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Temporal change of upper-crustal V_P/V_S ratios with volcanic evolution in Redoubt Volcano

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ABSTRACT

Volcanic activities accompany changes in the physical and chemical properties of the medium. The ratio between *P*- and *S*-wave velocities, V_P/V_S, is sensitive to the medium property changes. We investigate temporal variations of the V_P/V_S ratios in the upper crust around Redoubt Volcano in the 1989–2014 time period using the traveltimes of local earthquakes. The V_P/V_S ratios reached ~ 2.0 immediately prior to the 1989–1990 and 2009 eruptions. These high V_P/V_S ratios may be associated with partial melts in the edifice. The V_P/V_S ratios rapidly decreased to ~ 1.7 during the 1989–1990 and 2009 eruptions due to decreasing temperatures, fluids, and pore pressures and increasing effective stresses after melt eruptions and gas emission. The change rates of the V_P/V_S ratios showed evident spatial distributions. The V_P/V_S ratios increased at a rate of 0.025 (±0.003) yr^{-1} below the 2009 vent during the inter-eruption period between the 1989–1990 and 2009 eruptions due to an increase in the temperature, which may be associated with the recharge of the magma in the lower crust. The increase rate of the V_P/V_S ratios was as low as 0.005 (±0.001) yr^{-1} in the regions located away from the eruption site. The V_P/V_S ratios appear to have increased consistently at a rate of 0.017 (±0.004) yr^{-1} since the 2009 eruption.

1. Introduction

Active volcanoes are monitored year-round to mitigate volcanic hazards. The identification of a volcano is crucial for timely preparation. Most active volcanoes can be characterized by eruptive cycles in which prolonged months- to decades-long periods of quiescence are interspersed with episodes of eruptive activity. Many phenomena, such as ground uplift, gas emission and earthquake activity, can provide insights into the state of a volcano in its eruptive cycle (Young et al., 1998; Chouet et al., 1994; Sparks, 2003; Stephens and Chouet, 2001; Power et al., 2013). Understanding and identifying these characteristics is critical for mitigating volcanic hazards.

Eruptive cycles can be characterized by the significant changes in medium properties, including the chemical composition, temperature, local stress field, porosity, density, cracks, and fluid saturation (Wiemer and McNutt, 1997; Rubin et al., 1998; Roman et al., 2004; Sánchez et al., 2004; Pieri and Abrams, 2005; Koulakov et al., 2013; Hong et al., 2014). Seismic properties are sensitive to the properties of the medium (Brenguier et al., 2008; Duputel et al., 2009). The ratio between *P*- and *S*-wave velocities, the V_P/V_S ratio, is sensitive to the medium composition and fluid content and is therefore useful for monitoring the state of a volcano at any given point in its eruptive cycle (Nakajima and Hasegawa, 2003; Chiarabba and Moretti, 2006; Koulakov et al., 2013; Hong et al., 2014).

Volcanic regions are typically characterized by low seismic velocity zones beneath the volcanoes, which indicate the presence of magma (e.g., Nakajima et al., 2001; Sudo and Kong, 2001; Nakajima and Hasegawa, 2003; Koulakov et al., 2007; Koulakov et al., 2009; Lees, 2007; Prôno et al., 2009). The magmas also exhibit high V_P/V_S ratios (Nakajima et al., 2001; Sudo and Kong, 2001; Nakajima and Hasegawa, 2003; Judenherc and Zollo, 2004; Koulakov et al., 2009; Hong et al., 2014). Calderas are generally composed of sediments with open cracks and present low seismic velocities and V_P/V_S ratios (Nakajima and Hasegawa, 2003; Sherburn et al., 2003; Judenherc and Zollo, 2004; Lees, 2007; Koulakov et al., 2009). Non-molten intrusives feature high seismic velocities and V_P/V_S ratios (Sherburn et al., 2003; Judenherc and Zollo, 2004; Prôno et al., 2009). The seismicity, migration and intrusion of magma, fluid transport, heat transfer, and collapse of calderas perturb the medium properties, producing complex seismic velocity structures in the volcanic regions (Nakajima et al., 2001; Sudo and Kong, 2001; Nakajima and Hasegawa, 2003; Koulakov et al., 2009; Sherburn et al., 2003). Investigations of seismic velocities are useful for deducing the structures in volcanic areas. However, the seismic velocity changes during the eruptive cycle of volcanoes are only partially

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understood.

