Order of magnitude increase in subducted H_2O due to hydrated normal faults within the Wadati-Benioff zone

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ABSTRACT

It is widely proposed that the oceanic mantle is hydrated by outer rise normal faults, and carries large amounts of water to the deep mantle. However, the extent of oceanic mantle hydration is poorly constrained by existing observations, and is a major source of uncertainty in determining the total water delivered to the mantle. Full waveform modeling of dispersed P-wave arrivals from events deep within the Wadati-Benioff zone of northern Japan shows that hydrated fault zone structures are present at intermediate depths. Analysis of the P-wave coda associated with events 5–35 km below the top of the slab gives an overall indication of the bulk hydration of the subducting oceanic mantle, and can be explained by a 40-km-thick layer that is 17%–31% serpentinized. This suggests that the top of the oceanic mantle is 2.0–3.5 wt% hydrated, subducting 170–318 Tg/m.y. of water per meter of arc beneath northern Japan. This order-of-magnitude increase in the estimated H_2O flux in this arc implies that over the age of the Earth, the equivalent of as many as 3.5 present-day oceans of water could be subducted along the Kuril and Izu-Bonin arcs alone. These results offer the first direct measure of the lower lithosphere hydration at intermediate depths, and suggest that regassing of the mantle is more vigorous than has previously been proposed.

INTRODUCTION

Double Wadati-Benioff zone seismicity has been observed across the globe (Brudzinski et al., 2007), and it is widely thought that the lower plane of seismicity is associated with breakdown of hydrous minerals (e.g., Peacock, 2001; Seno et al., 2001). Outer rise normal faulting has been proposed as a pathway for hydration of the oceanic lithosphere (e.g., Peacock, 2001), and is apparent in many subduction zones across the globe due to the surface expression of fault scarps in oceanic trenches (Fig. 1). Seismic reflection studies have identified these faults at the outer rise (e.g., Ranero et al., 2003), and at several subduction zones the reactivation of outer rise normal faults at intermediate depths (70–300 km) has been shown (e.g., Ranero et al., 2005). The onset of outer rise faulting corresponds with a reduction in seismic velocity of the incoming plate interpreted as the onset of hydration and serpentinization of the oceanic lithosphere in the Central America trench (e.g., Grevemeyer et al., 2007) and the Tonga Trench (Contreras-Reyes et al., 2011). Geodynamic modeling suggests that bending and unbending of the subducted lithosphere cause a downward pressure gradient on the outer rise faults, forcing water into the deeper parts of the slab (Faccenda et al., 2009, 2012). It is proposed that these hydrated faults may carry large amounts of water to the mantle (e.g., Iyer et al., 2012).

Recent studies have estimated the amount of water subducted globally, but the extent of lithospheric mantle hydration remains the major source of uncertainty (e.g., van Keken et al., 2011). Mantle lithosphere hydration due
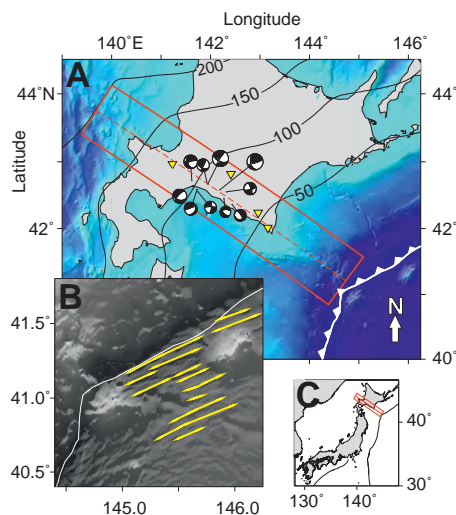

Figure 1. Summary map of Wadati-Benioff zone of northern Japan. A: Focal mechanisms (in black and white) of earthquakes used in full waveform analysis; stations are shown by yellow triangles. Black contours show depth to slab (Hayes et al., 2012). B: Outer rise fault scarps, highlighted in yellow, in Japan subduction zone trench. Bathymetry is from Gebco08 model (General Bathymetric Chart of the Oceans; www.gebco.net). C: Location map of study area. Red box shows profile area described in this study.

to normal faulting is potentially a major component of the global H_2O cycle, explaining the inferred hydrous transition zone (e.g., Lawrence and Wysession, 2006), with significant implications for the rate of convection (Hirth and Kohlstedt, 1996) and melt production (e.g., Hirschmann, 2006) in the deep mantle.

