Supplementary Materials for

High mantle seismic P-wave speeds as a signature for gravitational spreading of superplumes

Tim Stern*, Simon Lamb, James D. P. Moore, David Okaya, Katharina Hochmuth

*Corresponding author. Email: tim.stern@vuw.ac.nz

Published 27 May 2020, Sci. Adv. 6, eaba7118 (2020)
DOI: 10.1126/sciadv.aba7118

The PDF file includes:

Supplementary Materials and Methods
Figs. S1 to S12
Table S1
Legend for movie S1

Other Supplementary Material for this manuscript includes the following:

(available at advances.sciencemag.org/cgi/content/full/6/22/eaba7118/DC1)

Movie S1
Materials and Methods

Seismic velocity anisotropy of Type AG fabric
Seismic velocity anisotropy that may be produced by type AG fabric for an aggregate of forsterite-rich olivine can be extracted from its elastic properties. We used the elastic tensor form of this AG fabric within Christoffel equations in order to solve for anisotropic P and S wave velocities in all seismic propagation directions[34]. This AG tensor, as described below, was oriented in accordance with radial plume flow. In Figure S1 we illustrate the resulting $V_p$, plus the fast and slow $V_s$ draped on spheres that represent all azimuth and inclination directions, calculated for pressure = 20 kbars and temperature of 1100 °C [35] (Harigane et al. 2017). We also show the percent anisotropy for $V_p$ and $V_s$ based on this expression where $V_{\text{average}} = (V_{\text{max}}+V_{\text{min}})/2$, where percentage anisotropy = $(V_{\text{max}}-V_{\text{min}})/V_{\text{average}}$.

The $V_p$ sphere illustrates the radial symmetry of the P-wave anisotropy, with $V_p$ slower in the vertical direction (7.81 km/s) in contrast to the horizontal direction (8.65-8.77 km/s). In the horizontal direction the faster $V_s$ is in the range of 4.99 to 5.11 km/s and its wave particle motion direction is horizontal (red bars on V$s$-fast sphere). In contrast, the slower $V_s$ ranges between 4.65 to 4.68 km/s in the horizontal direction with vertical polarization motion. Correspondingly, the largest amounts of $V_S$ %anisotropy is in the horizontal direction.

The AG fabric elastic tensor for an aggregate of olivine (Fo90) under uppermost mantle conditions (P = 20kbars, T = 1100° C) has the following tensor elements in Voigt index notation and is diagonal symmetric [35]: $C_{11}=250.88$, $C_{22}=258.19$, $C_{33}=204.73$, $C_{44}=73.46$, $C_{55}=72.50$, $C_{66}=83.82$, $C_{12}=79.51$, $C_{13}=74.71$, $C_{14}=-0.030$, $C_{15}=0.088$, $C_{16}=-1.050$, $C_{23}=74.34$, $C_{24}=1.760$, $C_{25}=0.130$, $C_{26}=1.430$, $C_{34}=0.0600$, $C_{35}=-0.0320$, $C_{36}=0.130$, $C_{45}=-0.020$, $C_{46}=0.052$, $C_{56}=0.043$

Seismic experiments at the Hikurangi Margin
Estimates of upper mantle P-wave speeds for trench-parallel azimuths along the Hikurangi margin (Fig. S2) have been reported over the past 35 years 19-22. Most of these studies involve using earthquake waves as an energy source, although an active source seismic study was conducted in 1991 as a joint project between Victoria University of Wellington, Leeds
University (UK) and the Canadian Geological Survey. The latter used six large borehole explosions, recorded with 86 seismographs over a length of 300 km (Fig. S2). The key finding of the active source study was P-wave speeds of $8.7 \pm 0.1$ km/s in the upper mantle at depths greater than 32 km (Fig. S2).

The Seismic Array Hikurangi Experiment (SAHKE) project was a joint NZ-Japan-USA experiment in 2010 to 2012 to image the subduction zone beneath the southern North Island of New Zealand[12]. SAHKE consisted of both onshore and offshore seismic profiling across the subducting margin using active and passive source techniques. For the 90 km long onshore segment of SAHKE 04 (Fig. 1b), across the lower North Island, a dense array of 874 vertical and 291 three component seismographs was used, spaced at 50–100 m. These recorded 12 borehole explosions in order to image the deep mantle structure of the Pacific plate [19].

**Subduction zone structure at Hikurangi Margin**

A detailed analysis of the southern Hikurangi subduction zone interface (megathrust) beneath SAHKE 04, using seismic energy from onshore explosions, together with onshore-offshore shooting, shows that the megathrust increases in dip along the profile, from about 5° NW at the SE end to 14° at the NW end[14]. The dip of the megathrust in the mid-section beneath the SAHKE 04 profile is $9\pm1$° NW. Wide-angle reflections and refractions image the Moho of the Pacific plate (i.e. the Hikurangi Plateau) beneath SAHKE 04, giving an oceanic crustal thickness of $10 \pm 0.5$ km [14].

