaly in the area of the volcano. In April, the size of the anomaly decreased to 1 pixel. In March and April, rare weak volcanic earthquakes were registered in the volcano area.

At 18:30 UTC on September 20 for the first time in a long time, a weak, 1-pixel thermal anomaly was detected over the volcano in satellite data, though seismic activity did not yet register. On September 27 the size of the anomaly had grown to 4 pixels. From the end of September to the middle of October seismicity was low, though single volcanic earthquakes were registered. Satellite images showed a constant thermal anomaly. On October 10 gas–steam activity increased, which suggested the possible onset of a new eruptive cycle.

In the satellite image of October 17, at 18:04 UTC, the temperature of a 4-pixel thermal anomaly exceeded 50°C. This anomaly was probably associated with the extrusion of new lava blocks from the dome. An increase in seismicity was not detected, although power outages at the nearest seismic station severely limited seismic monitoring during this period. On October 25 shallow earthquakes, and seismic signals commonly associated with hot avalanches, began to appear. These avalanches resulted from collapse of the new blocks that had

been extruded since September 20. Spasmodic volcanic tremor began at 07:30 UTC on October 26. From October 27 to 29, the volcano was not visible due to clouds. Seismicity increased relative to the previous week. Beginning at 12:15 UTC on October 28 the energy of the earthquakes started to increase, and the series of seismic events (probably associated with hot avalanches) continued in earnest. On the morning of October 30 a gas–steam plume rose to 4 km a.s.l. and drifted northeast, while the brightness of the thermal anomaly increased. Starting at 10:00 UTC on October 30 the activity of the volcano continued to ramp up, with intense seismic activity observed from 13:46 to 14:15 UTC on October 30. Satellite images from October 31 showed an ash plume drifting about 55 km southeast from the volcano at 17:00 UTC, and extending to 80 km at 18:00 UTC. Visual observation from Kozyrevsk confirmed that a gas–steam plume rose to 4.5 km a.s.l. and drifted southeast at 17:30 UTC on October 30, and that a gas–steam plume containing ash rose to 6.0 km a.s.l. at 00:10 UTC on October 31. On October 30 at 22:30 UTC the Aviation Color Code was changed from Yellow to Orange (KVERT Report, 2000). At 03:06 UTC on November 1 a plume containing a small amount of ash and extending about 40 km northeast was detected in satellite imagery. At 04:47 UTC on November 1 a thermal anomaly 5 pixels in size with a temperature of 49°C was noted, while a gas–steam plume rose to 4.0–4.5 km a.s.l.

A strong explosive eruption was recorded on November 1 from 15:20 to 16:00 UTC, followed by a single explosive event at 18:26 UTC. On November 1 at 18:28 UTC satellite images showed an ash plume at a height of 6.5 km a.s.l. drifting 130 km southwest from the volcano. On November 2 starting at 00:00 UTC seismic activity of the volcano began to decrease, but remained elevated; at 04:21 UTC satellite images showed a 231 km long ash plume approximately 270 km southwest from the volcano, rising to at least 6.5 km a.s.l. The thermal anomaly over the volcano was 9 pixels in size. On November 3 satellite images showed a 30 km long ash plume stretching southeast of the volcano. The size and the temperature of the thermal anomaly started to decrease, and on November 3 and 6 it was only 4 pixels in size. By November 10 seismicity of the volcano had decreased to background levels, with only a single weak, shallow earthquake recorded. On November 12 the size of the thermal anomaly decreased to 1 pixel, and moderate gas–steam activity was observed at the summit (KVERT Report, 2000).

2.2.22. 2001

In January and February, moderate gas–steam activity was observed at Bezymianny. Seismic activity was low, though occasional weak, shallow earthquakes were recorded. On January 1 satellite images showed a weak 1–2 pixel thermal anomaly at the summit.

After July 25 seismicity of the volcano began to increase. From July 25 to 28 shallow earthquakes and weak, long-lived local seismic events were recorded, presumably associated with the formation of small avalanches. A 3-pixel thermal anomaly with a temperature of 26.8 °C over the volcano was detected on July 25 in satellite imagery. The linear, northwest-southeast trend of the anomaly suggested the resumption of extrusive activity, accompanied by small hot avalanches.

On August 6 at 22:28 UTC the volcano began to erupt explosively (Girina et al., 2005). Although seismicity from August 2 to 5 was low, on August 6, during a 24-hour-period, the number of weak local earthquakes increased rapidly. The magnitude of volcanic tremor began to gradually increase, and on August 6 from 22:28 to 23:00 UTC it reached 11.7 μm/s. From 00:00 to 01:00 UTC on August 7 the magnitude of tremor decreased to 1.0 μm/s, ceasing altogether soon after. At 22:28 UTC on August 6 an ash plume rose to 5 km a.s.l., moving east-southeast from the volcano. At 23:25 UTC the height of the ash cloud reached ~10 km a.s.l. On August 7 the staff of the Kronoki seismic station reported ash fall, with ash mass of 50 g/m^2. A 4-pixel thermal anomaly with a temperature of 49.5 °C was detected at the volcano on August 6 at 04:51 UTC, and an ash plume extended southeast from the volcano. On August 7 at 04:02 UTC the ash cloud was 200 × 100 km in size near Kronotsky Volcano in east Kamchatka and stretched farther (200 km from Bezymianny) to the south. On August 8 at 19:52 UTC a 3-pixel thermal anomaly with a temperature of 28 °C was observed at Bezymianny. On August 9, seismicity returned to background levels (Girina et al., 2005). The explosive eruption produced 5.5-km-long pyroclastic flow deposits, covering S = 1.31 km^2 and V = 0.003 km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

Beginning on November 10, after a short repose, the first weak earthquakes were recorded at the volcano. On November 22 their number and power began to gradually increase, although the level of seismicity did not exceed background levels. Regular weak gas–steam volcanic activity continued to be observed.

On December 9 at 18:17 UTC a satellite image showed a 2-pixel thermal anomaly with a temperature of 10.3 °C over the volcano and a weak gas–steam plume, presumably mixed with a small amount of ash that stretched for 87 km southeast. Visual observations from Kozyrevsk village indicated that on December 9 at 21:00 UTC a gas–steam plume rose to 3.3 km a.s.l. Seismic activity was elevated. In the subsequent days, the number of earthquakes and the size and intensity of the thermal anomaly grew. By December 14 the level of seismic activity had increased significantly: a large number of weak shallow earthquakes were recorded in the edifice of the volcano, including shallow signals presumably associated with avalanches and the destruction of new extrusive blocks. From December 11 to 12 the size of the anomaly increased to 3 pixels and the temperature reached 49 °C, indicating the presence of juvenile material near the surface. By 04:35 UTC on December 13 the size of the anomaly had grown to 10 pixels with a temperature of 33.8 °C and, by December 14, to 14 pixels with a temperature of 49.5 °C. On December 14 at 03:50 UTC a vigorous gas–steam plume issuing from the vent was seen in Klyuchi village; satellite images showed a 60-km-long plume extending north-northeast from the volcano. The Aviation Color Code was changed from Yellow to Orange at 22:25 UTC on December 14 (KVERT Report, 2002).

