Seismic Evidence for Subduction-Transported Water in the Lower Mantle

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We use seismic attenuation tomography to identify a region at the top of the lower mantle that displays very high attenuation consistent with an elevated water content. Tomography inversions with >80,000 differential travel-time and attenuation measurements yield 3D whole-mantle models of shear velocity (V_S) and shear quality factor (Q_μ). The global attenuation pattern is dominated by the location of subducting lithosphere. The lowest Q_μ anomaly in the whole mantle is observed at the top of the lower mantle (660–1400 km depth) beneath eastern Asia. The anomaly occupies a large region overlying the high-Q_μ sheet-like features interpreted as subducted oceanic lithosphere. Seismic velocities decrease only slightly in this region, suggesting that water content best explains the anomaly. The subducting of Pacific oceanic lithosphere beneath the eastern Asia likely remains cold enough to transport stable dense hydrous mineral phase D well into the lower mantle. We propose that the eventual decomposition of phase D due to increased temperature or pressure within the lower mantle floods the mantle with water, yielding a large low-Q_μ anomaly.

INTRODUCTION

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. Estimates for the water solubility in silicate perovskite range from a few ppm [*Bolfan-Casanova et al.*, 2003] up to 0.2–0.4 wt% (i.e., 2000–4000 ppm H_2O by weight) [*Litasov et al.*, 2003; *Murakami et al.*, 2002]. The water solubility for magnesiowüstite (~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 lower mantle solubilities of 0.05 to 0.2 wt%, the lower mantle may hold 1 to 5 times the water in the Earth's oceans.

While solubility provides an upper limit on possible water concentration, the actual concentration of the lower mantle remains uncertain. For water to reside in the lower mantle, water must either exist in primitive 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 should be relatively dry without replenishment. The subduction of cold lithosphere containing high-pressure hydrous phases, like phase D, provides a mechanism to re-hydrate the lower mantle.

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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]. Whether slabs penetrate to the core-mantle boundary or founder within the lower mantle, subduction clearly transports large volumes of material down into the lower mantle.

Recent mineral physics work suggests that significant volumes of water may also be transported into the lower mantle. 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 top of the upper 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 10 wt % water [*Ohtani et al.*, 1997]. When the subducted slab reaches a depth of 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.

Difficulties arise in estimating how much water reaches the lower mantle because we do not know how much water is initially stored in hydrous phases nor how much leaves the subducting slab at shallower depths. 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] estimates that 8.7×10^{11} kg/year of water enters subduction zones in sediments and ocean crust. Some amount of water may also be stored in the peridotite layer of subducting lithosphere. *Peacock* [1990] estimates 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 at subduction zone regions.

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. 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]. The lower mantle can hold oceans of water even if the average water concentration is low (< 0.05 wt%) and 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 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, showing lateral variations of a few percent within the mantle. In this study we use seismic attenuation, which ideally is a measure of energy loss per cycle of a seismic wave. Although seismic wave propagation relies on the elastic behavior of rock and fluids, the Earth does not behave perfectly elastically, and seismic energy is continuously lost to friction. This frictional anelastic energy loss, or attenuation, occurs more rapidly for higher-frequency than lower-frequency waves, which gives highly-attenuated seismic signals a smoothed and long-period appearance. The rate at which the seismic energy is damped out is expressed using the seismic quality factor Q (often conceptualized as the number of cycles it takes a dampened oscillating wave to reach $e^{-\pi}$, or ~4 %, of its original amplitude). High values of Q represent highly-elastic materials with slow rates of energy loss, so attenuation is often quantified in terms of the reciprocal of the quality factor, Q^{-1}.

Although seismic attenuation 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 often considered to result from temperature variations [e.g., *Romanowicz and Durek*, 2000] because Q^{-1} increases exponentially with temperature for most silicate materials [*Jackson*, 2000].

Relevant to this monograph, the presence of water can cause attenuation to increase drastically and viscosity decrease by several orders of magnitude [*Karato*, 2003]. For olivine grain boundary diffusion creep, *Mei and Kohlstedt* [2000] found that strain rate is proportional to water fugacity (i.e. OH concentration) approximately to the first power. It is 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. 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 [*Katayama et al.*, 2004].

