The emplacement of the active lava flow at Sinabung Volcano, Sumatra, Indonesia, documented by structure-from-motion photogrammetry

Brett B. Carr a,⁎, Amanda B. Clarke a, J. Ramón Arrowsmith a, Loých Vanderkluysen b, Bima Eko Dhanu c

a School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-6004, USA
b Department of Biodiversity, Earth and Environmental Science, Drexel University, Philadelphia, PA 19104, USA
c Department of Geological Engineering, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

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A B S T R A C T

An effusive eruption at Sinabung Volcano in Indonesia began in December 2013. We use structure-from-motion (SfM) photogrammetric techniques to create digital elevation models (DEMs) of the active lava flow. We build DEMs from photographs taken during two separate time periods and from two separate low-cost handheld cameras and compare them with a pre-eruption DEM to assess the quality and accuracy of photogrammetric DEMs created using different cameras, calculate flow volume and long-term average effusion rate, and document changes in flow morphology. On September 22nd, 2014, the lava flow was 2.9 km long and had a volume of $1.03 \pm 0.14 \times 10^8$ m³, leading to an estimated time-averaged discharge rate of $4.8 \pm 0.6$ m³ s⁻¹. Differentiating the photogrammetric DEMs shows that during the two-week field campaign, topographic changes of the flow occurred in zones along the flow front and on the upper flank, a finding supported by relatively high temperatures in corresponding thermal images. The deformation can be explained by active advance at the flow front and development of instabilities and collapse on the upper flanks. Large pyroclastic density currents associated with gravitational collapse of upper-flank instabilities in October 2014 and June 2015 were caused by lava growing over ridges that had initially confined the flow to a pre-existing channel. This work demonstrates the ability of SfM photogrammetry to measure or identify the lava flow volume, time-averaged discharge rate, flow emplacement rate and style, as well as the development of gravitational instabilities. Our results show the potential of SfM photogrammetry as a cost- and time-effective method of repeatedly measuring active volcanic features and monitoring hazards at Sinabung and during similar eruptions.

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1. Sinabung volcano and large viscous lava flows

Sinabung is a 2460 m high andesitic stratovolcano located in the North Sumatra Province of Indonesia (Fig. 1). Its ongoing eruption has produced ash columns over 10 km high, hundreds of block-and-ash type pyroclastic density currents (PDCs), and a 2.9 km long andesite lava flow (Global Volcanism Program, 2013, 2014b; Gunawan et al., 2017). Large viscous lava flows of this type are common at volcanoes around the world, but are rarely observed while active (Siebert et al., 2010). This eruption provides an opportunity to observe and document the emplacement of an active, high-viscosity lava flow with implications for improving our understanding of silicic eruption processes.

The stability of erupted lava presents the greatest hazard for silicic effusive eruptions because collapses of lava generate dangerous block-and-ash flows. However, the factors controlling the stability of lava flows and domes are difficult to observe directly, making the timing of collapses difficult to anticipate. Using observations of lava collapses at Soufrière Hills Volcano (SHV) on Montserrat, Calder et al. (2002) described collapses as being either ‘active’ or ‘passive’. Active collapses can be considered to be ‘pushed’ by mechanisms associated with the ongoing growth of a lava dome or flow or the sudden expansion of trapped gasses within the lava (Calder et al., 2002). Passive collapses occur with relatively low frequency in older lava, develop their instabilities in situ, and occur due to the pull of gravity. Though generally not the primary hazard during an effusive eruption, passive collapses do not correlate with effusion rate as active collapses often do (Nakada et al., 1999; Calder et al., 2002; Carr et al., 2016), and so can occur unpredictably with no obvious precursors, making them exceptionally hazardous.