DISPERSED P-WAVE ARRIVALS

To investigate the hydrated structure of the slab mantle we analyzed dispersed P-wave arrivals from events that occur well below the surface of the slab. The dispersion is noted at seismic stations in the forearc of northern Japan, and is only observed at stations close to the Hokkaido trench. These events occur between 100 km and 150 km depth, and are 5–35 km below the slab surface. The dispersion is measured using a spectrogram (see Fig. 2A). The high-frequency arrivals (>2 Hz) are delayed by ~1.5 s relative to the low-frequency arrivals (<0.5 Hz). The relative delay of the higher frequencies is shown for eight events in the lower Wadati-Benioff zone in Figure 2B. The associated spectrograms for five of these events are shown in the GSA Data Repository[1].

Dispersive P-wave arrivals similar to these observations have been observed in northern Japan, and subduction zones across the globe, from events occurring at depths of >100 km (Abers, 2000, 2005; Martin et al., 2003). The dispersion is attributed to a layer of low-velocity oceanic crust that acts as a waveguide. High-frequency (short wavelength) energy is retained and delayed in subducted low-velocity oceanic crust, while lower frequency (long wavelength) seismic energy travels at the faster seismic velocities of the surrounding mantle. These dispersion observations, however, all occur close to the top of the slab in the upper plane of seismicity, and it has been shown that for seismically slow crust to act as an effective waveguide the source must be on or near the low-velocity layer (Martin et al., 2003; Abers, 2005; Martin and Rietbrock, 2006). The events analyzed here occur well below the slab surface, implying that a layer of low-velocity oceanic crustal material cannot explain the observed dispersive P-wave arrivals. Our modeling shows that the presence of a lower low-velocity layer as has been inferred by detailed tomographic studies of northern Japan (Zhang et al., 2004; Nakajima et al., 2009) cannot explain the data. The geometry of this lower layer means that guided waves generated in this layer do not decouple deep enough to be seen at the surface. We also note that as

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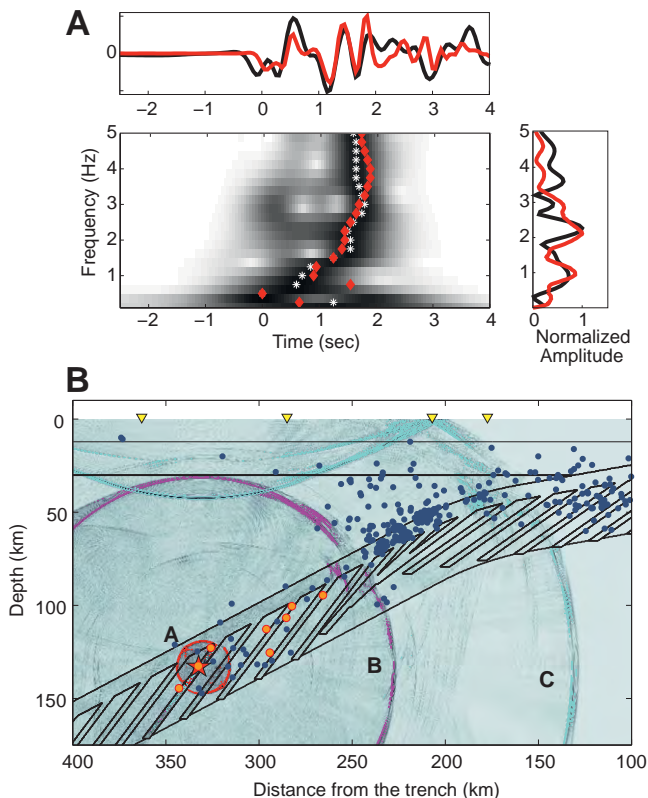Data Repository item 2014072 | doi:10.1130/G34730.1

