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SHORT SCIENTIFIC COMMUNICATION

Detection of a new summit crater on Bezymianny Volcano lava dome: satellite and field-based thermal data

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Abstract An explosive eruption occurred at the summit of Bezymianny volcano (Kamchatka Peninsula, Russia) on 11 January 2005 which was initially detected from seismic observations by the Kamchatka Volcanic Eruption Response Team (KVERT). This prompted the acquisition of 17 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images of the volcano over the following 10 months. Visible and infrared data from ASTER revealed significant changes to the morphology of the summit lava dome, later seen with field based thermal infrared (TIR) camera surveys in August 2005. The morphology of the summit lava dome was observed to have changed from previous year's observations and historical accounts. In August 2005 the dome contained a new crater and two small lava lobes. Stepped scarps within the new summit crater suggest a partial collapse mechanism of formation, rather than a purely explosive origin. Hot pyroclastic deposits were also observed to have pooled in the moat between the current lava dome and the 1956 crater wall. The visual and thermal data revealed a complex eruption sequence of explosion(s), viscous lava extrusion, and finally the formation of the collapse crater. Based on this sequence, the conduit could have become blocked/pressurized, which could signify the start of a new behavioural phase for the volcano and lead to the potential of larger eruptions in the future.

Keywords Bezymianny · Kamchatka · Remote sensing · ASTER · FLIR

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Introduction

Bezymianny (55.98°N, 160.59°E) is a Holocene andesitic composite volcano (Fig. 1a) with a summit elevation of approximately 2,900 m and is located 350 km north of Petropavlovsk-Kamchatsky (Bogoyavlenskaya et al. 1991). It forms part of the Klyuchevskaya group within the central Kamchatka depression. Previously inactive for about 1,000 years, Bezymianny reactivated in 1955, culminating in a cataclysmic eruption on 30 March 1956 (Gorshkov 1959; Belousov 1996). This directed blast generated a 1.3 km (north–south) by 2.8 km (east–west) horseshoe-shaped crater opening to the east. Following this, a long-term phase of lava dome growth began in the crater, which was mostly endogenous prior to 1969 (Bogoyavlenskaya and Kirsanov 1981). Similar to activity at Mt. St. Helens (Swanson et al. 1987), lava at Bezymianny was commonly extruded in a near-solidified state as rigid spines in different locations within the crater (Bogoyavlenskaya and Kirsanov 1981). After 1977, exogenous activity became more common, with lava lobes being emplaced periodically from a single location on the upper part of the dome, adding to its volume (Alidibirov et al. 1990; Bogoyavlenskaya and Kirsanov 1981). During the last 30 years Bezymianny has been regularly active, erupting one to two times per year on average (Belousov et al. 2002; Ramsey and Dehn 2004). However, this activity has been punctuated by much larger eruptions such as the sub-plinian events of 1985 and 1997

