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Magma reservoirs from the upper crust to the Moho inferred from high-resolution Vp and Vs models beneath Mount St. Helens, Washington State, USA

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ABSTRACT

The size, frequency, and intensity of volcanic eruptions are strongly controlled by the volume and connectivity of magma within the crust. Several geophysical and geochemical studies have produced a comprehensive model of the magmatic system to depths near 7 km beneath Mount St. Helens (Washington State, USA), currently the most active volcano in the Cascade Range. Data limitations have precluded imaging below this depth to observe the entire primary shallow magma reservoir, as well as its connection to deeper zones of magma accumulation in the crust. The inversion of P and S wave traveltime data collected during the active-source component of the iMUSH (Imaging Magma Under St. Helens) project reveals a high P-wave (Vp)/S-wave (Vs) velocity anomaly beneath Mount St. Helens between depths of 4 and 13 km, which we interpret as the primary upper–middle crustal magma reservoir. Beneath and southeast of this shallow reservoir, a low Vp velocity column extends from 15 km depth to the Moho. Deep long-period events near the boundary of this column indicate that this anomaly is associated with the injection of magmatic fluids. Southeast of Mount St. Helens, an upper–middle crustal high Vp/Vs body beneath the Indian Heaven Volcanic Field may also have a magmatic origin. Both of these high Vp/Vs bodies are at the boundaries of the low Vp middle–lower crustal column and both are directly above high Vp middle–lower crustal regions that may represent cumulates associated with recent Quaternary or Paleogene–Neogene Cascade magmatism. Seismicity immediately following the 18 May 1980 eruption terminates near the top of the inferred middle–lower crustal cumulates and directly adjacent to the inferred middle–lower crustal magma reservoir. These spatial relationships suggest that the boundaries of these high-density cumulates play an important role in both vertical and lateral transport of magma through the crust.

INTRODUCTION

Mount St. Helens (southwestern Washington State, USA) is part of the Cascadia volcanic arc, a series of volcanoes striking parallel to the west coast of the United States and Canada resulting from subduction of the Gorda and Juan de Fuca plates. The 18 May 1980 eruption of this volcano was the most destructive in United States history, with 57 deaths and >$1 billion in damage. Mount St. Helens, which is on top of a mostly volcanic Oligocene to early Miocene eastward-dipping Cascade predecessor (Evarts et al., 1987), is shifted 50 km west of the current Cascade axis, and is younger than nearby volcanoes of the Cascadia arc; recent volcanism began in this region at 300 ka (Clynne et al., 2008). Prominent regional features that may influence the Mount St. Helens magmatic system include the large accreted oceanic terrane Siletzia (Wells et al., 2014) and the southern Washington Cascades conductor (SWCC; Stanley et al., 1987). The eastern edge of Siletzia, which extends from southern Oregon to Vancouver Island (Wells et al., 1998), is at the northwestern end of the Mount St. Helens seismic zone, and it has been argued that this boundary may strongly influence volcanism and seismicity in the region (Parsons et al., 1999). The SWCC is an electrically conductive eastward-dipping zone that primarily underlies the region between Mount St. Helens, Mount Adams, and Mount Rainier (Stanley et al., 1987). This unit was originally attributed to the presence of forearc and/or accretionary prism Cretaceous to Eocene marine rocks (Stanley et al., 1987), although more recent studies argue for a magmatic origin (Hill et al., 2009; Wannamaker et al., 2014)

Several studies using a variety of data sets investigated the magmatic system beneath Mount St. Helens following the 1980 eruption. Seismicity, petrologic, and geodetic data all suggest a simple magma reservoir between 5 and 12 km depth below sea level directly beneath Mount St. Helens (e.g., Scandone and Malone, 1985; Williams et al., 1987; Weaver et al., 1987; Pallister et al., 1992, 2008). P-wave seismic velocity models that image the top of a low-velocity region at 7 km depth support this magma reservoir model, although an additional small low-velocity body between depths of 1 and 3 km below sea level has also been imaged (Lees, 1992; Waite and Moran, 2009). Below 7–10 km depth, knowledge regarding the magmatic system degrades as seismicity decreases and becomes more diffuse, limiting both the resolution of seismic velocity models and the inferences that can be made based upon earthquake locations. Isolated from this seismicity is a cluster of deep long-period (DLP) events southeast of the volcano concentrated at depths between 24 and 32 km (Nichols et al., 2011). Although the mechanism of DLP events is still being investigated (e.g., Aso and Tsai, 2014), several studies indicate that they are associated with the injection of magmatic fluids (White, 1996; Power et al., 2004; Hill and Prejean, 2005).

