Key Points:
- Redoubt Volcano structure is studied using the local earthquake tomography
- Areas of high Vp/Vs ratio represent magma or fluid conduits beneath the volcano
- Vp/Vs ratio strongly increases during the eruption of Redoubt in March 2009

Editorial panel: Seismic structure changes beneath Redoubt Volcano during the 2009 eruption inferred from the 2009 eruption inferred from local earthquake tomography

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Abstract We present seismic velocity models of the area beneath Redoubt Volcano (Alaska) corresponding to two time periods, before and after the strong eruption that occurred in March 2009. The calculations were based on tomographic inversion of P and S arrival time data recorded by 19 stations using the local earthquake tomography code LOTOS. We performed thorough analysis of the results based on synthetic tests in each of the time periods that allow real-time variations in structure to be distinguished from artifacts caused by changes in the observation system configurations. In the resulting images corresponding to the period before the eruption, the summit area is characterized by higher values of both P and S velocities and moderate values of the Vp/Vs ratio. This may correspond to the rigid igneous rocks composing the body of the volcano that lack significant liquid content. In the second episode corresponding to the time of the eruption, the P velocity remained high, whereas the S velocity became very low. The anticorrelation of P and S anomalies in the summit area produced a Vp/Vs ratio as high as 2.2, which is seen down to 2–3 km depth. This indicates presence of mobile phase at shallow depth beneath the volcano, which can be either in the form of partial melt or fluid-saturated rocks.

1. Introduction

Redoubt Volcano is located near the eastern end of the Aleutian volcanic arc in mainland Alaska (Figure 1). Redoubt is an active stratovolcano, which was built above the Aleutian subduction zone since mid-Pleistocene [Till et al., 1994]. Redoubt is one of five historically active volcanoes on the west side of Cook Inlet (in addition to Spurr, Iliamna, Augustine, and Fourpeaked), and one of 52 historically active volcanoes that form the Aleutian volcanic arc [Schaefren, 2011]. It is the highest summit in the Aleutian Range with an elevation of 3110 m; its base diameter is approximately 10 km. Redoubt Volcano is situated on top of the Jurassic basement composed of granodiorites to tonalites [Reed and Lanphere, 1973]. Magmas erupted at Redoubt are medium-K calc-alkaline basalts, andesites, and dacites [Till et al., 1994]. Redoubt Volcano has erupted five times since 1900: in 1902, 1922, 1966, 1989, and 2009. The eruptive products of Redoubt cover large areas of the Kenai Peninsula (southern coast of Alaska), reaching Anchorage and other Alaskan cities. This volcano poses a significant threat to southern Alaska’s coastal populations, infrastructure, and flight safety.

The most recent eruption of Redoubt in March 2009 was highly explosive and produced ash plumes, pyroclastic flows, and lahars; the ashfalls occurred more than 100 km away from the volcano [Bull and Buurman, 2013]. The total volume of the 2009 eruption products was estimated to be between 80 and 120 M m³ dense rock equivalent [Bull and Buurman, 2013]. The eruption produced crystal-rich andesites, which composition varied from 57.5 to 62.5 wt % SiO₂ [Coombs et al., 2013]. Petrological analysis suggests that the low-silica andesites (<58 wt % SiO₂), which erupted at earlier stages of the 2009 period of activity, likely arrived from the deeper parts of the crust (~30 km depth), whereas the high-silica andesites of the late stages of the eruption came from the upper crust (~3–6 km depth) [Coombs et al., 2013]. A detailed analysis of the volatile budget prior to, during, and after the eruption was performed by Werner et al. [2013]. They found minor emission of gases before the eruption which may point to the closed character of the magmatic system. They estimated a high content of CO₂ and S in the primary magma. During the eruption there were strong gas emissions reaching 33,000 t/d CO₂, 16,000 t/d SO₂, and 1230 t/d H₂S. According to Werner et al. [2013], most of the gases were released during the active stages of the eruption;
the posteruptive degassing period was responsible for approximately 27% and 30% of the total CO₂ and
SO₂, respectively. Seismological observations of volcanic events reveal several levels of magma activation
[Power et al., 2013]. The occurrence of deep long-period events in the preeruptive periods may indicate the
rise of magma from the lower crust at ~30 km depth. During the eruption, the distribution of volcanic-
tectonic events may indicate that the magmatic system consisted of a shallow system of cracks at 1–2 km
below the surface and a magma source at 3–9 km depth. Similar conclusions about the multilevel magma
source system beneath Redoubt were made by Grapenthin et al. [2013] based on continuous geodetic
observations of surface deformations. However, they conclude that the main magma source is located in
the middle crust (7–13 km below sea level) which is deeper than the depth suggested by Power et al. [2013]
based on seismological observations.

