Seismic Imaging of Magma Systems from Surface to Source: Four analogues for EarthScope

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Magma Reservoir Dynamics

Crustal reservoirs are perhaps the most obvious target for seismic imaging. However, the physics of wave propagation limits resolution to large scale structure. By contrast, geodetic methods are sensitive to small inflation/deflation, and petrologic methods give the detailed histories of hand samples. A project at Axial volcano, on the Juan de Fuca mid-ocean ridge, demonstrates the power of combining these approaches. An active source seismic array was deployed at Axial following a 1998 eruption. Tomographic images of the magma reservoir provide estimates of the magma volume. By combining this with geodetic estimates of the eruption volume, a residence time could be calculated and compared independently with petrologic results. This project demonstrated that the magma reservoir at Axial is a nearly steady state feature. Eruptions remove only a small portion of the melt in the system. Integration of the seismic and geodetic components of EarthScope in a similar fashion could provide a powerful tool for 4-D volcanic investigation.

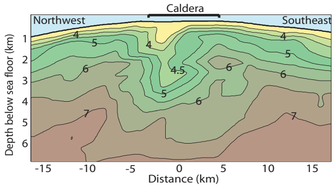

Figure 1 Cross-sectional view of Axial volcano velocity structure (West et al. 2001). Compressional-wave velocity is contoured in intervals of 0.5 km/s. The caldera width is indicated above panel. Depths are relative to the caldera floor, which is 1.46 km below sea level. This cross section is a slice through a 3D tomographic model based on the airgun-to-ocean bottom seismometer experiment. The area beneath the caldera shows velocities that are up to 2 km/s slower than expected in this environment.

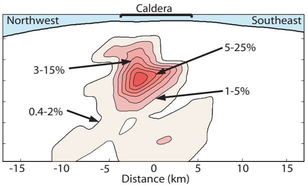

Figure 2 Cross section interpreted for partial melt content (West et al. 2001). The magma content is derived by differencing figure 1 with the background velocities that characterize the structure away from the caldera. After removing the velocity anomaly that could be due to thermal differences, the remaining anomaly is attributed to melt. The range of partial melt estimates reflects the range of velocity-melt relations in the literature. Summing the partial melt content yields a total magma volume of 5-21 km^3.

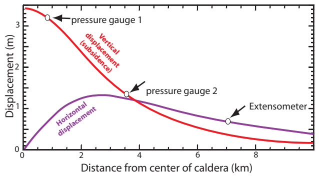

Figure 3 Strain measurements at Axial during the 1998 eruption. Modified from Fox et al. (2001). This strain is consistent with a volume decrease of 0.2 km^3 centered 3.8 km below seafloor. This eruption volume was used in conjuction with the tomography to estimate a residence time of magmas in the reservoir. Vertical displacements were measured with ocean bottom pressure gauges. Horizontal displacement measured with an acoustic extensometer.

West, M., Menke, W., Tolstoy, M., Webb, S. & Sohn, R., Magma storage beneath Axial volcano on the Juan de Fuca mid-ocean ridge. Nature 413, 833-836 (2001).
Fox, C.G., Chadwick, W.W. Jr & Embley, R.W. Direct observation of a submarine volcanic eruption from a sea - floor instrument caught in a lava flow. Nature 412, 727-729 (2001).

How do Volcanoes Make New Crust?

The continents have largely been built by volcanoes. Yet only a fraction of the new crust made by volcanoes is erupted at the surface. Most is emplaced at depth via sills, dikes and underplating. Unfortunately, the deep crust has been the most difficult part of the magmatic system to image. Models of lower crustal formation vary tremendously even in similar environments. At Krafla, the crust thins rapidly beneath the volcano and the magma body is underlain by unusually high velocity (mafic) rock. Axial volcano is also a basaltic mid-ocean ridge volcano. Like Krafla, it is underlain by a hot spot, albeit a much smaller one. However, a very different picture exists at Axial. The magma reservoir is underlain by slow velocity material thought to reflect high temperatures and possible partial melt. The base of the crust is distinctly opposite Krafla. Instead of rapid thinning, the crust exhibits a local thickening of several kilometers. These models are based heavily on the observation of seismic waves which have reflected off the Moho. Clearly the two different models raise as many questions as they answer. This type of investigation can only be carried out with dense seismic networks. Similar studies using the portable components of EarthScope have the potential to resolve this fundamental question of how new crust is created beneath volcanoes.

