Journal of Volcanology and Geothermal Research 259 (2013) 308–316

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Photogrammetric monitoring of lava dome growth during the 2009 eruption of Redoubt Volcano

Angela K. Diefenbach [a,*], Katharine F. Bull [b], Rick L. Wessels [c], Robert G. McGimsey [c]

[a] Cascades Volcano Observatory, U.S. Geological Survey, 1300 SE Cardinal Court, Suite 100, Building 10, Vancouver, WA 98683, USA
[b] Alaska Volcano Observatory/Alaska Division of Geological and Geophysical Surveys, 3354 College Road, Fairbanks, AK 99708, USA
[c] Alaska Volcano Observatory, U.S. Geological Survey, 4210 University Drive, Anchorage, AK 99508, USA

A R T I C L E I N F O

Article history:
Received 1 June 2011
Accepted 21 December 2011
Available online 29 December 2011

Keywords:
Oblique photogrammetry
Dome volume
Dome extrusion rate
Redoubt Volcano

A B S T R A C T

The 2009 eruption of Redoubt Volcano, Alaska, began with a phreatic explosion on 15 March followed by a series of at least 19 explosive events and growth and destruction of at least two, and likely three, lava domes between 22 March and 4 April. On 4 April explosive activity gave way to continuous lava effusion within the summit crater. We present an analysis of post-4 April lava dome growth using an oblique photogrammetry approach that provides a safe, rapid, and accurate means of measuring dome growth. Photogrammetric analyses of oblique digital images acquired during helicopter observation flights and fixed-wing volcanic gas surveys produced a series of digital elevation models (DEMs) of the lava dome from 16 April to 23 September. The DEMs were used to calculate estimates of volume and time-averaged extrusion rates and to quantify morphological changes during dome growth. Effusion rates ranged from a maximum of 35 $m^3\ s^{-1}$ during the initial two weeks to a low of 2.2 $m^3\ s^{-1}$ in early summer 2009. The average effusion rate from April to July was 9.5 $m^3\ s^{-1}$. Early, rapid dome growth was characterized by extrusion of blocky lava that spread laterally within the summit crater. In mid-to-late April the volume of the dome had reached $36 \times 10^6\ m^3$, roughly half of the total volume, and dome growth within the summit crater began to be limited by confining crater walls to the south, east, and west. Once the dome reached the steep, north-sloping gorge that breaches the crater, growth decreased to the south, but the dome continued to inflate and extend northward down the gorge. Effusion slowed during 16 April–1 May, but in early May the rate increased again. This rate increase was accompanied by a transition to exogenous dome growth. From mid-May to July the effusion rate consistently declined. The decrease is consistent with observations of reduced seismicity, gas emission, and thermal anomalies, as well as declining rates of geodetic deflation or inflation. These trends suggest dome growth ceased by July 2009. The volume of the dome at the end of the 2009 eruption was about $72 \times 10^6\ m^3$, more than twice the estimated volume of the largest dome extruded during the 1989–1990 eruption. In total, the 2009 dome extends over 400 m down the glacial gorge on the north end of the crater, with a total length of 1 km, width of 500 m and an average thickness of 200 m.

Published by Elsevier B.V.

1. Introduction

Measurements of the volume and rate of growth of active lava flows and domes are key parameters of volcano monitoring (Stevens et al., 1999; Hunter et al., 2003; Baldi et al., 2005; Harris et al., 2005; Schilling et al., 2008; Wadge et al., 2008; Coppola et al., 2010; James et al., 2010). These values can be used in conjunction with many datasets (e.g. gas geochemistry, seismicity, geodetic deformation, thermal flux) to better constrain our understanding of eruption dynamics (Iverson et al., 2006; James et al., 2006; Gerlach et al., 2008; Luckett et al., 2008). During eruption response, dome volume and rate of growth are also critical factors to provide effective assessment of volcanic hazards, particularly during dome-building eruptions where changes in eruptive conditions can initiate dome collapse and threaten societal assets on the ground and in the air (Watts et al., 2002; Sparks et al., 1998; Nakada et al., 1999; Calder et al., 2002).

