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V_P Structure of Mount St. Helens, Washington, USA, imaged with local earthquake tomography

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ABSTRACT

We present a new *P*-wave velocity model for Mount St. Helens using local earthquake data recorded by the Pacific Northwest Seismograph Stations and Cascades Volcano Observatory since the 18 May 1980 eruption. These data were augmented with records from a dense array of 19 temporary stations deployed during the second half of 2005. Because the distribution of earthquakes in the study area is concentrated beneath the volcano and within two nearly linear trends, we used a graded inversion scheme to compute a coarse-grid model that focused on the regional structure, followed by a fine-grid inversion to improve spatial resolution directly beneath the volcanic edifice. The coarse-grid model results are largely consistent with earlier geophysical studies of the area; we find high-velocity anomalies NW and NE of the edifice that correspond with igneous intrusions and a prominent low-velocity zone NNW of the edifice that corresponds with the linear zone of high seismicity known as the St. Helens Seismic Zone. This low-velocity zone may continue past Mount St. Helens to the south at depths below 5 km. Directly beneath the edifice, the fine-grid model images a low-velocity zone between about 2 and 3.5 km below sea level that may correspond to a shallow magma storage zone. And although the model resolution is poor below about 6 km, we found low velocities that correspond with the aseismic zone between about 5.5 and 8 km that has previously been modeled as the location of a large magma storage volume.

1. Introduction

Mount St. Helens (MSH) is a stratovolcano located in southwestern Washington State within the Cascades magmatic arc. The 300,000 year eruption history of MSH (Clynne et al., 2008) includes the most recent eruptive cycle that began in spring 1980 and culminated in the 18 May 1980 explosive eruption. This was followed by 6 years of dome-building eruptions and, after an 18-year pause, additional dome building in 2004–2008.

The unrest leading up to the 18 May 1980 eruption prompted detailed geological and geophysical studies of the volcano, which included the installation of an improved earthquake-monitoring network that continues operating today. Studies made using these earthquake data have revealed details about the tectonic setting (e.g., Weaver et al., 1987), spatial and temporal variations in the stress field (Barker and Malone, 1991; Moran, 1994), the structure of the magmatic plumbing system (Musumeci et al., 2002) and the subsurface velocity structure (Lees, 1992; Moran et al., 1999).

Regional seismic tomography studies (Lees and Crosson, 1989, 1990; Moran et al., 1999) have consistently imaged several large-scale features in the mid to upper crust that correlate with geological structures and geophysical anomalies in the region surrounding MSH. The most notable of these are: 1) a low-velocity zone that parallels a NNW trending zone of earthquakes, the St. Helens Seismic Zone (SHZ); and 2) high velocities beneath the Spirit Lake and Spud Mountain plutons north of MSH (Fig. 1). Parsons et al. (1999) recorded active sources with a linear, E–W array about 40 km north of MSH. They found a sharp velocity decrease from west to east at depths below 10 km where the array crossed the SHZ. Lees (1992) imaged smaller-scale features beneath MSH, including prominent low-velocity zones that were interpreted as elements of the magmatic system. Lees (1992) also imaged a high-velocity anomaly between about 6 and 9 km depth beneath the volcano that was interpreted as a plug of solidified magma on top of the main magma-rich volume.

In this study, we combined 25 years of network-recorded seismicity since the 18 May 1980 eruption with data from a temporary array of 19 broadband seismometers deployed from June 2005 through early 2006 to compute a new *P*-wave velocity model of the upper crust beneath MSH. The additional data, different inversion method (SIMULPS (Thurber, 1983; Eberhart-Phillips, 1990; Evans et al., 1994)) together with the 3-D ray shooting method (Haslinger and