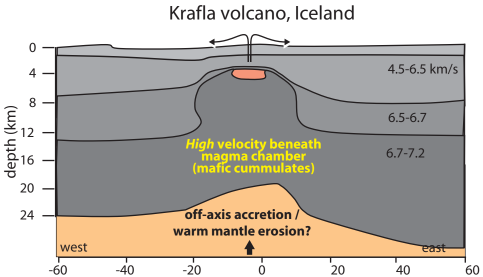

Figure 4 Cross-section of Krafla Volcano in NE Iceland. Krafla is a basaltic ocean ridge volcano influenced by the Iceland hotspot. Evidence for thin high velocity crust comes from two active source seismic experiments (Brandsdottir et al. 1997, Menke et al. 1998). Arrow represents hot spot source.

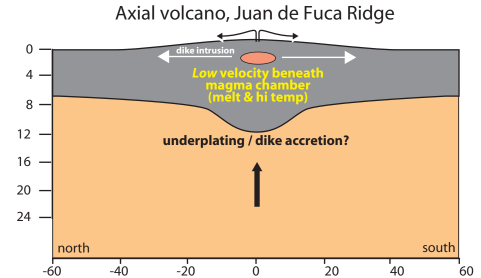

Figure 5 Cross-section of Axial Volcano on the Juan de Fuca ridge in the northeast Pacific. Axial is a basaltic ocean ridge volcano influenced by the Cobb hotspot. An airgun-to-ocean bottom seismometer experiment revealed the thick crust with additional evidence coming from gravity (West et al. in prep, Hooft et al. 1995).

Brandsdottir, B., Menke, W. Einarsson, P., White, R.S., & Staples, R.K. Faroe-Iceland Ridge experiment; 2, Crustal structure of the Krafla central volcano. J. Geophys. Res.102, 7867-7886 (1997).
Menke, W., M. West, B. Brandsdottir, and D. Sparks, Compressional and shear velocity structure of the lithosphere in Northern Ireland, Bull. Seis. Soc. Am., 88, 1561-1571 (1998).
West, M., W. Menke & M. Tolstoy, Focused magma supply at the intersection of the Cobb hotspot and Juan de Fuca ridge, in preparation.
Hooft, E. E. E., and R.S. Detrick, Relationship between axial morphology, crustal thickness, and mantle temperature along the Juan de Fuca and Gorda Ridges, J. Geophys. Res., 100, 22,499-22,508 (1995).

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Magma Sourcing in the Uppermost Mantle

Experiments using the PASSCAL pool of seismometers provide our best case studies of what might be achieved with the seismic components of EarthScope. One such project is RISTRA - a 1000 km linear array with 18 km instrument spacing. It provides higher resolution than could be achieved with the USArray Bigfoot initiative, but is representative of what could be done with the Flex Component. This array explores the source of magmatism associated with the Rio Grande Rift and the Jemez volcanic lineament in New Mexico. A combination of surface wave and receiver function results are being interpreted together with xenolith analyses. The picture of the uppermost mantle reveals a shallowing of the low velocity asthenospheric channel beneath central New Mexico. The lithosphere has been thinned, allowing hot mantle to come close to the base of the crust. It is an example of the lithosphere and asthenosphere dynamics which are central to the EarthScope science plan. This type of regional understanding of the mantle is perhaps the most assured result of EarthScope.

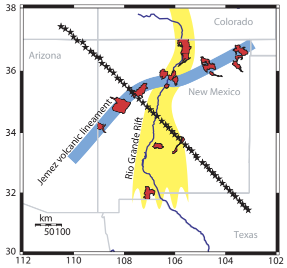

Figure 6 Major tectonic features of the Southwest (Baldridge et al. 1995). The Rio Grande Rift begins in central Colorado and widens through the middle of New Mexico before merging with the Basin and Range province in Texas and Chihuahua. The Jemez Lineament is a chain of volcanic features extending from southeast Arizona to the Rio Grande Rift and possibly continuing into Northeast New Mexico. Seismometers in the two year RISTRA deployment are shown as stars.

