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On Some Features Peculiar to the September 22, 2005 Eruption of Young Shiveluch Volcano, Kamchatka

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Abstract—An explosive eruption of Young Shiveluch Volcano occurred on September 22, 2005, discharging
3 a pyroclastic flow about 20 km long in the Baidarnaya River valley and an ashfall in the area of the Northern cluster of volcanoes.

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INTRODUCTION

Young Shiveluch is one of the more active volcanoes in Kamchatka. A new extrusive dome began to grow in the volcano's explosive crater from the autumn of 1980, nearly 16 years after the catastrophic eruption of November 12, 1964, and has continued to grow until today [Melekestsev et al., 1991; Girina et al., 2006]. The eruption varied in character as time went on: discrete powerful explosions began to occur in the lava dome area in 1984 [Fedotov et al., 1985]; viscous lava flows began to be extruded in 2001 [Girina, 2008; Girina et al., 2002]; however, the transport of magmatic material onto the ground surface in the area of Young Shiveluch Volcano was nearly continuous [Dvigalo, 1984; Zharinov et al., 1995; Girina et al., 2007b, among others]. Continuous transport of magmatic material onto the ground surface in the area of that volcano is understood here in the sense both that fresh lava occurs on the slopes of the lava dome and that magmatic gas is transported away, thus providing for nearly continuous recording of a thermal anomaly by satellite imagery in the Young Shiveluch area (http://www.kscnet.ru/ivs/kvert). Strong paroxysmal explosive phases of this eruption due to the growth of the lava dome were also observed before the event described here in 1993, 2001, 2004, and in February 2005 [Khubunaya et al., 1995; Fedotov et al., 2001; Girina et al., 2006, 2007a, 2007b].

On February 27, 2005 the largest explosive eruption of the volcano occurred since 1964, discharging about 0.5 km^3 of ejecta [Girina et al., 2006, 2007a]. The
3 deposits of tephra and pyroclastic flows covered areas of about 25 000 km^2 and 31.5 km^2, respectively [Girina et al., 2006]. Intensive extrusion of new lava material began on Young Shiveluch Volcano at once after the February eruption. According to N.V. Gorbach [2006], the rate of lava discharge was 4.5–5 m^3/s during 2 months (March and April).

PRECURSORY PROCESSES BEFORE THE ERUPTION

The seismic information on the phenomena prior to the September 22 explosive eruption is incomplete, because the seismic station operated by the Kamchatka Branch of the Russian Academy of Sciences Geophysical Service (8 km from the volcano) was destroyed by the February eruption [Girina et al., 2006; Senyukov et al., 2006]. The volcano was monitored in March–August 2005 from distant seismic stations; thus, some individual larger seismic events alone (magnitudes below 2.2) have been recorded, but a swarm of volcanic earthquakes was observed in mid-August (7–14 earthquakes with magnitudes of 1.5–2.2 at depths shallower than 2.5 km were recorded every day in the volcano area from August 13 to 16), indicating increased volcanic activity [Senyukov et al., 2006].

Visual observations showed that the volcano was very active in March to June: the lava dome rapidly grew (lava was extruded in the form of blocks and short lava flows) to the accompaniment of occasional explosive events and incandescent avalanches, which sent ash flying to heights of 3–5 km above sea level (a.s.l.) as they hit the dome slope [Girina et al., 2007a]. The first ash discharge to a height of 4 km a.s.l. since the February explosive eruption of the volcano occurred on June 1 [Girina et al., 2007a]. According to our observations from the Baidarnaya River area from June 29 to July 10, blocks from the growing dome nearly constantly fell and incandescent avalanches were formed: they descended uninterruptedly between 17:25 and 18:15 UTC on June 30, hurling ash clouds as

Fig. 1. Plastic lava on the southwestern slope of Young Shiveluch Volcano. Photograph by Yu. Demyanchuk, September 14, 2005.

high as 5 km a.s.l. and ash plumes were propagating west–southwestward from the volcano; on July 4–5 the ash due to incandescent avalanches also rose to 5 km a.s.l., the plumes were extending northwest and west of the volcano; explosions sent ash to 7.5 and 6 km a.s.l. at 01:07 and 21:39 UTC, respectively, on July 6, with the plumes propagating northwestward from the volcano. The deposits of the largest of the observed incandescent avalanches were extending for 4.5 km along the southwestern slope of the dome on July 10 [Girina et al., 2007a].