Among many geophysical methods used for studying volcanoes, seismic tomography is one of the
most effective approaches that can be employed to study three-dimensional internal structures
beneath active and dormant volcanoes. Local earthquake data have been actively used to study
volcanoes for decades and as a result dozens of different volcano models have been produced,
including models of Kilauea [e.g., Thurber, 1984; Dawson et al., 1999], Medicine Lake Volcano [Evans and
Zucca, 1988], Mount St. Helens [Lees, 1992], Mount Spurr [Power et al., 1998; Koulakov et al., 2013b],
Krakatau [Jaxybulatov et al., 2011], and the Klyuchevskoy volcano group [Koulakov et al., 2011, 2013a].
There are many successful examples of studying volcanoes based on the use of active seismic data,
such as Deception Island [Zandomeneghi et al., 2009] and Tenerife [García-Yeguas et al., 2012]. During
recent years, a number of studies based on ambient noise correlation were performed for different
volcanoes including Piton de la Fournaise [Brenguier et al., 2007], Toba Caldera [Stankiewicz et al., 2010],
and Okmok in Alaska [Masterlark et al., 2010]. Active volcanoes are thought to be very dynamic systems,
and their physical properties may change quickly during activity episodes. There have been several
attempts to detect these changes using seismic tomography. For example, successful 4-D tomography
models were obtained for Mount Etna [Patanè et al., 2006] and the Klyuchevskoy volcano group
[Koulakov et al., 2013a]. In these studies, significant changes in seismic structures were associated with
the occurrence of strong eruptions.

Figure 1. Redoubt Volcano study region with topographic relief and seismic stations (triangles). (inset) Location of Redoubt
Volcano with topographic relief, in relation to other surrounding volcanoes (triangles).
Redoubt has been the target of previous tomographic studies. For example, Benz et al. [1996] performed the first tomographic inversion. They obtained $P$ and $S$ velocity models and a $V_p/V_s$ ratio reflecting a low-velocity anomaly beneath the volcano’s edifice, which was interpreted to represent a magma conduit. A later study of Redoubt Volcano’s structure was reported by DeShon et al. [2007] who computed a 3-D $P$ wave velocity model using double-difference tomography combined with waveform cross-correlation techniques. For inversion they used all Redoubt data available through November 2005 recorded by 10 seismic stations. In contrast to the previous study by Benz et al. [1996], this model does not reveal the low-velocity feature that was interpreted as a magma conduit. DeShon et al. [2007] prefer the idea of an interconnected body of dikes and sills as the source of magma erupted from 1989 to 1990. One reason for the discrepancy between existing studies could be related to the fact that the underlying models were computed from data collected in different time periods. As was shown by Patanè et al. [2006] and Koulaev et al. [2013a], seismic properties beneath active volcanoes may vary considerably in relation to the phases of eruption activity.

