Supporting Information for

Imaging the Magmatic System of Newberry Volcano Using Joint Active Source and Teleseismic Tomography

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Introduction

In this section, we address the depth extent of the tomography model, the resolution of the inferred magma body as well as the resolution of a narrow, low velocity anomaly from ~1-3 km depth. In addition, seismograms for a teleseismic event are shown to support our argument for the presence of a low velocity larger than that imaged tomographically. Finally, we discuss the likelihood of a temporally stable magma system beneath Newberry volcano.

Depth Extent and Deeper Structure of the Tomography Model

To investigate the sensitivity of the data to deeper structure we conducted inversions that varied the vertical extent of the tomographic model. A model extending from the surface to 8 km bsl (~10 km depth) (Figure S1) is the smallest vertical extent that fits the observations and still maintains first-order features in both the deep and shallow models. We cannot resolve deeper structure due to the limitation of recording teleseismic events for only several weeks on a linear array.

While observed travel times (Figure 6 and Figure 7) show long wavelength trends that may result from mid- to lower-crustal anomalies, such structure will be mapped to long wavelength mid-crustal features in our result. Since we are interested in smaller scale structure in the vicinity of the caldera, any such long-wavelength anomalies do not affect our interpretations.

Depth slices through the deeper part of the recovered tomography model show a high velocity anomaly between 8 and 10 km depth beneath the caldera (Figure S2 and Figure 9).
The fast velocity beneath the magma body (Figure S2) is a robust feature, though the depth to the anomaly increases with the depth extent of the model (Figure S1).

**Magma Body Resolution**

We compared tomographic results obtained by inverting data from active sources and teleseismic events separately. For these tests our synthetic model is the preferred tomography result with a low-velocity anomaly, corresponding to a magma body, superposed (Figure S3a and Figure S4). The magma body anomaly is located from 3-4 km depth and extends from ~3 to 3 km in the x and y directions. The low-velocity anomaly has a compressional wave velocity of 2.3 km/s (representing 100% partial melt), which corresponds to ~0.5 fractional change in velocity ($\delta \ln(V)$). The synthetic magma body replaces the low velocity anomaly seen in our preferred tomography result. We predict both teleseismic and active source travel times using this synthetic model. For the resolution tests the inversions use a 1-D starting velocity model.

Figure S3c and Figure S5 show the results of inverting synthetic travel time data for active sources only. At depths less than 3 km the velocity structure is well recovered. However, analogous to results shown in *Beachly et al.* [2012], resolution of the LVV from 3 to 5 km depth and below is poor.

Figure S3d and Figure S6 show the results of inverting synthetic travel time data for teleseismic sources only. This inversion uses data for only the 2008 experimental geometry. There is reasonable sampling of deeper structure and good lateral resolution along the receiver array. However, features streak vertically and the resolution is poor at shallow depths due to limited ray crossings, the 2D geometry of the 2008 seismic array, and the small number of events recorded in a 2-3 week period.

Figure S3b and Figure S7 show that by jointly inverting predicted travel times for both the active source and teleseismic data, resolution of the LVV is improved (see further discussion below). The improved resolution of the LVV is because the active source data constrains the shallow crustal structure and the teleseismic data constrains the horizontal extent of the LVV.

While the larger-scale shape of the low-velocity anomaly is recovered for the coupled tomography model (Figure S3b and Figure S7), the magnitude and shape of superposed sill is not well imaged. This is due to ray bending, where the first arriving energy bends around a low-velocity anomaly whose spatial size is similar to or smaller than the seismic wavelength.

We evaluated the resolution of our preferred model in the horizontal plane by comparing inversions of synthetic and actual data. In the synthetic inversions, the recovered low velocity anomaly at 3 to 4 km depth (Figure S7) is relatively circular and does not exhibit the N-S elongation observed in our preferred tomography inversion (e.g., Figure 9), indicating that the N-S elongation of the LVV is likely real. The recovered magma body becomes more prominent at a deeper depth (~4 km) than in the synthetic input model (3 km) indicating that the true LVV could extend to shallow depths but be tomographically unresolvable.