The first observation of the frontal part of a lava flow overhanging the southwestern part of the dome was made on August 19. Incandescent avalanches became more frequent; they tore themselves away from the frontal parts of the flow and light was emitted by this flow and from incandescent avalanches during the dark time of the day on August 19–21 and 28. Two larger avalanches were observed on August 28 and three more on August 29; their ash plumes rose to heights of 5.5 km a.s.l. Satellite observations conducted by the Alaska Volcano Observatory (AVO), USA (http://www.avo.alaska.edu/) and by the Kamchatkan Volcanic Eruption Team (KVERT, http://www.kscnet.ru/ivs/kvert/) revealed a thermal anomaly of nine pixels that was continuously recorded in the dome area; incandescent avalanches were followed by ash plumes that were extending for as long as 40 km east of the volcano.

A new seismic station, viz., the Semkorok, Kamchatka Branch of the Russian Academy of Sciences Geophysical Service, (KB RAS GS), which began operation on September 11, 2005 on the eastern slope of Shiveluch Volcano 15 km from the lava dome, furnished some more detail to the general picture. Twenty-eight shallow earthquakes were recorded between September 11 and 21 with magnitudes 1.7–2.8 and volcanic tremor was observed between September 13 and 21 with amplitudes of 0.24 μm/s (http://emsd.iks.ru/~ssl/monitoring/main.htm). Video and visual observations showed continued extrusion of blocks of plastic lava at the summit of the western part of the dome (Fig. 1). This sector of the lava dome was observed to be luminescent on September 13, incandescent avalanches descended almost every day at the location. Satellite data provided evidence of a large thermal anomaly in the dome area until September 16 and the volcano was masked with dense clouds from September 16 to 24.

EXPLOSIVE ERUPTION

The paroxysmal explosive eruption of the volcano, which was related to the growth of the lava dome, occurred on September 22 and continued from 07:38 to 16:00 UTC (according to the seismic data supplied by the KB RAS GS [Senyukov et al., 2006]). Volcanic tremor with an amplitude of 4.46 μm/s was recorded during 8.6 h, in addition to volcanic earthquakes with magnitudes of 2.9 or less, with 11 of these being at depths as great as 11 km and 37 shallow ones (http://emsd.iks.ru/~ssl/monitoring/main.htm). Satellite observations showed an ash column rising to 7.5 km a.s.l., with the ash plume extending for 480 km southeastward of the volcano [Girina et al., 2007a]. Visual observations of the KB RAS GS seismologists who were on the southwestern crest of the volcano above the Baidarnaya River valley (approximately 9–10 km from the lava dome) recorded an ashfall at their camp between 06:00 and 08:00 UTC on September 22, with the ash deposits being about 2–3 cm thick. Yu.V. Demyanchuk reported that the axis of the main ash plume passed somewhat west of the Khapitsa River; the ash was deposited on the slope of Klyuchevskoi Volcano, 60 km from Shiveluch Volcano; this was about 0.3–0.5 cm thick and its total density was about 200 g/m^2 [Girina et al., 2007a].

