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Uplift of the Crater Bottom of the Sarychev Peak Volcano (Matua Island, Kurils) in 2017–2019 Inferred from Satellite Images As a Precursor of an Upcoming Strong Eruption

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Abstract—The lava plug in the crater of the Sarychev Peak volcano (Kuril Islands) was removed in June 2009 as a result of explosions that accompanied a strong eruption, and the crater-bottom elevation abruptly decreased thereafter. Based on satellite imagery and images taken during a helicopter overflight in 2016, the level of crater-bottom sinking was measured at about 190–220 m from the crater rim. The crater bottom had been stable up until autumn 2017, when it began to rise, as revealed from the satellite imagery. As of autumn 2019, the crater bottom has been uplifted by approximately 150 m. The crater volume filled during this rising is about 10 million m^3. The cycles of subsidence and rising in the last 75 years were repeated three times with respect to every strong (considerable) eruption. The new period of rising probably indicates the preparation for a new, potentially dangerous eruptive event.

Keywords: volcanism, environmental dynamics, hazardous processes, monitoring, Kuril Islands
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INTRODUCTION

Sarychev Peak, which is located on Matua Island (Fig. 1) in the central Kuril Island chain, is one of the most active volcanoes of the archipelago. In terms of intensity and productivity of eruptions, it can be compared only to Alaid, which is the largest volcano of the Kuril Islands; however, hazard levels of Sarychev Peak phenomena are higher than those of Alaid. During the 20th century, about ten eruptive events occurred on Matua Island, including the noticeable and strong explosive eruptions of 1928, 1930, 1946, 1960, and 1976; of these, the last one was of effusive-explosive type (Gorshkov, 1967; Andreev et al., 1978). Eruptions caused significant changes of the crater-bottom level. For the first time, the crater-bottom depth was measured in 1954 (Gorshkov, 1967) and was about 200 m.

During the strong effusive-explosive ~~explosion~~ of the Sarychev Peak in June 2009, the lava plug that sealed the crater up until its rim (Fig. 2a) was destroyed (Grishin, 2011; Urai, Ishizuka, 2011). Solid material of the plug was fragmented and removed by strong explosions. The crater-bottom level abruptly dropped and a rounded lava shield formed on the crater bottom (Fig. 2b). This state was being observed for more than 8 years, whereas gas–vapor emissions were repeatedly reported from the crater. The modern data on crater depth are absent, except for the estimated depth of 100 m, which was likely inferred from a visual survey from the crater rim in June 2017 (Chibisova, Degterev, 2019). As will be shown below, this value was not quite realistic. Based on the satellite imagery, the more reliable crater depth and its variations in the period of June 2009–September 2017 was inferred, the rising of the lava plug that began in 2017 was revealed, the height of crater-bottom rising was measured, and the period of rising to the present level was determined.

PARAMETERS OF THE CRATER AND ITS BOTTOM LEVEL BEFORE RISING

The relative height of the crater rim varies: the northern and eastern parts are higher than the southern and western ones. The lowest point in the rim corresponds to a reverse trapezoid groove of about 60 m wide at the base, located in the northwestern part of the crater; the highest point is a rocky lava residual (1446 m) in the southeastern part of the crater. The altitude difference between these two points in the period of 2009–2017 was, probably, about 150 m. Note that such altitude distribution of the rim, including the groove, also existed in the 1950s, prior to the eruptions of 1976 and 2009, judging by the perspective aerial image (Gorshkov, 1967, Fig. 33). The cross size of the crater, measured on the rim, was about 375 × 425 m (the major axis is oriented in NW–SE direction, whereas the minor axis is perpendicular to the major one). Thus, the average diameter is about 400 m;

Fig. 1. Matua Island. Image acquired by the WorldView-4 satellite on October 24, 2018. One can note a gas–vapor plume to the north of the crater and a band of thin ash sediments upon the snow to the southeast of the crater.

remarkably, it was the same before the 2009 eruption. For the first time, the same or a very close value was obtained from satellite imagery (Grishin, Melekestsev, 2010; Urai, Ishizuka, 2011).

