A 40-YEAR PHOTOGRAMMETRIC ANALYSIS REVEALS CHANGING ERUPTION STYLE AND DOME TO CONE TRANSITION AT BEZYMIANNY VOLCANO, KAMCHATKA

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Bezymianny Volcano is an active, ~3,000 m high andesitic volcano located in the central part of the Klyuchevskaya volcanic group, Kamchatka. After the 1956 catastrophic eruption, the volcano underwent several stages of development: While from 1956 to 1976, dome growth was mostly endogenous, subsequent activity was mainly characterized by exogenous growth with alternating extrusive, explosive, and effusive events (e.g., Bogoyavlenskaya et al., 1991; Carter et al., 2007). By 2009, the surface of the dome was completely covered by lava and pyroclastic flows. Previous works recognized that the basic style of the dome growth passed into the formation of a stratovolcano (Slezin, 1996). However, detailed analysis of its historic eruptions and geometric changes that are associated with the transition remain sparse. Here, we integrate high-resolution aerial imagery and tri-stereo Pléiades satellite imagery to investigate Bezymianny's structural and geomorphical evolution during 1976-2017. Thereby, we will provide first precise characterization of the volcano's genetic transition to a stratocone.

We applied photogrammetric processing of aerial images from 1976, 1977, 1982, 2006, 2009, and 2013, and compare to the most recent and accurate tri-stereo Pléiades satellite images from 2017. The overflight images were acquired with topographic analog cameras from flight heights of 1000-1500 m above the surface of the dome. The processing was performed in the Erdas Imagine 2015 and Photomod 5 software. Obtained point clouds were referenced relatively to the Pleiades dataset by aligning with several distinct points on the 1956 crater's rim using the CloudCompare v 2.9.1 software. Volumes of eruptive material were derived trough calculating the difference between two consecutive point clouds.

Results show that at the beginning of our dataset, endogenous dome growth dominated, accompanied by explosive events. Our 1976 photogrammetric data reveals that the complex dome and its talus filled almost the entire bottom of the 1956 crater, reaching an elevation of 2,882 m. There were several distinct centers of extrusion. While the dome's western sector consisted of remnants of the old dome from 1956-1965, the northern sector revealed remnants of the 1967-1969 dome named Nautilus (Kirsanov and Studenikin, 1971). The SSE sector accommodated two semi-circular remnants of domes located one inside the other. The oldest of them, Oktyabr dome, was formed during 1969-1973 (Kirsanov et al., 1971). The successive destruction of these domes was followed by extrusion of a new lava dome reaching a dimension of 150×310 m and a relative height of 70 m. The dome was segmented by a trough interpreted as a crease structure, which was 60 m in width and up to 8 m in depth; the trough passed into the debris chute on the southeastern slope.

The 1977 photogrammetric dataset clearly shows the first 300-m-long lava flow (35,000 m^2) emplaced on the north-eastern flank of the Bezymianny's dome. This signalizes a significant change in the eruptive character of Bezymianny, and agrees well with previous observations (e.g., Bogoyavlenskaya et al., 1991). The maximum elevation of the dome in 1977 remained constant since 1976. However, due to the large explosive activity, the dome volume decreased by 13 million m^3. Since then and until today, all the eruptions at Bezymianny have occurred according to one scenario. They began with a slow (from 0.4 to 0.9 m/day) extrusion of lava plug, which is solidified lava, remained in the vent since a previous eruption. Then, intensive explosive events took place with the destruction of lava plug, and the formation of pyroclastic flows up to 9 km in length. Explosive events were hence followed by lava flow formation, the dimensions of which increased with each eruption.

Analysis of the images from 1982 unveiled the existence of a 50-m-high lava plug with a base diameter of 300 m, which emplaced within a semi-circular remnant of a spherical body in the central part of the dome. This plug was also partially destroyed by an eastward opened funnel, from which stretched a 700-m-long lava flow that covered 176,000 m^2 of the eastern flank of the dome's edifice. Although, between 1977 to 1982, the elevation decrease of the dome was 17 m to 2,865 m, the estimated volume increase of 8 million m^3 was significant. The average eruption rate during 1977-1982 amounts to 4,500 m^3/day. The three observed landforms may add up strong evidence for Bezymianny's cyclic behavior of eruptions that occurred during 1979-1982.