THE EJECTA

Field studies of the ejecta were carried out by these
3 authors on October 4–5, 2005. The deposits of the pyroclastic flow were extending in a narrow band along the Baidarnaya River valley for 20 km. The average thickness of the deposits did not exceed 4–5 m; the total volume was 0.01 km^3 [Nuzhdaev et al., 2005]. The flow had a comparatively smooth surface because the amount of the filler (particles < 2 mm across) greatly exceeded the amount of broken rock fragments in it. Such flows are
3 called pyroclastic flows of porous andesites [Bogoyavlenskaya and Braitseva, 1988; Girina, 1998]. Lava fragments less than 30–40 cm across were dominant, but one also encountered some blocks (as long as 4 m) and their accumulations. The flow filled a new bed of the Baidarnaya River, which was formed in the deposits of the February
3 pyroclastic flow during 6 months, resulting from compaction of the deposits and erosion by brooks. The flow deposits completely filled the bed in the upper reaches of the river (Fig. 2a); the filling was only partial (see Fig. 2b) in the middle part where the new valley cut the deepest
3 into the pyroclastic deposits of the February 2005 eruption (up to 7–8 m) and the frontal parts of the flow lay on a flat plain composed of deposits due to the February eruption. The deposits at the flow front were not thicker than 2–2.5 m and 1.5 m where they eroded on the valley slopes. Numerous fumaroles were observed on fresh Sep-
3 tember pyroclastic deposits in the middle part of the Bai-
3 darnaya River valley. The deposits of the pyroclastic flow were highly charged with gases 12 days after the eruption, the volcanologists waded in these knee deep or even deeper, the density of the naturally lying deposits in the upper part of the pyroclastics varied in the range of 1.33– 1
1.71 g/cm^3 (14 samples taken by these authors), with the mean value being 1.54 g/cm^3. The temperature of the deposits as measured with a thermocouple reached 165°C at a depth of 15–20 cm and 378°C at 130 cm. The highest temperature of the deposits (those charged with gases and having the lowest density) was 430°C and 512°C at depths of 38 and 47 cm, respectively (Fig. 3a). Dry sand was found to be spouting near a heap of large blocks in the middle part of the pyroclastic flow 5 km from 3
the lava dome. The sand had a temperature of 332°C at a depth of 40 cm (see Fig. 3b). Volcanologists repeatedly noted that "rootless fumaroles" [Macdonald, 1972] frequently form around heaps of large hot blocks buried under layers of medium to coarse-grained pyroclastic 3
material. Gases from such fumaroles are mostly generated as a result of two interrelated processes, viz., degassing of pyroclastics during cooling and the boiling of meteoric 1
water inside the pyroclastics [Serafimova, 1992]. The sand 1
spouting referred to was probably caused by a powerful flow of the gases that were released during degassing of the blocks mixed with steam, because a metal plate, when inserted into the spouting sand, became wet.

In addition to the deposits of the pyroclastic flow, we 3
also studied the ash that was sampled by seismologists on September 22 at the southwestern crest of the volcano above the Baidarnaya River valley 9–10 km from the lava dome. This ash was probably deposited from the ash cloud that rose above the pyroclastic flow, that is, the ash con- 3
sisted of "deposits of the ash clouds due to the pyroclastic 3
flow," or more briefly, the "flow cloud ash" [Girina, 1998].

