Modelling of seismic anisotropy in the lowermost mantle with rheologically constrained geodynamic setup

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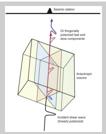
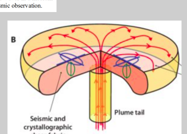
Introduction

Seismic anisotropy is an observation that is believed to yield information on the flow pattern in the mantle. There are many studies of anisotropy in the upper mantle; however, the lower mantle is still underexplored, due to problems in seismic imaging and complexities of modelling of flow laws of different minerals. In this study, we modelled the radially anisotropic behavior of two different geodynamic setups, one is the rising of a mantle plume from the core-mantle boundary to the surface, and another is subduction of a slab reaching the lowermost mantle. We use ASPECT for modelling large scale mantle flow and ECOMAN to simulate the development of lattice preferred orientation of mantle fabric. We use the slip system of Bridgmanite following the previous experimental study by Mainprice et al. (2008). We then couple the results from ASPECT to ECOMAN for modelling the radial anisotropy and maximum shear wave splitting direction. We show that in the part of the lowermost mantle surrounding the plume horizontally polarized shear waves (Vsh) are faster than the vertically polarized ones (Vsv) while the inside of the plume tail shows opposite signature. However, Vsh becomes greater than Vsv when the plume flattens out at the surface. We also find that the maximum splitting direction is horizontal outside the base of the plume and it becomes vertical inside the plume tail and again becomes horizontal at the surface. This result corroborates previous seismic observations (Wolf et al., 2019) of the Iceland plume at the core-mantle boundary. Moreover, our result for the slab setup reveals that as the slab reaches the lowermost mantle, Vsh becomes higher than Vsv and maximum splitting is horizontal at the base of the slab.

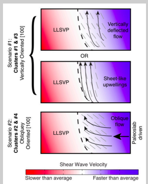
Motivation

Seismic anisotropy is the directional dependence of the velocity of seismic waves in a medium (rock) within the Earth. It is a powerful link between mantle flow and seismic observation.





Stern *et al.* 2020

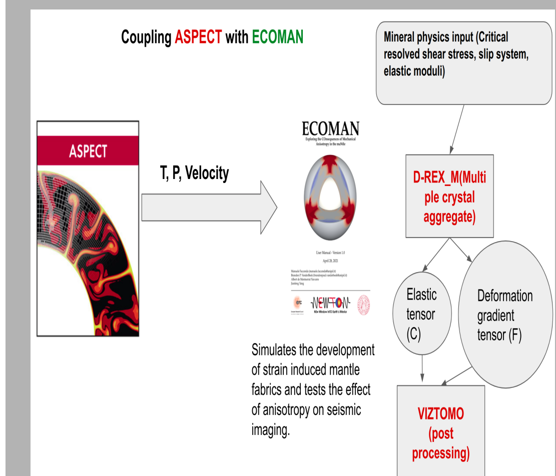


Ford *et al.* 2015

Key questions

- How upwelling generates self-consistently from core-mantle boundary?
- How the rheology of LLSVP affect the nature of mantle plumes?
- How subducted slab interacts with the LLSVP at the CMB and generate plumes?
- How plume geometry and characteristics change with different rheologies?
- What is the nature of mantle flow constrained from seismic anisotropy?

Workflow



Important equations related to anisotropy

$\xi = V_{SH}^2/V_{SV}^2 = N/L$ = Radial anisotropy

Radial anisotropy > 1, $V_{sh} > V_{sv}$
Radial anisotropy =1 means isotropic
Radial anisotropy < 1, $V_{sv} > V_{sh}$

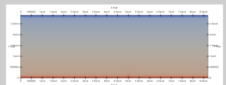
$N = \frac{1}{8}(\eta_{11} + \eta_{22}) - \frac{1}{4}\eta_{12} + \frac{1}{2}\eta_{66}$, $L = \frac{1}{2}(\eta_{44} + \eta_{55})$ = Elastic parameters

$dVs_{MAX} = (Vs_1 - Vs_2)/(Vs_1 + Vs_2) * 200$ (in %) = Maximum Vs splitting

Model Setup 1

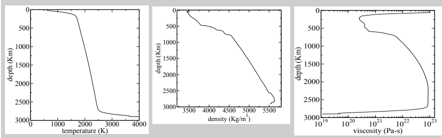
2D box model 8700 km X 2900 km

$$T = T_{ad}(z) - 1340\varepsilon(z/t_{lith}(x,y)) + 1520\varepsilon((z_{CMB} - z)/t_{CMB}(x,y))$$