Figure 2. Dispersive waveform modeling. A: Waveform fit of dispersive P-wave arrival recorded at station ERM in Wadati-Benioff zone of northern Japan. Recorded waveform (black) is compared to synthetic waveform (red) in spectrogram (bottom left) and in frequency domain (bottom right), allowing comparison of full waveform <2.5 Hz (top). B: Numerical model at 1 s (red circle), 12 s (pink), and 24 s (blue). High-frequency energy from source is trapped in low-velocity fault zone (A), before being transferred to low-velocity oceanic crust (B), and decoupling to be observed at surface (C). Gray events show background seismicity on profile shown in Figure 1; orange circles show events used in this study; red star shows location of event.

associated with Wadati-Benioff zone events observed in the forearc. While only some events clearly show the characteristic first motion dispersion, all events of depths between 100 km and 150 km on this profile recorded at the station ERM between A.D. 2000 and 2010 are associated with an extended P-wave coda, which has previously been noted for much deeper events in northern Japan (Furumura and Kennett, 2005). To quantify this observation, we calculate the amplitude of the P-wave coda relative to the first arrival (see the Data Repository). We observe that the magnitude of the high-frequency P-wave coda reduces compared to the first arrivals with distance from the trench (Fig. 3).

Full waveform models are used to assess the amount of coda produced by different models of slab mantle hydration. No coda is observed in synthetic waveforms based on velocity models that only have a single simple low-velocity layer. Only weak coda is generated for models with several regularly spaced low-velocity fault zones as used for the deterministic dispersion models for selected events. We therefore represent the hydrated fault zone structure as a random medium described by a von Kármán function with varying average velocity, size distribution, and degree of elongation. This stochastic model

the events analyzed here do not occur in a single plane, it is unlikely that they can be described by a single low-velocity layer.

We propose that dispersive P-wave arrivals from events occurring deep in the slab are explained by serpentinized outer rise normal faults that act as low-velocity waveguides penetrating deep into the slab. We simulate the waveforms arising from these events occurring on a low-velocity fault structure as shown in Figure 2C. The low-velocity fault zone retains high-frequency energy from an event that occurs upon it, while low-frequency energy is not retained and travels at the faster velocities of the surrounding cool slab material (A in Fig. 2C). The retained high-frequency energy is transferred to the low-velocity oceanic crust and travels updip in the crustal waveguide (B in Fig. 2C). The high-frequency energy then decouples from the crustal waveguide due to the bend of the slab (C in Fig. 2C). Hence, the dispersed arrivals are only seen at stations close to the trench where the delayed high-frequency energy has decoupled from the crustal waveguide (Martin et al., 2003).

Synthetic waveforms produced by our simulations are directly compared to the dispersive waveforms observed on the Japanese forearc as shown in Figure 2A. The synthetic and observed spectrograms (bottom left, Fig. 2A) are compared to constrain the relative arrival time of different frequency bands. The displacement spectra of the synthetic and observed signal (bottom right, Fig. 2A) are matched to constrain

the relative amplitude at different frequencies. Constraining the signal in these two ways means that the waveform (low pass filtered at 2.5 Hz) can be directly modeled (Fig. 2A).

This methodology is used to test a variety of velocity models (for descriptions of further detail, see the Data Repository). Waveform fits for the five events modeled in this way are also shown here. Our waveform modeling shows that the observed dispersions can be explained by fault zones of 2–3 km width with a velocity of 7.0–7.2 km/s (12%–15% slower than the surrounding mantle material). The modeled fault zones have an apparent dip of 25° to the slab surface (Fig. 1). The apparent dip corresponds to a true dip of ~39° on a profile that is perpendicular to the scarp of the outer rise normal faults. This is similar to the fault angle that is seen for outer rise normal faulting and reactivated normal faults in studies of South America and Central America (Ranero et al., 2005).

While these observations provide a good constraint on the structure of individual serpentinized faults in the subducted slab, and confirm the link between intermediate-depth seismicity and outer rise faulting, they cannot be used to estimate the overall extent of slab hydration due to outer rise faulting.