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 bulk sound velocity decrease of 2.8%. In 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].

Even less is known about the effects of water on seismic *attenuation*. 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 $\alpha = 0.3$ 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

Radial profiles of lower mantle Q_μ, from *Lawrence and Wysession* [2006a] do not show evidence of a significant amount of water in the lower mantle. They found that the transition zone has an average Q_μ of 276, increasing to 325 at the top of the lower mantle. The mean attenuation in the uppermost 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. The low attenuation at the top of the lower mantle suggests that the region should be relatively dry. However, the anelastic behavior of lower mantle phases is poorly understood, so there is no baseline by which to determine this.

3D ATTENUATION OBSERVATIONS

Three-dimensional modeling may show otherwise. Plate 1 shows a series of horizontal slices through a global 3D model (VQM3DA) of the mantle shear wave attenuation and velocity from *Lawrence and Wysession* [2006*b*]. 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 Plate 1, 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 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. It is striking 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 (Plate 2). This minimum occurs beneath northern China, just northwest of Beijing. The mean value of Q_μ is 311 at this depth with a maximum Q_μ of 367 within the western Pacific subducted lithosphere. Within the "China anomaly" seismic attenuation is almost as high as the mean asthenosphere value, even though the mean attenuation at that depth is much lower. Plate 2 shows a checkerboard retrieval test for this depth, demonstrating that there is ample resolution within the data 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 Plate 2, 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, and 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,