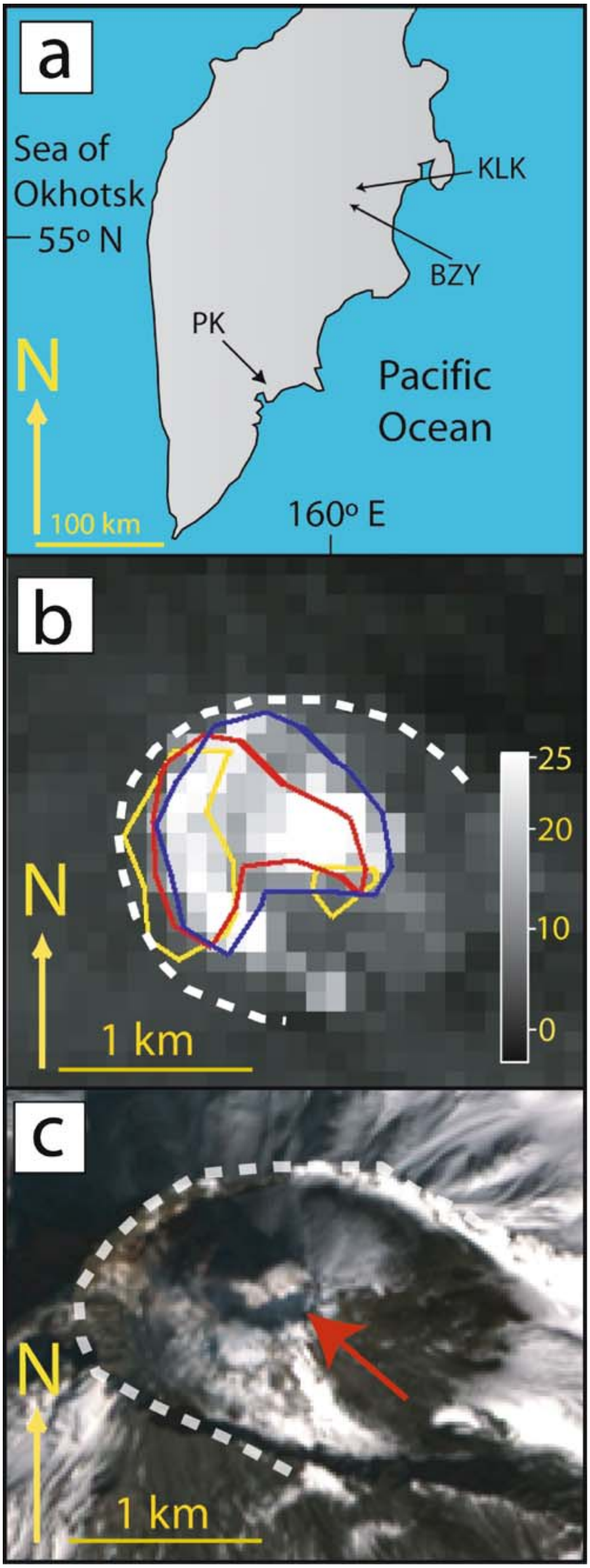

Fig. 1 Location and satellite-based observations of Bezymianny Volcano. **a** Map of the Kamchatka Peninsula centred on 55°N, 160°E, with Bezymianny (BZY) and Klyuchevskoy (KLK) volcanoes located to the north of the city of Petropavlovsk-Kamchatsky (PK). **b** Nighttime TIR ASTER temperature image in Celsius from 15 January 2005 showing a thermal anomaly around the summit. Overlain: temporal composite overlay of the 10°C contour above background temperature for the 15 January (*blue*), 16 February (*red*), 4 March (*yellow*) images. The cooling trend with time over the dome and a sustained anomaly over the deposit within the 1956 crater is evident. **c** Daytime ASTER VNIR image from 12 March 2005 showing the new collapse crater evident on the dome (*indicated by a red arrow*)

(Alidibirov et al. 1990; Belousov et al. 2002) and the recent 9 May 2006 eruption (Kamchatka Volcanic Eruption Response Team (KVERT) Report 2006).

The remote location combined with common cloud cover make satellite and field observations of the volcano difficult. However, it remains a critical volcano to monitor due to the chance of much larger eruptions that can form ash-rich plumes which traverse into north Pacific air traffic routes (Miller and Casadevall 2000). Similar surveys have also been completed elsewhere at remote or inaccessible volcanoes such as Láscar, Chile (Oppenheimer et al. 1993 and references therein) and Mount Belinda on Montagu Island (Patrick et al. 2005) and required similar verification of results by direct field surveys.

Satellite observations

The primary satellite instrument used for higher resolution data was ASTER, which acquires reflected solar and thermally-emitted electromagnetic radiation within three spectral regions and at three spatial resolutions (Yamaguchi et al. 1998). However, initial detection of an eruption was made on 11 January by KVERT, which issued a report stating an eruption had occurred at 08:02 A.M. (UTC) and produced an 8–10 km ASL ash column (Kamchatka Volcanic Eruption Response Team (KVERT) Report 2005). The eruption was also detected by the Alaska Volcano Observatory (AVO) Advanced Very High Resolution Radiometer (AVHRR) thermal anomaly detection system (Dehn et al. 2000), which then triggered an ASTER rapid response imaging sequence that involved targeted and regular data collection (Ramsey et al. 2004). This resulted in six daytime and eleven nighttime images from January to October 2005.

