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

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21 **Abstract.**

22 Mount Cleveland volcano (1730 m) is one of the most active volcanoes in the Aleutian arc,  
23 Alaska, but heightened activity is rarely accompanied by geophysical signals, which makes  
24 interpretation of the activity difficult. In this study, we combine volcanic gas emissions  
25 measured for the first time in August 2015 with longer-term measurements of thermal output  
26 and lava extrusion rates between 2011 and 2015 calculated from MODIS satellite data with the  
27 aim to develop a better understanding of the nature of volcanic activity at Mount Cleveland.  
28 Degassing measurements were made in the month following two explosive events (21 July and  
29 7 August, 2015) and during a period of new dome growth in the summit crater. SO<sub>2</sub> emission  
30 rates ranged from 400 to 860 t d<sup>-1</sup> and CO<sub>2</sub>/SO<sub>2</sub> ratios were <3, consistent with the presence of  
31 shallow magma in the conduit and the observed growth of a new lava dome. Thermal  
32 anomalies derived from MODIS data from 2011-2015 had an average repose time of only 4  
33 days, pointing to the continuous nature of volcanic activity at this volcano. Rapid increases in  
34 the cumulative thermal output were often coincident with visual confirmation of dome growth  
35 or accumulations of tephra in the crater. The average rate of lava extrusion calculated for 9  
36 periods of rapid increase in thermal output was 0.28 m<sup>3</sup> s<sup>-1</sup>, and the total volume extruded from  
37 2011 to 2015 was 1.9 - 5.8 Mm<sup>3</sup>. The thermal output from the lava extrusion events only  
38 accounts for roughly half of the thermal budget, suggesting a continued presence of shallow  
39 magma in the upper conduit, likely driven by convection. Axisymmetric dome morphology and  
40 occasional drain back of lava into the conduit suggests low-viscosity magmas drive volcanism at  
41 Mount Cleveland. It follows also that only small overpressures can be maintained given the  
42 small domes and fluid magmas, which is consistent with the low explosivity of most of Mount

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

51

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

54

## 55 **Introduction.**

56 Mount Cleveland volcano (52.825°N, -169.944°W, 1730 m) is an andesitic stratovolcano  
57 and one of the most active volcanoes in the Aleutian arc, having had eruptive activity recorded  
58 every year since 2005 (Herrick et al., 2014, Dixon et al., 2015, Cameron et al., 2017; Dixon et al.,  
59 2017). The volcano is part of a complex of volcanic centers called the Islands of Four Mountains  
60 (IFM), and lies about 1500 km SW of Anchorage, Alaska (Figure 1). Mount Cleveland's remote  
61 location makes volcano monitoring, and thus characterizing the magmatic processes leading to  
62 various volcanic behaviors, a real challenge. Permanent geophysical instrumentation and a web  
63 camera were only installed in mid-2014. Thus, until recently, eruptions and changes in activity

64 were almost exclusively detected using satellite data and from pilot reports (McGimsey et al.,  
65 2014). Since late 2011, distant infrasound arrays proved very useful for detecting explosions  
66 (De Angelis et al., 2012; Dixon et al., 2015), but of the explosions since 2014, none have been  
67 accompanied by enhanced seismicity recorded by permanent seismic monitoring stations.

68         The observations of eruptive activity and the appearance of the crater area and volcanic  
69 deposits at Mount Cleveland are documented in the Alaska Volcano Observatory's annual  
70 reports for years 2011-2015 (McGimsey et al., 2014; Herrick et al., 2014; Dixon et al., 2015;  
71 Cameron et al., 2017; Dixon et al., 2017). During this period, the activity was characterized by  
72 elevated temperatures and nearly-continuous degassing, intermittent minor explosions (often  
73 accompanied by limited tephra deposits in the summit crater), and dome growth. In most  
74 years, the emplaced domes would be completely destroyed in subsequent explosions (see  
75 Herrick et al., 2014, for a good example), but on two occasions, in 2011 and 2014, the recently  
76 emplaced domes were observed to deflate, or drain back, into the conduit. Sometimes these  
77 periods of subsidence were marked by ring fractures around the crater walls (McGimsey et al.,  
78 2014). Typically no activity would be observed in the summit crater during periods with no  
79 other indication of heightened volcanism (e.g. thermal anomalies). Satellite images suggest  
80 that the central crater is often funnel shaped when a dome is not present, and in many years  
81 the active vent area is visible as a central pit that varies from ~ 10-30 m in diameter at the  
82 surface, either in the center of the dome or pit. Satellite data also indicate that small lava flows  
83 sometimes extend several hundred meters down the flanks of the volcano, but more often  
84 flank deposits are described as patchy or as a dusting of ash, rather than extensive in nature  
85 (Herrick et al., 2014).

86           Since the installation of a web camera on nearby Chuginadak Island in 2014  
87 ([https://www.avo.alaska.edu/webcam/Cleveland\\_CLCO.php](https://www.avo.alaska.edu/webcam/Cleveland_CLCO.php)), the volcano is often observed  
88 emitting a low-altitude volcanic plume, and occasionally more robust plumes that extend 10s of  
89 km downwind of the volcano are observed both in web camera images and satellite data.  
90 While the majority of eruptive activity at Mount Cleveland is minor (VEI 0-2), major ash  
91 producing eruptions (VEI 3+) pose a threat to aviation and are a hazard in the region. Between  
92 1970 and 2008 there were 14 eruptions from Mount Cleveland in which the ash cloud extended  
93 to greater than 5 km height (VEI 3) above sea level (ASL) (Dean et al., 2015; Dean et al., 2004).  
94 In one of the most recent major eruptions of Mount Cleveland in 2001, three explosive events  
95 resulted in ash clouds that rose 12 km (39,000 ft) ASL (Dean et al., 2004). This eruption resulted  
96 in one documented non-damaging encounter between an aircraft and the volcanic cloud in the  
97 vicinity of San Francisco, California (Simpson et al., 2002; Guffanti et al., 2010).

