# **GSA DATA REPOSITORY 2014072**

## SUPPLEMENTARY MATERIALS

#### **SUMMARY OF METHODS**

#### WAVEFORM MODELLING

Synthetic waveforms are calculated using a 2-dimensional finite difference waveform propagation model (Bohlen, 2002). The slab shape is based slab1.0 (Hayes et al., 2012) as well as local seismicity reported by the JMA catalogue. Continental crust structure and seismic velocities are based on high resolution tomographies of the area (Zhang et al., 2004; Nakajima et al., 2009) Elongated scatterers are described using a von-Kármán function, with a range of velocities between 6.8-8.2 km/s. Deterministic fault zone structure is based on faults of constant dip and spacing relative to the top of the slab.

## DISPERSION MODEL FITTING

Body wave dispersion is identified and measured using a spectrogram following Abers (2005). The vertical-component seismogram measured at a broadband station is passed through a comb of narrow band pass filters with centre frequencies at 0.25 Hz increments between 0.25-7.50 Hz. The onset time is corrected to the peak amplitude of the 0.50 Hz frequency band. The spectrogram of the waveform recorded at the station ERM is then compared to the spectrogram of the synthetic waveform. The signal is also compared in the frequency domain so the whole waveform can be constrained up to a frequency of 2.5 Hz through a series of resolution tests.

The dispersion curve of a dispersive event is sensitive to the velocity contrast, width of the fault, and position of the source within the fault. These characteristics were varied in the sensitivity tests to find the optimum model fit. Velocity models with low velocity faults zones dipping  $22.5-27.5^{\circ}$  to the top of the slab, with velocities of 6.8-7.3 km/s and widths of 1-3 km were tested. In total five events are modelled in this way, and the comparison between the modelled and observed dispersive waveforms are shown in supplementary figure DR1.

#### CODA MODELLING

The amplitude of the high frequency (> 3 Hz) coda arriving 4-8 seconds after the first arrival is compared to amplitude of the first arrivals (0 - 4 seconds from first arrival) as shown in the equation below;

$$Coda Ratio = {Second Coda Window Amplitude \over First Coda Window Amplitude}$$

The *Coda Ratio* is calculated for each event for the four stations in the Japanese fore arc shown on the map (figure 1a) and profile (figure 2b). The coda decay is then normalised to the station with the highest coda ratio, and these normalised values are averaged for all events. This approach removes source specific contributions to give an averaged view of the scattering media.

A wide range of velocity models are tested to simulate this observation. A von Kármán function is used to describe a random scattering media, as has previously been done for deeper events in Northern Japan (Furumura & Kennett, 2005). The correlation length and aspect ratio of the scattering media is varied. Modelling shows that the coda decay is relatively insensitive to the shape of scatter (supplementary figure DR2). A single LVL and other scattering models, such as scattering in the mantle wedge or over riding crust cannot account for the observed extended P-wave coda (supplementary figure DR3). The amplitude of the coda can only be reproduced where the source is directly in the scattering media, and so S to P converts contribute to the strength of the P-wave coda. This gives further evidence that WBZ events deep within the slab are associated with low velocity hydrated scattering structure. Further modelling shows that scatterers elongated parallel to the slab, as proposed by Furumura & Kennett (2005), can describe the observed P-wave coda. The waveform modelling presented in this paper shows that hydrated normal faults are present at these depths, so we therefore propose that this low velocity structure is responsible for the observed P-wave coda (see main text). We also note that a dipping fault structure produces a stronger P-wave coda than slab parallel scatterers.

The coda ratio is sensitive to the velocity contrast of the scattering media (supplementary figure DR4). Average velocities for the slab mantle are tested in the range of velocities between 6.8 km/s (highly serpentized peridotite) and 8.2 km/s (dry deep peridotite). The scatters have a velocity that is one standard deviation around the average. An average velocity contrast of 8.025 km/s clearly does not describe the coda decay close to the trench adequately, while an average velocity of 7.5 km/s produces a coda decay of larger amplitude. Average velocities in the range of 7.625-7.85 km/s however produce a reasonable fit the coda decay within error.