DATA

The multidisciplinary iMUSH (Imaging Magma Under St. Helens; http://imush.org) experiment was designed to provide a comprehensive view of the entire magmatic system from the subducting Juan de Fuca slab to the surface. The active-source component of this experiment recorded data from 23 450–900 kg borehole shots and several regional earthquakes at ~6000 seismograph locations (Fig. 1). As a first view of the magmatic system, seismic wave traveltimes along two lines of instruments oriented N42E (X line) and S57E (Y line) were inverted to produce two-dimensional (2-D) seismic velocity models (see the GSA Data

GEOLOGY, June 2016; v. 44; no. 6; p. 411–414 | Data Repository item 2016134 | doi:10.1130/G37591.1 | Published online 28 April 2016

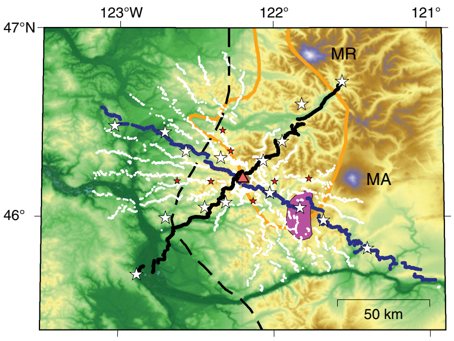

Figure 1. The iMUSH (Imaging Magma Under St. Helens; http://imush.org) active-source deployment. White dots show all instrument locations. Black (N42E; X line) and blue (S57E; Y line) dots are the two lines of instruments used for this study; the white stars along each line show shot locations. Red stars are additional shot locations not used in this study. Mount St. Helens is shown with a red triangle, and Mount Adams and Mount Rainier are labeled with MA and MR, respectively. Pink region is the Indian Heaven Volcanic Field (Hildreth, 2007); orange line is the boundary of the southern Washington Cascades conductor (SWCC) (Stanley et al., 1996); black dashed line is the eastern boundary of Siletzia as inferred from magnetic data (Wells et al., 1998).

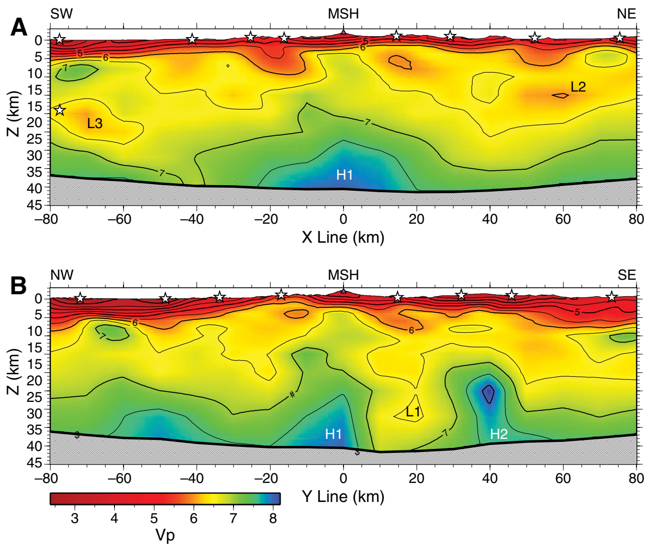

Figure 2. A: Vp for the X line. B: Vp for the Y line. White stars at the surface are shot locations, and the white star in the subsurface is the location of an M2.1 earthquake that occurred along the X line, and is used in this study. Magenta triangles mark the location of Mount St. Helens (MSH; Washington State, USA). Thick black line is the Moho. The underlying mantle (gray region) is not modeled. The labels H1, H2, L1, L2, and L3 correspond to features discussed in the text.