Instabilities in an actively advancing lava lobe or flow generally form along the flow front where collapse is due to oversteepening. Oversteepening can be caused by an increase in slope as observed at SHV (Calder et al., 2002) or by a vertical velocity gradient between the slower base of the flow and faster flow surface, as observed at Unzen (Yamamoto et al., 1993) and Santiaguito Volcano in Guatemala (Harris et al., 2002). Harris et al. (2002) and Carr et al. (under review) also observed a correlation between flow advance rate and collapse frequency for lava flows at Santiaguito and Sinabung, respectively.

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Sinabung has frequently produced voluminous viscous lava flows (Prambada et al., 2010), many of which can be identified on a digital elevation model (DEM) of the volcano (Fig. 1). However, Sinabung had no confirmed historical eruptions prior to a brief series of phreatic explosions in 2010 (Global Volcanism Program, 2013; Gunawan et al., 2017). Activity resumed at Sinabung in Fall 2013 and an effusive eruption began on 18 December 2013, when a new lava dome was first observed (Pallister et al., this issue). Block and ash-style PDCs associated with dome collapse became frequent, and the dome transitioned into a lava flow extending south down a valley following a large collapse event on January 10, 2014 (Pallister et al., this issue). Pallister et al. (this issue) describe the frequent PDCs that occurred in the following weeks as caused by oversteepening and collapse of the advancing flow front. Pallister et al. (this issue) do note however, that at least one PDC event associated with explosive decompression of the flow margin occurred on 1 February 2014, leading to a pyroclastic surge with further reach than previous PDCs and 16 fatalities.

Lava flow emplacement continued through 2014. On 13 March, the flow was 2.4 km long (Global Volcanism Program, 2014a). From April through September 2014 the lava flow grew in both length and thickness, although PDC activity decreased (Sinabung Volcano Observatory, pers. comm.: Nakada et al., 2017). On September 6, 2014, the lava flow was 2.9 km long (Global Volcanism Program, 2014b). Large collapses of the upper part of the lava flow began on September 30, 2014, and June 2, 2015, resulting in renewed PDC activity (Global Volcanism Program, 2014b, 2016; Nakada et al., 2017). Two new lava lobes broke out at the collapse sites and redirected the flow of fresh lava away from the original flow axis such that, despite continued effusion, the main flow was no longer active and remains 2.9 km long (Global Volcanism Program, 2015). As of this writing (May 2017) both lobes remain active and are the sources of frequent PDCs (Global Volcanism Program, 2017).

2. Measuring active domes and flows

The methods for measuring the surfaces and estimating the volumes of active lava domes or flows have greatly improved over the past decades. The United States Geologic Survey (USGS) used aerial photography to make high resolution (approximately 1 m grid size) DEMs of the Mount St. Helens lava dome in the 1980s (Fink et al., 1990), but the process took weeks. During the eruption of the Soufrière Hills Volcano on Montserrat (1995–present), dome volume was monitored by a combination of theodolite, photographs, and laser range measurement surveys, producing volume calculations as frequently as every few days (Sparks et al., 1998). A laser distance meter was used at Unzen Volcano in Japan during the 1990–1995 eruption (Nakada et al., 1999). The accuracy of these techniques is limited by the number and accuracy of survey points, forcing a trade-off between spatial and temporal resolution. Dome volume can be rapidly estimated using a single-camera at fixed points to measure dome height and/or radius and then assuming a simple geometry to calculate volume (e.g., Radtomo and Turpin, 2013). Multiple satellite images and geometric fitting techniques have also been used to calculate volumes and eruption rates (Pallister et al., 2013a; this issue). Other methods of estimating volume or eruption rate, such as from satellite thermal data, rely on empirical relationships and are not direct measurements of volume change (Harris and Baloga, 2009).

Multiple lava flows at Mount Etna in Italy have been measured using high-resolution techniques such as terrestrial laser scanning (TLS; James et al., 2009) and airborne Lidar surveys (Favalli et al., 2010). Ground-based TLS provides accurate, high-spatial-resolution results, however, it can be limited by restricted coverage in rugged or dangerous terrain. Airborne Lidar techniques, while producing the most accurate, complete, and high-resolution results, are costly and the logistics are not practical in many locations.