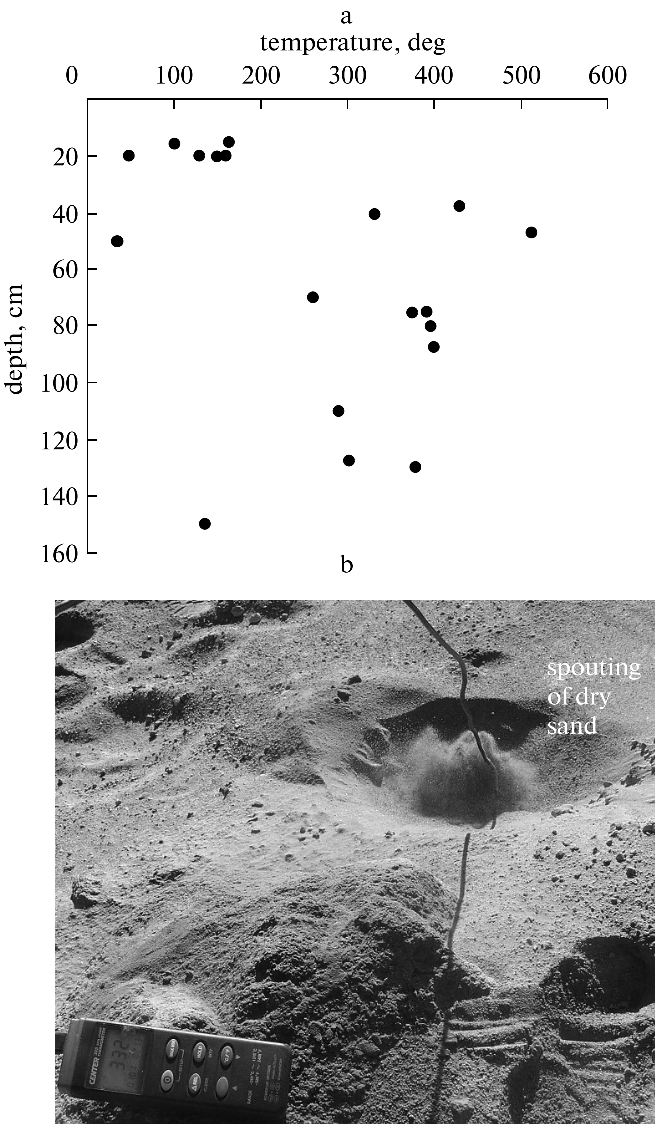
COMPOSITION OF THE ROCKS

The Shiveluch rocks mostly belong to the moderately potassium, calc-alkaline series, but differ from other Kamchatka rocks of this series in having higher concentrations of magnesium and nickel and higher magnesium/iron and nickel/cobalt ratios; the rocks are also notable for higher concentrations of mafic minerals in phenocrysts [Rudich et al., 1974; Popolitov and Volynets, 1981]. According to N.V. Gorbach [2006], the concentration of silicic acid in fresh fragments of dacite andesite lava, as sampled from the pyroclastic flow that was 3
erupted on September 22, varies between 63.5 and 63.9 wt %. The phenocryst composition is typical of Young Shiveluch lavas, viz., plagioclase, pyroxene, amphibole, and magnetite, with occasional biotite. The lavas have one distinctive feature, the presence of hornblende of two kinds: pure idiomorphic crystals and grains with a thin opacite rim [Gorbach, 2006]. Since the ejecta were studied 12 days after the explosive phase, the pyroclastic 3

3 **Fig. 2.** Deposits of the pyroclastic flow that was discharged in the Baidarnaya River valley on September 22, 2005: upper Baidarnaya R. (a), photograph by A. Nuzhdaev, October 5, 2005; middle reaches of the Baidarnaya (b), photograph by V. Shushlin, October 5, 2005.

deposits had higher gas saturation and temperature. It was
3 rather difficult to discriminate between pyroclastic flows
3 and the deposits of pyroclastic surges, which the eruption
3 naturally involved; consequently, we treated pyroclastic
3 deposits as unstratified products of pyroclastic flows.

According to grain size, the fillers (particles less than
2 mm across) in the deposits of pyroclastic flows are 3
medium to fine-grained sands, while the flow cloud ash is dust-like sand. The flow cloud ash is dominated by particles smaller than 0.056 mm (77%) (Fig. 4a). Their depos-



3 **Fig. 3.** The temperature of deposits of the pyroclastic flow that was discharged on September 22, 2005 (measured on October 4–5, 2005 (a); dry sand pouting: temperature was measured at a depth of 40 cm (b), photograph by A. Nuzhdaev, October 5, 2005.

