Azimuthal anisotropy in the Earth's mantle from normal mode spectra

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1. Introduction

Azimuthal anisotropy may be an indicator of deformation or flow in the Earth's mantle. Here, we present the results of incorporating upper-mantle azimuthal anisotropy in the forward calculations to produce synthetic normal mode spectra. This was done using the results of Beghein et al. (2008), who performed a model space search to find the most likely values of the elastic parameters that describe azimuthal anisotropy in order to fit the normal mode splitting coefficients measured by Resovsky & Ritszwoller (1998). The effects are clearly visible in the normal mode spectra.

2. Normal mode coupling

Earthquakes of sufficient magnitude have the ability to make the entire Earth oscillate at distinct eigenfrequencies, depending on the Earth's internal structure. The corresponding patterns of displacement, the eigenfunctions, are the Earth's normal modes. They are divided into spheroidal modes ${}_nS_l$ and toroidal modes ${}_nT_l$ (**figure 1**).

Normal mode coupling is the exchange of energy between normal modes. Mathematical coupling rules describe what type of modes may couple due to different mechanisms, such as the Earth's rotation, ellipticity and aspherical structure. **Figure 2** Illustrates the coupling due to the Coriolis force. The energy exchange between coupled normal modes can make toroidal modes appear on vertical-component recordings and spheroidal modes on horizontal-component recordings.

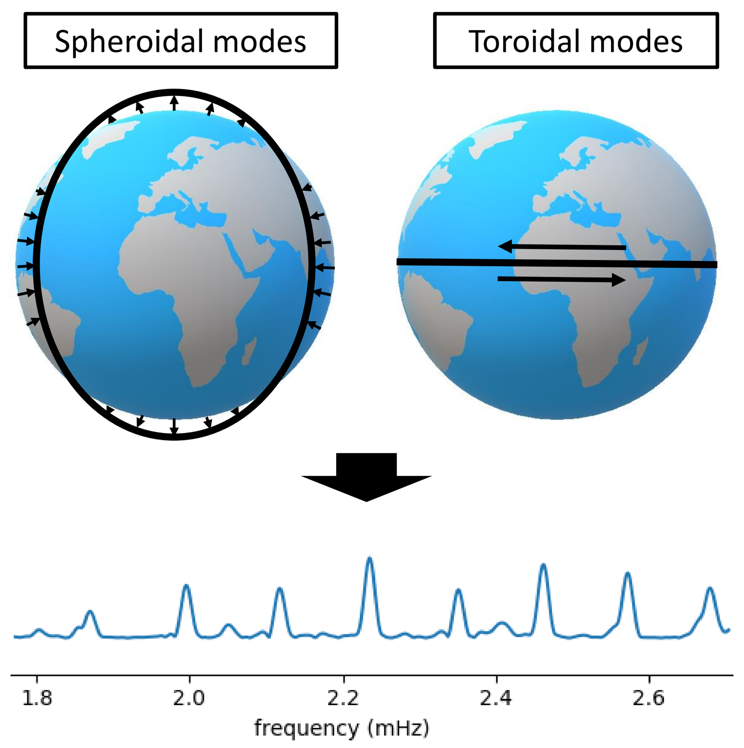

Figure 1: The Earth's oscillatory motion after a large earthquake is divided into spheroidal and toroidal normal modes, that appear on a seismogram as distinct peaks in the frequency domain.

Azimuthal anisotropy may be required to explain observed normal mode coupling that can not yet be reproduced with synthetic spectra, as shown in **figure 3**.

