

Anatomy of an active submarine volcano

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ABSTRACT

Most of the magma erupted at mid-ocean ridges is stored in a mid-crustal melt lens that lies at the boundary between sheeted dikes and gabbros. Nevertheless, images of the magma pathways linking this melt lens to the overlying eruption site have remained elusive. Here, we have used seismic methods to image the thickest magma reservoir observed beneath any spreading center to date, which is principally attributed to the juxtaposition of the Juan de Fuca Ridge with the Cobb hotspot (northwestern USA). Our results reveal a complex melt body, which is ~14 km long, 3 km wide, and up to 1 km thick, beneath the summit caldera. The estimated volume of the reservoir is 18–30 km³, more than two orders of magnitude greater than the erupted magma volumes of either the A.D. 1998 or 2011 eruption. Our images show a network of sub-horizontal to shallow-dipping (<30°) features that we interpret as pathways facilitating melt transport from the magma reservoir to the eruption sites.

INTRODUCTION

Axial volcano is located at the intersection of the Juan de Fuca Ridge and the Cobb–Eickelberg seamount chain, offshore northwestern United States (Fig. 1), and presents a warmer axial regime (Hooft and Detrick, 1995; Carbotte et al., 2008) and an increased crustal production rate relative to the adjacent ridge segments (Hooft and Detrick, 1995; West et al., 2003). It is the most recent eruptive center of the hotspot chain (Chadwick et al., 2005), which last erupted in A.D. 2011 (Caress et al., 2012; Chadwick et al., 2012; Dziak et al., 2012). The volcano rises ~700 m above the adjacent ridge axis and has two major rift zones extending to the north and

south, and its summit features an 8-km-long, horseshoe-shaped caldera, where hydrothermal fields are located (Embley et al., 1990) adjacent to recent lava flows (Caress et al., 2012). Axial volcano has been the site of numerous scientific expeditions spanning nearly three decades (Crane et al., 1985; Chadwick et al., 2012), with an increase in the number of studies since the late 1990s prompted by its strong and quasi-cyclic volcanic activity. All these investigations have enhanced our knowledge of the geology and dynamics of Axial volcano (e.g., Caress et al., 2012; Nooner and Chadwick, 2009), but little is known concerning its internal structure.

To date, seismic experiments have been one of the keys in our understanding of the internal structure of volcanic systems (Okubo et al., 1997; Kent et al., 2000; Zandomenighi et al., 2009; Paulatto et al., 2012). However, most experiments, especially subaerial-based ones, are restricted to refraction geometries with limited numbers of sources and receivers, and employ smoothing constraints required by tomographic inversions that are set to produce minimum-structure velocity images with spatial resolutions well below the length scale of important features that define these magmatic systems (Lees, 2007). A first attempt at investigating the inner structure of Axial volcano used 5025 air-gun shots to an array of six ocean-bottom seismometers (OBSs) and uncovered the outlines of a large crustal magma reservoir (~250 km³), containing up to 5–21 km³ of melt, with maximal lateral extensions of 8 km × 12 km and a thickness of ~2.5 km (West et al., 2001). Though encouraging, these results were limited to first-order features of the magmatic system, and the survey geometry precluded robust imaging beneath the eastern sector of the volcano.

DATA AND METHODS

In this study, we present new observations on the magmatic system of Axial volcano from four multichannel seismic (MCS) lines. These data are from the 2002 R/V *Maurice Ewing* EW0207 experiment (Carbotte et al., 2006) and were acquired using a 6-km-long, 480-channel digital streamer with 12.5 m receiver intervals. The source was fired each 37.5 m and consisted of a 49.2 L airgun array.

