Supporting Information for “Crustal formation on a spreading ridge above a mantle plume: receiver function imaging of the Icelandic crust”

J. Jenkins¹, J. Maclellan², R. G. Green¹, S. Cottaar², A. F. Deuss³, R. S. White²

¹GeoForschungsZentrum Potsdam, Potsdam, Germany
²Bullard Laboratories, Department of Earth Sciences, University of Cambridge, UK
³University of Utrecht, Netherlands

Copyright 2018 by the American Geophysical Union.
0148-0227/18/$9.00
Contents of this file
1. Text S1 to S6
2. Figures S1 to S17
3. Tables S1 and S2

Additional Supporting Information (Files uploaded separately)
1. Datasets S1 to S9
2. GMT .grd files for datasets S1 to S3

Introduction
This supplementary material contains additional details of methodology discussed in the main text, as well as copies of data files. This includes: an investigation into inversion sensitivity to various factors (Text S1.), details of grid-search set up for simplifying inversion model parameterisation (Text S2.), details of common conversion point (CCP) stacking methodology (Text S3.) and results (Text S4.) as well as a discussion of the velocity models used in RF time-depth conversion and how they effect CCP results (Text S5.). Included data files are: point observations of discontinuity A, point observations of discontinuity B, combined observations used to define the Icelandic crust and corresponding GMT .grd files used to plot the surfaces shown in paper figures. Descriptions of data files are detailed in Text S5.
Text S1. Sensitivity of inversions

To check the robustness of inversion results we test the sensitivity of inversions to a number of factors. We first apply a frequency dispersion weighting of 0.75:0.25. Higher weighting towards dispersion data leads to overly smoothed model results, while greater weighting towards RF data lacks absolute velocity constraints (Figure S3).

We define a constant $V_P/V_S$ velocity of 1.7 in our inversions. This may be considered to be on the lower end of Icelandic $V_P/V_S$ estimates, however tests show that the inversion results are not very sensitive to the $V_P/V_S$ ratio, with the general form of results remaining constant and only slight changes in absolute velocity (Figure S4a).

A density estimate is required for inversion calculations which we define based on $V_P$ estimates using the empirical formula of Berteussen [1977] ($\rho = 0.77 + 0.32V_P$). However, Schlindwein [2006] note that the empirical relationship of Berteussen [1977] yields unrealistic densities for Icelandic rocks in the $V_P$ range 2.8-6.7 km/s. Instead they suggest using the relationship of Carlson and Herrick [1990] which was derived specifically for basaltic rocks, such that $\rho = 3.81 - \sqrt{V_P}$. We test the variability in inversion results obtained using these two different empirical density relationships, the results of which are shown in Figure S4b. Similar to $V_P/V_S$ variation we find that the choice of density relationship causes only small changes in absolute velocity variation, but does not affect the overall shape of velocity profiles.

Previous RF studies use realistic starting models in inversions, while we use simple half space models. However, we find that a given starting model based on the average velocity structure of previous crustal models [Darbyshire et al., 2000; Allen et al., 2002] or surface wave only inversion results, the final inversion result differs little from those obtained from a half space starting model (Figure S4c). Thus our use of half space starting models is justified, since we find similar results as starting from a realistic structure, without the worry of introducing a pre-conceived bias towards a certain structure.

Ambient noise group velocity maps used in the joint inversion are reliable to 16 seconds, but coverage at longer periods was restricted due to path separation limitations. To be certain that the addition of deeper constraints would not affect our imaged discontinuity structure, we preformed a test on the average phase velocity curve of Berteussen and Nicholus and Rychert [2016], between periods of 15 and 95 s. The result of this test is shown in Figure S5a where they are directly compared to results using ambient noise dispersion curve data only in Figure S5b. Models shown in red lines are inverted velocity structure for 50 layer model parameterizations (as an average from 12 different half space starting models), green is velocity structure for a best-fitting 1-discontinuity parameterization and blue shows velocity structure for best-fitting 2-discontinuity velocity structure. The velocity structure resolved, though not identical, is very similar in 50 layered model parameterizations with and without longer period dispersion constraints. More importantly the discontinuity depths identified in our simplified model parameterisations are almost identical. Thus we are confident that future high resolution velocity imaging will not invalidate the discontinuity structure we observe in this study.

