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Magmatic degassing, lava dome extrusion, and explosions from Mount Cleveland volcano, Alaska, 2011—2015: Insight into the continuous nature of volcanic activity over multi-year timescales

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Abstract.

Mount Cleveland volcano (1730 m) is one of the most active volcanoes in the Aleutian arc, Alaska, but heightened activity is rarely accompanied by geophysical signals, which makes interpretation of the activity difficult. In this study, we combine volcanic gas emissions measured for the first time in August 2015 with longer-term measurements of thermal output and lava extrusion rates between 2011 and 2015 calculated from MODIS satellite data with the aim to develop a better understanding of the nature of volcanic activity at Mount Cleveland. Degassing measurements were made in the month following two explosive events (21 July and 7 August, 2015) and during a period of new dome growth in the summit crater. SO_2 emission rates ranged from 400 to 860 t d^{-1} and CO_2/SO_2 ratios were <3, consistent with the presence of shallow magma in the conduit and the observed growth of a new lava dome. Thermal anomalies derived from MODIS data from 2011-2015 had an average repose time of only 4 days, pointing to the continuous nature of volcanic activity at this volcano. Rapid increases in the cumulative thermal output were often coincident with visual confirmation of dome growth or accumulations of tephra in the crater. The average rate of lava extrusion calculated for 9 periods of rapid increase in thermal output was 0.28 m^3 s^{-1}, and the total volume extruded from 2011 to 2015 was 1.9 - 5.8 Mm^3. The thermal output from the lava extrusion events only accounts for roughly half of the thermal budget, suggesting a continued presence of shallow magma in the upper conduit, likely driven by convection. Axisymmetric dome morphology and occasional drain back of lava into the conduit suggests low-viscosity magmas drive volcanism at Mount Cleveland. It follows also that only small overpressures can be maintained given the small domes and fluid magmas, which is consistent with the low explosivity of most of Mount

Cleveland's eruptions. Changes between phases of dome growth and explosive activity are somewhat unpredictable and likely result from plugs that are related to the dome obtaining a critical dimension, or from small variations in the magma ascent rate that lead to crystallization-induced blockages in the upper conduit, thereby reducing the ability of magma to degas. We suggest the small magma volumes, slow ascent rates, and low magma viscosity lead to the overall lack of anomalous geophysical signals prior to eruptions, and that more continuous volcanic degassing measurements might lead to more successful eruption forecasting at this continuously-active open-vent volcano.

Keywords: degassing, extrusion rate, magma flux, Mount Cleveland volcano, explosion, dome growth, open vent

Introduction.

Mount Cleveland volcano (52.825°N, -169.944°W, 1730 m) is an andesitic stratovolcano and one of the most active volcanoes in the Aleutian arc, having had eruptive activity recorded every year since 2005 (Herrick et al., 2014, Dixon et al., 2015, Cameron et al., 2017; Dixon et al., 2017). The volcano is part of a complex of volcanic centers called the Islands of Four Mountains (IFM), and lies about 1500 km SW of Anchorage, Alaska (Figure 1). Mount Cleveland's remote location makes volcano monitoring, and thus characterizing the magmatic processes leading to various volcanic behaviors, a real challenge. Permanent geophysical instrumentation and a web camera were only installed in mid-2014. Thus, until recently, eruptions and changes in activity were almost exclusively detected using satellite data and from pilot reports (McGimsey et al., 2014). Since late 2011, distant infrasound arrays proved very useful for detecting explosions (De Angelis et al., 2012; Dixon et al., 2015), but of the explosions since 2014, none have been accompanied by enhanced seismicity recorded by permanent seismic monitoring stations.

The observations of eruptive activity and the appearance of the crater area and volcanic deposits at Mount Cleveland are documented in the Alaska Volcano Observatory's annual reports for years 2011-2015 (McGimsey et al., 2014; Herrick et al., 2014; Dixon et al., 2015; Cameron et al., 2017; Dixon et al., 2017). During this period, the activity was characterized by elevated temperatures and nearly-continuous degassing, intermittent minor explosions (often accompanied by limited tephra deposits in the summit crater), and dome growth. In most years, the emplaced domes would be completely destroyed in subsequent explosions (see Herrick et al., 2014, for a good example), but on two occasions, in 2011 and 2014, the recently emplaced domes were observed to deflate, or drain back, into the conduit. Sometimes these periods of subsidence were marked by ring fractures around the crater walls (McGimsey et al., 2014). Typically no activity would be observed in the summit crater during periods with no other indication of heightened volcanism (e.g. thermal anomalies). Satellite images suggest that the central crater is often funnel shaped when a dome is not present, and in many years the active vent area is visible as a central pit that varies from ~ 10-30 m in diameter at the surface, either in the center of the dome or pit. Satellite data also indicate that small lava flows sometimes extend several hundred meters down the flanks of the volcano, but more often flank deposits are described as patchy or as a dusting of ash, rather than extensive in nature (Herrick et al., 2014).

Since the installation of a web camera on nearby Chuginadak Island in 2014 (https://www.avo.alaska.edu/webcam/Cleveland_CLCO.php), the volcano is often observed emitting a low-altitude volcanic plume, and occasionally more robust plumes that extend 10s of km downwind of the volcano are observed both in web camera images and satellite data. While the majority of eruptive activity at Mount Cleveland is minor (VEI 0-2), major ash producing eruptions (VEI 3+) pose a threat to aviation and are a hazard in the region. Between 1970 and 2008 there were 14 eruptions from Mount Cleveland in which the ash cloud extended to greater than 5 km height (VEI 3) above sea level (ASL) (Dean et al., 2015; Dean et al., 2004). In one of the most recent major eruptions of Mount Cleveland in 2001, three explosive events resulted in ash clouds that rose 12 km (39,000 ft) ASL (Dean et al., 2004). This eruption resulted in one documented non-damaging encounter between an aircraft and the volcanic cloud in the vicinity of San Francisco, California (Simpson et al., 2002; Guffanti et al., 2010).

Here, we report the first measurements of volcanic gas composition and emission rates ever made at Mount Cleveland volcano, and compare with the longer-term record of degassing obtained from OMI (Ozone Monitoring Instrument) satellite data (Fioletov et al., 2016). The on-site measurements were obtained during a campaign to the central Aleutians in mid-August 2015. To place these measurements in a broader volcanic context, we analyze MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data to assess thermal output and estimate lava extrusion rates over the last five years (2011-2015). Thermal signatures are compared to visual observations of volcanic activity from satellite data, and specific periods of lava extrusion are quantified. Through merging observations from these multiple data streams, we formulate a conceptual model to explain shallow magmatic behavior for Mount Cleveland volcano that places Mount Cleveland in a broader context of open-system volcanoes globally.