# CALCULATING THE DEGREE OF SLAB MANTLE SERPENTINIZATION AND HYDRATION

This average velocity allows the degree of serpentinization to be calculated if the velocity of serpentinite and mantle periodite material is known at these temperature and pressure conditions. The velocity and hydration of serpentinite used in the calculations of bulk serpentinization are calculated using the subduction factory 4 excel macro (Hacker & Abers, 2004). Pressure conditions are calculated using the densities of the PREM model and temperature conditions are calculated using a 2-dimensional finite element model (Fry, 2010) which gives similar temperatures published profiles of Northern Japan (e.g. Hacker et al., 2003b, Syracuse et al., 2010). An average velocity of 8.2 km/s is assumed for the mantle peridotite based on high resolution tomographies of the area (Nakajima, et al., 2009) and numbers given in petrological modelling (Connolly & Kerrick, 2002).

At the pressure (1.5 - 4.8 GPa) and temperature  $(250 - 500^{\circ}\text{c})$  conditions present in the slab mantle beneath Northern Japan we calculate that serpentinite has a velocity of 6.19-6.51 km/s. Given that the average velocity of the slab mantle is 7.625-7.85 km/s this gives a range of serpentization values of between 17.4-31.1%. Given that the wt% of H<sub>2</sub>0 of serpentinite at these pressure temperature conditions is 11.3% (Hacker & Abers, 2004), this translates to an overall slab mantle hydration of 57-107 kg/m3. Given that the subduction rate at this arc is 7.5 cm/yr (van Keken et al., 2011), this implies that 170.4-318.7 Tg/Myr of water per metre of trench is subducted at this trench. Taken with estimate of van Keken et al., (2011) for total water subducted in the upper slab (i.e. in the oceanic crust and sediments) this gives an overall amount of 191.9-340.2 Tg/Myr of water per metre of trench subducted beneath Japan.

The slab mantle hydration accounts for 89-94% of this overall budget. If this amount is extrapolated along the Kurile and Izu-Bonin arcs where oceanic lithosphere of >120 Ma is subducting (approximately 3380 km), we show that this system could subduct up to 3.5 oceans over the age of the Earth. This suggests hydration of the lower lithosphere has a major role to play in the re-gassing of the lower mantle.

Reference	Description	H2O flux due to mantle lithosphere (Tg/Myr/m)
Schmidt & Poli (1998)	Average value, not specifically for subduction conditions seen here, assuming the subduction velocity of van Keken et al., (2011).	0.16
Rüpke et al., (2004)	120 Myr plate subducting at 6cm/yr	22.8
van Keken et al., (2011)	Assuming 2 wt% serpentization of 2km thick layer of mantle lithosphere	9.6
This study		170.4-318.7

**Supplementary Table DR1** – Summary of mantle lithosphere hydration from this and previous studies



**Supplementary Figure DR1** – Full waveform fits for five dispersive events observed in Northern Japan. **a**) Shows the location of the events with yellow circles, lettered A – E. The position of the stations used are shown by inverted yellow triangles. The modelled and observed waveforms shown are all recorded at the station ERM. The grey colour scale shows the velocity structure, and the velocities of different areas are labelled. **b**)-**f**) Shows the spectrogram (bottom left), displacement spectra (bottom right) and waveform (top) of each event recorded at the station ERM (black and white colours). Each of these waveforms is directly compared to the modelled waveform (red) as described in the main text.



**Supplementary Figure DR2** – Scattering model resolution. a) The velocity models used showing different correlation lengths and aspect ratios of scatterer. b) The decay in coda ratio for each of these models (red), compared to observed coda decay (black).



**Supplementary Figure DR3** – Alternative scattering models. A range of scattering models are shown, with the location of the sources shown in yellow. Above this the high pass filtered (>3 Hz) waveforms are shown in red, along with the coda envelope in grey. Below this the velocity model is shown, with the location of the sources shown in yellow. a) Velocity model with scattering in the upper crust does not produce a strong P-wave coda. b) Scattering media in the mantle wedge does not produce significant coda either. c) Scatterers parallel to the dip of the slab can account for the coda (e.g. Furumura & Kennett, 2005) but we propose that dipping fault zone structures are a better candidate. d) Simple LVL model proposed by previous guided wave studies (e.g. Abers 2000; 2005; Martin et al., 2003) is unable to explain the observed extended P-wave coda.