The first ASTER acquisition on 15 January 2005 (described in Carter et al. 2005) revealed nighttime thermal anomalies around the summit crater as well as up to 3 km away (Fig. 1b). The dome region had a maximum TIR-derived temperature of 26°C above the average background temperature (−24°C), which was derived from a 20 km^2 non-volcanic area to remove seasonal effects. Three nighttime scenes (15 January, 16 February, and 4 March 2005) show a cooling trend on the eastern portion of the dome (Fig. 1b). However, pyroclastic density current (PDC) deposits ponded between the 1956 crater wall and dome retained their heat much longer, and continued to show temperatures elevated above background during the field surveys in August 2005. On 12 March 2005, reduced shadowing in the crater and less snow cover allowed for improved viewing conditions of the dome and revealed a distinct circular crater structure at the summit (Fig. 1c). This was the first indication of a new summit pit structure on Bezymianny's dome. An ASTER-derived Digital Elevation Model (DEM) created from the 12 March images revealed a crater depth of ~50 m and a diameter of 310 m north–south and 385 m east–west. However, the first aerial observations in July 2005 suggested the crater could be up to 200 m deep (O Girina, pers. Comm. 2005). The DEM-derived depth was probably an underestimation due to the spatial averaging that occurs at the 30 m resolution of ASTER. Using an inverted, truncated cone as a simplified geometric model, with a large radius of 173.75 m (crater edge) and short radius of 82 m (inner crater base), the volumes calculated for depths of 50 m and 200 m were 2.6×10^6 m^3 and 10.7×10^6 m^3, respectively.

Aerial and ground-based observations

Field campaigns in August 2004 and 2005 were performed to verify the recent ASTER observations. During these, aerial high resolution TIR and visible photographic surveys of the dome and pyroclastic deposits were made from a helicopter. In August 2004 no summit crater was present; however, one year later the new summit crater and hot, ponded deposits originally detected with ASTER were verified (Fig. 2a). Thermal surveys were conducted using a Forward-Looking Infrared Radiometer (FLIR) camera. Similar surveys of volcanoes have become a useful monitoring tool in locations such as Stromboli, Italy (Harris et al. 2005) and Mount Saint Helens, USA (Vaughan et al. 2005) for example. The FLIR contains an uncooled micro-bolometer detector array that captures radiation from the 7.5–13 μm wavelength region. Still images were extracted from video data files taken between 19 and 25 August 2005, which were collected at a minimum of one image per second. A 24° FLIR lens was used, with an instantaneous field of view (IFOV) of 1.3 mrad. Helicopter altitude was around 3500 m and the distance to the upper dome region varied from 600 m to 850 m. Thus, the range of spatial resolutions was 0.78 to 1.11 m. The maximum derived pixel-integrated temperature was 163°C, with an average temperature of 10°C over the dome area (1.27 km^2). Digital photograph and thermal (FLIR) image mosaics were created and four regions of interests were identified (Fig. 2b and c): (1) a short (60 m long×150 m wide) lava lobe (Lobe A); (2) a 150 m long lava lobe (Lobe B); (3) the new central summit crater; and (4) two flat-bottomed oval collapse pits 20×30 m in diameter in the ponded pyroclastic deposits.

Lobe A flowed to the west and video footage showed that it exhibited partial ductile deformation, sagging back into the crater. Thus, we interpret that Lobe A had not completely solidified prior to crater formation. The flow surface of Lobe A contained deep ridges perpendicular to flow direction and the FLIR-derived temperature over its area was 10°C, with a maximum temperature of 77°C. Lobe B was located south of Lobe A, with no apparent cross-cutting relationship to it. The flow surface was visibly smoother and lighter in colour than Lobe A and it had an average temperature of 12°C, with a maximum of 56°C.