All the factors investigated here cause small changes in absolute velocity values in resulting models but do not significantly alter the shape of profiles. Since only $dV/dZ$, rather than absolute velocities of inversion results are directly interpreted in this study, we conclude that the small variations caused by varying these factors is not important to our overall conclusions and interpretations.

Text S2. Grid-search for optimum simplified model parameterisation

We initially parameterise inversion models with fifty 1 km layers. We then attempt to simplify the model parameterisation to define only major interfaces required by the data. We find that the greatest improvement to data fit comes from including the fine scale parameterisation of the high velocity-gradient upper crust in 1 km steps down to 6-10 km. We find that including upper crustal structure generally improves the fit to almost 80% of the 50 layered model fit. Addition of one extra interface below the upper crust increases fit by an average of 5%. For all potential interface depths the fit increase is calculated and the depth of the layer producing the largest increase to fit is identified. This is constrained to be a velocity increase as we are attempting to define the seismic Moho. Figure S6 shows example outputs from this 1-interface grid-search procedure for optimising model parameterisation. Simple cases show one large peak corresponding to a velocity jump which increases the fit to data (Figure S6a). We find that this almost always corresponds to the large velocity jump which is often seen in 50 layer inversion results as a sharp positive gradient at 25 km.

However, a large number of cases show a clear bimodal fit distribution indicating two potential depths where adding an interface representing an increase in velocity with depth improves the fit to data (Figure S6b and c). We define a bimodal pattern as any distribution which shows a second peak in data fit of amplitude $\geq 10\%$ of the amplitude of the maximum peak, where peaks are separated by at least 5 km. In most cases the shallower interface produces a greater improvement to fit than the deeper interface (Figure S6b), though in some models the deeper interface can have a greater impact (Figure S6c).

Depth variation of best fitting 1-interface models is shown in terms of spatial distribution in Figure S7. We observe large variations in the depth of the optimum layer over very short lateral spacings (Figure S7a). This is due to variation as to which of the two potential interface depths found produces the greatest increase to data fit at closely spaced inversion sites. Restricting model results to observations which show no suggestion of a two layered structure removes the areas showing apparently discrepant results, revealing consistent depths between 20-30 km observed in the northern NVZ and in south west Iceland (Figure S7b). For 1-interface models showing a double peaked fit structure, we separate these into those where the shallower peak is dominant (as in Figure S7c) and those where the deeper peak is dominant (as in Figure S7d). These results lead us to the conclusion that in some regions a 2-interface model is required by the data, while in others only 1-interface is required.

Any 1-interface model which indicates the presence of second interface (with a bimodal data fit, or a single station BAZ result showing a deep interface is preferred where all others show a shallower one) is parameterised to allow 2 interfaces below the fine scale parameterisation of the upper crust. The addition of a second interface is only deemed justified if the improvement to the data fit is significant relative to the equivalent 1-interface model. We make this decision based on a reduction in the value of the Akaike Information Criteron (AIC)[Akaike, 1974], which is defined as: $AIC = 2k - 2\ln(L)$, where $k$ is number of parameters and $L$ is model likelihood. The AIC can be used as a measure of the relative likelihood of a pair or group of models, such that a model with a greater AIC value represents a more likely model. Goodness of fit is rewarded based on the model likelihood while increasing number of parameters is penalised. 2-interface models may be expected to produce a reduction in misfit simply because they allow an extra degree of freedom in the model parameterisation. Thus we only accept models where the 2 discontinuity model also reduces the AIC (based on a RMS
misfit to RF data at $> 5s$ where differences between models are observed).