<table>
<thead>
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<th>Station Code</th>
<th>Latitude (deg)</th>
<th>Longitude (deg)</th>
<th>Elevation (km)</th>
<th>Open Date</th>
<th>Close Date</th>
<th>Description</th>
</tr>
</thead>
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<td>−1.09000</td>
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<td>1/1/1994</td>
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<td>24/8/2011</td>
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<td>30/12/1996</td>
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<td>−1.92100</td>
<td>1/3/1990</td>
<td>ACTIVE</td>
<td>Single-component short-period station</td>
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</table>

*Notes:*

- Dates are formatted as day/month/year.
The differences between the models found by Benz et al. [1996] and DeShon et al. [2007] might reflect differing stages of activity at Redoubt. Alternatively, the difference in models might be attributable to the different algorithms used in the two studies.

In the current study we use a tomographic algorithm that has been applied widely at volcanoes in the past several years [Jaxybulatov et al., 2011; Koulakov et al., 2009, 2011, 2013a, 2013b]. We also use a much larger data set compared to those used in previous studies at Redoubt. We compute two separate 3-D seismic models based on the data corresponding to time periods before and after the 2009 activity episode. The comparison of the models gives us information about dynamical processes in the crust during the eruption.

2. Data and Algorithm

We used the travel time data recorded at 19 stations installed around Redoubt Volcano (Figure 1) in a period of time from 1989 to 2012 as reported in the Alaska Volcano Observatory catalog [Dixon et al., 2012]. Figure 2 shows the locations of 16 and 12 recording sites in the area around the volcano corresponding to two periods before and after the March 2009 Redoubt eruption, respectively. General station information is given in Table 1. Figure 2 also shows the distributions of seismic events in the considered time periods. The total numbers of events in the earlier and later periods were comparable with 2500 and 2000, respectively. Note that most events in the period after March 2009 occurred within only a few months during the Redoubt unrest; thus, these data may represent the state of the volcano during the eruption. It can be seen that the locations of the main seismicity clusters differ slightly, and this difference of data distribution may affect the inversion results. To distinguish the real changes of seismic properties from artifacts related to changes in the observation system configuration, we performed a series of tests, presented in the next section.

The optimal starting model was estimated by performing the full inversion procedure for dozens of different 1-D models. In our case, the P velocity values were defined for several depth levels and were linearly interpolated between these levels. The Vp/Vs ratio was constant for each model and varied from 1.70 to 1.85 during the optimization procedure. We also tested the reference models from previous studies by Benz et al. [1996] and DeShon et al. [2007]. The main criteria used to select the best model were the lowest number of rejected phases with residual values that were larger than a predefined threshold (0.3 and 0.5 s for the P and S data, respectively) after the beginning of the 1-D velocity model, and a maximum number of remaining events with number of picks more than or equal to a predefined value (in our case 10). In the case of equal values of these parameters, the best model was determined according to the values of the root-mean-square (RMS) of travel time misfit.

Table 2 presents the information on the number of data and on the RMS values of the residuals before and after inversion for two models: one is our best 1-D model obtained after a series of trials (Model KAS_1D) and the second corresponds to the P velocity distribution reported by DeShon et al. [2007] with a Vp/Vs ratio equal to 1.75 (Model DESHON). This table includes the information for the two data subsets (before and after March 2009), as well as for the entire data set. It can be seen that the model DESHON provides the maximum number of data and minimum misfit; thus, it was selected as the main reference model in this study.
An example of inversion results for the entire data set based on two different starting models (KAS_1D and DESHON) are presented in Figure 3. The $P$ anomalies are almost identical, whereas the $S$ anomalies appear to be slower, relative to the reference velocities, for DESHON model. However, the general configuration of anomalies remains similar, testifying to the relatively weak effect of the reference model upon the inversion results. The parameters of the KAS_1D and DESHON velocity models are presented in Table 3.