The formation of a central summit crater was the most dramatic change observed at Bezymianny in recent observations. It contained concentric stepped ledges and fractures that surrounded the rim. The crater cut older lava lobes and pyroclastic material as seen in its walls. The warmest areas corresponded to more competent rock layers and hot cracks that bounded the concentric ledges. Surrounding the dome and within the main summit crater of the volcano, the moat was filled with newly-emplaced PDC deposits that contained several collapse pits. The areas within the pits had an average temperature of 33°C, with the hottest surfaces at 124°C. These collapse structures may be caused by PDC deposition onto (or the entrainment of) ice/snow, which was observed in ice-rich lahars by Branney and Gilbert (1995). At Bezymianny, the thickest part of this new deposit, located west of the dome summit inside the 1956 crater rim, was also the location of the small pits. It is most likely that the PDC deposit was emplaced onto the snow and ice present in this shadowed part of the crater during the January eruption. It cooled slowly over several months while differential melting occurred beneath the deposit, producing the pits (lower Fig. 2b-delimited by a black rectangle) and the thermal TIR anomaly (Fig. 1b).

Discussion and conclusions

An explosive eruption occurred at Bezymianny on 11 January 2005 and deposited juvenile and older dome material within the 1956 crater. The eruption also generated one or more PDC deposits, which, based on later field sampling, primarily contained fresh vesicular blocks and ash with smaller quantities of older, hydrothermally altered dome material. Based on the radial deposition observed, the presence of ash on the slopes outside of the 1956 crater, and the column height (8–10 km), we interpret that column