Again to find the best combination of model parameterisations including 2-interfaces beneath the upper crust we perform a large scale grid search over all possible combinations to determine the best fit. Examples of grid searches for the optimum 2-interface parameterisation are shown in Figure S8, with fit matrices describing the suite of generated models and the final best fitting velocity model. Often the best second interface is situated directly beneath the first interface, suggesting the data require a more gradational step there. In some scenarios the best fit layer is just before the step to a half-space, indicating that the model is not well satisfied by the imposed underlying half space velocity. Examples of both these scenarios are shown in the fit matrix of Figure S8c. It is necessary to take such behaviour into account when analysing fit matrix outputs. In some cases the inclusion of a 2-interface model explains discrepancies in previous estimates of crustal thickness, such that each layer describes the predicted crustal thickness of a previously calculated model, as shown in Figure S8b.

A comparison of data/syntheses generated from the resulting modelled velocity structure, is shown in Figure S9, illustrating cases where a two interface model is required to fit major peaks in the RF waveforms. 2-interface models are only required in specific regions: the NW fjords, central Iceland, around Vatnajökull ice cap and Eastern Iceland (Figure S5e), as discussed in the main body of the text.

Text S3. Methodological details of common conversion point stacking

In this study we utilise multi-phase common conversion point (CCP) stacking. This means that initially we create 3 separate CCP stacks, where each stack is time-depth converted assuming it is a Ps, PpPs or PsSs phase and is migrated back along the raypath of that phase (Figure S10abc). Multiple phases (PpPs and PsSs) are only migrated back to the final bounce/conversion point of the raypath where rays turn towards the recording station. In fact, multiples are sensitive to velocity structure across a wider region, from the point they enter the crust, but stacking across this wide region was found to introduce too high a degree of smoothing into the stacks.

Once the 3 CCP stacks have been created they are combined, by stacking together signals that are coherent between them. This is initially done using all 3 phase stacks, but we find that interference from shallow structure appears to mask arrivals in the Ps CCP stacks (Figure S10ad). (For further discussion of this issue and our attempts to address it please see Supplementary text S4). This issue is then propagated into combined stacks, as Ps CCP stacks often do not correspond well to the two multiple CCP stacks (Figure S10d). Thus we choose to merge only the two multiple CCP stacks, which show much greater similarities and less interference from shallow structure as arrivals appear much later and with greater time separation (Figure S10e).

Data smoothing is included in the CCP stack by adding RF amplitudes to all regions within 2 times the ray fresnel zone around the conversion point. Where the fresnel zone is defined as all points within wavelength $\lambda/2$. Amplitudes are weighted dependent on distance from the fresnel zone centre, as defined by the equation: $W = \frac{1}{\Delta^2}$, where $\Delta$ is distance from the centre of the fresnel zone as a fraction of fresnel half width.

This weighting gives values of $\approx 1$ throughout most of the fresnel zone before quickly and smoothly falling away to zero at the edges where unfiltered smoothing gives an image without abrupt changes at the edges of ray fresnel zones. Doubling the size of the fresnel zone increases smoothing, and is deemed reasonable given that multiple phases are in reality sensitive to a larger region than just the fresnel zone around the final conversion/bounce point.

CCP stacking is generally used to migrate RF energy back along the raypath of analysed Ps converted phases. In this study we also employ the technique to migrate back velocity profiles which were created from RF datasets, such that the velocity structure is migrated into the region the data is sensitive to rather than assuming represents a vertical profile directly beneath the recording station.

For CCP stacking of velocity profiles we only migrate back velocity structure along the Ps raypath, and again add across 2 times the fresnel zone. However no weighting is applied across the fresnel zone, unlike for migrated RF. For RF a low weighting at the fresnel zone edge which reduces amplitude values simply implies the presence of less significant structure, which is reasonable since RF are not sensitive to structure in this region. However a low weighting which reduces the value of velocity profile amplitudes suggests that velocities become reduced at the edge of the fresnel zone, which is not the case.

