Supplementary Materials for

Wide-angle seismic reflections reveal a lithosphere-asthenosphere boundary zone in the subducting Pacific Plate, New Zealand

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Fig. S1.
Complete onshore-offshore gathers at (a) BFZ station and (b) MRZ station with the airgun shots of SAHKE01 line, and (c) MRZ station with the airgun shots of PEGASUS23 line. Synthetic travel-times for the refraction in the oceanic crust ($P_o$), wide-angle reflection from the Moho ($P_{m1}P$) and upper mantle refraction beneath the Moho ($P_{n1}$) are shown. Black crosses indicate the pick arrivals of $R_0$-$R_3$ reflections.
Fig. S2.
Instantaneous frequency attribute of the common receiver gather at BFZ station with SAHKE01 airgun sources. The interpreted arrivals of $R_0$-$R_3$ reflections are denoted by black crosses and labelled.
Fig. S3.
Instantaneous frequency attribute of common receiver gather at MRZ station with SAHKE01 airgun sources. The interpreted arrivals of $R_0$-$R_3$ reflections are denoted by black crosses and labelled.
Fig. S4.
Projected travel-times of $R_0$ (observed) at BFZ station with the airgun shots of SAHKE01 line and $P_{m1}P$ (calculated) at zero offset using a parabolic fit. The difference in travel-time at zero offset between calculated $P_{m1}P$ and observed $R_0$ is about 11.19 sec. This time difference translates into a depth of about 47 km between the Moho and $R_0$, (absolute depths of about 74 km). Depth of Moho at zero offset ≈27 km. Average $V_P$ between the Moho and $R_0$ is assumed to be 8.4 km/s
Fig. S5.
Travel-time curves for P-wave reflections from velocity discontinuities. In (a)-(d), on the left, one dimensional P-wave velocity models are shown. On the right, travel-time curves for the reflections at the velocity discontinuities in the one-dimensional P-wave velocity models are shown. Incident angles indicate the angle of incidence of the raypaths with offset at each discontinuity. Our preferred model that best explains the travel-times of $R_0$-$R_3$ reflections is (c).
Fig. S6.
2D isotropic P-wave velocity and ray trace model of the wide-angle reflections at MRZ station with SAHKE01 airgun sources. (a) P-wave velocity model and traced raypaths in 2D for the observed wide-angle reflections and refractions recorded at MRZ station with the airgun sources of SAHKE01 line (Fig. 2f). (b) Travel-time picks of the phases observed in Fig. 2f color-coded as in (a). Height of an observed travel-time pick is twice the pick uncertainty. Calculated travel-times are in black. Note that the travel-time axis is reduced with a velocity of 8.0 km/s.
Fig. S7.
Perturbation test results for the uncertainty in the depth to the $R_0$ reflector observed in the common receiver gather at BFZ station from the airgun sources of SAHKE01 line (Fig. 2a). CI=confidence interval.

Fig. S8 - S19.
Synthetic common receiver gathers of $R_0$ and $R_1$ reflections for 2, 3 and 4 km thicknesses, different elastic tensors defining the anisotropic medium in the layer between them and rotation angles (azimuths) of the elastic tensor about the vertical axis. $V_{PX}$ is the P-wave velocity along the azimuth given by Azi, $V_{PY}$ is the P-wave velocity along the direction perpendicular to Azi in the horizontal plane, $V_{PZ}$ is the P-wave velocity along the vertical direction. Green circles indicate the travel-time picks and the green shading indicate the travel-time pick errors (0.2 sec) of $R_0$ and $R_1$ phases. These plots are visually inspected for the merging nature of $R_0$ and $R_1$ reflections at offsets of 190-200 km and their separation at offsets < 190 km to estimate the uncertainties in the estimated layer thickness, anisotropy and fast azimuth. Our estimated trade-offs are 2-4 km in thickness, 9.3-9.6 km/s in the velocity along an azimuth of 322°-342°. Note that beyond offsets > 200 km, changes in water depth and velocities of the top sediments (of the Chatham Rise) are expected to result in the delayed travel-times, but the calculated travel-times would be earlier because of the higher P-wave velocities adopted for the entire layer (Fig. 5a).
Fig. S8.
Fig. S9.