P-WAVE CODA ANALYSIS

To directly investigate the levels of hydration of the subducting mantle lithosphere we analyze the extended high-frequency P-wave coda
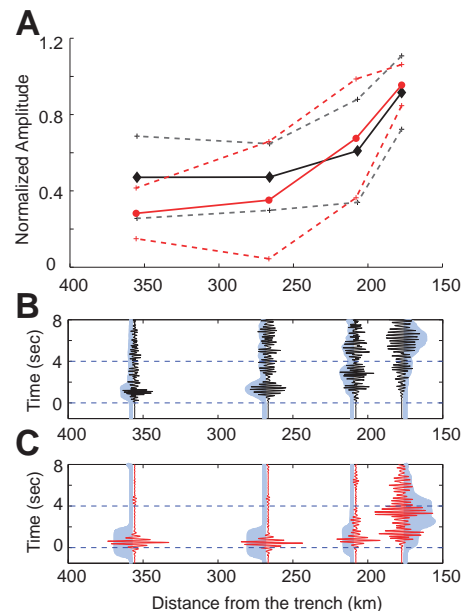

Figure 3. A: Scattering analysis for all events with observed coda decay (black) compared to modeled coda decay (red). Plot shows average coda ratio normalized to maximum coda ratio for given event. B: Observed high-frequency (>3.0 Hz) P-wave arrivals with extended coda (black); coda envelope is plotted in blue. C: Synthetic P-wave arrivals (high pass filtered at 3.0 Hz) from numerical model incorporating elongated random scatterers in Wadati-Benioff zone (northern Japan). (Example of von Kármán scattering medium is shown in Fig. 4; actual model is shown in Fig. DR4b [see footnote 1].)

provides low-velocity scatterers at a range of scale lengths, rather than the single scale length seen in the deterministic models used before.

Previous work has attributed extended P-wave coda arrivals from deep subduction zone events in northern Japan to scatterers elongated parallel to the slab (Furumura and Kennett, 2005), though there is no widely accepted geological interpretation for this structure. Our analysis shows that a wide range of scattering structures could potentially account for the observed coda decay, including elongate scatterers parallel to the dip of the slab (see the Data Repository). Guided wave analysis presented here shows that dipping normal fault structures are present at these depths. We propose that these structures are responsible for the observed extended P-wave coda. Dipping elongated scatterers also produce a stronger coda than other scattering media tested.

The decay in coda amplitude is, however, sensitive to the average velocity of the scattering medium. Modeling a range of scattering media average velocities shows that the average velocity for the Wadati-Benioff zone scattering media is 7.8 ± 0.2 km/s. Higher or lower average velocities do not account for the observed decay in coda amplitude (see the Data Repository).

DISCUSSION

Based on the analysis of dispersive P-wave arrivals and high-frequency P-wave coda, we suggest that the velocity structures in the lower subducting lithosphere are serpentinized peridotite along dipping faults of various length scales. Low-velocity fault zones of 1–2 km width are detectable, as they act as a seismic waveguide. Smaller-scale fault zones are not detectable in this way, but still act as scatterers, producing the extended P-wave coda seen close to the trench. Serpentinite has been shown to be stable at the pressure and temperature conditions found at this depth (Hacker et al., 2003), with a predicted P-wave velocity of 6.19–6.51 km/s, and a hydration of 11.3 wt% H_2O (Hacker and Abers, 2004).

The dispersion observations presented here provide direct seismic evidence of the presence of serpentinized normal fault structures at depth, and confirm that lower plane Wadati-Benioff zone seismicity is associated with these hydrous mineral assemblages. The measured velocity contrast of these faults would imply that they are 50%–71% serpentinized. These observations suggest that outer rise normal faults are a viable pathway for deep slab hydration.

The scattering models used to simulate the extended P-wave coda give a better constraint on the overall low-velocity structure, and hence the hydration of the subducted lithosphere. Using the velocities for serpentinite calculated here, we estimate that the mantle lithosphere is 17%–31% serpentinized. Given the water content of serpentinite at these pressure and

temperature conditions (Hacker and Abers, 2004), this would give an overall hydration of the mantle lithosphere as 2.0–3.5 wt% H_2O.

The scattering medium is interpreted as a hydrated fault zone structure related to Wadati-Benioff zone seismicity, and therefore we assume that the depth extent of the scattering medium in the slab is defined by the thickness of the Wadati-Benioff zone beneath northern Japan (~40 km) (Fig. 4). This would translate to 170–320 Tg/m.y. of water per meter of arc being subducted in the mantle lithosphere at the Hokkaido trench. This represents an order of magnitude increase in the amount of water predicted to be subducted by earlier models (van Keken et al., 2011; Rüpke et al., 2004) (see the Data Repository). Extrapolating these figures along the Kuril and Izu-Bonin arcs (where the oceanic plate is older than 120 Ma) shows that this arc alone could have subducted the equivalent of as many as 3.5 oceans present-day oceans over the age of the Earth.