The crustal structure in the overlying plate has been determined in previous analyses of seismic arrivals along the SAHKE array[12, 14, 18, 19]. This includes a number of shallow sedimentary basins and a low velocity (5 km/s) 1-3 km thick underplated sediment layer at the plate interface, with a large (7-8 km thick) hump of underplated sediments at the NW end of the line[12, 14].

**Upper mantle P-wave speed beneath SAHKE 04**

Several earthquakes were recorded during the two-week period when the onshore SAHKE 04 array was operating (Fig. S4). The most useful of these was Mw 2.5 event (Geonet event #3511915) with a hypocentral depth of $50 \pm 3$ km, and located 42 km offshore to the NW, almost
directly in line with the NW extension of the SAHKE profile (Fig. 1). This event was well
located by 16 stations of the Geonet network using 19 phases, and had a standard error for
location of 0.3s (www.geonet.org.nz/earthquake/technical/3511915). P and S wave arrivals from
the earthquake were recorded across the array (Fig. S4).

For the first 33 km of the line, all stations are on Mesozoic greywacke basement rock, and the
arrivals form roughly linear travel time plots. Beyond km 35, the profile crosses the Wairarapa
where thick Paleogene to Pliocene sedimentary basins up to 2.2 km[36]. The effect of the low
wave speeds in these basins is clearly visible in the short wavelength (km scale) features of the
travel time plots, giving rise to marked changes in apparent wave speed, but an overall linear
trajectory is evident across the whole array.

A least-squares fit to picks across the SAHKE04 line yield apparent upper mantle P and S wave
speeds of 10.15 ± 0.06 and 5.30 ± 0.08 km/s respectively (Table S1). These speeds are apparent
rather than real for two structural reasons. First, the sedimentary sequences occur along the SE
half of the line, delaying the arrivals, biasing downwards the apparent speed. Counteracting this
is the effect of the NW dip on the subduction zone interface, which biases upwards the wave
speeds. We can eliminate the effect of sedimentary basins by measuring the speeds at distances
of 3 and 31 km along the array, where the stations are all on basement. This yields apparent P
and S wave speeds of 11.1 and 5.7 (± 0.07) km/s, respectively.

Our first approach to resolving the upper mantle P-wave speed beneath the SAHKE array is a
simple analytical approximation, where we assume the wave-paths approximate critically
refracted waves, which travel up-dip along the interface of a dipping half space (Fig. S3a). This
assumption is reasonable given the sub-horizontal trajectory of the mantle ray paths, clearly
evident in the full ray tracing (Fig. 2a). Analytical solutions[37] exist for the simple
approximation of a dipping half-space with speed \( V_2 \) overlying a layer of lower speed \( V_1 \), and the
dip of the layer \( V_2 \) is \( \delta \) (Fig. S3a):

\[
\theta - \delta = \sin^{-1} \left( \frac{V_1}{V_{2up}} \right), \text{ and } V_2 = \frac{V_1}{\sin \theta} \quad (1),
\]
where $V_{2up}$ is the apparent up-dip wave speed and $\theta$ is the critical angle. The solution for $V_2$ is then:

$$V_2 = \frac{V_1}{\sin \left( \sin^{-1} \frac{V_1}{V_{2up}} + \delta \right)}$$  \hspace{1cm} (2).$$

Our first estimate for apparent up-dip P-wave speed ($V_{2up}$ in equation 3) across the first 31 km of the array is 10.15 km/s (Table S1). But the low wave-speeds in the sedimentary basins at the far end of the profile will bias the apparent velocity downwards. Accordingly, we make a delay-time correction for the sedimentary basins along the profile and recompute the apparent wave speed to be $11.1 \pm 0.06$ km/s (Table S1). Confidence for this corrected apparent wave speed is gained because an identical wave speed is obtained (Table S1) if we measure the apparent wave-speed stations over the first 30 km of the line at the northwestern end, which are located on basement greywacke. The shape and velocity structure of the basins are taken from previous studies (Fig. S2).

We solve Equation (1) for $V_{2up} = 11.1$ km/s, and a plausible range of values of $V_1$ (5.5-5.9 km/s) and dip angle ($9 \pm 1^\circ$ NW, Fig. S3). The largest source of uncertainty is the dip of the interface (Fig. S3). The associated predicted range of $V_2$ is 8.6 to 9.2 km/s, or an average of 8.85 km/s. The average speed is consistent with our previous determination of mantle P-wave speed from ray tracing, and with the values measured on margin parallel (NE-SW, see above) profiles[15].

