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Stratified inner core structure - a normal mode search for an isotropic top layer

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Introduction

Buried deep at the centre of the Earth, the inner core exhibits an intriguing property - it is anisotropic. However, recent body wave studies have suggest there is an isotropic layer at the top of the inner core, with a thickness of between 50km (Ouzounis & Creager, 2000) and 200km (Song & Helmberger, 1998). Inner core anisotropy models derived from normal mode data, created with inversions which use the self-coupling approximation, do not have such a layer. We have previously shown that the self-coupling approximation is not valid when considering mode interactions due to inner core anisotropy (Irving et al. 2008). Here we use full-coupling to try to reconcile the body-wave results with normal mode data. The presence of an isotropic top layer has implications for our understanding of the formation of the inner core; insights into the Earth's magnetic field could be gained by a comprehensive understanding of the anisotropy.

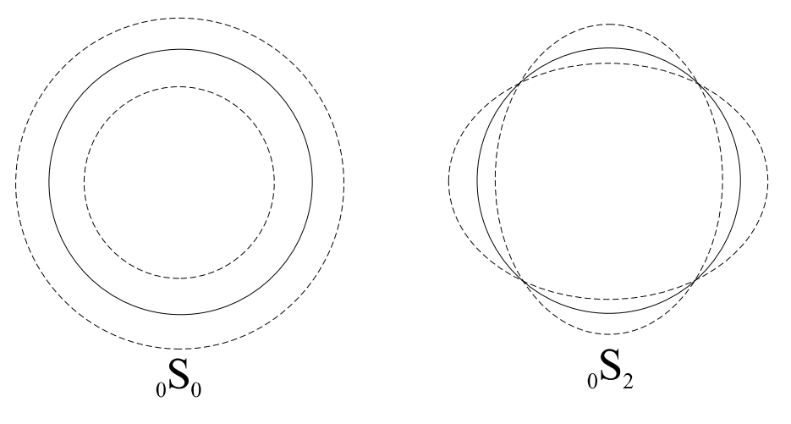

Figure 1: Cartoon of two normal modes. Normal modes are free oscillations of the Earth. Each spheroidal normal mode can be written in the form $_nS_l$ where n is the number of nodes in the radial direction and l the number of nodes in the longitudinal direction.

Methodology

The frequencies and quality factors of 97 inner core modes were calculated for mantle and inner core structure with the modes permitted to fully couple. Modes sensitive to only the mantle and crust were also included in the calculations where necessary. All calculations also include the effects of coupling through ellipticity, rotation and mantle structure.

The S20RTS model was used to describe lateral variations in mantle velocity and density, and PREM was used for the 1-D structure of the whole Earth. Synthetic data were compared with data from four earthquakes: the 1994 June 9th Bolivia earthquake (060994A), 1994 October 4th Bolivia earthquake (100494B), 1995 July 30th Chile earthquake (073095A) and 2004 December 26th Sumatra earthquake (122604A). The synthetic seismogram file contains the phase and amplitude information of the Fourier transformed, cosine tapered, synthetic seismogram for the vertical motion.

To determine how well a synthetic seismogram fits the data, the complex misfit is calculated:

$$misfit = \frac{1}{N}\sum^{N}\frac{\sum_{i=1}^{n}\left|z_{data,i}-z_{synth,i}\right|^2}{\sum_{i=1}^{n}\left|z_{data,i}+z_{synth,i}\right|^2}$$

where there are N spectral segments which each contain n data points in frequency space. By investigating the sensitivity to 1-D changes in inner core v_s and v_p, each of the 19 inner core sensitive normal modes studied was characterised as a radial, PKIKP or PKJKP mode.

Models of anisotropy

Models describing the anisotropy of normal modes have been produced by several authors; we have investigated four of them (Figure 2), the B&T model (Beghein & Trampert, 2003), the D&R model (Durek & Romanowicz, 1999), the Tr model (Tromp, 1993) and the W,G&L model (Woodhouse et al., 1986).

