Using new CMB Stoneley mode splitting function measurements to constrain seismic structures in the D'' region

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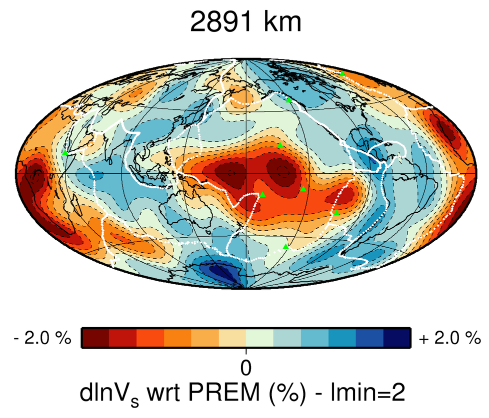
1. INTRODUCTION

The D'' layer is a thermal boundary layer, constraining the nature of convection in the mantle. LLSVPs dominate Vs models (**Fig 1**) and could be thermal or thermochemical structures. Information on their density and Vs/Vp ratio will help to assess their influence on mantle dynamics.



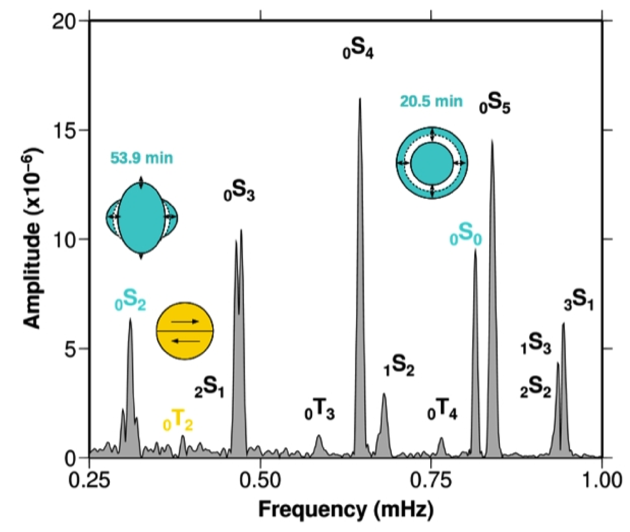
We invert for Vs and Vp independently using body wave, surface wave and normal mode data, including new CMB Stoneley mode measurements.

Fig. 1: Slice through Vs model S20RTS [1] at 2891 km depth.

2. NORMAL MODES

- Standing waves along the radius and surface of the Earth.
- Clear peaks in spectra at discrete frequencies (**Fig. 2**).
- Multiplet $_nS_l$ consists of 2l+1 singlets, degenerate for PREM.
- Singlets split by rotation, ellipticity and 3D heterogeneity.
- Splitting is visualised using splitting function map [3].
- Each mode is sensitive to Vs, Vp and ρ at different depths.

Fig. 2: Normal mode spectra for the Sumatra earthquake of 2004 (station ARU, Russia). Predicted frequencies are indicated with the sense of movement. Inspired by Park et al. 2005 [2].