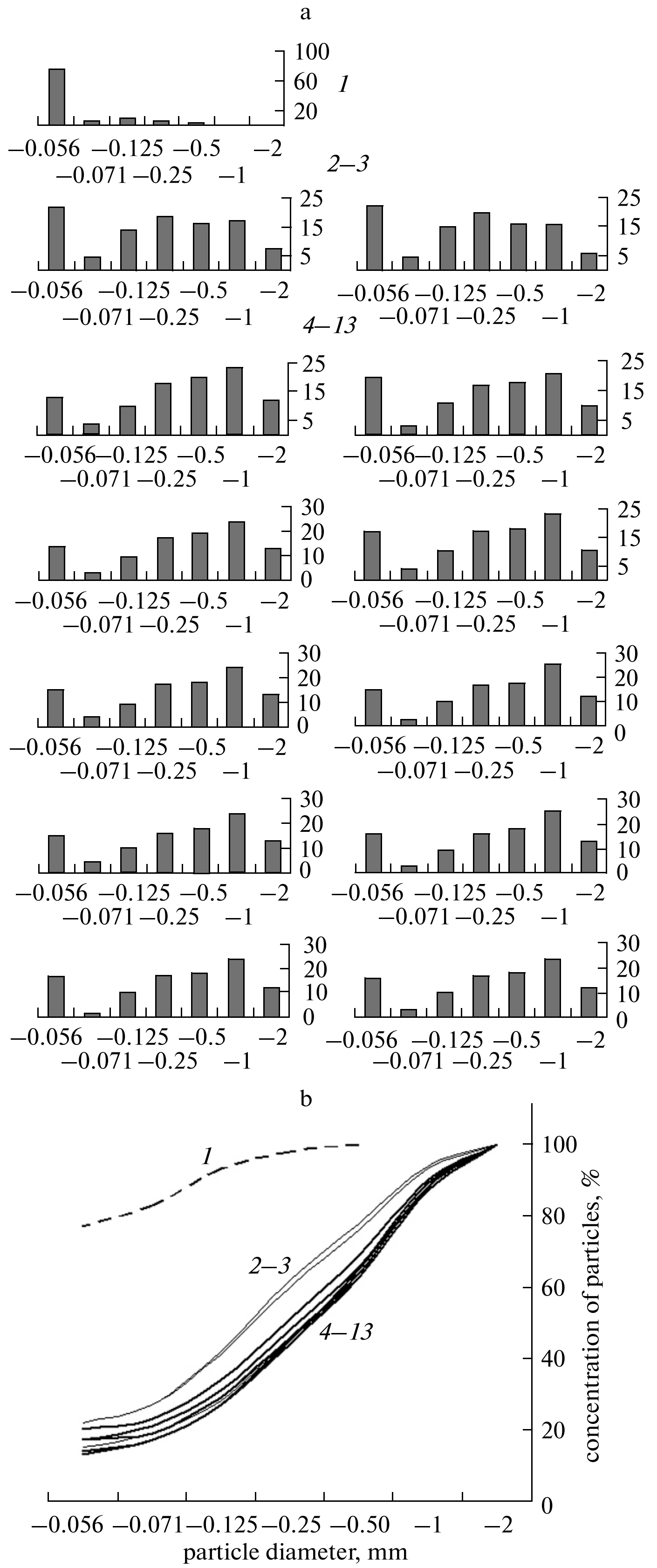
its are homogeneous, unstratified, and have a massive structure. Two samples (2 and 3) from among the fillers of
3 pyroclastic flows stand out in being dominated by fine- and small-grain fractions (particles less than 0.056 mm across make up ~22%, those of 0.125–0.25 mm are 19–20%), in contrast to the other samples, which are dominated by coarse (0.5–1.0 mm) grains (24–25%), but the fine-grained fraction (< 0.056) is 15–17% on average and in a single case it is 20% (see Fig. 4a). The cumulative curves of flow fillers in samples 2 and 3 with similar dip angles lie above the field of the other ten samples from the
3 fillers of pyroclastic flows (see Fig. 4b). Samples 2 and 3 also have the lowest median and mean size (Fig. 5a) among all flow fillers and possess the best sorting in the deposits (see Fig. 5b). Based on the features of pyroclastic 3
samples referred to above, it is quite logical to divide them into two types of pyroclastic flow. The particles of the flow 3
deposit filler consisted of lava fragments and fragments and growths of minerals: plagioclase, pyroxene, hornblende, and magnetite. Seventy percent of the flow cloud ash consisted of fragments of volcanic glass and plagioclase and 30% consisted of mafic minerals. According to the Petrographic Code of Russia [*Petrograficheskii* ..., 2008], all the rocks studied here, which are divided into flow cloud ashes and the two types of pyroclastic flow, 3
respectively, are normal alkaline; the flow cloud ashes are classified as plagioclase dacites and the fillers of pyroclas- 3
tic flows are classified as andesites (table).

DISCUSSION OF THE DATA

Prior to August 2005 volcanologists had data from ground-based observations only; these showed that the visible height of the lava dome decreased by 130 m during the eruption [Girina et al., 2006]. It is noteworthy that no traces of gravity sliding for any sector of the lava dome have been found, the dome rim was everywhere tall enough, with a small lowering being recorded in the south–southwestern part of the dome. Active emplacement of fresh lava made the western and the eastern part of the dome almost equal in height [Girina et al., 2006].

The August 2005 air-borne photographic survey of the Young Shiveluch dome (Fig. 6a) [Ramsey et al., 2012] shed some light on the precursory processes and the character of the explosive eruption that occurred on September 22, 2005.