98           Here, we report the first measurements of volcanic gas composition and emission rates  
99 ever made at Mount Cleveland volcano, and compare with the longer-term record of degassing  
100 obtained from OMI (Ozone Monitoring Instrument) satellite data (Fioletov et al., 2016). The on-  
101 site measurements were obtained during a campaign to the central Aleutians in mid-August  
102 2015. To place these measurements in a broader volcanic context, we analyze MODIS  
103 (Moderate Resolution Imaging Spectroradiometer) satellite data to assess thermal output and  
104 estimate lava extrusion rates over the last five years (2011-2015). Thermal signatures are  
105 compared to visual observations of volcanic activity from satellite data, and specific periods of  
106 lava extrusion are quantified. Through merging observations from these multiple data streams,

107 we formulate a conceptual model to explain shallow magmatic behavior for Mount Cleveland  
108 volcano that places Mount Cleveland in a broader context of open-system volcanoes globally.

109

## 110 **Methods.**

### 111 *Airborne Volcanic Gas Measurements.*

112 Measurements of SO<sub>2</sub> column concentrations were made using an upward-looking  
113 miniature DOAS (Differential Optical Absorption Spectroscopy) system. A small telescope  
114 mounted to the helicopter window collected scattered solar ultraviolet radiation from above  
115 the aircraft. A fused silica fiber optic cable coupled the light into an Ocean Optics USB2000+  
116 spectrometer located inside the helicopter. Using a laptop computer, spectral data were  
117 acquired between 285 and 430 nm at 0.6 nm resolution and approximately 1 Hz, and the  
118 instrument position was tracked using a Garmin 18x PC GPS receiver. The system was powered  
119 by an external 12 V battery to allow continuous operation throughout the day. In this manner,  
120 DOAS measurements were made during dedicated gas flights, but data were also collected  
121 during chance under-flights of the volcanic plume as the helicopter was performing other tasks  
122 (see below).

123 In situ gas compositions (H<sub>2</sub>O, CO<sub>2</sub>, SO<sub>2</sub>, H<sub>2</sub>S) were measured using a U.S. Geological  
124 Survey (USGS) Multi-GAS instrument that included an integrated GPS receiver (Garmin GPS 18x  
125 LVC), a non-dispersive infrared CO<sub>2</sub> and H<sub>2</sub>O analyzer (LI-COR, Inc. LI-840A, 0-5000 ppm for CO<sub>2</sub>,  
126 0-80 parts per thousand for H<sub>2</sub>O), and electrochemical SO<sub>2</sub> (City Technology, Ltd., 2T3STF, 0-100

127 ppm) and H<sub>2</sub>S sensors (City Technology, Ltd., EZT3H, 0-100 ppm). All data were logged at 1 Hz  
128 to the Multi-GAS datalogger (Campbell Scientific, CR1000) and displayed in real time with a  
129 tablet. An ideal gas-type correction for pressure and temperature was applied to the SO<sub>2</sub> and  
130 H<sub>2</sub>S sensor data, and the raw CO<sub>2</sub> signal was filtered using a digital single-pole recursive lowpass  
131 filter to better match the SO<sub>2</sub> and H<sub>2</sub>S sensor responses. Portable calibration gases (3000 ppm  
132 CO<sub>2</sub>, 10 and 2 ppm SO<sub>2</sub>, and 10 and 2 ppm H<sub>2</sub>S) were used to assess sensor responses in the  
133 field. All sensors were observed to be accurate within 10% of the standard values during the  
134 field campaign.

135           Gas measurements were made using two modes of operation on 14–15 August 2015.  
136 The majority of the DOAS data were collected when the helicopter traversed beneath the  
137 plume when shuttling back and forth to various field sites around the volcano from the  
138 Maritime Maid research vessel, from which all operations were based. Ten of the traverses  
139 were collected in this manner; the remaining five were collected during a dedicated gas flight  
140 (Table 1). One traverse during the gas flight likely missed part of the plume and is not included  
141 in the analysis, but it is retained in Table 1 for completeness. A dedicated gas flight was  
142 performed on 15 August to collect in situ gas concentrations of the volcanic plume. The  
143 majority of the in situ traverses were made at ~2.5 km downwind of the summit, and the entire  
144 flight covered an altitude range of sea level to 2500 m ASL; the plume was intersected between  
145 1500 and 1800 m ASL. Wind speed was measured directly at plume height during the gas flight  
146 measurements (Table 1). The remaining traverses relied on other methods to assess plume  
147 speed as detailed in Table 1.



148 *Thermal Infrared Imaging.*

149 Thermal images of the summit area and young lava dome were captured on 4 and 15  
150 August 2015 during helicopter flights using a FLIR® Systems model SC620 camera with a 640 x  
151 480 image size. The average air temperature was 6°C during the first flight and 8°C during the  
152 second flight. The slant distance between the dome and camera was ~1 km. Temperatures  
153 were calculated from the thermal images after applying an atmospheric correction and using an  
154 emissivity of 0.95. Maximum pixel temperatures of 550-600°C were recorded around the  
155 center of the dome in fume-free images on 4 August. Maximum dome temperatures recorded  
156 on 15 August were 450-500°C, but fume filled the crater and may have attenuated some of the  
157 thermal signal, and thus these values are minimum estimates.