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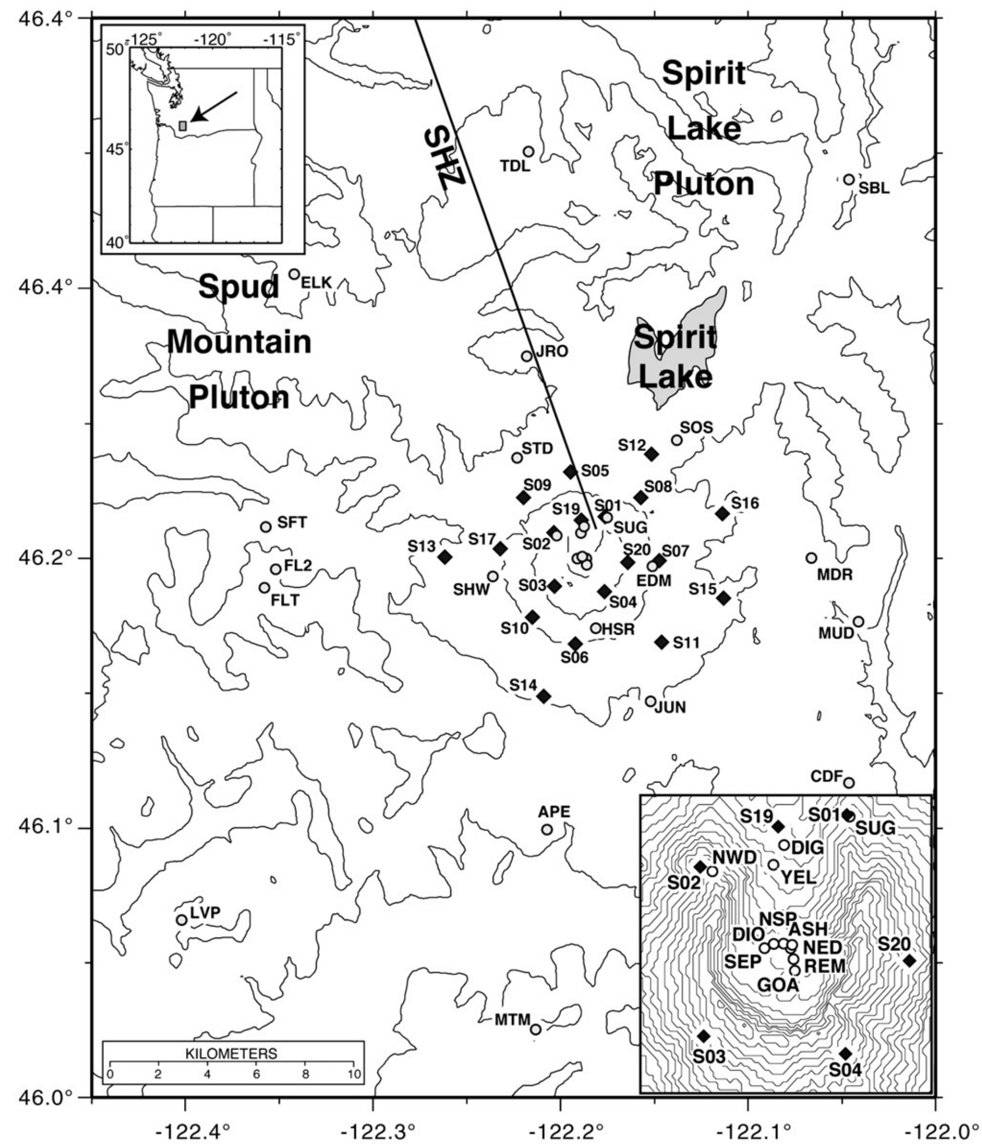

Fig. 1. Station location map shows the temporary broadband stations (dark diamonds) and a subset of the permanent network stations (light circles) plotted on topography contoured at 200 m intervals. Stations JRO and STD were the only permanent broadband stations running during the temporary deployment. Inset in the upper left corner shows the location of Mount St. Helens in southern Washington. Inset in the lower right corner shows a close up of the crater stations plotted on topography contoured at 40 m intervals. Spirit Lake, the St Helens Seismic Zone (SHZ) and the approximate locations of the Spud Mountain and Spirit Lake Plutons are also shown.

Kissling, 2001) that we use, provide a somewhat different image of the velocity structure than was determined previously by Lees (1992).

2. Earthquake data

The Pacific Northwest Seismic Network (PNSN), based out of the University of Washington, encompasses all of Oregon and Washington, including MSH. The network configuration has changed somewhat since 1980, but has always included about 10 stations within 10 km of the center of the volcano (Fig. 1). Until 2004, these stations were all vertical-component, short-period stations. In June 2005, we augmented this network with a temporary 19-station array of broadband stations within 6 km of the volcano, with stations removed by July 2006 (Waite et al., 2008).

Earthquakes near MSH are generally confined to a near-vertical, cylindrical volume directly beneath the edifice (Fig. 2) and the SHZ, which extends to the NNW and SSE of MSH (Weaver and Smith, 1983). Focal mechanisms for events in this zone are consistent with right-lateral motion along the NNW trend of the SHZ (Weaver et al., 1987). There are several concentrations of epicenters along a trend, which is approximately perpendicular to the SHZ, but this trend is less well defined. Focal mechanisms of one event in each of the two clusters to the NE of MSH are the same style as those in the SHZ and are interpreted by Weaver et al. (1987) to be related to sets of faults that strike nearly parallel to the SHZ. The densest seismicity is directly beneath MSH to a depth of about 10 km. An earthquake-free zone beneath the volcano beginning at a depth of about 6 km has previously been postulated as the location of the main crustal magma body (e.g., Scandone and Malone, 1985).

Between June 1980 and the September 2004, 19,379 earthquakes were located by the PNSN within a 50 × 50 km area centered on MSH. Because the shape of the volcano changed dramatically during the 18 May 1980 eruption, we only used data recorded following that event. An additional 6916 events were located in this area between October 2004 and the end of 2005, which represents a small fraction of the total number of events associated with the 2004–2008 eruption. The