Repository[1]). Transmitted P and S waves were recorded along both lines (Fig. DR1 in the Data Repository). P-wave Moho reflections were also recorded along both lines (Fig. DR1), although these arrivals tend to have smaller amplitudes west of Mount St. Helens (Hansen et al, 2015). This combination of data enabled modeling of P-wave seismic velocities throughout the crust to depths of ~40 km, and S-wave seismic velocities to depths of ~15 km (Figs. DR2–DR5). It should be noted that future 3-D modeling of the entire active-source data set will likely resolve smaller scale features than are observed in our results. However, preliminary traveltime residuals from the entire data set indicate that the length scales of velocity anomalies are large enough to support the use of 2-D modeling in this region (Fig. DR15).

RESULTS

P-wave seismic velocities (Vp) exhibit considerable lateral variations along both lines (Fig. 2; Fig. DR9). Where the two lines meet, relatively high Vp extends from near the volcanic edifice to the Moho. Within the lower crust, this anomaly (H1 in Fig. 2) varies in width from 25 km beneath the Y line to 45 km beneath the X line. An additional high Vp feature with similar width occurs near the Moho 40 km to the southeast of Mount St. Helens on the Y line (H2 in Fig. 2B). Separating the two high Vp features on the Y line is a low Vp column that extends from the Moho to ~15 km (L1 in Fig. 2B; Fig. DR12B). The middle crust generally has lower Vp east of Mount St. Helens, and a prominent low Vp anomaly exists 50–60 km to the northeast on the X line at ~15 km depth (L2 in Fig. 2A). Near the southwest edge of the X line, a low Vp anomaly occurs between 17 and 28 km depth, and dips to the east (L3 in Fig. 2A). The S-wave velocity (Vs) models show different spatial distributions of velocity anomalies near Mount St. Helens, with a low-velocity anomaly dominating beneath the volcano (Figs. DR9 and DR10). This leads to a high Vp/Vs body that is ~15 km wide and extends between 4 and 13 km depth (F1 in Fig. 3), although these dimensions are probably upper bounds due to resolution limitations (Figs. DR2–DR5). Additional high Vp/Vs features occur southwest (F2 in Fig. 3A) and northwest (F3 in Fig. 3B) of Mount St. Helens at distances of ~50 and 40 km on the X and Y lines, respectively. A prominent high Vp/Vs body exists 30–45 km southeast of Mount St. Helens on the Y line between depths of 3 and 14 km (F4 in Fig. 3B), although the top of this body has relatively large uncertainties (Fig. DR8), so this depth extent is probably an upper bound.

DISCUSSION

Seismic velocities are influenced by temperature (Christensen and Mooney, 1995), composition (Christensen, 1996), pore fluid properties (Mavko, 1980), and pore geometries (Takei, 2002). The Vp/Vs ratio can also be affected by composition (Christensen, 1996), although anomalies in this parameter are typically associated with fluid properties and pore geometries (Takei, 2002). Given the context of the high Vp/Vs body beneath Mount St. Helens (F1 in Fig. 3), the presence of melt provides the best explanation for this anomaly. The top of the anomaly at 4 km depth below sea level agrees reasonably well with petrologic estimates of the magma reservoir depth (Pallister et al., 1992), and clusters of seismicity thought to be associated with pressure changes within the reservoir (Weaver et al., 1987; Musumeci, 2002) extend to the bottom of the Vp/Vs anomaly at 13 km depth below sea level (Fig. DR13). In addition, more recent seismicity is concentrated in a nearly vertical, ~1-km-wide column extending from beneath the summit crater to ~4 km depth, and

