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Earth's hot lowermost mantle revealed by Stoneley mode splitting observations

Universiteit Utrecht

Arwen Deuss (a.f.deuss@uu.nl), Paula Koelemeijer, Jeroen Ritsema

I. INTRODUCTION & DATA

INTRODUCTION

Large Low Shear Velocity Provinces (LLSVP's) are consistently seen in lowermost mantle shear wave velocity models (see fig.1). Outstanding questions include:

- Are they dominantly thermal or thermochemical structures?
- What is their role in mantle dynamics?
- Are they long-lived? Could they be the hidden reservoirs of heat-producing elements in the Earth's mantle?

These questions can be answered by getting information on their density structure in addition to their velocity structure.

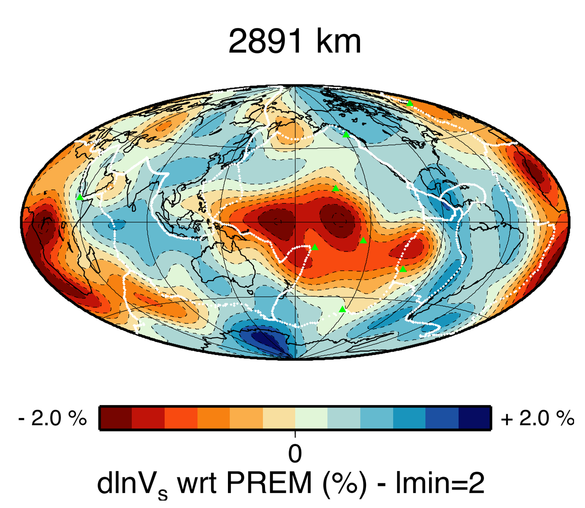

Figure 1: Variations in Vs (dlnVs) for mantle model S20RTS at 2891 km depth.

We use our new Vs and Vp model SP12RTS (Koelemeijer et al, 2015) to perform a model space search for density variations in the lowermost mantle using a new data set of normal mode splitting function measurements, in particular new CMB Stoneley mode data. We find that the LLSVPs have a low density, instead of a high density as suggested in previous studies.

DATA

Normal modes

We use whole Earth oscillations, which are standing waves along the surface and radius of the Earth. There are two types of modes, toroidal modes $_nT_l$ and spheroidal modes $_nS_l$, which are characterized by their angular order l and radial order n. Here we will use spheroidal modes which are sensitive to Vs, Vp and density of the Earth's mantle. Our data set contains almost 7000 splitting function coefficients for about 140 normal modes (Deuss et al, 2013, Koelemeijer et al, 2013).

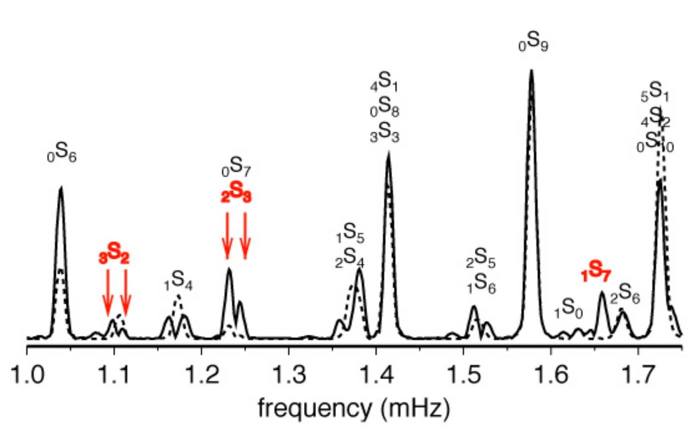

Figure 2: Normal mode spectrum for the boxing day 2004 Sumatra event. Red arrows point to strongly split inner core sensitive modes, which are disregarded in this study.

CMB Stoneley mode measurements

Stoneley modes are whole Earth oscillations which are confined to solid-liquid interfaces, such as the Core Mantle Boundary (CMB). They are very useful for studying the properties of the lowermost mantle, but are difficult to observe due to their very small excitation amplitude at the Earth's surface. We recently made the first observations of CMB Stoneley modes, providing us with the unique opportunity to study the CMB region without trade-off with upper mantle structure.