158 *Thermal Output and Lava Extrusion: MODIS-MIROVA Analysis*

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

168 Thermal flux was calculated by using the ‘MiddleInfraRed’ method (Wooster et al.,  
169 2003), according to which the radiant power of a sub-pixel hot source is proportional to the  
170 “above background” middle infrared (MIR) radiance:

$$171 \quad VRP_{PIX} = 18.9 \times A_{PIX} \times (L_{4alert} - L_{4bk}) \quad [1]$$

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

182 Different approaches have been developed to estimate heat flux and lava discharge  
183 from thermal satellite data, but the basic principle of these methods relies on a mutual  
184 relationship between effusion rates, the active flow area, and the thermal flux (Pieri and  
185 Baloga, 1986; Wright et al., 2001; Harris and Baloga 2009; Harris, 2013 and references therein).  
186 In particular, Coppola et al. (2013) showed that for a given eruptive case, the thermal energy  
187 radiated ( $VRE$ ) can be related to the erupted lava volume ( $Vol$ ) through a unique empirical  
188 parameter (called radiant density;  $c_{rad}$ ) that takes into account the appropriate rheological,

189 insulation, and topographic conditions for the studied lava body. The volume of an actively-  
190 extruded lava body ( $Vol$ ,  $m^{-3}$ ) is related to the  $VRE$  (in J) such that,

$$191 \quad Vol = \frac{VRE}{c_{rad}} \quad [2]$$

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

$$198 \quad c_{rad} = 6.45 \times 10^{25} \times (X_{SiO_2})^{-10.4} \quad [3]$$

199 where  $X_{SiO_2}$  is the silica content of the erupted lavas (wt. %). For the Mount Cleveland basaltic-  
200 andesite, expected silica contents of the active lava extrusion are on the order of  $X_{SiO_2}=57.5$  wt.  
201 % based on past eruptions (K. Nicholyasen, personal communication) which results in a  
202 calculated radiant density ( $c_{rad}$ ) of  $3.7 \times 10^7$ , or between  $1.6$  and  $4.8 \times 10^7$  considering the  $\pm 50\%$   
203 accuracy of the empirical fit. The values calculated for Mount Cleveland are similar to those  
204 obtained for the andesitic lava plug of Ubinas Volcano in Peru (Coppola et al., 2015) and the  
205 relatively low-viscosity dacitic lava flow of Nevados de Chillan Volcano in Chile (Coppola et al.,  
206 2016b).

207

## 208 **Results**

209 *Airborne gas measurements.*

210 Fourteen airborne measurements of SO<sub>2</sub> emission rate were made on 14 – 15 August,  
211 2015. DOAS transects were made between 3.8 and 6.4 km from the vent (Figure 2) and  
212 maximum column concentrations<sup>1</sup> ranged from 124 to 320 ppm·m SO<sub>2</sub> (Table 1). The winds  
213 were consistently out of the west and wind speeds ranged from 9 to 12 m s<sup>-1</sup>. The  
214 measurements resulted in SO<sub>2</sub> emission rates that varied from 4.7 to 10.0 kg s<sup>-1</sup> or from ~400 to  
215 860 t d<sup>-1</sup> SO<sub>2</sub> (Table 1, Figure 3), and the measurements made on 14 August show a steady  
216 decline in emissions from ~800 to 400 t d<sup>-1</sup> SO<sub>2</sub> over a five hour period. The highest column  
217 concentrations and emission rates were made when the sky was completely cloud free (Table 1  
218 and Figures 2a and 2c). The five measurements made during the gas flight were along transects  
219 that progressively increased in altitude such that the final traverse was made directly beneath  
220 the plume. These measurements together show less variation than the measurements made  
221 over the 2-day period (Figure 3), suggesting that no systematic variation was introduced from  
222 light scattering when flying at different altitudes beneath the plume over the two days of  
223 measurement. The average SO<sub>2</sub> emission rate derived from all the measurements during the  
224 campaign (except the one where a portion of the plume was missed, Table 1) was 6.9 ± 0.5 kg s<sup>-1</sup>  
225 <sup>1</sup>, or 600 ± 39 t d<sup>-1</sup> SO<sub>2</sub>, where the error indicated here is standard error of the mean.

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

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

230 was 0.53 ppmv during the traverses (Figure 4), but no discernable volcanic CO<sub>2</sub> signal was  
231 detected over ambient background levels and the instrumental noise ( $\pm 0.5$  ppmv,  $1\sigma$ ).  
232 Likewise, volcanic H<sub>2</sub>O could not be resolved above atmospheric background and no H<sub>2</sub>S was  
233 detected. If we define the CO<sub>2</sub> detection limit as 3 times the noise of the analyzer (i.e.  $3\sigma$ ; 1.5  
234 ppmv), then the data suggest that the molar CO<sub>2</sub>/SO<sub>2</sub> ratio was  $\leq 3$ . A CO<sub>2</sub>/SO<sub>2</sub> ratio higher than  
235 this value would have resulted in a statistically significant volcanic CO<sub>2</sub> signal (i.e.,  $> 1.5$  ppmv)  
236 above ambient background values.

### 237 *Thermal output of Mount Cleveland volcano between 2011 and 2015*

238 Between 2011 and 2015, MIROVA detected 415 alerts at Mount Cleveland out of a total  
239 of 5270 MODIS nighttime overpasses ( $\sim 7.9\%$ ). The radiant flux (or Volcanic Radiative Power,  
240 VRP) ranged from less than 1 MW to  $\sim 34$  MW, with the latter value recorded on 18 November  
241 2011 (Figure 5a). Thermal anomalies were reasonably persistent throughout the analyzed  
242 period (2011-2015) with the longest rest phase lasting 76 days (5 Oct – 20 Dec 2014; Figure 5a)  
243 and an average repose time of only  $\sim 4$  days (arithmetic mean of time lapse between two  
244 consecutive thermal detections).

245 As discussed by Coppola et al. (2016b), the presence of clouds (or fume filling the crater)  
246 and the viewing geometry angle may affect the thermal signal detected by MODIS so that single  
247 data point(s) may be strongly attenuated. Here, we calculate the weekly average of VRP in  
248 order to compensate for the effects of attenuation due to cloud and poor geometry conditions  
249 and apply the arithmetic mean of all VRP detections in a 7-day period to all days throughout  
250 each week. In this way, we smooth sharp variations in the VRP and constrain the long term

251 pattern of thermal output better by integrating the radiant flux only during the weeks where at  
252 least one thermal anomaly had been detected. Accordingly, we estimated that between 2011  
253 and 2015 Mount Cleveland radiated approximately  $2.1 \times 10^{14}$  J, with a time-averaged thermal  
254 output equal to  $\sim 1.35$  MW (Figure 5b). The volcanic gas measurements were made during the  
255 middle of one of the more heightened periods of activity (Figure 5a and 5c) relative to the long-  
256 term trends in thermal output.