The earthquake catalog from Redoubt Volcano is ideal for studying the eruptive cycle of a stratovolcano. Because Redoubt Volcano has been seismically monitored since 1989, the data set includes two major eruptions between extended periods of quiescence. Both the 1989–1990 and 2009 eruptions were accompanied by lava dome growth and magmatic explosions. The recent eruptions were monitored by a seismic network, providing the opportunity to investigate the changes in the seismic properties accompanying the volcanic activities (Power et al., 1994). Noticeable changes in the seismic velocities, stress fields, seismicity, event characteristics, and V_P/V_S ratios were reported during the eruptions (Stephens et al., 1994; Benz et al., 1996, Sáchez et al., 2004; Buurman et al., 2013b; Ketner and Power, 2013; Kasatkina et al., 2014). However, the temporal evolution of seismic properties within the volcanic edifice during the inter-eruption periods is poorly understood.

In this study, we investigate the V_P/V_S ratios in Redoubt Volcano recorded between 1989 and 2014. The V_P/V_S ratios are estimated using a modified Wadati analysis based on *P* and *S* traveltimes. We examine the correlation between the eruptive cycle and the V_P/V_S ratios. We also compare the changes of the V_P/V_S ratios during and after the eruptions to determine the dependence of the V_P/V_S ratios on the eruptive processes.

2. Geology and eruption history

Redoubt Volcano is an active stratovolcano located ~170 km southwest of Anchorage (Fig. 1). The volcano was formed by multiple eruptions. Most silicic parts of the volcano were formed by a large eruption that occurred 0.888 Ma (Till et al., 1994). The sequence includes the Proterozoic basement rock, mid-Pleistocene to Holocene dacitic and basaltic pyroclastic density current deposits, block and ash deposits, and lava flows formed in Jurassic tonalites. The height of the summit of the volcano is 3108 m, and the diameter of the base at the altitude of 1200–1500 m is 10 km (Schaefer, 2011; Grapenthin et al., 2013). The diameter of the summit crater is 1.5 km, and the summit is covered by ice.

Redoubt Volcano erupted in 1902, 1933, and 1966–1968 and recently in 1989–1990 and 2009. The last two eruptions were well monitored (Power et al., 1994; Power et al., 2013; Stephens and Chouet, 2001; Grapenthin et al., 2013; Bull and Buurman, 2013). In the last two eruptions, gas and andesitic lavas explosively erupted through the same vent in the northwest of the volcano (Bull and Buurman, 2013; Diefenbach et al., 2013). The eruptions produced ash clouds, pyroclastic flows, debris flows, and prolonged episodes of lava dome growth (Page et al., 1994; Woods and Kienle, 1994). Both of the recent eruptive episodes at Redoubt Volcano were accompanied by extensive seismicity, including volcanic tremor, long-period seismic events and volcano-tectonic earthquakes that were likely associated with magma migration (Lahr et al., 1994; Chouet, 1996; Morrissey and Chouet, 1997; Buurman et al., 2013b; Grapenthin et al., 2013; Power et al., 2013; Power et al., 2013;Power et al., 2013).

The eruption periods are divided into precursory periods, explosive periods, and effusive periods (Power et al., 2013; Power et al., 2013). The precursory periods are characterized by increases in seismicity, temperature, gas emission, and ground deformation. High-pressurized gas and magma may erupt during the explosive period. Lava domes grow during the effusive period. Precursory activity, including eruptive processes, volcano-tectonic earthquakes, long-period events, volcanic tremor, snow melting, and increased fumarolic activity, was observed from October 1989 to December 14, 1989 prior to the 1989–1990 eruption (Power et al., 1994; Gardner et al., 1994; Schaefer, 2011; Power et al., 2013).