Advances in computer processing power and software design have made photogrammetric techniques more practical for use in the geosciences (e.g., James and Robson, 2012). James and Varley (2012), Diefenbach et al. (2012), and Pallister et al. (2013b) use photogrammetric software (e.g., Bundler Photogrammetry Package, PhotoSynth™, and PhotoModeler Pro™) to process oblique airborne images of active lava domes and calculate volumes and eruption rates for Colima, Mount St. Helens, and Chaitén volcanoes, respectively. Diefenbach et al. (2012) were able to create DEMs of Mount St. Helens comparable in resolution to those of the 1980s (Fink et al., 1990), but did so in less time and with commercially available digital cameras, in contrast to the expensive and specialized equipment necessary three decades earlier. Photogrammetry has also been used to model a lava lake (Smath et al., 2016) and to...
extensively map active lava flow fields at Mount Etna (James et al., 2012; James and Robson, 2014; De Beni et al., 2015).

All photogrammetry techniques are based on the concept that the three-dimensional structure of an object can be determined by viewing the object at multiple angles and distances. Structure-from-motion (SFM) refers to a specific photogrammetric technique that allows for the camera position and orientation and the geometry of the subject (‘structure’) to be estimated simultaneously from a wide range of views (‘motion’) (Snavely et al., 2008). This technique makes photogrammetry more accessible, efficient, and economical as specialized camera equipment is not needed to reconstruct the 3D structure. Any set of digital photos of an object can be used to produce 3D models provided a few basic requirements are met: 1) there is significant overlap of the subject matter between images, 2) the photos are from suitably different perspectives, and 3) the target object has features that are visible and identifiable in multiple images. When additional spatial information, such as the coordinates of identifiable control points, is integrated with the 3D models, they can be georeferenced into high-resolution DEMs.

3. Methods

We conducted photographic surveys of Sinabung on September 17–18 and September 22, 2014. Our goals were to collect multiple sets of ground-based images in order to build photogrammetric models of the southeast flank of Sinabung to document the lava flow emplacement. The photos were taken from roads surrounding Sinabung (Fig. 1b) and encompass nearly 180° of viewing angles. We used two cameras to compare the quality of their resulting DEMs: 1) a Nikon D40X digital single-lens reflex (DSLR) camera (10.2 megapixels, 55 mm lens) and 2) an iPhone5 (8 megapixels, 33 mm lens). In total, we created four different DEMs of Sinabung - one from each camera and each survey period during our field campaign. Additional details on our processing workflow and the settings used are included as supplemental material (S1) to this document and downloadable photos, point clouds, DEMs, and shapefiles can be found at http://opentopo.sdsc.edu/datasets.

We used Agisoft PhotoScan Pro™ software (version 1.0.4) to align our photographs and build dense point clouds. During these steps, we added spatial information to each model from a combination of geotagged photographs from the iPhone5 and three-dimensional control points on the Sinabung edifice manually identified in the photographs and in Google Earth™ (-10° to 10° in position uncertainty). More accurately measured control points on Sinabung were not available due to the ongoing eruption. We chose 6–7 control points to be evenly distributed across the field of view and in locations unlikely to be affected by volcanic activity. The main source of error in this process was the difficulty in manually placing the control points in the precise location on both the oblique field photograph and Google Earth™ satellite image. The associated error is approximately 10−3 to 10−2 m (see Supplementary Table S1). Georeferencing each model using Google Earth™ provided a good initial spatial reference for checking model quality prior to further processing and alignment to higher-resolution topographic data.