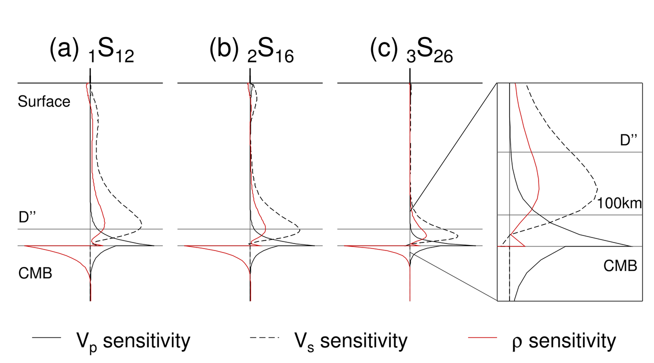

Figure 3: Sensitivity kernels for CMB Stoneley modes, showing their strong sensitivity to Vs, Vp and density near the CMB.

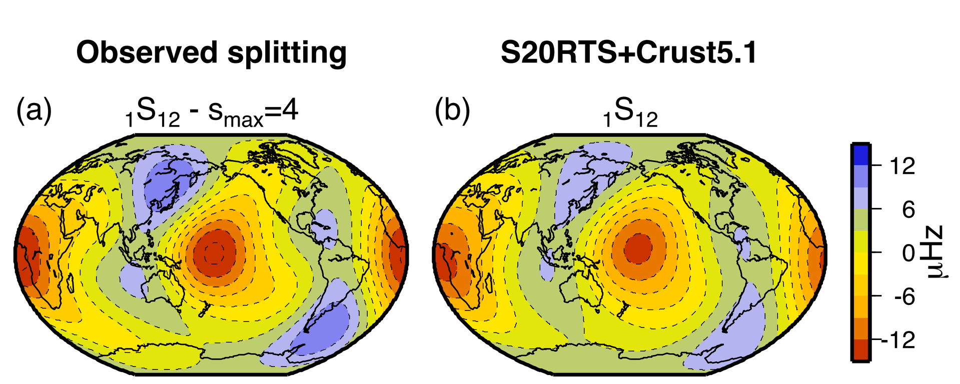

Figure 4: Splitting function observations for Stoneley mode $_1S_{12}$, compared to predictions for mantle model S20RTS (Koelemeijer et al, 2013).

II. FORWARD MODELLING RESULTS

INDIVIDUAL STONELEY MODES

We use model SP12RTS to describe Vs and Vp velocity structure. Above 2500 km depth we assume R=δρ/δVs=0.3. Below 2500 km depth, we search for scaling factors R_{LL} for the LLSPVs and R_{SR} for the surrounding regions which best fit our observed splitting function maps.

- SP12RTS underestimates the splitting function amplitudes by a factor of 0.75 to 0.9 (Fig. 5c and h).
- If we assume dense LLSVPs (as suggested in previous studies), the amplitudes are underestimated even more (Fig. 5d and i).
- We match the amplitudes when the LLSVPs are light (Fig. 5e and j).

We focus on structural degree 2, which is the dominant degree in the lowermost mantle (Fig. 6), and find again that the best fit is obtained when both R_{LL} and R_{SR} are positive (i.e. light LLSVPs and dense surrounding regions).

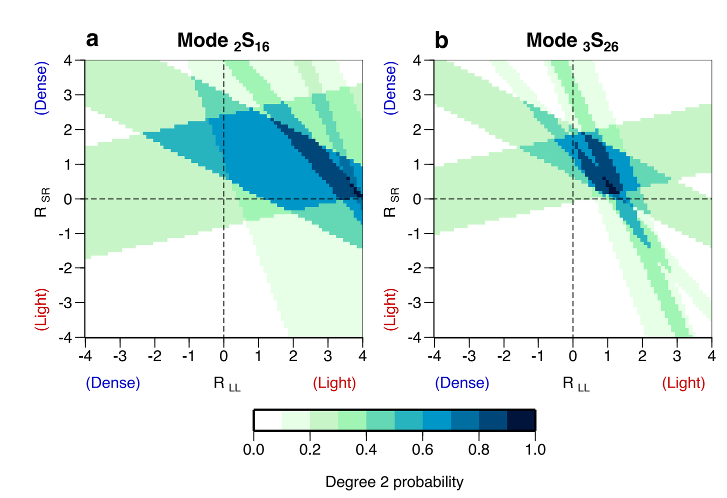

Figure 6: Probability of density models for individual Stoneley modes for degree 2. Darker colors indicate a better fit to the measurements. Density scaling factors are independently varied for the LLSVPs (R_{LL}) and the surrounding regions (R_{SR}). Variations in CMB topography are excluded.