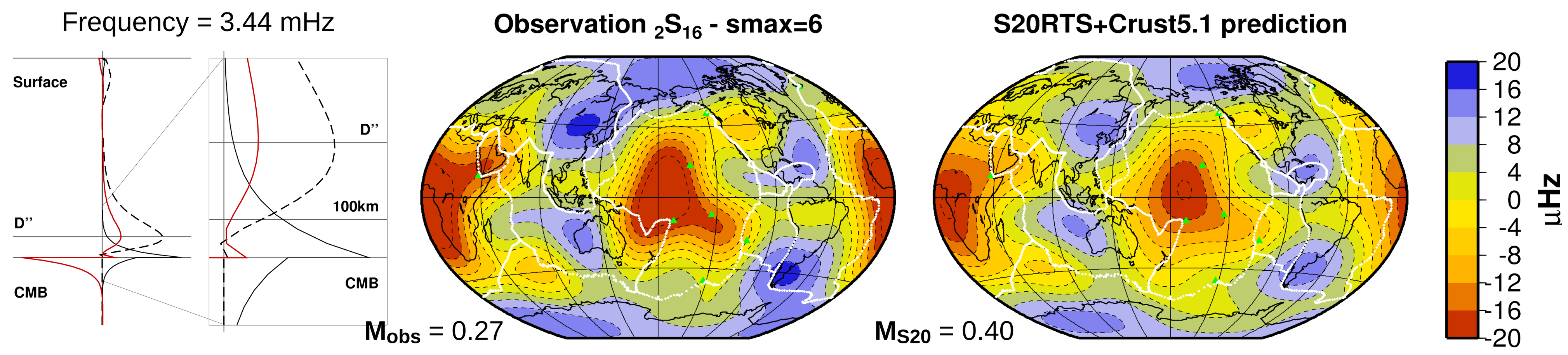


3. STONELEY MODES OBSERVATIONS

- Stoneley modes are confined to solid-liquid interfaces, like the CMB.
- We have measured 9 CMB Stoneley mode splitting functions [4].
- These are also sensitive to density variations in the D'' (**Fig. 3**).

Observations of CMB Stoneley modes provide unique constraints on structure of D'', as well as improved depth resolution.

Fig. 3: Sensitivity kernels (left) for Vp (solid), Vs (dashed) and density (red) and splitting function observation (right) for CMB Stoneley mode $_2S_{16}$.



4. DATA: BODY WAVE TRAVEL TIMES, SURFACE WAVE DISPERSION and NORMAL MODE SPLITTING

Phase	# Picks	Phase	# Picks
S,Sdiff, sS, sSdiff	193,510	P, Pdiff, pP, pPdiff	275,740
SS, sSS	124,373	PP, pPP	182,839
SSS	27,940	PPP, pPPP	17,358
SKS	34,913	PKP	18,833
SKKS	8,885		
ScS, sScS	10,141		
ScS2, ScS3, sScS2, sScS3	27,837		
SSm, SSSm, sSSSm, sSSSSm	14,378		
TOTAL	**441,977**		**494,770**

Table 1: Travel time data obtained using cross-correlation with PREM/CMT synthetics. Updated data set from [5,6].

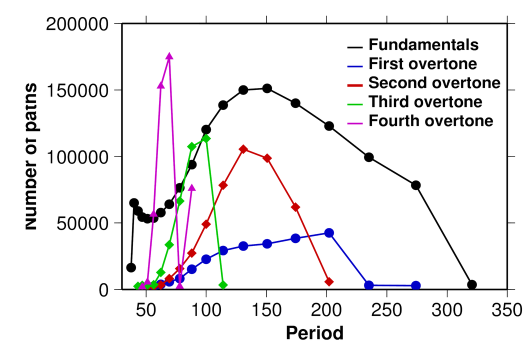
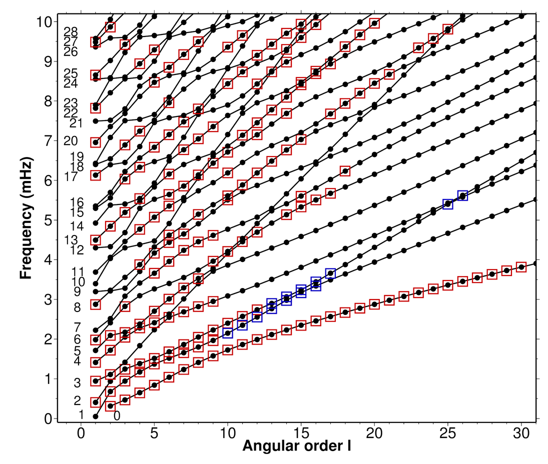


Fig. 4: Number of paths for surface wave dispersion data, obtained using the mode-branch stripping technique [7]. Total of 3,119,341 paths. Updated data set from [6,7].

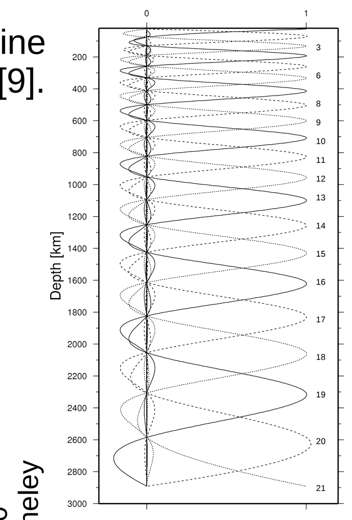
Fig. 5: Normal mode splitting function data set. Red boxes show modes in the mode data set [8], blue boxes show Stoneley modes [4]. A total of 143 modes with 6,970 splitting coefficients are used.



