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Crustal anisotropy and state of stress at Uturuncu Volcano, Bolivia, from shear-wave splitting measurements and magnitude–frequency distributions in seismicity

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A B S T R A C T

The physical signatures of unrest in large silicic magma systems are commonly observed in geophysical surveys, yet the interactions between magmatic processes and crustal stresses are often left unconstrained. Stresses in the mid and upper crust exert a strong control on the propagation and stalling of magma, and magma ascent can in turn change the magnitude and orientation of these stresses, including those associated with hydrothermal systems. This study assesses the state of stress at the restless Uturuncu Volcano in the Bolivian Andes with space, depth and time using observations of seismic anisotropy and the magnitude–frequency distributions of local earthquakes. Shear-wave splitting measurements are made for 677 events in the upper crust (1–25 km below sea level) between June 1, 2009 and March 10, 2012, and *b*-values are calculated using the Aki maximum likelihood method for a range of catalog subsets in the entire crust (−5 to 65 km below sea level). The *b*-value of the crustal events is unusually low ($b = 0.66 \pm 0.09$), indicating that the seismogenic region features strong material with high stresses that are released with limited influence from hydrothermal fluids. The 410 good quality shear-wave splitting results have an average delay time of 0.06 ± 0.002 s and an average percent anisotropy ranging from 0.25 ± 0.04% to 6.2 ± 0.94% with a mean of 1.70 ± 0.32%. Fast shear-wave polarization directions are highly variable and appear to reflect a combination of tectonic and magmatic stresses that overprint the regional E–W compressive stress associated with the convergence of the Nazca and South American Plates. The shear-wave splitting results and *b*-values suggest that the upper crust beneath Uturuncu (∼0–7 km below the summit) is characterized by a weak and localized hydrothermal system in a poorly developed fracture network. We conclude that stresses imposed by crustal flexure due to magmatic unrest above the Altiplano-Puna Magma Body activate crack opening on a pre-existing fault beneath the volcano, generating seismicity and a spatially variable 1–10% anisotropy above the brittle–ductile transition zone. These results suggest that strong stresses in relatively unfractured upper crustal rocks may locally inhibit fluid migration in large silicic magma systems, leading to pluton emplacement and effusive volcanism rather than explosive eruptions.

1. Introduction

Unrest in large silicic magma bodies may have significant consequences for the evolution of the continental crust and for society at large, yet our understanding of this phenomenon is limited. Intrusion and crystallization of large volumes of magma can change the density structure and chemical composition of the crust, while ascent and catastrophic eruption (VEI ≈ 8) of such magma would undoubtedly have a global impact. Whether magma stalls or propagates to the surface is in part influenced by the stress state of the upper crust, which can both inhibit magma ascent and change in response to it (Gudmundsson, 2006). Uturuncu Volcano in the Bolivian Andes is an ideal location to study this dynamic interaction. The volcano is located in a region distinguished by large-volume explosive volcanism, and it is deforming in response to magmatic unrest above what has been called the largest magma reservoir in the Earth's continental crust (Chmielowski et al., 1999). This study investigates spatiotemporal variations in crustal stress at Uturuncu using shear-wave splitting measurements and magnitude–frequency observations of local earthquakes in a 3-year seismic dataset.

Uturuncu is an unusual stratovolcano in a region characterized by geophysical anomalies (Fig. 1). Although the volcano has

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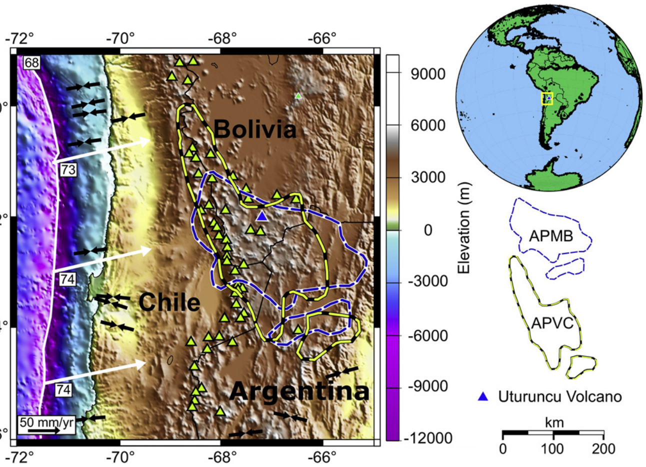

Fig. 1. Tectonic and geological context of Uturuncu Volcano (blue triangle). The white line defines the boundary between the oceanic Nazca Plate and the continental South American Plate. White arrows show the subduction direction of the Nazca Plate while numbers show the rate of subduction in mm/yr (Heuret and Lallemand, 2005). The eastward component of subduction is 50 mm/yr. Black arrows show the orientation of maximum horizontal compressive stress from focal mechanism solutions according to the World Stress Map 2016 (Heidbach et al., 2016). Green triangles show the locations of Holocene volcanoes (Siebert and Simkin, 2002). The outlines of the Altiplano-Puna Volcanic complex and the surface trace of the Altiplano-Puna Magma Body come from de Silva (1989) and Zandt et al. (2003), respectively. The map area is shown as a yellow box on the globe. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

been dormant for 270 ka (Sparks et al., 2008; Muir et al., 2014), it has been deforming with a "sombrero uplift" morphology since satellite observations began in 1992 (Pritchard and Simons, 2002; Fialko and Pearse, 2012). This curious pattern of central uplift (1–2 cm/yr) and peripheral subsidence ($\sim$4 mm/yr) is 150 km in diameter (Henderson and Pritchard, 2013) and centered $\sim$3 km WSW of Uturuncu's summit. The source of this deformation has been modeled by various magmatic processes and geometries at depths ranging from 9 to 28 km (Fialko and Pearse, 2012 and Hickey et al., 2013, respectively).

