Seismic Evidence for Subduction-Transported Water in the Lower Mantle

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Abstract:

Seismic attenuation tomography is used to identify a region at the top of the lower mantle that displays very high attenuation and is likely a result of elevated water content. The tomography consists of an inversion of more than 80,000 shear wave differential travel time and attenuation measurements for a 3D whole-mantle model of shear-wave velocity and Q_μ. The global pattern of high and low-attenuation values is dominated by the locations of subduction and of the Pacific and African megaplumes. However, the largest low-Q_μ anomaly occurs at the top of the lower mantle along the east coast of Asia, just above the signature of the subducted oceanic lithosphere. Seismic velocities show only a modest decrease in this region, suggesting that an increase in water is the best explanation for the anomaly. The subducting lithosphere beneath the eastern coast of Asia should remain cold enough well into the lower mantle to carry dense hydrous mineral phase D there in a stable manner. We propose that significant amounts of water are being pumped into the top of the lower mantle beneath Asia via hydrous phase D within subducting Pacific oceanic lithosphere.

Introduction:

Most of this monograph is concerned with water in the upper mantle (down to 410 km depth) and transition zone (410-660 km depth) because these regions are closer to the surface hydrosphere: there are hand samples of upper mantle xenoliths, the mineral physics experiments are at more easily-attained pressures, there are minerals in the transition zone that can hold large concentrations of water, and there is visible cycling of water in and out of subduction zones. Not one of these good reasons also applies to the lower mantle, so it is not surprising that little attention is paid to water in the lower mantle. However, there are important reasons for examining water in the lower mantle, even if it is difficult and relatively inaccessible.

To begin with, the lower mantle accounts for 62% of Earth's volume, so even if lower mantle minerals have low H_2O solubility (<0.1 wt%), the lower mantle may contain more water than the Earth's oceans. How much water the lower mantle can hold is a subject of some debate, and considerable discussion in this volume. Assuming a peridotite composition, most of the lower mantle is Mg-perovskite (~79%), which likely can hold between about 0.05 wt% H_2O [*Bolfan-Casanova et al*., 2003; *Litasov et al*., 2003] and 0.2 wt% H_2O [*Murakami et al*., 2002]. The water solubility for magnesiowustite (~16% of the lower mantle) is more uncertain, with measurements from zero [*Bolfan-Casanova et al*., 2002] to 0.2 wt% H_2O [*Murakami et al*., 2002]. For allowable average lower mantle solubilities (0.05 to 0.2 wt%), the fact remains that the lower mantle may hold as much as 1 to 5 times the water in the Earth's oceans.

While solubility provides an upper limit on lower mantle water concentration, the actual concentration remains uncertain. For water to currently exist in the lower mantle, water must either remain in the form of primative reservoirs or circulate back into the lower mantle. Because partial melts likely transport H_2O from the lower mantle into the transition zone [e.g., *Bercovici and Karato*, 2003] the lower mantle would likely be relatively dry without some form of replenishment. The subduction of cold lithosphere containing high-pressure hydrous phases like phase D provides a mechanism to re-hydrate the lower mantle.

All but the most stalwart hold-outs for layered-mantle convection now believe that subducted lithosphere penetrates into the lower mantle, so that some degree of mass transfer between the upper and lower mantles occurs. Current tomographic models of the mantle show narrow sheets of high velocity material descending continuously from subduction zones down deep into the lower mantle, with no indication of a thermal or chemical boundary layer at the 660-km discontinuity [*Antolik et al*., 2004; *Grand*, 2002; *Karason and van der Hilst*, 2001; *Masters et al*., 2000; *Megnin and Romanowicz*; 2000; *Ritsema and van Heijst*, 2000]. What happens to the slabs within the lower mantle is unclear. Whether slabs penetrate to the core-mantle boundary or founder in the lower mantle, it is clear that subduction acts like a pipeline, transporting materials down into the lower mantle.

Recent mineral physics work also suggests that there may be significant concentrations of water in this pipeline. Large concentrations of water (>> 0.05 wt%) can exist within the oceanic crust and lithosphere in common low-pressure hydrous silicate phases like serpentine. As the lithosphere subducts into the mantle, serpentine becomes unstable, but not all of its water is released: some water continues downward within the slab, locked in a suite of hydrous phases that are stable at different depths [*Shieh et al*., 1998; *Angel et al.*, 2001]. In the lower mantle, large amounts of water can be stored in the cold portions of subducted lithosphere by the presence of phase D, which can hold water of 10 wt % [*Liu*, 1986; *Ohtani et al.*, 1997; *Irifune et al.*, 1998]. When the subducted slab reaches a depth of roughly 1200-1400 km [*Shieh et al.*, 1998], phase D decomposes and H_2O is released into the lower mantle, to be absorbed by Mg-perovskite and magnesiowüstite, potentially filling the top of the lower mantle with vast quantities of water.

This is the story, at least. Difficulties arise in trying to assess how much water really reaches the lower mantle. The largest obstacles include not knowing how much water is initially stored in hydrous phases like serpentine, and how much water sweats out of the subducting slab as it passes down through the upper mantle and transition zone. We have a fairly good idea of how much water comes out of the slab in shallow subduction environments, because this water comes back out of arc volcanoes. *Peacock* [1990] estimated that 8.7×10^{11} kg/year of water enters subduction zones in sediments and ocean crust. The additional amount of water that might be stored in the peridotite layer of subducting lithosphere is much harder to estimate. *Peacock* [1990] also estimated that only 2×10^{11} kg/year of water degasses at arc and mid-ocean ridge volcanoes, suggesting that there is a net flux of water into the mantle.

Even with better constraints on how much water enters the mantle at subduction zones, it is unclear how much water is released and reabsorbed by other hydrous phases in a slab as it passes through the instability depths of the various hydrous phases. Additionally, water may preferentially leave the warm portions of a slab at the bottom of the transition zone depending on temperature and degree of slab stagnation in this layer

[*Komabayashi et al*., 2004]. In contrast, a cold slab may cool and viscously entrain water-rich transition zone minerals down into the lower mantle, creating another mechanism for bringing H_2O into the lower mantle [*Bercovici and Karato*, 2003]. We know that the lower mantle can hold oceans of water even if the average water concentration is low (< 0.05 wt%). And we know that there is a good mechanism for water to reach the lower mantle. But we don't know how much water, if any, is actually down there. We try to address these issues here by providing new seismic evidence that sheds some light on the uncertain fate of water in the lower mantle.

