Shear Wave Splitting Characteristics of vertically aligned Partial Melt Discs in a generic Subduction Zone Back-Arc Setting

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Abstract

Patterns of XKS shear-wave splitting (SWS), which depict the spatial distribution of fast orientation, ϕ, and delay time, δt, are commonly interpreted in terms of upper mantle deformation that causes lattice-preferred orientation (LPO) of anisotropic minerals such as olivine. However, shape-preferred orientation (SPO) of elastically distinct materials may influence SWS observations as well. Building on previous work (e.g., Hammond and Kendall, 2016), we have carried out global wavefield simulations using AxiSEM3D to understand the effects of vertically aligned partial melt discs (an endmember geometry) on anisotropy observations. We confirm earlier findings that the amount of splitting depends on aspect ratio, melt fraction, and thickness of the inclusion, and indicate the potential of this configuration to crucially influence the strength of observed SWS measurements in a setting where partial melt is present. We explore whether the occurrence of melt SPO (MPO) alongside with surrounding LPO of E-type olivine might be able to explain the enigmatic occurrence of exceptionally high δt in the southern Cascadia subduction zone back-arc, and how dehydration-related olivine fabric transitions to A-type could affect this ability considering 1) a singular box-like partial melt anomaly and 2) multiple smaller dike-like inclusions. We examine the spatial and statistical distribution of splitting parameters for all our models and evaluate the possibility for frequency and angular dependencies.

Title: Insights from new global seismic observations and thermochemical modeling of Earth's upper and mid-mantle discontinuities using ScS reverberation data

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The upper and mid-mantle represent a significant transformation in Earth's structure, rheology, and composition. Seismic topography models show the deflection and stagnation of both upwelling plumes and downgoing slabs within the mantle transition zone (MTZ, 410 – 660 km) and mid-mantle (MM, 800-1300 km). While the geodynamic effects and origin of MTZ discontinuities are well known the underlying causes of deflections of materials in the MM remain poorly understood. Mineral physics phase changes, despite their significance, cannot properly explain the various seismic reflectors observed at MM depths [Waszek et al., 2018].

To address these complexities, we introduce a new large global dataset of ScS reverberation in our study. This dataset is compiled using an automated waveform identification code based on Convolutional Neural Networks (CNN) [Garcia et al., 2021]. Here, we address the symmetry problem associated with some of the reverberated phases by employing a new correction method for 3D mantle structure. We utilize the "Adaptive stacking" parameterization technique to generate new global topography maps for MTZ discontinuities. This stacking technique accounts for topography, noise, and data coverage. Regional-scale fixed bin parameterizations are also applied to identify intermittent and double MTZ and MM reflectors.

These newly generated topography maps, coupled with existing maps built using SS and PP precursors, significantly enhance resolution, particularly in regions which had poor data coverage previously. We integrate our seismic observations with mineral physics calculations for various thermochemical models via synthetic modeling, performing Bayesian inversions to determine the best matching temperature and composition on regional scales. Our research helps elucidate the complex relationship between the MM and MTZ and their interlinked dynamical processes, and offers valuable insights into global mantle circulation, compositional layering in the upper mantle, and impacts for surface activity.

Short distance observations of mantle transition zone discontinuities

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Mantle transition zone discontinuities have previously been investigated using PP and SS precursors for the epicentral distances above 90 ° in most cases. In a recent study (Saki et al., 2018), we showed that anisotropy in the mantle transition zone influences reflection coefficients of PP and SS precursors for some epicentral distances, such that even polarities are reversed. This, happens, however, only for short distances, i.e. at distances of 30 to 70 degrees, where these waves are usually not detected or used. Here we searched a number of different datasets for the presence of these short-distance PP and SS precursor arrivals. Synthetic modelling confirms that the waves should be visible (Saki et al., 2018) and we search for the reflections from the 410 km discontinuity at short epicentral distance of 60 to 90 degrees for PP and SS precursors and using different source-receiver combinations. Our initial results indicate that the observations of underside reflections from 410 km boundary at the short epicentral distance range of 60 to 90 degrees are indeed possible but the examples where these waves are found are few, mostly due to interfering waves with large amplitudes at the same time. However, up to now, we also found examples where the reflections from 410 km discontinuity shows an opposite polarity compared to that of the main PP phase, which agrees with the results of the reflection coefficient modelling in the presence of anisotropy reported by Saki et al. (2018). These first results show that there may be a possibility to test the mantle transition and confirm the slip systems, deformation and style of anisotropy.