When considering the first derivative of velocity $dV/dz$ it again becomes possible to apply a weighted smoothing across the fresnel zone. By considering $dV/dz$ we reduce velocity structure to a positive or negative value with a reduction in amplitude simply indicating a lack of structure. Accordingly velocity profiles and first $dV/dz$ profiles are migrated in two separate CCP stacks, one with a smoothed weighting across the fresnel zone and the other with a constant weighting respectively.

Text S4. CCP Discontinuity observations

As discussed in Text S3 discontinuities are more poorly resolved in Ps CCP stacks than multiple CCP stacks (Figure S10a), which we speculated relates to masking of shallow structure and early direct Ps arrivals from the high velocity gradients of the upper crust. We attempt to address this potential masking issue by computing synthetic RF from models of the upper crust only (examples are shown in Figure S11), and removing these synthetic RF from the original data, converting from time to depth and restacking. This should remove the parts of the signal related to upper crustal structure and reduce masking of underlying features. Results of this CCP stacking with removed upper crustal signal as compared to the original CCP stack are shown in Figure S12. We find that the removal of upper crustal structure improves the Ps CCP stacks allowing a clearer observation of the 1st discontinuity, which is now distinct and not merged into shallower features. However it does not help increase the observability of the 2nd deeper discontinuity, Figure S12a. Possibly we do not remove enough of the signal to improve observability at later arrival times in the RF as the upper crustal models model extend to only 8 km depth. In some inversion results we note a decrease in velocity beneath the upper crust at 10–15 km, see examples in Figure S12 b and c. Such features are not accounted for in our upper crustal model parameterisations, and may be still masking deeper structure, given the wide negative polarity arrivals seen in the Ps CCP stacks underlying the shallower discontinuity. Given that the removal of upper crustal structure only slightly improves Ps CCP stacks and has little effect on multiple CCP stacks, we choose to to analyse non-upper crust removed CCP stacks created from multiple data only.

We must also consider other reasons that Ps phases are worse at imaging the deeper discontinuity than multiple phases. One possible explanation lies in the fact that RF used to image direct Ps conversions are built in a higher frequency band. Converted phases are sensitive to discontinuities equal to or less than half the wavelength of the incoming $P$ wave (Bostock, 1999). This means that the direct Ps RF
are less able to well resolve broader discontinuities, as compared to the lower frequency multiple RF, since arrivals from broader discontinuities would be greatly reduced in amplitudes at higher frequencies. Thus if the deeper discontinuity represented a wider transition than the shallower discontinuity we might expect higher frequency Ps depth converted RF to resolve it less well than lower frequency multiple RF.

Figure 9 of the main text shows a cross section through our CCP stacking region, highlighting picked depths for discontinuities A and B, which are shown to correspond well to those derived from inversion results. In Figure S13a, we show maps of these picked discontinuities across the stacking region. Discontinuity A is imaged clearly throughout the stacking region, generally showing deviations for < 2.5 km from depths predicted from inversion results (Figure S13c). However the same cannot be said of discontinuity B which is only well imaged in the western half of the stacking area, despite good data coverage throughout (Figure S13b). Even where discontinuity B is imaged the difference from inversion predicted depths can be significant, up to 10 km.

There are several legitimate reasons why discontinuity B is likely to be less well imaged than discontinuity A. Inversion results indicate discontinuity B is a relatively steeply dipping feature, which will be poorly imaged by CCP stacks where data is stacked over horizontal Fresnel zones. Another possibility for the poor observation of discontinuity B is that the simplified time-depth conversion used to create these stacks is not always sufficiently accurate to cause alignment and coherent stacking of deeper arrivals, which will be more affected by velocity model inaccuracies as they travel further through the crust. Another consideration is that our CCP stacks are created by stacking across across 2 times the fresnel zone, which gets wider as a function of depth. This means strong signals may be smoothed out across a wider region, which may help to explain some of the large depth differences compared to inversion results.