Starting at 20:00 UTC on December 15 the amplitude of persistent volcanic tremor increased sharply, a signal interpreted to indicate impending explosive activity. On December 15 at 20:45 UTC a vigorous gas–steam plume rose to 5 km a.s.l., stretching 60 km northwest of the volcano. At a distance of 20 km from the volcano the plume was seen to be dark, indicating the presence of ash. On December 16 from 00:00 to 14:00 UTC volcanic tremor was constant and reached a maximum intensity of 1.92 μm/s. Later the tremor intensity began to decline gradually and the tremor pattern changed from continuous to spasmodic (Senyukov et al., 2004). During December 16–18 there were 800 recorded earthquakes with M < 4.5. On December 19, beginning at 20:00 UTC, seismic activity began to decline. By December 28, seismicity had decreased to background levels, although weak earthquakes in the edifice of the volcano were recorded until January 5, 2002. The thermal anomaly also waned; on December 20–25 it was a 1-pixel size with a temperature of 9.8 °C (KVERT Report, 2002; McGimsey et al., 2004b).

2.2.23. 2002

Moderate gas and steam activity and a weak thermal anomaly were seen almost continuously throughout the year, as a viscous lava flow continued to effuse from the dome.

On December 9 weak shallow earthquakes began to appear, and on December 16 a volcanic earthquake M = 1.75 was detected. From December 19 to 22 seismic activity of the volcano was low, but beginning on December 23 it rapidly began to ramp up. On December 23, for the first time, a 1-pixel thermal anomaly was noted on the satellite image. On December 24 at 23:35 UTC a weak volcanic tremor was recorded (Senyukov et al., 2004). Over the next few days the anomaly sharply increased in both size and temperature: on December 24 there was a 2-pixel anomaly with a

temperature difference of 33 °C above background, and on December 25 the anomaly had grown to 10 pixels with a temperature of ~50 °C. A bright 20-km-long gas–steam plume was detected at 01:21 UTC on December 25 in Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image. After 2.5 h (at 03:57 UTC on December 25) this plume extending 200 km west of the volcano was noted in NOAA satellite image. In connection with the occurrence of the bright plume and the sharp increase in size and temperature of the thermal anomaly, O.A. Girina predicted an impending explosive eruption at Bezymianny and changed the Aviation Color Code from Yellow to Orange for Bezymianny at 08:10 UTC, December 25 in KVERT Release 62–02 (KVERT Report, 2003a). On December 25, a weak intermittent volcanic tremor began, and from 04:00 to 12:30 UTC on December 25 a swarm of shallow earthquakes was detected (about 70 events of $M < 1.7$).

On December 25 at 19:20 UTC the explosive eruption of the volcano began. The volcanic tremor reached $A = 0.88$ μm/s. No ash was detected in satellite images, but on December 25 from 21:10 to 23:15 UTC (2 h after the onset of the eruption) ash fall ~0.3 cm thick was noted at Kozyrevsk village, accompanied by a sulfurous smell. By 04:00 UTC on December 26 the level of tremor had decreased and the eruption intensity had declined. From December 26 to 31 the volcano was obscured by clouds (KVERT Report, 2003a; Neal et al., 2005). The eruption resulted in the formation of a 4.5-km-long pyroclastic flow, the deposits of which covered $S = 0.62$ km^2 with $V = 0.0025$ km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

2.2.24. 2003

In January only rare separate seismic events were registered, and from February 2 to July 23 seismic activity at the volcano was weak. From January 2 to 8 weak 1–4 pixels thermal anomalies were detected over the lava dome and at the foot of the volcano, presumably related to the effusion of a viscous lava flow on the dome flank, and to cooling pyroclastic flow deposits from the December 25, 2002 eruption. From January to July weak and moderate gas–steam activity of the volcano was observed.

According to satellite data, a thermal anomaly 2 pixels in size was detected in the area of the volcano beginning on July 6. On July 15, for the first time after a period of repose, seismic activity of the volcano increased slightly. Individual shallow earthquakes with M ~2.0 were recorded on July 23 and 25. On July 25 at 15:16 and 16:57 UTC a 12 pixel thermal anomaly was detected, and on July 25 at 23:58 UTC a gas–steam plume stretched for about 40 km west of the volcano.

According to seismic data, the explosive eruption of the volcano began on July 26 at 08:45 UTC (KVERT Report, 2003b). The eruption continued for over 3 h. At 10:20 UTC, an ash column at a height of 8 km a.s.l. was observed from Klyuchi village, heading west from the volcano. As was reported by the Meteorological Center at Elizovo Airport, at 09:26 UTC on July 26 pilots of international flights observed an ash plume at a height of 10–11 km a.s.l. west of the volcano. A 10–15 pixel thermal anomaly was noted in satellite imagery on July 26 at 09:22 UTC. A large pyroclastic flow probably occurred at the foot of the volcano around this time. On July 26 at 14:58 UTC satellite imagery showed a 9-pixel thermal anomaly and a 250 km ash plume drifting west-southwest from the volcano. From 23:02 UTC on July 26 to 19:15 UTC on July 27 an 8–10 pixel thermal anomaly with a temperature of 50 °C was observed. Ash was detected in plumes from the beginning of the eruption until 10:16 UTC on July 27. The explosive eruption of the volcano resulted in a 3-km-long pyroclastic flow deposits with $S = 0.81$ km^2 and $V = 0.001$ km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

After the explosive phase of the eruption was over, activity began to decrease. From July 27 to 29, while the volcano was obscured by clouds, seismicity returned to background level. A weak thermal anomaly, 1–3 pixels in size with a temperature from 16 to 25 °C, was noted on satellite images from July 28 to August 1. From August through December, seismic activity of the volcano was low, gas–steam activity of the volcano was weak or moderate, and a 1–2 pixel thermal anomaly was sporadically detected in the area of the volcano (KVERT Report, 2003b; McGimsey et al., 2005).

2.2.25. 2004

From January 1 to 12 seismicity of the volcano was low. According to satellite data, a 1 pixel thermal anomaly was noted in the area of the volcano on January 4, followed by a 2 pixels anomaly from January 11 to 12. On January 9 volcanic seismicity increased slightly, and a shallow earthquake with $M = 2.2$ was detected.

On January 13 at 22:50 UTC a strong explosive eruption of the volcano began (KVERT Report, 2004). No seismic precursors for Bezymianny were observed because a strong explosive eruption of Klyuchevskoy Volcano occurred at the same time, producing a continuous volcanic tremor of 20.5 μm/s on January 12 and 16, and 15 μm/s on January 13 and 14. During the explosive phase of Bezymianny Volcano its volcanic tremor was 3.81 μm/s. According to visual and video observations from Klyuchi, an ash cloud rose 6–8 km a.s.l. at the beginning of the eruption, likely associated with a large pyroclastic flow on the southeastern flank of the volcano. Satellite data from 23:42 UTC on January 13 showed the ash plume extending 70 km north-northeast from the volcano. On January 14 at 02:21 UTC the plume stretched for 190 km from the volcano. An 8-pixel thermal anomaly was detected during the eruption. On January 14 from 02:00 to 04:40 UTC an ash plume at a height of 4.2–3.5 km a.s.l. stretched to the north-northeast from the volcano, nearly reaching Ust-Kamchatsk village. On January 15 at 06:28 UTC a single ash cloud 15 × 35 km in size was observed 80 km away from the volcano drifting to the northeast. From January 15 to 17 and January 25 a 4-pixel thermal anomaly was registered over the volcano. This anomaly probably reflects the formation of a viscous lava flow at the dome, as is common at the end of explosive eruptions at Bezymianny.