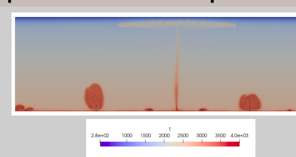
T = initial temperature
T_{ad} = adiabatic temperature profile
ε = complementary error function
t_{lith} = Lithosphere thickness *(Steinberger 2016)*
t_{CMB} = thickness of TBL at CMB
z = depth

initial set up of temperature, density and viscosity

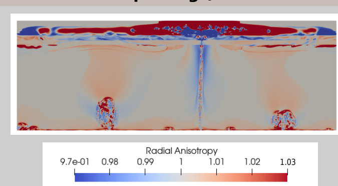


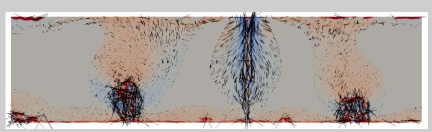
Result

2D plume shown as a temperature anomaly



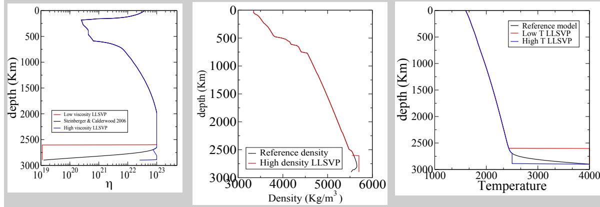
Radial anisotropy of a thermal plume at 120 Ma with shear wave splitting (shown as bkack lines)