The crater-bottom level immediately after the 2009 eruption, revealed from the image acquired from the *ALOS* satellite on June 22, 2009 (https://www.eorc.jaxa.jp/ALOS/img_up/l_pan_sarychev_090622.htm), dropped by about 50 m (Miyagi, 2010) or by approximately 200 m (Grishin and Melekestsev, 2010). After the high-quality satellite images of the crater became available, the bottom depth was measured by the author using two methods. According to the images acquired by the *WorldView-3* satellite on July 21, 2015, and *WorldView-2* one on August 31, 2016 (Fig. 3a), the crater depth was calculated from (a) the measured length of a shadow stretching from the crater rim to the bottom and (b) the known angle of solar altitude in the moment of shooting, taking into account the azimuth of shadow incidence. In addition, the crater depth (and its changes as well) was measured by overlapping the plain-view satellite images and perspective aerial images. The view of inner subvertical walls of the crater was obtained resulting from processing the video record made from a helicopter in June 2016 (Fig. 2b). The images of crater walls from the recognized topographic features were bridged to the satellite images. The measurement results obtained by both methods appeared to be similar. The crater-bottom depth in 2016 was about 220 m relative to the more elevated southeastern part of the rim (as measured by a shadow) or about 190 m relative to the north-northeastern part of the rim (as measured by the inner wall of the crater).

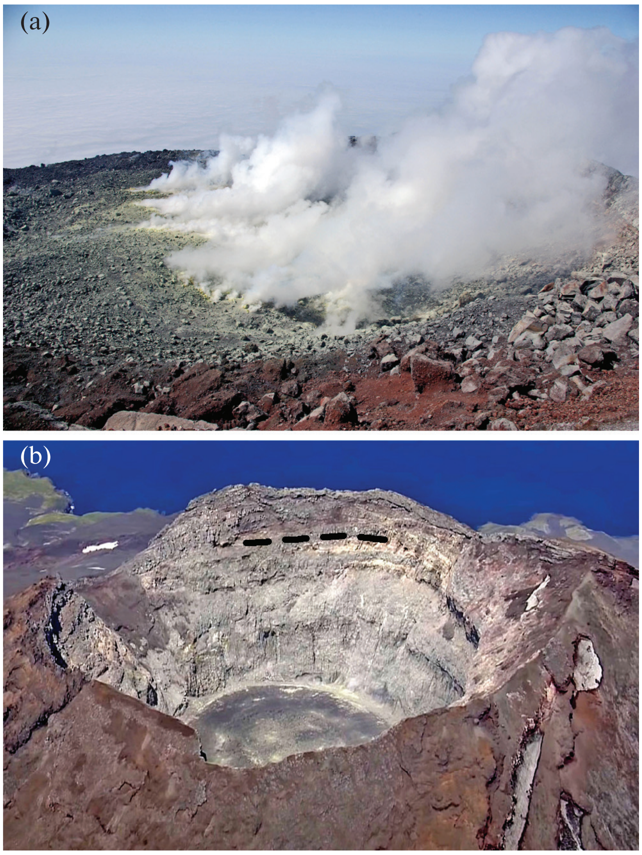

Fig. 2. Crater of Sarychev Peak in aerial images: (a) view from the rim to the north, August 2007, image is courtesy of A.K. Klitin; (b) view to the north-northeast from a helicopter during an overflight in June 2016, snapshot from the footage courtesy of A.G. Luk'yanov. The groove is seen in the northwestern slope, in the left; in the right, the volcano summit; in the ~~bottom,~~ the crater bottom. Dashed line indicates the crater-bottom level in September 2018.

Beginning in 2011, a weakly convex lava shield can be seen in the satellite images. In the subsequent period, up until September 2017, the crater bottom was likely stable. Based on the available images of 2015–2017, this can be concluded, in particular, from the positions of individual blocks and brighter spots (most likely, fumarole sublimates) clearly discernible in the background of the darker lava shield. The crater walls in 2009–2017 were subvertical (and, moreover, the crater noticeably widened in its upper part) and represented by alternation of thick light-colored lava flows (the largest lava flow was more than 40 m thick) and interbeds of reddish volcanic ~~ash~~ in the upper part of the outcrop (Fig. 2b).