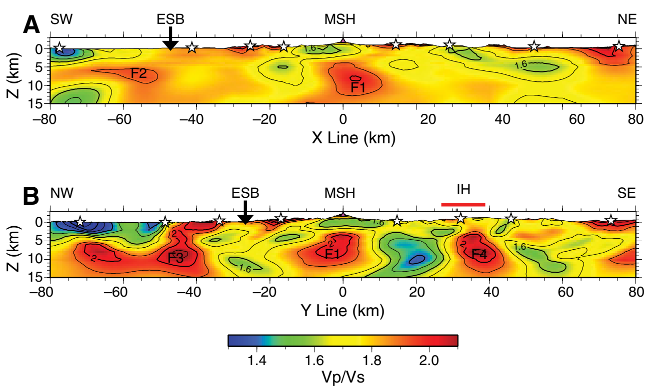

Figure 3. A: Vp/Vs for the X line. B: Vp/Vs for the Y line. The eastern boundary of Siletzia (ESB) determined from magnetic data is marked along each line (Wells et al., 1998). The Indian Heaven Volcanic Field (IH) is labeled (red bar) on the Y line (Hildreth, 2007) (MSH—Mount St. Helens). The labels F1–F4 correspond to features discussed in the text.

[1]GSA Data Repository item 2016134, Figures DR1–DR15, descriptions of data, methods, resolution, uncertainty, and additional models, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

has been suggested to represent a highly fractured conduit connecting the magma chamber to the surface (Hansen and Schmandt, 2015). The high Vp (Fig. 2) and Vp/Vs (Fig. 3) anomalies beneath Mount St. Helens agree with studies based upon gabbroic inclusions in recent eruptive products that argue that the magma reservoir is interspersed with either a Miocene intrusive complex (Williams et al., 1987; Pallister et al., 2008) or a mafic pluton associated with crystallization of basaltic magma that has intruded the system over the past 3 k.y. (Heliker, 1995). Low Vp/Vs regions surrounding the inferred magma reservoir may be associated with quartzite within the contact aureole (Fig. 3; Christensen, 1996). One feature observed in previous studies that is not present in our velocity models is the small shallow low Vp anomaly between 1 and 3 km depth (Waite and Moran, 2009). As resolution tests indicate (Figs. DR2 and DR4), features with length scales below 5 km are not well resolved with the 2-D data set.

In addition to the inferred magma reservoir beneath Mount St. Helens, at least three regions of high Vp/Vs exist southwest, northwest, and southeast of the volcano. Both the southwest (F2 in Fig. 3A) and northwest (F3 in Fig. 3B) anomalies have eastern boundaries close to the inferred eastern boundary of the accreted terrane Siletzia (Wells et al., 1998). This implies that the high Vp/Vs anomalies represent upper sections of the accreted terrane, with the source of the anomalies possibly being serpentinite (Christensen, 1996). The southeastern Vp/Vs anomaly (F4 in Fig. 3B) occurs below the Indian Heaven Volcanic Field, several north-south–oriented vents that produced 60–80 km^3 of mostly basalt between 780 and 9 ka (Hildreth, 2007). The correlation between the high Vp/Vs body and the Indian Heaven Volcanic Field suggests that this subsurface feature is a zone of remnant magmatic fluids associated with past volcanism.

Although a low Vp feature in the middle crust (L2 in Fig. 2A) that correlates well with the SWCC (Fig. 4A) is observed northeast of Mount St. Helens, a lack of Vs resolution below 15 km (Fig. DR3) precludes an interpretation of this body based upon Vp/Vs values. Using magnetotelluric data, Hill et al. (2009) imaged an upper crustal high-conductivity region ~20 km north of the high Vp/Vs body beneath Indian Heaven Volcanic Field (F4 in Fig. 4B), which is connected to the SWCC in the middle to lower crust. Assuming that the high Vp/Vs and high-conductivity upper crustal bodies are connected may support a magmatic interpretation of this shallow portion of the SWCC, although 3-D modeling of the entire active-source data set is needed to assess this conclusion.