Layer between R0 and R1
Thickness: 2 km, Vpx: 9.48 km/s, Vpy: 8.54 km/s, Vpz: 8.37 km/s

Azimuth: 322°

Azimuth: 332°

Azimuth: 342°

Azimuth: 352°

Offset [km]
Fig. S10.

Layer between R0 and R1
Thickness: 2 km, Vpx: 9.35 km/s, Vpy: 8.54 km/s, Vpz: 8.46 km/s

Azimuth: 322°

Azimuth: 332°

Azimuth: 342°

Azimuth: 352°
Fig. S11.
Layer between RO and R1
Thickness: 3 km, Vpx: 9.73 km/s, Vpy: 8.54 km/s, Vpz: 8.18 km/s

Azimuth: 322°

Azimuth: 332°

Azimuth: 342°

Azimuth: 352°

Fig. S12.
Layer between RO and R1
Thickness: 3 km, Vpx: 9.48 km/s, Vpy: 8.54 km/s, Vpz: 8.37 km/s

Azimuth: 322°

Azimuth: 332°

Azimuth: 342°

Azimuth: 352°

Fig. S13.
Layer between RO and R1

Thickness: 3 km, Vpx: 9.35 km/s, Vpy: 8.54 km/s, Vpz: 8.46 km/s

Azimuth: 322°

Azimuth: 332°

Azimuth: 342°

Azimuth: 352°
Layer between RO and R1
Thickness: 3 km, Vpx: 9.28 km/s, Vpy: 8.52 km/s, Vpz: 8.44 km/s

Azimuth: 322°

Azimuth: 332°

Azimuth: 342°

Azimuth: 352°

Fig. S15.
Layer between RO and R1
Thickness: 4 km, Vpx: 9.73 km/s, Vpy: 8.54 km/s, Vpz: 8.18 km/s

Azimuth: 322°

Azimuth: 332°

Azimuth: 342°

Azimuth: 352°

Fig. S16.
Layer between RO and R1
Thickness: 4 km, Vpx: 9.48 km/s, Vpy: 8.54 km/s, Vpz: 8.37 km/s

Azimuth: 322°

Azimuth: 332°

Azimuth: 342°

Azimuth: 352°

Fig. S17.
Fig. S18.
Fig. S19.
Fig. S20.

Isotropic and anisotropic P-wave reflection coefficients versus incident angles for (a) R₀, (b) R₁, (c) and (d) R₂ for two impedances of the layer below R₂ and (e) and (f) R₃ for two impedances of the layer above R₃ corresponding to (c) and (d). P-wave velocity (Vₚ), S-wave velocity (Vₛ), velocity ratio (Vₚ/Vₛ), density (ρ), and Thomsen’s parameters δ and ε for each layer are given in the table above each plot. Green shade indicates the range of incident angles for each wide-angle reflected phase obtained from raytracing.
Isotropic P-wave reflection coefficients versus incident angles for R\textsubscript{1} reflection with varying $V_P/V_S$ ratios for the layer below R\textsubscript{1}. Isotropic P-wave reflection coefficients versus incident angles for R\textsubscript{1} reflection with varying $V_P/V_S$ ratios for the layer below R\textsubscript{1}. Layer above R\textsubscript{1} has a P-wave velocity of 9.3 km/s, S-wave velocity of 5.3 km/s and a density of 3300 kg/m\textsuperscript{3}. Layer below R\textsubscript{1} has a P-wave velocity of 7.6 km/s and a density of 3100 kg/m\textsuperscript{3}. Gray shade indicates the range of incident angles for R\textsubscript{1} wide-angle reflected phase obtained from raytracing. Note that the positive polarity of the first break of R\textsubscript{1} can be explained for $V_P/V_S$ ratios $> 2.8$ for the layer below R\textsubscript{1}.