**Resolution of low-velocity pipe-like anomaly from 1 to 3 km depth**

We performed a resolution test to investigate whether the low-velocity, pipe-like feature from 1 to 3 km depth is a result of vertical streaking. In this test, we generated a synthetic starting velocity model by removing the low-velocity anomaly between 1 and 3 km depth from the preferred tomography model (Figure S8) and predicted travel times for both teleseismic and active sources. We then performed the coupled tomographic inversion using these predicted
delay and arrival times. The resulting velocity model does show streaking from the LVV to the surface, however the magnitude of this anomaly is less than the LV pipe recovered in our preferred seismic model (e.g., Figure 10). We conclude that while the LV pipe may partially result from streaking, it is at least partially the consequence of lower velocities between 1 and 3 km depth.

Coda resulting from the magma body

In Figure S9, we show a seismogram for an earthquake with a similar azimuth and ray parameter to the 2-D synthetic waveforms shown in Figure 12. This event shows large amplitude coda in the caldera on both horizontal channels implying large low velocity anomalies at depth. Synthetic waves propagated through the tomographic model (Figure 12 a, d, g) do not exhibit the large amplitude coda observed in Figure S9.

Figure 4 shows seismograms for a higher signal noise ratio event compared to the event in Figure S9, but which arrives is oblique to the 2-D model cross section. Noticeably, the ringing in the caldera is consistent between the two events.

Temporal Stability of the Magma Body

Petrologic studies indicate that the last caldera eruption was sourced from a magma body at pressures of ~1 kbar [Mandler et al., 2014], which is consistent with the depths inferred from our tomographic study. This suggests that there has been some form of shallow magma body at 3 to 5 km throughout a significant portion of the last ~75 kyr at Newberry. However, the observation that the LVV extends north of the caldera suggests that the LVV may have shifted northward since the most recent caldera forming eruption (~80 kyr, [Jensen et al., 2009]). In addition, geothermal models with magma bodies of similar size to the recovered LVV tend to over-predict temperature drop-off with distance from the magma body [Frone et al., 2014], suggesting that in the past a larger magmatic system was present than is currently imaged. However, thermal anomalies persist long after melt solidifies and our inference of solidified intrusions beneath the volcano’s flanks compare well with the predicted location of solidified sill for thermal models with a 200 kyr magma recharge interval [Frone et al., 2014].

Assuming the LVV we image represents a magma body, we perform calculations to place constraints on magma body size. We use a simple 1-D calculation from Turcotte and Schubert [2002] to investigate sill solidification times (Figure S10). Our values are 320 kJ kg⁻¹ for latent heat of fusion, 1.2 kJ kg⁻¹ K⁻¹ for the specific heat, and 0.5 mm²/s for thermal diffusivity [Turcotte and Schubert, 2002]. In contrast to 1-D thermal modeling by Beachly et al. [2012] who used a low background temperature, we vary the temperature difference between the melt and the background medium as well as the thickness of the sill to investigate the effect of ambient thermal structure and magma body size on solidification time. Using a purely conductive cooling model, for reasonably small sills (~800 m) it takes ~10 kyr to completely solidify depending on the temperature difference between the magma body and the background rock. These simple results indicate it is entirely plausible to expect a partially molten magma body beneath Newberry without having to invoke new magmatic input, given the relatively recent eruption 1,300 years ago. However, we hypothesize that due to the consistent repose time and lack of crystallization in erupted rhyolites [MacLeod and Sherrod, 1988], basaltic underplating may be keeping the magma body warm. Without underplating, about half of a
small 600-800 m sill would crystallize during the 2,000-3,000 year average repose time between rhyolitic eruptions.
Figures

Figure S1: Comparison of recovered velocity perturbations for tomographic models with different depth extents. a): Cross-section through the preferred tomographic model that extends to 8 km bsl. b): Cross-section for a model that extends to 12 km bsl. Results masked by derivative weight sum, DWS [Toomey et al., 1994]. Black triangles indicate station locations. Section taken from line A to A’ (Figure 2).