**Text S5. Multi-phase time-depth velocity models**

Multi-phase time-depth conversion of RFs are carried out using a VS model constructed by averaging all 800 fifty layered inverted velocity profiles. The depth dependent relationship of \( V_P / V_S \) derived by Allen et al. [2002] (\( V_P / V_S = 1.78 + (0.004 \times \text{depth}) \)) is used to generate an equivalent \( V_P \) model. The velocity structure used is depicted in Figure S14, and the time-depth and depth-horizontal distance to conversion point relationships derived based on this velocity model are shown in Figure S15. While we have previously noted that the absolute velocities of profiles are unreliable in individual station inversions, we assume that averaging over many models will cancel out major variability and give a reasonable first order approximation of average velocity structure. This assumption is tested by comparing our averaged velocity model to the velocity profile commonly used for earthquake location in Iceland based on a series of refraction experiments [Pálsson, Gunmundur, 1971; Gebrande, Miller and Einarsrud, 1980; Darbyshire et al., 1998]. Figure S14 shows the high degree of similarity between the two velocity profiles, giving us confidence in our average derived structure.

We also test the dependence of CCP stacking results on the chosen velocity model by preforming time-depth conversions using a different velocity model. This secondary model assumes a constant average \( V_P \) of 6.5 km/s, based on the crustal model of Darbyshire et al., [2000], and a constant \( V_P / V_S \) of 1.78. Figure S16 shows CCP stacked results using these two different time-depth conversions. We note that signals in the constant velocity stack are less coherent and of smaller amplitudes than using our averaged inversion velocity model. We also compare the depths of clear continuous layers imaged in the two stacks. We find that maximum deviation of discontinuity depths between stacks is up to +5 km. However these are outliers with the average depth change being only -1.3 km for discontinuity A and +1.3 for discontinuity B.

We see that in general discontinuity A becomes slightly uplifted when using our inversion derived velocity model as opposed to a constant velocity, as we account for strong low velocities in the upper crust. Discontinuity B becomes slightly depressed, accounting for the higher than average lower crustal velocities. The small scale of discontinuity variation observed when using these two different velocity models is unsurprising when time-depth and depth-horizontal distance relationships are directly compared (Figure S15), as these show little significant variation above 50 km depth.

**Text S6. Description of data files**

Uploaded separately are:

1. Point observations of discontinuity A (Discont_A.obs.txt) and associated GMT .grd file (uit_discontA_T0.5.grd)
2. Point observations of discontinuity B (Discont_B.obs.txt) and associated GMT .grd file (uit_discontB_T0.5.grd)
3. Point observations used to define the Icelandic crustal thickness (Discont_B.obs_plus_constraints.txt) and associated GMT .grd file (Moho_depth.grd)
4. README file explaining data structure of the contents of the following folders and files:
   5. Zipped folder of RF built with Gaussian pulse of 1
   6. Zipped folder of RF built with Gaussian pulse of 2
   7. Zipped folder of RF built with Gaussian pulse of 4
   8. Zipped folder of dispersion measurements used in joint inversion of Green, Priestly and White [2017]
   9. List of stations and locations used in study

Point observations of discontinuities A and B and associated grid files correspond to those plotted in Figure 7 of the main text. Observations represent optimum discontinuity depths found for simplified model parameterisations (allowing either one or two layers beneath a finely parameterised upper crust) of inversion of RF and dispersion curve data. Points mark the Ps piec e point of each RF used in the inversion at the modelled depth. Observations have been defined as belonging to layer A (where only a single layer parameterisation is required of the depth or shallower layers in a two layered parameterisation), or to layer B (where only a single layer parameterisation is required or the depth of deeper layers in a two layered parameterisation). Corresponding GMT .grd files can be used to plot extrapolated surfaces.

Point observations used to define Icelandic crustal thickness, correspond to those plotted in Figure 10b of the main text. Points comprise of discontinuity B points plus addition of Moho depths derived by refraction studies, shown in the Table S1. Corresponding GMT .grd files can be used to plot extrapolated surfaces, as shown in Figure S17. The README.txt file explains in detail the data format of all RF and dispersion data in folders: RF1Gauss, RF2Gauss, RF4Gauss and dispersion. When making use of any of this data please cite this paper and for dispersion data the paper of Green, Priestly and White [2017].