Saki, M., Thomas, C., Merkel, S., Wookey, J., 2018. Detecting seismic anisotropy above the 410 km discontinuity using reflection coefficients of underside reflections, Phys. Earth Planet. Int., 274, 170-183.

Modeling out-of-plane seismic signals in the global Earth: first results from a flat subducted slab

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Traditional seismology is based on seismic waves that travel through the mantle along the great circle path, in the sagittal plane along sources and receivers. Since the 1990s, it was already known that subducted oceanic lithosphere in the mantle could laterally deviate the path of seismic waves, which arrive with different angles (out-of-plane) at an array of sensors at teleseismic distances. Detection of these signals with array processing techniques, and the subsequent back-projection, have provided independent evidence for the location of both ancient and actual subducted slabs. A previous "proof of concept" test, carried out with preliminary modeling of P-to-P waves, showed that the search for out-of-plane signals is non-trivial. In this work, we conduct 3D waveform modeling to test the detectability of these signals and assess to which extent they can be used to infer physical properties of the slabs (e.g., thickness, orientation, slab edges, impedance contrast, etc.). An important aspect to investigate is how slabs affect the waveforms of out-of-plane signals and whether there is a source-mechanism dependency. Despite of its simplicity, the synthetic experiments shown here already provide useful information for more complex and realistic settings which are currently in progress.

The fate of oceanic crust in the mid-mantle

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The subducting oceanic plates (slabs) are primarily responsible for the recycling of the crust and lithospheric material in the deep mantle. However, there's a notable variability in the depth to which these materials penetrate the mantle. While some slabs extend all the way to the core-mantle boundary, others stall at different depths (660 km, 1000 km, 1200 km). What's not yet fully understood is the factor determining this behavior. Here, we investigate this phenomenon by comparing slabs with prolonged subduction histories to relatively newly formed slabs. It is expected that as slabs subduct, they will produce heterogeneities that can scatter seismic waves. We employ array techniques to search for potential mantle scatterers associated with slabs. Traditionally, small-aperture arrays have been used to detect P-wave (e.g. P to P) scatterers in the mantle, owing to their sensitivity to high-frequency teleseismic P-waves. However, in this study, we adopt a mixed approach by combining stations from a large aperture array (such as EarthScope USArray) encircling a small-aperture array. Utilizing the F-statistic coherence method, we amplify signals outside the great-circle path but within (±) 50 degrees of the earthquake backazimuth. This study aims to assess the benefits of integrating a small-aperture array within a larger array to enhance our understanding of the behavior of subducting slabs in the mid-mantle. Such a hybrid sub-array approach holds promise for advancing our knowledge of Earth's evolution, particularly as more regional seismic arrays are deployed in new locations across the Earth's surface.

On the importance of using directional information in the search for mantle reflectors

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Precursor signals are a powerful tool for mapping topography of mantle discontinuities, which are sensitive to the thermal and compositional structure of the mantle. The depth of mantle discontinuities is usually estimated by using the measured differential traveltime between the main arrival and its precursor. However, this method ignores potential travel path deviations that influence the travel time of precursor signals. Here, we use a different approach that takes into account directivity information as well as traveltime measurements to infer depth and location of mantle reflectors. Applying seismic array techniques, we measure slowness, backazimuth, and traveltime of the signals, and use this information to backproject to the point of reflection. We observe deviations from the predicted values in both slowness and backazimuth, which in turn lead to reflection locations that can differ considerably from theoretical reflection points calculated with great circle plane paths, as well as depths different from the depth calculated for in-plane propagation. Our results indicate that the travel-path deviations should be considered to avoid misinterpretation of mantle discontinuities and potentially reduce previously observed scatter in discontinuity depth.