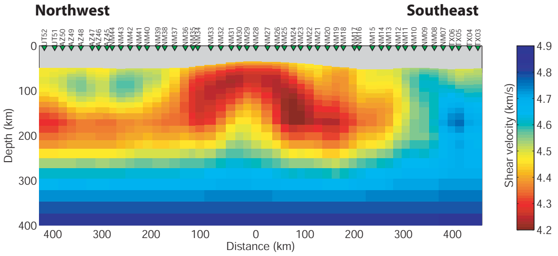

Figure 7 Shear wave seismic velocity of the uppermost mantle beneath the RISTRA array. This image was developed by analyzing the propagation of Rayleigh surface waves from 29 teleseismic earthquakes. The thickness of the crust, a frequent source of error, was previously constrained by receiver functions. Beneath the Great Plains cool craton-like velocities are found. Under the Colorado Plateau exists a low velocity asthenospheric channel typical of much of the western U.S. Beneath the Rift and Jemez Lineament, this channel shallows to a few tens of kilometers beneath the crust. Without the insulation offered by thick lithosphere, warm mantle is able to source magma to the crust.

Baldridge, W.S., G.R. Keller, V.Haak, E. Wendlandt, G.R. Jiracek, and K.H. Olsen,The Rio Grande Rift, from Continental Rifts: Evolution, Structure, Tectonics, K.H.Olsen ed., Elsevier, (1995).
West, M., J. Ni, D. Wilson, S. Baldridge, S. Grand & R. Aster, Structure of the uppermost mantle beneath the Colorado Plateau, Rio Grande Rift and Great Plains. In preparation.

Magma Genesis above the Subduction Wedge

Many of the active volcanoes in the U.S. are the result of melting associated with the subduction of the Juan de Fuca plate beneath the Pacific Northwest. Water released from the downgoing slab is thought to trigger melting in the overlying mantle. Though melting should occur along the entire slab, active Cascade volcanoes can be separated by 100 km or more. This implies significant horizontal transport of magmas in the uppermost mantle and the possible pooling of magma beneath volcanic centers. A project currently proposed by Grand and Ni, in the western volcanic belt in Mexico, demonstrates how seismic data can be used to image and quantify the transport of magmas in the mantle to individual volcanoes. In this test, we have combined data from teleseismic and local earthquakes in a joint inversion for seismic velocity. Our tests show that with the station coverage available under EarthScope, it is possible to resolve the uppermost mantle beneath discrete volcanic centers. A hypothetical low velocity zone associated with melt pooling beneath Colima volcano is resolved on a scale of 25 km. Many details of the slab and crust beneath Cascadia have already been explored, suggesting that EarthScope data could be pushed much further than in this simple test.

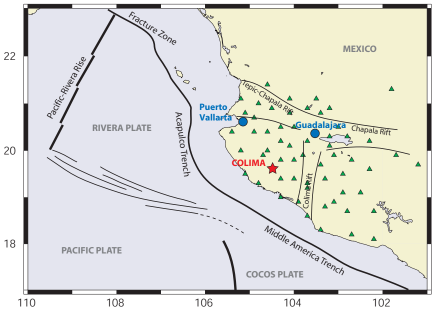

Figure 8 The northern end of the subduction zone along the west coast of Mexico. The young Rivera plate, created at the Pacific-Rivera Rise, is subducting beneath North America. On shore, a series of rifts bound the small Jalisco block. Colima volcano lies within this break-off province. Colima sits near the western end of the Mexico volcanic belt. The subduction of the Rivera plate is similar to Cascadia, where young oceanic crust (~10 Mya) from the Juan de Fuca ridge subducts beneath the Pacific Northwest ultimately feeding the Cascade volcanoes. Proposed sites for deployment of seismic stations (Grand and Ni) shown in green.

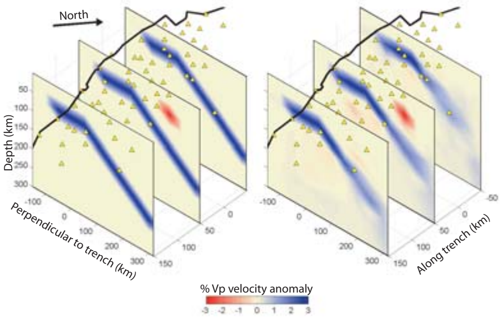

Figure 9 Cross sections through a compressional wave velocity model. The model includes the subducting Rivera plate and a low velocity feature beneath Colima to represent high temperatures and possible melt beneath the volcanic center. A synthetic model (left) was used to calculate traveltime delays. After adding random noise, a joint inversion of local and teleseismic data was performed to retrieve the structure (right). The slab model is resolved to depths of at least 250 km. The well-resolved Colima anomaly (red) demonstrates the power of such an array to image the pooling of magmas beneath discrete volcanic centers.