We further improve the spatial accuracy of our models (after the initial georeferencing described above) using the Cloud Compare open source software (http://www.danielgm.net/cc/). In Cloud Compare, using 7–8 visually identifiable control points located in unchanged areas of the volcano, we use a manual rigid-body transformation to align the unchanged portions of the point cloud of each model to a point cloud derived from a 5 m pre-eruption DEM of Sinabung provided to us by the Badan Informasi Geospasial and the Center for Volcanology and Geological Hazard Management (CVGHM) in Indonesia. The root mean square (RMS) error for each model alignment ranged from 26 to 51 m (see Supplementary Table S2). Manual alignment of the point clouds using known and easily identifiable unchangded control points proved to be a superior method to a global alignment using the iterative closest point (ICP) method (Besl and McKay, 1992) because topographic changes due to the eruption (i.e., lava emplacement, PDC deposits, erosion caused by PDCs) extended beyond the lava flow itself into a diffuse and unidentifiable region, leading to larger errors. For Model 4 (the best model), compare the average post-alignment point-to-point distance for the region not containing the lava flow of 0.67 m for ICP to 0.45 m for manual alignment and the standard deviation of the absolute distances of 6.1 m for ICP to 5.0 m for manual. For a more detailed discussion of this process, the reader is referred to section S1.2 of the supplemental material. We visualize the flow thickness for each model using the vertical component of the cloud-to-cloud distances (absolute value) calculated for this alignment.

We converted our point clouds into DEMs using a thin plate spline in ArcGISM™ and resampled to a 5 m cell size. We then subtracted the pre-eruption DEM from our DEMs, leaving only the values of flow thickness (ΔZ) and residual errors. We next clipped the difference DEM to two regions for each model: 1) the flow area as determined by comparing the hillshade of the DEM in ArcMap™ and the point cloud in Photoscan™ containing the flow thickness values and 2) the non-flow area of the DEM containing the residual errors where there is minimal or non-uniform change from volcanic activity (Fig. 2). We drew the outer boundary of the non-flow region such that the point density of the corresponding point clouds is ≥ 0.01 points/m2 (see Table 1 for average point density for each model calculated using lasgrid from LAStools—https://rapidlas.co/) and concavities in the boundary were minimized (Fig. 2).

We use the residual elevation differences in the region of our DEMs outside of the lava flow (light blue outline, Fig. 2) as the indication of the vertical error as in Albino et al. (2015) and correct an overall elevation bias in each photogrammetric DEM by the average of the residual differences (ΔZres, Table 1). This approach is valid provided the set of vertical differences in the assumed unchanged area for each model approximates a normal distribution about its mean, which we show to generally be the case in Fig. 3 and Section S1.5 of the supplemental material. The standard deviation of the residual differences (σres, Table 1) can then be used as the estimate for the vertical error (Wheaton et al., 2010; Albino et al., 2015). We assume the contribution to the volumetric error in each DEM from horizontal errors is negligible due to the relatively low and uniform slopes on the pyroclastic flow plain surrounding the lava flow (e.g., Wheaton et al., 2010). We limit the volume calculation to only the area covered by the lava flow (red outline, Fig. 1b). The volume of the lava flow (V) is then

\[ V = \sum_{i=1}^{n} (\Delta Z_i - \Delta Z_{ref}) A \]

(1)

and the volumetric error

\[ V_{error} = n \Delta A \]

(2)

where n is the number of pixels in the flow area and A is the pixel area (25 m²). We note here that Eq. (2) treats \( \Delta A \) as a systematic error, which represents a worst-case scenario. Rather, the error is more likely randomly distributed and the actual volumetric error could be much less than the values we report in Table 1.

We also compare our 3D models to each other in CloudCompare to identify changes in the flow that may have occurred between photo acquisitions (September 18th–September 22nd, 2014). An ICP alignment is appropriate in this case as the difference between the clouds is minor compared to the size of clouds (Supplementary Material S1.2). The iterative closest point technique finds a single rigid body transformation that best aligns two different point clouds (Besl and McKay, 1992). After the point clouds are aligned globally, we calculate the cloud-to-cloud distance, which returns the smallest distance from each point in one cloud to a point in the other cloud. For our application,

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the regions of the aligned point clouds with the greatest cloud-to-cloud distances highlight areas where collapses of lava or propagation of the flow front have occurred.