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

263 Overall, the annual sum of thermal output between 2011 and 2015 was relatively  
264 constant, with the annual cumulative VRE varying by less than a factor of three over the five  
265 years (minimum of  $2.2 \times 10^{14}$  J measured in 2014 and a maximum of  $5.7 \times 10^{14}$  J measured in  
266 2011, Figure 6). However, a closer look shows that two types of behavior can be observed in  
267 the thermal output trends: (1) overall there exists a slow increase in VRE that generally was not  
268 coincident with lava dome growth or observations of lava flows, and (2) very rapid increases in  
269 VRE that often were coincident with visual confirmation of dome growth or large accumulations  
270 of tephra in the crater (Figure 6). Nine periods of rapid VRE increase were observed (eleven

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<sup>2</sup> 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

271 periods reported in Table 2, see footnote for explanation) over the five years totaling 25 weeks  
272 together. The average duration of these rapid increases in VRE was  $2.8 \pm 1.6$  weeks (variability  
273 here is the standard deviation), and the average rate of lava extrusion calculated was  $0.28 \pm$   
274  $0.11 \text{ m}^3 \text{ s}^{-1}$  (Table 2), which together suggest an average lava extrusion of  $0.48 \text{ Mm}^3$  for each  
275 event. Summing the estimated lava extruded over these periods results in between 1.9 and 5.8  
276  $\text{Mm}^3$  over the five years, where the range here reflects the variability induced from the range in  
277  $c_{rad}$  (Table 2).

278 It requires noting that, over the five year period, while very good agreement exists  
279 between changes in thermal output and visual observations of changes in volcanic activity, not  
280 every increase in VRE was accompanied by visual confirmation of dome growth or new volcanic  
281 deposits. For instance, one period of rapid increase in November 2013 (Figure 6 and Table 2)  
282 did not have a coincident visual indication specifically of ongoing extrusion of a lava dome,  
283 rather the observations stated 'debris streaks' existed downslope of the summit (Dixon et al.,  
284 2015). There were also several periods of observed dome growth (e.g., January, April, and May,  
285 2012 and November 2014, Figure 6) that were not accompanied by an above-average increase  
286 in VRE. In all of these cases, the extrusion was either extremely slow (e.g. growth of a 70-m  
287 diameter dome over 1 month in January, 2012 that did not result in significant increase in VRE,  
288 as compared to 70 m of growth in 3 days in March, 2012 that did register a VRE increase), small  
289 (only 25-30 m domes in April and May, 2012 and November 2014), or unconfirmed as lava  
290 (November, 2012). Despite these discrepancies, overall, reasonable confidence can be gained  
291 from our approach because (1) the majority of the events resulted in good agreement between  
292 thermal output with the visual observations of dome growth and other lava extrusion events

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

299

## 300 **Discussion.**

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

302 The degassing measurements were made in the month following two explosive events  
303 (21 July and 7 August 2015) and a period of active dome growth (Figure 6e). On 28 July 2015,  
304 Alaska Volcano Observatory scientists reported that the very small dome, which had been  
305 growing episodically in the crater with little detectable thermal output from November 2014  
306 through to June 2015, had been destroyed and replaced with a  $\sim 40$  m diameter crater.  
307 Elevated surface temperatures in multiple satellite retrievals, and analysis of thermal output  
308 from MODIS data reported here, suggests that renewed dome growth commenced on 29 July,  
309 or roughly a week following the dome-destroying explosion (Figure 5c). FLIR thermal images of  
310 this young lava dome captured on 4 August 2015 during a helicopter overflight (Figure 8)  
311 suggest a dome diameter of 67 m based on the diameter of the crater rim, which is  $\sim 170$  m  
312 across. The images also showed a central core of the new dome, which was 18 m across, and  
313 minimal degassing anywhere in the crater. The central core likely represents the vent as it was



314 the hottest portion of the new dome with temperatures ranging from 550 to 600° C, while the  
315 rest of the dome varied between ~50 and 300° C (Figure 8a). The value of VRP measured on 4  
316 August 2015 (2.5 MW) corresponds to a hot spot at 550°C with a diameter of ~12 m (assuming  
317 emissivity equal to 0.95), which is in reasonable agreement with FLIR measurements.  
318 Concentric growth rings and radial cooling fractures were visible in the older portion of the  
319 dome, but the hot core of the dome was slightly elevated and was not deformed, suggesting  
320 that it was very recently extruded (Figure 8b). Based on fact that the cumulative VRE increased  
321 by  $0.77 \times 10^{13}$  J during the 2 week period of dome extrusion, we estimate that between 0.16  
322 and  $0.48 \text{ Mm}^3$  of lava extruded during the episode (Table 2), which suggests a range in dome  
323 thickness between 45 and 136 m, assuming a cylindrical shape. While it is difficult to assess  
324 this accurately, we suggest that the values closer to the lower end of this range of thickness are  
325 most reasonable based on visual observations (Figure 8) of the dome. Satellite observations  
326 indicated that the dome was partly deflated, but mostly intact, after an explosion on 7 August  
327 2015.