Lithospheric Imaging with Probabilistic Deconvolution of SS Waves

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Previous studies using the SS precursor technique mostly target the mantle transition zone by applying a narrow bandpass filter with long periods to the time-domain waveforms and interpreting seismic structures directly from the waveform stacks. While this treatment has been proven successful when targeting various mantle structures, alternate data processing methods are required when investigating lithospheric structures because the effect of these shallow seismic discontinuities is usually non-separable from the main SS phase. In this study, we propose to image the lithospheric structure by the deconvolution of SS waves using a transdimensional probabilistic Bayesian inference. The signature of seismic discontinuities is characterized by a lithospheric operator consisting of an unknown number of Gaussian pairs, whose time delay, amplitude, and width represent the depth, velocity difference, and gradient of the discontinuities. We also invert for noise parameters simultaneously in the Bayesian process, using a reversible-jump Markov-chain Monte Carlo (rj-McMC) implementation. Synthetic tests show that our approach can effectively recover the lithospheric operators for both single-discontinuity and multi-discontinuity models even when realistic background noise is present. In real data experiments, we propose to use the Hilbert transform of the direct S phase as the reference waveform in the deconvolution, as it resembles the shape of the SS arrival but does not carry information about the structures at the bounce point. Preliminary results from the NoMelt region southeast of Hawaii in the normal Pacific Ocean show a high correlation between the SS and the Hilbert transform of the direct S waveforms, showing promising potential for accurately imaging lithospheric structures using the proposed approach with the Hilbert transform of the direct S waveform as reference. We anticipate our approach will enable high-resolution lithospheric imaging especially at locations where seismic stations are sparsely deployed.

Africa's Lithospheric Architecture with Multi-mode Body Wave Imaging

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Africa's lithosphere hosts the longest-lived cratons on our planet and records a rich and diverse tectonic history: plate subduction to the North, a long rift system in the East, the super swell in the South, and a record of continental breakup to the West. However, gaps remain in our current efforts to study its lithospheric layering due to sparse coverage and noisy short-term seismic deployments. Here, we present ***a** body-wave **da**taset and **m**odel **a**ssessment products for investigating **A**frica's lithosphere* (ADAMA). We address the challenge of lithospheric imaging on the continent using sparse and noisy teleseismic body wavefields, i.e., receiver functions and SS precursors. The latter extends lithospheric illumination in regions without station coverage. In both cases, we explore novel denoising approaches: (1) *CRISP-RF* (***C**lean **R**eceiver Function **I**maging with **Sp**arse **R**adon **F**ilters*), which uses sparse Radon transforms to interpolate the sparse receiver function data and eliminate incoherent noise, and (2) *FADER* (***F**ast **A**utomated **D**etection and **E**limination of **E**choes and **R**everberations*), which deconvolves thin-layer reflections buried in long-period SS precursors. We improve constraints on bulk crustal structure and lithospheric layering, e.g., from H-k stacking, following CRISP-RF denoising. We extend spatial sampling and detections of lithospheric layering by jointly interpreting receiver functions and SS precursors following cepstral deconvolution of long-period SS precursor waveforms. Our final model, ACE-ADAMA-BW (*Africa's Continental Layering Evaluated with ADAMA's Body Waves*), will improve 3-D resolution of lithospheric layering spanning the cratons (West Africa, Tanzania, Congo, Kaapvaal, Zimbabwe), rifts (Gourma, East African Rift System) and basins (Taoudeni, Goo, Congo) of Africa.