Methods.

Airborne Volcanic Gas Measurements.

Measurements of SO_2 column concentrations were made using an upward-looking miniature DOAS (Differential Optical Absorption Spectroscopy) system. A small telescope mounted to the helicopter window collected scattered solar ultraviolet radiation from above the aircraft. A fused silica fiber optic cable coupled the light into an Ocean Optics USB2000+ spectrometer located inside the helicopter. Using a laptop computer, spectral data were acquired between 285 and 430 nm at 0.6 nm resolution and approximately 1 Hz, and the instrument position was tracked using a Garmin 18x PC GPS receiver. The system was powered by an external 12 V battery to allow continuous operation throughout the day. In this manner, DOAS measurements were made during dedicated gas flights, but data were also collected during chance under-flights of the volcanic plume as the helicopter was performing other tasks (see below).

In situ gas compositions (H_2O, CO_2, SO_2, H_2S) were measured using a U.S. Geological Survey (USGS) Multi-GAS instrument that included an integrated GPS receiver (Garmin GPS 18x LVC), a non-dispersive infrared CO_2 and H_2O analyzer (LI-COR, Inc. LI-840A,0-5000 ppm for CO_2, 0-80 parts per thousand for H_2O), and electrochemical SO_2 (City Technology, Ltd., 2T3STF, 0-100 ppm) and H_2S sensors (City Technology, Ltd., EZT3H, 0-100 ppm). All data were logged at 1 Hz to the Multi-GAS datalogger (Campbell Scientific, CR1000) and displayed in real time with a tablet. An ideal gas-type correction for pressure and temperature was applied to the SO_2 and H_2S sensor data, and the raw CO_2 signal was filtered using a digital single-pole recursive lowpass filter to better match the SO_2 and H_2S sensor responses. Portable calibration gases (3000 ppm CO_2, 10 and 2 ppm SO_2, and 10 and 2 ppm H_2S) were used to assess sensor responses in the field. All sensors were observed to be accurate within 10% of the standard values during the field campaign.

Gas measurements were made using two modes of operation on 14−15 August 2015. The majority of the DOAS data were collected when the helicopter traversed beneath the plume when shuttling back and forth to various field sites around the volcano from the Maritime Maid research vessel, from which all operations were based. Ten of the traverses were collected in this manner; the remaining five were collected during a dedicated gas flight (Table 1). One traverse during the gas flight likely missed part of the plume and is not included in the analysis, but it is retained in Table 1 for completeness. A dedicated gas flight was performed on 15 August to collect in situ gas concentrations of the volcanic plume. The majority of the in situ traverses were made at ~2.5 km downwind of the summit, and the entire flight covered an altitude range of sea level to 2500 m ASL; the plume was intersected between 1500 and 1800 m ASL. Wind speed was measured directly at plume height during the gas flight measurements (Table 1). The remaining traverses relied on other methods to assess plume speed as detailed in Table 1.

Thermal Infrared Imaging.

Thermal images of the summit area and young lava dome were captured on 4 and 15 August 2015 during helicopter flights using a FLIR® Systems model SC620 camera with a 640 x 480 image size. The average air temperature was 6°C during the first flight and 8°C during the second flight. The slant distance between the dome and camera was ~1 km. Temperatures were calculated from the thermal images after applying an atmospheric correction and using an emissivity of 0.95. Maximum pixel temperatures of 550-600°C were recorded around the center of the dome in fume-free images on 4 August. Maximum dome temperatures recorded on 15 August were 450-500°C, but fume filled the crater and may have attenuated some of the thermal signal, and thus these values are minimum estimates.

Thermal Output and Lava Extrusion: MODIS-MIROVA Analysis

Satellite data were analysed to estimate the thermal output and the amount of lava extrusion at Mount Cleveland over the past several years to place the degassing measurements in a broader volcanic context. We used the MIROVA (Middle Infared Observation of Volcanic Activity) automated global hot spot detection system (www.mirovaweb.it), which is based on near-real time ingestion of MODIS data (Coppola et al. 2016a). The system completes detection and location of high-temperature thermal anomalies (MODIS channel 22, or if saturated, channel 21, see Coppola et al., 2016a for details), and provides a quantification of the Volcanic Radiative Power (VRP) within 1 to 4 hours of each satellite overpass (2 night time and 2 daytime overpasses per day).

Thermal flux was calculated by using the 'MiddleInfraRed' method (Wooster et al., 2003), according to which the radiant power of a sub-pixel hot source is proportional to the "above background" middle infrared (MIR) radiance:

$$VRP_{PIX} = 18.9 \times A_{PIX} \times \left(L_{4alert} - L_{4bk}\right) \quad [1]$$

where A_{PIX} is the pixel size (1 km^2 for the resampled MODIS pixels), 18.9 is the constant of proportionality, L_{4alert} and L_{4bk} are the 4 µm MIR radiance of the detected high temperature pixel(s) and background, respectively. When two or more pixels (a cluster of pixels) are detected, the total radiative power is calculated as being the sum of each single VRP_{PIX} (see Coppola et al., 2016a for more details). The linearity expressed by equation (1) is restricted to targets areas (±30%) that have an integrated temperature between ~600–1500 K (Wooster et al., 2003). In the case of most active lava bodies this implies that the VRP calculated using (1) is not always directly correlated with the heat radiated by the entire surface area of the lava, but, more likely, it is representative of the radiative power emitted by a smaller, hotter, and younger portion of the lava surface (Coppola et al., 2013).