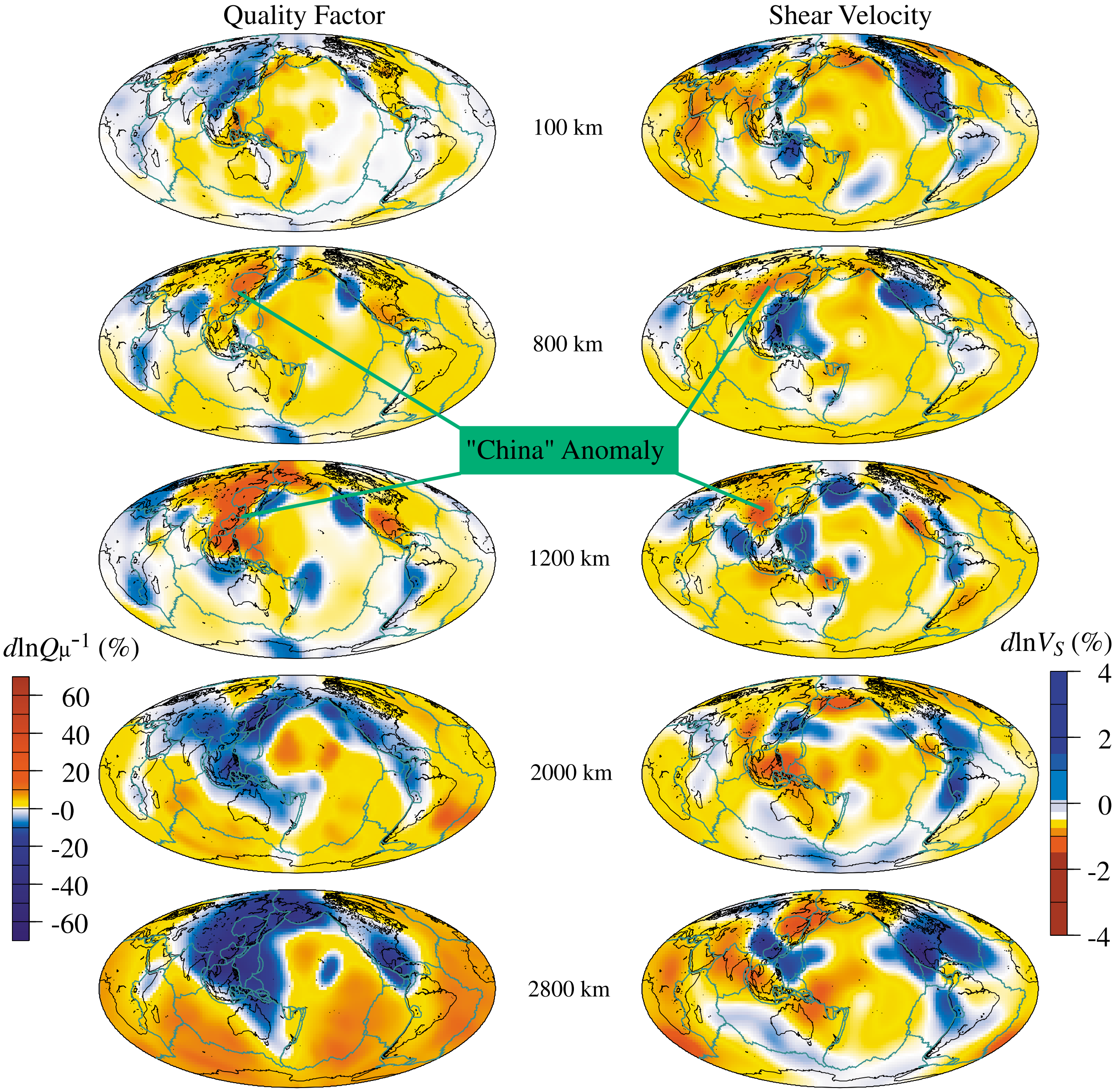

Plate 1. Six horizontal cross-sections through the quality factor (Q_μ) and shear velocity models of *Lawrence and Wysession* [2006b] showing large 3-D variation in the whole mantle. Blue indicates elevated Q_μ and velocity while red indicates low Q_μ and velocity. In the upper mantle the highest Q_μ is associated with dehydration and subduction processes. Deeper in the mantle (700–1400 km) a sizeable attenuation anomaly is 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.

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 China 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.

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, as well as if 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 good evidence that this signal is real. All of the techniques in the study are well-established, including 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]. The region beneath Asia also has some of the best data coverage of the mantle, and checkerboard resolution tests (Plate 2) show that we have good resolution for structures smaller-scale than this anomaly.

However, checkerboard resolution tests only show what is computationally possible from the inversion. A complication arises from the fact that seismic velocity anomalies will cause ray paths to anomalously bend (focus and defocus), which changes wave amplitudes and might mimic attenuation anomalies [*Ritsema et al.*, 2002]. However, the effect is hard to isolate because velocity models are highly contaminated by attenuation effects to begin with. The degree to which elastic effects affect attenuation will not be known until extensive modeling with fully 3-D synthetic seismograms can be done, which is computationally prohibitive at this point. Because of these concerns, we keep our model fairly low-order and do not attempt to interpret small-scale anomalies. In this context, we feel that the attenuation observed here is not due to velocity variations because (1) the lower-mantle attenuation anomalies are so much larger than the velocity anomalies, and (2) where there is overlap with existing attenuation models using other data and methods, agreement is very good.

While there are no other global models for the lower mantle that we can compare with, there are upper mantle models. Plate 3 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 Plate 3 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. Note that the effects of elasticity would be very different for both models, suggesting that effects of elastic focusing do not dominate. 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 values are even less contaminated than in the upper mantle, where our model is consistent with other results.

Assuming that the China anomaly is real, and not an artifact of elastic focusing effects, 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 China anomaly cannot be ignored. However, we do not think it is 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. We need also 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 within the mantle.

If the China anomaly is the result of anelasticity, then there are several different possible causes for it. One is grain size. Experiments show that smaller grain sizes cause increased seismic attenuation [*Jackson et al*., 2001] due to increased surface-to-volume ratios of smaller grains, which promotes frictional heat loss through grain boundary deformation. Small grains can also align into microfractures, are localizations for high levels of strain accumulation, and result in increased seismic attenuation [*Cooper*, 2002].

The region just above subducted lithosphere at the top of the lower mantle might have smaller grain sizes if rock is brought down through viscous drag along with the subducted lithosphere. Transition zone phases will 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). New perovskite and periclase crystals will nucleate, and for some distance into the lower mantle, there might be a smaller mean grain size. Because Q_μ may 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.

