This carefully conducted study offers an unprecedented view of the landscape of somatic mutations in normal melanocytes, providing new clues about the origins of melanoma and presenting many intriguing observations that should motivate further research. Together with similar efforts in other tissues, studies such as this one by Tang and colleagues are rapidly changing our understanding of somatic mutations in normal tissues and the relevance of these mutations for health and disease.

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1. Tang, J. *et al. Nature* **586**, 600–605 (2020).
2. Martincorena, I. *et al. Science* **348**, 880–886 (2015).
3. McGrath, J. A., Eady, R. A. J. & Pope, F. M. in *Rook's Textbook of Dermatology* (eds Burns, T., Breathnach, S., Cox, N. & Griffiths, C.) Ch. 3 (Blackwell, 2004).
4. Lodato, M. A. *et al. Science* **348**, 880–886 (2015).
5. Welch, J. S. *et al. Cell* **150**, 264–278 (2012).
6. Blokzijl, F. *et al. Nature* **538**, 260–264 (2016).
7. Yoshida, K. *et al. Nature* **578**, 266–272 (2020).
8. Jaiswal, S. *et al. N. Eng. J. Med.* **371**, 2488–2498 (2014).
9. Kennedy, S. R., Zhang, Y. & Risques, R. A. *Trends Cancer* **5**, 531–540 (2019).
10. Huang, F. W. *et al. Science* **339**, 957–959 (2013).

Geoscience

Melt mapped inside Earth's mantle

Laura Cobden

An analysis of seismic data reveals the location and quantity of melted rock, known as melt, in Earth's upper mantle. The results show how these factors are correlated with the movement of the planet's tectonic plates. **See p.555**

Throughout most of Earth, seismic waves speed up as they travel deeper. A notable exception is the boundary between the rocky mantle and the liquid outer core, at a depth of about 2,900 kilometres. A second slow region, commonly referred to as the low-velocity zone (LVZ), lies directly beneath the tectonic plates. The origin of this region, where wave speeds can suddenly drop by up to 10% (ref. 1), has been debated because reductions in wave speed can be caused by many factors. By combining measurements of wave speed with those of a second observable quantity, the attenuation (energy dissipation) of seismic waves, Debayle *et al.*[2] (page 555) demonstrate that partial melting of the mantle is the most probable explanation for the LVZ.

Earth's tectonic plates represent both a thermal and a mechanical boundary layer to the vigorous convection that takes place inside the mantle. Although other rocky planets also have a rigid outer layer (lithosphere), Earth is unusual in having moving plates. It is thought that plate mobility is aided by the presence of a low-viscosity layer, called the asthenosphere, over which the plates can readily slide (Fig. 1). The fact that the LVZ is seen at depths coincident with the asthenosphere (about 60–300 km) suggests a causal relationship. However, the LVZ might not be present at all locations around the globe, and has mostly been found beneath oceanic plates.

Observations of the LVZ date back as far as the 1950s[3]. Originally, the presence of melted rock (melt) was used to explain both the low wave speeds and the mechanical weakness of the LVZ. In the past 15 years, this interpretation has been questioned[1] because the amounts of melt required to give the observed wave-speed reductions are potentially too large to be dynamically stable, given estimated rates of melt production and extraction[4]. This discrepancy might be reconciled if the melt is concentrated into thin layers embedded in melt-free mantle regions[5]. Alternatively, the LVZ could be generated by the release of water from subducting plates[6] (whereby an oceanic plate sinks into the mantle) or by thermally activated deformation along grain boundaries[1] (the interfaces between mineral grains).

As seismic waves travel through Earth, they continually lose energy. Part of this attenuation is caused by geometric spreading of the waves and their scattering off large lateral or vertical structural changes in the mantle. However, a sizeable component is the result of the wave-propagating medium having intrinsic anelasticity — a delay in the deformation of a material in response to applied stress. Such anelasticity is mostly caused by internal friction (for example, along grain boundaries), and it leads to decreases in both wave speed and amplitude. At the temperatures and pressures of the upper mantle, the wave-speed reductions become substantial, and some studies suggest that anelasticity effects alone might be sufficient to generate the LVZ (see ref. 7, for example).

Seismic attenuation is defined in terms of the quality factor, Q, where Q^{-1} represents the fractional loss in energy per wave cycle. Combining measurements of wave speed and Q provides a powerful tool[8] for discriminating between the different hypotheses for the LVZ. This is because wave speed is sensitive to variations in temperature, chemical composition and melt fraction, whereas Q is predominantly controlled by temperature, at a given depth and seismic frequency, assuming that there is limited contribution from scattering. For a fixed chemical composition, one can vary the