Seismic Attenuation:

Seismic imaging provides our best means of examining the actual state of Earth's deep interior. This imaging is usually done with seismic velocities, which show lateral variations of a few percent within the mantle. An alternative is using the attenuation of seismic waves, which is a measure of the way in which seismic waves are damped out as they propagate. Although seismic wave propagation relies on the elastic behavior of rock and fluids, the Earth does not behave perfectly elastically, of course, and seismic energy is eventually lost to friction (otherwise, the Earth would still be shaking from every earthquake and impact that ever occurred!). This frictional anelastic energy loss, or attenuation, occurs more rapidly for higher-frequency than lower-frequency waves, which gives highly-attenuated seismic signals a strongly smoothed and long-period appearance. The rate at which the seismic energy is damped out is expressed using the seismic quality factor *Q*.(one intuitive definition for *Q* is as the number of cycles it takes a dampened oscillating wave to reach 4%, $e^{-\pi}$, of its original amplitude). High values of *Q* therefore represent highly-elastic materials with a slow rate of frictional energy loss, so a measure of attenuation is often given in terms of the reciprocal of the quality factor, Q^{-1}.

Although seismic attenuation (the reduction in amplitudes of waves on a seismogram) can have several different causes, including reflective scattering, focusing and defocusing, and geometric spreading, the primary cause of seismic attenuation in the mantle is considered to be anelasticity. This frictional energy loss is thought to occur over a wide range of scales from atomic to that of grain-boundary deformational processes, so attenuation is often associated with the same processes as creep, and Q is related to viscosity. This means that attenuation can be used to assess different rheologic properties than those observed with seismic velocities. Lateral variations in Q^{-1} are usually considered to result from temperature variations because Q^{-1} increases exponentially for most silicate materials [*Sato et al.*, 1989; *Jackson*, 2000]. Consequently, seismic attenuation is often used to examine lateral temperature anomalies within the mantle [*Romanowicz and Durek*, 2000].

Relevant to the theme of this monograph, another dominant cause of increased attenuation is the presence of water, which may also reduce viscosity by several orders of magnitude [*Karato*, 2003]. For olivine grain boundary creep, *Mei and Kohlstedt* [2000] found that viscosity was inversely proportional to oxygen fugacity. It has even been proposed that the reason that the asthenosphere has unusually high attenuation and low viscosity is because it is *not* partially melted, and is therefore water-rich in comparison to the lithosphere [*Hirth and Kohlstedt*, 1996; *Karato and Jung*, 1998]. The role of water is not a simple one, however. In fact, because an increase in water fugacity can affect relative changes in the resistance to dislocation motion and also increase the mobility of grain boundaries, the addition of water can change the fabric of silicates, even creating anisotropic textures [*Mackwell et al*., 1985].

Unfortunately for seismologists, very little experimental work exists on quantifying the effect of increased water content on the seismic attenuation of significant mantle phases. Work has been done to examine the effect of water on seismic velocities, but the results are complicated. It is generally considered that seismic velocities of mantle silicates decrease slightly when water is added to their structure [*Inoue et al*., 1998; *Crichton and Ross*, 2000]. For example, altering dry wadsleyite to incorporate 3.4 wt% H_2O results in a modest bulk sound velocity decrease of 2.8% (the effect on velocity of a decrease in elastic moduli is only partially countered by the simultaneous decrease in density). In places like the transition zone, where very high solubilities are possible, the decrease in velocity due to water saturation can be even greater than that expected from temperature increases [*Smyth et al*., 2004; *Jacobsen et al*., 2004].

When it comes to seismic *attenuation*, however, even less is known about the effects of water. However, it is likely that an increase in water content causes a large increase in seismic attenuation [*Karato*, 2003, 2005]. This has been found experimentally [*Jackson et al*., 1992], and is expected theoretically [*Karato*, 2005]. In the latter, the attenuation (Q_μ^{-1}) is proportional to $C_w^{\alpha q}$, where C_w is the water concentration, q = 1 for dislocation mechanisms, q = 2 for grain-boundary mechanisms, and α = 0.3 for the lower mantle. This suggests that a drop of seismic Q_μ in the lower mantle from a value of 300 to 100 could be explained by an increase in water content on the order of a factor of 10 or so. If ambient water concentrations in the lower mantle were initially small (<< 0.1 wt% H_2O), this kind of increase in attenuation could be expected for even modest increases in water content.

Expectations from Radial Models:

Looking at a radial profile of lower mantle Q_μ, it would not be obvious that there is a significant amount of water in the lower mantle. Figure 1 shows the radial model of shear wave attenuation from *Lawrence and Wysession* [2005a]. The radial model of shear wave attenuation (Q_μ^{-1}) is shown in two different parameterizations – with 12 (Figure 1a) and 21 layers (Figure 1b). It is important to note that the model of *Lawrence and Wysession* [2005a] has its best resolution in the lower mantle because it is based upon differential *ScS-S* attenuation measurements. Differential measurements are very useful because the two phases originate from the same earthquake and are recorded on the same seismograph, so errors due to earthquake mislocation and complex ruptures are minimized [*Flanagan and Wiens*, 1990; *Bhattacharyya et al*., 1996; *Warren and Shearer*, 2002]. The similar paths near the source and receiver also greatly reduce the sensitivities due to upper mantle structure. Because the S waves used for this study all turn in the lower mantle and the core-reflecting *ScS* waves cross the lower mantle twice, the coverage and sensitivity for the lower mantle are actually better than for the upper mantle.

Both the 12-layer and the 21-layer models exhibit clear patterns of high attenuation in the asthenosphere that decrease with depth towards the lower mantle. The transition zone has a Q_μ of 276, but this increases to 325 at the top of the lower mantle. The mean attenuation in the upper portion of the lower mantle is roughly constant as a function of depth, and decreases slightly in the mid-lower mantle, with a Q_μ value of 287 at a depth of 1500 km. Based on the low attenuation at the top of the lower mantle one might presume that the this region is relatively dry. However, as mentioned above, other influences such as temperature also cause attenuation variations. For example, the rapid attenuation increase at the base of the mantle is predicted due to the high temperatures within the thermal boundary layer, D″. Perhaps more problematic for interpreting any 1D model of *Q* is that the data are very scattered, indicating a large degree of lateral heterogeneity.

3D Attenuation Observations:

As usual, the 3D world is harder to model and is much more complex than any 1D approximation. So, 1D horizontally-averaged radial models, like those in Figure 1, can be very deceiving. Figure 2 shows a series of horizontal slices through a global 3D model (VQM3DA) of the mantle shear wave attenuation and velocity from *Lawrence and Wysession* [2005b]. This 12-layer model, with equal-area 5-degree blocks, is an inversion using an LSQR algorithm of over 80,000 seismic shear-wave measurements recorded globally for 898 earthquakes during 1990-2002. For a given seismogram, differential travel-time and attenuation measurements are computed between the S wave (the first shear-wave arrival) and later shear-wave arrivals (*S, sS, ScS, sScS, SS, sSS*). As shown in Figure 2, there are enormous lateral variations in lower mantle attenuation, and while the top part of the lower mantle has generally low attenuation, there are regions there of very high attenuation. The most significant of these is a broad low-Q_μ anomaly beneath eastern Asia that extends nearly from the equator to the pole. What is most striking is that this anomaly lies directly above the high-Q and high-velocity anomaly associated with the subducted Pacific oceanic lithosphere in the lower mantle.