By 2006, the morphology of the dome had noticeably changed. Interpretation of the July 2006 imagery showed that post 1977 extrusive bodies were almost completely buried beneath hundred-meter thick layers of lava that armored most of the dome's flanks. Only parts of the southern and northwestern slopes remained

free of lava, but were covered by thick, up to 50 m, deposits of pyroclastic flows. The summit of the dome was characterized by a complex system of coalesced craters. Its eastern sector displays fragments of two concentrically located craters of 300 m and 190 m in diameter that was formed in 2005 (Carter et al., 2007). The central and western parts were occupied by an explosive-subsidence structure (280×200 m) that was generated during the eruption on May 9, 2006. Between 1982 and 2006, the elevation increased to 2,981 m and the volume expanded by 180 million m^3. The inferred average eruption rate over this period adds up to 20,400 m^3/day. The 2009 imagery showed that the surface of the dome was completely hidden under multiple layers of lava and pyroclastic flows. Moreover, by that time, the edifice acquired a conical shape, with a summit crater as the single centre of all volcano activity.

Eventually, images from 2013 showed that all slopes of the cone were covered by lava flows. In particular, the flows on the northern flank were formed by 2006, the other slopes, were topped by lava flows from the 2009-2012 eruptions. The longest (1.4 km) of all recent Bezymianny lava flows originated from the spring eruption of 2009. The flow of March 8, 2012, poured along the southern slope and almost reached the southern wall of the 1956 crater. At this time, the summit crater had an average diameter of 270 m and the maximum elevation of the cone was 2,972 m. An increase in the cone volume from 2006 to 2013 amounted to 26 million m^3. The average eruption rate over this period was 10,200 m^3/day.

Finally, the 2017 digital elevation model (Fig. 1) showed that the highest point of the cone reached 3,003 m. New lava flows filled the summit crater, and poured onto the southwestern slope during the 2016-2017 eruptions, thereby covering an area of 0.3 million m^2. Additionally, most of the western lava flows from previous eruptions were covered by fresh pyroclastic deposits that reach a maximum thickness of 56 m within the atrium relative to the surface of 2013. The increase in the volume of the cone from 2013 to 2017 was 28 million m^3 with the average eruption rate of 18,000 m^3/day. Most strikingly, however, are the deposits of pyroclastic flows on the northern slopes, which appear to be spilled over the 1956 crater rim onto the outer flanks of the volcano.

Overall, the high-resolution photogrammetric dataset enabled a detailed time-lapse reconstruction of volumetric changes during the evolution of Bezymianny between 1976 and 2017. Based on derived image mosaics and digital terrain models, we determined detailed growth rates of the cone, identified summit subsidence events that clearly correlate with observed eruptions, and discovered landforms that agree well with the volcano's common eruption cycle. Finally, because Bezymianny was completely covered by lava flows in 2009, and because ever since the eruptive products were dominated by interchanging lava flows and pyroclastic deposits, we state that the previously documented lava dome has merged to a composite volcano. This transition goes in hand with an increase in summit elevation and the establishment of a central crater that is associated with a stable conduit system.

