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Anatomy of the Colima volcano magmatic system, Mexico

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ABSTRACT

Colima volcano is one of the most active volcanoes in continental north America. It is located within the Colima graben on the western part of the Colima rift zone. Although extensively studied, the internal structure and deep magmatic system remains unknown. This research gives new clues to understand how and where magmas are produced and stored at depth. Using ambient seismic noise, we jointly invert for Rayleigh and Love wave dispersion curves for both phase and group velocity, which is applied for the first time in a volcanic environment. We invert for both the shear wave velocity and radial anisotropy. The 3D high resolution shear wave velocity model shows a deep, large and well-delineated elliptic-shape magmatic reservoir below the Colima volcano complex at a depth of about 15 km. On the other hand, the radial anisotropy model shows a significant negative feature (i.e., $V_{SV} > V_{SH}$) revealed from $\geq$35 km depth until the top of the magma reservoir at about 12 km depth. The latter suggests the presence of numerous vertical fractures where fluids, rooting from a well-known mantle window, can easily migrate upward and then accumulate in the magma reservoir. Furthermore, the convergence of both a low velocity zone and a negative anisotropy suggests that the magma is mainly stored in conduits or inter-fingered dykes as opposed to horizontally stratified magma reservoir.

1. Introduction

Colima volcano, a major and active strato-volcano, is likely to be a surface expression of the exceptionally complex conjunction of geodynamical processes occurring in the Jalisco subduction zone, southwestern Mexico (e.g., Ferrari et al., 2011). Although Colima's current activity is moderated and characterized by an alternation of lava flows, dome formations and dome collapses generating small pyroclastic flows (e.g., Reyes-Dávila et al., 2016), a catastrophic eruption similar to the 1913 Plinian eruption (VEI = 4) is likely to threaten more than 300,000 inhabitants in the area (Saucedo et al., 2010). Understanding the nature and link between an active volcano and geodynamical processes are important when attempting to predict volcanic behavior. For example, the size and type of an eruption are influenced by magmatic processes that occur in the Earth's crust where magma chambers, dykes and/or sills are expected. It is known from surface geological records that magmatic reservoirs evolve over long time periods (thousands to millions of years) and grow in small increments, with the successive formation of dykes and/or sills (Annen et al., 2006). However, the possible mechanisms involved in the emplacement and ascent of the magma inside the crust are not well understood, mainly due to the lack of direct and convincing seismic images highlighting the geometry and properties of volcanic reservoirs. Most traditional Earth imaging techniques cannot achieve high resolution imaging of the shallow crust, but rather large-scale signatures of crustal melt intrusions in the middle-to-lower crust.

This issue has been partially overcome by the advent of ambient noise tomography (ANT), which allows for imaging of small magmatic features in the upper crust (e.g., Brenguier et al., 2007; Spica et al., 2015). This technique retrieves Green's functions between pairs of seismometers by averaging the ambient noise cross-correlation over long time periods (e.g., Shapiro et al., 2005). Assuming that the Green's function at the free surface is dominated by surface waves (e.g., Sánchez-Sesma et al., 2011), group and/or phase velocity maps can be constructed (e.g., Shapiro et al., 2005). Among the principal advantages of ANT over earthquake tomography are the absence of limitations related to the spatial and/or temporal distribution of seismicity and that the retrieved frequency band depends primarily on the seismic network geometry.

Several studies have been conducted in order to determine the seismic velocity structure in the region. In particular, the upper mantle (i.e., >50 km depth) has been well-studied since the in-

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stallation of the 'Mapping the Rivera Subduction Zone' (MARS) and the 'Colima Volcano Deep Seismic Experiment' (CODEX) seismic arrays in 2006 (Fig. 1) (Soto et al., 2009; Yang et al., 2009; Ferrari et al., 2011; Dougherty et al., 2012; Suhardja et al., 2015).

The lateral asthenospheric flow found around the edges of the Rivera plate extending toward the mantle wedge is explained by rollback (e.g., Soto et al., 2009; Yang et al., 2009; Ferrari et al., 2011). Shear-wave splitting and P-wave tomographic studies (Soto et al., 2009; Yang et al., 2009) support the idea of a slab gap (deeper than 150 km) between the Rivera and the Cocos plates starting north of the Colima volcano. Yang et al. (2009) also proposed the existence of a slab detachment in the Rivera plate (at a depth of about 400 km) allowing material to rise and likely to produce a locally warmer mantle wedge.

In contrast, the crustal structure in this region is less known. Andrews et al. (2011) suggested that a sharp change of the subducting slab angles takes place at the 40 km inland at a depth of $\sim$35 km, such that the Rivera microplate becomes steeper than the Cocos plate (dotted lines in Fig. 1). This results in a 'mantle window' close to the trench, south of the Colima graben (Andrews et al., 2011; Taran et al., 2013; Abbott and Brudzinski, 2015; Spica et al., 2014). Although the Jalisco Block is well delineated by the Colima graben to the East and the Tepic–Zacoalco rift to the North (Fig. 1), the nature and the exact location of the boundary between both subducting plates are still unclear. At present, it is believed that the boundary lies inland beneath the Colima graben (e.g., Dougherty et al., 2012), but the existing uncertainty makes it challenging to understand the dynamic interaction between the Rivera plate and the deformation of the overriding Jalisco Block.