This low-Q_μ anomaly beneath eastern Asia extends from about 700 km to 1400 km in depth, and reaches its minimum value of $Q_\mu = 95$ at about 1000 km depth (Figure 3). This minimum occurs beneath northern China, just northwest of Beijing. The mean value of Q_μ is 311 at this depth, and is as high as 367 within the western Pacific subducted lithosphere. Within the "Beijing anomaly" seismic attenuation is almost as high as the mean asthenosphere value, even though it occurs at a depth that generally displays much lower attenuation. Figure 3 shows a checkerboard retrieval test for this depth, demonstrating that there is ample resolution to retrieve a large anomaly of this size and location.

The presence of subduction totally alters the attenuation structure of the mantle, as seen in the vertical great-circle cross-section of Figure 3, which shows relative variations in attenuation as a function of depth. Along the southern part of the cross-section there are higher-than-average Q_μ values at the top of the lower mantle. We consider these to be representative of typical upper lower mantle. At the bottom of the lower mantle along the southern part of this cross-section we see lower-than-average Q_μ values, associated with the southern edge of the African megaplume [*Helmberger et al*., 2000; *Ni et al*., 2005]. At the top of the mantle, the path beneath young oceanic lithosphere has lower-than-average Q_μ values, which is expected due to relatively high temperatures.

Along the northern part of this great-circle cross-section the Q_μ structure is very different. The largely continental path appears as high-Q_μ regions at the top of the mantle. The base of the mantle, which has received cold subducted lithosphere throughout the

Mesozoic and Cenozoic Eras, has anomalously high-Q_μ values. At the top of the lower mantle, above the subducted lithosphere, is a long low-Q_μ anomaly that extends from beneath Southeast Asia around the Pacific Rim to Alaska, and is also seen beneath North America. Using a 5% decrease in Q_μ as the delineation of the Beijing anomaly, its volume is 1.8×10^{10} km^3. If it were to contain 0.1% water, then the mass of water would be slightly greater than the amount of water in the Arctic Ocean.

Interestingly, this puts the radial attenuation models of Figure 1 into a different light. While the mean radial mantle model has fairly low values of attenuation across the whole lower mantle (except at the very base of the mantle), this appears to result from averaging large 3D anomalies with opposing sign. Regions associated with the Pacific and African superplumes have low-Q_μ values in the lower half of the lower mantle, but higher-Q_μ values at the top of the lower mantle (perhaps these regions are dry?). Regions associated with subduction have high-Q_μ values at the bottom of the lower mantle, but can have low-Q_μ anomalies (like the Beijing anomaly) in the top part of the lower mantle. Over the entire Earth, these roughly balance out. Figure 4 shows radial attenuation beneath several locations, demonstrating that the lateral variation, while as large laterally as vertically, is consistent for similar types of structures. Nevertheless, the 1D radial average of the 3D model is very similar to that shown in Figure 1.

Discussion and Conclusions:

The lower-mantle high-attenuation anomaly beneath eastern Asia is very unusual, so it warrants a discussion of what could cause it. First, it is important to establish that the anomaly is real and required by the data. Seismic attenuation is a difficult parameter to use, and attenuation tomography is in its relative infancy. Yet, there is strong evidence indicating that this signal is real. First, all of the techniques in the study are well-established. This includes both the methods used to obtain the differential attenuation measurements [*Flanagan and Wiens*, 1990; *Bhattacharyya et al*., 1996] and the LSQR tomographic inversion method [*Paige and Saunders*, 1982; *Nolet*, 1987; *Masters et al*., 1996]. Second, this region beneath eastern Asia has some of the best data coverage of the mantle, and the checkerboard resolution tests (Figure 3) show that we have good resolution for structures smaller-scale than this anomaly.

In addition, we can compare some of our results to an existing model of mantle attenuation to see if our results are reasonable. While there are no other global models for the lower mantle that we can compare with, there are upper mantle models. Figure 5 shows our attenuation model compared with the attenuation model QRLW8 of *Gung and Romanowicz* [2002] at a depth of 300 km. The *Gung and Romanowicz* [2002] model is inverted from surface waves, and therefore has its best resolution closer to the surface because only long-period surface waves sample deeply into the upper mantle. In contrast, our model has better coverage and resolution in the lower mantle, but we still have strong signal retrievability in the upper mantle. It is clear from Figure 5 that these models are very similar, sharing the general trend that old continents have low-attenuation deep keels and ocean regions at this depth have high attenuation. Many of the smaller-scale anomalies are common to both models as well. To have two different models using two very different datasets and inversion methods give similar results is a reassuring measure of resolvability. As 3D heterogeneity is generally weaker in the lower mantle [e.g., *Masters et al*., 1996] than in the upper mantle, scattering and multipathing have weaker effects here, suggesting that the lower mantle is even less contaminated than the upper mantle, which we know to be consistent with other results.

Assuming, then, that the Beijing anomaly is real, the next question is whether it is a measure of anelasticity. As *Cormier* [2000] showed, scattering from small-scale heterogeneities can, in some cases, cause pulse broadening that has a similar appearance to the effects of anelasticity. Very little is known about the possible existence of very-small-scale heterogeneity in the lower mantle. *Kaneshima and Helffrich* [1998] found evidence of mantle scattering northeast of the Mariana subduction zone from S-to-P conversions, and interpreted them as chemically-distinct reservoirs. *Kaneshima and Helffrich* [1999] and *Castle and van der Hilst* [2002] postulated that these reflections, at a depth of about 1600 km, were due to fragments of ancient subducted oceanic crust. However, *Helffrich* [2002] estimated that these scatterers may be on the order of 8 km in diameter, and *Brana and Helffrich* [2004] identified a region at the base of the mantle with scatterers they estimated to be less than a kilometer in diameter. The presence of scatterers in the mantle is also consistent with *Hedlin et al.* [1997], who used *PKP* precursors to suggest that small-scale scatterers were distributed throughout the mantle.