As with the Vp/Vs anomalies beneath Mount St. Helens and the Indian Heaven Volcanic Field, it is important to consider the context of the low Vp anomaly that extends from 15 km depth to the Moho southeast of Mount St. Helens (L1 in Fig. 2B) in order to interpret its origin. Specifically, the cluster of DLP events at the boundary of this anomaly suggests that it is associated with the injection of magmatic fluids into the middle and lower crust (Fig. 4B). Additional prominent middle–lower crustal Vp anomalies include an east-dipping low Vp body southwest of Mount St. Helens (L3 in Fig. 2A) and two high Vp anomalies (H1 and H2 in Fig. 2) that bracket the low Vp column associated with magmatic fluids (L1 in Fig. 2). Similar east-dipping low Vp features have been observed north of L3, and may be associated with subducted and underplated sediments from the Juan de Fuca plate (Calvert et al., 2011). In contrast, the high Vp anomaly at the base of the crust beneath Mount St. Helens (H1 in Fig. 2) has not previously been observed. Given its location beneath an active volcano, and its velocity of ~8.0 km/s, an ultramafic source of the anomaly is likely (Christensen, 1996). In particular, this high Vp region may represent lower crustal cumulates (e.g., pyroxenites) associated with either recent Quaternary or Paleogene–Neogene Cascade volcanism. The margins of these impermeable dense cumulates may provide pathways for enhanced magma ascent in the middle and lower crust, which would explain the spatial correlation between the high Vp lower crustal region and the shallow reservoir beneath Mount St. Helens (F1 in Fig. 4), as well as the locations of DLP events near the boundary between the high (H1) and low (L1) Vp anomalies in the lower crust (Fig. 4). A similar argument can be made for the high Vp anomaly southeast of Mount St. Helens (H2 in Fig. 2B) underlying the Indian Heaven Volcanic Field and the associated shallow high Vp/Vs anomaly (F4 in Fig. 4B). We interpret the low Vp column between these high Vp regions (L1 in Fig. 4B) as a focus of lower crustal melt accumulation from which magma ascends to shallow storage zones.

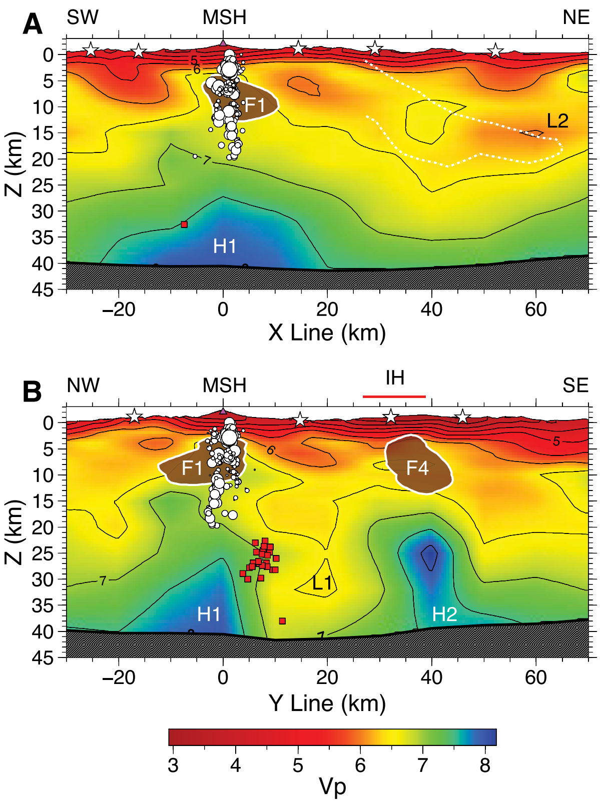

Figure 4. A: Summary of Vp and Vp/Vs anomalies along the X line. B: Summary of Vp and Vp/Vs anomalies along the Y line. The background model is Vp. Red transparent bodies are regions with Vp/Vs ≥ 1.9 associated with Mount St. Helens and the Indian Heaven Volcanic Field (MSH, IH; Washington State, USA). White dots are earthquakes during the first 24 h following the 18 May 1980 eruption scaled by magnitude within 3 km of each line. Red squares are all deep long-period (DLP) events between 1980 and 2015 within 3 km of each line. All earthquake and DLP event locations are from the Pacific Northwest Seismic Network (PNSN; www.pnsn.org) catalogue. The dash-dot white outline overlaying the X line velocity model in A is the approximate location of the southern Washington Cascades conductor (SWCC) based upon magnetotelluric data where the seismic and conductivity models intersect (Stanley et al., 1996). The H, L, and F labels correspond to features discussed in the text.

