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Geodetic observations during the 2009 eruption of Redoubt Volcano, Alaska

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ABSTRACT

In March 2009 Redoubt Volcano, about 160 km to the SW of Anchorage, Alaska, began its most recent explosive eruption. Deformation induced by this event was recorded by a GPS campaign network consisting of 14 benchmarks, which had been established in 1991 after the previous eruption. The network was partially reoccupied in 2001 and 2008 and no volcanic deformation was detected during that period. In response to precursory unrest starting in January 2009, the Alaska Volcano Observatory temporarily deployed continuously recording GPS instruments at four of the campaign benchmarks only days before the onset of explosive activity in March 2009.

The only GPS instrument recording continuously during the months prior to the eruption was the Plate Boundary Observatory (PBO) station AC17, about 28 km northeast of the volcano's summit. Data from this station reveals subtle motion radially outward from the volcano beginning as early as May 2008, which reversed with the onset of explosive activity.

Using simple analytical models we link the precursory activity to a point source intrusion of $0.0194\ ^{0.0092}_{0.0340}$ km^3 in volume at $13.50\ ^{10.17}_{17.33}$ km below sea level (bsl, superscripts and subscripts refer to upper and lower ends of confidence intervals at the 95% level). During the explosive phase about $0.05\ ^{0.028}_{>0.1}$ km^3 of magma was evacuated from a prolate spheroid with its centroid at $9.17\ ^{6.92}_{15.17}$ km bsl, a semimajor axis of $4.50\ ^{1.25}_{>10.00}$ km length and a semi-minor axis of $0.475\ ^{0.3}_{>4.0}$ km. The effusive activity is inferred to come from the same source, decreasing in volume by $0.0167\ ^{0.0106}_{0.0228}$ km^3.

Including observations from seismology and petrology, we hypothesize a mid-crustal two reservoir system with material sourced from >20 km flowing in at about 13.5 km depth and reheating residual material in the proposed spheroid. The mixture migrated to shallower depth (2–4.5 km bsl) and reheated material there. As this residual magma erupted, it was replaced by the material from the spheroidal reservoir at 7–11.5 km depth, which renders the shallow source undetectable for geodetic instruments.

In addition to long term displacements we investigate sub-daily kinematic positioning solutions and find that large, short-term positioning offsets correlate with large explosive events. Spikes in phase residuals plotted along the sky tracks of individual satellites can be related to individual plumes given favorable satellite–station-geometry, which may be of use in volcano monitoring.

1. Introduction

Redoubt Volcano lies in the Cook Inlet region on the northeastern segment of the Aleutian arc. It is about 160 km southwest of Anchorage inside the Lake Clark National Park and Preserve (Fig. 1, left) and about 400 km northwest of the Aleutian Megathrust (Fig. 1 inset), where the Pacific Plate subducts beneath Alaska. The last eruption prior to the 2009 event occurred in 1989–1990 and is described in detail in Miller and Chouet (1994). The region is volcanically active with historic eruptions at the neighboring volcanoes Augustine and Mt. Spurr.

Mt. Redoubt is a 3108 m high stratovolcano with a diameter of 10–12 km at its base at about 1200–1500 m above sea level. The ice filled summit crater is about 1.5 km in diameter and is breached to the north, which allows Drift Glacier to stretch up to 5 km down slope and into the Drift River Valley. Other smaller glaciers radiate from the summit region and dissect the volcanic edifice (Fig. 1, left). The overall largest mass of ice in the region is the Double Glacier ice cap, which covers Double Glacier Volcano (Reed et al., 1992) on the northern side of the Drift River Valley.

In the years since the 1989–90 eruption, surface deformation studies of volcanoes have made significant contributions to the field of volcanology. We can use simple models to link surface displacements to subsurface motion of material and thus infer knowledge of the plumbing system, displaced volumes and source depths as well as the general state of the volcano. These techniques have been applied successfully to a wide range of volcanoes worldwide (Dzurisin, 2003, and references therein).