The possibility of seismic scatterers causing the attenuated seismic signals cannot be ignored. However, it is not likely. The effect is not expected to be so large as to reduce Q_μ from 300 to 100. It would also be difficult for the scattering to mimic the constant-Q_μ behavior over the very wide frequency band of 0.01 – 0.1 Hz, which is what we observe in the slopes of the spectral quotients of our differential phases. There also has to be some mechanism to explain the location of the scatterers, lying above the subducted lithosphere in the lower mantle. One hypothesis is that the former ocean crust could break into many small pieces and delaminate from the rest of the subducting lithosphere. However, this is problematic because the ocean crust is rich in garnet, which is much stiffer than the surrounding mantle [*Karato*, 1997], and the effects of seismic scattering would be countered by a decrease in anelasticity. Advances in theoretical seismology need to be made in order to adequately measure the seismic attenuation of body phase resulting from various distributions of elastic scatterers in the mantle.

If the assumption is made (which it usually is) that the high-attenuation anomaly is representative of anelasticity, then we need to address the different possible causes for it. One possible factor is grain size. Experiments have shown that smaller grain sizes cause increased seismic attenuation [*Jackson et al*., 2001]. This likely results from the increased surface-to-volume ratio of smaller grains, which promotes frictional heat loss through grain boundary deformation. Small mineral grains can also align into microfractures, which can be localizations for high levels of strain accumulation, and result in increased seismic attenuation [*Cooper*, 2002].

It is reasonable to suggest that the region just above subducted lithosphere at the top of the lower mantle might have smaller grain sizes if the rock is brought down through viscous drag along with the subducted lithosphere. Transition zone phases likely convert to perovskite and periclase as they pass into the lower mantle – more rapidly for the $(Mg,Fe)_2SiO_4$ system (where spinel converts to perovskite and magnesiowüstite over a narrow pressure range), more slowly for the $(Mg,Fe)SiO_3$ system (where the garnet transition to perovskite and magnesiowüstite is quite gradual). As they do, new perovskite and periclase crystals nucleate, and for some distance into the lower mantle, there might be a smaller mean grain size. Because Q_μ is often considered to be proportional to the square root of the grain size [*Cooper*, 2002], reducing the grain size by a factor of 10 could provide the reduction in Q_μ by a factor of 3.

There are problems with the reduced grain size scenario. If viscous drag were bringing surrounding transition zone material into the lower mantle, it should happen on both sides of the slab. However, the low-Q anomaly is only observed above the subducted lithosphere, not beneath it. Additionally, if the anomaly were due to grain size and viscous drag, most other slabs in the lower mantle would show evidence of low-Q anomalies surrounding the slab, but this is not the case. Another problem with this idea is that it is hard to drag such a large volume of material down into the lower mantle with the subducting lithosphere.

While temperature is the usual prime suspect in interpreting seismic attenuation anomalies, especially high-attenuation anomalies, temperature is an unlikely cause in this case. Ongoing subduction for more than 200 Ma has transported an enormous volume of cold oceanic lithosphere into the mantle beneath eastern Asia. Even though the thermal conductivity of rock is exceedingly low, and so might not be an efficient way of chilling the lower mantle, it is hard to conceive that adding cold material would warm the lower mantle. We also have to keep in mind the size and magnitude of this low-Q_μ anomaly. A Q_μ value of less than 100 is on par with asthenosphere values, and much lower than the low-Q_μ anomalies associated with the megaplumes beneath the Pacific and African plates. While the megaplumes are evident in our model as broad slightly-low-Q_μ features, they do not drop to asthenospheric values. There is no known evidence of plume-like structures in the area of the Beijing anomaly from seismic tomographic studies [*Montelli et al.*, 2004]. Additionally, there is no known mechanism capable of creating such a large, horizontal thermal anomaly, stretching from the equator almost to the pole and lying atop a subduction zone. It is difficult to envisage a mechanism that could transport such a large volume of hot material around or through to the top side of a slab, and keep it there.

If the anomaly were due to increased temperatures, there would also be a very large low-velocity anomaly. This is graphically demonstrated in Figure 6, which is a plot based upon the calculations of Karato [1993] describing variations in Q and V as functions of water and temperature. While these relations are intended for upper mantle minerals and pressures, the general trend should hold true for the lower mantle. An increase in Q^{-1} of 200% (a decrease in Q from 300 to 100) requires a temperature increase of ~450°C. Yet, such a large temperature increase would also cause a decrease in seismic shear velocity of ~4%, which is clearly not observed in any seismic velocity model.

The remaining candidate for this low-Q_μ anomaly is an elevated concentration of water. Subducted lithosphere can act as an aqueduct, carrying water contained in hydrous phases continuously down into the lower mantle. As mentioned earlier, and elsewhere in this volume, hydrous phase D could hypothetically be an efficient means of carrying water down into the lower mantle [*Liu*, 1986; *Ohtani et al*., 1997; *Irifune et al*., 1998; *Shieh et al*., 1998; *Angel et al*., 2001]. The key factor to this is a low slab temperature (< 1000° C) in the transition zone and lower mantle [*Komabayashi et al*., 2004]. As the subducting lithosphere sinks into the mantle and heats up, it dehydrates and loses its water into the overlying mantle. Much of this water is released at a depth of about 100 km, which causes water-enriched melting in the overlying mantle wedge that leads to volcanic arc magmatism. Additional water is probably released into the transition zone, perhaps through the breakdown of dense hydrous magnesium silicate phases. If the subducting slab is cold enough for hydrous phase D to remain stable, then water remains within its cold, central core down to depths of 1200-1400 km [*Shieh et al*., 1998]. The slabs sinking beneath the western Pacific are very cold, and have some of the highest thermal parameter values of any subduction zone (product of the slab age, plate velocity, and the sine of the dip angle) [*Kirby et al*., 1996], so they are efficient at bringing cold material deep into the lower mantle, perhaps down to 1400 km depth.

There need not be a large amount of phase D present in the subducting lithosphere to cause a large concentration of water at the top of the lower mantle. The rapid rate and long duration of subduction beneath the western Pacific would provide sufficient flooding of water in the lower mantle to account for the observed anomaly. Interestingly, the total amount of water within the anomaly need not be large. The relative difference in saturation between the anomalous region and the surrounding mantle is more important than the absolute amount. For example, an increase in the amount of water in the lower mantle by a factor of 10-20 could be sufficient to cause the decrease in seismic Q_μ from 300 to 100 [*Karato*, 2005]. Interestingly, this large change in water likely does not cause a correspondingly large change in seismic velocity, as seen in Figure 6. This is important, because as Figure 2 shows, there is only a slight corresponding negative velocity anomaly in the region of the large attenuation anomaly.