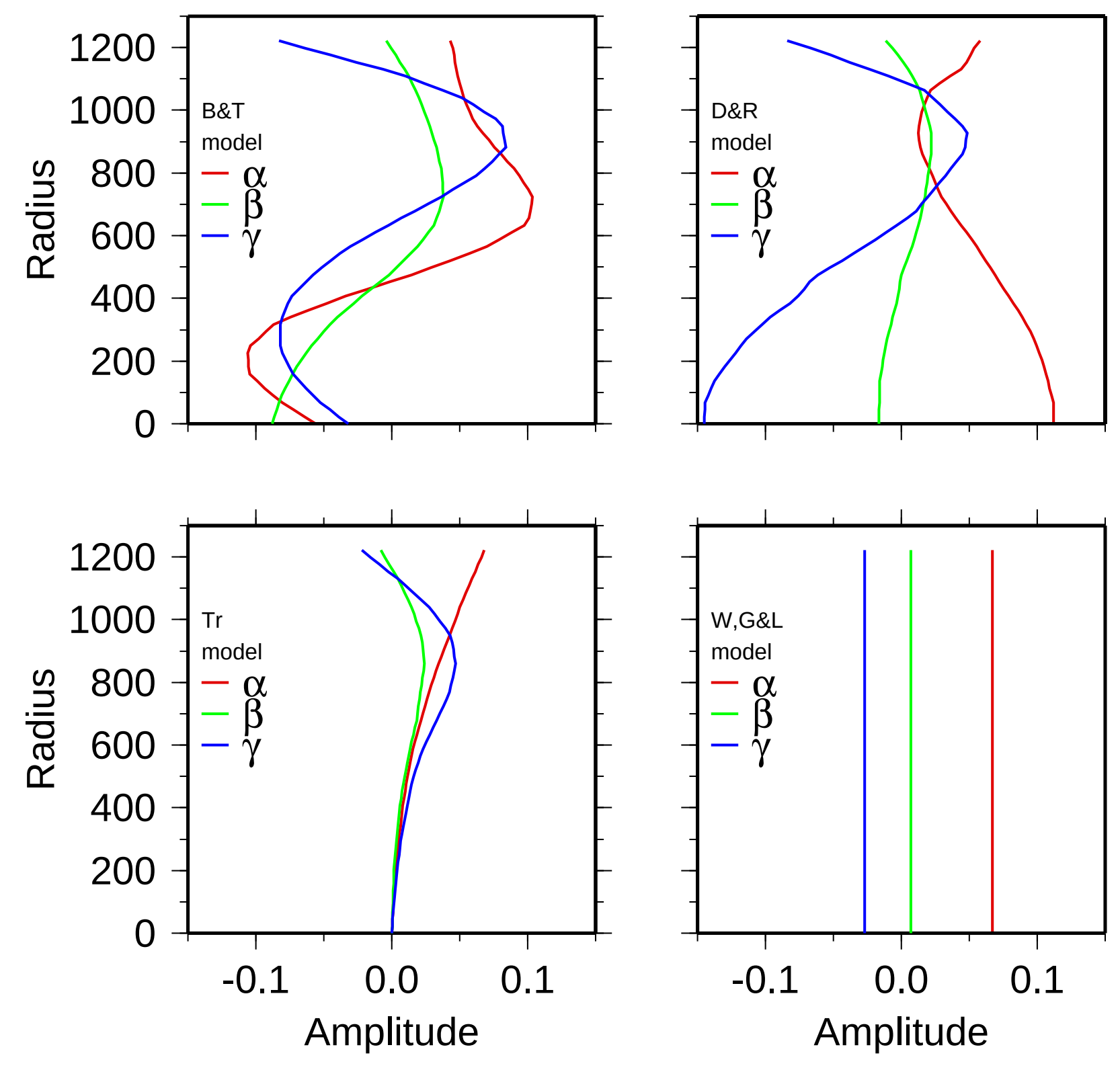

Figure 2: The four models of normal mode inner core anisotropy. They describe the anisotropy using three parameters: α, β and γ. α represents the relative speeds of inner core P-waves travelling along and perpendicular to the Earth's rotational axis. Similarly, β represents the relative speeds of inner core S-waves travelling along and perpendicular to the Earth's rotational axis. All of the parameters are defined by components of the fourth order elastic tensor Λ_{ijkl}.