Until September 2017, a rounded dark-colored lava discoid, about 230 m in diameter, was observed in the crater bottom; this discoid was generally weakly convex and consisted of three concentric zones, namely, central, intermediate, and marginal ones (Fig. 3a). The central and marginal zones were slightly (by 1–1.5 m)

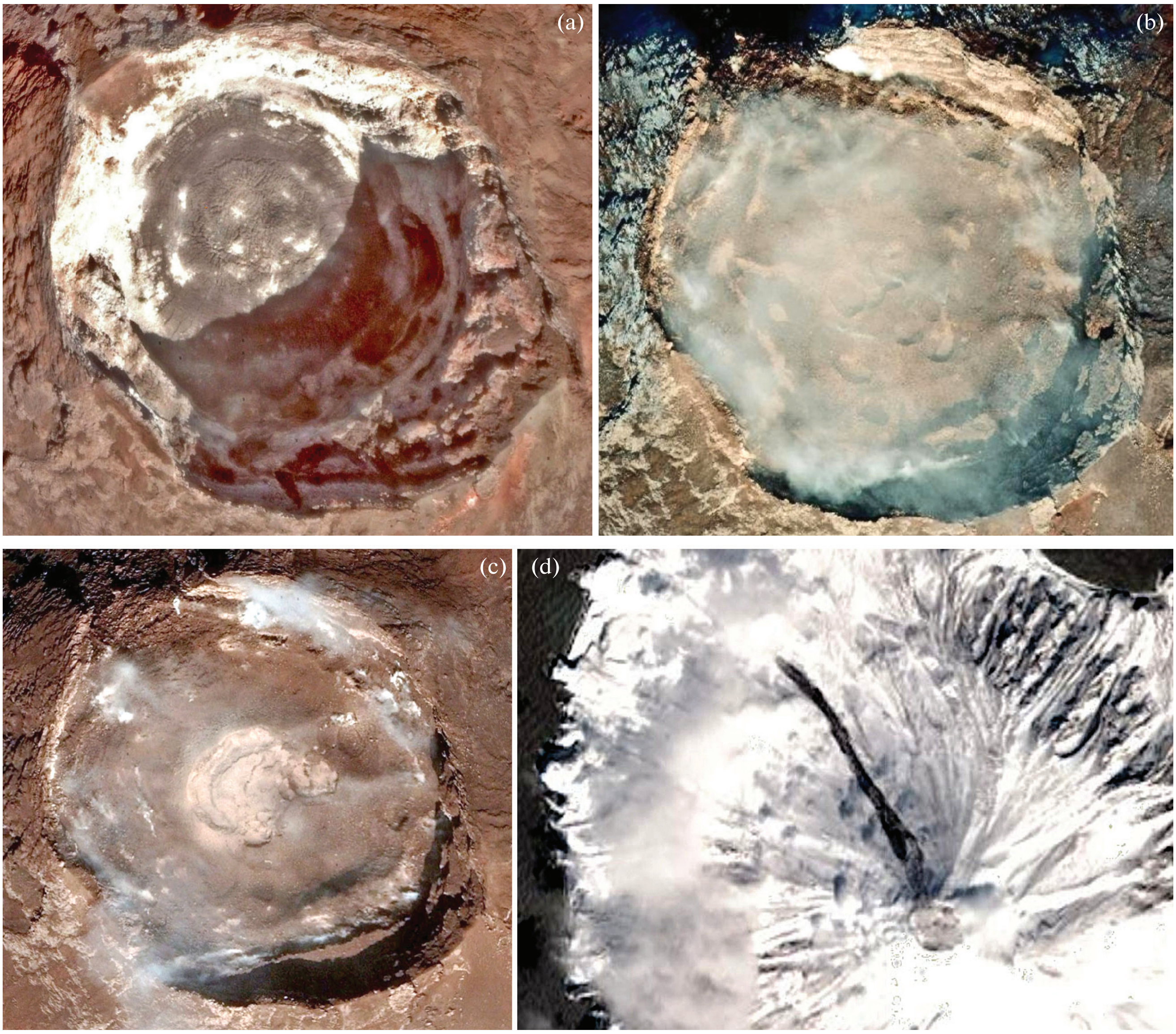

Fig. 3. Crater of Sarychev Peak in images acquired on different dates by different satellites: (a) August 31, 2016, *WorldView-2*; (b) October 5, 2018, *WorldView-4*; (c) September 7, 2019, *GeoEye-1*; and (d) ~~carter~~ and lava flow on the slope, April 16, 2021, *WorldView-2*.

