Seismic Evidence for Partial Melt Below Tectonic Plates

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Abstract

The seismic low-velocity zone (LVZ) of the upper mantle is generally associated with a low-viscosity asthenosphere that has a key role in decoupling tectonic plates from the mantle. However, the origin of the LVZ remains unclear. Some studies attribute its low seismic velocities to a small amount of partial melt of minerals in the mantle, whereas others attribute them to solid-state mechanisms near the solidus, or the effect of its volatile contents. Observations of shear attenuation provide additional constraints on the origin of the LVZ. On the basis of the interpretation of global three-dimensional shear attenuation and velocity models, here we report partial melt occurring within the LVZ. We observe that partial melting down to 150–200 kilometres beneath mid-ocean ridges, major hotspots and back-arc regions feeds the asthenosphere. A small part of this melt (less than 0.30 per cent) remains trapped within the oceanic LVZ. Melt is mostly absent under continental regions. The amount of melt increases with plate velocity, increasing substantially for plate velocities of between 3 centimetres per year and 5 centimetres per year. This finding is consistent with previous observations of mantle crystal alignment underneath tectonic plates. Our observations suggest that by reducing viscosity, melt facilitates plate motion and large-scale crystal alignment in the asthenosphere.

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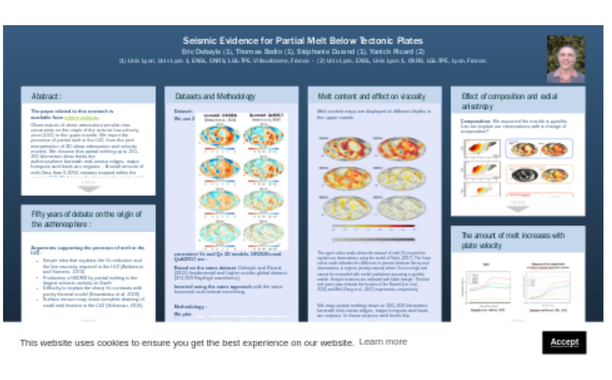

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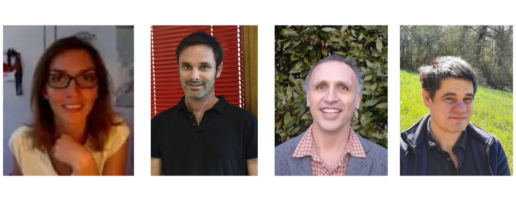

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ABSTRACT :

The paper related to this research is available from nature website.

Observations of shear attenuation provide new constraints on the origin of the seismic low-velocity zone (LVZ) in the upper mantle. We report the presence of partial melt in the LVZ, from the joint interpretation of 3D shear attenuation and velocity models. We observe that partial melting up to 150–200 kilometres deep feeds the asthenosphere beneath mid-ocean ridges, major hotspots and back-arc regions, . A small amount of melt (less than 0.30%) remains trapped within the oceanic LVZ. Melt is mostly absent under continental regions. The amount of melt increases with plate velocity, particularly when the plate velocities change from 3 cm/year to 5 cm/year. This finding is consistent with previous observations of mantle crystal alignment underneath tectonic plates. Our observations suggest that by reducing viscosity, melt facilitates plate motion and large-scale crystal alignment in the asthenosphere.

FIFTY YEARS OF DEBATE ON THE ORIGIN OF THE ASTHENOSPHERE :

Arguments supporting the presence of melt in the LVZ :

- Simple idea that explains the Vs reduction and the low viscosity required in the LVZ (Anderson and Sammis, 1970)
- Production of MORB by partial melting is the largest volcanic activity on Earth
- Difficulty to explain the sharp Vs contrasts with purely thermal model (Kawakatsu et al. 2009)
- Surface tension may resist complete draining of small melt fraction in the LVZ (Holtzman, 2016)

Arguments against the presence of melt :

- The Vs reduction in the LVZ can be explained by solid state mechanisms without the presence of melt or fluids (Faul and Jackson, 2005)
- Small melt fractions (>10^{-3}% volume) may move upward the lithospheric plate above and will solidify (Mc Kenzie, 1989)
- The sharp velocity reduction associated with the LAB and MLD may be explained by Elastically Accomodated Grain boundary Sliding (EAGBS), a subsolidus deformation mechanisms (Karato, 2012, Karato et al., 2015)

It is difficult to constrain the origin of the LVZ with seismic velocity alone. Adding quality factor provides new independant constraints!