4. Results

We created four models of the Sinabung lava flow (Table 1) from two periods of photo acquisition: 1) September 17 & 18 (Models 1 & 2 with the iPhone and DSLR, respectively) and 2) September 22 (Models 3 & 4 with the iPhone and DSLR, respectively). The resolution of the DEMs is directly related to the resolution of the photographs used to create them (Table 1). However, the accuracy of the models is more closely correlated to the clarity of the images. On September 17 & 18 (Models 1 & 2), viewing conditions at Sinabung were limited by atmospheric haze and clouds. Poor visibility decreases model accuracy by limiting the detail captured in the photographs and precludes views from multiple angles. The error estimates for Models 1 & 2 were $0.27 \times 10^8$ m$^3$ (22.1% of the volume estimate) and $0.29 \times 10^8$ m$^3$ (27.6%), compared to only $0.19 \times 10^8$ m$^3$ (17.2%) and $0.14 \times 10^8$ m$^3$ (13.8%) for Models 3 & 4 on September 22, which was a clear day (Fig. 4b). For these reasons, Model 4 (Fig. 4) is the best model as it was made with photographs from the higher resolution camera (Nikon DSLR) on the day with the clearest weather (Sept. 22).

From Model 4, in comparison to the pre-eruption DEM as explained above, we find that on September 22, 2014, the volume of the Sinabung lava flow was $1.03 \pm 0.14 \times 10^8$ m$^3$ (0.1 km$^3$) (Table 1). This compares

Table 1

| Model | 1       | 2       | 3       | 4       |
|-------|---------|---------|---------|---------|
| Camera | iPhone 5 | Nikon D40X | iPhone 5 | Nikon D40X |
| Date   | 9/17–18/2014 | 9/17–18/2014 | 9/22/2014 | 9/22/2014 |
| Weather | Haze & clouds | Haze & clouds | Clear | Clear |
| # of photos | 27 | 39 | 54 | 54 |
| DEM resolution (m/pix) | 5.27 | 3.37 | 6.51 | 3.84 |
| Point density (pts/m$^2$) | 0.036 | 0.088 | 0.024 | 0.068 |
| Dense cloud points | 134,060 | 425,607 | 188,367 | 386,883 |
| Flow surface area (m$^2$) | $1.83 \times 10^6$ | $1.86 \times 10^6$ | $1.81 \times 10^6$ | $1.74 \times 10^6$ |
| $\Delta Z_{nf}$ (m) | 4.9 | ~3.0 | 1.40 | 0.44 |
| $\sigma_{nf}$ (m) | 14.8 | 15.6 | 10.7 | 8.2 |
| Volume (m$^3$) | $1.14 \times 10^8$ | $1.11 \times 10^8$ | $1.09 \times 10^8$ | $1.03 \times 10^8$ |
| $V_{error}$ (±m$^3$) | $0.27 \times 10^8$ | $0.29 \times 10^8$ | $0.19 \times 10^8$ | $0.14 \times 10^8$ |
| % Error | 22.1% | 27.6% | 17.2% | 13.8% |
| TADR (m$^3$ s$^{-1}$) | 5.3 | 5.2 | 5.1 | 4.8 |
| TADR error (±m$^3$ s$^{-1}$) | 1.2 | 1.3 | 0.8 | 0.6 |

* Time-Averaged Discharge Rate-January 10, 2014 to September 17 (Models 1 & 2) or September 22 (Models 3 & 4), 2014.
well to the lava flow volume estimate of $1.1 \pm 0.11 \times 10^8$ m$^3$ by Nakada et al. (2017) who used laser distance meter surveys to create digital surface models of the flow and $1.1 \pm 0.22 \times 10^8$ m$^3$ by Pallister et al. (this issue). Using January 10, 2014, as the starting point of the effusive eruption (Pallister et al., this issue), the time-averaged discharge rate at Sinabung for those nine months was $4.8 \pm 0.6$ m$^3$ s$^{-1}$. This value for lava flow discharge is somewhat higher than the longer-term extrusion rate for September 2013 to January 2016 of about $3$ m$^3$ s$^{-1}$, which includes both pyroclastic flow and lava volumes (Pallister et al., this issue). The volume estimates from our four models overlap within error (Table 1), supporting the accuracy of our measurements.