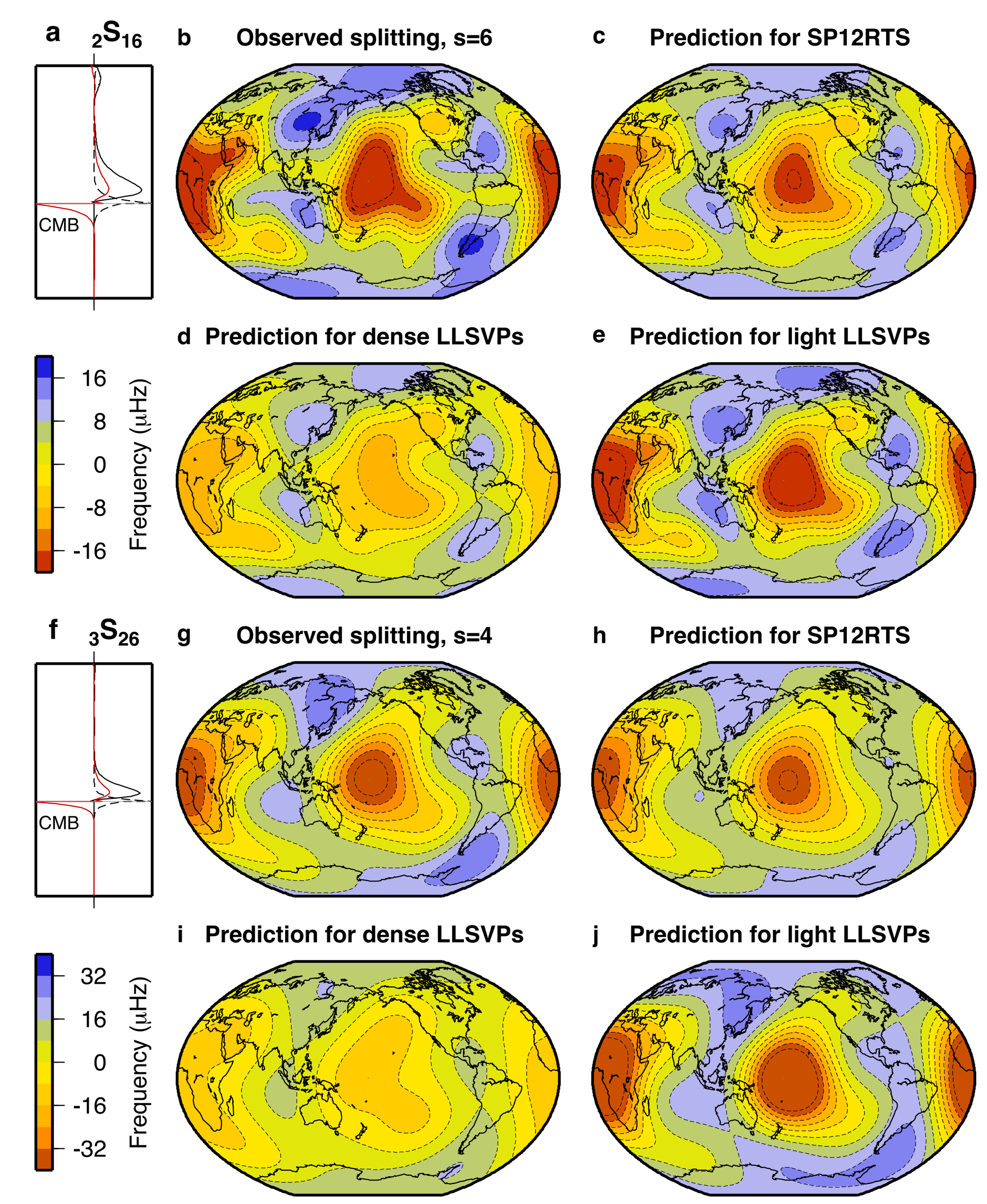

Figure 5: Observed and predicted splitting function maps for Stoneley modes $_2S_{16}$ and $_3S_{26}$. Dense LLSVPs (R_{LL}=-4 and R_{SR}=+0.3) are compared to light LLSVPs (R_{LL}= +4 and R_{SR}=+0.3).