An analysis of photographs of Young Shiveluch Volcano (see Fig. 6b) revealed an explosive crater about 600 m across in the western part of the lava dome resulting from the February 2005 paroxysm. It was due to this that the February 27, 2005 eruption produced such an enormous volume of ejecta (the pyroclastic flows extended for 3
25–28 km from the volcano crater, the total volume of ejecta was about 0.5 km^3 [Nuzhdaev et al., 2005; Girina et al., 2006]). An active, but quiet (not accompanied by any explosions) extrusion of plastic lava into the crater began at once after the February paroxysm; the process probably continued for 3 months (March to May), until the crater had been filled with extrusive material. The crown of the new lava dome (marked 5 in Fig. 6b) was about 400–450 m as of August 20, 2005 [Ramsey et al., 2012]. Explosive events were rather frequently observed in the lava dome area in June and July. A new explosive crater appeared at the center of the new dome, probably during intensive explosive activity of the volcano on June 29–30, and fresh portions of plastic lava then filled the crater. The crown of the most recent lava dome was about 300 m across (marked 6 in Fig. 6b) [Ramsey et al., 2012]. The high plasticity of the lava that was being squeezed out and



3 **Fig. 4.** Diagrams (a) and cumulative curves (b) showing the grain-size composition of pyroclastic deposits due to the Sep-
3 3 tember 22, 2005 eruption: (*1*) flow cloud ash; (*2–3*) fillers of type 1 pyroclastic flows; (*4–10*) fillers of type 2 pyroclastic flows.

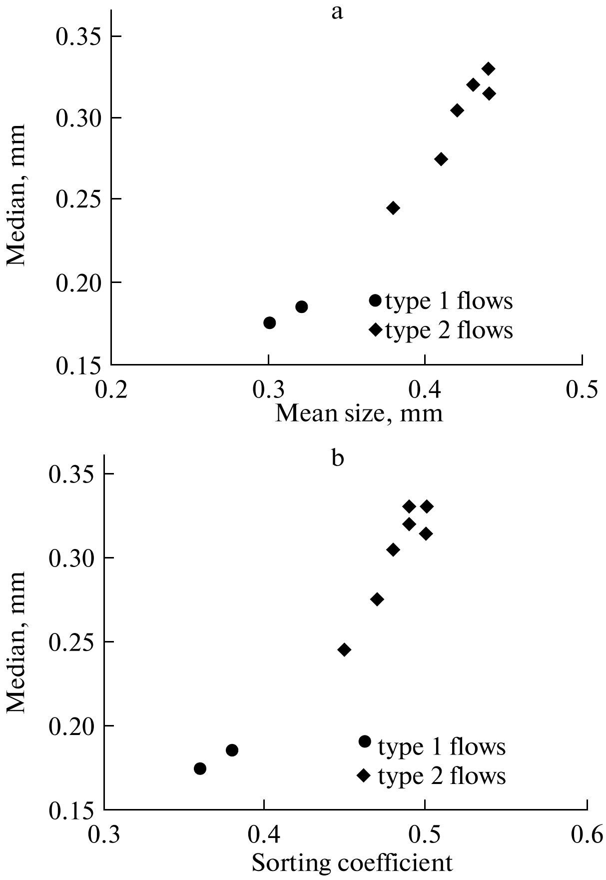


Fig. 5. Relationships between grain-size characteristics of
3 fillers of pyroclastic flows that were discharged on Septem-
ber 22, 2005: between median and mean size (a) and
between median and sorting coefficient (b).

its relatively rapid discharge onto the ground surface could be deduced from long curved lava bands that were extruded along a fissure at the summit of the most recent dome (marked 7 in Fig. 6b). Blocks of plastic lava continued to be extruded during June–September, with occasional short lava flows. Another strong explosion of September 22 provoked, on the one hand, collapse of part of the southwestern sector of the lava dome and, on the
other, caused rapid discharge of juvenile material, which
resulted in the generation of highly mobile pyroclastic 3
flows of porous andesite.

