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Transtensional deformation of Montserrat revealed by shear wave splitting

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ABSTRACT

Here we investigate seismic anisotropy of the upper crust in the vicinity of Soufrière Hills volcano using shear wave splitting (SWS) analysis from volcano-tectonic (VT) events. Soufrière Hills, which is located on the island of Montserrat in the Lesser Antilles, became active in 1995 and has been erupting ever since with five major phases of extrusive activity. We use data recorded on a network of seismometers between 1996 and 2007 partially spanning three extrusive phases. Shear-wave splitting in the crust is often assumed to be controlled either by structural features, or by stress aligned cracks. In such a case the polarization of the fast shear wave (ϕ) would align parallel to the strike of the structure, or to the maximum compressive stress direction. Previous studies analyzing SWS in the region using regional earthquakes observed temporal variations in ϕ which were interpreted as being caused by stress perturbations associated with pressurization of a dyke. Our analysis, which uses much shallower sources and thus only samples the anisotropy of the upper few kilometres of the crust, shows no clear temporal variation. However, temporal effects cannot be ruled out, as large fluctuations in the rate of VT events over the course of the study period as well as changes in the seismic network configuration make it difficult to assess. Average delay times of approximately 0.2 s, similar in magnitude to those reported for much deeper slab events, suggest that the bulk of the anisotropy is in the shallow crust. We observe clear spatial variations in anisotropy which we believe are consistent with structurally controlled anisotropy resulting from a left-lateral transtensional array of faults which crosses the volcanic complex.

1. Introduction

Active volcanoes experience dynamic processes such as dyke pressurization, and the migration of magmatic, hydrothermal and meteoric fluids, which may produce complex heterogeneous stress fields. This may be further complicated through their interaction with local tectonic structures such as active faults. One approach to explore these relationships is through the use of S-wave splitting (SWS) analysis to estimate seismic anisotropy of the crust (e.g. Boness and Zoback, 2006; Johnson et al., 2011). This approach may be used to investigate spatial and temporal changes in rock properties, providing a powerful tool for monitoring volcanoes. Here we investigate seismic anisotropy of the upper crust in the vicinity of Soufrière Hills Volcano (SHV) on the island of Montserrat, using SWS analysis from volcano-tectonic (VT) events.

SWS occurs when S-wave energy propagates through an anisotropic medium as two orthogonally polarized waves that travel at different speeds. A measure of the anisotropy along a ray-path can be characterized by the delay time between the fast and slow wave arrivals (δt) and the polarization direction of the fast wave (ϕ), which provides an indication of the orientation or symmetry of the anisotropy. Anisotropy is typically related either to fabrics associated with geologic structure (e.g. crystal lattice preferred orientation, aligned faults and fractures, sedimentary layering, rock foliation), or to the stress field due to the presence of stress aligned microcracks. Therefore, temporal variations in anisotropy can be interpreted in terms of changes in the stress field (e.g. Teanby et al., 2004a).

There have been growing number of studies using SWS to investigate anisotropy in volcanic settings, many of which link observations of temporal changes in anisotropy to stress changes associated with volcanological processes (e.g. Gerst and Savage, 2004; Keats et al., 2011; Johnson and Savage, 2012). Care must be taken, however, to determine whether the observed SWS is related to stresses (i.e. through stress-aligned microcracks) or to structural anisotropy (Boness and Zoback, 2006; Johnson et al., 2011). Similar effects have been observed in petroleum reservoirs (e.g. Teanby et al., 2004a; Baird et al., 2013).

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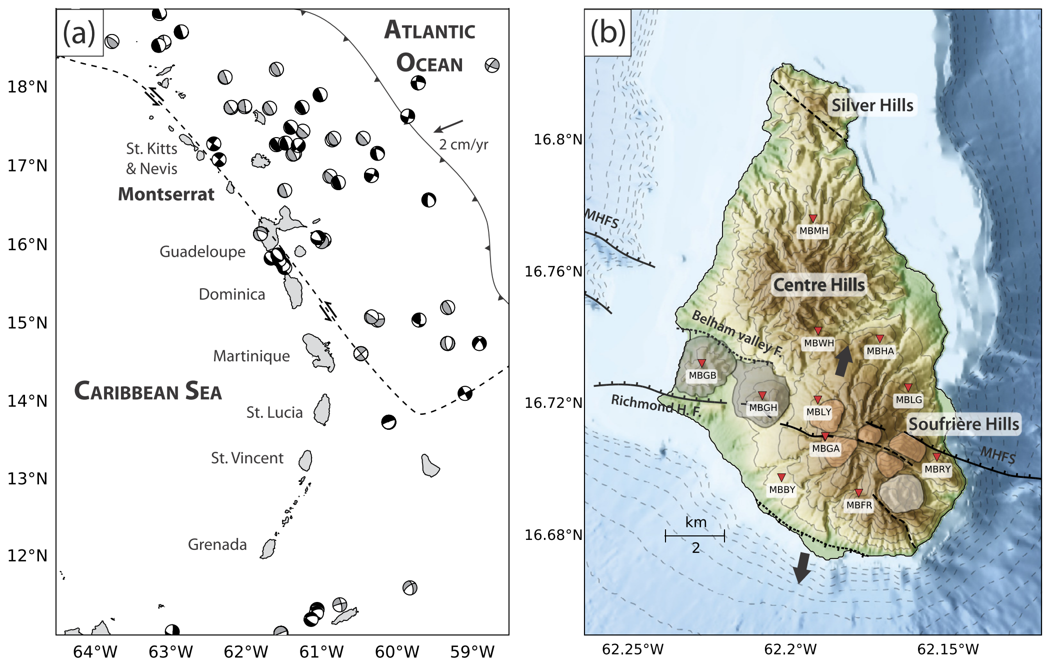