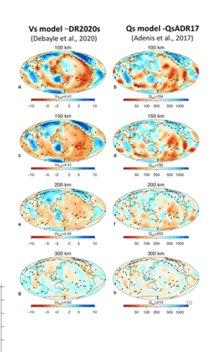
DATASETS AND METHODOLOGY

Dataset:

We use 2 consistent Vs and Qs 3D models. DR2020s and QsADR17 are :

Based on the same dataset: Debayle and Ricard, (2012) fundamental and higher modes global dataset (372,629 Rayleigh waveforms).

Inverted using the same approach with the same horizontal and vertical smoothing



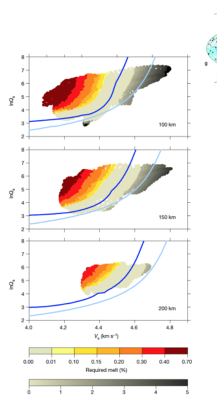
Methodology :

We plot Vs as a function of ln(Qs) for each geographical point and compare our observations with predictions from :

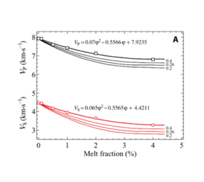
- a temperature dependent model (Takei, 2017) - dark blue curve
- experimental results from Jackson et al., (2002) - light blue curve

assuming a pyrolitic mantle.

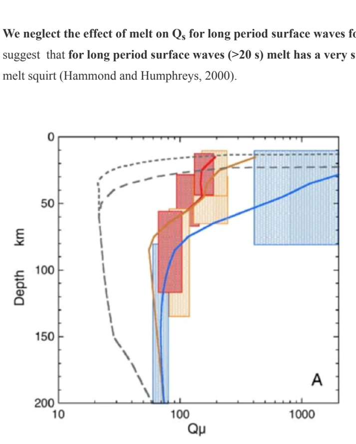
The blue curves do not explain all data. Adding melt reduces velocities and shift the blue curves to the left. The color scale indicates the amount of melt (%) required to explain data at each geographical point. **We prefer Takei's model (dark blue curve) as it minimizes the required amount of melt.**

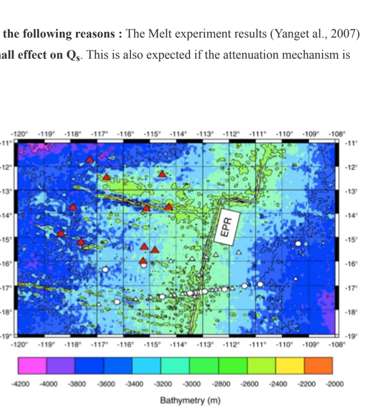


The effect of melt on Vs is predicted using experimental results from Chantel et al., 2016 (red curve)



We neglect the effect of melt on Q_s for long period surface waves for the following reasons : The Melt experiment results (Yanget al., 2007) suggest that **for long period surface waves (>20 s) melt has a very small effect on Q_s**. This is also expected if the attenuation mechanism is melt squirt (Hammond and Humphreys, 2000).

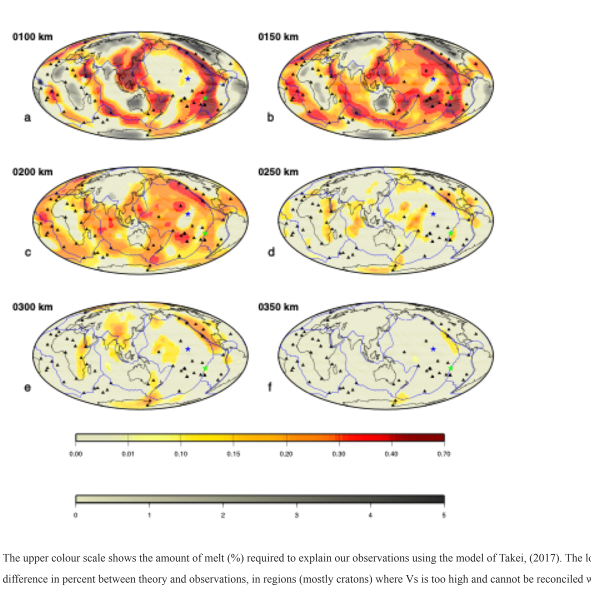




The figure above (left) shows range of acceptable Qs average after Yang et a., (2007) for a 2 Ma seafloor (red boxes), a 6 Ma sea floor (orange boxes) and the average oceanic values (about 80 Ma, blue boxes).