FULL MODEL SPACE SEARCH

All data

When we apply our model space search to all our Stoneley modes splitting functions, we again find that the LLSVPs are light. Adding all other mantle modes makes the signal less strong, but the maximum probability is still for positive R_{LL} and R_{SR}. Our results are our contrary to previous studies (i.e. Ishii & Tromp, 1999, Trampert et al, 2004), which are based on a smaller number of modes and Stoneley modes were missing. We can in fact reproduce the previous results using their original splitting function measurements and find only a marginal preference for dense LLSVPs. Thus, Stoneley modes are key to resolve lower mantle density structure.

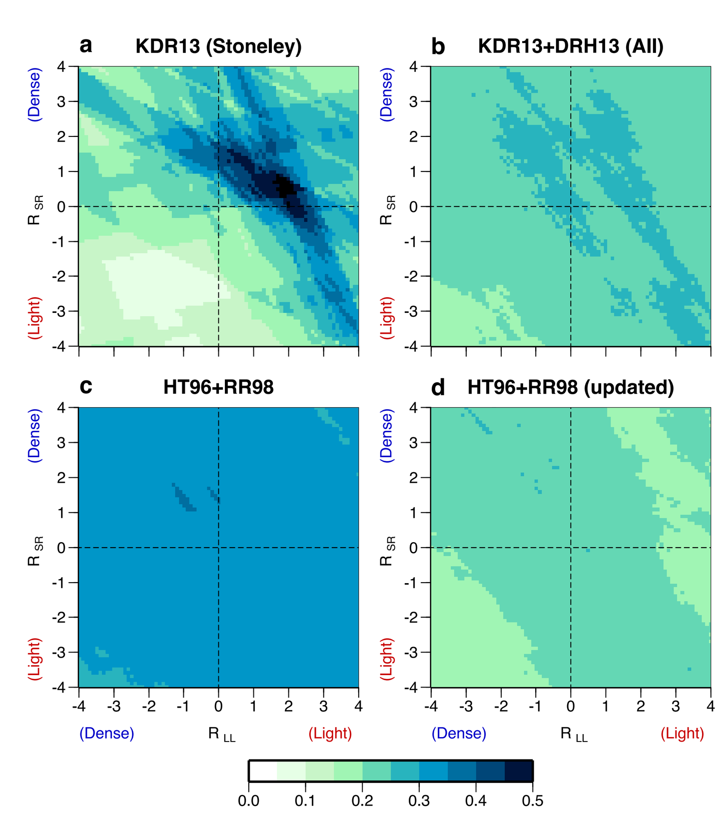

Figure 7: Probability of density models for all Stoneley modes and new and old data sets. KDR13 (Koelemeijer et al, 2013), DRH13 (Deuss et al, 2013), HT96 (He & Tromp, *JGR*, 1996), RR98 (Resovsky & Ritzwoller, *JGR*, 1998).

CMB topography

Lateral variations in CMB topography also perturb the splitting of Stoneley modes. If we incorporate CMB topography as a third model parameter H, two classes of successful density models emerge. (1) The CMB is elevated below light LLSVPs (H < 0), (2) Dense LLSVP's cover an elevated CMB (H > 0). We reject the second class of models on geodynamical grounds.

The most probably model is characterized by R_{LL} = 0.9, R_{SR} = 0.2 and H = -2 (equivalent to degree 2 CMB undulations of +/- 1km).