After the explosive eruption, activity at Bezymianny began to decrease rapidly. Seismicity was mainly low from April 18 to 29, with earthquakes of M ~ 1.25. Fumarolic activity of the volcano was mostly moderate. From January 20 to May 31, the size of the thermal anomaly over the volcano decreased to 1–2 pixels. On May 21 aerial observations revealed that lava flows entirely covered the dome, with blocks occasionally rolling down the flow surface. Significant amounts of ash were observed on snow south-southwest of the dome foot. The explosive eruption resulted in 3.5-km-long pyroclastic flow deposits, with $S = 0.37$ km^2 and $V = 0.001$ km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

From June 2 to 3, for the first time after a period of repose, weak shallow earthquakes were recorded and seismicity increased slightly. On June 3 a 1–2 pixel thermal anomaly was detected at the dome. From June 5 to 6, along with shallow earthquakes, weak intermittent volcanic tremor was noted. On June 11 three shallow earthquakes with $M = 1.25$ were recorded, and on June 12 two earthquakes with $M = 1.5$ and weak intermittent volcanic tremor were registered. Observer Mike Zelensky, who was near the volcano on June 12, reported unusually intense fumarolic activity at the volcano throughout much of the day. A dense bluish-white and dark-orange plume formed. On June 13 two earthquakes with $M = 1.25$ were recorded. In general seismicity at the volcano was increasing gradually, indicating a renewed period of activity that would likely culminate in an explosive eruption.

On June 14 the number of weak shallow seismic events increased rapidly. Among these events three earthquakes with $M = 1.25$ were recorded. On June 14 Mike Zelensky noted the presence of glowing lava in an upper part of the dome. On June 15 and 16 the number of weak seismic events increased to 60 and 100, respectively. Stronger earthquakes were also registered including ten with $M = 1.25$–1.7, two with $M = 2.0$ (on June 15), and eight with $M = 1.25$–1.55 (on June 16). From June 15 to 16 weak intermittent spasmodic volcanic

tremor was recorded. A 2-pixel thermal anomaly continued to appear in satellite images on June 15–16. On June 16 the character of the volcanic tremor changed from intermittent to continuous and reached 0.32 μm/s. This intensification of seismic activity was probably related to the extrusion of new lava blocks on the dome, as is common before paroxysmal eruptions. On June 15 at 04:55 UTC the Aviation Color Code was changed from Yellow to Orange (KVERT Report, 2004). KVERT suggested that an explosive eruption of the volcano could occur at any time.

On June 18 at 19:40 UTC an explosive eruption of Bezymianny began. According to seismic data, the most active phase of the eruption occurred from 19:40 to 20:20 UTC. In addition two strong events were recorded probably related to two powerful ash-forming explosions. Continuous spasmodic tremor was registered with M = 0.43 μm/s, in addition to 21 shallow earthquakes with M = 1.25–1.7. Dense cloudiness prevented visual observations of the eruption, although videocameras in Klyuchi and Kozyrevsk sporadically captured individual events. At 20:30–20:55 UTC on June 18 an ash-gas cloud rose to 8–10 km a.s.l. and drifted northeast from the volcano. From 21:35 until 21:55 UTC on the same day a dense, ash-saturated eruptive column was observed at the volcano, with an ash plume drifting southeast from the volcano. On June 18–20 ash plumes and clouds reached Korovin Island (in the Aleutians). On June 19 the seismicity was moderate; only weak shallow earthquakes were registered, while volcanic tremor was weak and intermittent. Later, seismicity decreased to low. A 1–4 pixel thermal anomaly was observed over the lava dome in satellite images from June 18 through late November, probably caused by the effusion of a viscous lava flow on the dome slope.

On June 21, Mike Zelensky noted that there were no fresh ash deposits in the area of the volcano, indicating that no ash from the June 18 eruption fell on the northeast part of the volcano. Light-gray eruptive clouds above the slope of Klyuchevskoy Volcano were observed to carry a small amount of ash, and snowfalls on June 19–20 easily covered the ash deposits. Mike Zelensky and Nataliya Gorbach reported that by August 4 the new lava flow had reached the inner somma wall on the northern dome slope. The flow front was 15-m-thick. From July 2 to December 31 seismic activity at the volcano was very low.

On December 25, seismic activity at the volcano gradually began to increase, and from December 27 to 28 it exceeded background levels. On December 25 the Bezymianny seismic network detected three volcanic earthquakes with M = 1.2–1.4 at depths up to 2.2 km, and on December 27 five earthquakes with M = 0.6–1.7 at the same depth (KVERT Report, 2004).

2.2.26. 2005

In early January the seismicity of the volcano was elevated, and between two and seven seismic events per day (with the exception of January 6 with ten events) were registered with M = 0.7 to 2.2 at depths up to 3.5 km. This increase of seismic activity was likely related to the extrusion of new lava blocks at the dome, an occurrence which usually precedes paroxysmal eruptions. On January 6 at 23:05 UTC the Aviation Color Code was changed from Yellow to Orange (KVERT Release, 2005a). KVERT suggested that an explosive eruption at the volcano could occur in the following week.

The thermal anomaly over the dome also increased in size considerably, from 2 to 6 pixels, on those days. From January 7 to 10 a rapid increase in the number of earthquakes at depths up to 3 km was detected, from 14 volcanic earthquakes on January 7 to 22 on January 9, and to 46 on January 10; M = 1.7–2.7 on those days. Spasmodic volcanic tremor of 0.2 μm/s began on January 10.

On January 11 at 08:02 UTC an explosive eruption of the volcano began (Girina et al., 2007). According to seismic data, the most active phase of the eruption from 08:02 to 08:45 UTC was accompanied by an ash cloud that reached heights of 8–10 km a.s.l. Continuous spasmodic tremor at 0.48 μm/s was registered during that time, and about 30 shallow earthquakes with M = 1.0 to 2.2 were recorded. On January 11 at 10:14 UTC an ash cloud 50 km in diameter at heights of 8–9 km a.s.l. was located 160 km west-southwest of the volcano. At 11:54 UTC, the ash cloud was 30 km in diameter, and was detected 360 km away from the volcano at a height of 7 km a.s.l. In a MODIS AQUA satellite image taken on January 12 at 02:35 UTC a wide strip of ash deposits were noted from Ichinsky Volcano to the Okhotskoe Sea. Ash deposits at Kamchatka covered S ~ 5000 km^2 (Girina et al., 2007).