The pyroclastic flows that were produced by the Sep- 3
tember 22, 2005 eruption were formed of lava material from the dome that grew during March to September 2005, of the juvenile material that had been discharged from the interior of the volcano during the explosive phase of the eruption, as well as (in part) of the dome rocks that
were generated in 2001–2004 and earlier. The high
mobility of the pyroclastic flows which extended for 3
20 km from the volcano was due to several factors: rock composition (andesites and dacite andesites); a high concentration of gases in fresh lava material and juvenile
pyroclastics, the auto-explosivity of the fragments that 2 1
were moving with the flow, and convective gravity differ-
entiation of the pyroclastics as they travelled on the vol- 1
cano slope [Girina, 1998, 2010]. Because pyroclastic 3
flows do not arise simultaneously [Macdonald, 1972; Alidibirov et al., 1988; Girina, 1990; Girina et al., 2006], but during a comparatively long time (8.6 h in the present case), portions of the flows were constantly mixing. How-
ever, macrofragmental flows, if any were present during 4

3 Chemical composition (in wt %) of Shiveluch pyroclastic rocks that were discharged on September 22, 2005

3 Sample no.	Ash	Type 1 pyroclastic flows		Type 2 pyroclastic flows 3									
	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	67.36	62.42	62.89	62.57	63.13	62.44	62.54	62.53	62.55	62.58	62.18	62.29	62.09
Al_2O_3	15.03	16.27	16.41	16.03	16.31	16.09	16.03	16.08	16.17	16.07	16.12	16.05	16.08
Fe$_2$Î$_3$	1.47	2.18	2	2.28	2.11	2.15	2.08	2	1.98	2.21	2.07	2.19	1.97
FeO	1.58	2.15	2.01	2.01	1.94	2.01	2.15	2.15	2.08	2.01	2.15	2.15	2.37
CaO	4.47	6.13	5.97	6.25	5.97	6.1	6.18	6.12	6.05	6.12	6.2	6.36	6.27
MgO	2.48	3.69	3.51	3.82	3.59	4.08	3.9	3.93	4.03	3.87	4.14	3.89	4.02
Na_2O	4.68	4.29	4.43	4.34	4.45	4.47	4.39	4.43	4.51	4.42	4.44	4.32	4.35
TiO_2	0.434	0.536	0.506	0.533	0.509	0.519	0.529	0.52	0.513	0.521	0.528	0.543	0.539
K_2O	1.55	1.33	1.33	1.27	1.29	1.23	1.26	1.25	1.23	1.24	1.23	1.26	1.22
MnO	0.059	0.086	0.079	0.086	0.081	0.081	0.084	0.081	0.08	0.083	0.083	0.087	0.087
P_2O_5	0.15	0.151	0.149	0.151	0.145	0.15	0.147	0.15	0.149	0.147	0.15	0.149	0.15
L.O.I.	0.58	0.58	0.56	0.5	0.3	0.52	0.054	0.6	0.5	0.56	0.56	0.54	0.68
Total	99.84	99.813	99.844	99.84	99.825	99.84	99.83	99.841	99.842	99.831	99.851	99.829	99.826

The analyses were made at the Analytical Center of the Institute of Volcanology and Seismology, Far East Branch, Russian Academy of Sciences. The ash sample (*1*) was supplied by S.L. Senyukov (Kamchatka Branch of the Russian Academy of Sciences Geophysical Service).