The model we suggest is shown in Figure 7. Water is brought into the lower mantle via the subducting Pacific lithosphere, which is old, cold and sinking fast enough for hydrous phase D to be stable to depths of at least 1400 km. As the slab gradually warms, phase D becomes less stable and the water is released. Because the entire slab does not cool instantaneously, the water is released over a broad range of depths. Our attenuation model suggests that there is a large difference in water concentration between the Beijing anomaly and the ambient upper lower mantle, but this can occur in two ways: 1) It is possible that the top of the lower mantle is normally quite dry (<< 0.1 wt% H_2O), with water contents well below the maximum saturation (on the order of 0.1 wt% H_2O). The regional flooding of the lower mantle might still be below saturation levels, but the elevated levels would be enough to cause the large attenuation increase. 2) The ambient lower mantle might normally contain higher concentrations of water, but the lower-mantle region above the subducted Pacific slab could be very over-saturated. This second scenario would require that fluids have a low diffusion rate, otherwise they might rapidly escape up into the transition zone, which is known to have a much higher water capacity. Saturation would likely result in partial melt, which could have a variety of effects on seismic velocity and quality factor depending on the geotherm, the type of melting, and the geometry of flow [*Karato and Jung*, 1998]. However, the lack of a strong seismic velocity anomaly likely indicates that there is not likely much -if any- melt present, so the anomaly is not saturated.

In either case, the flow rates of water are an important, and as of yet unconstrained factor. Laboratory experiments suggest that water might be stable in a solid ice state at deeper lower mantle pressures [*Lin et al.*, 2005], but this has not been experimentally observed for upper lower mantle conditions. The low-Q_μ anomaly is distributed over a large volume. So either fluid transport (most likely along grain boundaries) or advection of mantle rock (facilitated by decreased viscosities) distributes the water efficiently. The increased water levels likely have enormous, if poorly understood, implications for convection due to the strong dependencies of viscosity upon water. It is usually assumed that an increase in water content lowers a rock's melting point and weakens it, decreasing its viscosity [*Hirth and Kohlstedt*, 1996]. However, there are also suggestions that an increase in water might have the opposite effect, actually causing the rock to stiffen while still displaying an increased seismic attenuation [*Karato*, 2005]. If the rock were to stiffen, then there would need to be high fluid flow rates in order to allow for a broad distribution of the water.

Another unanswered question regarding the fate of dehydrated water is whether the water in the lower mantle interacts with the transition zone, and if so, then how? The low-Q_μ anomaly has a sharp, roughly flat upper boundary that coincides with the 660-km discontinuity. Therefore, either the water concentration does not increase in this region of the transition zone, or the rise in water concentration is small relative to the average transition zone water concentration. It is thought that transition zone is likely > 20 times more hydrated than the lower mantle [*Bercovici and Karato*, 2003], and that the attenuation in the transition zone is equivalently low [e.g., *Durek and Ekstrom*, 1996], suggesting that the addition of water under transition zone conditions has little effect on attenuation there. This makes sense because the attenuation is a measure of the instability of a material, and the transition zone is perfectly stable containing large quantities of water. It is also possible that water may pass up into the transition zone, but that some of that rock may be advected back down into the lower mantle adjacent to the subducting lithosphere, creating a circulation vortex that may trap water at the region above and below the 660-km discontinuity in this region.

As with many geological processes, there may be multiple causes influencing the anomaly. The low-Q_μ anomaly could involve the presence of water combined with small grain sizes due to a phase change to perovskite/periclase and also combined with the presence of scattering chemical heterogeneities associated with fragments of post-eclogitic ocean crust. Yet, as with dehydration in the upper mantle wedge [*Zhao et al.*, 1992], it seems that dehydration has a significant role in the formation of this anomaly. Imaging the presence of water in the deep mantle is a relatively recent endeavor [*van der Meijde et al.*, 2003], but one that could prove to be very important in understanding the mechanisms of convection within planets.

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Figures:

Figure 1. Radial models of seismic shear attenuation obtained by inverting ~30,000 differential *ScS/S* attenuation values using a niching genetic algorithm (NGA) [*Lawrence and Wysession*, 2005a]. a) 12-layer and b) 21-layer quality factor models produced from the NGA inversions using shallow events (dashed), deep events (dotted), and both shallow and deep events (solid). The shaded area represents all models with less than twice the most optimal model's cost (or error) for the combined shallow and deep event NGA inversion. c) These quality factor models are similar with varying degrees to

viscosity models of 1) *Hager and Richards*, [1989], 2) *Forte and Mitrovica* [2001], 3) *Forte and Mitrovica* [1996], 4) *Steinberger and Calderwood* [2001], and 5) *McNamara et al.*, [2003].

Figure 2. Six horizontal cross-sections through the quality factor (Q_μ) and shear velocity models of *Lawrence and Wysession* [2005b] showing large 3-D variation in the whole mantle. Blue indicates elevated Q_μ and velocity while red indicates low Q_μ and velocity. In the upper mantle the highest Q_μ is associated with dehydration and subduction processes. Deeper in the mantle (700-1400km) a sizeable attenuation anomaly is strikingly visible beneath eastern Asia (a reduction of Q_μ from the mean value of around 300 to a value of around 100). High Q_μ and velocity form a ring around the Pacific in the lower mantle.

Figure 3. Great-circle vertical cross-section and horizontal cross-section at a depth of 1000 km through the attenuation model of *Lawrence and Wysession* [2005b], with accompanying checkerboard resolution test images. There is a long high-attenuation (low-Q_μ) anomaly at the top of the lower mantle just above the locations of the subducted Pacific ocean lithosphere along the western and northern rim of the Pacific.

Figure 4. . Radial quality factor of the mantle from QLM9 (thin solid) [*Lawrence and Wysession*, 2005a], the radial average of VQM3DA (thick solid), and vertical Q structure beneath North America (thin dashed), eastern Asia (thick dashed), and southern Africa (grey).

Figure 5. Comparison of the body shear wave attenuation model of *Lawrence and Wysession* [2005b] compared with the surface wave attenuation model QRLW8 of *Gung and Romanowicz* [2002] at a depth of 300 km. These models are constructed with different data types and different inversion methods, which lends support to the reality of the shared anomalies.

Figure 6. Plot showing the changes in temperature and water concentration that would be needed to give a 200% increase in attenuation, based upon *Karato* [1993]. Note that the increase in temperature is expected to also cause a large velocity decrease, which is not observed in the data.

Figure 7. Tomographic slices through the high-attenuation anomaly, with some possible flow paths for the water that is being pumped into the lower mantle via subduction of oceanic lithosphere. a) Water can enter the deep mantle in hydrous phases contained within a cold slab. b) Hydrous transition zone minerals may be viscously entrained along with c) a cold slab containing hydrous phase D. d) at 1100 to 1400 km depth hydrous phase D may break down releasing water into the lower mantle. e) This water may percolate or diffuse through the lower mantle and possibly f) back up into the transition zone. g) Alternatively, water may continue to circulate through the lower mantle.