We next take a forward modelling approach by building a ray tracing model (Fig. 2a) that uses Geonet event #3511915 as a seismic source. Ray tracing is done interactively and is based on ray theory[38, 39]. This approach has allowed us to include the dip of the subduction zone, and the previously determined crustal structure in the overlying plate [12, 14, 18]. We searched for a best-fit P-wave speed for the upper mantle by considering four upper mantle velocity models that have uppermost mantle wave speeds of 8.1, 8.3, 8.7 and 8.9 km/s respectively. A vertical gradient of $5 \times 10^{-3}$ s$^{-1}$ is imposed so that the waves turn and come back to the surface (that is, the speed increases downwards by 0.3 km/s from top to bottom of ~ 80 km thick plate). We showed that having mantle P wave speed gradients in the range 2 to $10 \times 10^{-3}$ s$^{-1}$ made no significant difference to travel-time fits.
The ray tracing (Fig. 2a) shows that the waves turn within a vertical zone 5-10 km thick so P-wave speeds no greater than the 0.05 km/s above the initial wave speed are encountered. Figure 2c shows observed P-wave arrival picks compared with calculated model values. The earthquake energy source is located at the subduction interface, and the radiating seismic energy forms nearly horizontal turning waves that mimic $P_n$ and $S_n$ critically refracted waves (Fig. 2a). As we are modelling the wave speed, and not absolute travel time, we arbitrarily fix the calculated travel times at the northwestern end of the profiles and compare their slope on the reduced travel-time plot. From visual inspection, the model with the upper mantle P-wave speed of 8.7 km/s at the top gives the best fit of the four trial models. We considered a range of models with different choices of the wave speed at the top of the mantle, ranging between 8.1–8.9 km/s. This indicates that the maximum uncertainty in the P wave velocity determination for our models is ±0.2 km/s, consistent within the uncertainties in the analytical methods discussed above. Thus, our ‘best’ estimate for the speed of upper mantle and subhorizontal P wave rays in the Hikurangi plateau, regardless of azimuth, is 8.85 ± 0.2 km/s.

**Upper mantle P-wave speeds beneath SAHKE 01 with OBS gathers**

High upper-mantle P wave speeds are observed from gathers of seismic arrivals recorded by ocean bottom seismometers (OBS) for the offshore south-eastern part of SAHKE 01 line [12], (Fig. 1b). A multi-channel seismic reflection profile was shot along the SAHKE 01 line and the interpretation of that [40] was used to constrain the crustal structure of our interpretation (Fig. 2b). The MCS data show the top of the Pacific plate at about 10 km beneath the sea floor but cannot resolve structure beneath that. OBS gathers 14 and 15 (Fig. S5) were shot in opposed directions, which gives control on the dip of interfaces, but not necessarily on overlapping segments. OBS 14 and 15 are shown at reduction speeds of 6 and 8 km/s respectively (Fig. S5). Both gathers show a triplication in the travel time branches at an offset of ~60 km from the OBS, which is typical of a thin, medium-speed, layer sandwiched between a slower and faster layer [37]. A simple 2D ray tracing solution (Fig. 2b), using the bathymetry and upper sedimentary structure[40], shows the data are consistent with a regular Moho at about 24 km depth beneath a thin (3.5 km) layer of high speed (7.4-7.6 km/s) lower crust (Fig. S6a). However, we could also change the thin layer P-wave speeds to be 8-8.1 km/s (i.e. regular upper mantle speed) and get
the same fit. This latter interpretation, of regular mantle P-wave speeds overlying faster ones, would be in line with that of Chadwick (Fig. S2). We tried fits with \( P_n \) speeds that varied from 8 to 9.2 km/s to the OBS 14 data (Fig. S7b, c, d, e) and the best fit is a P-wave speed of 8.8 ± 0.2 km/s, with a vertical speed gradient of 3.75 x10^{-3} s^{-1}. The uncertainty in \( P_n \) is because the section of \( P_n \) pics only occurs on a short segment about 40 km long.

**Upper mantle polarisation of S-waves at the Hikurangi margin**

Earthquake # 3511915 generated clear S-waves. We found the optimal display for these data is in the band-pass range of 0.1-4 Hz (Fig. S4). We also applied static corrections for elevation and then plotted against trace number (Fig. 2e). We identify various phases. The slowest we interpret as S-waves that have travelled in the oceanic crust. Arrivals for a faster S-wave indicates an apparent speed 5.7 km/s. We also identify an even faster, and much weaker, S-wave phase with an apparent speed ~ 6.6 km/s with arrivals that can only be traced to kilometre 33 along the profile.