By subtracting the pre-eruption DEM from our DEMs we created a map of the thickness of the lava flow (Fig. 5b-c). Topographic profiles across the flow (Fig. 5b-f) show that the thickest part of the flow is around 160 m near the vent (Fig. 5b) and that the flow front is consistently ~100 m thick (Fig. 5f). By the time of Model 4, the flow had overtopped the southwestern (left) ridge of the valley that initially confined the lava (Fig. 5b-c). This overtopping led to increased instability of...
the flow in this area, as it was the source of frequent rock falls during our field campaign and the September 30, 2014 collapse event. The profiles also identify areas of erosion (Fig. 5c-d) and deposition (Fig. 5b-d) from PDCs. We attribute similar patterns in Fig. 5e and on the ends of each profile to local regions of decreased DEM accuracy caused by edge or topographic shadowing effects that limited our ability to image these areas in multiple photographs.

Our comparative analysis of Models 2 and 4 show areas where the flow morphology changed between acquisitions (5 days) of the photos used to create the models (Fig. 6a). The regions that exhibit the biggest changes between DEMs correspond to zones of higher temperature observed in ground-based thermal images acquired with a FLIR ONE™ camera attachment for the iPhone5 (Fig. 6b). These regions also correspond to the source locations of rock falls and localized areas of flow degassing we observed in the field. The region of greatest change is located at the flow front. The maximum change of $-35$ m is greater than the Model 4-to-Model 2 alignment RMS error of $19.7$ m, and we thus estimate a corresponding flow advance rate of $3–11$ m d$^{-1}$ in these isolated zones (Fig. 6c). Areas along the upper end of the flow also show high relative change and correspond to surface change by rock falls as lava began to overtop this ridge (Fig. 5b-c) and subsequently became gravitationally unstable due to the steep slopes on the opposite side of the ridge. A moderate-sized collapse in this region (Fig. 4c) on September 24th, 2014, generated a 2 km-long PDC (Sinabung Volcano Observatory, pers. comm.).

5. Discussion

Our results highlight ongoing activity over a two-week period during Sinabung’s persistent effusive eruption. At the time of our observations, propagation of the flow was focused at isolated regions 100–200 m wide along the flow front where hotter lava from the flow interior was able to push through the thick insulating crust (Fig. 4d). Our measurements of flow propagation in these regions (Fig. 6c) suggest a maximum rate of $3–11$ m d$^{-1}$. These advancing or breakout regions are similar in size and advance rate to those described by Tuffen et al. (2013) at the Cordón Caulle rhyolite flow in Chile. Additionally, Sinabung observatory staff noted that the flow inflated as flow advance slowed in April–September 2014 and visible satellite images show well-developed pressure ridges on the flow surface (see also, Pallister et al., this issue). These observations support previous work demonstrating that viscous flows can have similar properties to basalt flows and thus their emplacement is likely controlled by similar processes (Harris et al., 2004; Tuffen et al., 2013).

The hazard of PDCs caused by the collapse of unstable regions of the flow is directly linked to flow emplacement processes. Data compiled by the Global Volcanism Program (2014b) describe both flow advance rate and PDC activity decreasing around the same time in April 2014, despite visual observations of flow inflation and seismic signals that indicated continued effusion of lava. This observation demonstrates that PDC activity during effusive eruptions is correlated to flow advance rate, in addition to the effusion rate, as has been shown in previous studies (Nakada et al., 1999; Calder et al., 2002; Carr et al., 2016). Our observations of frequent rockfall in the regions of flow front breakouts (Fig. 6), while no rockfalls occurred along other regions of the flow margin during the time of our study, further supports the idea that instability and collapse are directly related to the advance of the flow. Furthermore, identifying the locations of the most active advance along a flow front, through photogrammetry or other methods, can inform collapse hazards for areas downslope of these parts of the flow.