5. INVERSION

- Invert independently for dlnVs and dlnVp.
- S20RTS parameterisation [1]: 21 depth splines (**Fig. 6**), lateral spherical harmonics up to l=12.
- Correct for crust structure using Crust5.1 [10].
- Density variations included using dlnp = 0.3 * dlnVs.
- Combine all data with different depth sensitivity (**Fig. 7**).
- Vary data weighting factors and density scaling.

Fig. 6: Depth spline parameterisation [9].



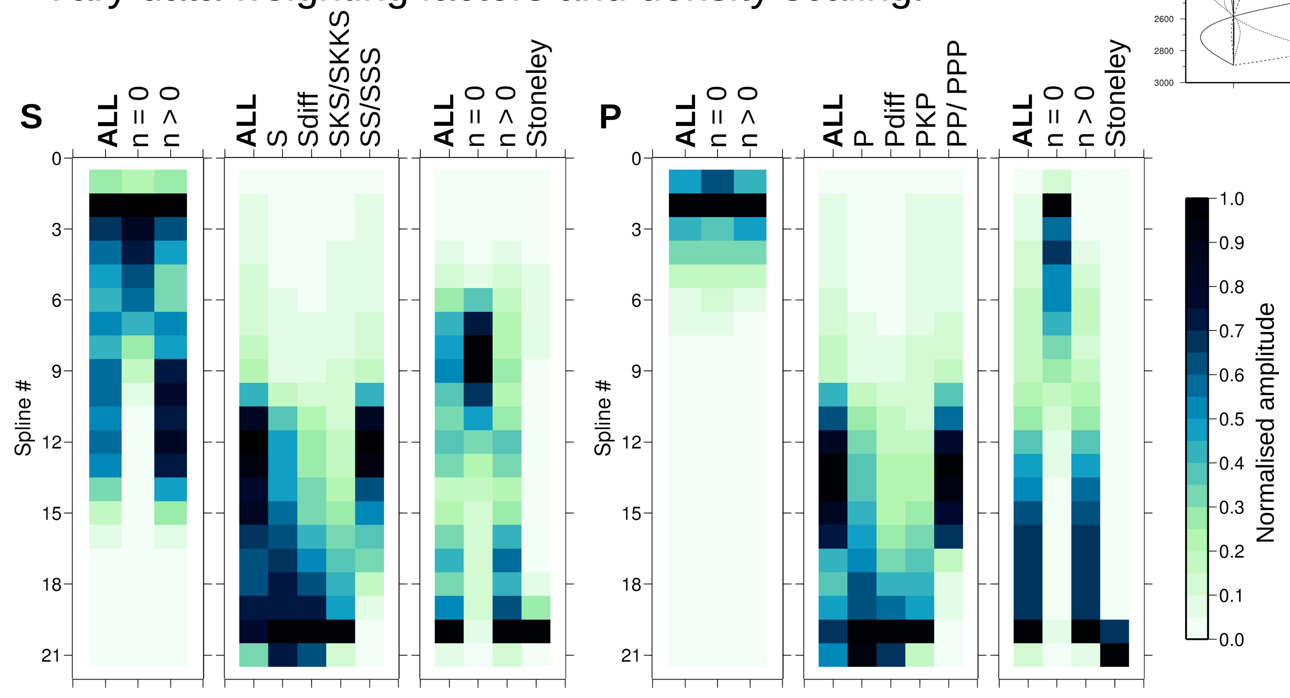


Fig. 7: Normalised sensitivity of individual data sets to the 21 spline functions for dlnVs (left) and dlnVp (right), similar to [11].

6. INVERSION RESULTS

Stoneley modes are explained best by a decreased dlnVs and increased dlnVp at the CMB, and an increased dlnVs above D'' (Fig. 8 & 9). This is also reflected in the dlnVs/dlnVp ratio.