Ray tracing, using the same subduction zone structure as our P-wave model, but with velocities reduced to appropriate S-wave speeds, indicates that the faster phases have travelled in the upper mantle with true speeds of 5.1 and 4.65 km/s, and uncertainties of ± 0.15 km/s (Fig. 2d). We interpret these two phases as the horizontally polarised \( S_H \) (5.1 km/s) and the vertically polarised \( S_V \) (4.65 km/s) The wave speeds are consistent with those predicted for the AG fabric, as discussed in the main text (Fig. S1). A feature of the S-wave seismogram is the dominance in amplitude of the \( S_V \) phase over that of the \( S_H \) phase at all offsets (Fig. S6). This could represent a dominance of \( S_V \) in the earthquake source or that the dominate energy is created by a converted P to \( S_V \) at a regular interface near the source[37]. \( S_H \) energy cannot be traced east of km 33 where layered shallow sedimentary sequences would be predicted to selectively attenuate \( S_H \) energy that would be coming to the surface at a high angle[22].

We also checked our interpretation of \( S_V \) and \( S_H \) by rotating the seismogram data from the field orientations into the transverse and radial components with respect to the azimuth of the ray path to the seismic stations (Fig. S6). The first arrivals on the transverse component become sharper in the offset range of 3-18 km, which is consistent with the first arrivals being \( S_H \). But beyond
offsets of 35 km, the radial component becomes sharper and stronger and this is consistent with our interpretation that $S_v$ is more dominant at these distances. In reality we can expect both $S_v$ and $S_h$ on all three components as both the source and ray path through the crust will have complexities, such as crustal anisotropy, which will cause $S_v$ and $S_h$ to be seen on all three components.

A check on the validity of our S-wave anisotropy analysis is to measure the splitting times at a well-determined point along the ray. The best locality for this is at about km 33 where there is a 1 s split (Fig. S6 and Fig. 2e, f). The relationship between this split-time ($\Delta t$) and the vertical ($S_v$) and horizontal ($S_h$) shear wave speeds ($V_{Sv}$ and $V_{Sh}$), given the length of travel path in the mantle is ($\Delta x$) is:

$$\Delta t = \Delta x \left( \frac{1}{V_{Sv}} - \frac{1}{V_{Sh}} \right) \quad (3).$$

For $S_h = 5.1 \text{ km/s}$ (see above), then $V_{Sv} = 4.65 \text{ km/s}$, and $\Delta t = 1 \text{s}$, and the predicted travel distance ($\Delta x$) in the mantle is 52 km. From our ray tracing model (Fig. S8) the total travel path for arrivals at kilometre 33 is 63 km. This would imply $V_{Sh}$ is 5.02 km/s to satisfy equation 3, well within the $\pm 0.15 \text{ km/s}$ uncertainty of our estimate of $V_{Sh}$.

**P-wave speeds in the Manihiki Plateau**

The crustal structure of the Manihiki plateau was investigated in 2012 with active source seismic profiling along two ~ 450 km-long lines[23, 41] (Fig. S8a). Although the published interpretations focus on the crustal, rather than mantle, structure[23], the OBS receiver gathers reveal high apparent P-wave speeds in the upper mantle of the Manihiki plateau (Fig. S8). We examined 60 gathers[41], identifying $P_n$ phases on 33 of them where the apparent wave speed is $> 8.2 \text{ km/s}$. These results are summarised in Table S1, where we tabulate average apparent $P_n$ speeds for each line. Although the averages for the two lines are roughly the same (8.86 and 8.77 km/s for lines 0100 and 0200 respectively), the standard deviations of the estimates vary between the two lines (0.42 km/s for line 100, and 0.26 km/s for line 0200). This difference is likely to be an effect of the markedly smoother ocean floor along line 0200, compared to that along line...
Irregularities in the ocean floor would be predicted to introduce noise due to scattering of seismic energy, giving rise to increased uncertainty in estimates of apparent wave speed.

For seismic refraction lines were the source and receiver positions are reversed, then the true wave speed is close to the average of the two apparent wave speeds from opposing directions. We use this property to better define the true wave speeds on each line by selecting pairs of $P_n$ apparent wave speeds that are measured in opposing directions and are spaced at the appropriate distance such that the $P_n$ waves, from different directions, are sampling the same part of the upper mantle. This way, we identify 9 pairs of data for each line, and their results are summarised in Table S1. The true $P_n$ estimates (with standard error, assuming true speed is the same for all pairs) are now $8.86 \pm 0.1$ and $8.77 \pm 0.03$ km/s for lines 0100 and 0200 respectively.