When the explosive phase was over, activity decreased rapidly. From January 12 to 23 a 5-pixel thermal anomaly was detected over the volcano, probably related to the effusion of the lava flow to the dome slope. From February to March, the anomaly size varied between 2 and 3 pixels over the lava dome. In April and early May the thermal anomaly slightly increased in size to 5 pixels; the increase was related to increased gas emission throughout the springtime caused by sudden alterations in weather conditions at the volcano. The run-out of the pyroclastic flow was about 5 km, S = 0.53 km^2 and V = 0.0026 km^3 (Girina and Gorbach, 2006) (Fig. 4) (Table 1).

From February to November weak fumarolic activity at the volcano was observed. Satellite imagery on June 7, 16, and 28–30 revealed a thermal anomaly of 1–3 pixels. Visual observations from volcanologists who were working on the flank of the volcano indicated that from June 19 to 27 the volcano produced numerous small avalanches caused by the slow movement of the lava flow. Aerial observation on July 27 revealed that the January 11, 2005 eruption caused the formation of a central crater on the dome; its southeastern slope was cut by a crack that opened into the crater. A viscous, steam-emitting lava flow from the crater effused over the southwestern slope of the dome. Satellite imagery from July to November showed a 1–4 pixel thermal anomaly over the volcano. In August seismicity of the volcano increased slightly, including shallow earthquakes with M < 2.6. From September to October, seismicity at the volcano was low.

After November 11 volcanic seismicity started to increase gradually, accompanied by sporadic shallow earthquakes of M = 1.4. From November 21 to 24, one to three shallow earthquakes were detected per day, with M < 1.7. After November 25 the number of earthquakes began to increase. Satellite imagery from November 3 to 21 showed a 1–3-pixel thermal anomaly. On November 29 seismic signals consistent with hot avalanches began to be detected, in addition to volcanic tremor at 0.1 μm/s. From November 28 to 29 strong fumarolic activity at the volcano was observed, including a gas–steam column rising to 4.5 km a.s.l. All events indicated an upcoming explosive eruption. On November 29 at 23:30 UTC the Aviation Color Code was changed from Yellow to Orange (KVERT Release, 2005b). KVERT suggested that explosive eruption at the volcano could occur during the next several days.

Seismic data revealed a moderate explosive eruption of Bezymianny on November 30 from 12:00 to 13:15 UTC. Volcanic tremor was 0.14 μm/s in that time. Cloudiness prevented visual observations of the explosive activity of the volcano. According to satellite images taken on November 30 at 13:50 and 17:32 UTC, an ash cloud 70 × 80 km in size was observed 40 km and 85 km away from the volcano, respectively, moving west-southwest at a height of 6 km a.s.l. On November 30 at 18:30 UTC, the ash cloud was observed 250 km west of the volcano and at 19:58 UTC, the cloud was 280 km west-northwest. On December 01 at 00:17 UTC an ash cloud 60 km in size was detected 420 km west of the volcano. No ashfalls were reported in Klyuchi and Mayskoye villages. Observers from Kozyrevsk village reported that ash in the air, but no ash cloud was observed. Satellite imagery showed that from 17:32 until 20:32 UTC on November 30, both the size and the density of the ash cloud decreased. Seismic activity of the volcano returned to background levels on December 1, though the effusion of the lava flow on the dome slope continued (KVERT Report, 2005).

2.2.27. 2006

Aerial observations conducted by helicopter on April 1 by staff from the KBGS RAS and the F.Yu. Levinson-Lessing Kamchatkan

Volcanological Station revealed a new extrusive block on the summit of the dome, though no anomalous seismicity had been detected from January to March. On April 01 at 14:50 UTC satellite imagery revealed a 5-pixel thermal anomaly over the volcano.

The first precursors of renewed activity (three shallow M = 1.6 volcanic earthquakes) were detected on April 11. The number of shallow events started to increase in time relative to earthquakes at a depth of 20 km. Volcanic tremor with M < 0.5 μm/s was registered at the volcano on April 11, 15, 17, 20, and 24. In early May the number of shallow earthquakes began to increase from 10 events per day on May 1, to 28 events per day on May 5 (Girina et al., 2006). The duration of the daily volcanic tremor increased as well. On May 4 the first hot avalanche was observed on the dome. Ash produced by the avalanche rose to 4 km a.s.l. on May 4 and 6. On May 7 at 00:15 UTC the Aviation Color Code was changed from Yellow to Orange (KVERT Release, 2006a). KVERT suggested that explosive eruption at the volcano could occur during the next one or two weeks.

Activity continued to ramp up, including an increase in the number of hot avalanches and the growth of the thermal anomaly over the dome. At approximately 05:00 UTC on May 9 a large vertical gas–steam column began to grow above the dome, accompanied by continuous volcanic tremor up to 0.56 μm/s. These events indicated that an explosive eruption of Bezymianny was imminent, and KVERT changed the Aviation Color Code from Orange to Red at 06:35 on May 9 (KVERT Release, 2006b).

On May 9 at 08:21 UTC an explosive eruption of the volcano began. Volcanic tremor was 1.01 μm/s in the strongest eruptive phase. An umbrella-like ash cloud about 60–80 km in diameter formed above the dense vertical eruptive column and rose to about 15 km a.s.l. The ash plume was split by inhomogeneous tropospheric convection processes and drifted in multiple directions simultaneously (north, northeast, and southeast) from the volcano (Girina et al., 2006).

Seismic activity had decreased to background levels by 12:00 UTC on May 9. Satellite imagery on June 12 at 00:30 UTC showed a wide field of ash deposits which stretched east to the Pacific Ocean and northeast to Ust'-Kamchatsk village. In June-July the seismicity of the volcano was relatively low. In July volcanologists observed pyroclastic flow deposits 4.5-km-long at the foot of the volcano. On July 25 the collapse of a small hot avalanche was observed. Run-out of these deposits was about 3.5 km from the volcano. Aerial observations by helicopter on July 31 revealed a small lava flow on the southwestern dome flank, and two explosive funnels that the May 9 eruption had opened on the dome summit. After July 15 daily satellite imagery showed a thermal anomaly at the volcano summit. Its size varied from 1 to 12 pixels, indicating that the volcano continued to effuse a new viscous lava flow on the dome. The pyroclastic flow deposits were 4.5-km-long with S = 1.25 km^2 and V = 0.005 km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

In August, the seismicity of the volcano increased. Volcanic tremor was registered on August 8. During the month 58 volcanic earthquakes of M = 0.7 to 1.5 were recorded; six of them were between −1.6 and 5.3 km depth, while the others were shallow earthquakes, 31 of type IV, using the classification of Tokarev (1966). Visual observations revealed weak and moderate fumarolic activity. Satellite imagery showed that the thermal anomaly on the dome remained, but did not exceed 5 pixels. From September to November the seismicity at the volcano mainly remained low; the volcano produced only weak gas–steam plumes during this period, while the size of the thermal anomaly on the dome varied from 1 to 9 pixels.