Different approaches have been developed to estimate heat flux and lava discharge from thermal satellite data, but the basic principle of these methods relies on a mutual relationship between effusion rates, the active flow area, and the thermal flux (Pieri and Baloga, 1986; Wright et al., 2001; Harris and Baloga 2009; Harris, 2013 and references therein). In particular, Coppola et al. (2013) showed that for a given eruptive case, the thermal energy radiated (*VRE*) can be related to the erupted lava volume (*Vol*) through a unique empirical parameter (called radiant density; c_{rad}) that takes into account the appropriate rheological, insulation, and topographic conditions for the studied lava body. The volume of an actively-extruded lava body (*Vol,* m^{-3}) is related to the *VRE* (in J) such that,

$$Vol = \frac{VRE}{c_{rad}} \qquad [2]$$

where c_{rad} is the radiant density (in J m^{-3}), and is mainly controlled by its bulk rheological properties (Coppola et al., 2013). Low-viscosity basaltic lava flows exhibit the highest range of c_{rad} (1-4 x 10^8 J m^{-3}), while viscous silicic flows result in lower values (< 1 x 10^7 J m^{-3}). Coppola et al. (2013) provided an empirical method to calculate the radiant density of a lava body (±50%) on the basis of the silica content of erupted lavas, which can be considered a first-order proxy of its bulk rheological properties,

$$c_{rad} = 6.45 \times 10^{25} \times \left(X_{SiO_2}\right)^{-10.4} \qquad [3]$$

where X_{SiO2} is the silica content of the erupted lavas (wt. %). For the Mount Cleveland basaltic-andesite, expected silica contents of the active lava extrusion are on the order of X_{SiO2}=57.5 wt. % based on past eruptions (K. Nicholyasen, personal communication) which results in a calculated radiant density (c_{rad}) of 3.7 x 10^7, or between 1.6 and 4.8 × 10^7 considering the ±50% accuracy of the empirical fit. The values calculated for Mount Cleveland are similar to those obtained for the andesitic lava plug of Ubinas Volcano in Peru (Coppola et al., 2015) and the relatively low-viscosity dacitic lava flow of Nevados de Chillan Volcano in Chile (Coppola et al., 2016b).

Results

Airborne gas measurements.

Fourteen airborne measurements of SO_2 emission rate were made on 14 − 15 August, 2015. DOAS transects were made between 3.8 and 6.4 km from the vent (Figure 2) and maximum column concentrations[1] ranged from 124 to 320 ppm·m SO_2 (Table 1). The winds were consistently out of the west and wind speeds ranged from 9 to 12 m s^{-1}. The measurements resulted in SO_2 emission rates that varied from 4.7 to 10.0 kg s^{-1} or from ~400 to 860 t d^{-1} SO_2 (Table 1, Figure 3), and the measurements made on 14 August show a steady decline in emissions from ~800 to 400 t d^{-1} SO_2 over a five hour period. The highest column concentrations and emission rates were made when the sky was completely cloud free (Table 1 and Figures 2a and 2c). The five measurements made during the gas flight were along transects that progressively increased in altitude such that the final traverse was made directly beneath the plume. These measurements together show less variation than the measurements made over the 2-day period (Figure 3), suggesting that no systematic variation was introduced from light scattering when flying at different altitudes beneath the plume over the two days of measurement. The average SO_2 emission rate derived from all the measurements during the campaign (except the one where a portion of the plume was missed, Table 1) was 6.9 ± 0.5 kg s^{-1}, or 600 ± 39 t d^{-1} SO_2, where the error indicated here is standard error of the mean.

Airborne measurements of in situ gas concentrations were completed on 15 August. The plume was traversed eight times at ~2.6 km downwind of the vent (Figure 2b). Given the recent explosive activity at the volcano (~ 1 week prior to the airborne measurements), we were unable to obtain in situ gas measurements closer to the vent. The maximum SO_2 detected

[1] Here and throughout, column concentrations are converted from molecules·cm^{-2} to ppm·m assuming standard temperature and pressure (T = 20 C and P = 1013 hPa), 1ppm·m = 2.5 × 10^{15} molec·cm^{-2}

was 0.53 ppmv during the traverses (Figure 4), but no discernable volcanic CO_2 signal was detected over ambient background levels and the instrumental noise (± 0.5 ppmv, 1σ). Likewise, volcanic H_2O could not be resolved above atmospheric background and no H_2S was detected. If we define the CO_2 detection limit as 3 times the noise of the analyzer (i.e. 3σ; 1.5 ppmv), then the data suggest that the molar CO_2/SO_2 ratio was ≤ 3. A CO_2/SO_2 ratio higher than this value would have resulted in a statistically significant volcanic CO_2 signal (i.e., > 1.5 ppmv) above ambient background values.

Thermal output of Mount Cleveland volcano between 2011 and 2015

Between 2011 and 2015, MIROVA detected 415 alerts at Mount Cleveland out of a total of 5270 MODIS nighttime overpasses (~7.9%). The radiant flux (or Volcanic Radiative Power, VRP) ranged from less than 1 MW to ~34 MW, with the latter value recorded on 18 November 2011 (Figure 5a). Thermal anomalies were reasonably persistent throughout the analyzed period (2011-2015) with the longest rest phase lasting 76 days (5 Oct – 20 Dec 2014; Figure 5a) and an average repose time of only ~4 days (arithmetic mean of time lapse between two consecutive thermal detections).

As discussed by Coppola et al. (2016b), the presence of clouds (or fume filling the crater) and the viewing geometry angle may affect the thermal signal detected by MODIS so that single data point(s) may be strongly attenuated. Here, we calculate the weekly average of VRP in order to compensate for the effects of attenuation due to cloud and poor geometry conditions and apply the arithmetic mean of all VRP detections in a 7-day period to all days throughout each week. In this way, we smooth sharp variations in the VRP and constrain the long term pattern of thermal output better by integrating the radiant flux only during the weeks where at least one thermal anomaly had been detected. Accordingly, we estimated that between 2011 and 2015 Mount Cleveland radiated approximately 2.1 x 10^{14} J, with a time-averaged thermal output equal to ~1.35 MW (Figure 5b). The volcanic gas measurements were made during the middle of one of the more heightened periods of activity (Figure 5a and 5c) relative to the long-term trends in thermal output.

To investigate the relationship between thermal output (cumulative VRE) and lava extrusion over a longer time period, the MIROVA thermal output data were compiled with the visual observations and the Alaska Volcano Observatory's (AVO) hazard assessments over the five year period extending from 2011− 2015 (Figure 6a-e). In these plots, the annual cumulative VRE is plotted for each year between 2011 and 2015 and compared with the visual observations of dome growth and other activity gathered from satellite[2] images (Figure 6).