We determine that the largest collapses at Sinabung occurred due to instabilities that developed passively, as renewed PDC activity in September 2014 and June 2015 did not coincide with an increase in flow advance rate or effusion rate (Global Volcanism Program, 2014b, 2016). Instead, our topographic data show that the renewed PDC activity appears to have been caused by inflation of the flow that filled the valley and then

Fig. 5. Thickness map and profiles of Sinabung lava flow. A thickness map of the Sinabung lava flow is shown in (a). White lines show the trace of the profiles across the flow shown in (b–f). White scale bar in (a) refers to distance scale. Colour scale bar in (a) refers to flow thickness. Areas of erosion (c and d) and deposition (b–d) from PDCs are identified in the profiles, as is a local region of decreased DEM accuracy (e). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
overtopped the ridges that originally confined it (Fig. 5b-c). The overtopping exposed the lava to the steep outer slopes of the bounding ridges, leading to large PDC-generating collapses. This observation supports the conclusions of Calder et al. (2002) who found that the topography confining lava flows is an important factor that controls the development of large passive collapses of lava flows or domes. Calder et al. (2002) observed that large collapses at SHV that were not correlated with high effusion rates were caused by the failure of a confining crater wall and/or lava overtopping a crater wall (Calder et al. 2002). A similar process was observed at Merapi Volcano in 2006 when erosion by PDCs and loading by the growing lava dome caused a section of the crater wall to collapse (Ratdomopurbo et al., 2013). The crater wall collapse released the confining force on the dome and exposed the lava to the steep upper flanks of the volcano, causing large collapses that traveled down a drainage that had not seen PDC activity in decades (Charbonnier and Gertisser, 2008; Carr et al., 2016).

Instabilities related to topography, either by overtopping or failure of underlying slopes, do not require higher levels or changes in activity to develop, unlike those related to effusion or flow advance rates. Specifically, the collapses referred to above at Merapi and Sinabung occurred in the weeks or months following the peak eruption phases. Topographic instabilities can build slowly over time and collapse when other observations may suggest that a volcano’s activity is at low levels and less hazardous. Due to the removal of confining topography, such collapses can occur in new directions and thus impact previously unaffected areas. The unexpected, larger-than-average PDCs that result have been deadly at Sinabung, causing fatalities in May 2016 (Global Volcanism Program, 2017) when people temporarily re-entered the exclusion zone within 5 km of the vent during a period they themselves may have perceived to be of comparatively low activity. Similar collapse events also caused fatalities during the eruptions of SHV (Calder et al., 2002) and Merapi in 2006 (Charbonnier and Gertisser, 2008), in all cases because the hazard in the affected region was not properly appreciated. The evidence from Sinabung, SHV, and Merapi suggests that topography-generated instabilities are most likely to develop in steep terrain around the vent and upper flanks of the volcano, where crater walls and ridges can confine the flow, allowing lava to accumulate. The accumulation of lava leads to overtopping or failure of the confining topography, which suddenly exposes the lava to steeper slopes and causes an increase in gravitational collapses. An understanding of changing volcano edifice topography at sufficient resolution is thus necessary to properly assess PDC hazards.

We are not able to determine a PDC deposit volume at Sinabung separately from the lava flow volume. Any PDC deposits since covered by the lava flow are included in the lava flow volume estimate. Small areas of apparent deposition and erosion in the topographic profiles (Fig. 5b-f) are on the same scale as our errors and are not included in our volume calculation as they are outside of the flow area. If PDC deposits constituted a significant volume of material beyond the flow margins, this layer of deposits would appear in our flow profiles (Fig. 5b-f) as misalignment between Model 4 and the pre-eruption DEM, but this is not observed. Model 4 has a vertical error of ±8.2 m (Table 1), so we conclude that the thickness of pyroclastic deposits is less than this error and thus adds no significant volume to our estimate.

