Analysis of shear-wave splitting from volcano-tectonic events at Soufrière Hills volcano, Montserrat

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Introduction

Active volcanoes experience many dynamic processes that can 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. Here we investigate seismic anisotropy of the upper crust in the vicinity of Soufrière Hills volcano on the island of Montserrat, Lesser Antilles using SWS analysis from volcano-tectonic (VT) events.

Geological background

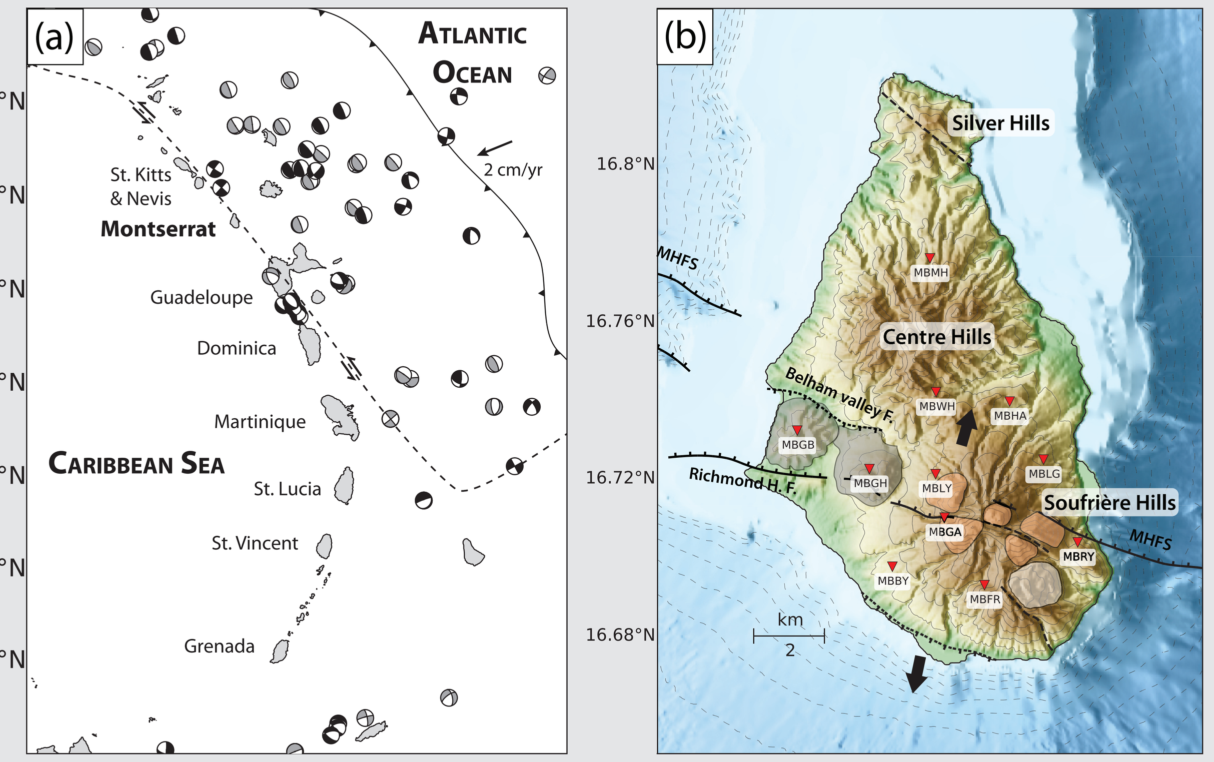

Figure 1: (a) Location of Montserrat within the Lesser Antilles arc showing focal mechanisms (black <20 km, grey <40 km depth). Dashed line marks the proposed boundary of the northern Lesser Antilles forearc block[1]. (b) Map of Montserrat showing the location of the stations used in the study, active faults (solid lines), less active or inferred faults (dashed lines), and volcanic complexes (coloured areas) (after Feuillet et al.[2]).

A series of active WNW trending faults cross the volcanic complex at the southern portion of the island. These faults represent a right-step in an en echelon transtensional array of faults accommodating both normal and left-lateral slip, that trend NNW and accommodate the trench parallel component of oblique convergence between the North American and Caribbean plates[1-3] (Fig. 1). Volcanic domes of the most recent Soufrière Hills complex align along a trend coincident with the strike of these faults suggesting that they both formed as a consequence of NNE-SSW crustal extension. This indicates an approximately WNW S_H in the vicinity of Montserrat.

Shear wave splitting results

Shear wave splitting was analyzed from relatively shallow (~2.5–4 km) VT events recorded between 1996 and 2007, ensuring that any observed anisotropy is from the upper few kms of the crust. However, due to fluctuations in the rate of VT seismicity and changes in the seismic network configuration we do not have data covering the full period over all the stations (Fig. 2). A summary of the mean splitting results for each station is shown in Table 1.