**Supplementary Figure DR4** – Velocity sensitivity of scattering media. a) Coda ratio decay is show for models with an average velocity of 7.50, 7.76, 7.85 and 8.03 in red, blue, purple and pick respectively. The lowest average velocity (red) over exaggerate the decay, while the highest average velocity(blue) does not adequately describe the decay close to the trench. Average velocities in the range of 7.68 - 7.85 km/s describe the decay within error. b) Velocity model that produces the best fitting coda decay shown in figures above. The events for which extended coda is measured and modeled are shown by orange circles, with the stations at which the coda is observed by a yellow triangle.

## SUPPLEMENTARY REFERENCES

- Abers, G.A., 2000, Hydrated subducted crust at 100–250 km depth: Earth and Planetary Science Letters, v. 176, p. 323–330, doi:10.1016/S0012-821X(00)00007-8.
- Abers, G.A., 2005, Seismic low-velocity layer at the top of subducting slabs: Observations, predictions, and systematics: Physics of the Earth and Planetary Interiors, v. 149, p. 7–29, doi:10.1016/j.pepi.2004.10.002.
- Bohlen T., 2002, T. Parallel 3-D viscoelastic finite difference seismic modelling: Computers & Geosciences, v. 28, p. 887-899.
- Connolly, J. A. D. & Kerrick D. M., 2002, Metamorphic controls on seismic velocity of subducted oceanic crust at 100-250 km depth: Earth and Planetary Science Letters, v. 204, p. 61-74.
- Fry, A., 2010, Modelling stress accumulation and dissipation in subducting lithosphere and the origin of double and triple seismic zones: [PhD thesis]: University of Liverpool.
- Furumura, T., and Kennett, B., 2005, Subduction zone guided waves and the heterogeneity of the subducted plate: Intensity anomalies in northern Japan: Journal of Geophysical Research, v. 110, B10302, doi:10.1029/2004JB003486.
- Hacker, B.R., Abers, G.A., and Peacock, S.M., 2003, Subduction factory, 1, Theoretical mineralogy, densities, seismic wave speeds, and H<sub>2</sub>O contents: Journal of Geophysical Research, v. 108, 2029, doi:10.1029/2001JB001127.
- Hacker, B.R., and Abers, G.A., 2004, Subduction factory 3: An Excel worksheet and macro for calculating the densities, seismic wave speeds, and H<sub>2</sub>O contents of minerals and rocks at pressure and temperature: Geochemistry Geophysics Geosystems, v. 5, Q01005, doi:10.1029/2003GC000614.
- Hayes, G.P., Wald, D.J., and Johnson, R.L., 2012, Slab 1.0: A three-dimensional model of global subduction zone geometries: Journal of Geophysical Research, v. 117, B01302, doi:10.1029/2011JB008524.
- Martin. S., Rietbrock, A., Haberland, C., and Asch, G., 2003, Guided waves propagating in subducted oceanic crust: Journal of Geophysical Research, v. 108, 2536, doi:1029/2003JB002450.
- Nakajima, J., Tsuji, Y., Hasegawa, A., Kita, S., Okada, T., and Matsuzawa, T., 2009, Tomographic imaging of the hydrated crust and mantle in the subducting Pacific slab beneath Hokkaido, Japan: Evidence for dehydration embrittlement as a cause of intra slab earthquakes: Gondwana Research, v. 16, p. 470–481, doi:10.1016/j.gr.2008.12.010.
- Schmidt M.W., Poli S., 1998, Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation: Earth and Planetary Science Letters, v. 163, p. 361–379.Syracuse, E. M., van Keken P. E. & Abers G. A., 2010, The global range of subduction zone thermal models: Physics of the Earth and Planetary Interiors, v. 183, p. 73-90.
- Syracuse, E. M., van Keken P. E. & Abers G. A., 2010, The global range of subduction zone thermal models: Physics of the Earth and Planetary Interiors, v. 183, p. 73-90.

- van Keken, P.E., Hacker, B.R., Syracuse, E.M., and Abers, G.A., 2011, Subduction Factory:
  4. Depth-dependent flux of H<sub>2</sub>O from subducting slabs worldwide: Journal of Geophysical Research, v. 116, B01401, doi:10.1029/2010JB007922.
- Zhang, H., Thurber, C.H., Shelly, D., and Ide, S., 2004, High-resolution subducting-slab structure beneath northern Honshu, Japan, revealed by double-difference tomography: Geology, v. 32, p. 361–364, doi:10.1130/G20261.2.