328         The low  $\text{CO}_2/\text{SO}_2$  of the volcanic gas measured during the airborne measurements ( $\leq 3$ )  
329 on 15 August 2015 (Figure 4) is consistent with the presence of shallow magma in the system  
330 and the observed growth of a new lava dome in the weeks preceding the gas measurements  
331 (Figures 5 and 8) (e.g. Werner et al., 2011, Werner et al., 2013). The measured  $\text{SO}_2$  emission  
332 rates (ranging from 400 to  $\sim 860 \text{ t d}^{-1}$ ) are similar to other active open-vent arc volcanoes with  
333 basaltic-andesite magma compositions where magma is expected very near the surface (e.g.,  
334 Fuego Volcano, Rogriguez et al., 2004; White Island, Werner et al., 2008; Karymsky during a  
335 pulsatory degassing phase, Lopez et al., 2013). The emission rate of  $\text{SO}_2$  measured during this

336 campaign is, however, significantly higher than long-term emissions from Mount Cleveland  
337 estimated from OMI satellite data (Fioletov et al., 2016). For example, the long-term average  
338 SO<sub>2</sub> emission rate for 2005-2014 based on the OMI satellite measurements was ~165 t d<sup>-1</sup>,  
339 whereas 2011–2014 the average SO<sub>2</sub> flux was slightly higher (~196 t d<sup>-1</sup>). The highest SO<sub>2</sub>  
340 emissions from Mount Cleveland based on OMI data since 2004 were detected in 2011 (the  
341 average SO<sub>2</sub> flux was ~450 t d<sup>-1</sup> during that year), which also happens to be the year of highest  
342 thermal output reported here. The 2015 gas measurements were made during a period of  
343 relatively high thermal output compared to the long term average (the average magma flux was  
344 0.133 m<sup>3</sup> s<sup>-1</sup> vs. 0.055 m<sup>3</sup> s<sup>-1</sup>, respectively, Table 2). Thus, both the gas data presented here, and  
345 that from OMI analysis, suggest that higher SO<sub>2</sub> emissions correlate with periods of higher  
346 thermal output and lava extrusion.

347

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

349 The calculation of extruded volumes from thermal data relies on the fundamental  
350 assumption that the heat realised by the volcanic activity is associated with the extrusion of a  
351 lava body. This assumption is clearly valid during periods of confirmed lava dome growth, as for  
352 example during August-October 2011 (Wang et al., 2015), or during the July–August 2015  
353 period, both of which resulted in the extrusion of Mm<sup>3</sup> of lava (Table 2, Figure 7b). Conversely,  
354 the assumption may be incorrect during periods where the thermal anomalies are related  
355 exclusively to the presence of magma high in the conduit and the related degassing / fumarolic  
356 activity. As stressed by Coppola et al. (2013), the usage of the 4µm radiance data (MIR channel)  
357 to calculate the radiant power of active lavas (equation 1) relies on the notion that the flow

358 surfaces at temperatures below 226–326 °C (500-600K) do not contribute substantially to the  
359 pixel-integrated MIR radiance. Accordingly, in addition to the active extrusion of lava domes,  
360 the persistently high VRP estimated at Mount Cleveland volcano over long periods must also be  
361 related to very hot temperatures in the summit crater, which we suggest are maintained by the  
362 presence of magma high in the volcanic conduit, emitting heat likely through the vent area, but  
363 without actual lava output.

364 In the following discussion, we address whether the thermal anomalies could be  
365 sustained by simple cooling of the emplaced lava domes, or degassing in the summit region,  
366 without the presence of magma high in the conduit. In the first case, that of the cooling of the  
367 lava dome without magma replenishment, one might expect a rapidly waning trend of thermal  
368 anomalies. For instance, Hon et al. (1994) show that lava flow surface temperatures decline  
369 exponentially and cool from > 600 °C to less than 200 °C in less than 10 hours. Similar  
370 timescales were modelled for Soufrière Hills Volcano, Montserrat, where the dome surface was  
371 modelled to cool from 830 °C to 330 °C in ~ 5 hours (Matthews et al., 2004). Even a more  
372 sophisticated modelling study that incorporated the effect of degassing through the dome rock  
373 of Soufrière Hills demonstrated that the flow surface decreased to a steady state temperature  
374 of 212 °C in less than a day (Hicks et al., 2009). In all of these cases, in the absence of new lava  
375 being present at the surface (for instance, Matthews et al. 2004 modelled the effect of  
376 reoccurring rockfalls on the dome surface temperature, which resulted in exposing hot dome  
377 rock periodically), the temperature dropped below the 226–326 °C threshold in less than a day  
378 or two. Furthermore, even following the extrusion of a 23 Mm<sup>3</sup> dome at Augustine Volcano in  
379 March, 2006 (Coombs et al., 2010), thermal output measured both with FLIR and by satellite

380 remote sensing was shown to decline rapidly over the course of a week (Wessels et al., 2010;  
381 Coppola et al., 2013). These trends are opposite to the trends observed at Mount Cleveland  
382 where the heat flux and degassing appears quite steady during inter-eruptive periods (i.e.  
383 between observations of lava extrusion or explosive activity) over periods of months to years.  
384 This in turn supports the argument of a continuous supply of heat (and hence magma) to the  
385 uppermost parts of the conduit during inter-eruptive periods.

386 We can also consider the effect of degassing and varying the level of the magma column  
387 at other volcanoes worldwide. The best example is that of the 2007 flank eruption of Stromboli  
388 volcano, where thermal anomalies suddenly diminished (Coppola et al., 2012) after the upper  
389 300 m of the magma column drained away (Ripepe et al., 2015). A few low sporadic thermal  
390 anomalies were detected during the following months (likely related to the cooling lava field),  
391 and during this time the SO<sub>2</sub> emission rate was always higher than normal ( $> 200\text{t d}^{-1}$ , Burton et  
392 al., 2008), suggesting a continuous supply of fresh magma to the conduit. However, normal  
393 thermal activity only resumed in 2008 after the level of the magma column increased and  
394 strombolian activity was once again observed at the summit craters. Therefore, Stromboli  
395 provides a clear case where the magma column level modulated the thermal flux at the surface.  
396 High degassing rates ( $200\text{-}600\text{t d}^{-1}$ ), sourced by a (relatively) deep magma column (likely  $>300$   
397 m below the craters), were not sufficient to produce thermal anomalies at the surface. A  
398 similar pattern was also observed at Nyiragongo volcano, where copious amounts of SO<sub>2</sub>  
399 degassing ( $16\text{ kt d}^{-1}$ ) occurred in the months following the 2002 flank eruption (Carn et al.,  
400 2004), but this activity was accompanied by weak thermal anomalies (Wright and Flynn, 2003),  
401 presumably because the magma level had dropped several hundred meters. Thermal anomalies

