The formation of hot thermal anomalies in cold regions of Earth's lowermost mantle

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Overview

The Earth's lowermost mantle is characterized by two large-low shear velocity provinces (LLSVPs). The regions outside the LLSVPs have been suggested to be strongly influenced by subducted slabs and therefore, much colder than the LLSVPs. However, localized low-velocity seismic anomalies have been detected in the subduction-influenced regions of the lowermost mantle, but their origin remains unclear.

Here, 3D geodynamic calculations are performed, and they show linear, ridge-like hot thermal anomalies, or "thermal ridges", form in the subduction-influenced regions of the lowermost mantle.

Through a systematic exploration of model parameters, I find that the formation of thermal ridges is induced by thermal heterogeneities in cold downwellings.

The hot thermal ridges may explain the low-velocity seismic anomalies in the subduction-influenced regions of the lowermost mantle.

Method

1. 3D partial spherical models
2. Boussinesq and extended-Boussinesq approximation
3. CitcomCU code
4. Earth-like vigor of mantle convection, Rayleigh number is 5×10^7
5. Purely thermal and thermochemical models are performed
6. Viscosity depends on temperature and depth: $\eta=\eta(r)\exp[A(0.6-T)]$, $\eta(r)=0.3$, 0.03, and 1.0 at 0-100 km, 100-670 km, and 670-CMB, respectively. The dimensionless activation energy A=6.91, or 11.51, leading to 10^3- or 10^5-times change of viscosity as temperature increases from 0 to 1.
7. Post-perovskite (pPv) phase transition is included in some models, with 500-times reduction of viscosity, 1% increase of density. Latent heating of pPv phase transition is considered in some models.
8. Two types of models performed:

Type I: from surface to CMB, the longitude and the co-latitude range from 0-120° and 30-150°, respectively. 256x256x64 elements.

Type II: lowermost 300 km, the longitude and the co-latitude range from 0-40oand 70-110o, respectively. 256x256x64 elements, Radial resolution is 4.7 km

Conclusion

1. Low-velocity seismic anomalies have been previous reported in the lowermost mantle outside of the LLSVPs.
2. 3D mantle convection models show the formation of linear, ridge-like, hot thermal anomalies, or thermal ridges, in relatively cold, downwelling regions of the lowermost mantle.
3. The formation of thermal ridges is induced by the thermal heterogeneities in the cold downwellings.
4. The thermal ridges may explain the low-velocity seismic anomalies outside the LLSVPs in the lowermost mantle.
5. The thermal structure of subducting slabs significantly affects the lowermost mantle temperature field.