Hazards associated with dome collapse are especially relevant to Redoubt Volcano, Alaska (Fig. 1). During the 1989–1990 eruption of Redoubt Volcano, 14 lava domes were extruded, of which 13 collapsed by gravitational force and explosive activity, causing large ash clouds that wreaked havoc for air traffic and local communities in the Cook Inlet region (Casadevall, 1994; Miller, 1994). A problem during the 1989–1990 eruption response was the inability to assess dome size, volume and growth rates rapidly. Often, such measurements were difficult to attain due to hazardous conditions, limited daylight, lack of resources and/or time constraints.

After 19 years of eruptive repose and several months unrest (Bull and Buurman, 2013), an eruption began at Redoubt Volcano with a phreatic explosion on 15 March 2009. A series of 19 major explosions

* Corresponding author at: U.S. Geological Survey, Cascades Volcano Observatory, 1300 SE Cardinal Court, Bldg 10, Suite 100, Vancouver, WA 98683, USA. Tel.: +1 360 993 8957; fax: +1 360 993 8980.
E-mail address: adiefenbach@usgs.gov (A.K. Diefenbach).

0377-0273/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.jvolgeores.2011.12.009

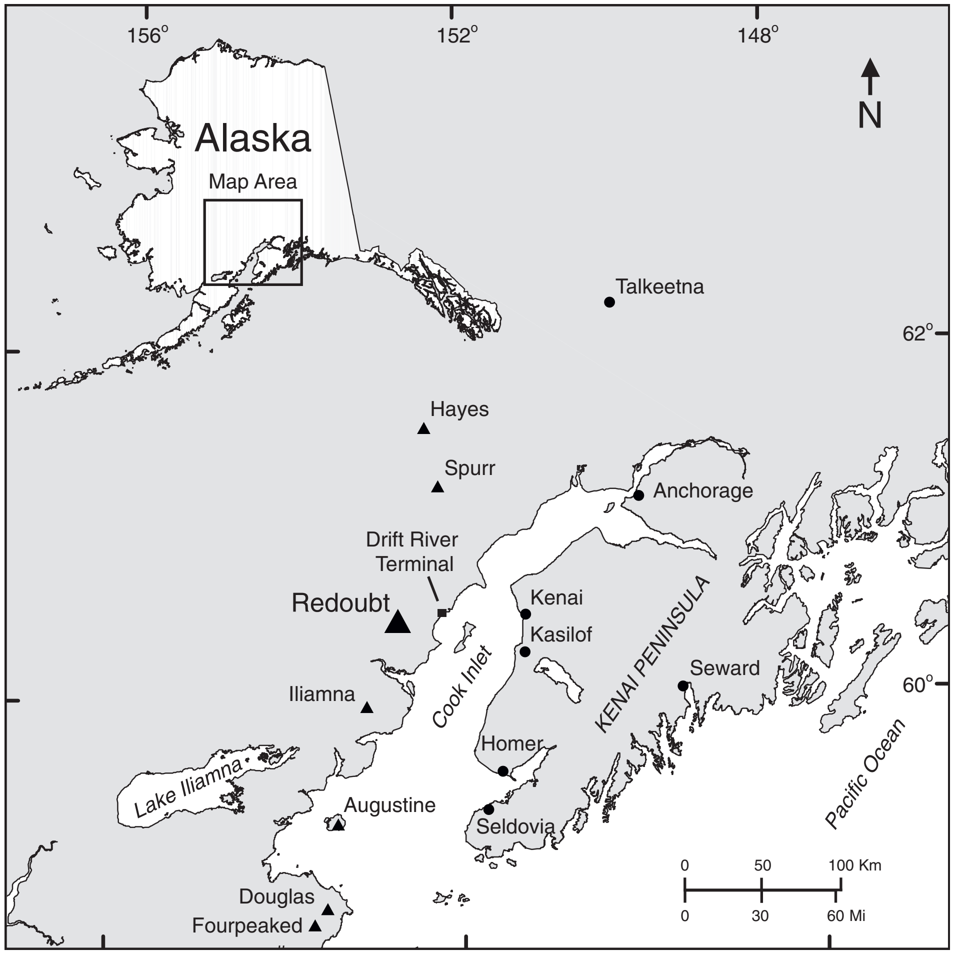

Fig. 1. Location map of Redoubt Volcano and other Cook Inlet volcanoes (black triangles) as well as nearby communities and locations mentioned in the text.

occurred between 22 March and 4 April, each sending ash clouds more than 5 km into the atmosphere. During this time, visual and seismic observations suggest that two and possibly three lava domes grew inside the 2009 explosion crater just south of the last dome emplaced in 1990. All three domes were subsequently destroyed by explosions. On 4 April the largest and final explosion occurred, resulting in the removal of previously emplaced 2009 material as well as most, if not all, of the remaining 1990 dome material. This explosion sent an ash cloud to 18 km above sea level (a.s.l.) that traveled southeast over nearby communities, produced pyroclastic flows and caused lahars in excess of 60×10^6 m^3 that extended 40 km down the Drift River Valley (Bull and Buurman, 2013; Schaefer, in press; Schneider and Hoblitt, 2013; Wallace et al., 2013; Waythomas et al., 2013). Following the 4 April event, the explosive phase of the eruption ended and was followed by a period of continuous extrusion that produced the fourth lava dome of the eruption.