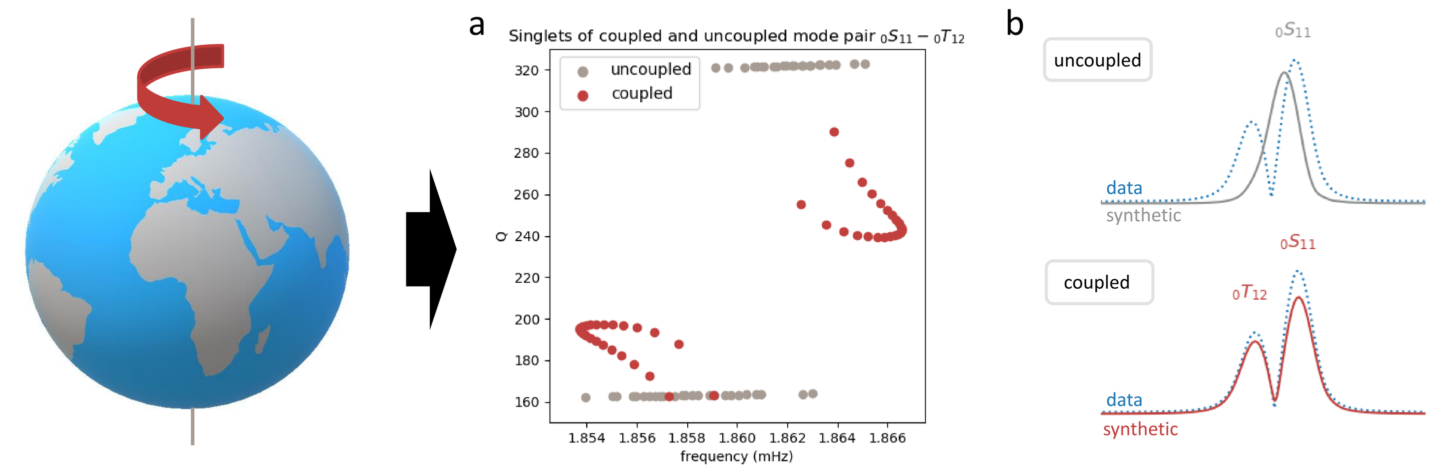

Figure 2: The Coriolis force due to Earth's rotation couples normal modes of type ${}_nS_l - {}_nT_{l\pm1}$. **2a:** Singlets of coupled and uncoupled modes ${}_0S_{11}$ and ${}_0T_{12}$. The $2l+1$ eigenfrequencies of a coupled mode repel those of the mode it is coupled with, while attenuation is shared. **2b:** Schematic vertical-component spectrum for coupled and uncoupled modes ${}_0S_{11}$ and ${}_0T_{12}$. Toroidal mode ${}_0T_{12}$ is observable on the vertical component of the frequency spectrum when it is coupled with spheroidal mode ${}_0S_{11}$. This coupling is required in order to fit the data.

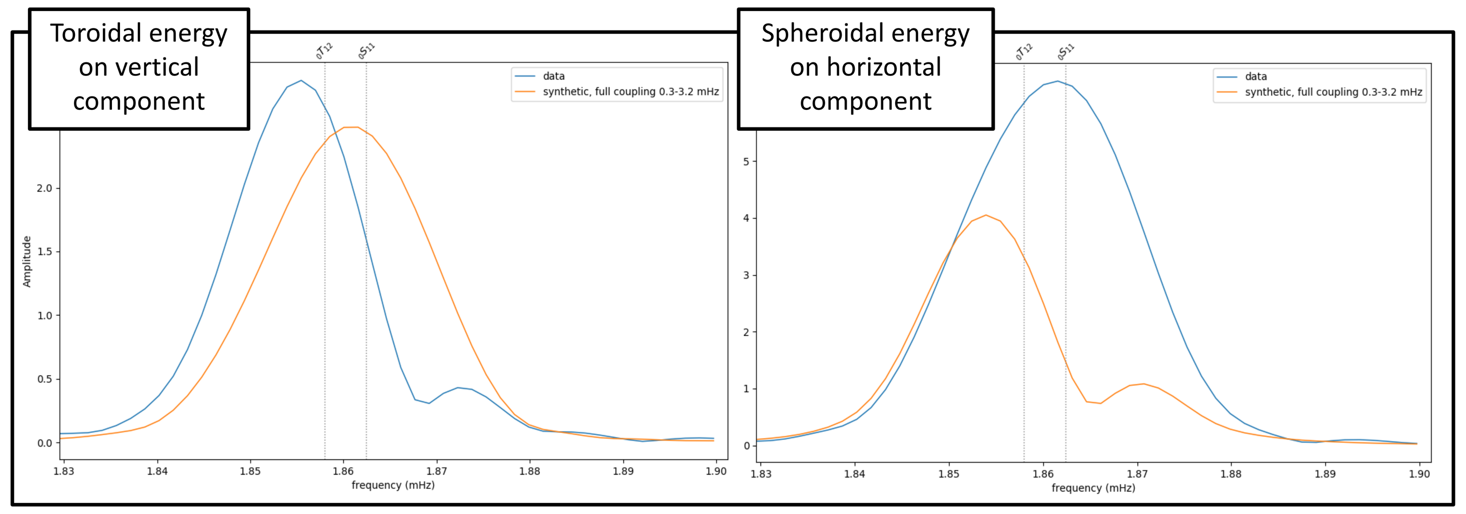

Figure 3: Vertical (left) and horizontal (right) component spectra at station GRFO from the 11 March 2011 Tohoku earthquake, showing a large exchange of energy between modes ${}_0S_{11}$ and ${}_0T_{12}$ in the data (blue). The synthetic data (orange), which were computed for S20RTS including Earth's rotation and ellipticity, do not predict this strong coupling. Another coupling mechanism is therefore required to explain these observations, which is most likely azimuthal anisotropy.