At Redoubt Volcano surface deformation is measured with high-precision GPS in a network of 14 geodetic benchmarks. InSAR based studies are generally difficult, because the glaciated, steep terrain affects signal coherence and the strongest deformation signal related to the 2009 eruption spreads over a wide region with an amplitude

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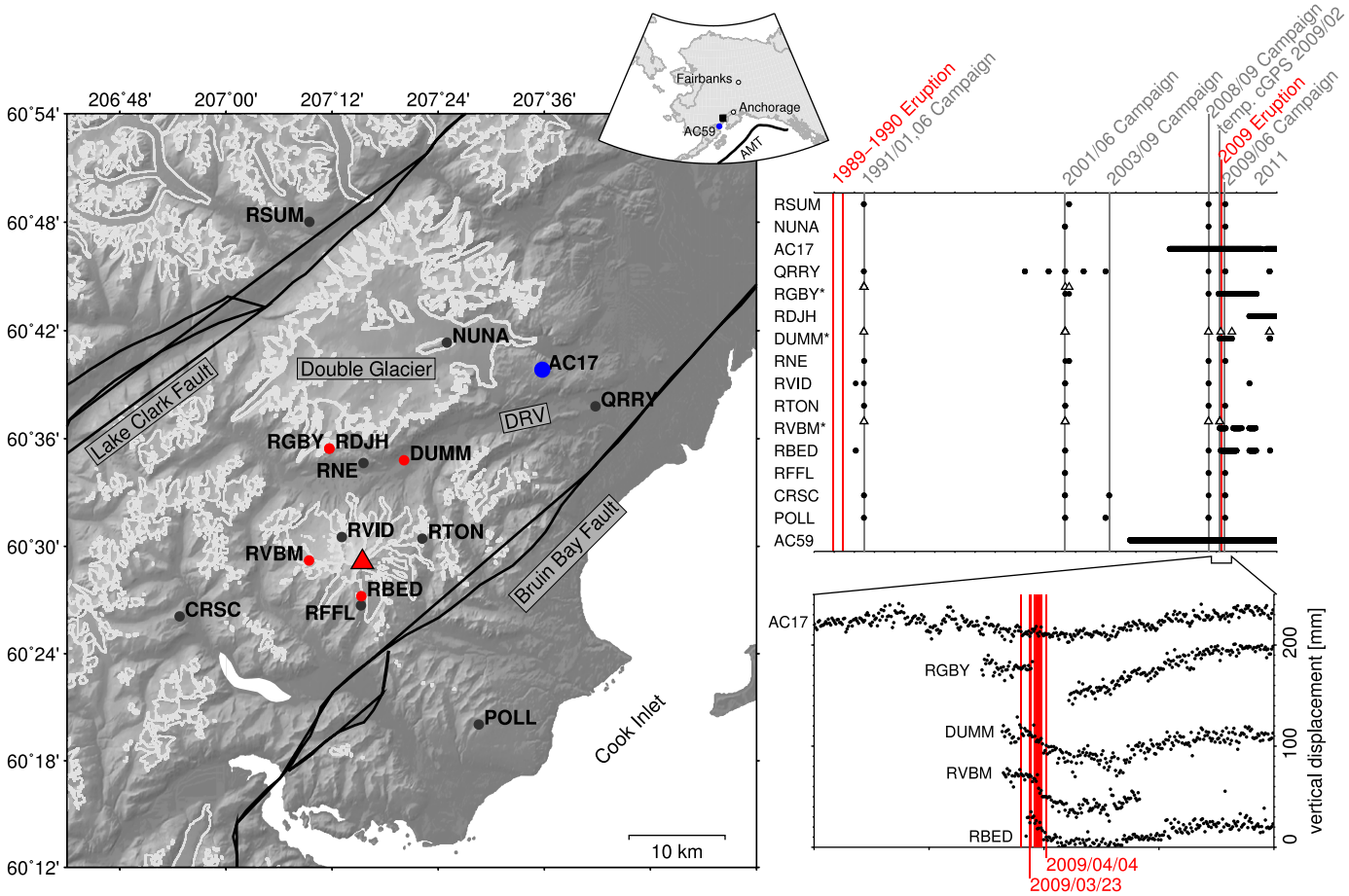