Concern regarding the activity and stability of the lava dome during this effusive phase led to the application of a safe, rapid and effective photogrammetry approach to quantify dome growth. Like previous studies that have used photogrammetry to model and study active volcanic processes (Cecchi et al., 2003; Donnadieu et al., 2003; Herd et al., 2005; Schilling et al., 2008; Wadge et al., 2008; Darnell et al., 2010; Ryan et al., 2010; Wadge et al., 2010; Diefenbach et al., 2011), oblique photogrammetry was employed during the 2009 Redoubt Volcano eruption to produce a series of digital elevation models (DEMs) of the growing lava dome. We used the DEMs to calculate dome volumes and time-averaged extrusion rates, and to evaluate evolving dome morphology and assess potential hazards. We will show that oblique photogrammetry is a flexible and rapid tool for monitoring lava dome growth, especially when used in conjunction with other monitoring techniques. Here, we describe the growth of dome 4 during the last effusive phase of the eruption from April to July and compare and contrast the 1989–1990 and 2009 dome-building eruptions.

2. Methods

During the 2009 eruption of Redoubt Volcano, visual observation and FLIR (Forward Looking Infrared Radiometer) helicopter flights as well as fixed-wing airplane gas surveys provided platforms to acquire hand-held oblique imagery of the growing lava dome. These photographs were processed using a simple and accurate oblique photogrammetry method to produce a series of DEMs from which volume, subsequent time-averaged extrusion rates and morphological changes were quantified. Typically, imagery was processed and volume and rates calculated within a few hours of acquisition, which enabled rapid analysis of dome growth and evaluation of potential volcano hazards during the ongoing eruption response.

The photogrammetric software PhotoModeler Pro[1] was used for this study and provides a general case geometric solution for a series of convergent (typically 45°) oblique images where some exterior control and interior camera parameters, such as ground control and camera focal length, are known. Oblique images of the dome were acquired with a digital single lens reflex (SLR) camera (Nikon D70, Nikkor 24–120 mm lens, 6 megapixel resolution) and a lens set at a fixed focal length of 24 mm. Photographs were taken at various

[1] Use of trade names in this manuscript is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.