402 increased only after the magma column rose again, forming the lava lake (Wright and Pilger,  
403 2008). Thus, these examples further suggest that degassing in the absence of a shallow magma  
404 body does not produce thermal anomalies in the 4 micron band of MODIS. It is interesting to  
405 note that two periods of dome subsidence or 'drain back' were observed at Mount Cleveland in  
406 2011 (Figure 6a), and that during these periods, there were no thermal anomalies detected.  
407 Periods of drain back are thought to be due to collapsing of a shallow foam layer at other  
408 volcanoes (Matthews et al., 1997), and this process would result in the lowering of the magma  
409 column. The above discussion further supports the notion that, during inter-eruptive periods,  
410 magma has been sustained at very shallow levels at Mount Cleveland. However, additional  
411 modelling studies are needed to assess the maximum depth of the magma column possible to  
412 produce a thermal anomaly at the surface, which likely depends on the specific context of a  
413 particular volcano.

414         Calculating the volume of magma present in the upper conduit is challenging. When the  
415 magma is at some depth below the surface, the observed amount of thermal flux must be  
416 produced by a magma supply rate that is higher than the apparent discharge rate if the lava  
417 were extruding. Furthermore, in the absence of dome extrusion, the parameter  $c_{rad}$  ( $J m^{-3}$ ) will  
418 be lower than  $c_{rad}$  during the effusive phases (less energy will be radiated by magma stalled at  
419 some depth than from lava at the surface). For these reasons, the application of the radiant  
420 density approach (equation 2) during periods of high thermal output without lava extrusion will  
421 result in minimum estimates of the magma volume at depth required to produce the anomaly  
422 at the surface. Our data suggest that, during periods of background activity, a minimum of  
423  $0.055 m^3 s^{-1}$  of magma was supplied to shallow levels at Mount Cleveland to produce the steady

424 output of 1.35 MW. This steady supply of magma to the near surface results in persistent  
425 thermal anomalies and gas output (Fioletov et al., 2016) at the surface over long periods.  
426 Integrating VRP over the entire five year period suggests that a minimum of 4.4 to 13.1 Mm<sup>3</sup>  
427 (average of 8 Mm<sup>3</sup>, Figure 7a) intruded to a shallow level, which is roughly twice the total  
428 extruded volume calculated for periods coincident with observations of dome growth or other  
429 volcanic deposits (on the order of 1.9 to 5.8 Mm<sup>3</sup>, Table 2 and Figure 6). We also note that the  
430 average rate of lava extrusion during dome growth (0.28 m<sup>3</sup> s<sup>-1</sup>, Table 2) is more than 5 times  
431 that of the background magma supply rate (0.055 m<sup>3</sup> s<sup>-1</sup>, Table 2). Taken together, over the five  
432 year period, we calculate that at least 2.4 -7.3 Mm<sup>3</sup>, or at least half of the overall magma  
433 budget, likely intruded to a shallow depth beneath the edifice, but did not erupt.

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

446  $\leq 8 \text{ Mm}^3$  in  $<5$  years, Siswamidjono et al., 1995). Large eruptions in 2006 and 2010 at Merapi  
447 were accompanied by rates of lava extrusion that were much higher ( $1.2$  and  $> 25 \text{ m}^3 \text{ s}^{-1}$ ,  
448 respectively, Pallister et al., 2013); this is also consistent with extrusion rates at Mount  
449 Cleveland during periods in which larger eruptions occurred (e.g.  $4.5 \text{ m}^3 \text{ s}^{-1}$  for the 2001  
450 eruption, Smith, 2005). Such high extrusion rates can result in lava domes that can reach  $10^6$   
451  $\text{m}^3$  over periods of days to months, as was the case with the 2010 eruption of Merapi (Pallister  
452 et al., 2013), and 2001 eruption of Cleveland (Smith, 2005), respectively. Another interesting  
453 comparison is with Popocatepetl volcano in Mexico (Gómez-Vázquez et al., 2016). Here, the  
454 long-term lava extrusion rates calculated during recent eruptive periods (between 1994 and  
455 2016) vary between  $0.07$ - $0.26 \text{ m}^3 \text{ s}^{-1}$ , which are the same order of magnitude as individual  
456 periods of extrusion at Mount Cleveland ( $0.15 - 0.38 \text{ m}^3 \text{ s}^{-1}$ , Table 2). Yet, individual periods of  
457 lava extrusion at Popocatepetl are an order of magnitude higher ( $1.3 - 11.4 \text{ m}^3 \text{ s}^{-1}$ , Gómez-  
458 Vázquez et al., 2016) than those calculated here for Mount Cleveland. This finding is consistent  
459 with the overall level of degassing observed at both volcanoes, where Popocatepetl volcano  
460 produces between a factor of 3 to an order of magnitude more  $\text{SO}_2$  than Mount Cleveland  
461 according to long-term OMI data (Fioletov et al., 2016). In comparison to more silicic  
462 volcanoes, the average rate of lava discharge during dome growth at Mount Cleveland is also  
463 lower. Examples include the 2009 eruption of Redoubt Volcano in Alaska, where minimum  
464 values of  $0.6 \text{ m}^3 \text{ s}^{-1}$  were reported (Diefenbach et al., 2013), and the 1995-present eruption of  
465 Soufrière Hills volcano (minimum values of  $0.5 \text{ m}^3 \text{ s}^{-1}$ , Ryan et al., 2010). Such volcanoes  
466 typically demonstrate higher rates of output over shorter durations during periods of dome  
467 growth (Gómez-Vázquez et al., 2016). Mount Cleveland is similar to Merapi and Popocatepetl

468 volcanoes in that the episodes of dome growth and disruption are much more continuous over  
469 the long term (Ogburn et al., 2015, Gómez-Vazquez et al., 2016), suggesting a high degree of  
470 openness in the shallow plumbing system. We therefore suggest that the estimates of extrusion  
471 rate during individual periods of dome growth are reasonable in comparison to other open-  
472 system volcanoes like Merapi and Popocatepetl, and that the magma supply to the near surface  
473 may be at least twice that of the lava extruded.