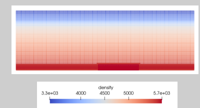




Model Setup 2

Self consistent plume generation from LLSVP



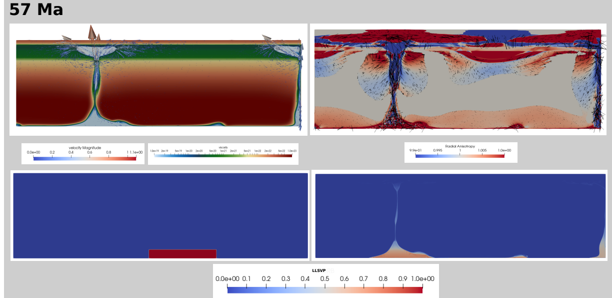


Steinberger rheology

Result

Low viscosity LLSVP

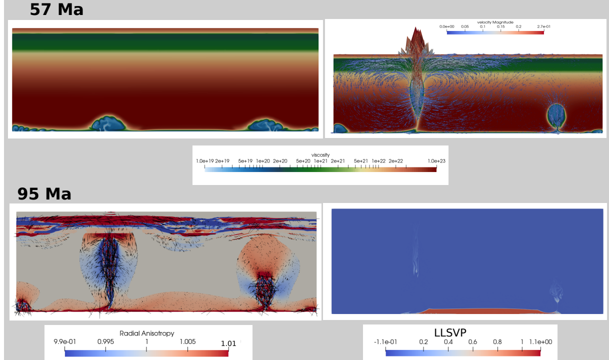
57 Ma



High viscosity LLSVP

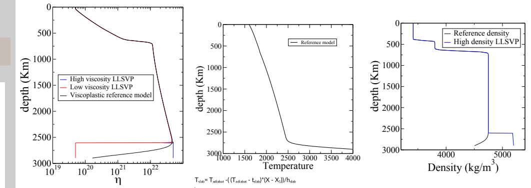
57 Ma

95 Ma



Model Setup 3

Plume generation by LLSVP and subducted slab interation

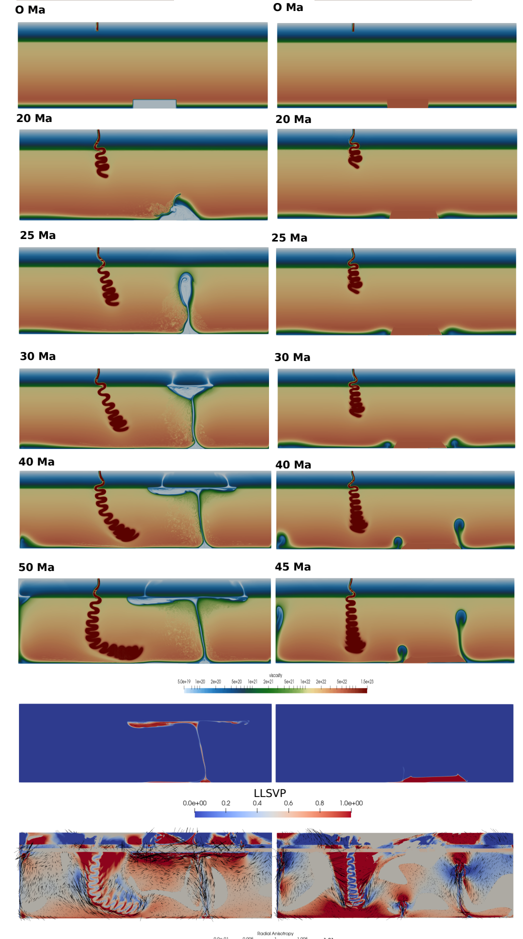


Viscoplastic rheology

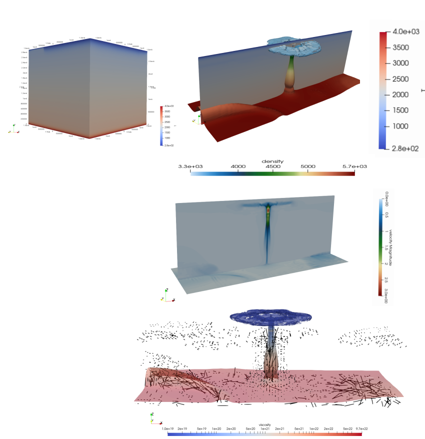
$T_{slab} = T_{adiabat} - ((T_{adiabat} - t_{slab})*(X - X_1))/h_{slab}$

T_{slab} = Temperature of slab
$T_{adiabat}$ = Adiabatic surface temperature
t_{slab} = Initial slab temperature
X= X coordinate
$h_{slab} = X_2 - X_1$ (In this case, 100 Km)

Result

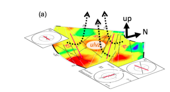


3D plume model with splitting



Conclusion

- Plume generation can take place at the two sides of LLSVP if the LLSVP has higher viscosity than the ambient mantle.
- If the LLSVP has low viscosity, it splits into two parts and each of the part can make separate plumes.
- Slab induced flow helps the plume to come up from the LLSVP boundary.
- Vertically polarized shear wave is faster inside the plume conduit and horizontal shear wave is faster at the base of the plume in the lower mantle and when the plume flattens out in the upper mantle. Maximum splitting is vertical inside the plume and maximum splitting is horizintal at the base of the plume.
- Slab generates horizontally polarized shear wave to be faster at the base of the mantle and suurounding the slab boundary.



Wolf *et al.* 2019

ScS splitting observation (Wolf et al. 2019) shows Vsh > Vsv outside or away from the Iceland plume and Vsv> Vsh directly beneath Iceland plume. Our plume models show that Vsh > Vsv surrounding the plume base and Vsv > Vsh inside the plume conduit.

Future Work

- 3D subduction with LLSVP model simulation.
- Introduction of post-Perovskite phase at D” layer and seismic anisotropy modelling including post-Perovskite phase transition.

Acknowledgement

- Funding has been provided by German Academic Exchange Service (DAAD).
- Simulations were made by resources of the North-German Supercomputing Alliance (HLRN).

References

- Mainprice, D., Tommasi, A., Ferré, D., Carrez, P., Cordier, P., 2008. Predicted glide system and crystal preferred orientations of polycrystalline silicate Mg-perovskite at high-pressure: implicaitons for the seismic anisotropy in the lower mantle. Earth Planet. Sci. Lett. 271, 135–144.
- Faccenda. (2014). Mid mantle seismic anisotropy around subduction zones. Physics of the Earth and Planetory Interiors.
- Wolf, J., Creasy, N., Pisconti, A., Long, M.D., Thomas, C., 2019. An investigation of seismic anisotropy in the lowermost mantle beneath Iceland. Geophys. J. Int. 219, S152–S166.