All of these models were created using the self-coupling approximation which assumes that frequency differences between modes are much greater than the magnitude of coupling due to heterogeneous structure, so that the modes are effectively independent. Irving et al. (2008), Andrews et al. (2006) and Deuss & Woodhouse (2001) have shown that this approximation is not always valid, especially when inner core properties are varied.

Response to an isotropic top layer

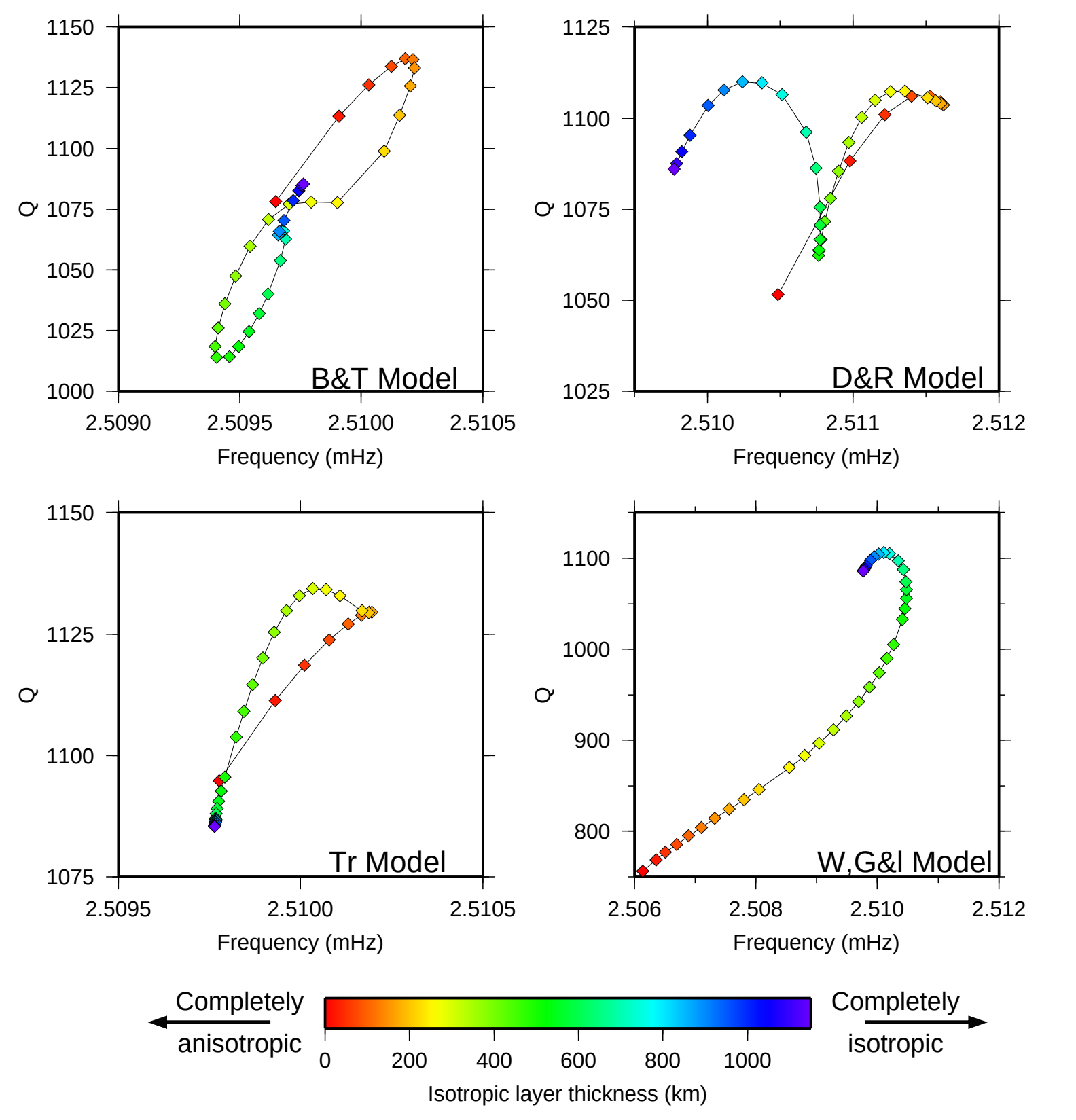

Figure 3: Response of mode $_2S_0$ to the inclusion of an isotropic top layer when full-coupling is used.

When an isotropic layer is imposed on the top of a model, both the frequency and quality factor (Q) of the mode change. The changes are non-linear, and depend on the coupling interactions cause by the anisotropy model. If $_2S_0$ was only permitted to self-couple there would be no change to the frequency or Q of the mode.

Changes on an observable scale

Strongly affected modes have changes in both their frequency and Q. The shape of a mode and its position in the spectrum will vary as the isotropic layer is thickened.