Twenty-five explosive eruptions occurred between December 15, 1989 and April 21, 1990 (Power et al., 1994). The erupted pyroclastic flows with temperatures of 600–700 K reached a height of 12 km (Woods and Kienle, 1994). Following the explosive eruptions, a lava dome grew and failed 13 times until June 15, 1990, defining the effusive period (Page et al., 1994; Miller, 1994). The largest volume of the lava dome was 30 Mm^3 (Miller, 1994). Approximately 88 Mm^3 of magma erupted with an effusion rate of 5.8 m^3/s. The total dense-rock-equivalent volume of the magma that erupted during the 1989–1990 eruption is ~200 Mm^3 (Gardner et al., 1994). The total dense-rock-equivalent volume of the deposits is ~30–50 Mm^3 (Scott and McGimsey, 1994).

The precursory activity leading to the 2009 eruption began in June of 2008. Increased gas flux, ice melting, ground deformation, volcanic tremors, and volcano-tectonic earthquakes were observed at the volcano over a period of nine months prior to the eruption (Schaefer, 2011; Bleick et al., 2013; Grapenthin et al., 2013; Power et al., 2013; Werner et al., 2013). A weak increase of the surface temperatures was also observed (Wessels et al., 2013). Twenty-eight explosive eruptions occurred between March 15, 2009 and April 4, 2009. The eruption column heights reached as high as 19 km during the 2009 eruption (Schneider and Hoblitt, 2013; Wallace et al., 2013). The effusive period followed the explosive eruptions until June, 2009, producing a lava dome with a volume of 72 m^3 (Diefenbach et al., 2013). Approximately 80 Mm^3 of magma erupted with an effusion rate of 9.5 m^3/s (Diefenbach et al., 2013). The total eruption volume of the materials is

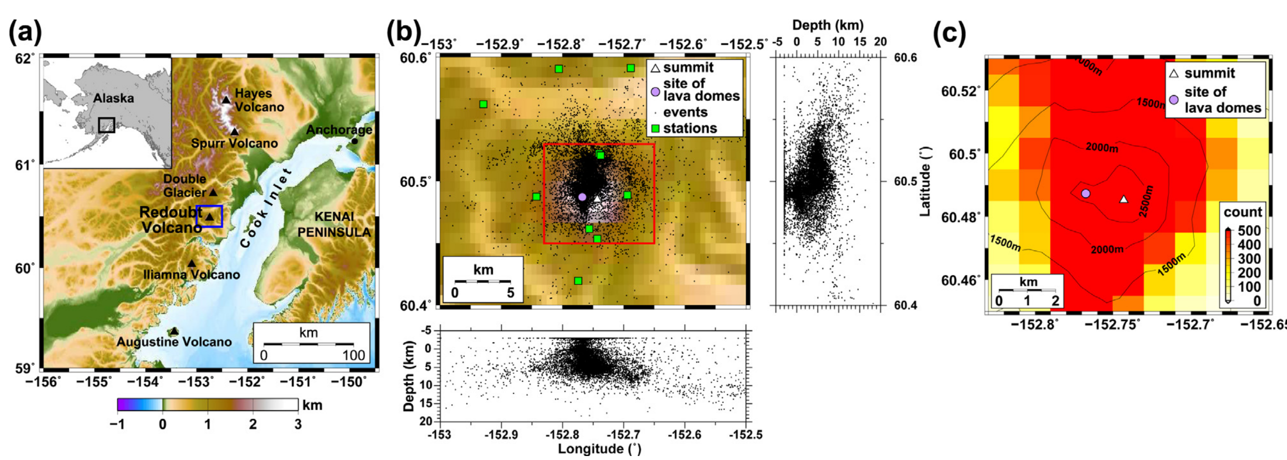

Fig. 1. (a) Map of the major volcanoes in the northeastern Aleutian volcanic arc. A region around Redoubt Volcano is marked with a rectangle. (b) Enlarged map and seismicity around Redoubt Volcano. The locations of the volcano summit (triangle) and the lava domes of the 1989–1990 and 2009 eruptions (circles) are shown. Eleven stations (squares) are available around the volcano. Earthquake depths with latitude and longitude are included as side panels. High seismicity is observed around the volcano. (c) Cell-hit counts of discretized media. The spatial coverage of the raypaths is dense around the summit.