To image the detailed geometry of the magmatic system beneath Axial volcano, we followed a strategy consisting of the following steps (additional information is provided in the GSA Data Repository¹):

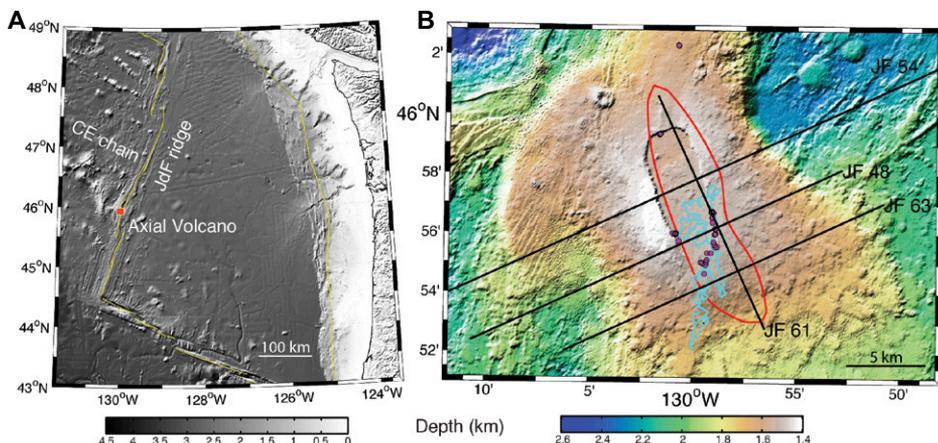


Figure 1. Bathymetry of Axial volcano (offshore northwestern USA). **A:** Study area on Juan de Fuca (JdF) Ridge, and seamounts from Cobb-Eickelberg (CE) chain. Yellow lines outline contour of JdF plate. **B:** Analyzed seismic profiles (black lines) superimposed on bathymetric map of Axial volcano. Cyan line outlines extent of the A.D. 2011 lava flows (Caress et al., 2012). Red line highlights extent of our interpreted magma body at depth. Purple circles mark locations of hydrothermal vents on seafloor.

¹GSA Data Repository item 2014243, additional details of downward-continuation, full waveform inversion, and reverse-time migration methods; velocity and reflectivity structure along seismic lines 48 and 54; synthetic tests: pitfalls of reverse-time migration imaging and reflectivity response from a melt or mush reservoir, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

(1) The MCS data were first downward-continued to the seafloor (Arnulf et al., 2014a). This process unwraps the layer 2A/2B triplication, moving the refracted energy in front of the seafloor reflection, providing information about near-surface velocities.

(2) A high-resolution velocity model was then obtained by performing elastic full waveform inversion (FWI) (Arnulf et al., 2012, 2014b) focused on energy arriving ahead of the seafloor reflection. The strength of FWI is that it can use the full seismic wavefield to create a high-resolution velocity image of the crust, which can be used for geological interpretation.

(3) The FWI velocity models were then used to create reflection images using the surface MCS data and a pre-stack depth reverse time migration (RTM) algorithm (Baysal et al., 1983). The advantage of RTM imaging compared to standard migration techniques is that it has no dip limitation and handles extreme lateral velocity variations using all possible arrivals.

(4) Finally, the reflectivity and seismic energy attributes of the RTM images were used to delineate the geometry (lateral extent and thickness) of the melt body, as well as other upper crustal structural features (Fig. 2; Fig. DR1 in the Data Repository).

Beneath Axial volcano, our velocity models (Figs. 2A and 2B; Figs. DR1A and DR1B) constrain the fine-scale architecture of the shallow volcanic complex down to the top of the magma reservoir. Within this reservoir, the velocity structure is not fully constrained (and its presumed low velocity is overestimated) because the FWI, as implemented, is restricted to seismic events that have been isolated ahead of the seafloor reflection in data downward-continued to a level ~1.5 km below the sea surface. In this volcanic setting, the maximum penetration of layer 2A/2B refraction event recorded on a 6-km-long streamer is ~1.25 km. Any changes in velocities below this level are manifested primarily in amplitude variation with offset (AVO) patterns of the magma chamber reflections, but these patterns are mainly sensitive to the impedance contrast at the reflection point (Gauthier et al., 1986) and do not fully constrain the large-scale background velocity. Nonetheless, the high resolution and fidelity of the FWI models of the upper ~1.5 km, which capture the largest velocity variations, allow the creation of geometrically accurate RTM images of the deeper magmatic system (Figs. 2 and 3; Figs. DR1 and DR2).