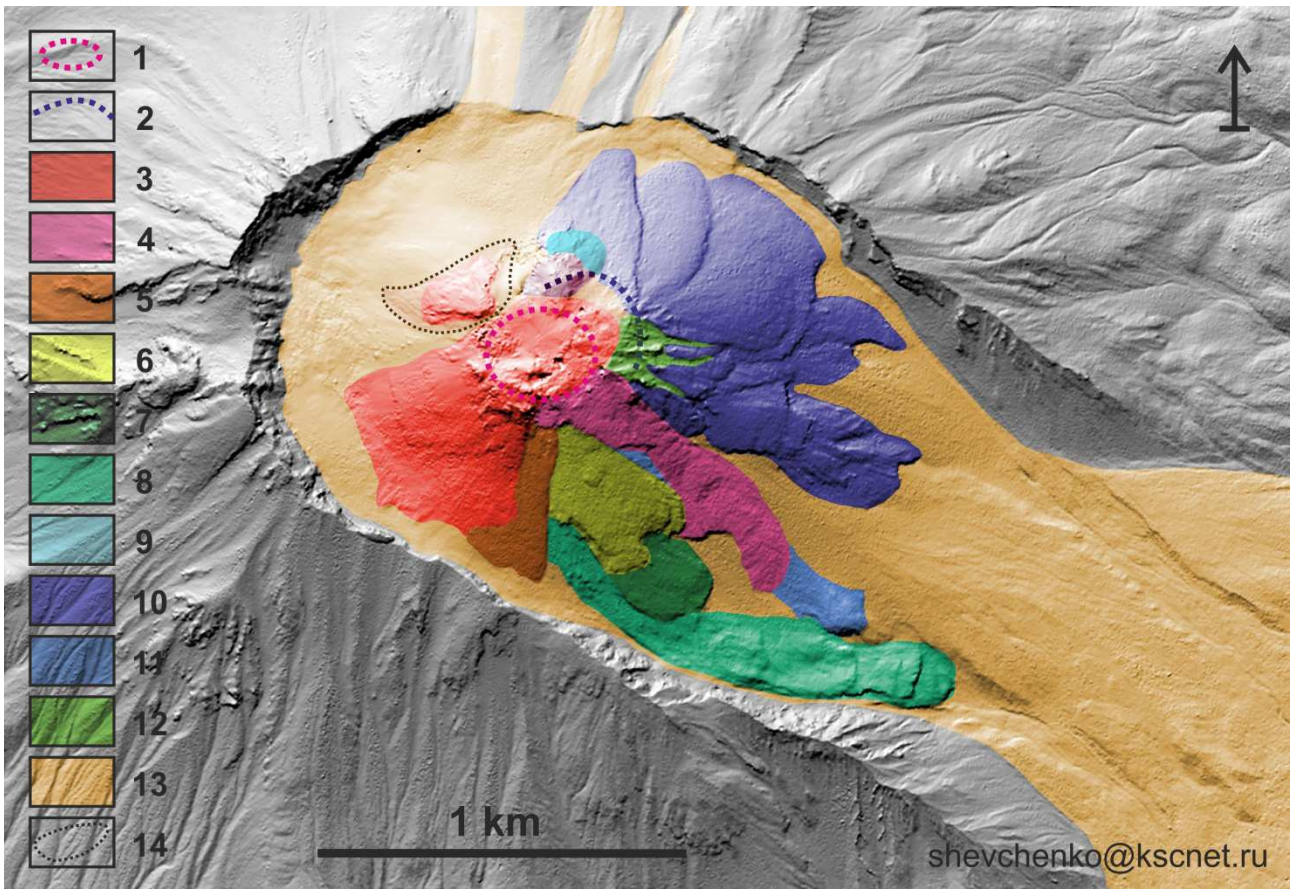

Fig. 1. Shaded relief map of Bezymianny Volcano from Pleiades images of September 9, 2017: 1 – crater of the 2006-2017 eruptions; 2 – crater of the 2005 eruption; 3 – 2016-2017 lava flows; 4 – lava flow from the September 1, 2012 eruption; 5 – lava flow from the March 8, 2012 eruption; 6 – lava flow from the April 13, 2011 eruption; 7 – lava flow from the May 31, 2010 eruption; 8 – lava flow from the 2009 spring eruption; 9 – 2005 lava flow; 10 – lava flows that was formed before 2005; 11 – lava flow that was formed before 1994; 12 – debris chutes; 13 – pyroclastic deposits; 14 – deformation zone of the 2016-2017 eruption

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