474

#### 475 *Conceptual model of Mount Cleveland volcano: Implications for eruption forecasting*

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

487 This study highlights the continuous nature of volcanic activity at Mount Cleveland  
488 volcano where, over the studied period (2011–2015), the volcano experienced nearly constant  
489 thermal output and periods of quiescent dome growth interrupted by minor explosions. This



490 type of behavior is typical of the volcanic activity that has been observed at Mount Cleveland  
491 since the last major eruption in 2001 (Herrick et al., 2014; Dixon et al., 2015). The flat and  
492 circular morphology of the 2015 dome (Figure 8) is a classic example of a dome described in the  
493 literature as a 'pancake' or axisymmetric dome (Fink and Griffiths, 1998). Lavas that form  
494 axisymmetric domes typically have the lowest yield stress of all dome-forming lavas, are  
495 typically basalt to basaltic andesite in composition, exhibit high extrusion rates relative to  
496 cooling rates, and have low viscosities (Fink and Griffiths, 1998). These characteristics limit the  
497 amount of pressure that is able to build up in the magma column, and generally result in a  
498 lower explosivity from such volcanoes, which is consistent with the minor but frequent  
499 explosive behavior observed at Mount Cleveland (Figure 6) and observations of persistent  
500 degassing in web camera and satellite images. Concentric fractures, like those visible in 2015 at  
501 Mount Cleveland (Figure 8), have been observed at Lascar volcano in Chile (Matthews et al.,  
502 1997) and at Popocatepetl in Mexico (Gómez-Vázquez et al., 2016). At Lascar, fractures were  
503 thought to result from subsidence due to foam collapse, leaving a degassed plug in the conduit  
504 which then blocked volatile escape, leading to pressurization and explosive activity (Matthews  
505 et al., 1997). At Popocatepetl, intense degassing and crystallization was suggested to increase  
506 the density of the magma so much as to reverse lava extrusion through increased draining of  
507 dense, degassed magma back into the conduit (Gómez-Vázquez et al., 2016). At Mount  
508 Cleveland, the observation of several periods between 2011 and 2015 when lava drained back  
509 into the conduit (Figure 6) supports the interpretation of the low viscosity of the lavas inferred  
510 from the morphology of the August 2015 dome. Drain back could result from either foam  
511 collapse or through intense degassing suggested in the aforementioned studies. On one

512 occasion (in 2011) drain back was followed by an explosion as observed at Lascar volcano  
513 (Matthews et al., 1997), however more continuous data and observations during such  
514 subsidence episodes would likely be needed to further assess the specific mechanism leading to  
515 this condition.

516         Maintaining the persistent heat output at the summit of Mount Cleveland requires the  
517 presence of the top of the magma column at or very near the surface and a steady flow of fresh  
518 magma from depth. We speculate that this continual presence of magma near the surface and  
519 persistent degassing is most likely the result of convection within the magmatic system to very  
520 shallow levels, similar to that presented in Shinohara (2008). Most often convection is proposed  
521 for volcanoes with basaltic magma compositions (Rose et al., 2013) and those that support lava  
522 lakes (e.g. Villarrica, Witter et al., 2004; Izu-Oshima, Kasahaya et al., 1994; or Ambrym, Sheehan  
523 and Barclay, 2016), and less often for more silicic volcanoes that experience lava dome growth  
524 (e.g., Popocatepetl, Witter et al., 2005). Here, the observation of low viscosity lavas, despite  
525 the more silicic composition (57.5 wt. % SiO<sub>2</sub>) at Mount Cleveland, supports the possibility that  
526 convection drives the continuous heat and gas output because the lava remains fluid, even  
527 after loss of volatiles. The observations at Mount Cleveland are consistent with the conceptual  
528 model of convection of silicic magmas proposed by Shinohara (2008), where persistent  
529 degassing (here degassing and thermal output) is caused by the convecting lava column. When  
530 the convecting lava column reaches the surface, part of the degassed magma can flow out as a  
531 lava dome or flow. Vulcanican explosions are explained in this model by blockages in the  
532 convective overturn in the upper conduit, which leads to overpressure due to the persistent  
533 degassing of the rising magma. Our data provide a minimum constraint on the long-term

534 magma supply rate to the surface ( $0.055 \text{ m}^3 \text{ s}^{-1}$ ) that is necessary to produce the observed heat  
535 flux (Coppola et al., 2013) and support the process of convection, but melt inclusion data of  
536 initial volatile contents would be needed to estimate the magma volume from the measured  
537 gas emission rates (Werner et al., 2013).

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

556 Soufriere Hills and other volcanoes, is beyond the scope of this study as the volcanic system is  
557 not well constrained. Fundamental parameters of these models, like the size and depth of a  
558 magma chamber, have not yet been proposed for Mount Cleveland. Still, the somewhat cyclic  
559 nature of the thermal output and eruption dynamics (Figure 5) lead us to suggest that Mount  
560 Cleveland is similar to a number of volcanoes worldwide where the periodic and pulsatory  
561 behavior is related to non-linear dynamics and the balance of magma supply rate,  
562 crystallization, and degassing. We propose that a promising tool for eruption forecasting at this  
563 volcano would be more continuous SO<sub>2</sub> degassing measurements, where decreases from the  
564 average emission rate values might indicate pressurization is occurring, similar to the “open and  
565 shut” case at Karymsky Volcano (Fischer et al., 2002), but on a longer timescale. In addition to  
566 emission rates, continuous and real-time measurements of gas composition (i.e. CO<sub>2</sub>/SO<sub>2</sub>,  
567 where high values would be indicative of deep magmatic input) might provide valuable insight  
568 into the timing and duration of deep magmatic recharge into the shallow volcanic system. Such  
569 data have been proven to be even more valuable than emission rates for eruption forecasting  
570 at multiple volcanic systems worldwide in recent years (e.g. Stromboli Volcano, Aiuppa et al.,  
571 2009; Redoubt Volcano, Werner et al., 2013; Merapi Volcano, Surono et al., 2012, and Turrialba  
572 Volcano, deMoor et al., 2016). The only issue is that deployment and maintenance of a  
573 continuous MultiGAS instrument for monitoring purposes at the summit of Mount Cleveland  
574 would be very challenging, if not impossible, due to the associated hazards.