Seismic buildup for the next explosive eruption started in late November, when both the number and the magnitude of shallow volcanic earthquakes began to increase. Multiple series of low-frequency seismic events, presumably related to avalanches traveling down the flanks of the volcano, began to be detected starting on November 30, and were registered almost daily starting on December 9 (Girina et al., 2006). These were likely the result of extrusive activity having resumed within the dome. Five such series were recorded on December 19, ten series on December 20, and nineteen series on December 21. In total, about 110 volcanic earthquakes were registered during December at M = 0.6 to 2.1; 36 of them were registered at depths between −1.7 and 7.4 km, while the others were shallow events, 48 of them type IV. Visual observations revealed relatively strong fumarolic activity that sent gas–steam plumes to heights of about 4.5 km a.s.l. Satellite imagery showed that the thermal anomaly on the dome remained, its size varying from 1 to 6 pixels, increasing to 15 pixels on December 6, and 13–15 pixels on December 18. Video observations showed that starting at 23:52 UTC on December 23 sporadic avalanches and explosions sent ash to a height of about 6 km a.s.l.

Due to the increase in the activity of the volcano, at 20:30 UTC on December 23, the Aviation Color Code was changed from Yellow to Orange (KVERT Release, 2006c), (Girina et al., 2006). KVERT reported that an explosive eruption, accompanied by an eruptive column up to 15 km a.s.l., will possible between December 23 and 31. Video surveillance showed that, starting 23:52 UTC on December 23, large sporadic avalanches and explosions sent ash to a height of about 6 km a.s.l. At 02:40 UTC on December 24, the Aviation Color Code was changed from Orange to Red (KVERT Release, 2006d).

A strong explosive eruption started on December 24 at 09:17 UTC and lasted until 10:20 UTC the same day (Girina et al., 2006) with volcanic tremor of M = 0.77 μm/s. Visual observation showed that an eruptive column rose to about 13–15 km a.s.l. The final phase of the eruption occurred at night, and the height of the column was estimated from observations of lightning inside the ash cloud. December 24–27 satellite imagery showed a local ash cloud that drifted gradually 850 km northeast of the volcano. On December 24 ash fall, accompanied by a strong sulfurous smell, was noted in Klyuchi village, leaving ash deposits in the village up to 1 cm thick. Seismicity of the volcano returned to background levels at about 22:00 UTC on December 24, though about 30 hot avalanches were detected from 10:20 to 24:00 UTC on December 24, with two more detected on December 25. Data from aerial observations by helicopter on December 27 showed that a part of the southern slope of the dome had been destroyed. The run-out of pyroclastic flow deposits was about 6–7 km. Satellite imagery showed that the flow produced a distinct thermal anomaly, as the temperature of the deposits on the flank was about 500–600 °C. The eruption produced pyroclastic flow deposits about 6.5-km-long, with S = 1.94 km^2 and V = 0.008 km^3 (Borovkov, 2011) (Fig. 4) (Table 1). According to Carter et al. (2008), the pyroclastic flow deposits S = 2.04 km^2. The volcano mainly produced weak-to-moderate fumarolic activity from December 26 to 31.

2.2.28. 2007

In January occasional volcanic earthquakes and a series of low-frequency events were recorded related to the formation of a new lava flow on the slope of the volcano. During January, five seismic events were recorded at depths from −1.5 to 5.9 km (the latest on December 21); eight shallow earthquakes (the latest on December 31) and twelve series of events (the latest on December 27). A thermal anomaly periodically observed at the dome was associated with a viscous lava flow effusion. From February to mid-April seismicity at the volcano remained low. From January 1 through May 10 weak fumarolic activity of the volcano was observed.

Activity of the volcano began to increase in April. Two shallow earthquakes of M = 2.2 and 1.9 were recorded on April 21 and April 24, respectively. On May 10, one shallow earthquake was recorded with M = 2.5; and a large thermal anomaly with a temperature of 51 °C was detected in satellite images. On May 5 and 8, hunters from Klyuchi village reported mud flows in the vicinity of the Sukhaya Khapitsa River near Bezymianny. These flows likely

started to form on May 5 or earlier due to the onset of active lava extrusion and hot avalanches that melted snow. The Aviation Color Code was changed from Yellow to Orange at 22:55 UTC on May 10 (KVERT Release, 2007a). KVERT suggested that an explosive eruption of the volcano could occur at any time.

The large eruption of Klyuchevskoy Volcano that was occurring at that time prevented seismic detection and prediction of eruptive activity at Bezymianny. The strongest explosive phase of the Bezymianny eruption was initially interpreted by seismologists as a new period of Klyuchevskoy activity. These eruptive events at Bezymianny were retroactively interpreted by O.A. Girina using indirect data, and were described on May 13, 2007 (KVERT Release, 2007b).

The main explosive phase of the eruption occurred on May 11 from 14:45 to 15:10 UTC (Girina et al., 2009) accompanied by volcanic tremor of 15.44 μm/s. Visual reports from Kozyrevsk village on May 11 at 22:30 UTC indicated one hot avalanche that sent ash up to 4 km a.s.l. Ash fall was observed in Klyuchi village from 16:00 to ~22:00 UTC on May 11; it consisted mainly of gray ash from Bezymianny, but including some black ash from Klyuchevskoy Volcano, which was also erupting explosively at the time. An Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite image from May 11, 2007 clearly showed a large ash plume stretching northeast from Bezymianny. A thin ash plume from Klyuchevskoy joined the plume from Bezymianny at a distance of about 20–30 km away from Klyuchevskoy. Farther afield, the large mixed plume stretched for more than 100 km. Due to unstable weather patterns in the area of the Northern volcanic group of Kamchatka, satellite images from 16:00 UTC on May 11 showed different directions of movement of the plumes and clouds. A large, bright thermal anomaly (11 pixels) indicated fresh hot deposits from a pyroclastic flow (NOAA-18, 14:29 UTC on May 12). An ASTER image from July 07, 2007, clearly showed the pyroclastic flow indicated by the thermal anomaly. On May 17, hunters again reported large mud flows in the Sukhaya Khapitsa River: a vigorous 200 m wide flow moved over snow down the bed of the river. The vigorous mud flows, which continued for more than a week after the eruption, were related to the interaction of the hot pyroclastic flow material with snow on the flank of the volcano. This eruption resulted in the formation of pyroclastic flow deposits 6-km-long, with $S = 1.12$ km^2 and $V = 0.004$ km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

After the Klyuchevskoy eruption was over, seismic events at Bezymianny were much more easily detected. Until the end of September volcanic earthquakes (shallow and at depths from −1.9 to 3.6 km) were recorded almost every day in the area of Bezymianny (for example, six events occurred on June 17 and 22, and the same from July 8 to 19). About 24 earthquakes per month occurred in August and September. Series of about four and six shallow seismic events, presumably indicating avalanches, were detected on September 24 and 25, respectively. A satellite image from September 25 showed a 35 km ash plume stretching east from the volcano. In addition, on October 1 and 3–4 the size and intensity of the thermal anomaly grew over the lava dome; on October 6, 8, and 11 the anomaly was very bright. On October 3 and 10, one series of low-frequency seismic events per day was again recorded. Though the Aviation Color Code was Yellow, at 21:50 UTC on October 11, KVERT suggested that explosive eruption at the volcano could occur during the next weeks (KVERT Release, 2007c).