Overall, the annual sum of thermal output between 2011 and 2015 was relatively constant, with the annual cumulative VRE varying by less than a factor of three over the five years (minimum of 2.2 x 10^{14} J measured in 2014 and a maximum of 5.7 x 10^{14} J measured in 2011, Figure 6). However, a closer look shows that two types of behavior can be observed in the thermal output trends: (1) overall there exists a slow increase in VRE that generally was not coincident with lava dome growth or observations of lava flows, and (2) very rapid increases in VRE that often were coincident with visual confirmation of dome growth or large accumulations of tephra in the crater (Figure 6). Nine periods of rapid VRE increase were observed (eleven

[2] Satellite data sources for visual observations include Landsat 5 TM, Worldview-2 visible wavelength satellite images, TerraSAR-X images, and occasionally International Space Station Images

periods reported in Table 2, see footnote for explanation) over the five years totaling 25 weeks together. The average duration of these rapid increases in VRE was 2.8 ± 1.6 weeks (variability here is the standard deviation), and the average rate of lava extrusion calculated was 0.28 ± 0.11 $m^3 s^{-1}$ (Table 2), which together suggest an average lava extrusion of 0.48 Mm^3 for each event. Summing the estimated lava extruded over these periods results in between 1.9 and 5.8 Mm^3 over the five years, where the range here reflects the variability induced from the range in c_{rad} (Table 2).

It requires noting that, over the five year period, while very good agreement exists between changes in thermal output and visual observations of changes in volcanic activity, not every increase in VRE was accompanied by visual confirmation of dome growth or new volcanic deposits. For instance, one period of rapid increase in November 2013 (Figure 6 and Table 2) did not have a coincident visual indication specifically of ongoing extrusion of a lava dome, rather the observations stated 'debris streaks' existed downslope of the summit (Dixon et al., 2015). There were also several periods of observed dome growth (e.g., January, April, and May, 2012 and November 2014, Figure 6) that were not accompanied by an above-average increase in VRE. In all of these cases, the extrusion was either extremely slow (e.g. growth of a 70-m diameter dome over 1 month in January, 2012 that did not result in significant increase in VRE, as compared to 70 m of growth in 3 days in March, 2012 that did register a VRE increase), small (only 25-30 m domes in April and May, 2012 and November 2014), or unconfirmed as lava (November, 2012). Despite these discrepancies, overall, reasonable confidence can be gained from our approach because (1) the majority of the events resulted in good agreement between thermal output with the visual observations of dome growth and other lava extrusion events

(Figure 6), and also (2) the specific comparison of the lava extrusion volumes obtained using equation 2 with those independently estimated by Wang et al. (2015), during the episode of dome growth that occurred in Aug−Oct 2011 (Figure 7b.). The excellent agreement between the MODIS-derived volume (this work) and those based on analysis of a series of TerraSAR-X images (Figure 7b.) suggests that the thermal proxy can provide erupted lava flux and volumes with a reasonable level of uncertainty (±50%).

Discussion.

Volcanic activity during the degassing measurements and short vs. long-term trends

The degassing measurements were made in the month following two explosive events (21 July and 7 August 2015) and a period of active dome growth (Figure 6e). On 28 July 2015, Alaska Volcano Observatory scientists reported that the very small dome, which had been growing episodically in the crater with little detectable thermal output from November 2014 through to June 2015, had been destroyed and replaced with a ~40 m diameter crater. Elevated surface temperatures in multiple satellite retrievals, and analysis of thermal output from MODIS data reported here, suggests that renewed dome growth commenced on 29 July, or roughly a week following the dome-destroying explosion (Figure 5c). FLIR thermal images of this young lava dome captured on 4 August 2015 during a helicopter overflight (Figure 8) suggest a dome diameter of 67 m based on the diameter of the crater rim, which is ~170 m across. The images also showed a central core of the new dome, which was 18 m across, and minimal degassing anywhere in the crater. The central core likely represents the vent as it was the hottest portion of the new dome with temperatures ranging from 550 to 600° C, while the rest of the dome varied between ~50 and 300° C (Figure 8a). The value of VRP measured on 4 August 2015 (2.5 MW) corresponds to a hot spot at 550°C with a diameter of ~12 m (assuming emissivity equal to 0.95), which is in reasonable agreement with FLIR measurements. Concentric growth rings and radial cooling fractures were visible in the older portion of the dome, but the hot core of the dome was slightly elevated and was not deformed, suggesting that it was very recently extruded (Figure 8b). Based on fact that the cumulative VRE increased by 0.77 x 10^{13} J during the 2 week period of dome extrusion, we estimate that between 0.16 and 0.48 Mm^3 of lava extruded during the episode (Table 2), which suggests a range in dome thickness between 45 and 136 m, assuming a cylindrical shape. While it is difficult to assess this accurately, we suggest that the values closer to the lower end of this range of thickness are most reasonable based on visual observations (Figure 8) of the dome. Satellite observations indicated that the dome was partly deflated, but mostly intact, after an explosion on 7 August 2015.

The low CO_2/SO_2 of the volcanic gas measured during the airborne measurements (≤ 3) on 15 August 2015 (Figure 4) is consistent with the presence of shallow magma in the system and the observed growth of a new lava dome in the weeks preceding the gas measurements (Figures 5 and 8) (e.g. Werner et al., 2011, Werner et al., 2013). The measured SO_2 emission rates (ranging from 400 to ~860 t d^{-1}) are similar to other active open-vent arc volcanoes with basaltic-andesite magma compositions where magma is expected very near the surface (e.g., Fuego Volcano, Rogriguez et al., 2004; White Island, Werner et al., 2008; Karymsky during a pulsatory degassing phase, Lopez et al., 2013). The emission rate of SO_2 measured during this campaign is, however, significantly higher than long-term emissions from Mount Cleveland estimated from OMI satellite data (Fioletov et al., 2016). For example, the long-term average SO_2 emission rate for 2005-2014 based on the OMI satellite measurements was ~165 t d^{-1}, whereas 2011−2014 the average SO_2 flux was slightly higher (~196 t d^{-1}). The highest SO_2 emissions from Mount Cleveland based on OMI data since 2004 were detected in 2011 (the average SO_2 flux was ~450 t d^{-1} during that year), which also happens to be the year of highest thermal output reported here. The 2015 gas measurements were made during a period of relatively high thermal output compared to the long term average (the average magma flux was 0.133 m^3 s^{-1} vs. 0.055 m^3 s^{-1}, respectively, Table 2). Thus, both the gas data presented here, and that from OMI analysis, suggest that higher SO_2 emissions correlate with periods of higher thermal output and lava extrusion.

