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The seismicity of the 2009 Redoubt eruption

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ABSTRACT

Redoubt Volcano erupted in March 2009 following 6 months of precursory seismic activity. The 4.5-month-long eruptive sequence was accompanied by phreatic and magmatic explosions, periods of steady dome growth, lahars, seismic swarms, extended episodes of volcanic tremor and changes in the background seismicity rate. This study presents a seismic chronology of the eruption and places it in context with the variety of other geological and geophysical data that were recorded during the eruptive period. We highlight 6 notable seismic swarms, 3 of which preceded large explosions. The swarms varied from an hour to several days in duration, and contained tens to over 7000 earthquakes. Many of the swarms were dominated by low frequency type earthquakes that contained families of repeating events. Seismic tremor varied considerably in frequency, amplitude and duration during the eruption with distinct characteristics accompanying different types of volcanic activity. The explosion signals during March 23–24 were the most energetic, and the explosions on March 26–29 contained proportionally more low frequency energy (0.033–0.3 Hz). Two seismic stations were particularly well-suited to recording lahars that flowed down the Drift River valley. Data from these stations showed that lahars were generated by the majority of the explosion events, as well as during the continuous eruptive activity on March 29 when no large explosions occurred. We also examine the seismicity which occurred outside of the explosion and swarm episodes, and find several families of repeating VT earthquakes which begin shortly before the April 4 explosion and that continue through May 2009, locating between 3 and 6 km below sea level.

1. Introduction

Redoubt Volcano is a 3108 m high stratovolcano in the Cook Inlet region of south-central Alaska that has erupted three times since the mid 1960s (Schaefer, 2012; Bull and Buurman, 2013). Given its recent eruptive history, its location near communities, oil platforms, an oil storage facility, and its potential impact to air traffic routes, Redoubt Volcano was closely monitored when unrest began in summer 2008. The seismic network at that time consisted of 5 single-component and 2 3-component L-4 and L-22 model telemetered short-period seismometers within 25 km of the vent, operated by the Alaska Volcano Observatory (AVO) (Fig. 1). As the level of unrest increased the network was augmented: two additional telemetered broadband Guralp 6TD instruments and a telemetered single-component short-period L-4 seismometer were installed in late February 2009 and 4 campaign-style broadband Guralp 6TD seismometers with on-site recording were deployed in the 2 days prior to the magmatic explosions that occurred in late March 2009.

In this paper we present an overview of the seismic activity that was associated with the 2009 eruption of Redoubt Volcano. There are many aspects to the seismicity both prior to and during the eruptive episode, including swarm activity, tremor episodes, seismicity from explosion signals and lahars and variations in the background hourly earthquake rates. When referring to explosion events, we follow the numbering scheme used by Schaefer (2012) who numbers them 0–19. Our objective is to place each set of seismic patterns in the context of other geological and geophysical observations. As a result, this paper encompasses a wide variety of seismic signals that were generated by a range of volcanic processes. For organisational simplicity we include brief discussion and speculation of the seismic sources within the individual sections instead of in a lengthy discussion section at the end, and close with a brief eruption summary that encompasses the major conclusions drawn from the seismic record. We begin with a short eruption overview to provide context for our seismological interpretations.

2. Eruption overview

Retrospective analysis of continuous GPS data indicates that inflation began as early as May 2008 (Grapenthin et al., 2013), but the earliest signs of unrest at Redoubt Volcano recognised by AVO were reports by field geologists working on the edifice of H_2S odors from fumaroles near the ice-covered 1990 lava dome in July 2008. Brief bursts of tremor in the 2–6 Hz range were recorded in September 2008 coincident with reports from local part-time residents of explosion-type noises in the vicinity of the summit,

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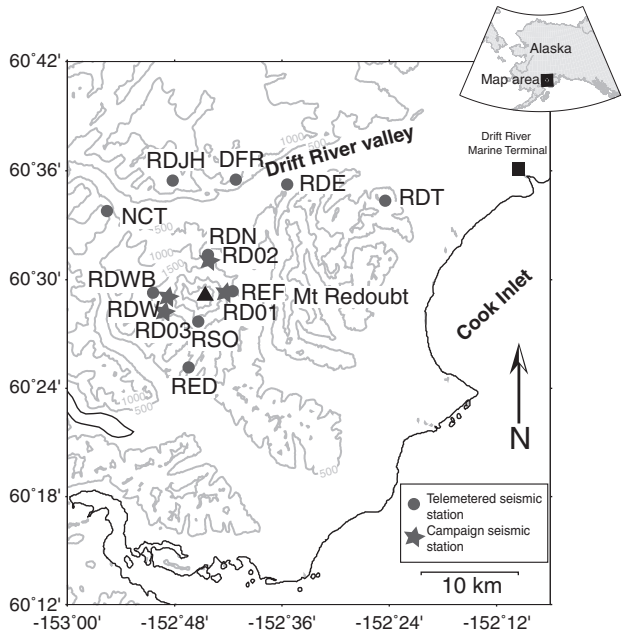

Fig. 1. Map of the Redoubt seismic network that was operational during the 2009 eruption. The inset shows the location relative to Alaska. Stars indicate campaign-style seismometers with on site recording, and circles indicate the telemetered seismic stations used for monitoring during the eruption.