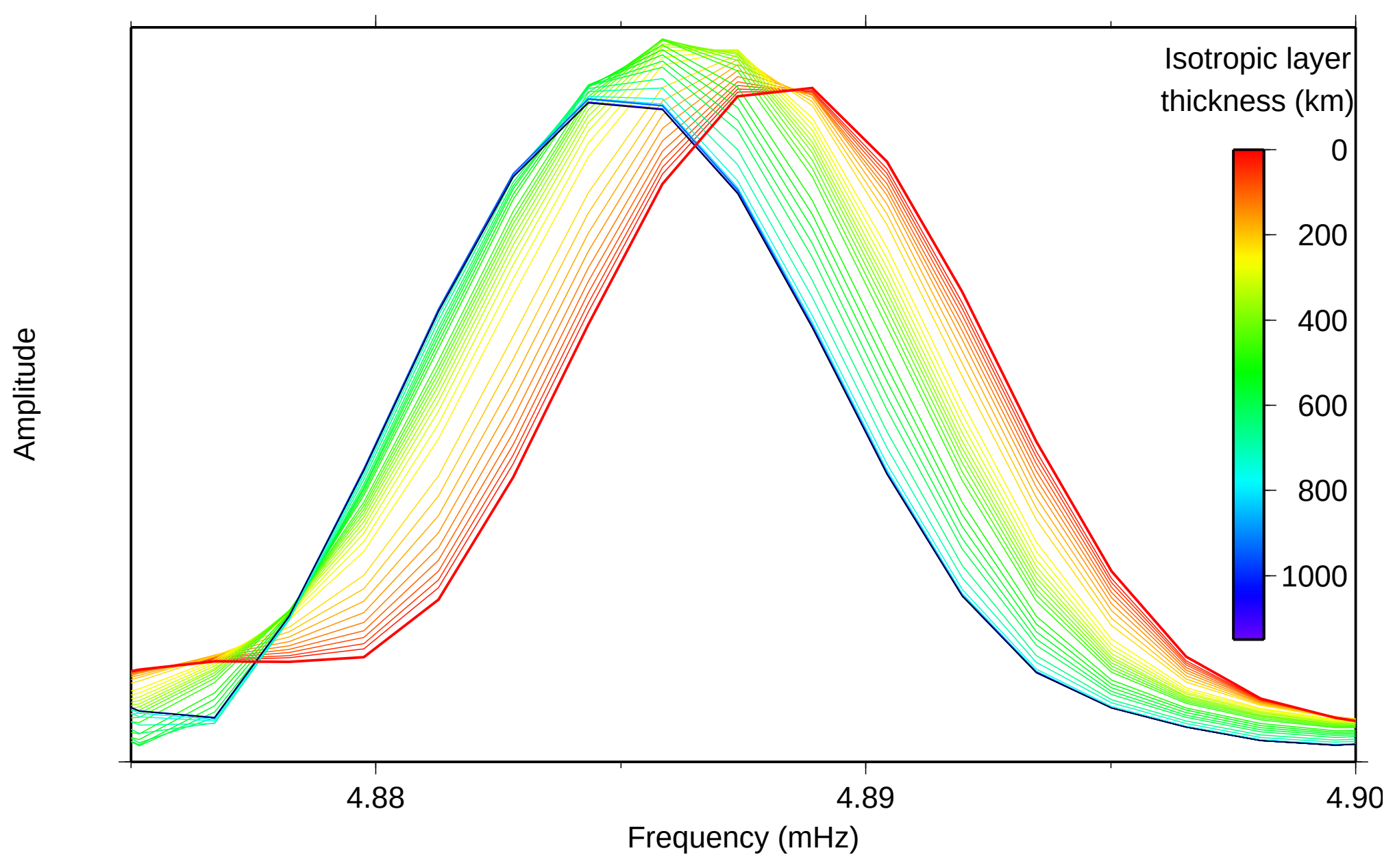

Figure 4: Event 122604A, station ARU, 50-110 hours. Mode $_5S_0$ responds to the introduction of an isotropic top layer on the fully-coupled B&T model by decreasing its frequency and also slightly increasing its Q.