The tomographic inversions were executed using the LOTOS code [Koulakov, 2009] which performs an iterative inversion for $P$ and $S$ velocity parameters and source locations based on arrival times of $P$ and $S$ body waves from local sources. The initial stage of calculation uses the 1-D velocity model to locate sources. It uses a grid search method and linear approximation of the raypaths. By computing new source locations, we remove biases inherited from the original catalog locations. We then use an iterative process that includes the relocation of sources and inversion for velocity parameters. Relocation of sources in the 3-D velocity model is carried out using the bending algorithm for ray tracing which employs a general principle proposed by Um and Thurber [1987].

The velocity model is parameterized using a set of nodes distributed within the study volume according to the ray coverage. In map view, the nodes are installed with constant spacing (1 km in our case) in a regular grid only in areas where data exist. In the vertical direction, the grid spacing depends on the ray density; however, the distance between nodes does not exceed a predefined spacing (1 km in our case). To reduce the effect of the grid distribution upon the results, we performed the inversions for four different grids with different predefined azimuthal orientations (0°, 22°, 45°, and 67°). After computing all models, the results were averaged and recomputed in a regular mesh. The same parameterization grids were used for all iterations.

The inversion was performed simultaneously for $P$ and $S$ velocity models and source parameters (three coordinates and origin time for each source). The $V_p/V_s$ ratio was computed by subdividing the resulting $P$ and $S$ velocities. The adequacy of this approach was validated using different synthetic tests. The tests were also used to check the resolution and to define the optimal values of free parameters used in calculations.

**Table 3. One-Dimensional Velocity Models**

<table>
<thead>
<tr>
<th>Depth</th>
<th>$V_p/V_s$ = 1.75</th>
<th>$V_p/V_s$ = 1.78</th>
</tr>
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<tr>
<td>5</td>
<td>5</td>
<td>2.9</td>
</tr>
<tr>
<td>0</td>
<td>5.2</td>
<td>5.4</td>
</tr>
<tr>
<td>10</td>
<td>5.8</td>
<td>5.75</td>
</tr>
<tr>
<td>30</td>
<td>7.0</td>
<td>6.3</td>
</tr>
<tr>
<td>55</td>
<td>8.1</td>
<td>6.5</td>
</tr>
<tr>
<td>70</td>
<td>8.2</td>
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</tr>
<tr>
<td>240</td>
<td>8.4</td>
<td>6.8</td>
</tr>
</tbody>
</table>
For example, we defined the values of regularization for the real data inversion to insure that the anomaly sizes were not smaller than the minimal synthetic patterns resolved in our tests. Similarly, based on the results of synthetic modeling we estimated the optimal number of iterations at five for both real and synthetic cases.

Table 4. Parameters of the Synthetic Models

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Size of Anomaly (km)</th>
<th>Spacing Between Anomalies (km)</th>
<th>Number of Anomalies</th>
<th>Amplitude of Anomalies (%)</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>1 x 1</td>
<td>±10</td>
</tr>
<tr>
<td>BOARD_02</td>
<td>3 x 3</td>
<td>3</td>
<td>2 x 2</td>
<td>±10</td>
</tr>
<tr>
<td>BOARD_03</td>
<td>2 x 2</td>
<td>2</td>
<td>3 x 3</td>
<td>±10</td>
</tr>
<tr>
<td>VER_BRD1</td>
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<td>0</td>
<td>1 x 1</td>
<td>±10</td>
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<tr>
<td>VER_BRD2</td>
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<td>1 x 2</td>
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<td>4 x 4</td>
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<td>2 x 2</td>
<td>±10</td>
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<td>VER_BRD4</td>
<td>5 x 5</td>
<td>0</td>
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<td>±10</td>
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</table>

Figure 4. Reconstruction results for three synthetic models related to two episodes of observation: (a) before the 2009 eruption and (b) after the 2009 eruption. P and S velocities and Vp/Vs ratios are shown at 0 km depth (sea level). The shapes of the anomalies are highlighted with black lines. Black triangles depict seismic stations. Redoubt summit is marked by a red and yellow triangle.
3. Verification