RESULTS AND DISCUSSION

Geometry of the Magma Reservoir Beneath Axial Volcano

Our RTM images (Figs. 2 and 3; Figs. DR1C and DR1D) reveal a geometrically complex magma reservoir underlying the caldera and ex-

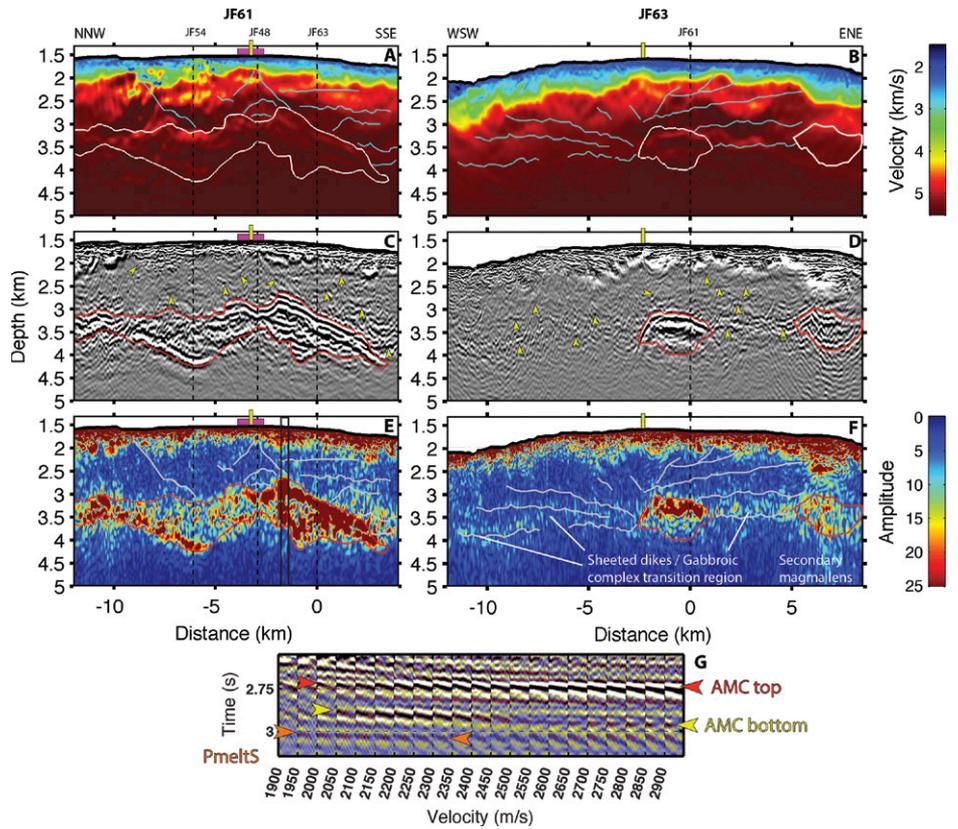


Figure 2. Upper crustal velocity, reflectivity, and amplitude structure of Axial volcano along seismic lines 61 (left) and 63 (right). **A, B:** P-wave velocity sections. **C, D:** Reverse time migrated (RTM) images. **E, F:** Amplitude envelope of the RTM images. White lines (**A, B**) and red lines (**C–F**) outline magma reservoirs. Cyan lines (**A, B**), gray lines (**E, F**), and yellow arrows (**C, D**) highlight bright reflectors interpreted as planes of weakness from the RTM images, which might be activated to transport melt from magma reservoir to eruption sites. Vertical yellow rectangles mark location of south rift zone. Purple rectangles mark extent of hydrothermal field along seismic line 61. Dashed vertical lines mark intersection of different seismic lines. **G:** Constant velocity stacks computed within black rectangle shown in **E** along seismic line 61 are shown ranging from 1900 m/s to 2900 m/s. Multiple events include conventional P-wave reflection from the top of the Axial Magma Chamber (AMC) (red arrows), as well as a complex P-wave event from the bottom of the AMC (yellow arrows) and a converted S-wave (PmeltS) reflection (orange arrows).

