Mantle skewness and ridge segmentation

Arising from: D. R. Toomey, D. Jousselin, R. A. Dunn, W. S. D. Wilcock & R. S. Detrick *Nature* **446**, 409–414 (2007)

Mantle upwelling is generally assumed to be symmetric. Toomey *et al.*[1] observe low seismic-wave velocity in off-axis mantle, and suggest that mantle upwelling is skewed, which has important implications for asthenospheric flow, ridge segmentation, crustal accretion, and volcanic, tectonic and hydrothermal vent activities along the ridge axis. However, we point out here that the mantle low-velocity zone (MLVZ) presented by Toomey *et al.*[1] is not constrained by their data. We conclude that inferences pertaining to ridge segmentation and mantle flow are not reliable.

The estimation of seismic velocity in the mantle beneath the Mohorovičić discontinuity (Moho) will depend on turning ray depths, crustal thickness and Moho topography, which are variable[2,3] and are poorly constrained, particularly beneath the ridge axis (Fig. 1a). Toomey *et al.*[1] show the MLVZ at 9 km below the sea floor (b.s.f.; Fig. 1a), but Fig. 1b shows that the maximum depth of turning rays is 8 km b.s.f. As Toomey *et al.*[1] use ray theory for travel time tomography[4], there are no constraints at 9 km b.s.f. because rays are sensitive to anomalies along the ray path only.

For velocity to be interpretable at 9 km b.s.f., the velocity has to be independent of depth down to this depth, which means that there would be no turning rays in the mantle and the claim of Toomey *et al.*[1] that the velocity is constrained within 4 km of the Moho is not valid.

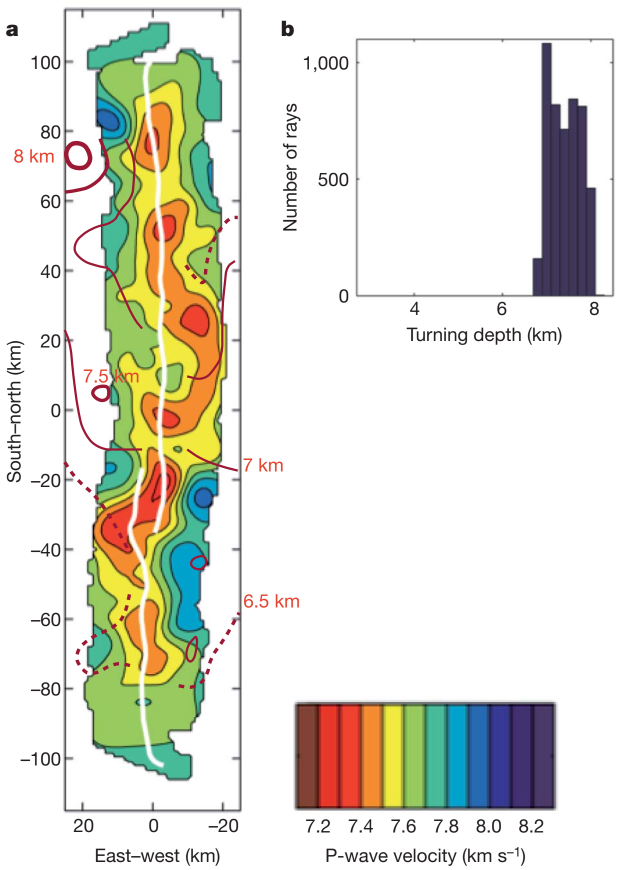

Figure 1 | P-wave velocity and ray turning depth. a, P-wave velocity determined by Toomey *et al.*[1] at 9 km b.s.f. (modified from their Supplementary Fig. 1). The crustal thickness is plotted as brown contours at 0.5 km intervals[2] from 6.5 to 8.0 km. Note the lack of crustal thickness information beneath the ridge axis. **b**, Histogram showing the ray turning depth below the sea floor (modified from Toomey *et al.*[1]).

There are several factors that could introduce uncertainty in the crustal thickness estimation. Layer 2A thickness could vary significantly (300–750 m or 200–500 ms)[5,6] at the source entry points along the outer profiles. As the ocean bottom seismometer spacing is 12–30 km, layer 2A is poorly constrained, particularly in the upper 500 m (Figs A1 and B2 in Canales *et al.*[2]). In the absence of any precise knowledge of layer 2A thickness, we can assume that the uncertainty due to layer 2A is ~50 ms (ref. 7). Canales *et al.*[2] suggest that the uncertainty in the upper crustal (P_g) arrival is 25 ms, which is reasonable, whereas Toomey *et al.* use 10 ms. The Moho reflection (P_mP) is generally a secondary arrival and is observed at offsets >30 km, and hence has a large uncertainty. Canales *et al.*[2] show in their Figs A4–A7 that 60% of P_mP arrivals are of poor quality and difficult to pick. After a careful study, Seher[7] suggested that the uncertainty in P_mP arrivals should be ~40 ms; Toomey *et al.*[1] use 15 ms. As there are no turning rays in the lower crust, there is a trade-off between Moho depth and lower crustal velocity estimation from P_mP arrivals; this is confirmed by the synthetic tests of Canales *et al.*[2], who also showed that such uncertainties could be up to 1 km. The velocity in the lower crust varies over 6.8–7.3 km s^{-1}, which for 3–4-km-thick lower crust can introduce an uncertainty of 40–60 ms. As the uncertainties are uncorrelated and errors propagate with depth, the total uncertainty due to crust could be ~80 ms (ref. 7), the same as the average anomaly for the mantle (P_n) arrivals at 40 km offsets (Fig. 2 in ref. 1).