3.1. Synthetic Tests

We used synthetic tests to assess the spatial resolution of the modeling in two independent time episodes. Synthetic reconstructions were based on the same source-receiver pairs as used for inversion of the observed data. The source coordinates in the synthetic model correspond to the locations after five iterations in the main models, presented in the next section. The travel times in the synthetic models were computed based on 3-D ray tracing using the bending algorithm. The 3-D synthetic model was defined as a superposition of the 1-D reference model and 3-D anomalies. In the LOTOS code there are several options for defining 3-D anomaly models. Here we present two types of checkerboard models defined in map view and in vertical sections. After computing the synthetic data, we discarded the known locations of sources and performed the full processing, following the same procedure as in the observed data inversion. Trade-offs between velocity and source location introduce significant vertical smearing in the velocity anomalies and offsets in the relocated sources.

In the first test we explore horizontal resolution with several checkerboard models using the data corresponding to the two time periods. We present the results for three different models with one, four, and nine anomalies defined in map view. In the vertical direction these anomalies remain unchanged. The parameters of these models are given in Table 4. We define the opposite signs of the $P$ and $S$ anomalies to enable strong variations of the $V_p/V_s$ ratio in the models. Figure 4 presents the reconstruction results for $P$ and $S$ anomalies.
and the Vp/Vs ratio for these three cases at 0 km depth. It can be seen that in all cases the anomalies are correctly reconstructed, which may be evidence that in the case of the observed data inversion, anomalies larger than 2 km size can be robustly resolved based on the existing data configuration. It is important to note that the same anomalies are similarly resolved for the data subsets corresponding to the two time periods. This may indicate that changes in the observation system do not strongly affect the main patterns in the central part of the study area.

In passive tomography vertical resolution is commonly poorer than horizontal resolution; this is because source and velocity parameters trade off against one another. To assess this, we present four synthetic models in a vertical section (Figure 5). These anomalies extend into and out of the figure as side-lying columns. These tests were performed independently for two data subsets. For a single row of anomalies in models VER_BRD1 and VER_BRD2, the lateral locations of the anomalies are correctly recovered. However, they are strongly smeared in the vertical direction. In the case of VER_BRD1, the upper limit of a single anomaly located at 1 km depth is correctly recovered, whereas the lower limit at 5 km depth is strongly smeared downward. In model VER_BRD3, there are four anomalies located in two depth intervals with the transition at 5 km depth. It can be seen that the lower row of anomalies appears to be masked by downward

Figure 5. Results of reconstructions of four synthetic models related to two episodes of observation defined in a vertical section (P and S anomalies and Vp/Vs ratio): (a) before the 2009 eruption and (b) after the 2009 eruption. The locations of synthetic anomalies are indicated with thin black lines. The A1–A2 cross section is the same as in Figure 7. Black dots indicate the projections of earthquake hypocenters located at distances of less than 0.4 km from the profile.
smearing of the upper anomalies. At the same time, comparison of the reconstruction results for VER_BRD2 and VER_BRD3 gives a clear difference in the lower part of the plot. In a case when the transition of the anomaly sign occurs at a depth of 2 km, as in VER_BRD4, both lower and upper rows are reconstructed correctly. These tests demonstrate that horizontal anomalies can be robustly resolved at all depths, whereas the vertical patterns are only resolvable for depths above 2–3 km. These conclusions should be taken into account when interpreting the results of observed data inversion. At the same time, it can be seen that the reconstruction results look similar for the cases corresponding to two different time periods. We conclude that as in the cases of horizontal tests, the vertical resolution is not strongly affected by changes in observation system configurations between two observation episodes.