Thermal data implications for the magma supply rate vs. lava extrusion

The calculation of extruded volumes from thermal data relies on the fundamental assumption that the heat realised by the volcanic activity is associated with the extrusion of a lava body. This assumption is clearly valid during periods of confirmed lava dome growth, as for example during August-October 2011 (Wang et al., 2015), or during the July−August 2015 period, both of which resulted in the extrusion of Mm^3 of lava (Table 2, Figure 7b). Conversely, the assumption may be incorrect during periods where the thermal anomalies are related exclusively to the presence of magma high in the conduit and the related degassing / fumarolic activity. As stressed by Coppola et al. (2013), the usage of the 4µm radiance data (MIR channel) to calculate the radiant power of active lavas (equation 1) relies on the notion that the flow surfaces at temperatures below 226−326 ^{o}C (500-600K) do not contribute substantially to the pixel-integrated MIR radiance. Accordingly, in addition to the active extrusion of lava domes, the persistently high VRP estimated at Mount Cleveland volcano over long periods must also be related to very hot temperatures in the summit crater, which we suggest are maintained by the presence of magma high in the volcanic conduit, emitting heat likely through the vent area, but without actual lava output.

In the following discussion, we address whether the thermal anomalies could be sustained by simple cooling of the emplaced lava domes, or degassing in the summit region, without the presence of magma high in the conduit. In the first case, that of the cooling of the lava dome without magma replenishment, one might expect a rapidly waning trend of thermal anomalies. For instance, Hon et al. (1994) show that lava flow surface temperatures decline exponentially and cool from > 600 ^{o}C to less than 200 ^{o}C in less than 10 hours. Similar timescales were modelled for Soufrière Hills Volcano, Montserrat, where the dome surface was modelled to cool from 830 ^{o}C to 330 ^{o}C in ~ 5 hours (Matthews et al., 2004). Even a more sophisticated modelling study that incorporated the effect of degassing through the dome rock of Soufrière Hills demonstrated that the flow surface decreased to a steady state temperature of 212 ^{o}C in less than a day (Hicks et al., 2009). In all of these cases, in the absence of new lava being present at the surface (for instance, Matthews et al. 2004 modelled the effect of reoccurring rockfalls on the dome surface temperature, which resulted in exposing hot dome rock periodically), the temperature dropped below the 226−326 ^{o}C threshold in less than a day or two. Furthermore, even following the extrusion of a 23 Mm^3 dome at Augustine Volcano in March, 2006 (Coombs et al., 2010), thermal output measured both with FLIR and by satellite remote sensing was shown to decline rapidly over the course of a week (Wessels et al., 2010; Coppola et al., 2013). These trends are opposite to the trends observed at Mount Cleveland where the heat flux and degassing appears quite steady during inter-eruptive periods (i.e. between observations of lava extrusion or explosive activity) over periods of months to years. This in turn supports the argument of a continuous supply of heat (and hence magma) to the uppermost parts of the conduit during inter-eruptive periods.

We can also consider the effect of degassing and varying the level of the magma column at other volcanoes worldwide. The best example is that of the 2007 flank eruption of Stromboli volcano, where thermal anomalies suddenly diminished (Coppola et al., 2012) after the upper 300 m of the magma column drained away (Ripepe et al., 2015). A few low sporadic thermal anomalies were detected during the following months (likely related to the cooling lava field), and during this time the SO_2 emission rate was always higher than normal (> 200t d^{-1}, Burton et al., 2008), suggesting a continuous supply of fresh magma to the conduit. However, normal thermal activity only resumed in 2008 after the level of the magma column increased and strombolian activity was once again observed at the summit craters. Therefore, Stromboli provides a clear case where the magma column level modulated the thermal flux at the surface. High degassing rates (200-600t d^{-1}), sourced by a (relatively) deep magma column (likely >300 m below the craters), were not sufficient to produce thermal anomalies at the surface. A similar pattern was also observed at Nyiragongo volcano, where copious amounts of SO_2 degassing (16 kt d^{-1}) occurred in the months following the 2002 flank eruption (Carn et al., 2004), but this activity was accompanied by weak thermal anomalies (Wright and Flynn, 2003), presumably because the magma level had dropped several hundred meters. Thermal anomalies increased only after the magma column rose again, forming the lava lake (Wright and Pilger, 2008). Thus, these examples further suggest that degassing in the absence of a shallow magma body does not produce thermal anomalies in the 4 micron band of MODIS. It is interesting to note that two periods of dome subsidence or 'drain back' were observed at Mount Cleveland in 2011 (Figure 6a), and that during these periods, there were no thermal anomalies detected. Periods of drain back are thought to be due to collapsing of a shallow foam layer at other volcanoes (Matthews et al., 1997), and this process would result in the lowering of the magma column. The above discussion further supports the notion that, during inter-eruptive periods, magma has been sustained at very shallow levels at Mount Cleveland. However, additional modelling studies are needed to assess the maximum depth of the magma column possible to produce a thermal anomaly at the surface, which likely depends on the specific context of a particular volcano.

Calculating the volume of magma present in the upper conduit is challenging. When the magma is at some depth below the surface, the observed amount of thermal flux must be produced by a magma supply rate that is higher than the apparent discharge rate if the lava were extruding. Furthermore, in the absence of dome extrusion, the parameter c_{rad} (J m^{-3}) will be lower than c_{rad} during the effusive phases (less energy will be radiated by magma stalled at some depth than from lava at the surface). For these reasons, the application of the radiant density approach (equation 2) during periods of high thermal output without lava extrusion will result in minimum estimates of the magma volume at depth required to produce the anomaly at the surface. Our data suggest that, during periods of background activity, a minimum of 0.055 m^3 s^{-1} of magma was supplied to shallow levels at Mount Cleveland to produce the steady output of 1.35 MW. This steady supply of magma to the near surface results in persistent thermal anomalies and gas output (Fioletov et al., 2016) at the surface over long periods. Integrating VRP over the entire five year period suggests that a minimum of 4.4 to 13.1 Mm^3 (average of 8 Mm^3, Figure 7a) intruded to a shallow level, which is roughly twice the total extruded volume calculated for periods coincident with observations of dome growth or other volcanic deposits (on the order of 1.9 to 5.8 Mm^3, Table 2 and Figure 6). We also note that the average rate of lava extrusion during dome growth (0.28 $m^3 s^{-1}$, Table 2) is more than 5 times that of the background magma supply rate (0.055 $m^3 s^{-1}$, Table 2). Taken together, over the five year period, we calculate that at least 2.4 -7.3 Mm^3, or at least half of the overall magma budget, likely intruded to a shallow depth beneath the edifice, but did not erupt.