The Vp and Vp/Vs results suggest that there are at least two magma reservoirs that feed Mount St. Helens (L1 and F1 in Fig. 4). No direct connection between these reservoirs is imaged in the 2-D velocity models (Fig. 4), possibly suggesting that magma transport between these bodies is transient and involves a system of small-scale dikes and sills. Seismicity between these reservoirs is rare (Fig. DR11) with the exception of a column of events that extended from the edifice to 20 km depth immediately following the 18 May 1980 eruption (Fig. 4). This column of seismicity was probably associated with stress changes within the upper–middle crustal plumbing system due to volume loss following the eruption (Barker and Malone, 1991; Moran, 1994). The orientation of the seismicity is similar to northeast-striking fractures in the region, suggesting that one or more of these fractures plays an important role in transporting magma from the middle crust to the shallow reservoir (Weaver et al., 1987). The column of seismicity associated with the 18 May 1980 eruption also terminates near the top of the inferred middle–lower crustal cumulate body beneath Mount St. Helens (H1 in

Fig. 4) and adjacent to the inferred deep magma reservoir to the southeast (L1 in Fig. 4). This observation suggests that the top boundary of the inferred cumulate body may serve as an interface along which lateral migration of magma can occur between the deep reservoir and the fracture network that directly feeds the reservoir beneath Mount St. Helens.

ACKNOWLEDGMENTS

We thank Rick Aster and two anonymous reviewers for their useful comments. The active-source experiment and data analysis were funded by National Science Foundation (NSF) grants EAR-1144455 and EAR-1545750. Densification of the active source array in close proximity to Mount St. Helens was supported by NSF grant EAR-1445937. We thank IRIS (Incorporated Research Institutions for Seismology) for providing the Reftek 125A data recorders and geophones used for the experiment. We are grateful for the excellent field support of Lloyd Carothers, Mouse Reusch, Katherine Anderson Aur, and Federica Lanza from PASSCAL (Portable Array Seismic Studies of the Continental Lithosphere) during the iMUSH (Imaging Magma Under St. Helens) active-source seismic experiment. The experiment would not have been possible without access to land owned and/or managed by the Gifford Pinochet National Forest, Mount St. Helens National Monument, Weyerhaeuser, Columbia Timberlands, Pope Resources, Port Blakely, Sierra Pacific Industries, the State of Washington Department of Transportation and Department of Natural Resources, numerous counties in Washington and Oregon, the Castle Rock, Woodland, and Stevenson-Carson school districts, and numerous private landowners. We thank Ryan Cole and Ellie Lathrop for the numerous hours that they devoted to helping us with the permitting process, and the iMUSH active-source deployment team, which involved 70 volunteers from 36 institutions in the United States and Europe. Their time and effort were essential for the success of this project.

REFERENCES CITED

Aso, N., and Tsai, V.C., 2014, Cooling magma model for deep volcanic long-period earthquakes: Journal of Geophysical Research, v. 119, p. 8442–8456, doi:10.1002/2014JB011180.

Barker, S.E., and Malone, S.D., 1991, Magmatic system geometry at Mount St. Helens Modeled from the stress field associated with posteruptive earthquakes: Journal of Geophysical Research, v. 96, p. 11,883–11,894, doi:10.1029/91JB00430.

Calvert, A.J., Preston, L.A., and Farahbod, A.M., 2011, Sedimentary underplating at the Cascadia mantle-wedge corner revealed by seismic imaging: Nature Geoscience, v. 4, p. 545–548, doi:10.1038/ngeo1195.

Christensen, N.I., 1996, Poisson's ratio and crustal seismology: Journal of Geophysical Research, v. 101, p. 3139–3156, doi:10.1029/95JB03446.

Christensen, N.I., and Mooney, W.D., 1995, Seismic velocity structure and composition of the continental crust: A global view: Journal of Geophysical Research, v. 100, p. 9761–9788, doi:10.1029/95JB00259.