3.2. Odd/Even Test

To determine the stability of the solution and the effect of noise on the result, we performed an odd/even test consisting of independent inversions of data subsets obtained by splitting the data set into two equal groups using an arbitrary criterion (for example, using odd- and even-numbered events). If the data are mostly affected by random noise, the inversion results would consist of random patterns which would be different for the two different subsets. In the case of low noise level, the images should be similar. We performed this test for two separated time episodes that resulted in two models before March 2009 and two models after.
The results of the inversions according to this test are presented in Figure 6. The results for odd and even tests in each of the time episodes are almost identical, whereas between the episodes the difference of models is significant. The similarity of odd and even data models suggests that the data are of good quality and the changes between the results in the two episodes are not caused by random errors in the travel time data.

Figure 6. Results of independent inversions using two independent data subsets (with odd and even numbers of events, “odd/even test”) presented in one horizontal section and one vertical section, related to two episodes of observation: (a) before the 2009 eruption and (b) after the 2009 eruption.
4. Description of the Results

The main results of this study are two 3-D velocity models corresponding to the time periods before and after the March 2009 eruption of Redoubt Volcano. Both models were calculated in five iterations using identical starting models (DESHON) and the same inversion parameters. The values of variance reduction after five iterations can be found in Table 3. The initial values of residuals after source location in the starting model
were quite small (see Table 2), testifying to the quality of the data. The final residuals after five iterations were similar for both episodes and had the value of approximately 0.05 s for the $P$ residuals and 0.07 s for the $S$ residuals. The variance reduction for the first subset was 31% and 37% for the $P$ and $S$ data, respectively. In the second subset, the corresponding values were 27% for both $P$ and $S$ data.

We present horizontal cross sections of these models (Figure 7) at two depths (0 and 5 km) and in two vertical cross sections (Figure 8). For both horizontal and vertical sections we show the locations of seismic events. The absolute velocities are presented in vertical sections in Figure 9. Note that most of the events in the second subset occurred during the main unrest phase; thus, this model represents the state of the volcano during the eruption and immediately after.

The $P$ velocity structure is similar for both periods. A large high-velocity anomaly is observed below the summit in both cases, though for the latter period, this anomaly appears smaller. To the south and to the north of this high-velocity anomaly we observe two local low-velocity anomalies that appear to be more prominent in the latter period. In the western part of the study area we observe a large low-velocity anomaly which looks similar in both cases. Based on comparison of the $P$ models we conclude that the eruption-related processes did not strongly affect the $P$ velocity.

The $S$ velocity models are quite different, however. Before the eruption the $S$ velocity anomalies generally correlate with the $P$ velocity anomalies. In particular, we observe the summit-related high-velocity structures with low-velocity anomalies to the south and to the north, similar to the case of the $P$ velocities.

**Figure 8.** Anomalies of $P$ and $S$ velocities and $Vp/Vs$ ratio in vertical sections through final tomographic models: (a) before the 2009 eruption and (b) after the 2009 eruption. The locations of vertical sections are shown in Figure 7. Black dots depict the locations of events at distances of less than 0.4 km from the profile.
The model in the latter period corresponding to phases during and after the eruption shows quite different structures. S velocities in the southern part of the high-velocity body drop by more than 10%. Before the eruption the $V_p/V_s$ ratios were moderately high at 1.75–1.80; in the latter period this parameter in the summit area exceeds 2.0.

It is interesting that at 5 km depth the pattern is opposite to that observed near sea level. In the first episode below the summit we observe high-$P$ and low-$S$ velocities resulting in a higher $V_p/V_s$ anomaly. In the second period, both $P$ and $S$ velocities are high, and the $V_p/V_s$ ratio is low beneath the volcano. However, we should keep in mind the results of synthetic tests which demonstrate considerable smearing at 5 km and deeper. Thus, the amplitude of anomalies might appear to be smaller than they are in reality. At the same time the synthetics tests demonstrate that the shapes of the patterns are well resolved.