It is interesting to compare rates of lava extrusion calculated for Mount Cleveland with other volcanoes globally to put the data in context. The lava extrusion rates calculated in this study (0.15 – 0.38 $m^3 s^{-1}$) are similar to those published for Merapi volcano (Indonesia) for episodes of dome growth going back to the beginning of the 20th century, where individual rates of extrusion varied between 0.01 and 0.71 $m^3 s^{-1}$ (average of 0.15 $m^3 s^{-1}$, Siswowidjoyo et al., 1995, see also Hammer et al., 2000). The long-term lava extrusion rate was slightly lower at Merapi (0.039 $m^3 s^{-1}$ for a 100-year average, Hammer et al., 2000), compared to the 5-year magma supply rate of 0.055 $m^3 s^{-1}$ at Mount Cleveland. What is also interesting about this comparison is that the rates published for Merapi were measured over months (Siswowidjoyo et al., 1995), not weeks as in the case here with Mount Cleveland. Yet, the integrated amount of lava extrusion over individual eruptive episodes between 1990 and 1992 at Merapi show similar amounts of total accumulation of extruded lava to those observed in this study (typically

≤ 8 Mm^3 in <5 years, Siswowidjoyo et al., 1995). Large eruptions in 2006 and 2010 at Merapi were accompanied by rates of lava extrusion that were much higher (1.2 and > 25 m^3 s^{-1}, respectively, Pallister et al., 2013); this is also consistent with extrusion rates at Mount Cleveland during periods in which larger eruptions occurred (e.g. 4.5 m^3 s^{-1} for the 2001 eruption, Smith, 2005). Such high extrusion rates can result in lava domes that can reach 10^6 m^3 over periods of days to months, as was the case with the 2010 eruption of Merapi (Pallister et al., 2013), and 2001 eruption of Cleveland (Smith, 2005), respectively. Another interesting comparison is with Popocatepetl volcano in Mexico (Gómez-Vazquez et al., 2016). Here, the long-term lava extrusion rates calculated during recent eruptive periods (between 1994 and 2016) vary between 0.07-0.26 m^3 s^{-1}, which are the same order of magnitude as individual periods of extrusion at Mount Cleveland (0.15 – 0.38 m^3 s^{-1}, Table 2). Yet, individual periods of lava extrusion at Popocatepetl are an order of magnitude higher (1.3 – 11.4 m^3 s^{-1}, Gómez-Vazquez et al., 2016) than those calculated here for Mount Cleveland. This finding is consistent with the overall level of degassing observed at both volcanoes, where Popocatepetl volcano produces between a factor of 3 to an order of magnitude more SO_2 than Mount Cleveland according to long-term OMI data (Fioletov et al., 2016). In comparison to more silicic volcanoes, the average rate of lava discharge during dome growth at Mount Cleveland is also lower. Examples include the 2009 eruption of Redoubt Volcano in Alaska, where minimum values of 0.6 m^3 s^{-1} were reported (Diefenbach et al., 2013), and the 1995-present eruption of Soufrière Hills volcano (minimum values of 0.5 m^3 s^{-1}, Ryan et al., 2010). Such volcanoes typically demonstrate higher rates of output over shorter durations during periods of dome growth (Gómez-Vazquez et al., 2016). Mount Cleveland is similar to Merapi and Popocatepetl volcanoes in that the episodes of dome growth and disruption are much more continuous over the long term (Ogburn et al., 2015, Gómez-Vazquez et al., 2016), suggesting a high degree of openness in the shallow plumbing system. We therefore suggest that the estimates of extrusion rate during individual periods of dome growth are reasonable in comparison to other open-system volcanoes like Merapi and Popocatepetl, and that the magma supply to the near surface may be at least twice that of the lava extruded.

Conceptual model of Mount Cleveland volcano: Implications for eruption forecasting

Mount Cleveland has been described alongside Shishaldin and Pavlof volcanoes in the central Aleutians, Alaska, as a system that sustains an open-conduit (Lu and Dzurisin, 2014). Lu and Dzurisin (2014) demonstrated a lack of measureable deformation in InSAR data prior to volcanic eruptions, and thus inferred that no appreciable shallow magma storage occurs at Mount Cleveland. This observation, in addition to the volcano producing very little background seismicity since seismic instruments were installed in July 2014, is consistent with the small volumes of extruded lava and overall low value of magma supply calculated in this study. The fact that the extrusion of lava occurs through frequent (2-3 episodes per year on average) and small-volume (~0.5 Mm^3) episodes of dome growth over periods of years (and perhaps even decades) is consistent with other volcanoes globally that exhibit steady-state open-vent volcanism with small subsurface storage volumes (Wadge, 1982, Rose et al., 2013).

This study highlights the continuous nature of volcanic activity at Mount Cleveland volcano where, over the studied period (2011−2015), the volcano experienced nearly constant thermal output and periods of quiescent dome growth interrupted by minor explosions. This type of behavior is typical of the volcanic activity that has been observed at Mount Cleveland since the last major eruption in 2001 (Herrick et al., 2014; Dixon et al., 2015). The flat and circular morphology of the 2015 dome (Figure 8) is a classic example of a dome described in the literature as a 'pancake' or axisymmetric dome (Fink and Griffiths, 1998). Lavas that form axisymmetric domes typically have the lowest yield stress of all dome-forming lavas, are typically basalt to basaltic andesite in composition, exhibit high extrusion rates relative to cooling rates, and have low viscosities (Fink and Griffiths, 1998). These characteristics limit the amount of pressure that is able to build up in the magma column, and generally result in a lower explosivity from such volcanoes, which is consistent with the minor but frequent explosive behavior observed at Mount Cleveland (Figure 6) and observations of persistent degassing in web camera and satellite images. Concentric fractures, like those visible in 2015 at Mount Cleveland (Figure 8), have been observed at Lascar volcano in Chile (Matthews et al., 1997) and at Popocatepetl in Mexico (Gómez-Vazquez et al., 2016). At Lascar, fractures were thought to result from subsidence due to foam collapse, leaving a degassed plug in the conduit which then blocked volatile escape, leading to pressurization and explosive activity (Matthews et al., 1997). At Popocatepetl, intense degassing and crystallization was suggested to increase the density of the magma so much as to reverse lava extrusion through increased draining of dense, degassed magma back into the conduit (Gómez-Vazquez et al., 2016). At Mount Cleveland, the observation of several periods between 2011 and 2015 when lava drained back into the conduit (Figure 6) supports the interpretation of the low viscosity of the lavas inferred from the morphology of the August 2015 dome. Drain back could result from either foam collapse or through intense degassing suggested in the aforementioned studies. On one occasion (in 2011) drain back was followed by an explosion as observed at Lascar volcano (Matthews et al., 1997), however more continuous data and observations during such subsidence episodes would likely be needed to further assess the specific mechanism leading to this condition.