Clynne, M.A., Calvert, A.T., Wolfe, E.W., Evarts, R.C., Fleck, R.J., and Lanphere, M., 2008, The Pleistocene eruptive history of Mount St. Helens, Washington, from 300,000 to 12,800 years before present, *in* Sherrod, D.R., et al., eds., A volcano rekindled: The renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750, p. 593–627.

Evarts, R.C., Ashley, R.P., and Smith, J.G., 1987, Geology of the Mount St. Helens area: Record of discontinuous volcanic and plutonic activity in the Cascade Arc of southern Washington: Journal of Geophysical Research, v. 92, p. 10,155–10,169, doi:10.1029/JB092iB10p10155.

Hansen, S.M., and Schmandt, B., 2015, Automated detection and location of microseismicity at Mount St. Helens with a large-N geophone array: Geophysical Research Letters, v. 42, p. 7390–7397, doi:10.1002/2015GL064848.

Hansen, S.M., Schmandt, B., Levander, A., Kiser, E., Vidale, J., and Moran, S., 2015, Subsurface Imaging at Mount St. Helens with a Large-N Geophone Array: American Geophysical Union Fall Meeting, Abstract S44B-02, https://agu.confex.com/agu/fm15/webprogram/Paper83155.html.

Heliker, C., 1995, Inclusions in Mount St. Helens dacite erupted from 1980 through 1983: Journal of Volcanology and Geothermal Research, v. 66, p. 115–135, doi:10.1016/0377-0273(94)00074-Q.

Hildreth, W., 2007, Quaternary magmatism in the Cascades; geologic perspectives: U.S. Geological Survey Professional Paper 1744, 1744 p.

Hill, D.P., and Prejean, S., 2005, Magmatic unrest beneath Mammoth Mountain, California: Journal of Volcanology and Geothermal Research, v. 146, p. 257–283, doi:10.1016/j.jvolgeores.2005.03.002.

Hill, G.J., Caldwell, T.G., Heise, W., Chertkoff, D.G., Bibby, H.M., Burgess, M.K., Cull, J.P., and Cas, R.F., 2009, Distribution of melt beneath Mount St Helens and Mount Adams inferred from magnetotelluric data: Nature Geoscience, v. 2, p. 897–897, doi:10.1038/ngeo703.

Lees, J.M., 1992, The magma system of Mount St. Helens: Non-linear high-resolution P-wave tomography: Journal of Volcanology and Geothermal Research, v. 53, p. 103–116, doi:10.1016/0377-0273(92)90077-Q.

Mavko, G.M., 1980, Velocity and attenuation in partially molten rocks: Journal of Geophysical Research, v. 85, p. 5173–5189, doi:10.1029/JB085iB10p05173.

Moran, S.C., 1994, Seismicity at Mount St. Helens, 1987–1992: Evidence for repressurization of an active magmatic system: Journal of Geophysical Research, v. 99, p. 4341–4354, doi:10.1029/93JB02993.

Musumeci, C., 2002, Magma system recharge of Mount St. Helens from precise relative hypocenter location of microearthquakes: Journal of Geophysical Research, v. 107, 2264, doi:10.1029/2001JB000629.

Nichols, M.L., Malone, S.D., Moran, S.C., Thelen, W.A., and Vidale, J.E., 2011, Deep long-period earthquakes beneath Washington and Oregon volcanoes: Journal of Volcanology and Geothermal Research, v. 200, p. 116–128, doi:10.1016/j.jvolgeores.2010.12.005.

Pallister, J.S., Hoblitt, R.P., Crandell, D.R., and Mullineaux, D.R., 1992, Mount St. Helens a decade after the 1980 eruptions: Magmatic models, chemical cycles, and a revised hazards assessment: Bulletin of Volcanology, v. 54, p. 126–146, doi:10.1007/BF00278003.

Pallister, J.S., Thornber, C.R., Cashman, K.V., Clynne, M., Lowers, H., Mandeville, C.W., Brownfield, I.K., and Meeker, G.P., 2008, Petrology of the 2004–2006 Mount St. Helens Lava Dome—Implications for magmatic plumbing and eruption triggering, *in* Sherrod, D.R., et al., eds., A volcano rekindled: The renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750, p. 647–702.