A new explosive eruption began on October 14 at 14:27 UTC, and lasted (with brief pauses) until 14:00 UTC on October 15 (Girina et al., 2009). The maximum volcanic tremor during the eruption reached $M = 1.08$ μm/s. Although earthquakes recorded on October 14 were of higher magnitude, the main explosive phase occurred on October 15. Series of eight and eighteen low-frequency seismic events and 117 and 209 shallow earthquakes were recorded on October 14 and 15, respectively.

Visual data confirmed that an ash column rose to 9–10 km a.s.l., and the ash plume stretched south-southeast of the volcano. Satellite date from October 14 to 15 indicated a bright, 25-pixel thermal anomaly in the area of the lava dome. From October 14 to 16 ash plumes stretched 1000 km mainly to the east and southeast of the volcano, at heights of 10 km a.s.l. on October 14 and 7–8 km a.s.l. on October 15–16 (Girina et al., 2009).

Although volcanic tremor ceased to register after 14:00 UTC on October 15, from October 16 to 19 seismic activity at the volcano remained elevated. Forty-six shallow earthquakes were recorded on October 16, and sixteen and nineteen events on October 17 and 18, respectively. According to satellite data, from October 16 to 18 ash clouds were still in the area of Kamchatka, above the Kronotsky Gulf. NOAA and TERRA MODIS satellite images indicated a streak of ash deposits extending from the volcano to the ocean coast on October 18. A large bright thermal anomaly was observed from October 16 to 18 in the area of the volcano. This anomaly indicated both a viscous lava flow on the dome flank, and deposits of pyroclastic flow at the volcano slope. Volcanologists aboard an observation flight at the volcano on October 21 detected a deep trench stretching from the summit to the somma side on the south-southeast dome flank half filled by a 400 m long lava flow. As it had been 5–6 days since the eruption, the rate of the flow was roughly estimated at 3 m/h. Pyroclastic flow deposits were 5.5-km-long, and occupied $S = 1.31$ km^2, with $V = 0.005$ km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

In November seismic activity of the volcano was mainly low. At times shallow earthquakes in the volcanic edifice were recorded related to the effusion of a viscous lava flow on the dome flank and avalanches from the flow front. Visual data confirmed weak fumarolic activity of the volcano. Satellite imagery showed a weak thermal anomaly in the area of the dome.

Seismic data indicated that a series of explosive events occurred on November 5 from 08:43 to 10:10 UTC. Seven shallow and eight low-frequency series with $M < 10.9$ μm/s, and volcanic tremor with $M = 0.36$ μm/s were recorded. Two hot avalanches were observed: a moderate one at 15:45 UTC and a weak one at 18:07 UTC on November 5. The height of the ash plumes is uncertain because clouds obscured the volcano from November 1 to 6. Satellite data (NOAA-16) showed a bright thermal anomaly over the dome at 17:52 UTC on November 5.

An observation flight on November 9 showed that the fronts of Bezymianny lava flows formed in 1989–2001 had collapsed as a result of explosive events that occurred on November 5. The long-lasting explosive eruption of October 14–16 and the deepening of the trench beneath the frontal parts of the above-mentioned flows led to increased instability and eventually to partial collapse. The collapses produced ash clouds generally 6–8 km a.s.l. Because part of the lava flows collapsed, 4-km-long pyroclastic flow deposits formed, covering $S = 0.43$ km^2 with $V = 0.002$ km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

On November 9, satellite images showed a bright gas–steam plume near the volcano (Girina et al., 2009). Earlier experience in investigations of Bezymianny suggested that a possible strong explosive eruption was imminent. A 100 km long bright gas–steam plume stretching east of the volcano was observed in satellite imagery from November 9 to 13. In this instance, the explosive eruption either did not occur or went unnoticed. It should be noted that nine shallow earthquakes with $A = 1.26$ μm/s and one series of low-frequency seismic events at $A = 1.26$ μm/s were detected on November 12 in the area of Bezymianny. One shallow earthquake and one series of events with $A = 2.26$ μm/s were registered on November 13, and two series at $A = 2.17$ μcm/s and one shallow earthquake on November 16. Towards the end of the year seismic activity at the volcano was low but weak volcanic earthquakes were recorded almost daily and weak or moderate fumarolic activity was observed at the volcano. A 5-pixel thermal anomaly was detected over the volcano in satellite images, indicating that the lava flow effusion on the dome flank was continuing.

2.2.29. 2008

From January to April seismic activity was slightly elevated: volcanic earthquakes of M = 0.8–1.95 were registered at depths from −0.6 to 2.4 km, in addition to shallow events and random series of low-frequency events. All this activity was presumably related to the collapse of single lava flow fragments or to the small hot avalanches that are common during effusive events. From May to July seismicity was relatively low. Visual data indicated moderate fumarolic activity from January to July. On May 18, a gas–steam plume extended for 53 km southeast of the volcano. Satellite imagery during this period showed a continual weak thermal anomaly near the volcano.

A slight increase of seismic activity was noted on July 11, when volcanic tremor was recorded. Visual reports confirmed secondary phreatic bursts from the pyroclastic flow deposits formed during October 14–15, 2007, resulting from the interaction of hot pyroclastic deposits with brooks. Visual reports from the slope of the volcano indicated slow effusion of the lava flow on the southern dome flank during July 18–22, and occasional small avalanches.

On August 11, a slight elevation of seismic activity of the volcano and a sudden increase in the summit thermal anomaly size and temperature were observed. Visual reports from Tatiana Churikova and her team (IVS FED RAS) who were camping 6.5 km away from the Bezymianny summit indicated that they heard loud, dull bangs coming from the volcano. On August 11 at 23:30 UTC the Aviation Color Code was changed from Yellow to Orange (KVERT Release, 2008). KVERT suggested that an explosive eruption of the volcano could occur within the week.

The explosive eruption of the volcano occurred on August 19 from 10:30 to 11:30 UTC (Manevich et al., 2011). Recorded seismic data indicated that eleven type II and III volcanic earthquakes occurred with M = 0.1; forty shallow earthquakes, six series of seismic events with M = 8.9 μm/s, and volcanic tremor at A = 0.4 μm/s. Visual reports by Tatiana Churikova confirmed that on August 19 at 11:30 UTC noises began to be heard from the volcano, which rapidly increased in volume. Against a dark background of clouds up to 4.0 km a.s.l. over the volcano, a bright scarlet incandescence was observed. Above this, the volcano was obscured by clouds. The sounds increased continuously. At first these were separate pounding noises, but they eventually joined to make a short-lasting rumble and finally a persistent low-pitched hum similar to a rocket launch, which continued for more than 1 h. Flashes of lightning began to be observed. During brief periods when the crater could be seen, the red incandescence of the lava dome top surface was visible. Red and white jets rose up to 500 m above the dome. After 13:00 UTC on August 19 the roar began to abate, although discrete explosions and periods of rumbling several minutes long continued. By that time the volcano had been obscured by clouds, and the incandescence could no longer be seen. Occasional thumping noises were heard again later, but by 15:00 UTC they had essentially ceased. On August 19, a weak ash fall and a slightly sulfurous smell were noticed in Kozyrevsk village. During this period, the volcano remained obscured by clouds. Satellite images detected a bright thermal anomaly on August 14 and from August 18 to 21; on August 19, at the beginning of the eruption, the size of the anomaly was 31 pixels. During the course of the eruption, an ash cloud rose to 9 km a.s.l. (according to the temperature profile) and drifted west of the volcano. At 02:01 UTC on August 20 the 125 × 35 km cloud had drifted over the western coast of Kamchatka (570 km away from Bezymianny). On August 20 traces of this cloud were noted in the southern part of the Okhotskoe Sea, at a distance of 1300 km from the volcano. Tatiana Churikova reported that from August 22 to 24 moderate fumarolic activity was observed; a gas–steam column rose to 5–6 km a.s.l. Avalanches coming down from the lava flow front were observed from time to time. Satellite images showed long pyroclastic flow deposits 4.5 km away from the crater on the south-southeast slope of the volcano. The temperature of these deposits remained elevated into September. The pyroclastic flow was 4.5-km-long and covered S = 0.68 km^2, with V = 0.003 km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