Figure S2: Depth slices through the preferred tomographic model from 5 to 9.4 km depth showing the presence of a high velocity anomaly from 8-10 km depth beneath the caldera.

Figure S3: Comparison of tomographic results for different subsets of the travel time data calculated for a synthetic input velocity model. a): Cross section through the synthetic model; see text for description. b): Cross section for an inversion obtained using both predicted teleseismic and active source data. c): Cross section through an inversion obtained using only predicted teleseismic data. d): Cross section through an inversion obtained using only predicted active source data. Vertical cross sections are from x = -20, y = -20 to x = 20, y = 20. Masking and symbols identical to Fig. S1.

Figure S4: Map-view sections through a synthetic velocity model that includes a molten sill; see text for description. White triangles indicate station locations.

Figure S5: Tomographic velocity model obtained using only synthetic active source travel times. Stations shown as white triangles. See text for discussion.

Figure S6: Tomographic velocity model obtained using only synthetic teleseismic delay times recorded on the stations shown as white triangles. See text for discussion.

Figure S7: Tomographic model obtained using both active and teleseismic synthetic data. See text for discussion. Masking identical to Fig. S1; white triangles indicate station locations.

Figure S8: Synthetic and recovered velocity models used to test the existence of a low-velocity, pipe-like anomaly from 1-3 km depth. a): The starting velocity model is plotted as fractional change in velocity with respect to a 1-D model. The model is our preferred velocity result (Figures 9-10), with the low-velocity anomaly between 1 and 3 km depth removed. b): Recovered tomographic model using travel times and delay times predicted for the synthetic velocity model. See text for discussion.

Figure S9: Seismograms from Event 1103 plotted as in Figure 4. Event 1103 has a ray parameter 0.075 s/km. The teleseismic event is located at 51.4° N, -178.4°E and is approximately incident along the line A-A’ (Figure 2). Large amplitude coda on both horizontal channels compare favorably with synthetics with larger low velocity anomalies than tomographically images (Figure 12 a, d, g).

Figure S10: Plot of solidification time for different magma sill thicknesses and different temperature differences between the magma sill and background crust using sill solidification formula and physical property values from Turcotte and Schubert [2002]. Property values are 320 kJ kg⁻¹ for latent heat of fusion, 1.2 kJ kg⁻¹ K⁻¹ for the specific heat, and 0.5 mm²/s for thermal diffusivity.
Figure S1

Preferred Model

Deeper Model
Figure S2

- 5 km
- 6 km
- 7 km
- 8 km
- 9 km
- 9.4 km

Distance (km)

\[
\ln(V) - \delta \ln(V)
\]
Figure S3

a.) Synthetic Model

b.) Coupled Model

c.) Active Source Model

d.) Teleseismic Model
Figure S4
Figure S5

0.4 km

1 km

2 km

3 km

4 km

5 km

Distance (km)

Distance (km)

Distance (km)

Distance (km)

Distance (km)

δ ln(V)

-0.15 -0.1 -0.05 0 0.05 0.1 0.15
Figure S7

Distance (km)

0.4 km

δ ln(V)

-0.15 -0.1 -0.05 0 0.05 0.1 0.15

1 km

2 km

3 km

4 km

5 km

Distance (km)

Distance (km)
Figure S8

(a).

Synthetic Model

(b).

Resolved Model from Synthetic Data
Figure S9
Figure S10

Time to Solidification

Temperature Difference (deg C)

- 1000 meter thick sill
- 800 meter thick sill
- 600 meter thick sill
- 400 meter thick sill
- 200 meter thick sill