CONCLUSIONS

We have shown that serpentinized normal faults are present at 50–150 km depth, and are directly linked to lower plane Wadati-Benioff zone seismicity. In addition, we quantified the volume of mineral-bound H_2O in the mantle lithosphere due to hydration from outer rise faulting, and showed that the mantle lithosphere is the most significant contributor to subducted water, transporting more than 10 times as much water as the oceanic crust and sediments put together.

Thermopetrological modeling (Rüpke et al., 2004) and coda observations from the Tonga

Trench (Savage, 2012) suggest that much of the water carried in the lithospheric mantle may be transported to the transition zone. This work suggests that the slab mantle in Japan is able to carry much larger volumes of water than previously thought, providing a mechanism to explain the hypothesized highly hydrated mantle transition zone. This greater flux of H_2O in old subducting slabs may provide an explanation for the Earth's inferred missing water (Jacobsen and van der Lee, 2006).

REFERENCES CITED

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.

Brudzinski, M.R., Thurber, C.H., Hacker, B.R., and Engdahl, R., 2007, Global prevalence of double Benioff zones: Science, v. 316, p. 1472–1474, doi:10.1126/science.1139204.
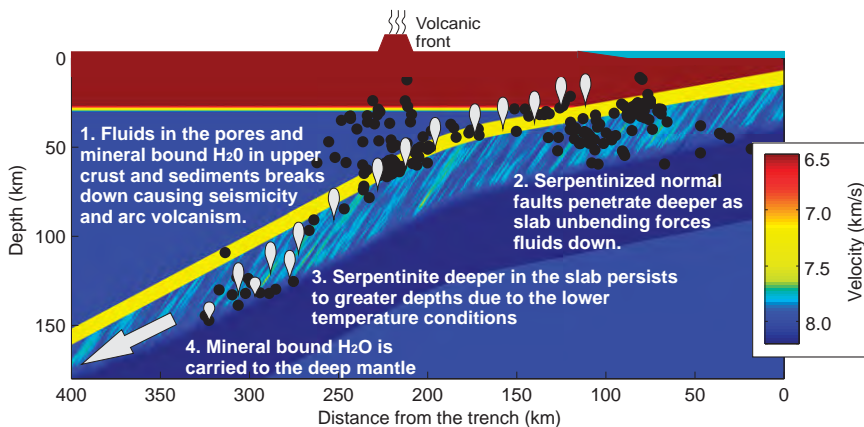

Figure 4. Summary of subduction zone structure inferred for waveform modeling of dispersed P-wave arrivals. Hydration of slab mantle is described by von Kármán function, which provides large-scale elongate structures representing normal fault structures inferred. Smaller scale structures are required to provide observed P-wave coda. Fault depth increase with distance from outer rise is due to downward forcing of fluids (Faccenda et al., 2009, 2012). Black dots show Wadati-Benioff zone (northern Japan) seismicity. Approximate depth at which mineral-bound water is released is shown by white balloon shapes. Some mineral-bound water is delivered to mantle transition zone (e.g., Rüpke et al., 2004; Savage, 2012), indicated by white arrow. Depth of penetration of these hydrated fault zone structures is controlled by temperature at which serpentinite is stable. As slab is heated at depth, stability field of serpentinite becomes restricted to cool core of slab.

Contreras-Reyes, E., Grevemeyer, I., Watts, A.B., Flueh, E.R., Peirce, C., Moeller, S., and Papenberg, C., 2011, Deep seismic structure of the Tonga subduction zone: Implications for mantle hydration, tectonic erosion, and arc magmatism: Journal of Geophysical Research, v. 116, B10103, doi:10.1029/2011JB008434.

Faccenda, M., Gerya, T.V., and Burlini, L., 2009, Deep slab hydration induced by bending-related variations in tectonic pressure: Nature Geoscience, v. 2, p. 790–793, doi:10.1038/ngeo656.