Both ambient noise Rayleigh wave tomography (Spica et al., 2014) and local earthquake P-wave tomography (Ochoa-Chávez et al., 2015) indicate low seismic velocities beneath the Colima volcanic complex (CVC) that might be associated with sediments filling the first few km of the Colima Graben and with the presence of an upwelling of fluids/melts under the Colima Volcano at mid-crustal depth (about 10–25 km). However, due to the poor resolution of both studies, these seismic images have not provided clear information on the links between these low velocities and the active volcanism in the region.

In this contribution, we investigate the relationship between crustal fluids and active volcanism in the region. We perform an ANT to assess both shear wave velocity and radial anisotropy structure of the region to a depth of 35 km. We refer here to radial anisotropy as in Xie et al. (2013): i.e., anisotropy with a vertical symmetry axis. Assessing the radial anisotropy with ambient noise measurements has previously shown a strong potential to better understand and interpret seismic data at regional (e.g., Bensen et al., 2009; Xie et al., 2013) or volcanic scales (Jaxybulatov et al., 2014; Mordret et al., 2015).

The tomography is performed in three steps. First, the group and phase travel times of the Rayleigh and Love waves are calculated at different periods for every possible inter-station distance (section 2.2). Second, the four sets of travel times are inverted to construct velocity maps at different periods (section 4). Finally, dispersion curves (DC's) are extrapolated at each node of the grid used to parameterize the 2-D period-velocity maps and are inverted in depth. The resulting 1-D layered profiles are merged into a final 3-D model (section 3). Potential magmatic sources of Colima volcano are discussed in light of previous knowledge (section 7). Our model is strongly reinforced by the use of four different DC's to constrain V_S structure and this approach is applied for the first time with ambient noise data in a volcanic context.

2. Noise correlations and surface wave dispersion curves

2.1. Data and processing

We combine continuous seismic data of the MARS, CODEX and SSN seismic networks (Fig. 1). The three networks together count 70 broad band stations (MARS: 50; CODEX: 18 and SSN: 2) deployed in western Mexico from January 2006 to March–June 2008. All the networks have at least 5 months overlap.

The three-component data are pre-processed with a down sampling to 20 Hz. The mean, trend and instrumental response are removed, followed by a 0.5- to 40-s band-pass filtering. We then compute the power-normalized cross-correlation (cross-coherence) (e.g., Nakata et al., 2015). The cross-correlation functions (CCFs) are obtained for all synchronous pairs of stations for vertical-vertical (ZZ), and rotated radial-radial (RR) and transverse-transverse (TT) components.

The resulting CCFs are folded at the origin time and stacked to reduce the effect of source distribution. Selecting the CCFs with high ($>$10) signal-to-noise ratio (SNR) leads to a final set of measurements composed of a total of 1713 ZZ-components, 1702 RR-components and 1862 TT-components. Fig. 2 shows the resulting CCFs as a function of inter-station distance. The apparent velocity of the Love waves is observed in the TT components and ($\sim$3.1 km/s) while the apparent velocity of the Rayleigh waves ($\sim$2.8 km/s) is observed in the ZZ and RR components. The right panels of the CCFs show the associated histograms of the number of CCFs at different inter-station distances for 10 km bins. The majority of the CCFs are retrieved for inter-station distances $<$200 km.

2.2. Dispersion measurements

Even if group ($U = \frac{d\omega}{dk}$) and phase ($\frac{\omega}{k}$) velocities are related by

$$U(\omega) = \frac{c(\omega)}{1 - \frac{\omega}{c(\omega)}\frac{dc}{d\omega}} \approx c(\omega) + \omega\frac{dc(\omega)}{d\omega}, \quad (1)$$

their joint inversion for shear wave structure gives notably better results than either one individually for two main reasons (e.g., Shapiro and Ritzwoller, 2002). First, both U and c are sensitive to different depths (e.g., Dziewonski and Anderson, 1981), providing exclusive constraints on structures and helping to better resolve the trade-off between crustal and mantle structures in the inversion. Second, the velocities U and c are computed separately allowing consistency checks. Therefore, they are used as independent data with different sensitivity to anisotropy during the inversion for shear wave structure (section 4).

The Rayleigh and Love surface wave dispersion measurements (U and c) are calculated using a semi-automatic implementation of the Frequency-time ANalysis (FTAN; Levshin et al., 1972), which allows a quick processing of a large amount of CCFs. While the group speed curve ($U(\omega)$) is measured by analyzing the envelope function $|A(t,\omega)|$, the phase speed curve ($c(\omega)$) requires the knowledge of the intrinsic phase ambiguity term (as explained in details in Bensen et al. (2007) or in Lin et al. (2008)). The Love and Rayleigh terms are first approximated by using the regional isotropic 3-D model of Spica et al. (2016) to match the phase speed at long periods and are then refined at each cell to take into account of the anisotropy and to be coherent with group speed. This process is explained with more detail in section 4.

The automated FTAN has the drawback that the resulting diagrams may be contaminated by high-amplitude overtones, leading to a wrong assignation of the DC. In the auxiliary material (Fig. A.1), we show that this effect is unlikely for the Colima volcano. Reliable DC's selection is enforced according to several crite-

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