3. Modelling azimuthal anisotropy

Azimuthal anisotropy can be expressed in terms of perturbations to the fourth-order elastic tensor. Surface waves (**figure 4**) and normal modes are sensitive to some of the same elastic parameters containing these perturbation terms.

Normal mode coupling due to the Earth's structure is described by structure coefficients c_s^t that contain the elastic parameters for azimuthal anisotropy. Resovsky & Ritzwoller (1998) found that the structure coefficients of degree-two structure ($s = 2$) for modes ${}_0S_l - {}_0T_{l+1}$ differ significantly from those expected for an isotropic Earth. These modes are sensitive to six elastic parameters describing azimuthal anisotropy (H_c, G_c, B_c, K_s, J_s and M_s) and are mainly sensitive to the upper mantle and the transition zone.

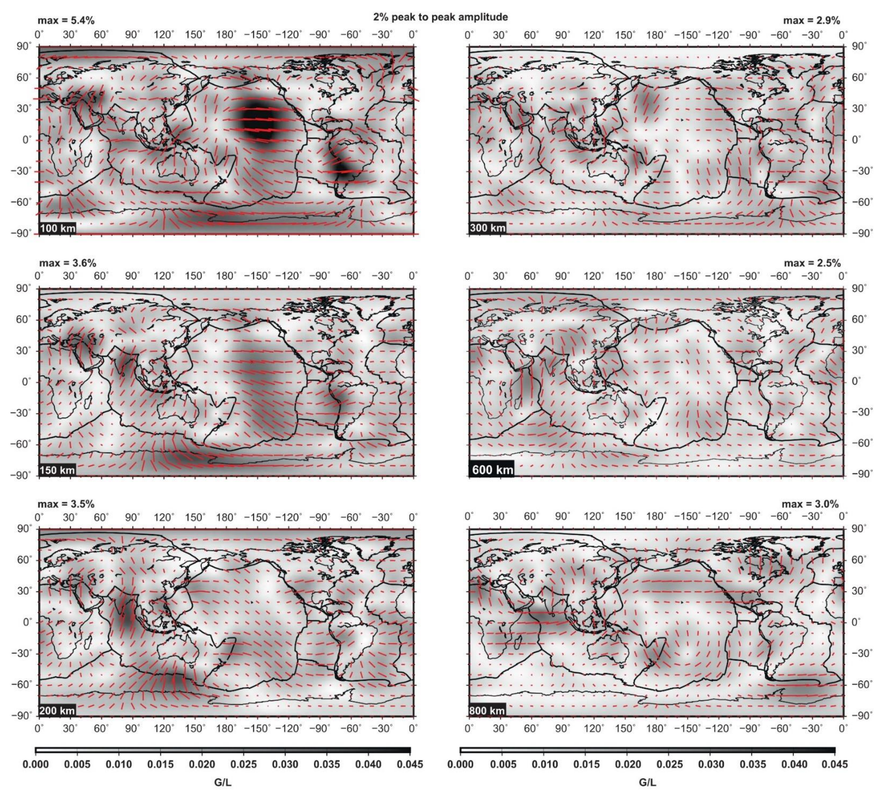

Figure 4: Azimuthal anisotropy at several depths in the mantle from fundamental and higher mode Rayleigh wave phase velocities, showing fast anisotropic directions in red. The grayscale indicates the value of elastic parameter G_c. From Yuan & Beghein (2013).

Beghein et al. (2008) determined, by means of a model space search, what the most likely values of these elastic parameters are in order to produce the degree-two structural coefficients of Resovsky & Ritzwoller (1998). We used their values of the elastic parameters to determine the corresponding structure coefficients, which were in turn used to calculate synthetic normal mode spectra (see also **figure 5**).