Fig. S21.
Fig. S22.
Grid search for density, P-wave velocity ($V_P$) and $V_P/V_S$ ratio of the layer below $R_1$ reflector for the selected incident angles within the range of incident angles from raytracing ($52^\circ$ to $72^\circ$) that can explain the positive polarity of its first break. Note that the positive reflection coefficients result only for $V_P/V_S$ ratios $\geq 2.8$. 
Fig. S23.
2D isotropic P-wave velocity ray trace model of the wide-angle reflections at MRZ station with PEGASUS23 airgun sources. (a) P-wave velocity model and traced raypaths in 2D for the observed wide-angle reflections and refractions recorded at MRZ station with the airgun sources of PEGASUS23 line (Fig. 2g). (b) Travel-time picks of the phases observed in Fig. 2g color-coded as in (a). Height of an observed travel-time pick is twice the pick uncertainty. Calculated travel-times are in black. Note that the travel-time axis is reduced with a velocity of 8.0 km/s.
Fig. S24.

Grid search test results for the P-wave speed ($V_P$) and the thickness of the layers in between (a) $R_1$ and $R_2$, and (b) $R_2$ and $R_3$. White lines indicate root mean square travel-time misfit ($T_{RMS}$) contours. Yellow arrow indicates the maximum possible uncertainty in $V_P$ and thickness. Green stars indicate P-wave velocity and thickness combinations used for raytracing and AVO modelling in Fig. S20.
Fig. S25.
Grid search for density, P-wave velocity ($V_P$) and $V_P/V_S$ ratio of the layer below R2 reflector for the selected incident angles within the range of incident angles from raytracing (40° to 50°) that can explain the negative polarity of its first break. Note that the negative reflection coefficients result for $V_P/V_S$ ranging from $\approx 1.8$ to $\approx 2.6$. 
**Fig. S26.**

2D isotropic P-wave velocity ray trace model of the wide-angle reflections at BFZ station with SAHKE01 airgun sources. (a) P-wave velocity model and traced raypaths in 2D for the observed wide-angle reflections and refractions recorded at BFZ station with the airgun sources of SAHKE01 line (Fig. 2a). Note the low P-wave velocity layer \( (V_P=8.3 \text{ km/s}) \) just above \( R_0 \) reflector compared to the same model in Fig. 4. (b) Travel-time picks of the phases observed in Fig. 2a color-coded as in (a). Height of an observed travel-time pick is twice the pick uncertainty. Calculated travel-times are in black. Note that the travel-time axis is reduced with a velocity of 8.0 km/s. (c) Enlarged section of P-wave velocities of the region shown by the black, dashed rectangle in (a).
Fig. S27.
2D isotropic P-wave velocity ray trace model of the wide-angle reflections at BFZ station with SAHKE01 airgun sources. (a) P-wave velocity model and traced raypaths in 2D for the observed wide-angle reflections and refractions recorded at BFZ station with the airgun sources of SAHKE01 line (Fig. 2a). Note the low P-wave velocity layer ($V_P=8.3$ km/s) just above $R_0$ reflector compared to the same model in Fig. 4, and the relatively low P-wave velocity ($V_P=9.0$ km/s) in the anisotropic layer. (b) Travel-time picks of the phases observed in Fig. 2a color-coded as in (a). Height of an observed travel-time pick is twice the pick uncertainty. Calculated travel-times are in black. Note that the merging nature of $R_0$ and $R_1$ reflections is less prominent here when compared with Figs. 4 and S26. Travel-time axis is reduced with a velocity of 8.0 km/s. (c) Enlarged section of P-wave velocities of the region shown by the black, dashed rectangle in (a).
Fig. S28.
Ray trace test to assess whether $R_0$, $R_1$, $R_2$ and $R_3$ observed in the common receiver gather at BFZ with the airgun sources of SAHKE01 line (Fig. 2a) could be explained as peg-leg multiples of the $P_{n2}$ upper mantle refracted phase between prominent reflectors within the sedimentary section. (a) Structure and raypath diagram. Blue rectangle indicates the extents of (b). (b) Zoomed section of the depth converted multichannel seismic reflection image along SAHKE01 showing the two prominent reflectors A and B in the sedimentary section. (c) Observed (color-coded as in (a) and (b)) and calculated travel-times (black).
Ray trace test to assess whether $R_0$, $R_1$, $R_2$ and $R_3$ observed in the common receiver gather at MRZ with the airgun sources of SAHKE01 line (Fig. 2f) could be explained as peg-leg multiples of the $P_{n2}$ upper mantle refracted phase between prominent reflectors within the sedimentary section. (a) Structure and raypath diagram. Blue rectangle indicates the extents of (b). (b) Zoomed section of the depth converted multichannel seismic reflection image along SAHKE01 showing the two prominent reflectors A and B in the sedimentary section. (c) Observed (color-coded as in (a) and (b)) and calculated travel-times (black).
Fig. S30.
Particle motion plots between vertical (Z), radial (R) and transverse (T) components to test if (a) \( P_{n_2} \), (b) \( R_0 \), (c) \( R_1 \), (d) \( R_2 \) and (e) \( R_3 \) are incoming shear waves into BFZ from the airgun sources of SAHKE01 line. Particle motion corresponds to the trace at the center of each rectangle within a time window of 400 msec (shown by the height of each rectangle).
Fig. S31.
Particle motion plots between vertical (Z), radial (R) and transverse (T) components to test if (a) \( P_{n2} \), (b) \( R_0 \), (c) \( R_1 \), (d) \( R_2 \) and (e) \( R_3 \) are incoming shear waves into MRZ from the airgun sources of SAHKE01 line. Particle motion corresponds to the trace at the center of each rectangle within a time window of 400 msec (shown by the height of each rectangle).
Fig. S32.