Structure-from-motion has broad applications for observing volcanoes and documenting their activity (e.g., James and Robson, 2012; James and Varley, 2012; De Beni et al., 2015; Smets et al., 2016). Oblique, ground-based photographs can be used with SfM to generate 3D photogrammetric models that allow for the calculation of volumes of erupted material and identification of regions with measurable change for an entire lava flow or volcanic edifice. The accuracy of the models is most improved by having clear weather that enables photographs from all necessary angles to be taken in one day. The quality of the camera improves the DEM resolution but does not guarantee improved accuracy (Models 1 & 2, Table 1); a good model can be made using only the camera on a smart phone (Model 3, Table 1), as demonstrated here and by Micheletti et al. (2015). Our methodology is best applied in cases where topographic change is significant (i.e., the emplacement of tens of meters of lava or collapse of large features) so that the measurement error (σd = 8.2–15.6 m) that results from a relatively large viewing distance (25 km from the vent due to safety concerns) and lack of elevation variance (due to all photos being ground-based) remains small compared to the volume change (errors ≤ 30%, Table 1). We are unable to measure with high accuracy smaller changes, such as the rate of flow breakout advance in the four days between Models 2 and 4, due to the above limitations. Obtaining images capable of measuring change on the order of meters requires shorter viewing distances and a greater variety of viewing perspectives (such as multiple elevations), and is an observation that supports the use of unmanned aerial vehicles, or drones, for observing volcanic activity.

The techniques described here can easily be utilized by volcano observers, as they require no expensive equipment or specialized expertise. A standardized workflow for an observatory could be similar to the following: 1) establish a standardized set of control points on the volcano to use for georeferencing; 2) take photographs from around...
a volcano (ideally using a camera with geotagging capability) every few days or whenever a clear-weather opportunity presents itself – this task can be accomplished by 1–2 people in a few hours; 3) follow all processing steps as described in the Methods section above and the Supplementary Material provided (S1). Additionally, if the purchasing of software licenses is not feasible, the alignment, georeferencing, and data processing steps we describe can be accomplished using freely available, open source alternatives such as Bundler Photogrammetry Package, Cloud Compare, LAStools, and R (a software environment for statistical computing and graphics, https://www.r-project.org/). Frequent surveys conducted by an observatory could be used to create a time series of models with which to document and quantify effusion rate, propagation of the flow, and areas of high change in lava flows and domes that are at risk of collapsing and generating PDCs.

6. Conclusions

The activity of the andesite lava flow at Sinabung presents an opportunity to observe the progression of a ubiquitous, but rarely observed, style of silicic volcanism. The ongoing activity shows that these are dangerous eruptions with persistent hazards not limited to the initial explosive and rapid lava flow advance phases. A relatively steady effusion of lava causes periods of low and high PDC activity as the lava switches from flowing down a confined valley to overtopping that valley, leading to large collapses. PDC activity during silicic effusive eruptions is thus related to the effusion rate, flow advance rate, and the underlying topography. Structure-from-motion photogrammetry techniques are valuable for documenting these types of eruptions. Because of the low cost and relative ease, we were able to achieve both good temporal resolution and relatively high accuracy when considering the safety limitations of image acquisition. We find that 0.1 km² of lava had erupted at Sinabung since effusion began in late 2013 at a long-term average rate of 4.8 m³/s through September 2014, with an error of ~14%. We compare multiple photogrammetric models and identify isolated regions of rapid flow, as well as high rates of change in a region on the upper flanks that collapsed two days after the photos were taken. Structure-from-motion photogrammetry can be used to frequently, efficiently, and safely monitor volcanic activity and hazards and provide insight into the processes controlling ongoing eruptions.

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