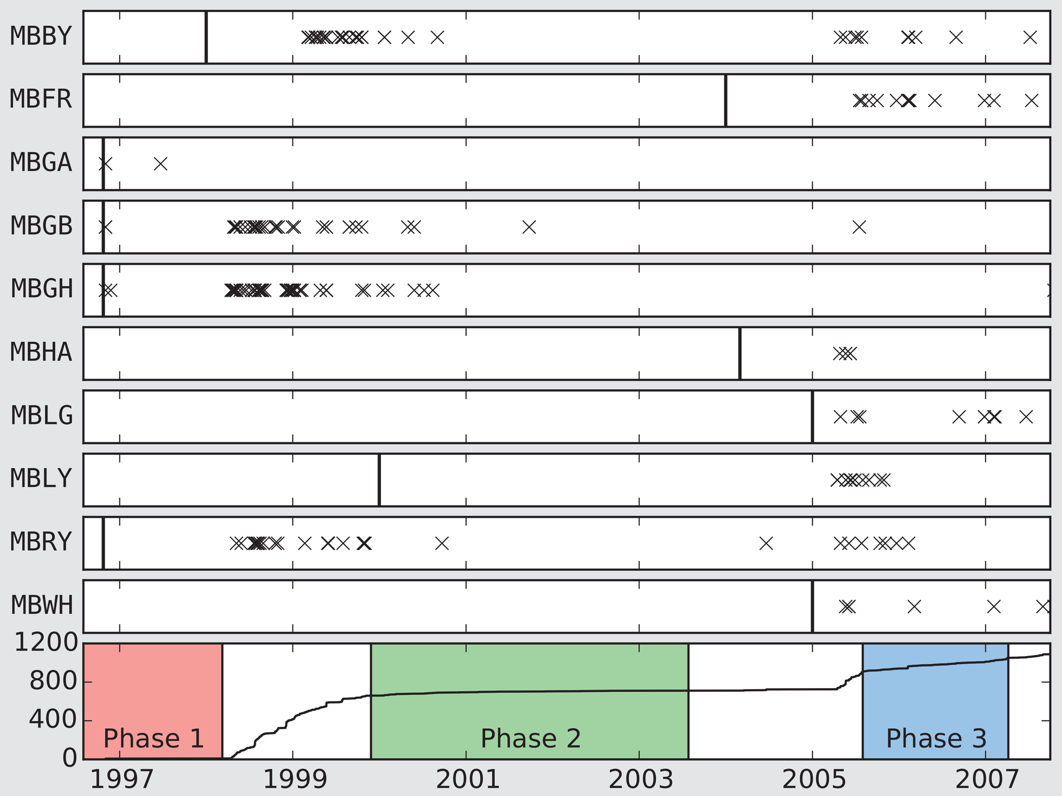

Figure 2: Good quality splitting measurements at each station over time. Vertical bars mark the installation date of each station. Bottom panel shows cumulative number of located VT events recorded by the network. Colours indicate extrusive phases of the eruption.

Station	n	$\overline{\phi}$ (°)	$\overline{R}$	$\overline{R}_{crit(95\%)}$	$\overline{\delta t}$ (s)
MBBY	42	-45.2 ± 8.3	0.629	0.266	0.26 ± 0.03
MBFR	13	-58.2 ± 20.8	0.411	0.475	0.27 ± 0.03
MBGA	2	48.5 ± 31.4	0.731	—	0.22 ± 0.09
MBGB	36	62.9 ± 11.9	0.443	0.287	0.16 ± 0.03
MBGH	66	56.4 ± 7.9	0.518	0.213	0.22 ± 0.01
MBHA	4	55.6 ± 35.6	0.448	0.837	0.18 ± 0.04
MBLG	10	-29.8 ± 24.0	0.401	0.540	0.14 ± 0.03
MBLY	10	-49.5 ± 16.5	0.650	0.540	0.13 ± 0.05
MBRY	33	5.4 ± 16.0	0.262	0.300	0.23 ± 0.03
MBWH	8	-86.8 ± 12.6	0.818	0.602	0.28 ± 0.03

Table 1: Mean value and 95% confidence interval for fast orientation $\overline{\phi}$ and delay time $\overline{\delta t}$ for each station.

Patterns of anisotropy

Temporal variations in anisotropy for the two periods of increased VT activity prior to the 2nd and 3rd eruptive phases are shown in Fig. 3. Most stations show relatively stable splitting parameters except for possible minor rotations of ϕ between NW-SE and E-W for stations MBGB and MBGH in the months preceding the phase 2 eruption. These stations also show ϕ orientations that contrast markedly with the NW-SE trend observed at neighbouring stations (Fig. 4a).