tending across the southeast flank of Axial volcano in a region previously thought to be devoid of significant amounts of melt (West et al., 2001). MCS profiling outlines a magma body that is at least 14 km long and 3 km wide. In places, a pair of vertically offset strong reflections is imaged that is interpreted as top and bottom reflections from a stacked, magma sill complex, as weaker reflection arrivals are seen in between. The maximum thickness of the complex is 0.6–1 km, with the lower value corresponding to a pure melt case (Fig. DR3). This is an order of magnitude thicker than magma reservoirs commonly found at mid-ocean-ridge spreading centers (Singh et al., 1998). The depth between the seafloor and the top of the magma reservoir varies between 1.1 km and 2.3 km, with the two shallowest portions bounding the south rift hydrothermal field (Embley et al., 1990) and the eruptive centers of the 1998 and 2011 events (Figs. 2 and 3). On the other hand, right below the south rift hydrothermal field, the magma reservoir locally deepens,

which might be related to enhanced hydrothermal cooling (Figs. 2 and 3). Interestingly, the amplitude of the magma reflector (Figs. 2E and 2F; Figs. DR1C and DR1D) is stronger to the southeast of the caldera, between 0 and 5 km off axis, which might reflect the location of melt delivery at depth from the Cobb hotspot to Axial volcano (Fig. 4).

Ideally, detailed constraints on P-wave, S-wave, and anisotropic velocity structures are needed to determine the physical properties of magma bodies (Taylor and Singh, 2002). In this experiment, however, we did not fully recover such information, but our RTM approach clearly outlines the limits of the magma reservoir, which if interpolated in three dimensions yields a maximum volume of ~30 km³ (Fig. 4). In a pure melt case, this volume would be reduced to ~18 km³ (Fig. DR3). To refine estimates of the total melt volume present (i.e., melt versus mush content) would require further investigations. However, high melt concentration is expected within part

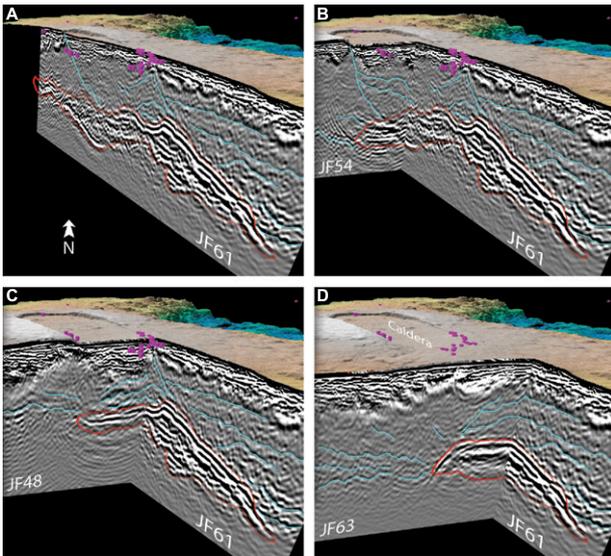


Figure 3. Perspective views of Axial volcano magma reservoir. A: Reverse time migration (RTM) image along seismic profile 61. B: Intersection of profiles 61 and 54. C: Intersection of profiles 61 and 48. D: Intersection of profiles 61 and 63. Red lines highlight the contour of the magma reservoir. Cyan lines highlight a network of sub-horizontal to shallow-dipping faults that likely form the magma pathways of Axial volcano. Purple cylinders mark location of hydrothermal vents on seafloor.

of this reservoir, especially the southeastern sector where the strength of the magma chamber reflection, along with its AVO characteristics and the presence of a coherent P- to S-wave conversion (PmeltS reflection), suggest both high impedance contrasts at, and negligible S-wave velocity (i.e., melt with disconnected crystals) within, the top of the magma chamber (Figs. 2E–2G; Figs. DR1 and DR4). The significant travel-time delays (~0.5 s) of first-arrival Pg phases refracting through and below the magma reservoir in the previous OBS experiment (West et al., 2001) also suggest high melt concentration. Most of this travel-time delay now accumulates within the smaller 18–30 km³ reservoir imaged here, as opposed to the much larger reservoir (250 km³) estimated from the OBS study. In fact, simple estimations of a one-way vertical delay through a 0.6–1-km-thick magma body could account for 0.16–0.33 s; similarly, 0.06–0.1 s might be explained by the low-velocity lavas

present in the subsiding caldera, while the rest of this travel-time delay is likely explained by three-dimensional bathymetry effects, as well as a probable low-velocity region lying beneath the magma reservoir. During the 1998 and 2011 volcanic eruptions of Axial volcano, ~0.1–0.2 km³ of magma was removed from the summit reservoir, while an even smaller portion (~0.02–0.1 km³) was erupted at the surface (Fox et al., 2001; Caress et al., 2012; Chadwick et al., 2012). These volumes are more than two orders of magnitude smaller than the Axial volcano magma reservoir, suggesting that only a small fraction of melt is extracted during each eruptive sequence. Finally, our RTM images reveal several superimposed reflectors within the summit reservoir (Figs. 2 and 3; Fig. DR2), suggesting multiple imbricated melt sills. Therefore, the presence of melt in the upper crust beneath Axial volcano is likely to be distributed in a complex system of dikes, sills, and conduits.