Maintaining the persistent heat output at the summit of Mount Cleveland requires the presence of the top of the magma column at or very near the surface and a steady flow of fresh magma from depth. We speculate that this continual presence of magma near the surface and persistent degassing is most likely the result of convection within the magmatic system to very shallow levels, similar to that presented in Shinohara (2008). Most often convection is proposed for volcanoes with basaltic magma compositions (Rose et al., 2013) and those that support lava lakes (e.g. Villarrica, Witter et al., 2004; Izu-Oshima, Kasahaya et al., 1994; or Ambrym, Sheehan and Barclay, 2016), and less often for more silicic volcanoes that experience lava dome growth (e.g., Popocatepetl, Witter et al., 2005). Here, the observation of low viscosity lavas, despite the more silicic composition (57.5 wt. % SiO_2) at Mount Cleveland, supports the possibility that convection drives the continuous heat and gas output because the lava remains fluid, even after loss of volatiles. The observations at Mount Cleveland are consistent with the conceptual model of convection of silicic magmas proposed by Shinohara (2008), where persistent degassing (here degassing and thermal output) is caused by the convecting lava column. When the convecting lava column reaches the surface, part of the degassed magma can flow out as a lava dome or flow. Vulcanican explosions are explained in this model by blockages in the convective overturn in the upper conduit, which leads to overpressure due to the persistent degassing of the rising magma. Our data provide a minimum constraint on the long-term magma supply rate to the surface (0.055 m^3 s^{-1}) that is necessary to produce the observed heat flux (Coppola et al., 2013) and support the process of convection, but melt inclusion data of initial volatile contents would be needed to estimate the magma volume from the measured gas emission rates (Werner et al., 2013).

The overall lack of observed precursory geophysical signals related to explosive activity or dome growth makes eruption forecasting challenging at Mount Cleveland. The trends in thermal output (Figure 6) likewise do not provide a consistent tool for forecasting explosions or the onset of renewed dome growth. Of the 32 explosive events reported in this study, 18 were within 3 months of observed higher thermal output and dome growth, 5 were during periods of average heat output, and 9 were when the heat output was minimal. The seemingly rapid and somewhat unpredictable fluctuation between explosive and effusive behavior is likely related to the creation of blockages, as proposed by Shinohara (2008). We suggest that blockages could be formed by small changes in the ascent rate of the magma that might lead to rheological stiffening of magma as crystallization proceeds close to the surface (Sparks, 2003) and thus inhibits the ability of gas to escape. We further suggest that the extrusion of the domes could also form plugs that impede degassing, leading to explosions. Evidence for this mechanism is supported by the overall lack of degassing observed on 4 August 2015, 3 days before an explosion, compared to the degassing observed on 15 August (Figure 8). The low level of explosivity of the eruptions is likely related to the small overpressures that develop in the upper conduit due to these temporary blockages or when the lava domes reach a critical dimension (Melnik and Sparks, 1998). Modelling such behavior for Mount Cleveland explicitly, as in Girona et al., (2015) or Barmin et al. (2002), and as in Melnik and Sparks (1998) for

Soufriere Hills and other volcanoes, is beyond the scope of this study as the volcanic system is not well constrained. Fundamental parameters of these models, like the size and depth of a magma chamber, have not yet been proposed for Mount Cleveland. Still, the somewhat cyclic nature of the thermal output and eruption dynamics (Figure 5) lead us to suggest that Mount Cleveland is similar to a number of volcanoes worldwide where the periodic and pulsatory behavior is related to non-linear dynamics and the balance of magma supply rate, crystallization, and degassing. We propose that a promising tool for eruption forecasting at this volcano would be more continuous SO_2 degassing measurements, where decreases from the average emission rate values might indicate pressurization is occurring, similar to the “open and shut” case at Karymsky Volcano (Fischer et al., 2002), but on a longer timescale. In addition to emission rates, continuous and real-time measurements of gas composition (i.e. $CO_2/SO_{2,}$ where high values would be indicative of deep magmatic input) might provide valuable insight into the timing and duration of deep magmatic recharge into the shallow volcanic system. Such data have been proven to be even more valuable than emission rates for eruption forecasting at multiple volcanic systems worldwide in recent years (e.g. Stromboli Volcano, Aiuppa et al., 2009; Redoubt Volcano, Werner et al., 2013; Merapi Volcano, Surono et al., 2012, and Turrialba Volcano, deMoor et al., 2016). The only issue is that deployment and maintenance of a continuous MultiGAS instrument for monitoring purposes at the summit of Mount Cleveland would be very challenging, if not impossible, due to the associated hazards.

While the low lava discharge rates calculated from the thermal flux are consistent with the low explosive activity observed (VEI 0-2), should higher thermal output occur such that extrusion rates exceed those reported herein (> 0.3 m^3/s), a higher level of explosivity might be expected as documented for multiple volcanoes in Ogburn et al. (2015) and at Merapi Volcano in Pallister et al. (2013). Indeed the 2001 eruption of Mount Cleveland (VEI 3) was associated with lava extrusion rates that were an order of magnitude higher that the rates calculated here with peak values around 4.5 m^3/s (Smith, 2005).

Conclusions.