Numerous lines of evidence suggest that the source of ground deformation is associated with magmatism at the top of the Altiplano-Puna Magma Body (APMB), a giant zone of low seismic velocity (Chmielowski et al., 1999; Zandt et al., 2003; Ward et al., 2014), low electrical resistivity (Comeau et al., 2016) and low density (Del Potro et al., 2013) at $\sim$19–20 km depth. The APMB is the source for large eruptions that produced the calderas and ignimbrites of the 11–1 Ma Altiplano-Puna Volcanic Complex (APVC; de Silva, 1989; Salisbury et al., 2011), in which Uturuncu resides. This voluminous igneous activity is associated with the ENE subduction of the Nazca Plate beneath the South American Plate, which has thickened the crust of the Altiplano-Puna plateau to a remarkable 70 km (Fig. 1; James, 1971). For a review of published models of the APMB and the source of ground deformation, the reader is referred to Table 1 of Comeau et al. (2016).

The enigmatic relationship between Uturuncu, the APVC and the APMB raises several open questions. Is the current unrest a sign of large-volume pre-eruptive magma ascent (e.g., Sparks et al., 2008), or a more benign re-organization of magmatic fluids associated with pluton emplacement (e.g., Gottsmann et al., 2017)? Why has Uturuncu had an exclusively effusive eruptive history (Muir et al., 2014) in a region otherwise distinguished by explosive volcanism? Previous studies have addressed these questions by constraining the volume (e.g., Ward et al., 2014), melt fraction (e.g., Comeau et al., 2016; Farrell et al., 2017) and chemistry (Muir et al., 2014) of the magma, but the surrounding rocks also hold important information. The stress state of the upper crust plays a crucial role in halting magma ascent (Gudmundsson, 2006) and it can record past and present perturbations by magmatic forces. This study investigates spatiotemporal variations in the stress state at Uturuncu using shear-wave splitting measurements of raypaths from events between 1 and 25 km below sea level (BSL) and seismic *b*-values for earthquakes in the entire crust ($\leq$65 km BSL).

2. Background

2.1. *b*-values

One approach to inferring the stress state of an area is through the magnitude–frequency distributions of local earthquakes. In most cases the frequency of earthquakes decreases logarithmically with magnitude by the Gutenberg–Richter (G–R) relationship:

$$\log_{10} N = a - bM, \tag{1}$$

where N is the number of earthquakes with magnitudes greater than or equal to M, and a and b are constants (Gutenberg and Richter, 1954). The *b*-value (b) defines the slope of the cumulative magnitude–frequency distribution such that many small earthquakes yield a high *b*-value and vice versa. The global average *b*-value for tectonic settings is close to 1.0 (Frohlich and Davis, 1993), however, b has been found to vary with pore fluid pressure (e.g., Wiemer and McNutt, 1997) and faulting regime (Schorlemmer et al., 2005). High *b*-values are commonly observed in active volcanic environments where high-temperature fluids and high pore fluid pressures lower the differential stress required to break the rock (e.g., Wilks et al., 2017). A literature review of *b*-values at 34 volcanoes in unrest by Roberts et al. (2015) finds that b varies from 1.4 to 3.5 and is never less than 1.0.

Previous studies find unusually low *b*-values beneath Uturuncu Volcano. Table 1 shows that published estimates of b range from 0.49 $\pm$ 0.02 to 1.04. Using the highest number of events and the rigorous Aki maximum likelihood method, Jay et al. (2012) find a value of $b = 0.49 \pm 0.02$. This is low not only for a volcanic environment, but for any crustal setting. It implies that the seismogenic region consists of a strong crust with a poorly developed fracture network and little to no influence on stress release by pore fluid pressure. This contradicts the prediction that b should be high ($b > 1.0$), since sulfur-bearing fumaroles near Uturuncu's summit indicate that a hydrothermal system connects the edifice to a magmatic source of fluids (Sparks et al., 2008). Moreover, this hydrothermal system may be associated with a shallow, past or present pre-eruptive magma reservoir. This reservoir is evidenced by a zone of low shear-wave velocity (Jay et al., 2012) and low electrical resistivity (Comeau et al., 2016) at approximately -3 to 1 km BSL. These depths correspond to the pre-eruptive storage depths inferred for Uturuncu's Pleistocene lavas (Muir et al., 2014). This study seeks to elucidate the relationship between this shallow anomaly and crustal stresses by calculating b with depth and time using many events and the Aki maximum likelihood method.

2.2. Seismic anisotropy and shear-wave splitting

While *b*-values indicate the way that stress is released in the seismogenic zone, seismic anisotropy reflects the strength and orientation of the stress field itself. Anisotropy is a property of materials in which seismic velocities vary with raypath azimuth and shear-wave polarization. There are many mechanisms that lead to seismic anisotropy including the preferred orientation of crystals, and the periodic layering of materials of contrasting elastic properties. A predominant cause of anisotropy