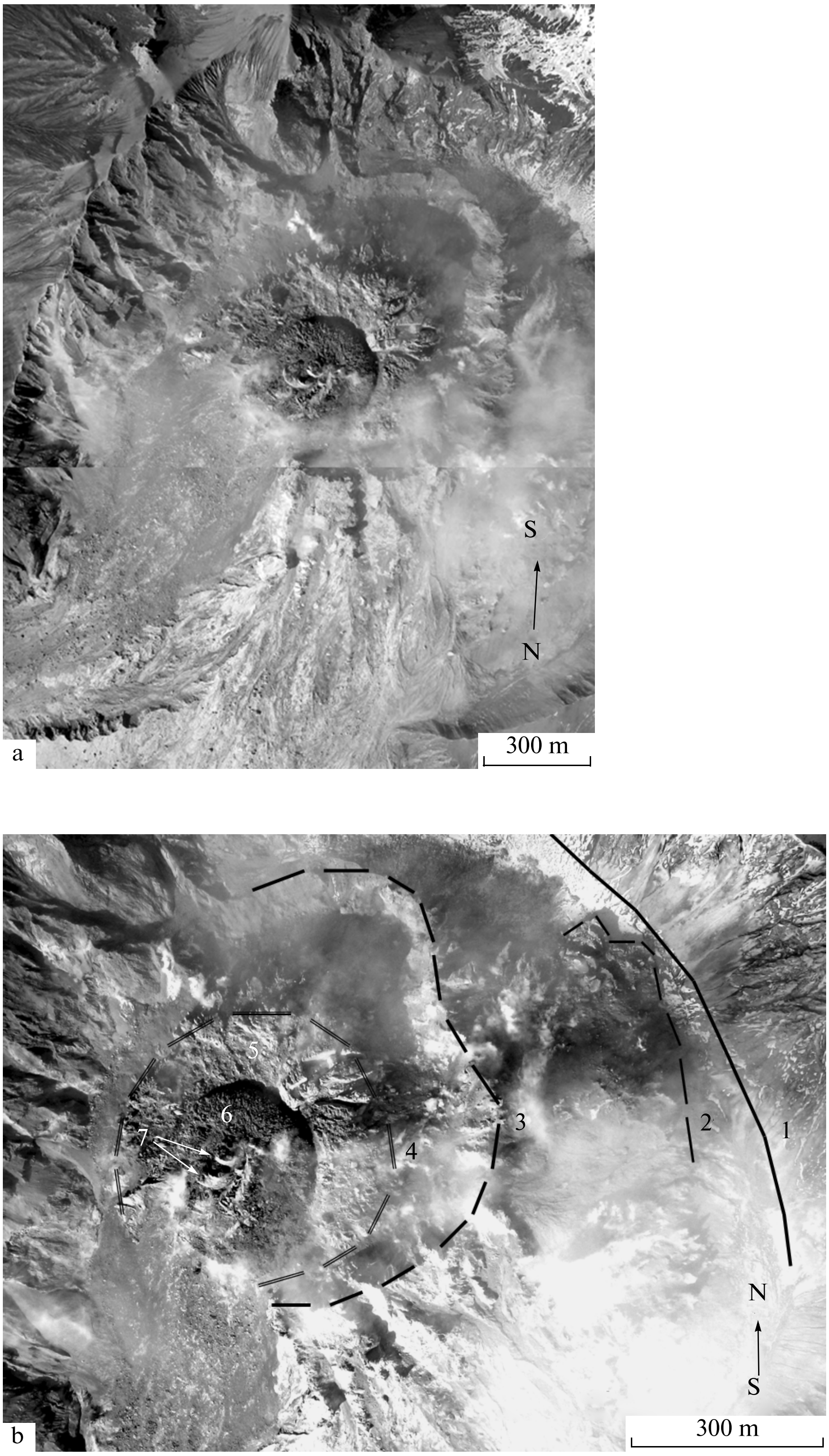


Fig. 6. Lava dome on Young Shiveluch Volcano, August 20, 2005, photographed by M. Ramsey: general view (a); volcano structure (b): (*1*) edge of the explosive crater that was formed during the 1964 catastrophic eruption; (*2*) base of the present-day lava dome as of 2005; (*3*) explosive crater that was formed during the February 27, 2005 eruption; (*4*) the crown of the new lava dome (*5*) that was formed in the crater in March–August 2005; (*6*) most recent lava dome inside the new one; (*7*) plastic lava bands that were extruded along a fissure at the summit of the most recent dome.

this eruption, were in any case buried under more highly
3 mobile medium to small grain pyroclastic flows and we
had no data on these flows 12 days after the eruption
(because of the high temperatures of the deposits on the
ground surface).

3 The two types of pyroclastic flow that we identified by
1 careful study of the pyroclastics were probably due to a
complicated process of their generation. Although the
two types of flow had rather similar chemical composi-
tions their grain-size characteristics are different. The
3 type 2 flows (ten samples of fillers of pyroclastic flows)
seem to consist mostly of material coming from destruc-
tion of fresh blocks of the lava dome that were formed in
March to September 2005 and, to a lesser degree, of juve-
1 nile pyroclastics that were discharged during the Septem-
3 ber 22 explosive eruption. The deposits of the type 1 pyro-
clastic flow (two rock samples), having the higher mobil-
ity (higher gas concentrations) and being small-grained,
are probably composed mostly of juvenile material and to
a lesser degree of products coming from the destruction of
the blocks of the lava dome that were formed in March–
September 2005.

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SPELL: 1. pyroclastics, 2. explosivity, 3. pyroclastic, 4. macrofragmental