Read orange texts to get the key points quickly

1. Low-velocity seismic anomalies outside the LLSVPs

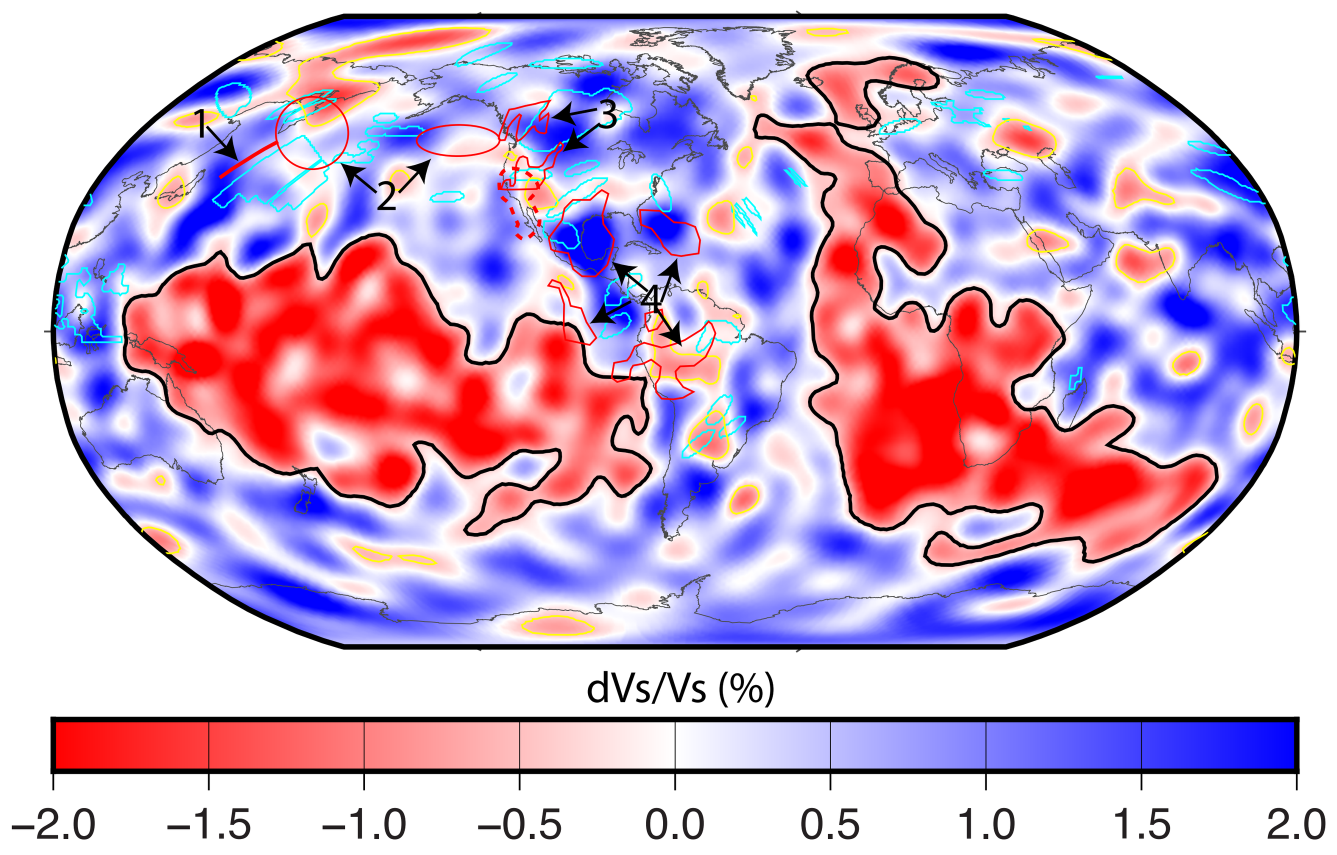

Figure 1. Localized zones with lower-than-average seismic velocities have been detected in the relatively cold, subduction-influenced regions outside the LLSVPs. The low-velocity anomalies outside the LLSVPs are shown by (**a**) yellow contours with Vs anomaly of -0.46%, (**b**) cyan contours with detection of ultra-low velocity zones (ULVZs), (**c**) red contours at the location of low-velocity structures observed by He et al. (2014; #1), Suzuki et al., (2016; #2), Sun et al., (2013; #3), and Borgeaud et al. (2017; #4), and (**d**) dashed red contours for the root of the Yellowstone plume (Nelson and Grand, 2018). The base map shows the SEMUCB-WM1 model (French and Romanowicz, 2014) at 2,800 km.