Mount Cleveland volcano was continuously active during 2011- 2015 as evidenced by intermittent lava extrusion and explosions, and by near continuous emission of gas observed in web camera images (https://www.avo.alaska.edu/webcam/Cleveland_CLCO.php) and OMI satellite data. The SO_2 emission rate measured in 2015 (400-860 t d^{-1}) was higher than the long-term emission rate calculated from OMI measurements (< 200 t d^{-1}), which is consistent with the fact that the 2015 gas measurements were made during a period of heightened activity characterized by explosions and dome growth. Steady and moderate thermal output indicated by MODIS satellite data suggests that there is a near constant, but low, magma flux near the surface, which is consistent with relatively low and constant output of magmatic gas. We calculate that roughly half of the overall magma volume is extruded as small lava domes in the crater, whereas the remaining magma convects in the conduit. Images of the summit area in 2015 showed a hot and axisymmetric dome, which is typical of low-viscosity basaltic-andesite lavas that do not support highly explosive eruptions. Two periods of drain back observed in the reporting period further support the inference of low viscosity magmas, where drain back could be related to collapse of a foam layer in the upper conduit, or to perhaps reversal in output due to intense degassing and convection. Mount Cleveland eruptive activity is typically characterized by the growth of small lava domes and by small Vulcanian explosions, where the transition from dome growth to explosive activity is likely related to achieving a critical, but relatively small, overpressure. Such overpressures are likely achieved when the lava dome reaches a critical dimension, or perhaps are due to small changes in the magma supply rate and reduction in the ability of magma to degas through the upper conduit due to crystallization. Such behavior is similar to other open-system basaltic-andesite volcanoes that support dome growth, such as Merapi, Karymsky, White Island, Lascar, and Popocatepetl volcanoes. It follows that the failure to achieve large overpressures would result in the overall lack of anomalous seismicity in precursory monitoring data as observed, and the low magma flux likewise results in the absence of geodetic signals related to eruptions. We suggests that Mount Cleveland, alongside other open vent volcanoes in the Aleutians such as Shishaldin and Pavlof volcanoes, would benefit from continuous monitoring of SO_2, where decreases in the open-system degassing may signal the pressurization of the volcanic system and the likely onset of explosive activity. Furthermore, should conditions allow the installation of a continuous MultiGAS instrument for monitoring of volcanic gas composition, this could provide insight into deep magmatic recharge into the volcano. Finally, the observation of thermal output or extrusion rates in excess of that reported herein might signal an increase in magma flux that might lead to more explosive eruptions than those typically observed.

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Figure Captions.

Figure 1. Location map of Mount Cleveland volcano in the Island of Four Mountains. Cleveland lies approximately 70 km west of the settlement of Nikolski, Alaska, in the Central Aleutians. Volcanoes are shown with triangles and settlements with plus symbols.

Figure 2. A time series of SO_2 emission rates measured using an upward-looking DOAS mounted on the Bell 207 Helicopter during 14-15 August 2015. See Table 1 for details of the measurements.

Figure 3. (a) Image of Mount Cleveland volcano during the measurements shown in (b). (b) Two DOAS transects where data was recorded at 1Hz and the color represents the column concentration of SO_2 measured. The plume can be clearly seen heading to the east. (c) Flight path during the dedicated gas flight where data points were recorded at 1 Hz. Data marked as DOAS transects show the column concentrations of SO_2 at each location. The transects marked as ‘in situ’ show the location where the plume was traversed and show that little SO_2 was observed in the column above these locations during the transects.

Figure 4. Time series plot of gas concentrations during the airborne measurement. SO_2 is shown in blue and shows peaks up to 0.53 ppmv during the plume transects. No volcanic CO_2 (shown in red) was observed over ambient concentrations (data shown with background concentrations subtracted, see text for more details).

Figure 5. The thermal radiant flux (VRP in MW) measured between 2011 and 2015 in MW (nighttime passes only). (a) The blue line indicates the measured values and the red line indicates the weekly averaged data between 2011 and 2015. Grey shaded areas shows periods of enhanced radiant flux that were mainly coincident with visual observation of lava extrusion over the 5 years as documented in Table 2. The dotted box shows the timeframe plotted in (c). (b) The cumulative radiant energy (VRE, in J) over the 5 years in red and the average thermal flux of 1.35 MW over this time period (dotted blue line). (c) VRE over 2015 showing the period of clearly increased thermal output due to dome growth starting on 29 July, the timing of the explosions on 21 July and 7 August, and the day the gas measurements were made.

Figure 6. The cumulative radiant energy (VRE, in J) for each individual year 2011-2015. All years have the same scale of 0-7x10^{13} J. The graphical representation of the visual observations and volcano alert levels are also shown on this graph, and are published each year by the Alaska Volcano Observatory (McGimsey et al., 2014; Herrick et al., 2014; Dixon et al., 2015; Cameron et al., 2017; Dixon et al., 2017). The color bar at the top indicates the aviation color code assigned by the Alaska Volcano Observatory which indicates the overall level of hazard to aviation at the volcano (in order from background to elevated the colors proceed from green, to yellow, to orange, to red. For more information on color code please refer to https://volcanoes.usgs.gov/vhp/about_alerts.html), grey solid bars indicate periods of dome growth and the number under the bar indicates the diameter of the dome (in m) at a given time. A '+' in front of a number indicates that there is further growth on top of a previously emplaced dome. The thin dotted grey lines connecting the periods of dome growth indicate that there was 'no change' from the previous observation as per the written reports. When no thin dotted line exists, this means the crater is free of deposits. The red stars indicate explosions detected by infrasound arrays (designated by the letter 'i'). The number written beneath the stars indicates the number of detections by infrasound, if multiple exist, in a short time frame. The blue upward-pointing arrows indicate observations of other significant volcanic deposits, and the grey upward-pointing arrows indicate when various monitoring was established or measurements made (e.g., seismic, gas). The thick dotted grey line at the bottom of the figure indicates the periods of dome growth calculated from the MODIS data as shown in Table 2.

Figure 7. The cumulative volume of lava calculated to be responsible for the thermal output during 2011-2015. The average extrusion rate implied from the trend is 0.055 $m^3 s^{-1}$, however above-average increases were observed during periods of dome growth (see Table 2). The grey bar in (a) is the period plotted in (b). (b) The dome volume estimated from our study and that by *Wang et al.* (2015).

Figure 8. (a) FLIR image of the summit dome on 4 August 2015, 3 days before an explosion and 10 days before the gas measurements. The hottest temperature recorded was 600^{o}C. (b)

Visual image of the summit dome showing strong concentric rings and an undeformed central vent. (c) FLIR image of summit area on 15 August 2015 during gas flight. (d) Visual image of crater during gas flight on 15 August 2015. See text for details.