No Globally-Detectable Seismic Interfaces within Earth's Mantle Transition Zone: Evidence for Basalt Enrichment

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Earth's mantle transition zone (MTZ) is characterized by multiple mineral phase changes. The depth range of the MTZ is bounded by the 410- and 660-km elastic discontinuities, which are interpreted to be the phase changes from olivine to wadsleyite and ringwoodite to bridgmanite, respectively. Within the transition zone, the phase change from wadsleyite to ringwoodite has been assigned to a seismic feature observed at 520 km depth. Here we show that SS precursors, the most common seismic tool for imaging MTZ structure at global scale, are susceptible to signal-processing artifacts within the transition zone. Owing to the narrow frequency range in which the SS wave is typically examined, S waves scattered by the bounding MTZ discontinuities generate Gibbs-effect overshoots that map into features within the transition zone, including at 520-km depth. These results suggest that the inference of a global interface at 520-km depth and, in some studies, a global interface at 560-km depth, are problematic. If such interfaces are not detectable, it suggests that Earth's mantle transition zone departs significantly from the pyrolite composition. Earth's mantle may be enriched in a basalt component derived from subducted oceanic crust, which in the mid-mantle would have a high proportion of garnet. Our result does not imply that the wadsleyite-to-ringwoodite phase transition is absent within Earth's MTZ. However, our results suggest that the geophysical processes associated with nominal seismic features at 520-km and 560-km depth may be more diffuse, weaker, and/or more irregular than previously thought.

Thermochemical layering in the upper mantle from measurements of the X and 520 discontinuities

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The physical properties of the discontinuities in the upper mantle and mantle transition zone (MTZ) provide insight into its thermochemistry and dynamics, with important implications for global circulation patterns. The depths of the global discontinuities at 410 and 660 km may be used to obtain a first order thermometer for the MTZ, and their amplitudes inform regarding composition. Typically, studies examine both discontinuities simultaneously, however it is known that the 660 impedes both down and upwelling flow, leading to compositional and perhaps thermal layering.

Discontinuities at 300 (the "X") and 520 km depth are predicted by mineral physics modelling to be near-global, but are not observed as such. The X is observed within depth ranges of more than 100 km, and subsequently thought to result from two different phase transitions, mostly in basaltic compositions of partial melt within upwelling plumes. The 520 marks the phase transformation from wadsleyite to ringwoodite, with a secondary transformation at around 560 km observed for basalt enriched material. This causes the 520 signal to become complex, sometimes split into two, or absent. Thus, their presence and properties give important constraints on temperature and composition.

Here, we use large global datasets of precursors to SS and PP, and new multiple global datasets of ScS reverberations, to obtain new high resolution measurements of the X and 520. We combine our results with mineral physics modelling, along with our existing maps of the MTZ thermochemistry from inversion for the 410 and 660 discontinuity properties computed with our adaptive stacking regime. We also present new measurements of the 410 and 660 discontinuities obtained for individual seismograms, representing a new form of data for constraining the MTZ.

We interpret our observations within the context of waveform modelling and mineral physics computations. Our most significant finding is that a split 520 signal can be caused by a negative discontinuity at this depth, which would match modelling results for a compositional transition to basalt enriched material, i.e. a stagnant slab. This work provides critical insights into chemical segregation and stagnation of convecting material within and above the MTZ.

A Global View of Upper Mantle Stratification: CRISP-RF

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Short Abstract:
Our planet's mantle is the largest rock-layer by volume. Across its old and stable Archean and Proterozoic terranes, seismological evidence suggests ubiquitous, spatially variable, and puzzling discontinuities, within, across and beneath the upper mantle lithosphere (~50- 350 km). A variety of explanations have been proposed, including phase transformations, melting and compositional anomalies, anisotropy, and elastically accommodated grain. To evaluate these, and other models, it is crucial to improve our threshold for detecting such discontinuities especially in reverberant and noisy environments. Here, we present a new method for sifting through the echoes and reverberations: CRISP-RF (***C***lean ***R***eceiver function ***I***maging with ***Sp***arse ***R***adon ***F***ilters). With a global dataset of Ps converted waves, we use CRISP-RF to isolate hard-to-detect wave conversions buried in reverberations and noise. This refined, high-resolution, global view of upper mantle stratification will ensure robust evaluation of proposed models of upper mantle structure, evolution, and dynamics.