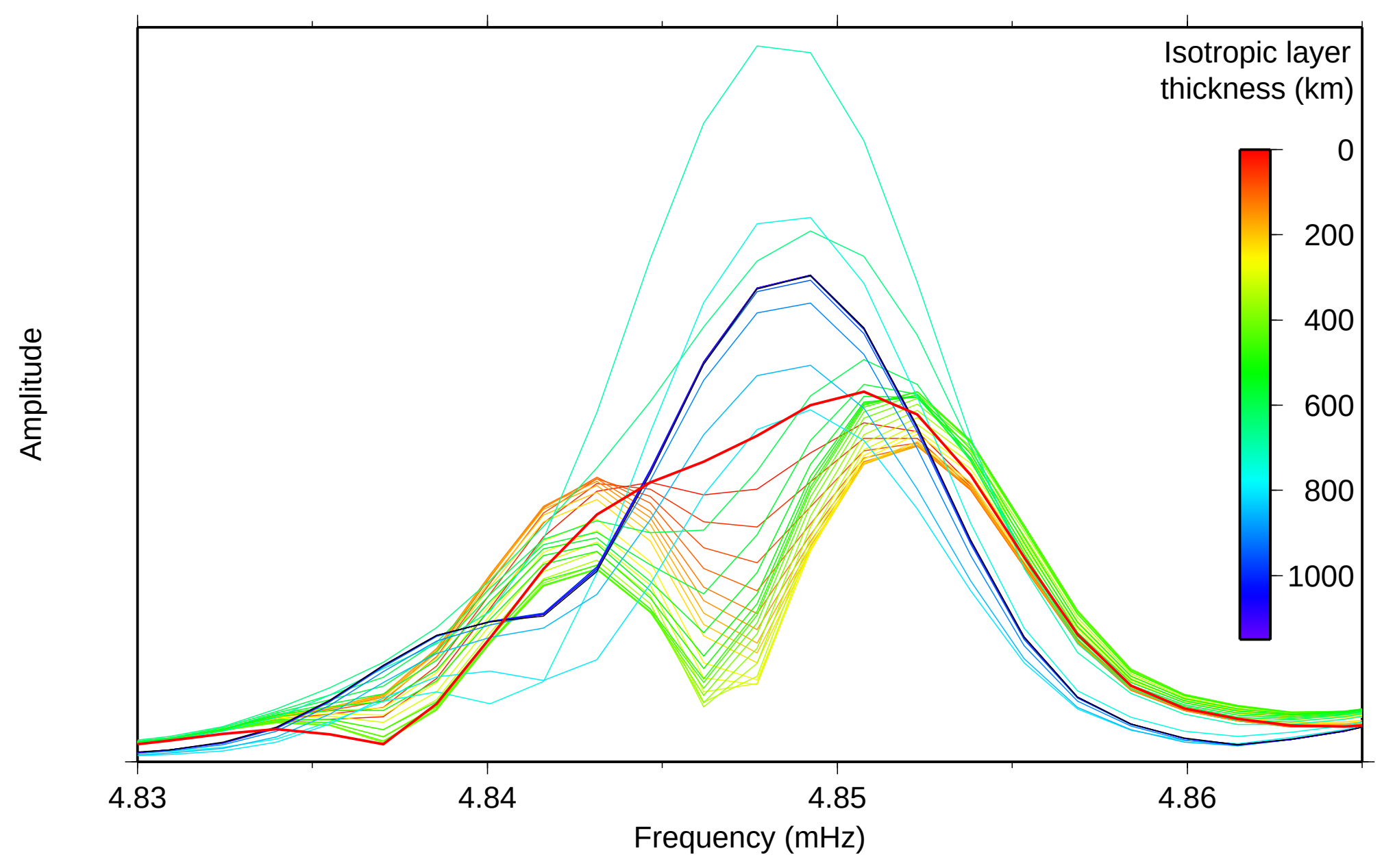

Figure 5: Event 122604A, station ARU, 50-110 hours. Using the B&T model and full-coupling, when there is no isotropic layer, mode $_{13}S_2$ is a single peak. When an isotropic layer is introduced, the mode splits into two peaks, and then reforms into one peak when the isotropic layer is 650km thick.