Fig. 1. Regional setting and available GPS data. **Left**: Map of Redoubt area with GPS stations. The red triangle marks Mt. Redoubt. Red circles indicate temporary continuous GPS stations, black circles mark campaign GPS stations, and the blue circle indicates the continuous PBO site AC17. White outlines mark glaciers in the region (Paul, 2010). The Double Glacier ice cap to the north of Redoubt is outlined in gray and labeled; it seems to influence the time series at RGBY located on a cliff above one of its southern outlet glaciers. NUNA is located on a large nunatak that sticks out of the ice. The black lines from SW to NE indicate major faults in the region: Bruin Bay Fault to the south, and Lake Clark Fault north of Redoubt Volcano. DRV labels the mouth of the Drift River Valley. The black square in the inset indicates the location of this detail map. It also shows the location of the PBO site AC59 and the Aleutian Megathrust (AMT). **Right:** Overview of site occupations. Asterisks mark sites with composites of two tied markers. Each dot marks an existing daily positioning solution. Triangles mark occupations of DUMB, RGRB, and RVBR which are tied to DUMM, RGBY and RVBM, respectively. Times of individual campaigns are given on the top and are marked by gray lines. Red lines mark the 1989–1990 eruption and the recent event of 2009. The timescale is linear. The lower right figure is a blow up of the (temporary) continuous stations from the decimal year 2008.75 to 2009.75 and shows vertical displacements for this time period. Vertical red lines indicate individual explosions (Table 1 in Bull and Buurman, 2013). Times are given for the first deformation inducing eruption on March 23, 2009, and the largest and last explosion on April 4th, 2009.

much smaller than the SAR wavelength. From 1991 to 2008, 4 GPS campaigns were carried out, each occupying a set of benchmarks for a few days (Fig. 1). In response to observed changes in activity of the volcano (e.g., Bull and Buurman, 2013) 4 temporary continuous GPS stations (DUMM, RBED, RGBY, RVBM; Fig. 1) were installed several weeks prior to the 2009 eruption.

An overview of the event, summarizing key observations from various disciplines, is given by Bull and Buurman (2013). They separate the eruption into three distinct phases: precursory (July 2008–15 March 2009), explosive (15 March–04 April 2009), and effusive phase (April 4–July 2009). The precursory phase is characterized by sulfur odors Bull et al., 2012, increased melting of Drift River glacier showing collapse pits (Bleick et al., 2013) and deep seismicity beginning in December 2008 (Power et al., 2013). For the explosive phase, Bull and Buurman (2013, Fig. 2) describe a complex interplay of dome growth, collapse and explosive activity, and count 28 explosions with plumes reaching up to >18 km above sea level (asl) (Table 1 in Bull and Buurman, 2013). The final, persisting lava dome was extruded during the effusive phase. Its initial rapid growth slowed during the final stage of dome building through lava intrusions into the dome (Bull and Buurman, 2013; Diefenbach et al., 2013).

Here, we present the first geodetic study of Redoubt Volcano and focus on observations during the 2009 eruption. We start with an overview of the geodetic network and data recorded at Redoubt since 1991. We investigate GPS time series for the different phases of the eruption, from which we infer source geometry, location and volume change for each phase of the eruption. Since deep pre-eruptive long period earthquakes indicate migration of material below 20 km depth (Power et al., 2013) and petrologists suggest that the magma of this event was sourced relatively shallow at 2–4.5 km bsl (Coombs et al., 2013), we are particularly interested in the question whether Redoubt presents us with a multi-source system. Furthermore, we investigate whether subdaily, kinematic positioning solutions can resolve any deformation that correlates with explosive activity.

2. GPS data

2.1. GPS network history and site description

The geodetic network at Redoubt Volcano consists of 14 markers (Fig. 1, Table 1); most of these were installed in response to the 1989 eruption and were first occupied during a campaign in 1991.