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Stress, strain rate and anisotropy in Kyushu, Japan

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ABSTRACT

Seismic anisotropy, the directional dependence of wave speeds, may be caused by stress-oriented cracks or by strain-oriented minerals, yet few studies have quantitatively compared anisotropy to stress and strain over large regions. Here we compare crustal stress and strain rates on the Island of Kyushu, Japan, as measured from inversions of focal mechanisms, GPS and shear wave splitting. Over 85,000 shear wave splitting measurements from local and regional earthquakes are obtained from the NIED network between 2004 and 2012, and on Aso, Sakurajima, Kirishima and Unzen volcano networks. Strain rate measurements are made from the Japanese Geonet stations. JMA-determined S arrival times processed with the MFAST shear wave splitting code measure fast polarisations (Φ), related to the orientation of the anisotropic medium and time delays (dt), related to the path length and the percent anisotropy. We apply the TESSA 2-D delay time tomography and spatial averaging code to the highest quality events, which have nearly vertical incidence angles, separating the 3455 shallow (depth $<$ 40 km) from the 4957 deep ($>=$40 km) earthquakes. Using square grids with 30 km sides for all the inversions, the best correlations are observed between splitting from shallow earthquakes and stress. Axes of maximum horizontal stress (SHmax) and Φ correlate with a coefficient c of 0.56, significant at the 99% confidence level. Their mean difference is 31.9°. Axes of maximum compressional strain rate and SHmax are also well aligned, with an average difference of 28°, but they do not correlate with each other, meaning that where they differ, the difference is not systematic. Anisotropy strength is negatively correlated with the stress ratio parameter determined from focal mechanism inversion ($c = -0.64$; significant at the 99% confidence level). The anisotropy and stress results are consistent with stress-aligned microcracks in the crust in a dominantly strike-slip regime. Eigenvalues of maximum horizontal strain rate correlate positively with stress ratio ($c = 0.43$, significant at 99% confidence). All three orientations are E–W in central Kyushu, where the compressional strain rate is highest. Both splitting and stress suggest plate-boundary-parallel maximum principal stress just off the coast of Kyushu, where strain rate measurements are sparse. South western Kyushu has the largest difference between directions of strain rate and stress. Φ from shallow and deep earthquakes are not well aligned, suggesting that the deep earthquake waveforms are not simply split in the crust. Causes for the anisotropy may be olivine crystals aligned by drag of the subducting Philippine Sea plate in the mantle and stress-aligned microcracks in the crust.

1. Introduction

Stress in the Earth is fundamentally tied to the mechanisms of earthquakes and volcanoes. Earthquakes are usually caused by brittle failure on faults, when the accumulated stress exceeds the material strength, and subsurface magmatic activity can modify local stress fields, causing both earthquakes and eruptions. Therefore understanding stress is a critical endeavour for Earth physicists, and several techniques have been devised to measure stress. Kyushu Island in south-western Japan is an optimum location to compare stress measurements using different methods because there are several well-monitored volcanoes and a subduction mar-

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gin with large networks of seismometers and GPS stations that have been running for over ten years. Here we systematically compare three methods to determine the state of stress and its regional variation.

The most direct method to determine stress in the crust is through strain measurements in boreholes (e.g., Townend, 2006); both stress magnitudes and directions can then be determined, however, drilling boreholes to seismogenic depths is difficult and expensive. Another well-established method is to invert earthquake focal mechanisms for the direction of stress in an area (e.g., Hardebeck and Michael, 2006). Earthquake faults slip in response to the stress in a region, and the fault orientation can be determined from earthquake focal mechanisms. Differential stresses are more likely to cause those faults with favourable orientations to slip, and inversion of many different focal mechanisms can be used to determine the stress orientations where earthquakes occur. Global Positioning System (GPS) networks are widely used to determine strain rates in the Earth (Davis et al., 1989; Shen et al., 1996). Assuming simple linear elasticity, stress and strain should be parallel for small strains, and strain rate changes should be proportional to stress rate changes.

Seismic anisotropy, the directional dependence of wave speed, can be used to characterise mineral or crack alignment in the crust and mantle. In the crust it is thought that one of the main causes of crack alignment is anisotropic stress; cracks perpendicular to the maximum principal stress are closed, leaving only those cracks open that are parallel to the maximum principal stress (Nur and Simmons, 1969). Thus the anisotropic fast direction may lie parallel to the maximum principal stress direction. One of the most common methods to determine seismic anisotropy is by using its birefringent effect on shear waves, often called "shear wave splitting". Shear waves entering anisotropic material are separated into two components, with the polarisation of the first arriving wave (ϕ) determined by the orientation of the anisotropic symmetry axes and the propagation direction, and the time between the first and later (nearly orthogonal) component (dt) is a non-linear product of the strength of the anisotropy and the path length through the anisotropic medium.