Temporal variation in anisotropy

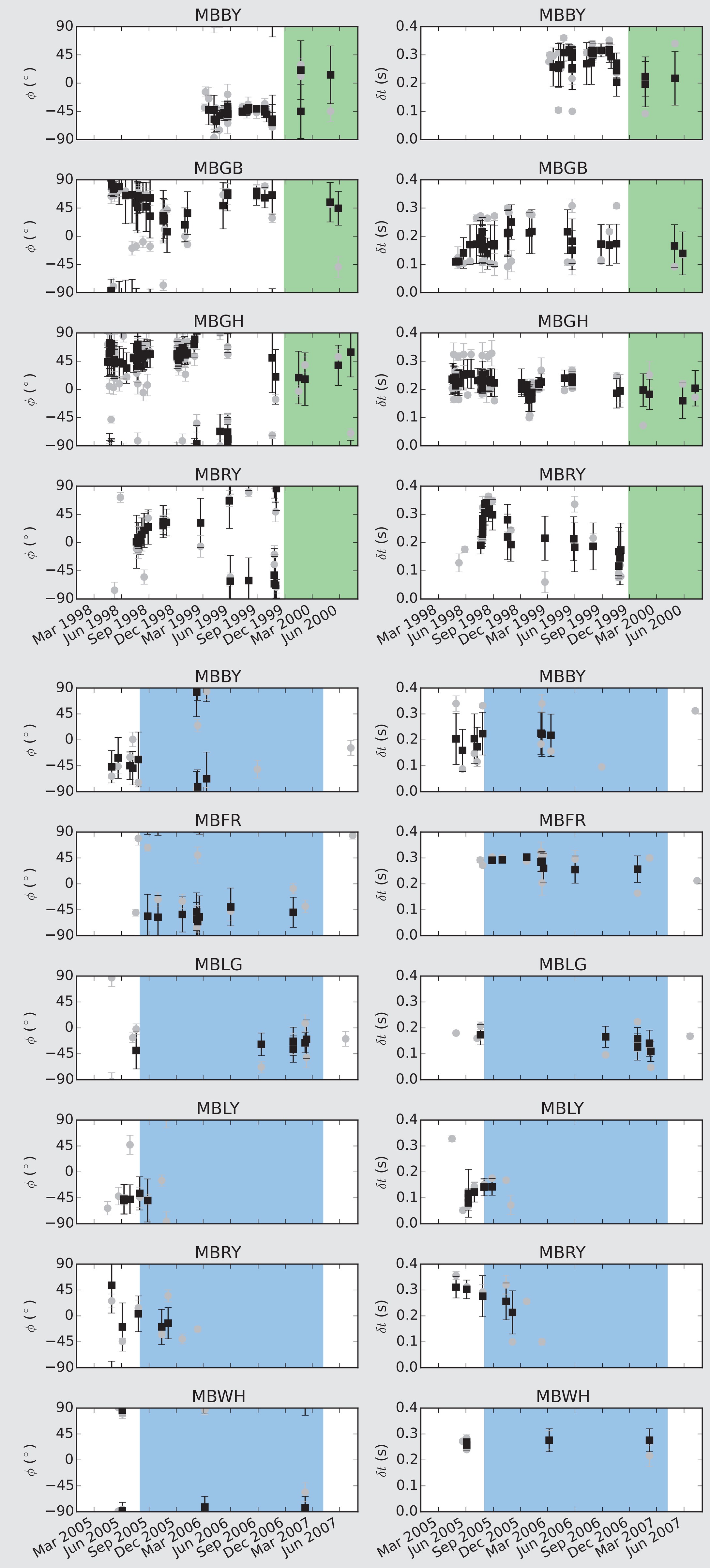

Figure 3: Time series of of ϕ and δt for stations with 5 or more measurements during the 2 periods of increased VT activity. Grey points are individual measurements with errors, black points are 5 point moving averages with 95% confidence interval of the mean. Shading indicates extrusive phases of the eruption with colours as indicated in Fig. 2.