Faccenda, M., Gerya, T.V., Mancktelow, N.S., and Moresi, L., 2012, Fluid flow during slab unbending and dehydration: Implications for intermediate-depth seismicity, slab weakening and deep water recycling: Geochemistry Geophysics Geosystems, v. 13, Q01010, doi:10.1029/2011GC003860.

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.

Grevemeyer, I., Ranero, C.R., Flueh, E.R., Kläschen, D., and Bialas, J., 2007, Passive and active seismological study of bending-related faulting and mantle serpentinization at the Middle American trench: Earth and Planetary Science Letters, v. 258, p. 528–542, doi:10.1016/j.epsl.2007.04.013.

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_2O contents of minerals and rocks at pressure and temperature: Geochemistry Geophysics Geosystems, v. 5, Q01005, doi:10.1029/2003GC000614.

Hacker, B.R., Abers, G.A., and Peacock, S.M., 2003, Subduction factory, 1, Theoretical mineralogy, densities, seismic wave speeds, and H_2O contents: Journal of Geophysical Research, v. 108, 2029, doi:10.1029/2001JB001127.

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.

Hirth, G., and Kohlstedt, D.L., 1996, Water in the oceanic upper mantle: Implications for rheology, melt extraction and the evolution of the lithosphere: Earth and Planetary Science Letters, v. 144, p. 93–108, doi:10.1016/0012-821X(96)00154-9.

Hirschmann, M.M., 2006, Water, melting, and the deep earth H_2O cycle: Annual Review of Earth and Planetary Sciences, v. 34, p. 629–653, doi:10.1146/annurev.earth.34.031405.125211.

Iyer, K., Rüpke, L.H., Phipps Morgan, J., and Grevemeyer, I., 2012, Controls of faulting and reaction kinetics on serpentinization and double Benioff zones: Geochemistry Geophysics Geosystems, v. 13, Q09010, doi:10.1029/2012GC004304.

Jacobsen, S.D., and van der Lee, S., 2006, Earth's deep water cycle: American Geophysical Union Geophysical Monograph 168, 313 p., doi:10.1029/GM168.

Lawrence, J.F., and Wysession, M.E., 2006, Seismic evidence for subduction-transported water in the lower mantle, in Jacobsen, S.D., and van der Lee, S., eds., Earth's deep water cycle: American Geophysical Union Geophysical Monograph 168, p. 251–261, doi:10.1029/168GM19.

Martin, S., and Rietbrock, A., 2006, Guided waves at subduction zones: Dependencies on slab geometry, receiver locations and earthquake sources: Geophysical Journal International, v. 167, p. 693–704, doi:10.1111/j.1365-246X.2006.02963.x.

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.

Peacock, S.M., 2001, Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle?: Geology, v. 29, p. 299–302, doi:10.1130/0091-7613(2001)029<0299:ATLPOD>2.0.CO;2.

Ranero, C.R., Phipps Morgan, J., McIntosh, K., and Reichert, C., 2003, Bending-related faulting and mantle serpentinization at the Middle America trench: Nature, v. 425, p. 367–373, doi:10.1038/nature01961.

Ranero, C.R., Villaseñor, A., Phipps Morgan, J., and Weinrebe, W., 2005, Relationship between bendfaulting at trenches and intermediate depth seismicity: Geochemistry Geophysics Geosystems, v. 6, Q12002, doi:10.1029/2005GC000997.

Rüpke, L.H., Phipps Morgan, J., Hort, M., and Connolly, A.D., 2004, Serpentine and the subduction zone water cycle: Earth and Planetary Science Letters, v. 223, p. 17–34, doi:10.1016/j.epsl.2004.04.018.

Savage, B., 2012, Seismic constraints on the water flux delivered to the deep Earth by subduction: Geology, v. 40, p. 235–238, doi:10.1130/G32499.1.

Seno, T., Zhao, D., Kobayashi, Y., and Nakamura, M., 2001, Dehydration in serpentinized slab mantle: Seismic evidence from southwest Japan: Earth, Planets and Space, v. 53, p. 861–871.

van Keken, P.E., Hacker, B.R., Syracuse, E.M., and Abers, G.A., 2011, Subduction Factory: 4. Depth-dependent flux of H_2O 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.