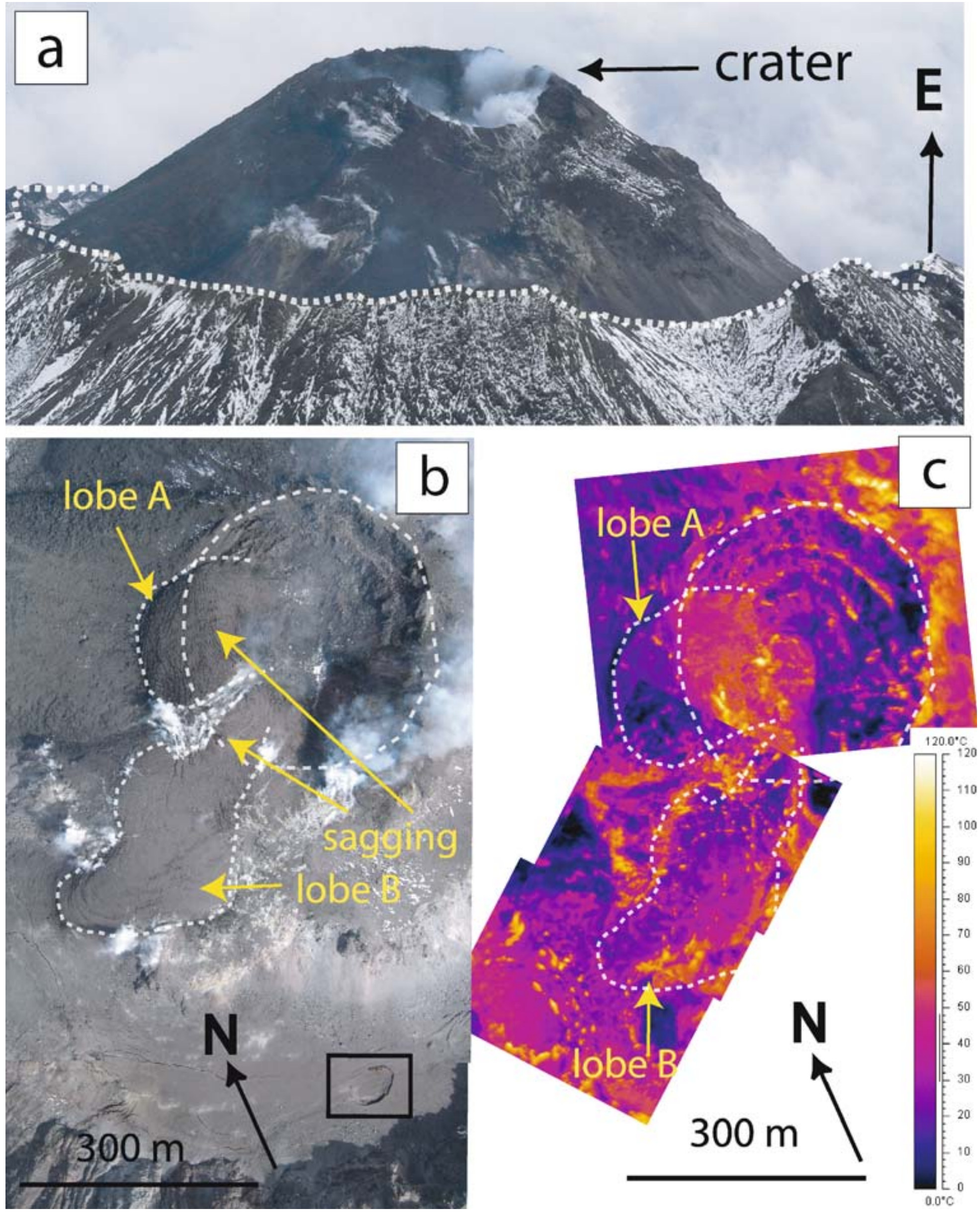

Fig. 2 **a** Aerial, digital photograph from 19 August 2005 showing the new summit crater on the lava dome. The 1956 crater (1.3 km north-south) opening to the east is denoted by the white dashed line. **b** Part of the 19 August 2005 digital photograph composite taken simultaneously with FLIR observations. Lobes A/B and the collapse crater are *marked with arrows and dashed lines*, with sagging back into the crater *marked with arrows*. In the *lower right* (delimited by a *black rectangle*) one of the *oval pits* observed within the ponded PDC deposits is shown. **c** FLIR colour composite image with a temperature range from 0°C to 120°C. The temperatures were derived using an average distance to the dome of 725 m, an assumed emissivity of 0.97 for the surface, a humidity of 30%, and an atmospheric temperature of 5°C. The stepped ledges within the crater can be seen, with both Lobes A and B partially draped into the crater

collapse most likely formed these deposits. A large fraction of the material pooled between the 1956 crater rim and the dome, with the remainder of this flow continuing down slope to the southeast, carrying hot ash and blocks with unweathered vesicular centres as far as 3 km from the vent.

We infer that the eruption sequence progressed from explosive to extrusive with the emplacement of two short viscous lava lobes (Lobe A and Lobe B) that appear to have erupted from near or at the summit of the existing dome, similar to the previous exogenous dome growth at Bezymianny. Following the flow emplacement, a crater with a volume estimated to be between 2.6×10^6 $m^3$and 10.7×10^6 m^3 formed within the older lava dome. We cannot infer the exact timing of the crater formation; however, field observations confirmed the lack of a crater in August 2004 and no unusual activity was observed over August–December 2004. Based on field observations and superposition relationships we infer that a collapse at the dome summit occurred following emplacement of these lava flows to form the crater. We propose that the crater is of at least partial collapse origin, based on aerial views of Lobe A that showed a steep cliff on the western rim. In addition, some ductile deformation occurred on the flows as both lobes sagged back into the newly formed crater. This style of deformation further suggests a relatively slow, low-energy collapse process. In addition, the collapse-origin model is supported by concentric fractures seen in proximity to the crater rim as well as stepped terraces within the crater, which could represent inward-dipping blocks. This crater-forming event was a deviation from recent eruptive behaviour and indicates that the sub-surface conduit structure may have been modified or partially blocked within the lava dome. We hypothesize that if this was the case, it could promote a build-up of pressure, leading to a larger eruption in the future. This was potentially validated by a larger than average eruption on 9 May 2006 that produced a 15 km ASL ash column, which was 5 km higher than most eruptions during the past five years (KVERT 2006). This new phase of activity of Bezymianny may be part of a larger cycle of explosions, dome effusion, and subsidence, as observed at Láscar volcano, Chile (Matthews et al. 1997). This work highlights a possible change in the eruptive behaviour of Bezymianny volcano, which was successfully observed first using the high resolution data from ASTER and later confirmed with detailed ground and airborne observations.

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