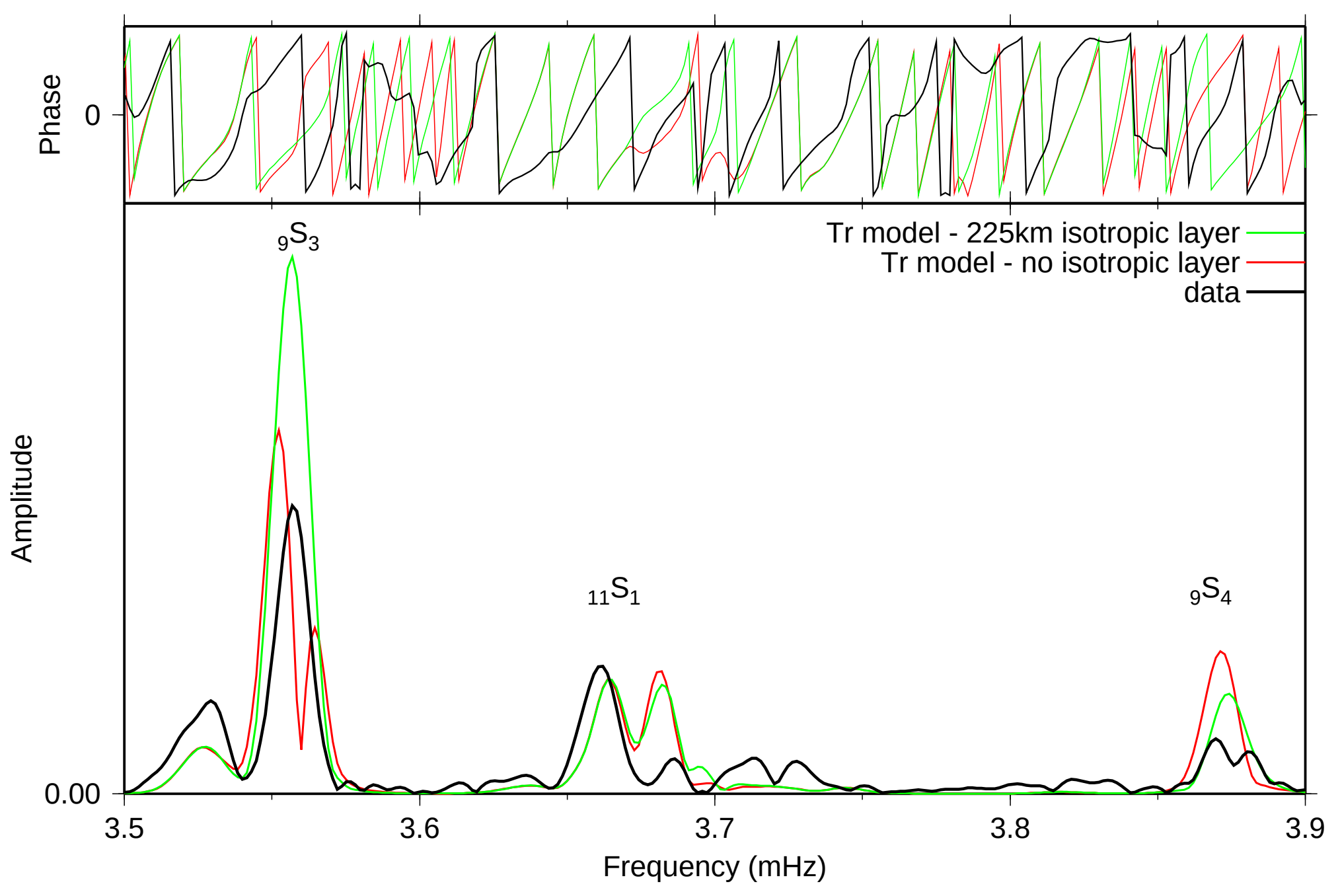

Figure 6: Event 060994A, station ENH, 30-80 hours. Data and synthetic seismograms for the frequency range 3.5 - 3.9mHz. Three inner core sensitive modes are present in this range: $_9S_3$, $_{11}S_3$ and $_9S_4$. 66 mantle modes were also included in seismograms. The two synthetic spectra have been created using full-coupling for the Tr model, with no isotropic layer and a 250km isotropic layer.

Looking for the isotropic layer

The misfit between synthetic seismograms and data from four events was calculated using both the full-coupling and the self-coupling approximation. For each event, time and frequency windows containing each one of 19 inner core sensitive modes were selected for up to 52 stations. Modes were characterised as radial, PKIKP (sensitive to inner core v_p and v_s) or PKJKP (sensitive to inner core v_s only).