elevated, judging by the shadow that fell from their edges. The marginal zone was 25–30 m wide and covered with a network of radial fractures that were arranged in an almost regular manner, 3–5 m from each other. The central zone of about 100 m in diameter, was covered with dense and chaotic fractures ~~(as of 2016),~~ and, as a result, it resembled a foamy surface of fermenting liquid. The fractures framing the central zone coincided to some fumaroles. Beyond the limits of this lava discoid, between the marginal zone and the crater walls, the transitional zone of up to 20–25 m wide was expressed; it was of light gray (in places, pale yellowish) color, with outcrops of steaming fumaroles and with rock fragments and blocks.

RISING OF THE CRATER BOTTOM

Satellite images acquired in 2018 and 2019 (Figs. 3b, 3c) have shown an abrupt rising of the crater bottom. Rising began, most likely in the autumn 2017. Contrary to the image from the *WorldView-4* satellite acquired on September 7, 2017, where the lava shield is clearly seen on the crater bottom and the shadow indicated a large depth of the crater, in the images acquired by the *WorldView-4* satellite on October 21 and 25, 2017, one can see the crater with supposedly altered bottom topography; this was likely the time when the crater was filling with lava. In the images acquired by the *TERRA* (*MODIS*) satellite on October 21, 2017, the thermal anomaly was revealed; this anomaly was accompanied by weak gas–vapor emissions with ash and was observed until mid-November 2017 (Chibisova, Degterev, 2019). These effects were likely related exactly to the rising of the lava plug. The changed level of the crater bottom is reflected in the satellite images acquired by the *WorldView-4* satellite on March 31 and April 18, 2018, and by the *Sentinel-2* satellite on April 4, 2018.

The ~~crater bottom level changed~~ in the northern and northeastern walls of the crater, which are exposed to the south and southwest, respectively (Fig. 2b). The bottom rose by 140–145 m by October 2018 and a small additional uplift (probably, by no more than 5–10 m) by September 2019. As a result, the crater appeared to be filled by approximately three-quarters of its height relative to the bottom level in 2009–2017, ~~and, notably, it is~~ the main part of the crater, with the steepest subvertical walls ~~that appeared to be~~ covered. The groove in the northwestern part of the crater also appeared to be partially covered. The filled volume can be approximately estimated ~~at~~ 10 million m^3, which corresponds to a volume of truncated cone of 150 m high, with the lower diameter of 240 m and the upper diameter of 330 m.

In the satellite image acquired on October 5, 2018 (Fig. 3b), through the fumarole vapors, one can see quite flat bottom covered with loose clastic material. A short shadow from the uplifted southeastern rim of the crater indicates the depth of about 60 m from the rim. Closer to the center of the crater, there is a step with a decrease in level by 15–20 m. In the central part of the crater (which is probably weakly concave), the bottom is covered with ~~multiple~~ oval or rounded hollows, up to 20–30 m in cross size. Judging by the shadow length, these hollows are no more than 3–6 m deep. These are likely subsidence structures formed in loose rock sequence that accumulated above the lava plug during a small eruption that occurred in summer–autumn 2018 (Girina et al., 2018). Fumaroles coincide mainly to the peripheral part of the bottom, within the band of up to 30–40 m wide adjoining the crater walls. The fumaroles may reflect the fractured zone in the stressed zone, along which the crater bottom rises.

In the satellite image acquired on September 7, 2019 (Fig. 3c), the fumarole zone is clearly seen in the marginal band of the crater bottom. In the center of the crater, one can see an irregularly rounded structure about 80–100 m in cross size. The western half of this structure is limited an arc-shaped bar of loose sediments of 30–40 m wide, with a gently angled outer slope and relatively steep inner wall. The western inner wall of the bar is illuminated by sunlight, and there is no shadow here; however, topographic features suggest that its height is at least 10 m. The structure in the center of the crater is probably a vent partially covered with loose sediments. In the satellite image acquired on September 28, 2019, by the *Sentinel-2* satellite, a thermal zone ~~is located~~ in this part of the crater (Global Volcanism Program, 2019).