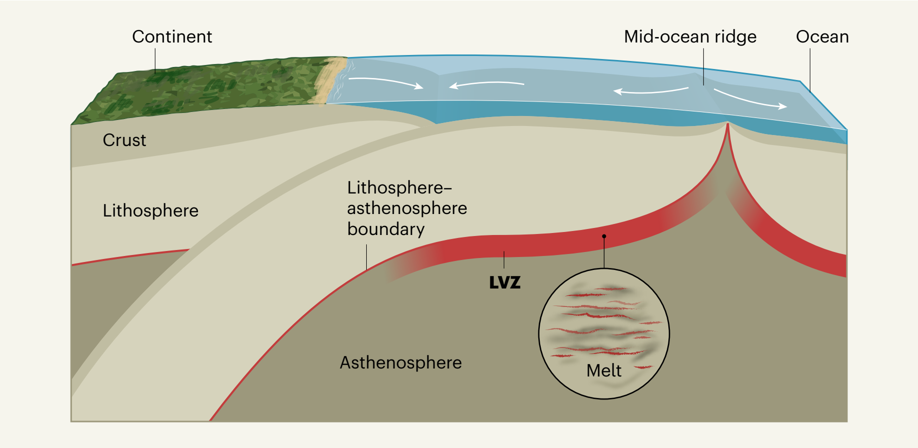

Figure 1 | Location and possible origin of the low-velocity zone (LVZ). The movement of Earth's tectonic plates (white arrows) is thought to be aided by a low-viscosity layer known as the asthenosphere. Shown here is an oceanic plate being pushed beneath a continental plate, and the separation of two oceanic plates at a mid-ocean ridge; each of these plates consists of a lithosphere (rigid outer layer) and crust. The LVZ is a region in which the velocity of seismic waves is lower than that in the layers above and below. This region is situated close to the boundary between the lithosphere and asthenosphere, mostly beneath oceanic plates. Debayle *et al.*[2] show that the most probable explanation for the LVZ is the presence of melted rock (melt). Such melt is probably concentrated into thin layers embedded in melt-free regions[5].

temperature and calculate *Q* as a function of wave speed. If the observed wave speed differs from that predicted by the observed *Q*, then a factor other than temperature must be contributing to the wave speed.

Debayle and colleagues used surface waves — large-amplitude seismic waves that travel close to Earth's surface — to simultaneously constrain wave speed and *Q* for the whole globe between depths of 100 and 300 km. They show that the observed variations of wave speed and *Q* cannot be explained simultaneously by temperature variations, hydration, grain deformation, major-element composition or preferential grain orientation, but can be explained by partial melting of the mantle. Similar inferences have been made in regional studies of Europe[8] and the East Pacific Rise[9], a mid-ocean ridge that runs along the southeast margin of the Pacific Ocean. However, Debayle *et al.* extended this type of deductive analysis to a global scale, and the strength of their study is that the models of wave speed and *Q* were obtained from the same initial data set, with the same resolution and modelling technique, making them entirely consistent with each other.

The authors took their analysis a step further by mapping the melt fraction in three dimensions, providing global melt models. In addition to revealing an absence of melt beneath the continents, these models show that melt fractions are highest where tectonic plates are moving the fastest, supporting the idea that plate mobility is enhanced by the weakness of the underlying asthenosphere. Although the sub-oceanic melt fractions in Debayle and colleagues' model are larger than some dynamic predictions[1,4], the authors argue that the parameters defining rates of melt migration and accumulation in those predictions are poorly constrained.

The robustness of the melt maps depends on the reliability of the assumptions underlying the calculations — in particular, that water does not influence wave speed or *Q* at seismic frequencies and that melt affects only wave speed. The former assumption is based on experiments on olivine (the most abundant mineral in the upper mantle) at pressures lower than those of the mantle[10], and it is possible that water behaves differently at mantle pressures and in assemblages of multiple minerals. The impact of melt on *Q* is also uncertain. Furthermore, the calculation of *Q* at a given temperature involves many parameters, such as activation energy (the minimum energy required to induce attenuation) and grain size, for which limited data exist[11].

Despite these uncertainties, Debayle *et al.* have been thorough in using the strongest constraints that are currently available, and their results are an exciting step forward in understanding the fundamental dynamics of our planet. With continuing laboratory experiments to constrain mineral attenuation parameters, supported by the deployment of dense arrays of seismometers, we can expect future work to identify mantle melt with ever-increasing precision.

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1. Karato, S.-I. *Earth Planet. Sci. Lett.* **321–322**, 95–103 (2012).
2. Debayle, E., Bodin, T., Durand, S. & Ricard, Y. *Nature* **586**, 555–559 (2020).
3. Gutenberg, B. *Physics of the Earth's Interior* (Academic, 1959).
4. Hirschmann, M. M. *Phys. Earth Planet. Inter.* **179**, 60–71 (2010).
5. Kawakatsu, H. *et al. Science* **324**, 499–502 (2009).
6. Richards, M. A., Yang, W.-S., Baumgardner, J. R. & Bunge, H.-P. *Geochem. Geophys. Geosyst.* **2**, 2000GC000115 (2001).
7. Goes, S., Armitage, J., Harmon, N., Smith, H. & Huismans, R. *J. Geophys. Res.* **117**, B12403 (2012).
8. Cobden, L., Trampert, J. & Fichtner, A. *Geochem. Geophys. Geosyst.* **19**, 3892–3916 (2018).
9. Yang, Y., Forsyth, D. W. & Weeraratne, D. S. *Earth Planet. Sci. Lett.* **258**, 260–268 (2007).
10. Cline, C. J. II, Faul, U. H., David, E. C., Berry, A. J. & Jackson, I. *Nature* **555**, 355–358 (2018).
11. Faul, U. & Jackson, I. *Annu. Rev. Earth Planet. Sci.* **43**, 541–569 (2015).