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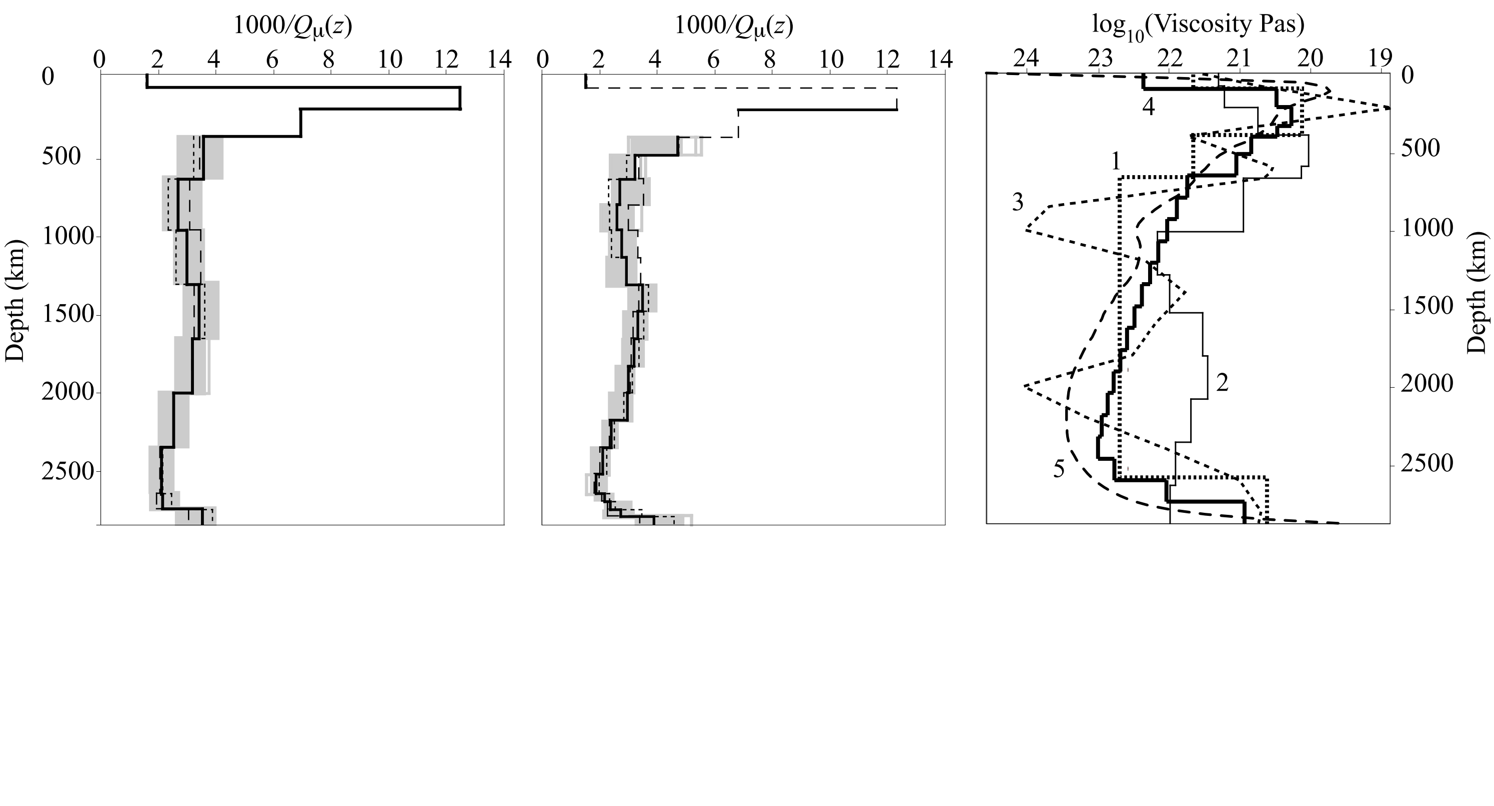