5. Discussion

The relative magnitude and location of $P$ and $S$ velocity anomalies provide constrains on the geological composition and structure beneath Redoubt. Several studies, including some using the LOTOS code, have demonstrated that in most areas $P$ and $S$ velocities respond similarly to particular geological units. For example, sedimentary basins or fault zones manifest as low $P$ and $S$ velocity features, whereas large batholiths and subducted slabs tend to show as high-$P$ and high-$S$ velocity patterns. For dormant volcanoes this correlation is valid in most tomography studies. However, this is usually not the case for active volcanoes. For example, beneath Klyuchevskoy volcano, Koulakov et al. [2011] observed a large low-$S$ and high-$P$ velocity...
pattern resulting in very high \( V_p/V_s \) ratios of up to 2.2. A similar situation is observed beneath Mount Spurr [Koulakov et al., 2013b] where a magma conduit is associated with higher \( P \) and lower \( S \) velocities. The same patterns were observed in this study for Redoubt Volcano during the second episode corresponding to the unrest phase. Indeed, for areas surrounding Redoubt, parallel patterns are observed in the \( P \) and \( S \) anomalies, whereas for the central part of the ediifice, the results look completely different. Note that the horizontal
resolution in the central area is highest; thus, the observed discrepancy between $P$ and $S$ patterns appears to be robust. The lack of correlation of $P$ and $S$ anomalies might serve as a signature of active tectonic processes related to migration of fluids and melts.

The prominent high-$P$ velocity anomaly beneath Redoubt appears to be quite typical for many other large stratovolcanoes [Koulakov et al., 2011, 2013a, 2013b]. A similar feature was found in the previous study of Redoubt by DeShon et al. [2007]. One explanation for this is that the accumulation of a large volume of solidified magmatic material has erupted during the volcano’s history. Every new layer loads the crust, which subsides due to isostatic compensation. After eruptive activity lasting tens or hundreds of thousands of years, the solidified magma layers may occupy an important part of the crust beneath the volcano. High velocity beneath stratovolcanoes might also be explained by the lithostatic loading below topographic features. For example, at sea level, the pressure below Redoubt is more than 3 times larger than below the surrounding areas. Taking into account the influence of the lithostatic pressure on seismic velocity, the seismic velocities beneath the volcano should be higher.

For the $S$ model in the second episode, a strong low-velocity anomaly is located just below the summit to a depth of approximately 3 km below sea level. The existence of high-$P$ velocity and low-$S$ velocity leads to considerable increase of the $V_p/V_s$ ratio. The deeper portion of this anomaly coincides with a concentration of earthquakes. The synthetic tests show poorer vertical resolution; however, they demonstrate an ability to resolve vertical contrasts at and above 3 km. The observed $V_p/V_s$ feature occupies the entire volcanic edifice. The concurrent high-$P$ and low-$S$ velocities require a reduction in the shear strength in the rock while preserving a matrix that maintains strong compressional strength. One way to achieve this is with high temperature and the presence of small amounts of melts. We propose that the complex of dikes, sills, and pore space beneath the volcano accommodates melt in small quantities. The high temperatures needed to sustain melt, and the melt itself, have a significant impact on the shear strength of the rock, while affecting the $P$ velocities only modestly. Though the melt fraction must be low in order to sustain the high-$P$ velocities, when integrated over the volume of the high $V_p/V_s$ volume, it is possible that the system holds considerable volumes of magma. We do not see any evidence for the existence of separated magma chambers within the volcano.

Below 3 km depth the general patterns look opposite to those observed in the near-surface areas. In the first episode prior to the eruption we observe lower $S$ velocity which results in a higher $V_p/V_s$ anomaly located just below the summit. In the second episode during and after the eruption, the $S$ velocity anomaly below 3 km depth becomes positive and $V_p/V_s$ ratio decreases. This may indicate that before the eruption the fluids and melts were contained in a conduit located below 3 km depth, whereas the shallower areas were “dry” and manifested a relatively low $V_p/V_s$ ratio. During the eruption, a large portion of fluids and melts from the deep conduit migrated upward and caused fluid saturation within the summit and a deficit of liquids in deeper parts. This observation seems to be consistent with the petrological model of Coombs et al. [2013] that suggests multilevel magma sources, with low-silica andesites coming from the lower crust early in the eruption and replaced later with higher-silica andesites from shallow depths. Migration of magma sources from deeper levels to the shallowest crust was also proposed by Power et al. [2013] who found three levels of seismicity at ~30 km, 3–9 km, and 1–2 km below the crater. In our results, the existence of a high $V_p/V_s$ anomaly below 3 km depth before the eruption may correspond to the intermediate source identified by Power et al. [2013], whereas the strong $V_p/V_s$ anomaly during and after the eruption may represent the shallowest source.