We made a simple ray tracing model of the OBS gathers at stations 7, 15, 23 and 29 for line 0200 (Fig. S9). $P_n$ is seen as first breaks on all gathers, constraining the $P_n$ speed to be $8.9 \pm 0.1$ km/s, for a crustal thickness that varies between 24 and 27 km. We also plotted the travel time curves for $P_n$ wave speeds of 8.3, 8.5, 8.9 and 9.2 km/s, calculated for the OBS #29 gather (Fig. S9). Our visual best fit upper mantle $P$ wave speed for subhorizontal rays is $8.9 \pm 0.1$ km/s., identical within error to those determine along line 0100, and in the Hikurangi Plateau (Fig. 2a).

**Plume Model**

We solve Stokes equation in 3-D for a spherical buoyancy anomaly at depth, which develops into an axisymmetric plume, rising and spreading out beneath the lithosphere under gravity. We non-dimensionalise and simplify the equations under the assumption of cylindrical symmetry, valid when the plume ascent rate is greater than any surface plate motions. This reduces the number of dimensions in the computational model to 2, whilst producing a solution which is strictly equivalent to the 3-D axisymmetric case. We consider both end member cases for the near surface boundary condition, with either a melt layer at the top of the plume (i.e. free slip), or a rigid zero-displacement boundary condition. As this is a dynamic model we do not need to assume any internal boundary conditions in the mantle, such as those required by kinematic models [29], which *a priori* enforce a Poiseuille flow regime. All quantities scale with the layer.
thickness, L, and the buoyancy flow timescale, \( \tau \), representing the e-fold time for a mantle instability to evolve [42]:

\[
\tau = \frac{\eta}{\Delta \rho g L}
\]

(4)

And \( \tau = t/t' \) where \( t \) is absolute time and \( t' \) is dimensionless time. For the model of Fig. 1a & b \( t' = 80 \) and \( 300 \), respectively. Thus for adopted values of \( \eta = 1 \times 10^{20} \) Pa s, \( \Delta \rho = 30 \) kg/m\(^3\) and \( L = 1 \times 10^6 \) m, the respective time steps are 1 and 4.4 my.

We assume a Newtonian rheology, as we are interested in the long-time behaviour of the system. The finite-element Lagrangian ‘particle-in-cell’ code Underworld is used to solve the Stokes equation, assuming incompressibility. Under the axisymmetric assumption, a Cartesian mesh (co-ordinates: radial distance from plume centre, and depth) is used with model domain length to height ratios of 4:1, and a uniformly spaced element resolution of 1024×256. Each element is populated with at least 32 particles, representing a maximum particle spacing of 2km.

We tested plume head collapse in an analogue model using “silly putty”; this is also effectively a test of the role of rheology because silly putty has a non-Newtonian viscosity, whereas our numerical simulations were for a Newtonian fluid. The experiments were performed at room temperature on a flat formica surface for silly putty surrounded by air. Photographs were taken using a Canon EOS 60D equipped with an EF100mm f/2.8L Macro lens and Speedlight 580EX II; ISO 200 with 1/10 second exposure at f/16. Underlying graph has 1mm grid spacing. Time-lapse video produced with time dilation factor of 60 (I.E. 1 second per minute) (Movie S1).

The analogue model replicated the late stage flow patterns in the numerical models, indicating that gravitational collapse is a robust feature of plume head evolution, independent of rheology.
Figure Captions

Figure S1. Seismic properties of AG fabric in an aggregate of olivine (Fo90) at uppermost mantle conditions | Spheres orientated with Z vertical, and X, Y horizontal, defining AG fabric. Colours show seismic properties where ray intersects sphere. Red and black bars show vibration directions. Calculations for spheres are described in Methods for P = 20 kbars and T = 1100°C.

Figure S2. Upper mantle P-wave speeds at the Hikurangi margin | (a) Map of eastern North Island, New Zealand, showing location and results of seismic studies, with arrows indicating direction of profiling. NW-SE orientated arrows are published results using earthquake seismic sources from [16, 17]. Active source survey of Chadwick (1997)[15] is shown by the double headed red arrow, with results in inset (b). Two P-wave speed determinations on the NW-SE orientated line at south end of North Island are based on this study.

Figure S3. Effect of dip on refracted ray arrivals | (a) Simple model of refracted ray path for a wave travelling up-dip along a layer with a dip = theta. The apparent wave speed that is measure is called V_{2up} because its shooting up dip. Resolution of the true value of V_2 is via Methods equation 2 and the main plot shows the result of this equation where V_2 is plotted against dip of the half space. (b) Three curves for different values of the average speed in the upper (crustal) V_1 layer for 5.5 (red line), 5.7 km/s (black line) and 5.9 km/s (blue line). V_1=5.7 km/s is the average weighted speed of the overlying crust used in this study for ray tracing model. Dashed box shows sensitivity of upper mantle P wave speeds (V_2) to dip of interface, ranging between 8.7 and 9.1 km/s (for V_1=5.7 km/s), given dips between 8° and 10°.