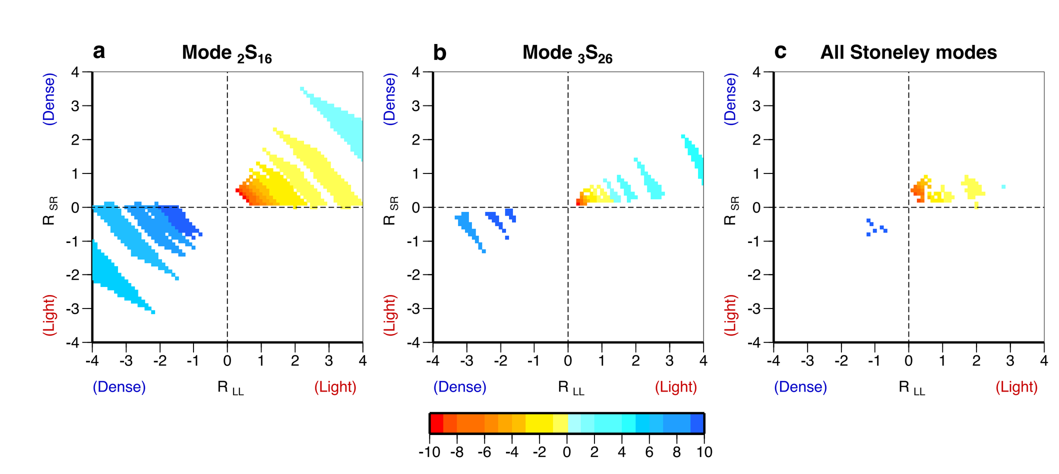

Figure 8: Range of best fitting density and CMB topography models for Stoneley modes. The models for which the probability is higher than 0.85 (a-b) or 0.5 (c) are colored by the CMB topography scaling factor H.

III. INTERPRETATION

EARTH'S HOT LOWERMOST MANTLE

We hypothesize that the LLSVPs signify the hidden reservoirs of heat-producing elements, as suggested to be present in the deep mantle from analysis of Sm/Nd isotopes. The LLSVPs may contain ~43% of Earth's U, Th and K, and produce 3-25TW of radiogenic power, giving rise to the inferred low densities. While currently light or neutrally buoyant, the LLSVPs can retain their long-term stability if they have dense, compositionally distinct roots and are passively deformed by subducting slabs in the deep mantle while free to migrate along the CMB. Such rising LLSVPs will cool down and subsequently sink due to their intrinsic higher density, similar to the periodically rising and collapsing of thermochemical superplumes. The current rise of light LLSVPs also explains the excess-ellipticity of the core and uplift of the Earth's surface.

GEONEUTRINO'S?

The high abundance of heat-producing elements in two antipodal regions of the Earths mantle would give rise to a characteristic geoneutrino signal. These geoneutrino's are very difficult to detect, and require large detectors of which only two are currently operational in continental regions (one in Japan and one in Italy). Whether the LLSVPs indeed represent hidden reservoirs of U and Th in the deep mantle can be tested with forthcoming deployments of geoneutrino detectors in the oceans.

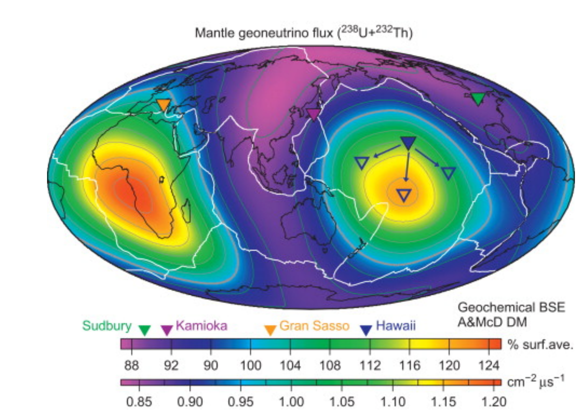

Figure 9: Global map of predicted geoneutrio flux from ^{238}U+^{232}Th decay in the mantle calculated from seismic tomography. Locations of geoneutrino detectors are plotted: Kamioka (KamLAND Japan), Gran Sasso (Borexino, Italy), Subury Canada (SNO+, operational soon) and Hawaii (Hanohano, proposed). From Sramek et al (2013).

KEY POINTS

- **Stoneley modes, a unique class of free oscillations that are perturbed primarily by velocity and density variations at the core-mantle boundary, are optimally fit when the LLSVPs have a lower density than the surrounding material**
- **We hypothesize that these low-velocity, low-density structures in the lower mantle are extremely hot due to the high concentration of heat-producing elements**
- **Ensuing geoneutrino research will test this hypothesis by mapping the distribution of U and Th in the deep mantle.**

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