MELT CONTENT AND EFFECT ON VISCOSITY

Melt content maps are displayed at different depths in the upper mantle.

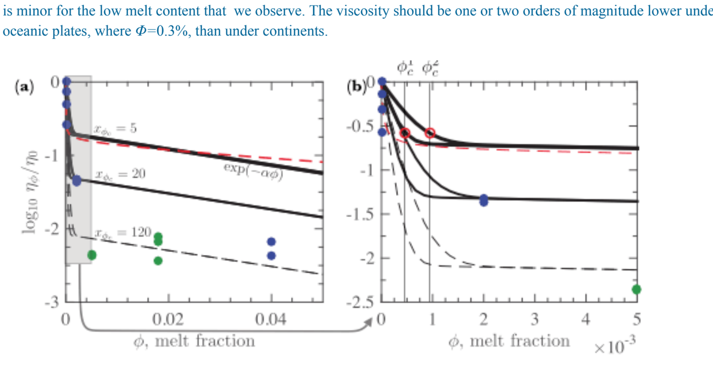


The upper colour scale shows the amount of melt (%) required to explain our observations using the model of Takei, (2017). The lower colour scale indicates the difference in percent between theory and observations, in regions (mostly cratons) where Vs is too high and cannot be reconciled with model predictions assuming a pyrolitic mantle. Hotspot locations are indicated with black triangle. The blue and green stars indicate the location of the Nomelt (Lin et al., 2016) and Melt (Yang et al., 2007) experiments, respectively.

We map partial melting down to 150–200 kilometres beneath mid-ocean ridges, major hotspots and back-arc regions. In these regions melt feeds the asthenosphere. A small part of this melt (less than 0.3%) remains trapped within the oceanic LVZ. Melt is mostly absent under continental regions, where compositional heterogeneities and depletion of incompatible elements contribute to the high seismic velocities.

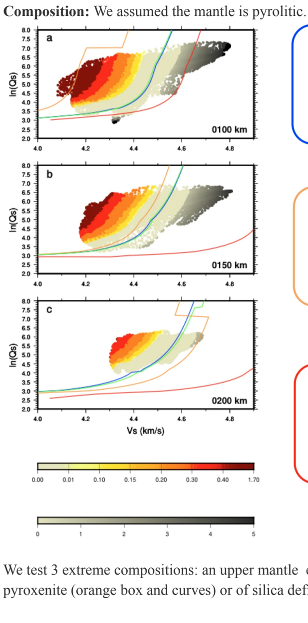
Effect of melt on viscosity :

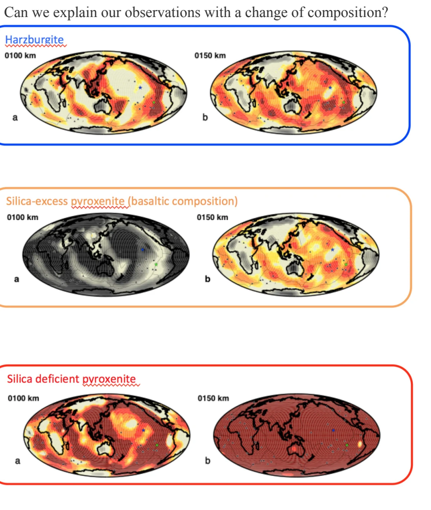
The figure below by Hotzmann (2016) shows that the variation in viscosity as a function of melt content occurs in two steps. First, the onset of melting has a strong effect on viscosity when a connected network of melt tubules is established. The viscosity η decreases by one or two orders of magnitude before the melt fraction Φ reaches 0.1%. Second, for larger melt content, the viscosity decreases further, with $d\ln\eta/d\Phi$ = -26; this effect is minor for the low melt content that we observe. The viscosity should be one or two orders of magnitude lower under oceanic plates, where Φ=0.3%, than under continents.