Ando et al. (1980) first examined seismic anisotropy in Japan. They suggested that differential arrival times of shear waves from deep earthquakes recorded on stations in central Japan were caused by either anisotropic olivine fabric or aligned melt-filled cracks in the mantle. Since then many articles have been written on anisotropy in Japan, confirming and extending their suggestions. Olivine orientations caused by mantle flow patterns have been used to explain shear wave splitting on large scales for paths that travel through the mantle (Long and van der Hilst, 2006; Salah et al., 2009; Terada et al., 2013; Tono et al., 2009) as well as P-wave anisotropy in the same areas (Wang and Zhao, 2013). Crustal anisotropy has been attributed to cracks and also to faulting structures and mineral alignment (Kaneshima, 1990; Salah et al., 2009). Furthermore, in regions of stress-controlled anisotropy in central Japan, an increase in normalised delay time with increasing strain rate has been used to measure a stressing rate of 3 kPa/yr, comparable to the GPS-derived rates in the region (Hiramatsu et al., 2010).

Kyushu is the southern-most island of the main Japanese archipelago. It lies at an arc–arc junction between the subducting Philippine Sea Plate to the north and the Ryukyu arc to the southwest and has many subduction zone volcanoes (e.g., Mahony et al., 2011) (Fig. 1). Oblique convergence of the Philippine Sea plate occurs primarily as dip-slip movement on the subduction interface, at a rate of 62–68 mm/yr in the N55W direction (Heki and Miyazaki, 2001). Some dextral strike-slip motion is taken up on the Median Tectonic Line (MTL) and its extensions, which make up the southern boundary of the Central Volcanic Region (CVR) (e.g., Itoh et al., 1998).

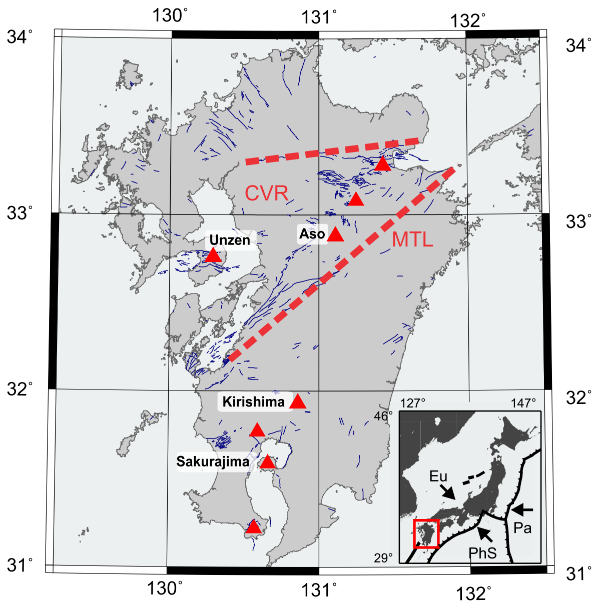

Fig. 1. Map of Quaternary volcanoes (red triangles) in Kyushu. Labelled volcanoes are discussed in the text. CVR is the Central Volcanic Region, delineated by the red dashed lines. The southern-most boundary is also often considered the extension of the Median Tectonic Line (MTL). The inset shows the tectonic setting of the region, with plates labelled Eu for Europe, PhS for Philippine Sea and Pa for Pacific. Red box in inset is outline of box. Blue lines are active faults. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methodology and data

2.1. Anisotropy

2.1.1. Splitting analysis

For the anisotropy measurements, we used the automatic shear wave splitting measurement tool MFAST (Savage et al., 2010b). Starting from pre-determined S-wave arrival times, the program determines the best filter from a set of fourteen filters, as measured by the product of the signal-to-noise ratio and the bandwidth. The filters are described in Savage et al. (2010b), and range from 0.4–4 Hz at the lowest end to 4–10 Hz at the highest end. Using the best filter, the Silver and Chan (1991) 2-D eigenvalue minimisation technique is used to determine shear wave splitting parameters over a set of 75 phase arrival windows that start and end at various times before and after the S arrival. A grid search uses trial values of Φ and dt to correct for splitting. The eigenvalues of the corrected particle motion are determined and the values of Φ and dt yielding the minimum of the smallest eigenvalue are considered the best measurements for that window. The grid search examines Φ between -90 and 90 in increments of 1°, and between 0 and 1.0 s in increments of 0.01 s. The best window is chosen via cluster analysis (Teanby et al., 2004) and the final measurement is graded based on several factors, including whether other similar sized clusters exist with markedly different results, the signal to noise ratio of the measurement, and the formal error bars of the final measurement. We use version 2.0 of MFAST, which corrects for a mistake in the previous methodology of measuring error bars (Walsh et al., 2013). Here we present the highest quality measurements from the best filters (AB), in which the maximum eigenvalue on the contour plots is larger than 5 times the 95% confidence interval (emax $>$ 5) (Savage et al., 2010b). Briefly, AB measurements are not null, i.e., Φ is further from than 20 de-