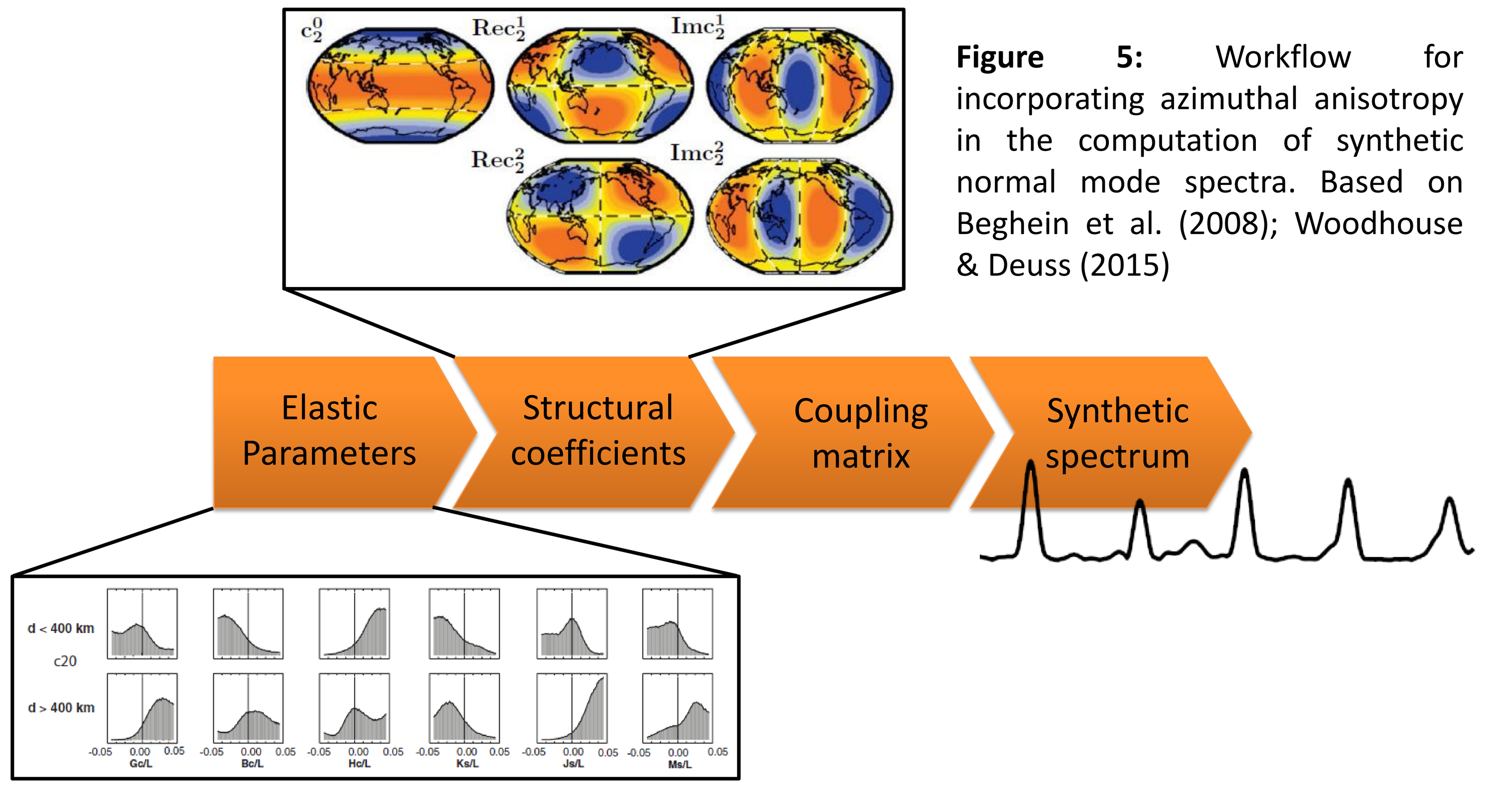

Figure 5: Workflow for incorporating azimuthal anisotropy in the computation of synthetic normal mode spectra. Based on Beghein et al. (2008); Woodhouse & Deuss (2015)

4. Results

For coupled fundamental modes ${}_0S_l - {}_0T_{l+1}$, **figure 6** shows the degree-two structure coefficients for azimuthal anisotropy confined to the top 670 km of the mantle, calculated using the elastic parameter values from Beghein et al. (2008); the data from Resovsky & Ritzwoller (1998) and the coefficients for an isotropic Earth based on velocity models S20RTS and CRUST5.1. Coefficients c_2^0 and Rec_2^1 have similar values for the anisotropy model and the data, while the other coefficients for anisotropy show little agreement with the data. We did however proceed to compute synthetic spectra using this model for azimuthal anisotropy, in order to find out whether the effects of azimuthal anisotropy on the coupling of modes ${}_0S_l - {}_0T_{l+1}$ were visible in the synthetic data (**figure 7**).