2. Hot thermal ridges outside a thermochemical pile

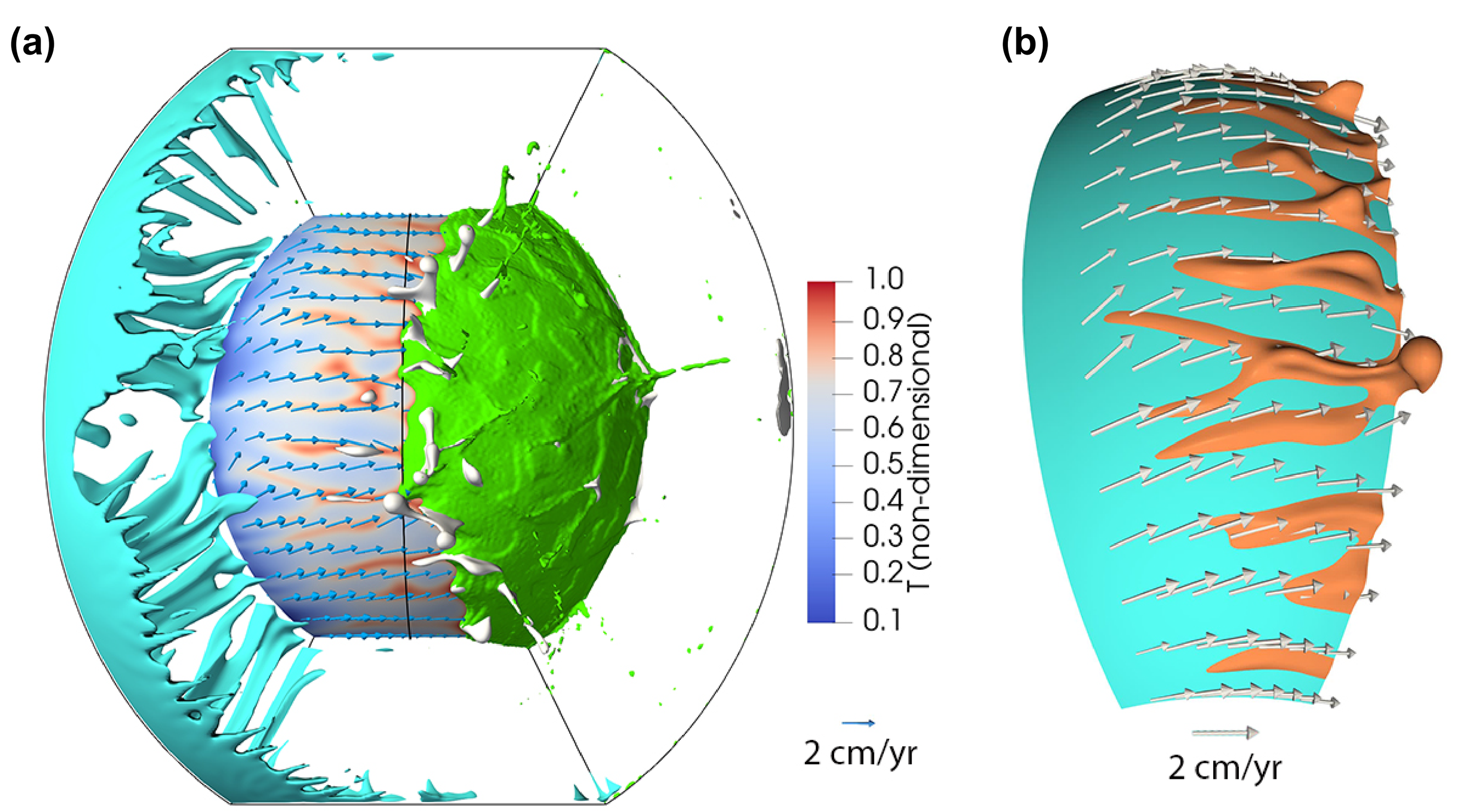

Figure 2. 3D mantle convection model showing the formation of hot, linear, thermal ridges in relatively cold regions of the lowermost mantle outside a thermochemical pile. (**a**) Temperature and composition fields. Green = thermochemical pile which is ~2% intrinsically denser than the surrounding mantle. Cyan = cold downwellings. Gray = mantle plumes that preferentially rise at the edges of the thermochemical pile. The temperature field and the mantle flow velocities (Arrows) are both shown at 45 km above the CMB. (**b**) 3D view of thermal ridges in regions from the western boundary to that marked by the solid black lines in panel (a).