WITHOUT STONELEY MODES

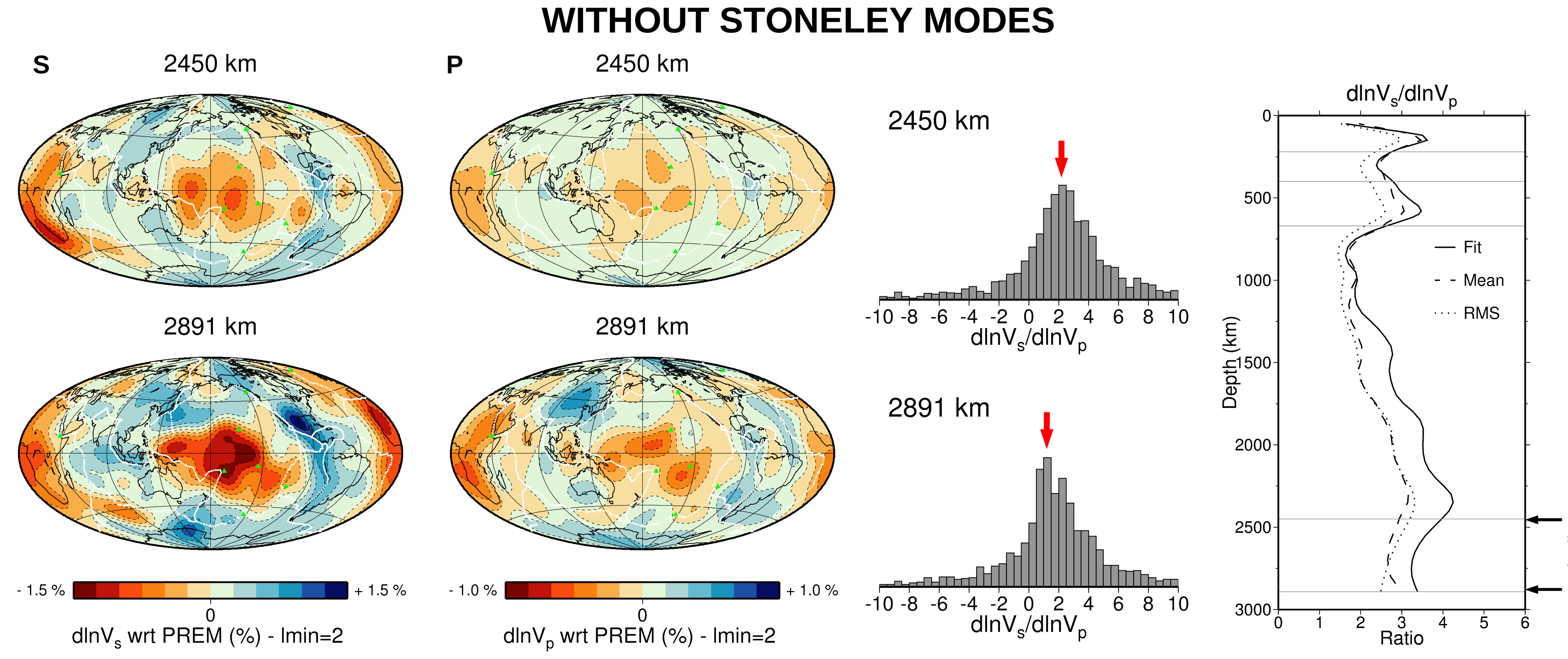


Fig. 8: Inversion results without Stoneley modes. Travel time and splitting data are weighted with a factor of 20 and 1000 relative to dispersion data (ttwt:splwt=20:1000). From left to right, we show the S-wave and P-wave variations and histograms of the dlnVs/dlnVp ratio at 2450 (top) and 2891 (bottom) km depth. On the far right we show this ratio for the entire mantle, computed in three ways.