Notably different velocity structures in the two time episodes strongly suggest that the eruption led to considerable changes in the rock structure below the volcano. We hypothesize that prior to the eruption the edifice region was cool, well-consolidated rock evidenced by typical, and even high, $P$ and $S$ velocities. During the first eruptive episode, some of the magmas and fumarolic gases fractured the rock, penetrating from the deeper conduit zone marked by a high $V_p/V_s$ ratio. During the second episode, the injected fluids and melts likely remained in cracks and pore spaces leading to a marked decrease in $S$ velocities and minimal decreases in $P$ velocities. The data are insufficient to allow a higher-resolution examination of the temporal history, so it is not possible to pinpoint the exact time when this changed. However, it is clear that the 3.5 years of data following the 2009 eruption point to much slower edifice velocities than the average model of the previous 18 years. If this is true, we expect the velocities (and $S$ velocities in particular) to slowly increase to previous values in the coming years.
6. Conclusion

We present new 3-D velocity models of the upper crust beneath Redoubt Volcano corresponding to two episodes before and after the eruption of 2009. These models contain \( P \) and \( S \) velocities and the ratio of these two parameters. Similar observation conditions made it possible to compare the results and revealed temporal changes likely related to the eruption activity. In both episodes, \( P \) velocities remained generally higher below the summit than in surrounding areas. This is likely an indication of well-consolidated igneous rock, accumulated over thousands of years of eruption activity, which is not strongly affected by the presence of fluids and melts released during the eruption. \( S \) velocities, by contrast, change markedly between the two periods. Prior to the eruption, the summit area is generally higher velocity than surrounding areas, though not as strong as the \( P \) velocity anomaly. In the period after the eruption this feature was replaced by prominent low velocities. The \( P \) and \( S \) velocity changes result in a very high \( V_P/V_S \) ratio in the period after the eruption. We cannot pinpoint the exact timing of the velocity changes. The sharp differences between the two models point to this change occurring relatively quickly near the time of the eruption. This supports the hypothesis proposed by Koulakov et al. (2013a) for Klyuchevskoy volcano that magma sources exist in sponge-structured volumes containing overheated rocks. The materials in these areas can change their aggregate properties from liquid to solid and back in response to hot fluids percolating through the system. As these fluids move upward, some escape to the atmosphere while others remain in crust and cool down. Together, these effects return a volcano to its previous state in the years following eruption. If this is true, then the presence of distributed fluids in the shallow crust beneath volcanoes is a potential harbinger of pending eruptions. This idea suggests that monitoring in situ fluids and gases, in addition to those vented into the atmosphere, could be useful in forecasting eruptions. Results such as these at Redoubt suggest that seismic tomography has the capacity to assess velocity changes associated with the migration of fluids through shallow volcanic systems. A complete assessment of this methodology would require a denser, more uniform seismic network. However, the current work offers strong evidence that eruption-related seismic velocity changes do exist and hold the potential for real-time monitoring applications.

All the results presented in this study can be reproduced by any interested parties using the template at www.ivan-art.com/science/LOTOS/redoubt_lotos12.zip. This file contains the Fortran source and executable files of the LOTOS code, the initial data, and the parameter sets for all real and synthetic models presented in this paper. Instructions in the README file allow users to run all calculations and produce the same images as are presented in this paper.

References


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