3. The effects of thermal structure of cold downwellings and weak pPv phase

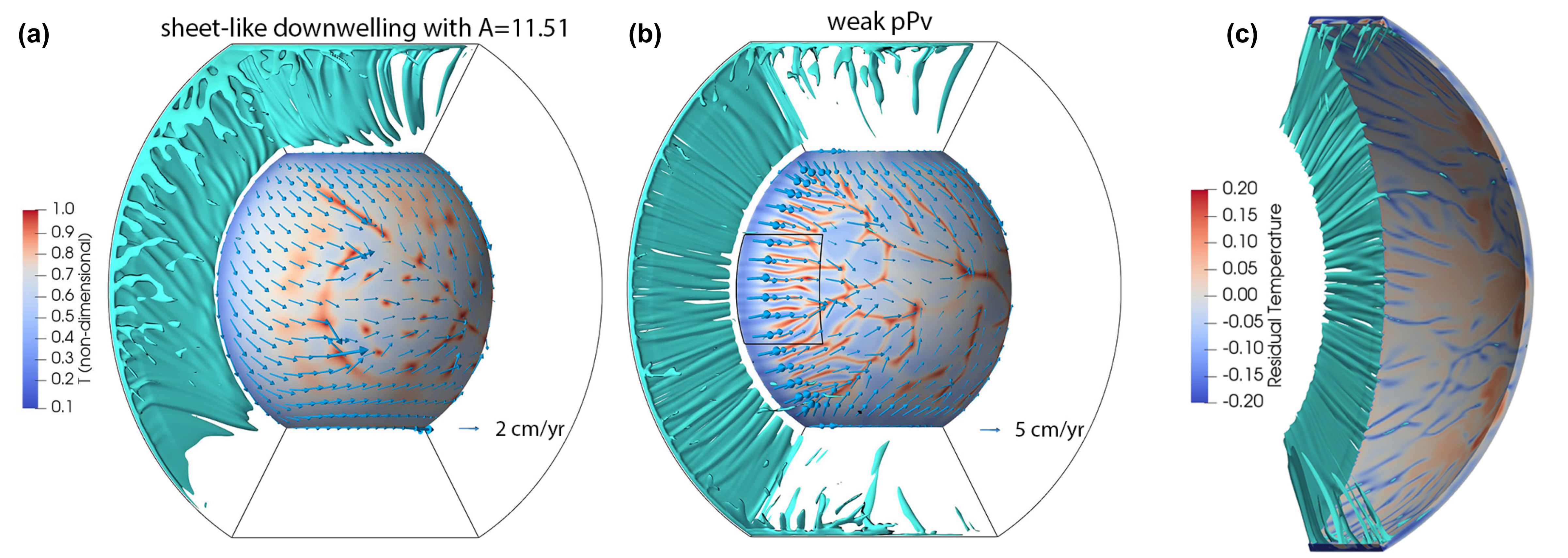

Figure 3. The formation of thermal ridges is sensitive to the thermal structure of cold downwellings, and the lowermost mantle viscosity. (**a**) As the degree of temperature dependence of viscosity increases, the cold downwellings (cyan isosurface) become more sheet-like, and the formation of thermal ridges is impeded. (**b**) The post-Perovskite (pPv) phase is 500 times less viscous than the surroundings. Thermal ridges form as the viscosity in relatively cold regions of the lowermost mantle is significantly reduced, even though the downwellings are sheet-like. (**c**) Temperature heterogeneities exist in the sheet-like downwellings, which origin from that at the base of the lithosphere caused by small-scale convection.

4. Thermal heterogeneities are found in slabs for the true Earth

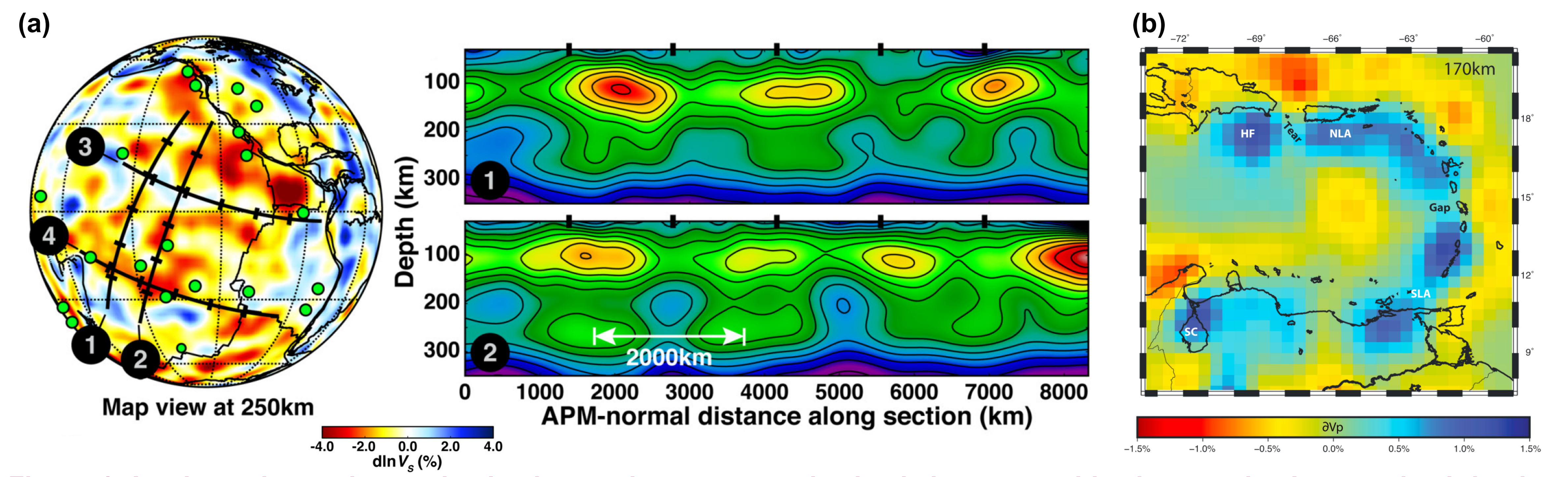

Figure 4. As shown in previous seismic observations, gaps and seismic heterogeneities in oceanic plates and subducting slabs are not uncommon. (**a**) Seismic S-wave anomaly of the Pacific lithoshere from French and Romanovicw (2013). (**b**) Seismic P-wave anomaly of the central America lithosphere. Reproduced from Harris et al. (2018)

Our numerical modeling experiments suggest thermal heterogeneities in slabs may cause hot thermal anomalies forming in cold downwelling regions of the Earth's lowermost mantle.

5. Reference

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