1000/$Q_\mu(z)$
0
2
4
6
8
10
12
14
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500
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1500
2000
2500
Depth (km)
1000/$Q_\mu(z)$
0
2
4
6
8
10
12
14
log$_{10}$(Viscosity Pas)
24
23
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19
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2000
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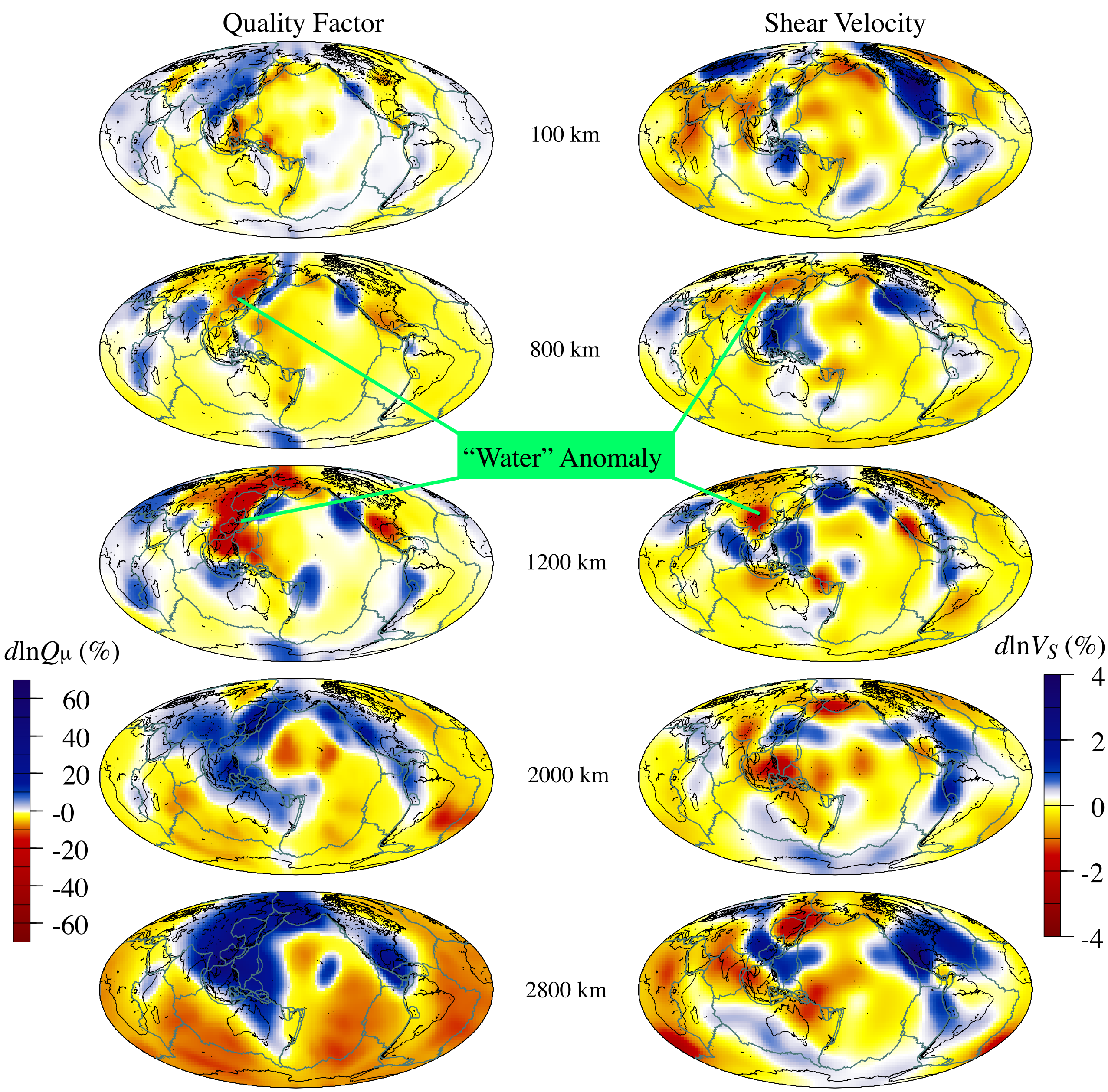
Quality Factor
Shear Velocity
100 km
800 km
"Water" Anomaly
1200 km
2000 km
2800 km
$d\ln Q_\mu$ (%)
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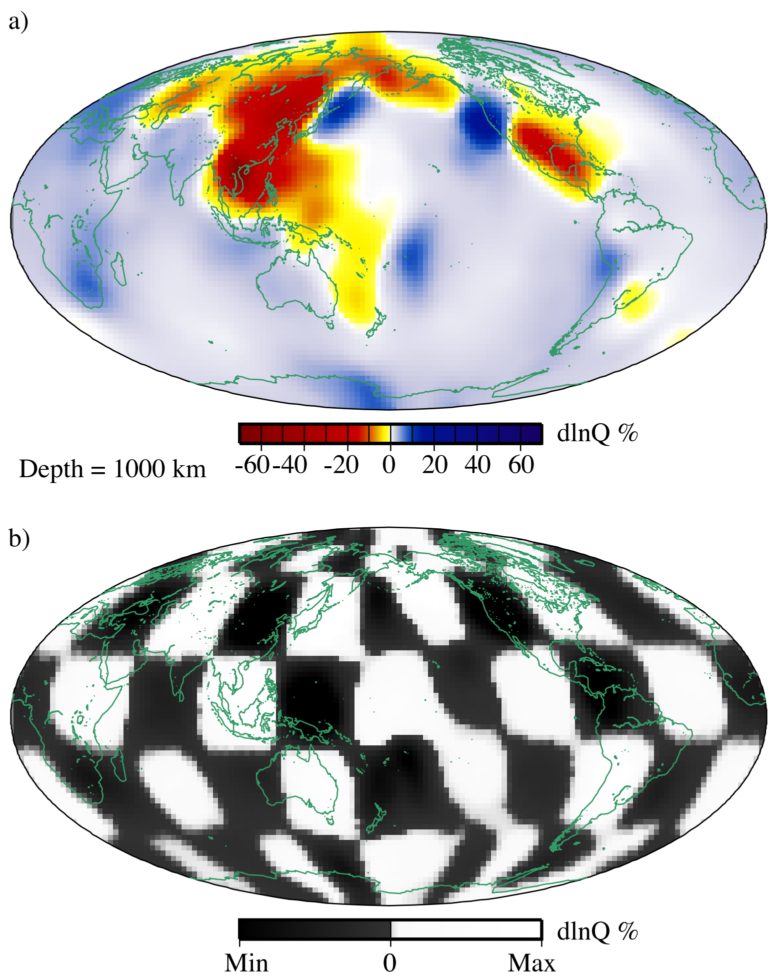
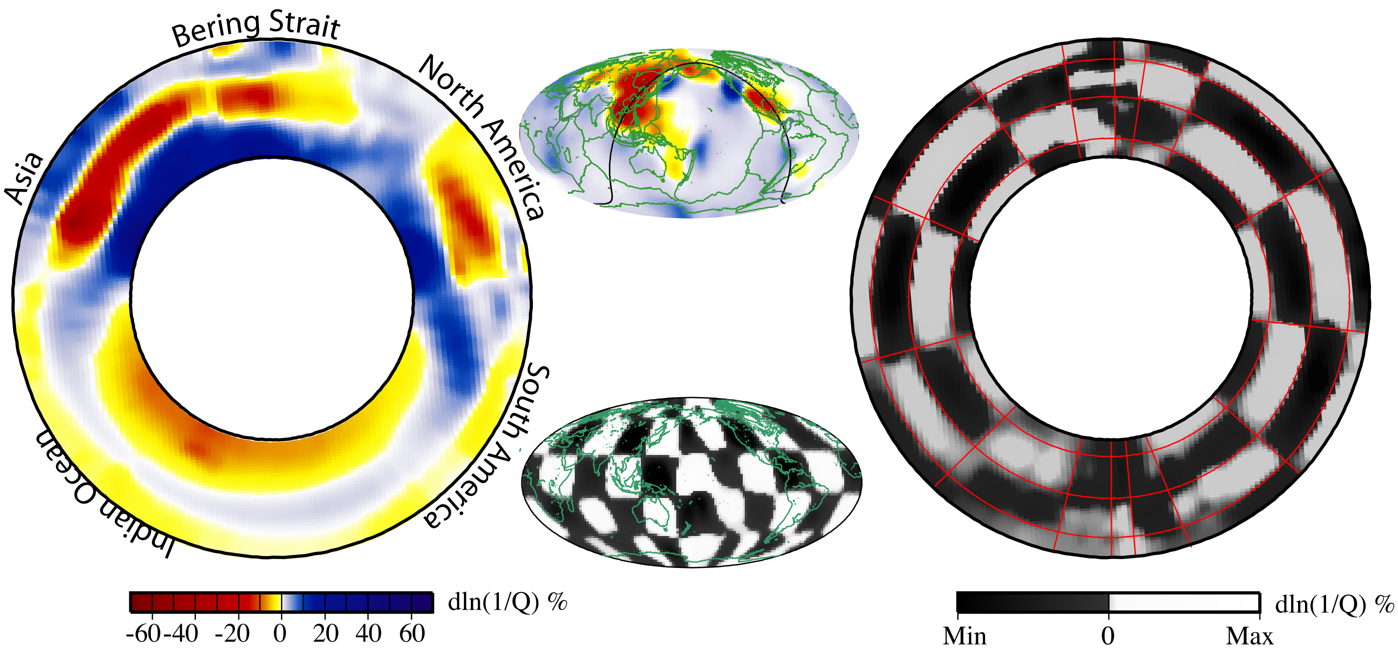
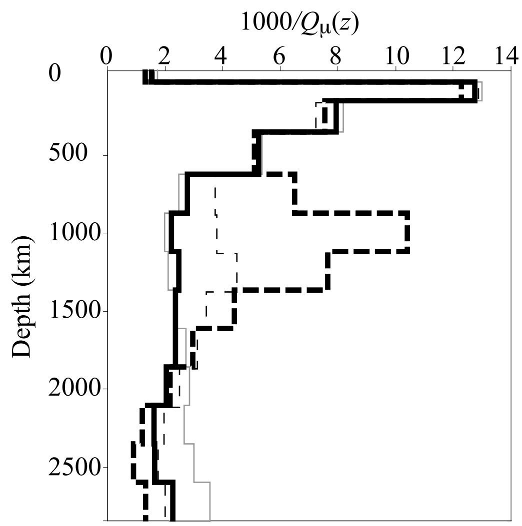
-20
-40
-60
$d\ln V_S$ (%)
4
2
0
-2
-4