and in late September crevasses began to expand in the upper Drift Glacier (Bleick et al., 2013; Schaefer, 2012). Continued enlargement of these ice fractures, combined with increased and anomalous gas emissions (Werner et al., 2013) prompted AVO to increase the Volcano Alert Level and Aviation Color Code to advisory/yellow on November 5, 2008 (Schaefer, 2012). Deep long-period earthquakes began in December 2008 at depths between 28 and 32 km below the edifice (Power et al., 2013). The onset of high amplitude, broadband tremor in late January 2009 marked a further increase in seismicity at Redoubt Volcano. This tremor was accompanied by increased gas emissions, the appearance of collapse holes in the glacier and reports of mudflows emerging from various locations along the Drift glacier (Bleick et al., 2013; Werner et al., 2013; Schaefer, 2012). The tremor became sustained in early February, ending abruptly with the first seismic swarm on February 26, 2009 (Table 1).

The first explosion of the eruption sequence (event 0) occurred on March 15, accompanied by weak tremor (Table 2). This explosion formed a hole in the crater glacier and deposited a small amount of ash that lacked juvenile material at the summit (Bleick et al., 2013; Wallace et al., 2013). The second seismic swarm began 5 days later, marking the build-up to the first magmatic explosion (event 1; see Table 1). The swarm lasted 66 h and was dominated by repeating earthquakes comparable to those observed during the previous eruption of Redoubt Volcano in 1989 (Power et al., 1994; Power et al., 2013). Towards the end of the swarm a small lava dome was observed in the hole formed by event 0. During the final hours of the swarm volcanic tremor increased significantly before culminating in a 9-hour sequence of six magmatic explosions (events 1–6) that destroyed the small lava dome and produced ash plumes up to 18 km ASL (Schaefer, 2012; Bull and Buurman, 2013; Schneider and Hoblitt, 2013). The explosions produced pyroclastic density currents and tephra fall, as well as lahars which travelled down the Drift River valley, reaching the coast (Table 3; Bull and Buurman, 2013; Waythomas et al., 2013; Wallace et al., 2013). Sustained, high amplitude tremor continued for 9 h following this initial explosion sequence.

Two more explosions occurred on March 26 (events 7–8), the second of which produced the highest ash cloud of the eruption to 18.9 km ASL (Schaefer, 2012; Schneider and Hoblitt, 2013; Table 2). Fall deposits from these explosions suggest that a second lava dome may have effused in the pause between events 6 and 7 (Wallace et al., 2013), but no satellite observations were available to confirm the dome's presence. Events 7 and 8 were followed by an 8-hour-long vigorous seismic swarm that merged into tremor immediately before the next explosion (event 9) on March 27. This event marked the first in a sequence of powerful explosions (events 9–18) that produced finer-grained ash deposits than the March 23–24 sequence (Wallace et al., 2013). These later explosions produced many lahars and were preceded by distinctive episodes of tremor that exhibited steady, exponential increases in dominant frequency up to nearly 30 Hz (Hotovec et al., 2013). The fourth seismic swarm on March 29 marked the end of this explosion sequence, and was followed by a high amplitude spasmodic tremor episode lasting 20 hours accompanied by continuous, low-level ash emissions (Schneider and Hoblitt, 2013). Effusion of a third lava dome was observed in the days following the seismic swarm before it was destroyed by the explosions on April 4. The final explosion of the eruption (event 19) occurred on April 4 and was preceded by a 43-hour swarm of low amplitude repeating earthquakes. Retrospective analyses of satellite images, the seismic and infrasound records and the fall deposits from event 19 suggest that failure of the lava dome played a part in the onset of the explosive activity (Bull and Buurman, 2013). Event 19 also produced the longest sustained ash emissions and the largest and most water-rich lahars, inundating the Drift River valley to the coast (Waythomas et al., 2013).

Lava effusion followed these explosions for the remainder of the eruption. A new lava dome was observed on April 5 and continued to grow throughout May and into mid-June, after which time the growth rate slowed considerably (Bull et al., 2013; Diefenbach et al., 2013). Several clusters of high-frequency repeating earthquakes located at depths of 3–6 km below sea level accompanied the dome growth and continued through the end of May. The final and longest-lived seismic swarm began on May 2 and lasted through May 7, producing over 7000 low-amplitude, repeating earthquakes. This seismic swarm coincided with a change in the vesicularity and texture of the extruding lava dome, which continued to grow until

Table 1
The timing of the six seismic swarms identified during the 2009 Redoubt unrest, as well as total number of earthquakes, earthquake rates per hour, and repeating earthquake rates per hour. The percent of earthquakes which repeat is calculated by dividing the total number of earthquakes in the swarm by the number of earthquakes which meet the similarity criteria discussed in Section 3.

Swarm	Swarm start	Swarm end	Duration (h)	Total earthquakes	Maximum earthquake rate (per h)	Maximum repeating earthquake rate (per h)
February 26	2/26/2009 6:00:00	2/27/2009 13:00:00	31	897	91	12
March 20	3/20/2009 12:00:00	3/23/2009 6:34:00	66	2000	82	54
March 27	3/27/2009	3/27/2009 8:28:00	8	438	92	81
March 29	3/29/2009 7:50:00	3/29/2009 9:00:00	1	37	32	32
April 2	4/2/2009 19:00:00	4/4/2009 13:58:00	43	1949	107	100
May 2	5/2/2009 21:00:00	5/8/2009 1:00:00	123	7470	191	164