**References**


Allen, Richard M and Nolet, Guust and Morgan, W Jason and Vogfjord, Kristn and Nettles, Meredith and Ekström, Göran and Bergeson, Bertry H and Eldersonsd, Palmi and Foulger, GR and Jakobsdottir, Steinmann and others (2002). Plume-driven plumbing and crustal formation in Iceland, JGR: Solid Earth, 107(B8)


Carlson, RL and Herrick, CN (1990), Densities and porosities in the oceanic crust and their variations with depth and age, JGR: Solid Earth, 95(B6), 9153–9170.


Pálmason, Guðmundur (1971), Crustal structure of Iceland from explosion seismology, Prentsmjón Leiftar, 40.


Shorttle, O and Maclellan, J (2011), Compositional trends of Icelandic basalts: Implications for short-length scale lithological heterogeneity in mantle plumes, Geochemistry, Geophysics, Geosystems, 12(11).


Corresponding author: J. Jenkins, 4.2 Geomaterials and Rheology, Helmholtz Centre Potsdam, GFZ - German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany. (jjenkins@gfz-potsdam.de)
**Figure S1.** Depth sensitivity kernels for Rayleigh wave group velocity ($U$) for periods between 5 and 18 seconds. Greatest sensitivity is found at shallower depths < 15 km depth. Absolute sensitivity to shear velocity ($Vs$) deteriorates below 25 km depth.

**Figure S2.** Example of RF data throughout selection steps applied for crustal imaging. Numbers show incoming BAZ for each RF. a) All RFs recorded at station BRE. b) High quality RF remaining after automated quality control and visual inspection, with a stack of all data plotted together above. c) High quality data split into 4 BAZ subsets containing highly similar waveforms, with a data stack plotted above.
Figure S3. Inversion results from 2 different stations GRA and ADA, where inversion weighting between RF and dispersion measurements is varied from 1 (RF only) to 0 (dispersion only), showing the increase in smoothing of the resulting velocity profile with increased weight of dispersion measurements.

Table S1. Point constraints of crustal thickness estimates based on seismic refraction experiments. Data from the following experiments are included: ICEMELT [Darbyshire et al., 1998], FIRE (Staples et al., 1997), SIST (Bjarnason et al., 1993), RISE (Weir et al., 2001), and B96 (Menke et al., 1998).