Seismicity of the volcano remained mostly low through the end of August and from September to December. In October, an explosive eruption began at Klyuchevskoy, and its seismicity prevented any detection of seismic events at Bezymianny. A weak or moderate fumarolic activity was continuing from August 29 until the end of December. Satellite data showed a thermal anomaly that existed until the end of December, gradually declining in intensity (Manevich et al., 2011).

2.2.30. 2009

Growth of the Bezymianny lava dome continued in 2009 (Girina et al., 2011a) (Fig. 2E). Typically, a fumarolic plume rose above the actively growing dome, while seismicity was moderate or low. A thermal anomaly over the lava dome was common in satellite images due to the continued effusion of a viscous lava flow.

The temperature of the Bezymianny thermal anomaly began to increase on December 6. The number of volcanic earthquakes increased from two on December 8 to eighteen on December 15, though they were difficult to distinguish from earthquakes associated with Klyuchevskoy Volcano, which was also in an elevated state of activity at the time.

According to seismic data, an explosive eruption began on December 16 at 21:45 UTC lasting until 04:00 UTC December 17, when an ash plume from explosions rose to an estimated 10 km a.s.l. Seismic records showed a 1.1 μm/s volcanic tremor on December 16. The Aviation Color Code was changed to Red at 22:30 UTC on December 16 (KVERT Release, 2009) and remained at that level until December 17. Due to cloudy in the area of the volcano, the eruption was not observed visually. Strong winds moved the ash plumes to the west and northwest of the volcano. According to satellite data, from December 16 to 17 the ash plume was over 25 km wide in the area of Kozyrevsk village. A separate, 75 × 42 km ash cloud was observed >370 km from the volcano on December 17. Significant ash fall was noted in Kozyrevsk from 22:20 until 23:30 UTC on December 16. The initial ash fall was about 2–3 mm thick, and weak ash falls continued for the next few hours. Over 35 km of the main road near Kozyrevsk was covered with ash deposits (Girina et al., 2011a).

As result of the eruption, it is inferred that a part of the lava flow on the southern dome slope was destroyed. Over the 6 h of the eruption pyroclastic flows and associated pyroclastic surges traveled down the southern slope of the volcano. Deposits were noted at the Vostochnaya valley on the southeastern flank of the volcano. The run-outs of the pyroclastic flow deposits and associated pyroclastic surges were about 3.5 and 15 km, respectively. The pyroclastic flow was S = 1.06 km^2 and V = 0.002 km^3 (Borovkov, 2011) (Fig. 4) (Table 1).

After the eruptive event on December 17, a large thermal anomaly was noted over the lava dome summit and on the southeast flank of the volcano, now mantled by hot pyroclastic flow deposits. The high temperature of anomalies over the dome (66–53 °C) from December 17 to 26 indicated effusion of a new lava flow on the dome flank.

2.2.31. 2010

As was typical for this volcano, a fumarolic plume rose above the actively growing dome and seismicity was mainly low. A thermal anomaly at the approximate position of the lava dome was common in satellite images because a viscous lava flow continued to effuse.

Analysis of satellite data suggests that a strong explosive event probably occurred in the period from 23:42 UTC February 5 until at least 01:58 UTC February 6, and possibly longer: the intensity and size of the thermal anomaly over the area of the volcano increased dramatically on February 6 (Girina et al., 2011b). Unfortunately, ash plumes were not detected on satellite images, because dense clouds covered the volcano from February 5 to 6. Due to these events, the

Aviation Color Code was changed to Orange on February 7 at 23:30 UTC (KVERT Release, 2010a). Elevated background seismic activity due to the eruption of Klyuchevskoy Volcano continued from August 2009 until November 2010, making it difficult to detect explosive events at Bezymianny using from seismic data. However, there was strong fumarolic activity at the volcano on February 13; such activity is often seen at the end of explosive eruptions at Bezymianny. There were also clearly visible ash deposits on the slopes of the volcano in the TERRA ASTER image on March 10, 2010. The high temperature of the anomaly (60–50 °C) continued until mid-February and then gradually decreased to negative values.

Another increase in the temperature of the thermal anomaly over the lava dome, from 18 to 49 °C, was detected in satellite images on May 19. The forecast (based on satellite data) of an explosive eruption of Bezymianny between May 21 and June 10 was published by O.A. Girina on May 21. The Aviation Color Code was changed to Orange at 02:20 UTC on May 24 (KVERT Release, 2010b).

The main phase of a strong explosive Bezymianny eruption was detected in seismic data on May 31 from 12:34 to 12:50 UTC. The magnitude of the seismic series was about $A/T_{avr.} = 18.9$ μm/s. A second phase of explosive activity was also noted at 17:00 UTC that day. Ash from the first explosions rose to about 10 km a.s.l., and extended 250 km west of the volcano. Ash fall was observed in Kozyrevsk. Further ash plumes rose to above 10 km a.s.l. and traveled to the north-northeast from the volcano for about 160 km. Clouds ~200 × 50 km in size drifted over 700 km from the northern area of the Kamchatka peninsula to the southwest, and later to the south over the Pacific Ocean to the northern Kuriles Islands from June 1 to 4 (Girina et al., 2011b).

According to visual observations in August, a pyroclastic flow deposits were formed on the southeastern and southern slopes of the volcano. The pyroclastic flow was 6-km-long, $S = 5.75$ km^2, $V = 0.02$ km^3 (Borovkov, 2011) (Fig. 4) (Table 1). The lava flow, which began to effuse from the southeastern slope of the lava dome in 2006, had advanced farther its length exceeded about 1.2 km. Regular moderate fumarolic activity of the volcano continued from June to December, 2010.

3. Discussion

The Bezymianny lava dome has continued to develop from 1956 until the present time (Fig. 2F). A relatively quiet extrusion of plastic lava blocks in various sectors of the volcanic crater occurred from 1956 to 1960. By 1960, the extrusion filled the entire bottom of the crater, and acquired a monolithic structure. Extrusion of hard lava blocks was observed throughout the channel cross section, accompanied by explosions of varying strength and character. The most powerful explosive eruptions occurred yearly in the spring during 1960–1965. Interestingly, that after the explosive activity, the volcano entered a resting phase during 1–2 months so that even fumarolic activity ceased.