Spatial variation in anisotropy

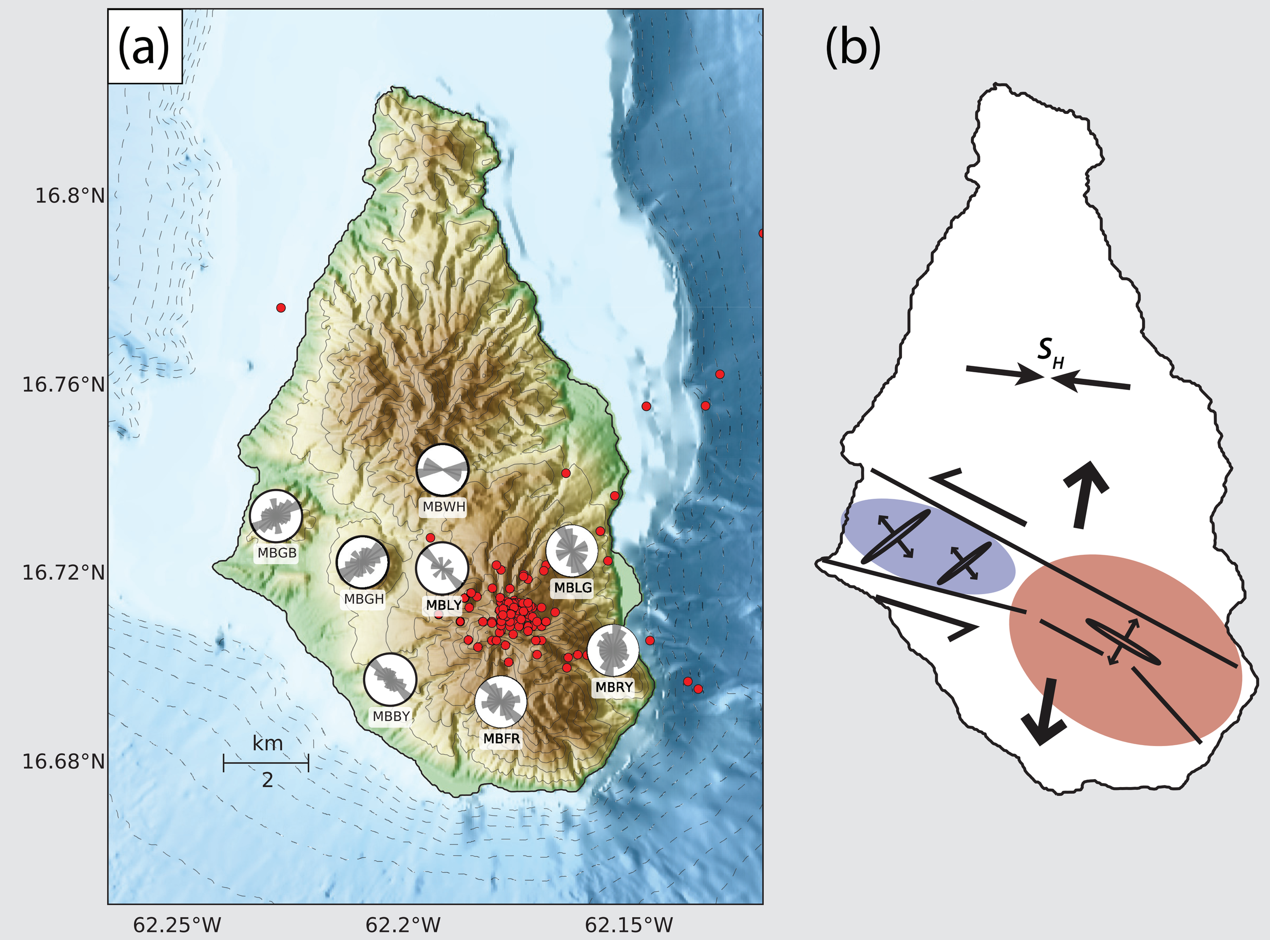

Figure 4: (a) Rose diagrams of ϕ centered at each station. (b) Conceptual model explaining the the spatial variation of ϕ. Several stations show a NW-SE trend which correlates with the orientation of S_H and the general trend of faults crossing the island (red shaded zone). Stations MBGH and MBGB show a NE-SW trend which may indicate a localized stress rotation due to their presence between faults which are accommodating both extension and left lateral slip (blue shaded zone).

Discussion

1. Delay times of ~0.2 s similar to previously reported SWS from much deeper events[4,5], suggest the upper mantle beneath Montserrat is relatively isotropic.
2. Spatial variations in ϕ suggest structurally controlled anisotropy resulting from a left-lateral transtensional array of faults which crosses the volcanic complex (Fig. 4b).
3. Strike slip movement of faults may support a locally rotated NE oriented S_H to the NW of SHV.
4. A matter of debate is the orientation of the dyke feeding SHV, which has been estimated to align NW[6,7] or NE[5,8]. Although our model provides a means to locally rotate S_H we see no indication of this occurring beneath SHV itself. Thus, the evidence suggests a ~NW oriented dyke.

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