Figure S4. Seismic arrivals along SAHKE 04 line for Geonet earthquake#3511915, plotted as reduced travel time for a velocity of 8 km/s | (a) Data resolved into vertical, horizontal radial and transverse components with respect to earthquake epicentre. Note strong P and S waves on all components and the splitting of the S-wave into a fast and slow component, most visible in the transverse component. Mantle P and S wave velocities are typical of AG fabric in forsterite-rich olivine fabric, with best-fit true seismic velocities: mantle P wave (green dashed lines and green arrows) = 8.9 km/s; mantle fast S wave (Sh), red dashed lines and red arrows) =
5.1 km/s; mantle slow S wave (SV, blue dashed lines and blue arrows) = 4.6 km/s; crustal S wave phases <4 km/s (pink dashed lines and pink arrows).

**Figure S5. OBS receiver gathers 14 and 15 from the SAHKE 01 line** | The high P-wave speed upper mantle phases can be seen at offsets > 60 km on both lines (red arrows). Ray-tracing interpretation models are shown in Fig. 2.

**Figure S6. Sensitivity tests of upper mantle P wave speed for OBS 14 receiver gather data** | (a) Simple velocity model for crust and upper mantle beneath OBS 14 (see Fig. 1 for location), showing various P wave arrivals, including Pn which has been refracted in uppermost mantle. (b) to (e) Observed and model picks for models with upper mantle P wave speed ranging between 8 km/s and 9.2 km/s. Best fit model has an upper mantle P wave speed in range 8.8 - 8.9 km/s. (f) Best fit velocity model based on ray tracing for SAHKE 01 derived from gathers for airgun seismic sources for OBS 14 and 15.

**Figure S7. S waves in mantle across subducted edge of Hikurangi Plateau (SAHKE 04 line)** | (a) Diagram illustrating how subhorizontal S wave ray generated by earthquake is split into fast horizontal and slow vertical components because of strong upper mantle radial anisotropy. (b) Model showing earthquake seismic rays for crustal and mantle S wave speed structure (see model fits in Fig. 2d).

**Figure S8. Seismic profiling of Manihiki Plateau** | (a) Location map for the Manihiki Plateau (Fig.1) showing active source seismic lines 0100 and 0200 with location of Ocean Bottom Seismometers (OBS) used in this study (white circles and bold red numbers), from Hochmuth (2015) and Hochmuth et al. (2014). (b) Data from line 0100 for OBS #12 plotted at reduced speed of 8 km/s. High speed phase of ~ 8.9 km/s is indicated by red arrows. (c) As in (b) but for OBS 25. (d) As in (b) but for OBS 7 on line 0200. (e) As in (b) but for OBS 29 on line 0200.

**Figure S9. Ray tracing model for Line 0200 across Manihiki Plateau** | (a) Ray tracing model. (b) Arrival times at Ocean Bottom Seismometers (OBS) #7, #15, #23, #29 show excellent fits for a subhorizontal mantle P wave velocity of 8.9 km/s, consistent with that predicted by an olivine
AG fabric. (c) Sensitivity test for upper mantle picks for OBS 29 for a range of P wave velocities. Crosses show picks and lines show model arrival times.

**Figure S10. Numerical simulation of a mantle plume with free top.** (a) and (b) show cut away images of the plume surface derived from a numerical model at time intervals t= 1 and 4.4 Myr (for a length scale L=1000 km and viscosity $1 \times 10^{20}$ Pa s, see methods). The translucent hemisphere at the base represents the locus of the initial buoyant plume material at the base of the mantle for t = 0; the dashed white ellipse shows the horizontal extent of the plume head, and solid ellipses the model boundaries. Note that in the later stage (b) the material flux in the plume tail has ceased (dashed yellow line) and the plume head is collapsing and compacting under gravity. Boxes c and d illustrate a plan-view of the maximum horizontal shear-strain rate at the top of the plume head ($z = 0.99L$), which for $L = 1000$ km is 10 km from top of plume-head. Crossed blue arrows indicate principal axes of horizontal strain rate, and vertical dimensions are in normalised units. Dashed white circles corresponds to the horizontal extend of the plume head, and ellipses in (a) and (b). Dashed reference circles are introduced at 1 Myr at radial positions of 0.2L (red) and 0.9 L(green) from centre of plume in (c), tracked to 4.4Myr. In (d) the original (dashed) and tracked (solid) circles are shown in their new positions. A reference circle placed off-axis and away from the edge of the plume shows uniform strain such that the circle grows as a circle and shows negligible shear strain. This property is maintained over most of the area of the plume head except at its edge as shown by the axes shear strain rate.