EFFECT OF COMPOSITION AND RADIAL ANISOTROPY

Composition: We assumed the mantle is pyrolitic. Can we explain our observations with a change of composition?



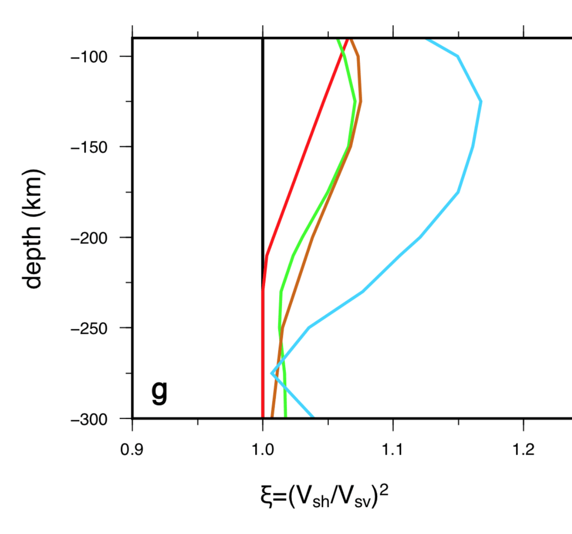


We test 3 extreme compositions: an upper mantle entirely made of harzburgite (blue box and curves), of silica-excess pyroxenite (orange box and curves) or of silica deficient pyroxenite (red boxes and curves.

Neither of these extreme compositions can remove the melt layer in the LVZ.

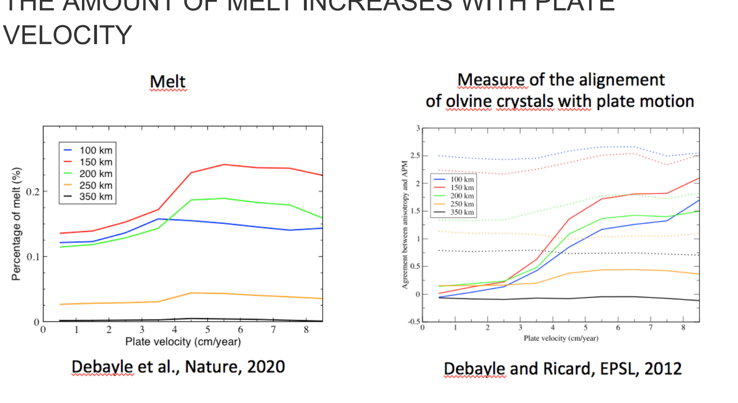
Radial anisotropy: can we explain our observations without melt, only by invoking radial anisotropy (displayed with ξ=(Vsh/Vsv)^2) ?

The figure below shows the global average of the radial anisotropy (blue curve) needed to explain our observations without melt. The ξ values are unrealistic and much larger than the global average in 3D models SEMUCB (French et al., 2013, green curve), S362ANI (Kustowski et al., 2008, brown curve) or PREM (Dziewonski & Anderson, 1981, red curve).



We show in the Method and Supplementary information of our paper that the low Vs value cannot be reconciled with Qs by adding radial anisotropy, elastically accomodated grain-boundary sliding, or the effect of composition or water.

THE AMOUNT OF MELT INCREASES WITH PLATE VELOCITY



Melt fraction at different depths (left panel) and anisotropy along absolute plate motion (right panel, continuous lines) as a function of plate velocity expressed in a no-net reference frame for different depths in the upper mantle. The amount of melt increases substantially in the asthenosphere (100-200 km) for plate velocities between 3 and 5 cm/yr (left panel). This links with previous observations by Debayle and Ricard (2013) (right panel) of an increase in the proportion of anisotropy aligned with APM for plate motions between 3 and 5 cm/yr.

Plate crystal alignment beneath plates movig faster than 4 cm/yr (right panel) is associated with a greater amount of melt (left panel).

This requires either that melt facilitates deformation or that deformation favours melt retention or both

Our results suggest that by reducing viscosity, melt facilitates plate motion and large-scale crystal alignment in the asthenosphere.

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