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Crustal Thickness (km)</th>
<th>Experiment and position on line</th>
</tr>
</thead>
<tbody>
<tr>
<td>65.74</td>
<td>-19.6</td>
<td>28.3</td>
<td>ICEMELT: -80 km</td>
</tr>
<tr>
<td>65.36</td>
<td>-19.2</td>
<td>34.4</td>
<td>ICEMELT: -40 km</td>
</tr>
<tr>
<td>65.05</td>
<td>-18.4</td>
<td>41.7</td>
<td>ICEMELT: 0 km</td>
</tr>
<tr>
<td>64.86</td>
<td>-17.6</td>
<td>43.3</td>
<td>ICEMELT: 40 km</td>
</tr>
<tr>
<td>64.54</td>
<td>-16.8</td>
<td>42.2</td>
<td>ICEMELT: 80 km</td>
</tr>
<tr>
<td>65.87</td>
<td>-17.5</td>
<td>24.7</td>
<td>FIRE: -40 km</td>
</tr>
<tr>
<td>65.71</td>
<td>-16.8</td>
<td>19.4</td>
<td>FIRE: -20 km</td>
</tr>
<tr>
<td>65.56</td>
<td>-16.1</td>
<td>27.8</td>
<td>FIRE: 0 km</td>
</tr>
<tr>
<td>65.28</td>
<td>-15.5</td>
<td>35.0</td>
<td>FIRE: 20 km</td>
</tr>
<tr>
<td>65.09</td>
<td>-14.8</td>
<td>35.0</td>
<td>FIRE: 40 km</td>
</tr>
<tr>
<td>64.48</td>
<td>-22.1</td>
<td>23.2</td>
<td>SIST: 820 km</td>
</tr>
<tr>
<td>64.14</td>
<td>-21.0</td>
<td>22.3</td>
<td>SIST: 780 km</td>
</tr>
<tr>
<td>63.79</td>
<td>-19.9</td>
<td>21.2</td>
<td>SIST: 650 km</td>
</tr>
<tr>
<td>63.95</td>
<td>-21.4</td>
<td>17.0</td>
<td>RISE: A120 km</td>
</tr>
<tr>
<td>63.89</td>
<td>-22.2</td>
<td>15.2</td>
<td>RISE: A80 km</td>
</tr>
<tr>
<td>63.81</td>
<td>-23.1</td>
<td>13.7</td>
<td>RISE: A40 km</td>
</tr>
<tr>
<td>63.61</td>
<td>-23.5</td>
<td>14.0</td>
<td>RISE: B120 km</td>
</tr>
<tr>
<td>63.33</td>
<td>-24.0</td>
<td>13.3</td>
<td>RISE: B80 km</td>
</tr>
<tr>
<td>63.10</td>
<td>-24.5</td>
<td>12.7</td>
<td>RISE: B45 km</td>
</tr>
<tr>
<td>63.03</td>
<td>-23.7</td>
<td>10.1</td>
<td>RISE: D50 km</td>
</tr>
<tr>
<td>65.50</td>
<td>-17.5</td>
<td>25.5</td>
<td>B96</td>
</tr>
<tr>
<td>65.30</td>
<td>-17.3</td>
<td>31.5</td>
<td>B96</td>
</tr>
</tbody>
</table>

Table S2. Iceland Depleted and Enriched end-member melt compositions used in petrological modelling are based on Shorttle Maclennan (2011) corrected to equilibrium with Fo90 by olivine addition using PETROLOG (Danyushevsky Pelchov, 2011).