However, if viscous drag were bringing surrounding transition zone material into the lower mantle, this should happen on both sides of the slab. The low-Q anomaly is only observed above the subducted lithosphere, not beneath it. Also, if the anomaly were due to grain size, other slabs entering the lower mantle would show evidence of low-Q anomalies surrounding them, but this is not observed. It is also hard to drag such a large volume of material as this 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 > 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. 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, which appear in our model as only broad slightly-low-Q_μ features. There is no known evidence of plume-like structures in the area of the China anomaly from seismic tomographic studies [*Montelli et al*., 2004].

If the anomaly were due to increased temperatures, there would also be a very large low-velocity anomaly. This is suggested in Figure 1, which is an extrapolation 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% here (a decrease in Q from 300 to 100) requires a temperature increase of ~450°C. However, 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 in this area.

The remaining candidate for this low-Q_μ anomaly is an elevated concentration of water. The key factor to the transport of water into the lower mantle via slab subduction is maintaining a low slab temperature (< 1000°C) [*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. If the subducting slab in the lower mantle is cold enough for hydrous phase D to remain stable,

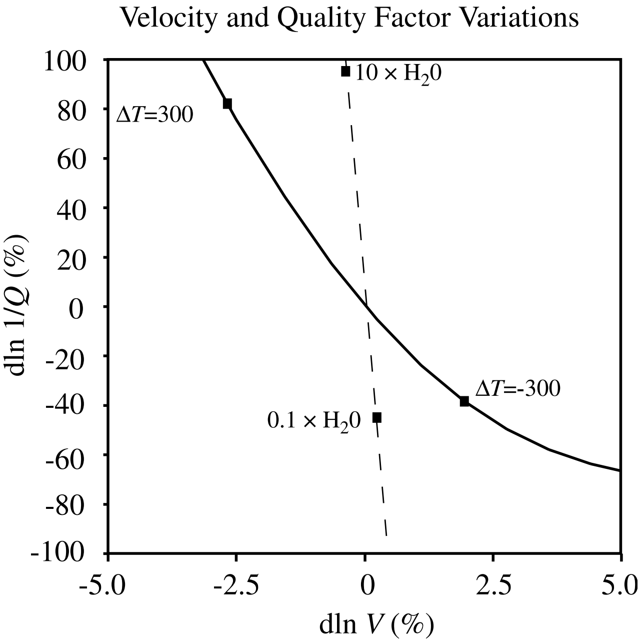

Figure 1. Plot showing the changes in temperature and water concentration that would be needed to give a 200% increase in attenuation, based upon *Karato* [1993]. Note that the increase in temperature is expected to also cause a large velocity decrease, which is not observed in the data.