The synthetic spectra in **figure 7** show the effects of azimuthal anisotropy, the Coriolis force and their combined effect on the coupling between modes ${}_0S_{11}$ and ${}_0T_{12}$ for a range of latitudes. Comparing the amplitudes of the spheroidal and the toroidal modes in **figure 7b** and **7c** shows that azimuthal anisotropy has a significant effect on the coupling of the two modes.

Figure 7 also illustrates that there is no Coriolis coupling for equatorial paths, as the Coriolis force is zero at the equator. Anomalous coupling between modes of type ${}_0S_l - {}_0T_{l+1}$ on equatorial paths may then be attributed to azimuthal anisotropy.

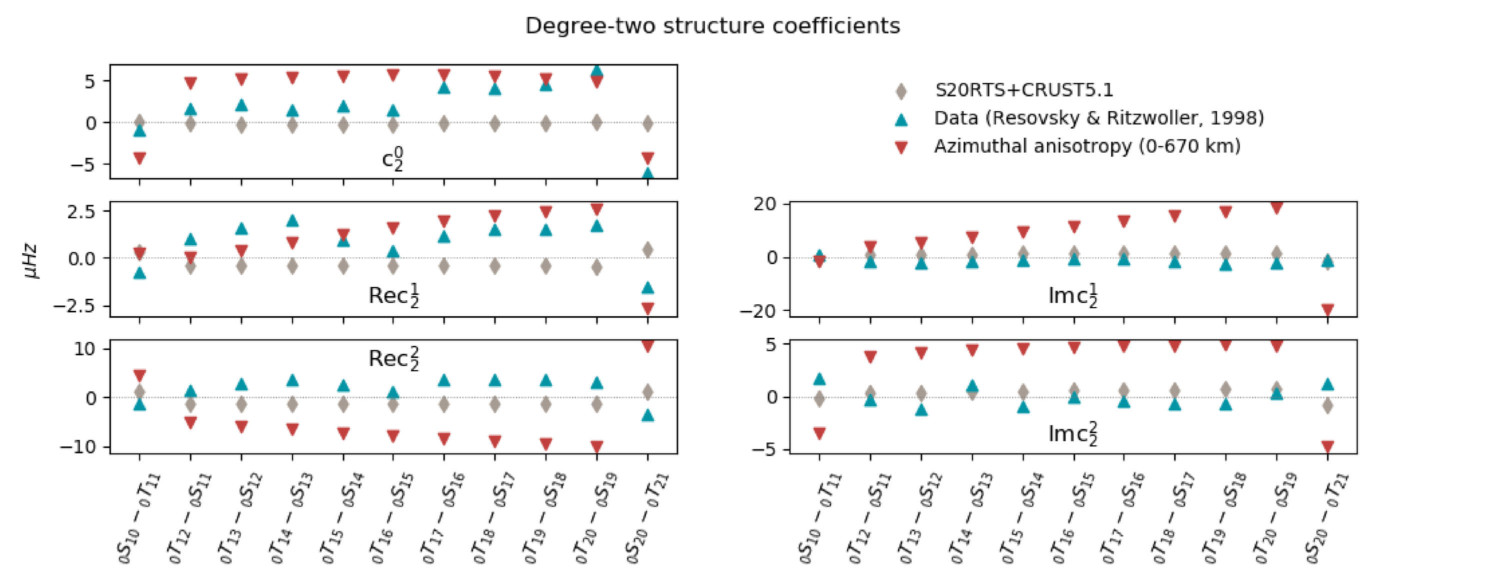

Figure 6: Degree-two structure coefficients for several ${}_0S_l - {}_0T_{l+1}$ modes as determined by Resovsky & Ritzwoller (1998) and as computed for two Earth models: with and without azimuthal anisotropy in the top 670 km of the mantle.