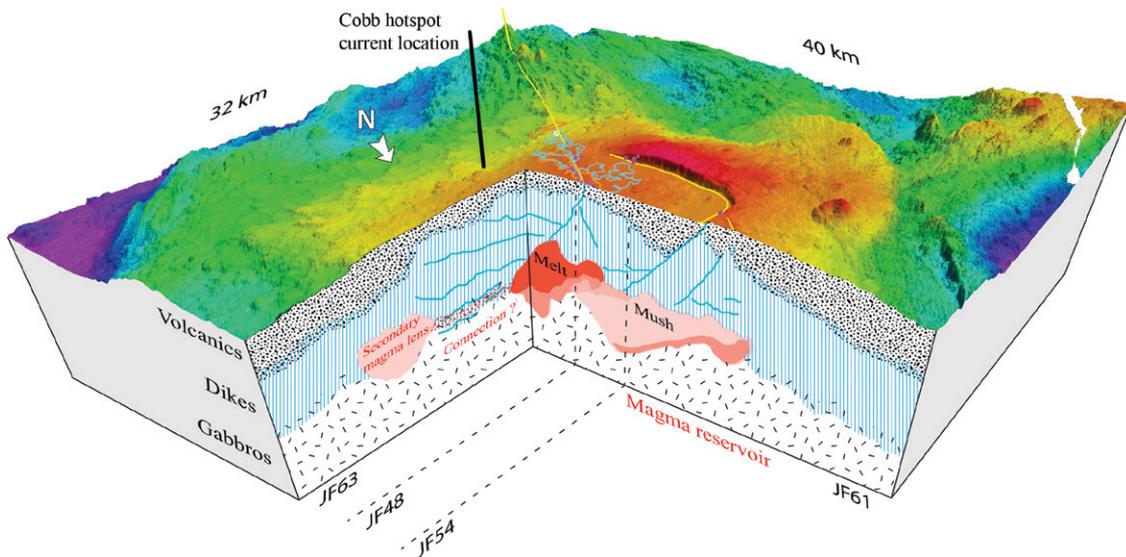


Figure 4. Schematic representation of Axial volcano magmatic system (4:1 vertical exaggeration). Axial volcano hosts the thickest magma reservoir (shades of red, depending on melt content) observed beneath a spreading center to date, which is principally attributed to juxtaposition of Juan de Fuca Ridge with the Cobb hotspot. Several sub-horizontal to shallow-dipping faults (cyan lines) might transport melt from the magma reservoir to eruption sites and help relieve stress buildup within the volcano. A secondary magma lens is located ~4 km away from the main reservoir.

and Cartwright, 2006), suggesting that both the 1998 and 2011 lava flows likely erupted from the same magmatic conduits in the upper crust.

CONCLUSIONS

In this study, we have applied an accurate solution for imaging an active volcano by combining FWI with RTM imaging. Our approach produces velocity models of the magmatic system at Axial volcano with spatial resolutions on the order of 50–100 m. In addition, RTM imaging provide reflectivity images with spatial resolution of tens of meters. We show the clearest example to date of an unambiguous basal reflector from a melt lens system beneath a spreading center. We find that the magma reservoir is up to 1 km thick, the thickest magma reservoir observed beneath a spreading center to date, which is principally attributed to the juxtaposition of the Juan de Fuca Ridge with the Cobb hotspot. In addition, we present a unique image of the magma pathways underlying an active volcano, which appear to be composed of a network of sub-horizontal to shallow-dipping faults (planes of weakness) that might cyclically be reactivated to transport melt from the magma reservoir to the eruption sites and to relieve stress build up within the volcano.

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