It is noted that the lava of the first blocks extruded from 1956 to 1960 was hornblende andesite, 35% of which was made up of crystals of plagioclase, hornblende (brown), and pyroxene (Bogoyavlenskaya and Kirsanov, 1981). In 1961, hornblende nearly disappeared, and two-pyroxene andesites came to the surface, containing 60% crystals. There was also a change of volatiles. In the early years of dome formation chlorine was the most common volatile; in the 1960s the amount of fluorine increased dramatically (from 30 mg/L in 1962 to 1050 mg/L in 1965) (Bogoyavlenskaya et al., 1971).

After a strong explosive eruption in 1965, a relatively quiet extrusion of plastic lava into the lava dome began, which continued until March 1969. This period was followed by the introduction of hard extrusions that lasted until 1976. From 1970 to 1976 the process of lava dome growth began again, accompanied by moderate explosive events. During the extrusion of the plastic lava andesite characterized by lower crystallinity (up to 50% by weight), hornblende was about 1–2% in phenocrysts. When the hard extrusive blocks began to extrude, the crystal content increased to 70%, and hornblende disappeared (Bogoyavlenskaya et al., 1971).

It seems likely that a monolithic extrusive block, filling the crater in 1960, blocked the path for free degassing magma. As a result the gas-saturation of the magma rose and the pressure of volatiles increased in the magma channel, leading to the first explosive eruptions of the volcano. As result of the explosive activity the monolithic blocks of lava were fragmented opening a path to the surface for new portions of magma. As the lava dome grew from 1956 to 1976 the following sequence of events occurred: extrusion of plastic lava for four years, followed by extrusion of hard blocks for five years, returning to the extrusion of plastic lava for four years, then hard blocks again for the final seven years.

In 1976, plastic lava reappeared in the central part of the lava dome top in the form of small swellings (Kirsanov et al., 1979). After the strong explosive eruption in 1977, the first lava flow came to the surface. Between 1977 and the present, a cyclical process of the lava dome growth has been observed. After a period of relative quiescence, an extrusion of the hard lava blocks at the top of the lava dome began. Then powerful explosive eruption of the volcano occurred, followed by a lava flow effusion on the dome slope. Finally the volcano entered a state of relative rest with moderate fumarolic activity.

Thanks to continuous observations by Malyshev (2000), we have a more detailed outline of the preparation Bezymianny to an explosive eruption: 1) fumarolic activity of the volcano and a viscous lava effusion, usually accompanied by a low level of seismicity; 2) a small lava dome deformation, and the appearance of the first seismic signals; 3) the appearance of a hard extrusion block on the dome top and increased seismicity; 4) the appearance of plastic lava which is transformed into lava swelling, with decreasing seismicity; 5) the formation of a new hard extrusion block with accompanying hot avalanches and a series of seismic events with steadily increasing seismic activity; and 6) the explosive eruption, with volcanic tremor at the highest level. Possibly, stages 3–5, which presage an explosive eruption, is repeated the lava dome growth stage from 1956 to 1976.

Between 1977 and 2010 forty strong explosive eruptions of the volcano occurred; nineteen of them produced ash clouds to a height of 10–15 km a.s.l. In eleven years the volcano erupted twice (1979, 1981, 1984, 1986, 1997, 2000, 2001, 2004, 2005, 2006, and 2007); as a rule, one of the eruptions was stronger than the other. The most powerful eruption was in 1985 (the volume of eruptive products reached 0.05 km^3). After powerful explosive eruptions, a lava flow effusion could continue for a few years. For example, after the 1985 eruption a lava flow effused for about four years, interrupted by two moderate explosive events in the 1986. The direction of lava effusion changed, so that by 2005 all the slopes of the dome were covered by thick lava flows. From 2006 to 2010, the same southeastern part of the lava dome was repeatedly destroyed during explosive eruptions, resulting in the movement of the lava flow down the volcanic atrium by about 1.2 km.

All explosive eruptions of the volcano from 1965 to 2010 were accompanied by the formation of pyroclastic flows. The largest flow with a length of 12.5 km was formed in 1985. Pyroclastic surges accompanying the eruption of juvenile pyroclastic flows have been observed since 1984. The most widespread pyroclastic surges were produced by eruptions in 1985, 1997, 2000, 2005, and 2010. The volumes of 26 of the total 41 pyroclastic flow deposits have been calculated, those for which sufficient data was available (Table 1). The total volume of the pyroclastic products of 26 eruptions is estimated at 0.25 km^3, with an average of 0.01 km^3 per eruption. On this basis, we can estimate the volume of pyroclastic flow deposits to be about 0.41 km^3 over 45 years. The total volume of tephra erupted from the volcano in the 45 years of activity has not yet been reliably calculated.

Interestingly, pyroclastic flow deposits have accumulated unevenly on the slopes of Bezymianny Volcano. For example, during eruptions from 1977 to 1979, pyroclastics accumulated near the northern side of the Vostochnaya valley; in 1984, 1989, 1990, and 1993, near its southern side; in 1985, 1986, and 1997, in the central part of the Vostochnaya valley; in 2001, 2002, and 2004–2009, in the Yuzhnaya valley (Fig. 4).

The author is aware that in one work it is not possible to discuss all the features of all the Bezymianny eruptions that have occurred in the life of this active volcano. I hope this work will help new researchers to better understand the nature of this volcano's activity. Today, we think that we know how to predict eruptions of Bezymianny, but its activity has changed in the past, sometimes gradually and sometimes quite dramatically. Scientists need to constantly monitor this volcano and to study the products of each eruption, lest we fail to recognize the beginnings of changes in its activity. Only on this basis will it be possible to reliably predict volcanic eruptions, and ensure the safety of people and aviation.

4. Conclusions

The lava dome of Bezymianny Volcano has developed almost continuously from 1956 until the present time. Since 1977, a cyclical process of lava dome growth has been observed. After a period of relative quiescence, an extrusion of hard lava blocks at the top of the lava dome begins. Then a powerful explosive eruption of the volcano occurs, followed by a lava flow effusion on the dome slope. Subsequently the volcano enters a state of relative rest, with moderate fumarolic activity.

During the period from 1977 to 2010 forty strong explosive eruptions of the volcano occurred; nineteen of them produced ash clouds that reached heights of 10–15 km a.s.l. The most powerful eruption was in 1985, when the volume of eruptive products reached 0.05 km^3.

After powerful eruptions, a lava flow could continue to effuse for a few years. For example, after the 1985 eruption a lava flow effused for about four years. The direction of lava effusion changed, so that by 2005 all the dome slopes were covered by thick lava flows. From 2006 to 2010 the same southeastern part of the lava dome was repeatedly destroyed during explosive eruptions; as a result, lava flows moved down the volcanic atrium by about 1.2 km.

All explosive eruptions of the volcano were accompanied by the formation of pyroclastic flows and surges. The largest 12.5-km-long flow was formed in 1985. The most widespread pyroclastic surges were produced by eruptions in 1985, 1997, 2000, 2005, and 2010. The total volume of pyroclastic flow deposits from 1965 to 2010 eruptions was about 0.41 km^3, or an average of 0.01 km^3 per eruption.

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