INCLUDING STONELEY MODES

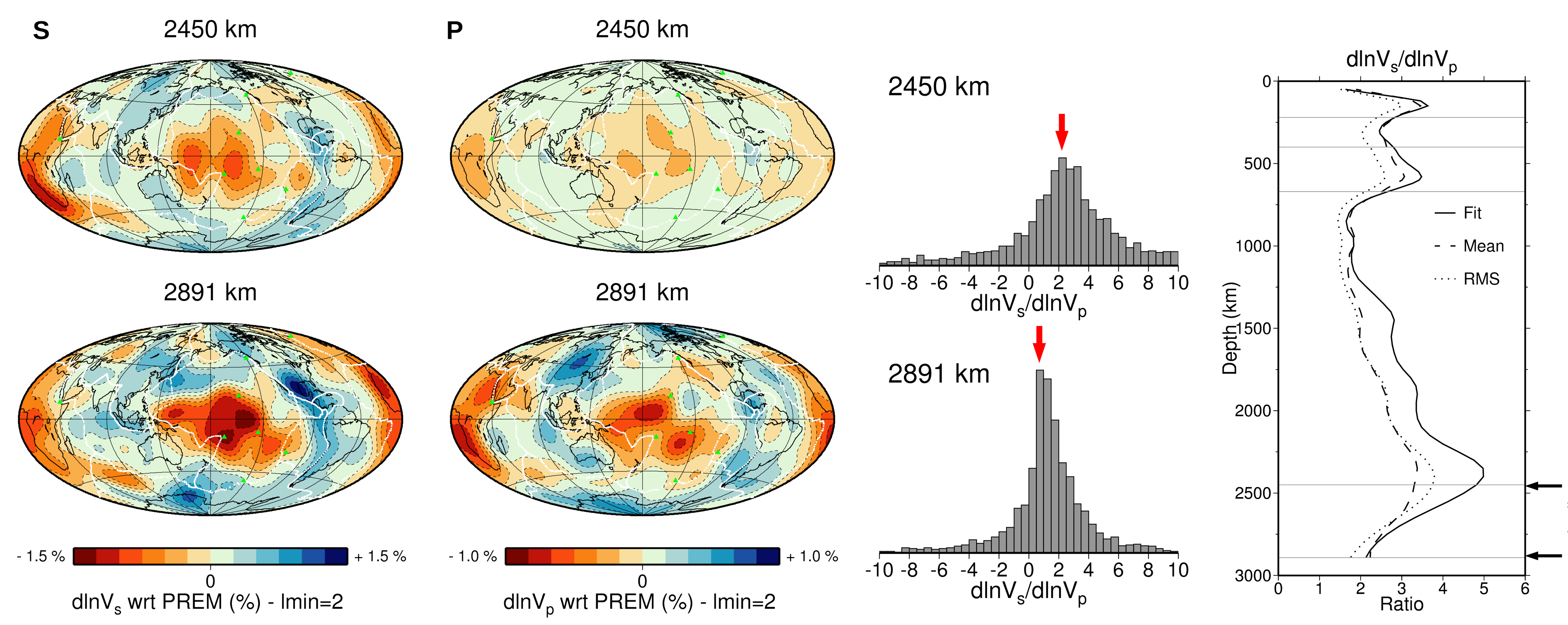


Fig. 9: Inversion results including Stoneley modes. All panels are the same as in **Fig. 8**.