Parsons, T., Wells, R.E., Fisher, M.A., Flueh, E., and ten Brink, U.S., 1999, Three-dimensional velocity structure of Siletzia and other accreted terranes in the Cascadia forearc of Washington: Journal of Geophysical Research, v. 104, p. 18,015–18,039, doi:10.1029/1999JB900106.

Power, J.A., Stihler, S.D., White, R.A., and Moran, S.C., 2004, Observations of deep long-period (DLP) seismic events beneath Aleutian arc volcanoes; 1989–2002: Journal of Volcanology and Geothermal Research, v. 138, p. 243–266, doi:10.1016/j.jvolgeores.2004.07.005.

Scandone, R., and Malone, S.D., 1985, Magma supply, magma discharge and readjustment of the feeding system of mount St. Helens during 1980: Journal of Volcanology and Geothermal Research, v. 23, p. 239–262, doi:10.1016/0377-0273(85)90036-8.

Stanley, W.D., Finn, C., and Plesha, J.L., 1987, Tectonics and conductivity structures in the Southern Washington Cascades: Journal of Geophysical Research, v. 92, p. 10,179–10,193, doi:10.1029/JB092iB10p10179.

Stanley, W.D., Johnson, S.Y., Qamar, I., Weaver, C.S., and Williams, J.M., 1996, Tectonics and seismicity of the southern Washington Cascade Range: Seismological Society of America Bulletin, v. 86, p. 1–18.

Takei, Y., 2002, Effect of pore geometry on Vp/Vs: From equilibrium geometry to crack: Journal of Geophysical Research, v. 107, 2043, doi:10.1029/2001JB000522.

Waite, G.P., and Moran, S.C., 2009, VP Structure of Mount St. Helens, Washington, USA, imaged with local earthquake tomography: Journal of Volcanology and Geothermal Research, v. 182, p. 113–122, doi:10.1016/j.jvolgeores.2009.02.009.

Wannamaker, P.E., Evans, R.L., Bedrosian, P.A., Unsworth, M.J., Maris, V., and McGary, R.S., 2014, Segmentation of plate coupling, fate of subduction fluids, and modes of arc magmatism in Cascadia, inferred from magnetotelluric resistivity: Geochemistry, Geophysics, Geosystems, v. 15, p. 4230–4253, doi:10.1002/2014GC005509.

Weaver, C.S., Grant, W.C., and Shemeta, J.E., 1987, Local crustal extension at Mount St. Helens, Washington: Journal of Geophysical Research, v. 92, p. 10,170–10,178, doi:10.1029/JB092iB10p10170.

Wells, R.E., Weaver, C.S., and Blakely, R.J., 1998, Fore-arc migration in Cascadia and its neotectonic significance: Geology, v. 26, p. 759–762, doi:10.1130/0091-7613(1998)026<0759:FAMICA>2.3.CO;2.

Wells, R., Bukry, D., Friedman, R., Pyle, D., Duncan, R., Haeussler, P., and Wooden, J., 2014, Geologic history of Siletzia, a large igneous province in the Oregon and Washington Coast Range: Correlation to the geomagnetic polarity time scale and implications for a long-lived Yellowstone hotspot: Geosphere, v. 10, p. 692–719, doi:10.1130/GES01018.1.

White, R.A., 1996, Precursory deep long-period earthquakes at Mount Pinatubo: Spatio-temporal link to basaltic trigger, *in* Newhall, C.G., and Punongbayan, R.S., eds., Fire and mud: Eruptions and lahars of Mount Pinatubo, Philippines: Seattle, University of Washington Press, p. 307–328.

Williams, D.L., Abrams, G., Finn, C., Dzurisin, D., Johnson, D.J., and Denlinger, R., 1987, Evidence from gravity data for an intrusive complex beneath Mount St. Helens: Journal of Geophysical Research, v. 92, p. 10,207–10,222, doi:10.1029/JB092iB10p10207.

Manuscript received 5 December 2015
Revised manuscript received 31 March 2016
Manuscript accepted 6 April 2016

Printed in USA