Fig. 1. (a) Location of Montserrat within the Lesser Antilles arc showing focal mechanisms from shallow earthquakes (black <20 km and grey <40 km depth) from the Global CMT Project catalog. Dashed line indicates the proposed strike-slip boundary of the northern Lesser Antilles forearc block (López et al., 2006). (b) Map of Montserrat showing the location of the stations used in the study, active faults (solid black lines), less active or inferred faults (black dashed lines), and volcanic complexes coloured by age. In orange are the Soufrière Hills domes (170 ka to present), in white is the South Soufrière Hills dome, and in grey Garibaldi Hill and St. Georges Hill (∼282 ka). Light grey lines indicate topographic contours, and double black arrows indicate local direction of extension (after Feuillet et al., 2010). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Previous work investigating SWS on Montserrat (Roman et al., 2011) used regional earthquakes. These regional earthquakes were not associated with volcanological processes on Montserrat but related to the tectonics of the Lesser Antilles region. They found that at most stations ϕ was oriented primarily NE–SW, but temporal variations in ϕ were observed in the months preceding the onset of extrusive activity at SHV in 1999. This temporal variation was found to be coincident with an observed change in the p-axis orientation of volcano tectonic earthquakes from dominantly NE–SW to NW–SE (Roman et al., 2006, 2008). Together, these observations were interpreted as being caused by the pressurization of a NE–SW oriented dyke prior to the eruption, which temporarily perturbed the surrounding stress field. Others, however, disagree with the NE–SW dyke interpretation (e.g. Hautmann et al., 2009).

A major drawback of the approach of Roman et al. (2011) is that ray-paths from regional earthquakes may pass through very different geological environments, possibly with different anisotropic fabrics, before arriving at the station. It is therefore difficult to constrain where along the ray-path the observed SWS has accrued. Nevertheless, Roman et al. (2011) interpreted their observations under the assumption that most of the SWS occurred in the crust beneath the island. In this paper we investigate SWS using local volcano-tectonic earthquakes as sources. In doing so we ensure that any observed anisotropy is localized in the upper few kilometres of the crust. We consider seismicity recorded between 1996 and 2007, partially spanning three extrusive phases.

2. Background

The island of Montserrat lies between the islands of Guadeloupe and Nevis in the Lesser Antilles arc, which was formed as a result of subduction of the North American plate beneath the Caribbean plate. Fig. 1 shows focal mechanisms of shallow earthquakes in the Lesser Antilles. Most of the activity to the east of Montserrat shows thrust mechanisms with p-axes consistent with an arc-normal direction of maximum horizontal compressive stress (S_H). However, it is likely that the upper plate has local tectonic domains where S_H departs markedly from the plate scale system. Wadge (1986) mapped dyke orientations throughout the Lesser Antilles and found evidence of a change in S_H from approximately arc-normal in the northern portion of the arc to arc-parallel in the south, with Montserrat lying near the transition between these two zones. Notably, however, that study did not include dyke observations from Montserrat. Mapping of fault systems in the upper plate in the region around Montserrat (Feuillet et al., 2002, 2010; Kenedi et al., 2010) indicates localized tectonic domains.

More recently, López et al. (2006) found that although the convergence vector between the Caribbean and North American plates is oriented ENE, GPS measurements in the Northern Lesser Antilles suggest the upper plate arc crust is moving in a more northerly direction than expected. They proposed that there is a northern Lesser Antilles forearc block, that is separated from the Caribbean plate by a strike slip fault system accommodating the left lateral component of oblique convergence across the arc. López et al. (2006) proposed a boundary of the block, based on the alignment of shallow strike slip earthquake focal mechanisms, which passes across Montserrat (Fig. 1a, dashed line), suggesting an approximately WNW S_H orientation.

The geology of the island of Montserrat is dominated almost entirely by volcanic rocks in three distinct andesitic volcanic massifs (Le Friant et al., 2004), the oldest being Silver Hills in the North (2600–1200 ka), to the south of which lies the Centre Hills (950–550 ka), and the currently active South Soufrière Hills–Soufrière Hills (170 ka to present) (Fig. 1b). There are a series of WNW trending faults which cross the SHV volcanic complex, the most prominent being the Belham Valley and Richmond Hill faults at the southern portion of the island which extend offshore to the NW forming the Montserrat–Havers fault zone (Feuillet et al., 2010). These faults represent a right-step in an *en echelon* transtensional array of faults accommodating both normal and left-lateral slip, that trend NNW between Montserrat and