Previous studies suggest that the uncertainty in crustal thickness could be ±0.5 km (refs 2, 3). Travel time anomaly (Δt) for P_n due to crustal thickness variation (Δz) can be written as $\Delta t = \frac{2\Delta z}{V_1}\sqrt{1-\frac{V_1{}^2}{V_2{}^2}}$, which for $V_1 = 7$ km s^{-1} (crustal velocity) and $V_2 = 7.8$ km s^{-1} (mantle velocity) would be ±64 ms, which is >70% of the mean delay (Fig. 2c in ref. 1). It should be noted that Δt is independent of offset and will map into mantle velocity during the inversion. Full waveform inversion analyses[8,9] suggest that only structure on the scale of one wavelength can be resolved from wide-angle reflection data, which for P_mP arrival is ~700 m, consistent with waveform modelling studies[10].

Crustal structures at rays piercing the Moho are very important. Canales *et al.*[2] show that >70% of possible piercing points are not constrained by their data (Fig. 9 in ref. 2), and therefore, crustal thickness estimation within ±200 m by Toomey *et al.*[1] is not supported by data. If the uncertainty in the P_n travel time arrival is ≥40 ms (ref. 7), it would be difficult to determine the orientation of anisotropy within 10° of the ridge axis from Fig. 2b in ref. 1, which is the size of their mantle skewness.

Therefore, we conclude that the MLVZ shown at 9 km depth by Toomey *et al.*[1] is an artefact of the travel time tomography, and so interpretations based on these results are not reliable[11].

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We think that the Singh and Macdonald[1] description of the experimental uncertainties in our data[2] is a misrepresentation of what we have done, and that they are incorrect in stating that our results[2] on the structure of the uppermost mantle in the subaxial region beneath the East Pacific Rise are unconstrained by data.

We state[2] that the tomographically imaged mantle low-velocity zone (MLVZ) represents an average of structure over the upper several kilometres of the mantle. This is a consequence of the effects of wavefront healing[3,4]. Calculations show that: (1) for a sub-axial MLVZ with a vertical extent of 2 km (or less), the shortest time path is below the anomaly and the predicted delay time is five (or more) times smaller than the observed range of P_n anomalies (~350 ms); and (2) only for a MLVZ more than 3–4 km thick is the shortest time path through (not below) the MLVZ, and only in this case can the observed P_n anomalies be reproduced. Considering the effects of wavefront healing, the MLVZ must be several kilometres thick, and thus our results immediately beneath the Mohorovičić discontinuity (Moho) and at 9 km beneath the sea floor are the same (Fig. 1).

The skew of mantle flow beneath the East Pacific Rise is best constrained by the azimuth of seismic anisotropy, which is rotated ~10°