7. DISCUSSION

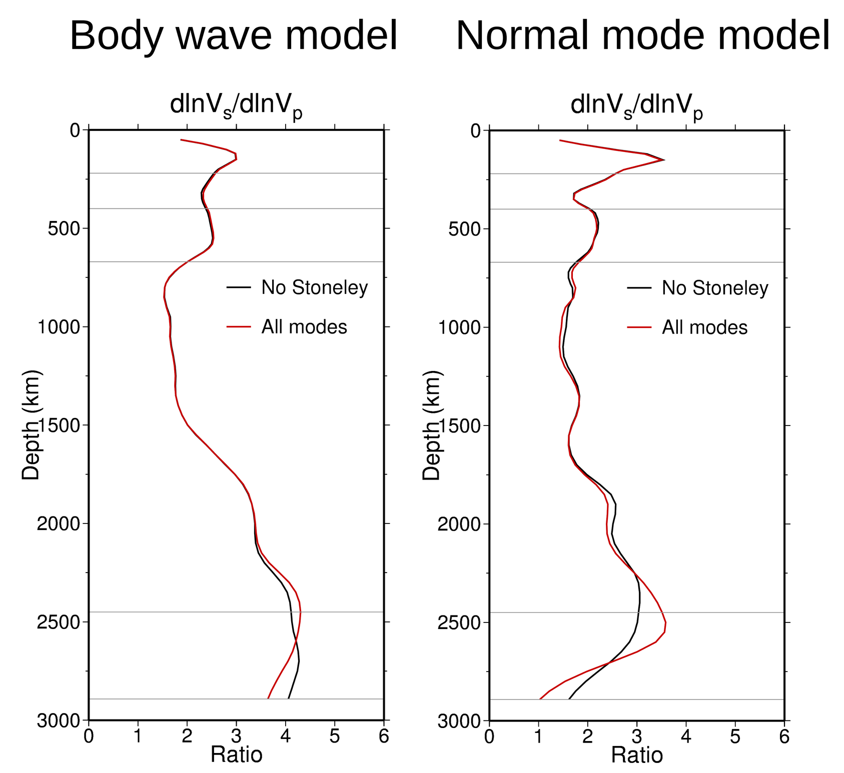


Fig. 10: dlnVs/dlnVp ratio computed using the RMS velocities for inversion results with (red) and without (black) Stoneley mode data. We vary the weights of travel time (ttwt) and splitting data (splwt) relative to dispersion data. Left: body wave dominated model with ttwt:splwt = 50:100. Right: normal mode dominated model with ttwt:splwt = 1:1000.

Changing data weighting has a large effect (**Fig. 10**):

- Body wave dominated model shows high dlnVs/dlnVp ratio in the LM.
- Normal mode dominated model gives a low dlnVs/dlnVp ratio in the LM.

Including Stoneley modes always increases dlnVs/dlnVp above the D'' and decreases it in the D'' – this averages to the same ratio.

For a mixed model (ttwt:splwt = 20:1000), the normal mode misfit reduces significantly for the model with Stoneley mode data (**Table 2**). The body wave data shows a negligible misfit change suggesting they cannot distinguish between the two models. The dlnVs/dlnVp ratio resembles the trend of previous studies, especially for R01 [14] in the lower mantle (**Fig. 11**).

Misfit for data	Model without Stoneley	Model with Stoneley	Misfit reduction
Without Stoneley	0.0960	0.0939	-2.27 %
All Modes	0.0959	0.0882	-8.74 %
Stoneley modes	0.0971	0.0637	**-52.54 %**
S body waves	0.3702	0.3703	0.03 %
P body waves	0.5630	0.5653	0.41 %

Table 2: Misfit for splitting and travel time data for our mixed model inversion results with and without CMB Stoneley modes.

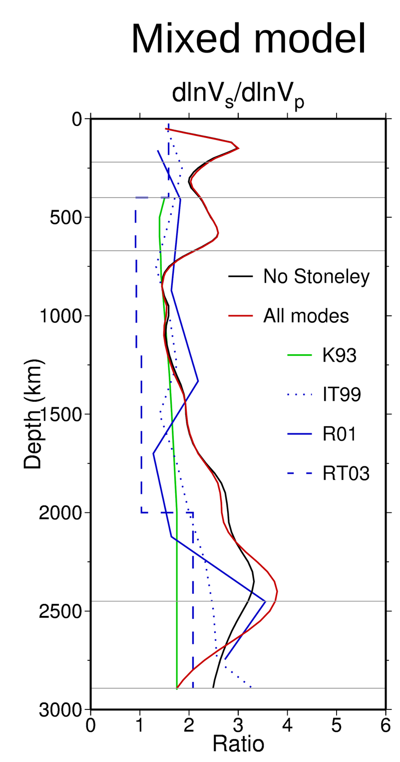


Fig. 11: Same as in **Fig. 10** but now for a mixed model with weights 20 and 1000. As comparison, we show the dlnVs/dlnVp ratio from other studies: K93 [12], IT99 [13], R01 [14], and RT03 [15].

8. SUMMARY

- **We invert independently for Vs and Vp variations in the mantle, focusing on the effect of including CMB Stoneley mode splitting functions.**
- **Including Stoneley modes increases dlnVs/dlnVp above the D'' and decreases it in the D'', producing on average the same ratio as for a model without them.**
- **Body wave data are insensitive to this difference, suggesting they lack the depth resolution to distinguish between these models (Fig. 8 & 9).**

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