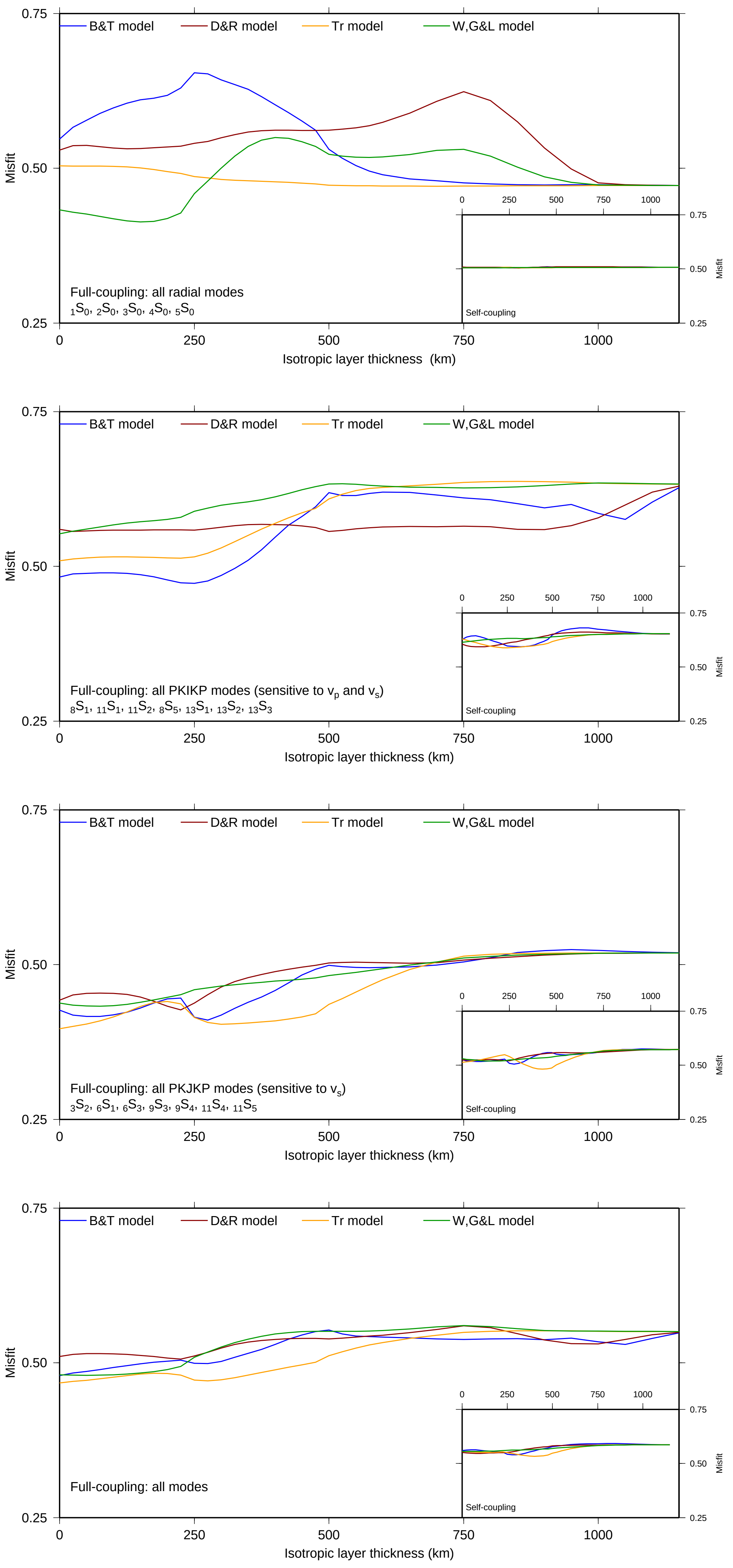

Figure 7: Misfit between data and synthetic seismograms for an inner core with an isotropic top layer.

The misfits for radial modes fluctuate strongly depending on the inner core anisotropy model used. The PKIKP modes permit an isotropic layer of up to 225km with all models, but do not rule out the absence of an isotropic layer. The misfits for PKJKP modes show that all four models fit the data better when there is an isotropic top layer of between 50 and 275km thickness. The bottom panel of Figure 7 shows that the misfit is not noticeably worsened by the presence of an isotropic layer of up to 250km. The misfit is higher when the core is completely isotropic than when any of the anisotropy models is used. The misfit between the synthetic seismograms and the data is also lessened when full-coupling is used instead of the self-coupling approximation.

Conclusions

- An isotropic top layer changes the frequency and attenuation of normal modes. These changes are dependent on the inner core anisotropy model used and on the thickness of the layer.
- The presence of an isotropic top layer causes an observable effect on synthetic spectra. The magnitude of this effect is of the order of the differences between synthetic and observed seismograms.
- We have shown that an isotropic layer of up to 250km thickness at the top of the inner core is compatible with seismic data. Normal mode observations can therefore be reconciled with the conclusions drawn from body wave studies.

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