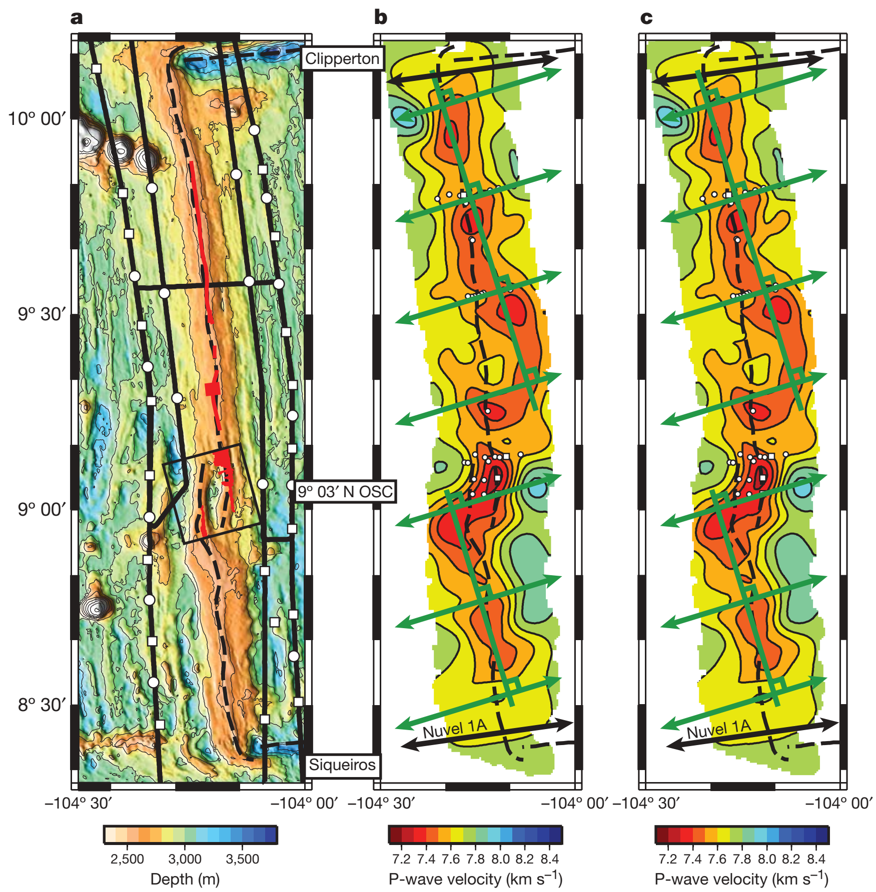

Figure 1 | Location and geometry of the seismic experiment, tomographic images of the MLVZ, and orientation of mantle anisotropy. a, Experiment location and geometry. **b,** Tomographic image; depth of section is 9 km beneath the sea floor. **c,** Tomographic image; depth of section is 800 m beneath the Moho. The smoothing constraints applied to the tomographic inversion require the mantle structure to be vertically invariant. The caption to Fig. 1b of ref. 2 should not indicate a specific depth, but rather state that the tomographic image represents the average structure of the upper few kilometres of the mantle. See ref. 2 for details of features on graphs.

from the spreading direction. Singh and Macdonald[1] are concerned that anisotropy would be difficult to constrain given the uncertainty of a P_n travel time. However, to determine the anisotropy we bin and average the P_n delays by azimuth, and thus each mean is obtained from a sample size of ~100. Even if we accept the estimate of Singh and Macdonald[1] for the uncertainty of a single P_n travel time (±40 ms), the uncertainty in the estimate of the mean decreases by $\sim 1/\sqrt{n}$ (where n is the sample size), or to ±4 ms. The azimuth of anisotropy is extraordinarily well known, with a standard error of $\pm 1^\circ$ (see Fig. 2b in ref. 2).

Singh and Macdonald[1] are right to be concerned about the effects of crustal structure on P_n travel times, but we consider their analysis to be flawed. First, uncertainties should not be compared to the mean delays of Fig. 2c in ref. 2, as the latter are defined relative to a reference velocity ($7.8\,\mathrm{km\,s^{-1}}$). Mean delays relative to $8.2\,\mathrm{km\,s^{-1}}$ or $7.6\,\mathrm{km\,s^{-1}}$ would be larger or close to zero. Nevertheless, the variation of P_n anomalies about the means would be identical and we would obtain the same tomographic result irrespective of the reference model, as noted in the Supplementary Information of ref. 2. In short, what requires heterogeneity is the range of delays (which is 350 ms), not the mean delay relative to an arbitrary reference.

Second, layer 2a, the lower crust and the crustal thickness do not need to be resolved independently in order to image mantle structure. Instead, what must be known is the integrated time it takes for P_n to traverse the crust. We use P_g and P_mP data from four rise-parallel lines to constrain off-axis crustal structure. Inversion of these data alone yields a root-mean-square misfit of 12 ms and 22 ms for P_g and P_mP, respectively; this level of misfit is common[5–8]. These results provide an estimate of the standard deviation in the time it takes to traverse the crust (±22 ms). This estimate is only 6% of the range of P_n delays, so even in the presence of a substantially larger uncertainty, our results would be robust because of the magnitude of the signal (350 ms). We do agree that our data cannot resolve layer 2a, nor can they independently resolve crustal thickness and lower-crustal velocity, as discussed in ref. 6. Nevertheless, the integrated time it takes to traverse the crust is well known, and thus we can correct P_n data for this effect.

Crustal thickness variations beneath the axial high have a negligible effect on P_n travel time because the wave propagates horizontally beneath the rise. Three-dimensional ray-tracing calculations show that if crust beneath the axial high thickens or thins by 1 km relative to our starting model — which we consider unlikely as our starting model is comparable to the results from a reflection experiment[9] — the effect on a P_n time is only 25 or 0 ms, respectively.

Finally, Macdonald *et al.*[10] agree that our tomographic image reveals a pattern of uppermost mantle segmentation that matches the ~25 km segmentation of sea-floor volcanoes remarkably well, though we differ on the interpretation. By contrast, there is no evidence from either refraction or reflection data[6,9] that the crustal thickness or two-way travel time is segmented on this scale. It is thus difficult to see how crustal uncertainties could yield the model we obtain. And it seems equally unlikely that the inversion of noise would yield a result that agrees so well with sea-floor mapping.

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