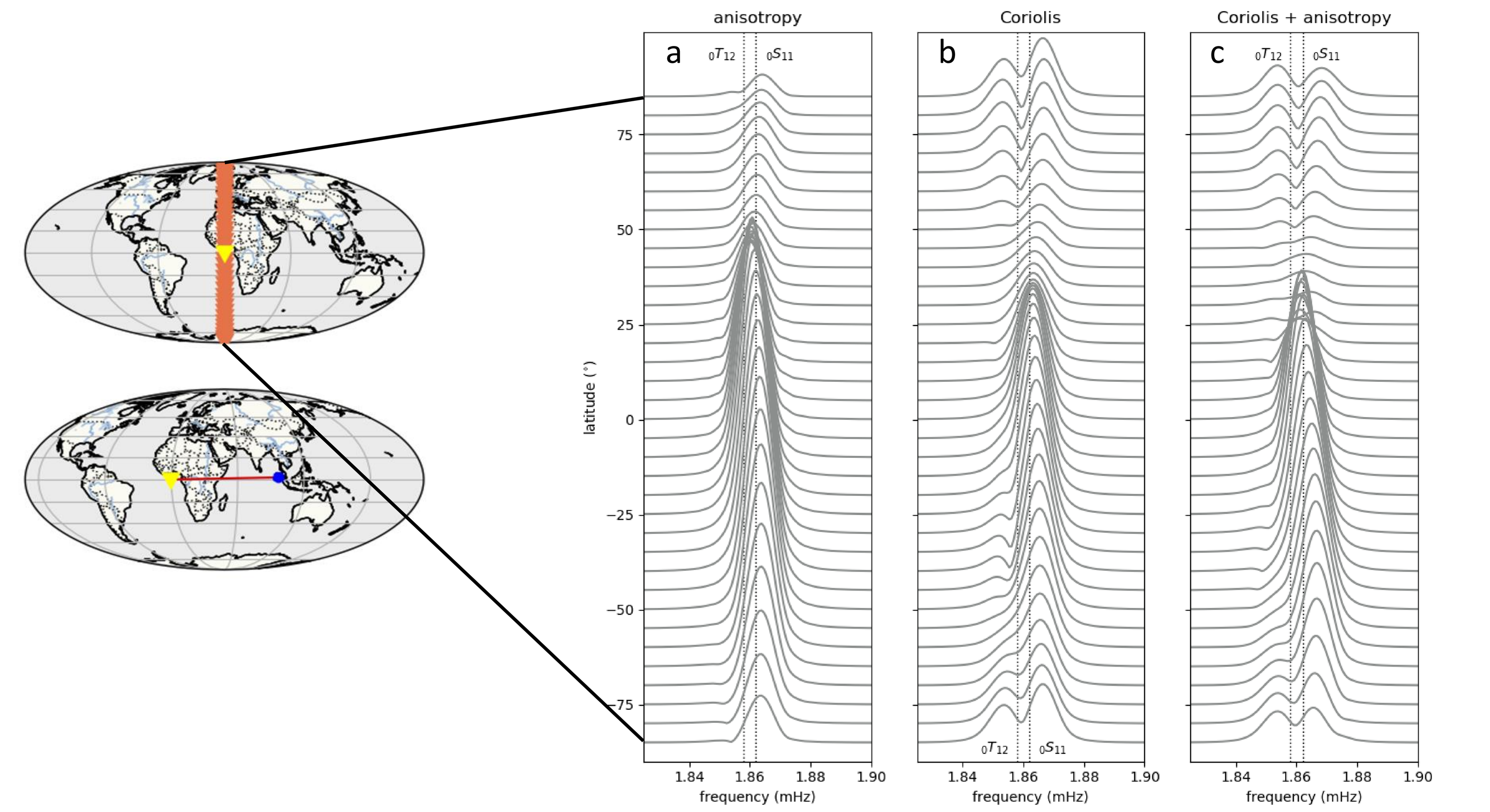

Figure 7: Synthetic vertical-component spectra of modes ${}_0S_{11}$ and ${}_0T_{12}$ at a range of latitudes for the 28 March 2005 Sumatra earthquake. Synthetics were calculated for coupling due to **7a:** azimuthal anisotropy only; **7b:** the Coriolis force only and **7c:** both azimuthal anisotropy and the Coriolis force.

5. Outlook

➡ We will implement the surface wave models of azimuthal anisotropy from Yuan & Beghein (2013) and Yuan & Beghein (2014) and study their effect on synthetic normal mode spectra.

➡ We will use normal modes to study the presence of azimuthal anisotropy in regions that are out of reach for surface wave studies, such as the D''-region.

6. References & acknowledgements

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