575           While the low lava discharge rates calculated from the thermal flux are consistent with  
576 the low explosive activity observed (VEI 0-2), should higher thermal output occur such that  
577 extrusion rates exceed those reported herein ( $> 0.3 \text{ m}^3/\text{s}$ ), a higher level of explosivity might be

578 expected as documented for multiple volcanoes in Ogburn et al. (2015) and at Merapi Volcano  
579 in Pallister et al. (2013). Indeed the 2001 eruption of Mount Cleveland (VEI 3) was associated  
580 with lava extrusion rates that were an order of magnitude higher than the rates calculated here  
581 with peak values around  $4.5 \text{ m}^3/\text{s}$  (Smith, 2005).

582

### 583 **Conclusions.**

584 Mount Cleveland volcano was continuously active during 2011- 2015 as evidenced by  
585 intermittent lava extrusion and explosions, and by near continuous emission of gas observed in  
586 web camera images ([https://www.avo.alaska.edu/webcam/Cleveland\\_CLCO.php](https://www.avo.alaska.edu/webcam/Cleveland_CLCO.php)) and OMI  
587 satellite data. The  $\text{SO}_2$  emission rate measured in 2015 ( $400\text{-}860 \text{ t d}^{-1}$ ) was higher than the  
588 long-term emission rate calculated from OMI measurements ( $< 200 \text{ t d}^{-1}$ ), which is consistent  
589 with the fact that the 2015 gas measurements were made during a period of heightened  
590 activity characterized by explosions and dome growth. Steady and moderate thermal output  
591 indicated by MODIS satellite data suggests that there is a near constant, but low, magma flux  
592 near the surface, which is consistent with relatively low and constant output of magmatic gas.  
593 We calculate that roughly half of the overall magma volume is extruded as small lava domes in  
594 the crater, whereas the remaining magma convects in the conduit. Images of the summit area  
595 in 2015 showed a hot and axisymmetric dome, which is typical of low-viscosity basaltic-andesite  
596 lavas that do not support highly explosive eruptions. Two periods of drain back observed in the  
597 reporting period further support the inference of low viscosity magmas, where drain back could  
598 be related to collapse of a foam layer in the upper conduit, or to perhaps reversal in output due  
599 to intense degassing and convection. Mount Cleveland eruptive activity is typically

600 characterized by the growth of small lava domes and by small Vulcanian explosions, where the  
601 transition from dome growth to explosive activity is likely related to achieving a critical, but  
602 relatively small, overpressure. Such overpressures are likely achieved when the lava dome  
603 reaches a critical dimension, or perhaps are due to small changes in the magma supply rate and  
604 reduction in the ability of magma to degas through the upper conduit due to crystallization.  
605 Such behavior is similar to other open-system basaltic-andesite volcanoes that support dome  
606 growth, such as Merapi, Karymsky, White Island, Lascar, and Popocatepetl volcanoes. It follows  
607 that the failure to achieve large overpressures would result in the overall lack of anomalous  
608 seismicity in precursory monitoring data as observed, and the low magma flux likewise results  
609 in the absence of geodetic signals related to eruptions. We suggests that Mount Cleveland,  
610 alongside other open vent volcanoes in the Aleutians such as Shishaldin and Pavlof volcanoes,  
611 would benefit from continuous monitoring of  $\text{SO}_2$ , where decreases in the open-system  
612 degassing may signal the pressurization of the volcanic system and the likely onset of explosive  
613 activity. Furthermore, should conditions allow the installation of a continuous MultiGAS  
614 instrument for monitoring of volcanic gas composition, this could provide insight into deep  
615 magmatic recharge into the volcano. Finally, the observation of thermal output or extrusion  
616 rates in excess of that reported herein might signal an increase in magma flux that might lead  
617 to more explosive eruptions than those typically observed.

618

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635

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#### 846 **Figure Captions.**

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

850 **Figure 2.** A time series of SO<sub>2</sub> emission rates measured using an upward-looking DOAS  
851 mounted on the Bell 207 Helicopter during 14-15 August 2015. See Table 1 for details of the  
852 measurements.

853 **Figure 3.** (a) Image of Mount Cleveland volcano during the measurements shown in (b). (b)  
854 Two DOAS transects where data was recorded at 1Hz and the color represents the column  
855 concentration of SO<sub>2</sub> measured. The plume can be clearly seen heading to the east. (c)  
856 Flight path during the dedicated gas flight where data points were recorded at 1 Hz. Data  
857 marked as DOAS transects show the column concentrations of SO<sub>2</sub> at each location. The  
858 transects marked as 'in situ' show the location where the plume was traversed and show that  
859 little SO<sub>2</sub> was observed in the column above these locations during the transects.

860 **Figure 4.** Time series plot of gas concentrations during the airborne measurement. SO<sub>2</sub> is  
861 shown in blue and shows peaks up to 0.53 ppmv during the plume transects. No volcanic CO<sub>2</sub>  
862 (shown in red) was observed over ambient concentrations (data shown with background  
863 concentrations subtracted, see text for more details).

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

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

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

899 **Figure 8.** (a) FLIR image of the summit dome on 4 August 2015, 3 days before an explosion and  
900 10 days before the gas measurements. The hottest temperature recorded was 600°C. (b)

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