<table>
<thead>
<tr>
<th>End Member</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>Cr₂O₃</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>P₂O₅</th>
<th>H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depleted</td>
<td>48.88</td>
<td>0.69</td>
<td>14.96</td>
<td>1.00</td>
<td>0.03</td>
<td>7.62</td>
<td>11.84</td>
<td>12.95</td>
<td>1.71</td>
<td>0.04</td>
<td>0.08</td>
<td>0.20</td>
</tr>
<tr>
<td>Enriched</td>
<td>46.68</td>
<td>1.41</td>
<td>12.99</td>
<td>1.54</td>
<td>0.04</td>
<td>9.83</td>
<td>14.95</td>
<td>9.87</td>
<td>1.77</td>
<td>0.20</td>
<td>0.18</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Figure S4. Inversion results from two stations GRA and ADA varying a) $V_p/V_s$ ratio from 1.7 to 1.85, for constant half space starting model $V_s$ (4.5 km/s); b) empirical equations linking density and $V_p$ based on Berteussen [1977] and Carlson and Herrick [1990] for constant $V_p/V_s$ (1.7) and half space starting model $V_s$ (4.5 km/s); c) starting models. Starting models are shown in left panels with corresponding inversion velocity models shown in right panels.
Figure S5. Examples of inverted velocity structure for station KSK using a) ambient noise dispersion curves and additional longer period average phase velocity dispersion curve for Iceland of Harmon, Nicolas and Rychert (2016) and b) using ambient noise dispersion curves alone. Red lines are results of 50-layered model parameterisations (averaged from 12 half space starting models), blue lines are best results for a 1-interface model below the upper crust and, green lines are best fitting model for 2-interface model below a finely parameterised upper crust.
Figure S6. Examples of one layer forward modelling for stations a) ADA b) KLU and c) FJAS. Left panel shows velocity profile for 50 layered inversion in red and all possible models in grey. Central panel shows all possible 1-layer forward model results with the best fitting profile highlighted in green. Right panels show the increase to fit for each possible depth parameterised in the forward model compared to an upper crustal only model. Across all panels predicted crustal thickness are shown as lines from the models of Darbyshire et al. [2000] (purple) and Allen et al. [2002] (blue).
Figure S7. Forward modelling results for: a) all 1-layer forward models, b) 1-layer models suggesting the need for one major layer; c) models suggesting the need for 2 crustal layers where the shallower of the two is dominant and d) the deeper of the two is dominant. e) Results of 2-layer forward modelling.
Figure S8. Results of 2-layer forward modelling for stations a) KSK, b) HNJO and c) ADA. Left panels show velocity models from 50 layer inversions (red), best fitting 1-layer models (brown) and best fitting 2-layer models (green). Adjacent to these a graph of variation in fit with the depth of a second layer with the optimal 1-layer depth is shown. Fit relative to an upper layer only model is shown in pink, and fit relative to the best-fit one layer model is shown in blue. Peaks showing the maximum increase in fit are highlighted by green points. Right panels show fit matrices where the increase to fit relative to an upper crustal model is shown as a function of the depth of the two forward modelled layers. Best second layer depths are chosen for each first layer depth, shown circled in green, with the maximum overall increase to fit double circled. Across both panels predicted crustal thicknesses are shown as lines from the models of Darbyshire et al. (2000) (purple) and Allen et al., (2002) (blue).
Figure S9. Examples of data that require a two layered model fit. Left panels - velocity profiles from forward modelling for: upper crustal structure only (red), 1-layer models (green) and 2-layer models (orange). Right panels - comparisons between stacked RF data (black with $\pm 2$ SE dashed lines) with synthetic RF generated based on forward modelling results, and arrows highlighting major peaks fitted with the addition of structure in the model.
Figure S10. N-S cross-section through CCP stacking region showing stacks coloured as a function of RF amplitude (left panels) and RF wiggle plots (right hand panels) where peaks $>2$ SE are coloured red for positives and grey for negatives. Stacks for individual phase depth conversions are shown in a) for Ps phases, b) for PpPs phases and c) for PpSs phases, and multi-phase stacks are shown in d) including all crustal phases and e) for only crustal multiple phases.
**Figure S11.** Black lines show 50 layer models, red lines show upper crustal only parameterisations used to compute synthetic RF which are removed from data to better image masked structure, for stations a) RIFR b) REN and c) K050.

**Figure S12.** CCP stacks as used in the current paper (left) and after RF have had model upper crustal structure removed (right). a) CCP stack using just Ps time-depth converted RF, b) multi-phase CCP stack using Ps PpPs and PsSs phases and c) multi-phase CCP stack using only multiple phases.
Figure S13. a) Depth of picked discontinuities A (left) and B (right) from CCP stacking results coloured by depth. b) Data coverage in CCP stacks at approximate depths of discontinuity A (20 km) and B (30 km). c) Differences in discontinuity depth between CCP picked and inversion derived depths. White masked areas contain < 5 RF, green outline shows CCP stacking region.
Figure S14. Vs and Vp models used in time-depth conversion of RFs. Grey shows all models derived by joint inversion of RF and dispersion curves at each station BAZ grouping. Red shows the average or all these models which is used in time-depth conversions and blue shows a velocity model constructed based on refraction experiments commonly used in earthquake location in Iceland.

Figure S15. Comparison of time-depth (left) and depth-distance of conversion point (right) relationships derived from using either a constant average crustal velocity and $V_p/V_S$ (solid lines) or a 2D velocity model derived from the inversion results of this study (dashed lines).
Figure S16. Comparison of CCP stacks built using our derived inversion velocity model compared to a constant average crustal velocity. Examples are shown for two CCP longitude slices. Picked discontinuities are picked out in reds for discontinuity A and in blues for discontinuity B.
Figure S17. Map of crustal thickness estimates derived by the study, from inversion of RF and surface wave data. Contours are marked every 2.5 km.