CRATER-BOTTOM DYNAMICS AND A NEW UPCOMING ERUPTION

The periodic changes in the crater-bottom level during the last 75 years, beginning from the strong Sarychev Peak eruption in 1946, were studied using the aerial images of 1950–1980, satellite images of 1994–2021, and visual observations (as well as images made by) of researchers and eyewitnesses that visited the crater rim. The general regularity revealed is that the crater bottom lowered three times, after every strong or considerable eruption (namely, those of 1946, 1976, and 2009). After the period of lowering the crater bottom also rose three times: before the eruptions of 1976 and 2009 and in the present. Remarkably, in the case of the recent situation, the crater bottom underwent a considerable rise as early as 8 years after the last eruption in 2009, whereas in the previous periods, during which the crater bottom could be either lowered or risen, were longer than 20 years. For example, according to images made by people who visited the crater rim in 1989 and 2007, the crater bottom almost reached the rim (Fig. 2a), and the strong eruption occurred only 20 years after the observation in 1989.

In recent years, with respect to the rising of the crater bottom in 2017–2018, and also after it, the volcano demonstrates certain activity (Girina et al., 2019; Chibisova, Degterev, 2019; Global Volcanism Program, 2019, 2021). Small ash releases occurred in autumn 2018 and in 2019; additionally, thermal anomaly was revealed in the crater in 2019 (Global Volcanism Program, 2019). In the image made by the *Sentinel-2* satellite on January 20, 2021, lava pouring from the central part of the crater to the distance of about 400 m was recorded (Global Volcanism Program, 2021). Probably, lava partially filled the crater, and the lava flowed out of the crater to the slope through the trapezoid groove (in the northwestern part of the crater rim), which was not completely covered during the period of bottom rising in 2017–2019. By January 24, 2021, the lava flow reached an altitude of about 800 m on the northwestern slope, covering the distance of about 800–900 m from the crater rim (image acquired by the *WorldView-2* satellite). In the image from February 25, 2021, one can see that the lava-flow tip is at the distance of about 2000 m from the crater rim and is located at the altitude of about 380 m (image acquired by the *WorldView-3* satellite). The width of the lava flow in its lower part is no more than 100 m, and it likely flowed over the lava flow produced by the 1976 eruption, advancing below its tongue by approximately 500 m. The volume of lava that outflowed in 2021 is around 3 million m^3. After the outpouring, a dark-colored contour of about 50 m in diameter (probably, a vent) is noticeable in the center of the crater (image acquired by the *WorldView-2* satellite on

April 16, 2021; Fig. 3d). The Sarychev Peak is generally characteristic of intensive explosive activity combined with episodic explosive–effusive eruptions, such as the eruptive volcanic events of 1976 and 2009. However, there is information about quiet outflowing of lava in 1878–1879 (Gorshkov, 1967). An analogous event likely occurred in winter 2021.

The crater-bottom dynamics revealed for the last 75 years shows that the rising–lowering cycle ends with a considerable eruption that is hazardous for the population, infrastructure, and ecosystems of Matua Island. The eruptive events of 1946 and 1976 caused massive evacuation of people from this island; as of 2009, Matua Island was uninhabited (otherwise, there would also be evacuation). Small eruptions, similar to those of 2018–2021 (formation of the vent, episodic renewal of the vent with ash-releasing explosions, filling of the crater with lava, and subsequent lava outpouring from the crater), which are likely only intermediate episodes of the rising–lowering cycle. These events can hardly be precursors of a strong eruption, although they may delay its occurrence. Contrarily, the rising of the crater bottom in 2017–2019 (which is obviously has not finished yet) may indicate the preparation of the volcano to a new, potentially destructive eruption. In the light of recently appeared exploration projects related to Matua Island, these indications are important for the purpose of volcanic-hazard assessment.

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