**Figure S11. Numerical simulation of a mantle plume head with free top.** (a) and (b) Plan view showing maximum horizontal shear strain rate and dilatation, respectively, at the top of the plume head at end of simulation. Crossed arrows in (a) indicate principal axes of horizontal strain rate, and grey vectors in (b) indicate flow direction and magnitude. (c) and (d) Cross-sectional view showing total radial and vertical strains, respectively, during simulation. Horizontal and vertical dimensions are in normalised units.

**Figure S12. Numerical simulation of a mantle plume head with fixed top boundary** | (a) and (b) Plan view showing maximum horizontal shear strain rate and dilatation, respectively, at the top of the plume head at end of simulation. Crossed arrows in (a) indicate principal axes of
horizontal strain rate, and grey vectors in (b) indicate flow direction and magnitude. (c) and (d) Cross-sectional view showing total radial and vertical strains, respectively, during simulation. Horizontal and vertical dimensions are in normalised units.

Table S1. Shallow mantle p-wave speeds beneath Manihiki Plateau

Movie S1 – Time-lapse silly putty experiment
AG fabric in Olivine Aggregate (Fo90)

Fig. S1. Seismic properties of AG fabric in an aggregate of olivine (Fo90) at uppermost mantle conditions | Spheres orientated with Z vertical, and X, Y horizontal, defining AG fabric. Colours show seismic properties where ray intersects sphere. Red and black bars show vibration directions. Calculations for spheres are described in Methods for P = 20 kbars and T = 1100°C.
Fig. S2. Upper mantle P-wave speeds at the Hikurangi margin | (a) Map of eastern North Island, New Zealand, showing location and results of seismic studies, with arrows indicating direction of profiling. NW-SE orientated arrows are published results using earthquake seismic sources from Brisbourne and Stuart (1998), Galea (1992), Kayal and Smith, (1984). Active source survey of Chadwick (1997) is shown by the double headed red arrow, with results in inset (b). Two P-wave speed determinations on the NW-SE orientated line at south end of North Island are based on this study.
Fig. S3. Effect of dip on refracted ray arrivals (a) Simple model of refracted ray path for a wave travelling up dip along a layer with a dip = theta. The apparent wave speed that is measure is called $V_{2up}$ because its shooting up dip. Resolution of the true value of $V_2$ is via Methods equation 2 and the main plot shows the result of this equation where $V_2$ is plotted against dip of the half space. (b) Three curves for different values of the average speed in the upper (crustal) $V_1$ layer for 5.5 (red line), 5.7 km/s (black line) and 5.9 km/s (blue line). $V_1=5.7$ km/s is the average weighted speed of the overlying crust used in this study for ray tracing model. Dashed box shows sensitivity of upper mantle P wave speeds ($V_2$) to dip of interface, ranging between 8.7 and 9.1 km/s (for $V_1=5.7$ km/s), given dips between 8° and 10°.
Fig. S4. Seismic arrivals along SAHKE 04 line for Geonet earthquake#3511915, plotted as reduced travel time for a velocity of 8 km/s | (a) Data resolved into vertical, horizontal radial and transverse components with respect to earthquake epicentre. Note strong P and S waves on all components and the splitting of the S-wave into a fast and slow component, most visible in the transverse component. Mantle P and S wave velocities are typical of AG fabric in forsterite-rich olivine fabric, with best-fit true seismic velocities: mantle P wave (green dashed lines and green arrows) = 8.9 km/s; mantle fast S wave (S_H, red dashed lines
Fig. S5. OBS receiver gathers 14 and 15 from the SAHKE01 line | The upper mantle phases with high P-wave speeds can be seen at offsets > 60 km on both lines. Note that reduction velocities for plotting data are 6 and 8 km/s for OBS #15 and #14 respectively. Phase interpretation is as follows: 
Pn = upper mantle refracted phase; PmP = upper mantle wide angle reflection; Plc = lower crust refraction; Poc = oceanic crust refraction; PocP= wide angle reflection from oceanic crust. Ray-tracing interpretation models are shown in Fig. 2.
Fig. S6. Sensitivity tests of upper mantle P wave speed for OBS 14 receiver gather data