a)
dlnQ %
-60 -40 -20 0 20 40 60
Depth = 1000 km
b)
dlnQ %
Min
0
Max


Bering Strait
North America
Asia
South America
Indian Ocean
-60 -40 -20 0 20 40 60
dln(1/Q) %
Min
0
Max
dln(1/Q) %



1000/$Q_\mu(z)$
0
2
4
6
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12
14
0
500
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1500
2000
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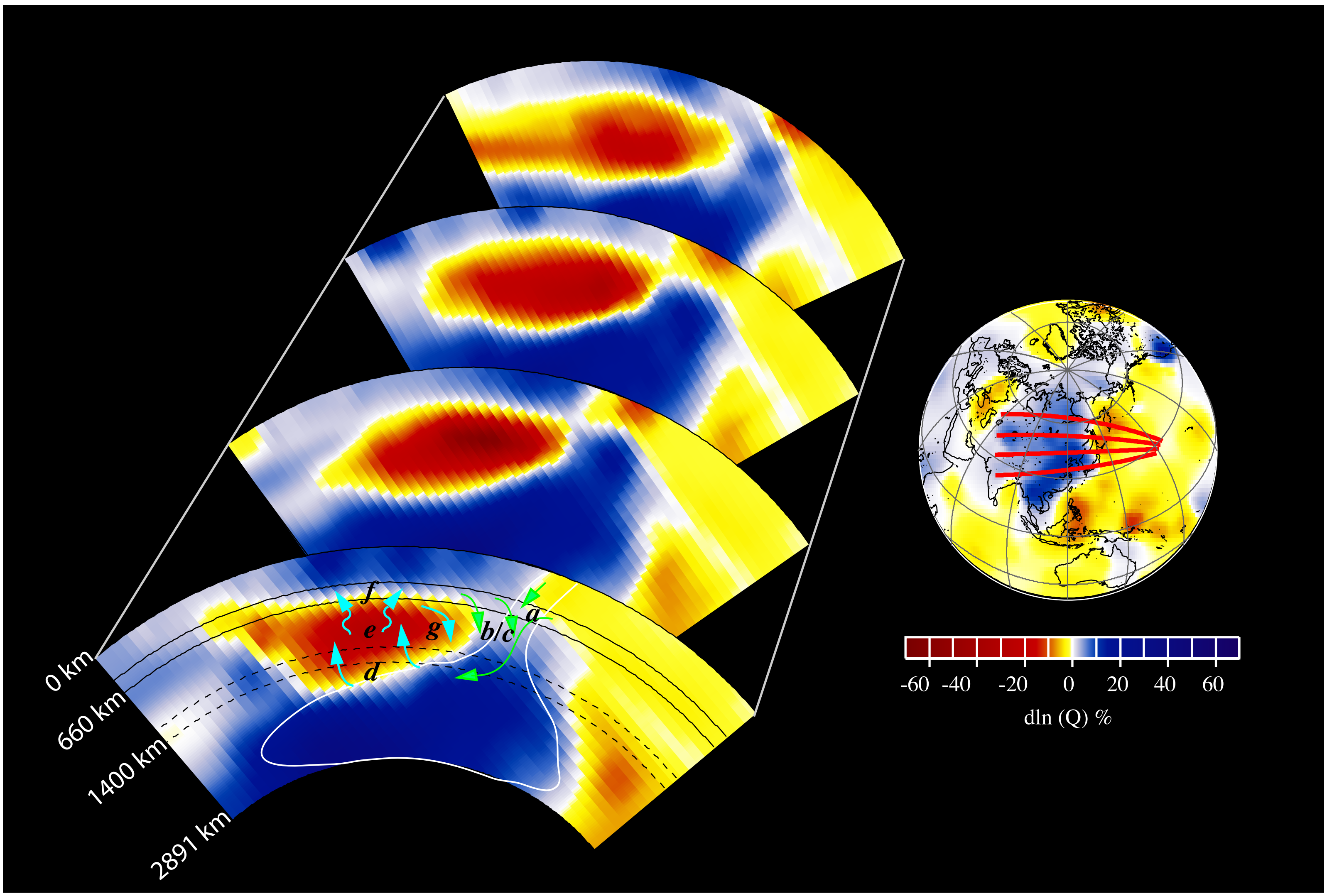
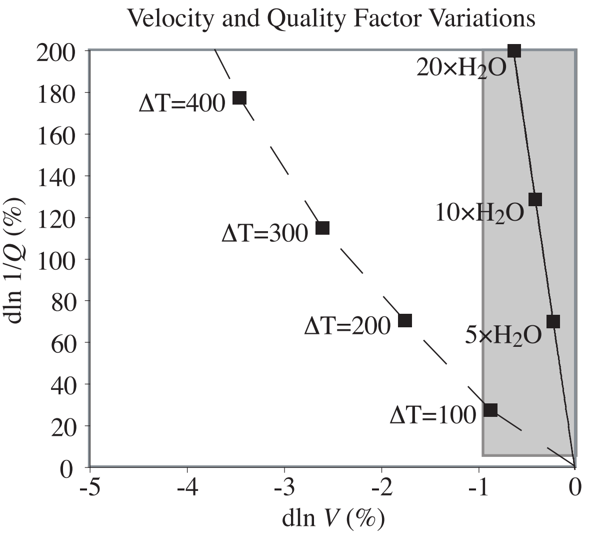
Depth (km)



0 km
660 km
1400 km
2891 km
a
b/c
d
e
f
g
-60
-40
-20
0
20
40
60
dln (Q) %



Velocity and Quality Factor Variations
200
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140
120
100
80
60
40
20
0
dln 1/Q (%)
-5
-4
-3
-2
-1
0
dln V (%)
ΔT=400
ΔT=300
ΔT=200
ΔT=100
20×H2O
10×H2O
5×H2O