(a) Difference in water depth between the original location of the airgun shots along the SAHKE01 line and their projected locations on to the PEGASUS23 line. Note the hump near 200 km model distance is due to the Hikurangi channel. (b) Histogram of the depth differences in (a).
Fig. S33.

(a) Difference in water depth between the original location of the airgun shots along the SAHKE01 line and their projected locations on to the PEGASUS25 line. (b) Histogram of the depth differences in (a).
Table S1.
2D raytracing statistics using RAYINVR for the wide-angle reflections observed in the common receiver gathers shown in Fig. 2 in the main text.

| Phase | MRZ/PEGASUS23 | MRZ/SAHKE01 | BFZ/SAHKE01 |
|-------|---------------|-------------|-------------|
|       | Av. Unc. | N | T_{RMS} | $\chi^2$ | Av. Unc. | N | T_{RMS} | $\chi^2$ | Av. Unc. | N | T_{RMS} | $\chi^2$ |
| $R_0$ | na | na | na | 0.200 | 590 | 0.084 | 0.175 | 0.200 | 741 | 0.202 | 1.021 |
| $R_1$ | 0.200 | 265 | 0.191 | 0.914 | 0.200 | 372 | 0.219 | 1.203 | 0.200 | 654 | 0.132 | 0.435 |
| $R_2$ | 0.200 | 439 | 0.039 | 0.038 | 0.200 | 1112 | 0.141 | 0.496 | 0.200 | 368 | 0.115 | 0.335 |
| $R_3$ | na | na | na | na | 0.200 | 126 | 0.130 | 0.433 | 0.200 | 166 | 0.052 | 0.067 |

Av. Unc. = Average uncertainty in travel-time picks in seconds
N = Number of travel-time picks
$T_{RMS}$ = Root mean square travel-time misfit in seconds
Table S2.
3D raytracing statistics using ANRAY for the wide-angle reflections observed in the common receiver gather at BFZ station with SAHKE01 shots in Fig. 2a in the main text.

| Phase | Av. Unc. | N  | \(T_{\text{RMS}}\) | \(\chi^2\) |
|-------|----------|----|---------------------|---------|
| \(R_0\) | 0.200    | 371 | 0.133               | 0.443   |
| \(R_1\) | 0.200    | 327 | 0.171               | 0.737   |
| \(R_2\) | 0.200    | 184 | 0.188               | 0.891   |
| \(R_3\) | 0.200    | 83  | 0.208               | 1.095   |

Av. Unc. = Average uncertainty in travel-time picks in seconds  
N = Number of travel-time picks  
\(T_{\text{RMS}}\) = Root mean square travel-time misfit in seconds