(a) Simple velocity model for crust and upper mantle beneath OBS 14 (see Fig. 2 for location), showing various P wave arrivals, including Pn which has been refracted in uppermost mantle. (b) to (e) Observed and model picks for models with upper mantle P wave speed ranging between 8 km/s and 9.2 km/s. Best fit model has an upper mantle P wave speed in range 8.8 - 8.9 km/s. (f) Best fit velocity model based on ray tracing for SAHKE 01 derived from gathers for airgun seismic sources for OBS 14 and 15.
Fig. S7. S waves in mantle across subducted edge of Hikurangi Plateau (SAHKE 04 line) | (a) Diagram illustrating how subhorizontal S wave ray generated by earthquake is split into fast horizontal and slow vertical components because of strong upper mantle radial anisotropy. (b) Model showing earthquake seismic rays for crustal and mantle S wave speed structure (see model fits in Fig. 2d).
Fig. S8. Seismic profiling of Manihiki Plateau | (a) Location map for the Manihiki Plateau showing active source seismic lines 0100 and 0200 with location of Ocean Bottom Seismometers (OBS) used in this study (white circles and bold red numbers), from Hochmuth (2015) and Hochmuth et al. (2014). (b) Data from line 0100 for OBS #12 plotted at reduced speed of 8 km/s. High speed phase of ~ 8.9 km/s is indicated by red arrows. (c) As in (b) but for OBS 25. (d) As in (b) but for OBS 7 on line 0200. (e) As in (b) but for OBS 29 on line 0200
Fig. S9. Ray tracing model for Line 0200 across Manihiki Plateau | (a) Ray tracing model. (b) Arrival times at Ocean Botton Seismometers (OBS) #7, #15, #23, #29 show excellent fits for a subhorizontal mantle P wave velocity of 8.9 km/s, consistent with that predicted by an olivine AG fabric. (c) Sensitivity test for upper mantle picks for OBS 29 for a range of P wave velocities. Crosses or vertical bars (±0.1 s) show picks, and lines show model arrival times.
**Fig. S10. Numerical simulation of a mantle plume with a free top.** (a) and (b) show cut away images of the plume surface derived from a numerical model at time intervals t = 1 and 4.4 Myr (for a length scale L=1000 km and viscosity 1x 10^20 Pa s, see methods). The translucent hemisphere at the base represents the locus of the initial buoyant plume material at the base of the mantle for t = 0; the dashed white ellipse shows the horizontal extent of the plume head, and solid ellipses the model boundaries. Note that in the later stage (b) the material flux in the plume tail has ceased (dashed yellow line) and the plume head is collapsing and compacting under gravity. Boxes c and d illustrate a plan-view of the maximum horizontal shear-strain rate at the top of the plume head (z =0.99L), which for L = 1000 km is 10 km from top of plume-head. Crossed blue arrows indicate principal axes of horizontal strain rate, and vertical dimensions are in normalised units. Dashed white circles correspond to the horizontal extend of the plume head, and ellipses in (a) and (b). Dashed reference circles are introduced at 1 Myr at radial positions of 0.2L (red) and 0.9 L(green) from centre of plume in (c), tracked to 4.4Myr. In (d) the original (dashed) and tracked (solid) circles are shown in their new positions. A reference circle placed off-axis and away from the edge of the plume shows uniform strain such that the circle grows as a circle and shows negligible shear strain. This property is maintained over most of the area of the plume head except at its edge as shown by the axes shear strain rate.
Fig. S11. Numerical simulation of a mantle plume head with free top. | (a) and (b) Plan view showing maximum horizontal shear strain rate and dilatation, respectively, at the top of the plume head at end of simulation. Crossed arrows in (a) indicate principal axes of horizontal strain rate, and grey vectors in (b) indicate flow direction and magnitude. (c) and (d) Cross-sectional view showing total radial and vertical strains, respectively, during simulation. Horizontal and vertical dimensions are in normalised units.
Fig. S12. Numerical simulation of a mantle plume head with fixed top boundary (a) and (b) Plan view showing maximum horizontal shear strain rate and dilatation, respectively, at the top of the plume head at end of simulation. Crossed arrows in (a) indicate principal axes of horizontal strain rate, and grey vectors in (b) indicate flow direction and magnitude. (c) and (d) Cross-sectional view showing total radial and vertical strains, respectively, during simulation. Horizontal and vertical dimensions are in normalised units.
Table S1. Shallow mantle P-wave speeds beneath Manihiki Plateau

|                              | Line 0100 | Line 0200 |
|------------------------------|-----------|-----------|
| Number of observations      | 18        | 15        |
| Apparent speed (km/s)       | 8.79      | 8.75      |
| Standard deviation (km/s)   | 0.4       | 0.26      |
| Standard error (km/s)       | 0.1       | 0.07      |
| Number of reversed pairs    | 9         | 9         |
| Apparent speed (km/s)       | 8.86      | 8.77      |
| Standard deviation (km/s)   | 0.3       | 0.07      |
| Standard error (km/s)       | 0.1       | 0.03      |