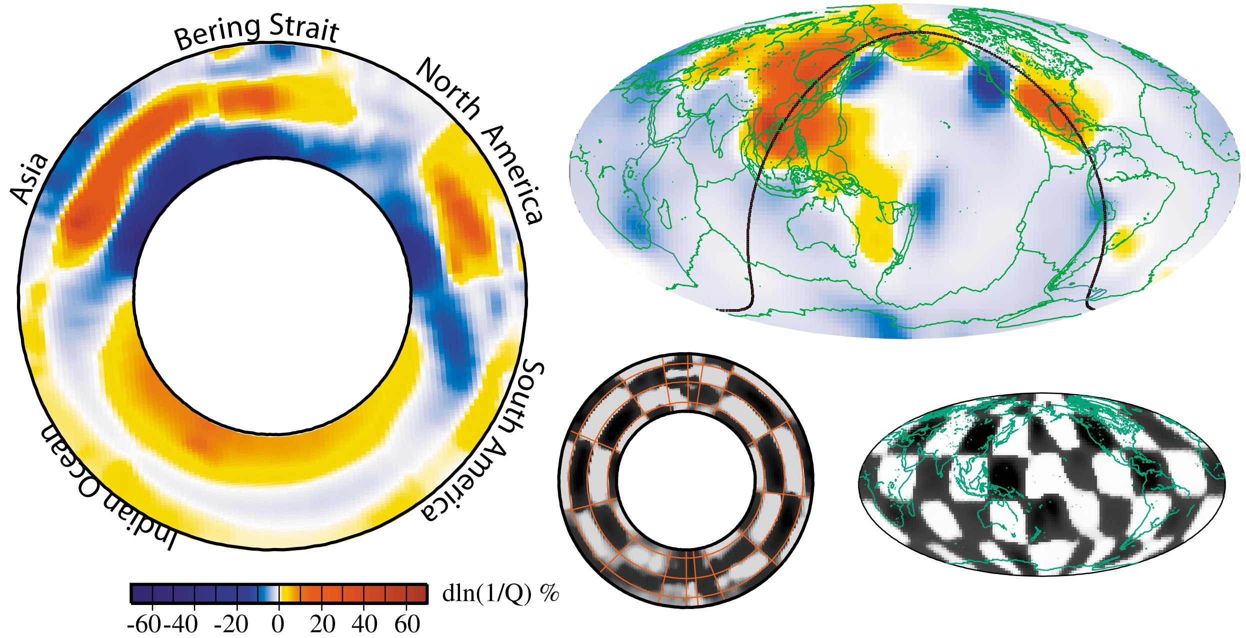

Plate 2. Great-circle vertical cross-section and horizontal cross-section at a depth of 1000 km through the attenuation model of *Lawrence and Wysession* [2006b], with accompanying checkerboard resolution test images. There is a long high-attenuation (low-Q_μ) anomaly at the top of the lower mantle just above the locations of the subducted Pacific ocean lithosphere along the western and northern rim of the Pacific.

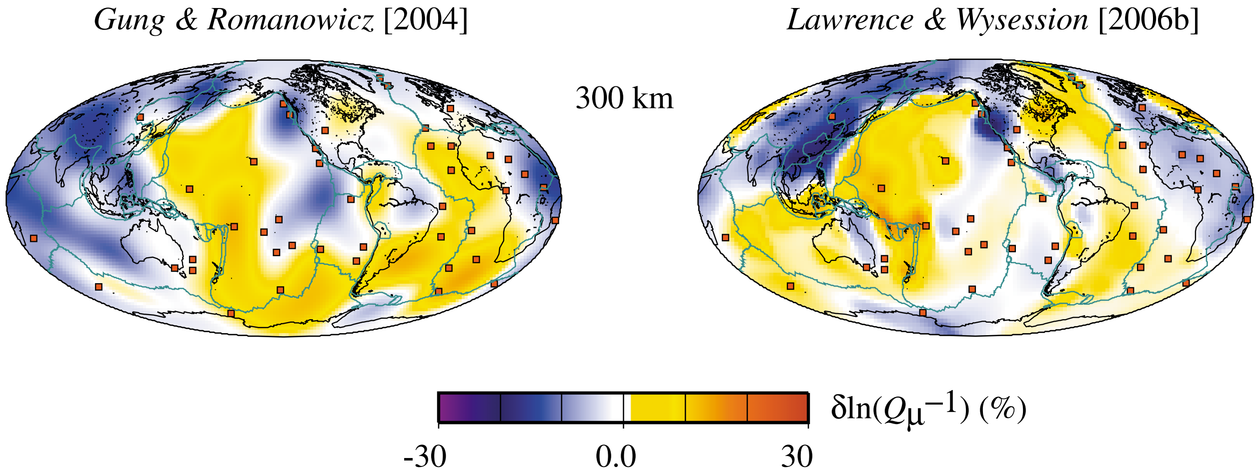

Plate 3. Comparison of the body shear wave attenuation model of *Lawrence and Wysession* [2006b] compared with the surface wave attenuation model QRLW8 of *Gung and Romanowicz* [2002] at a depth of 300 km. These models are constructed with different data types and different inversion methods, which lends support to the reality of the shared anomalies.

then water can remain within its cold, central core down to depths of 1200–1400 km according to *Shieh et al.* [1998], who observed the breakdown of phase D above 42 GPA at 1550°C and above 46 GPa at 1320°C. At pressures closer to a depth of 660 km *Kawamoto* [2004] found the breakdown to be at around 1200°C. 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. The relative difference in water 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 might be sufficient to cause the decrease in Q_μ from 300 to 100 [*Karato*, 2005]. Interestingly, this change in water might not cause a correspondingly large change in seismic velocity, as seen in Figure 1. This is important because as Plate 1 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 Plate 4. 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 China 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 H_2O concentrations, but the lower-mantle region above the subducted Pacific slab is 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 has a much higher water capacity. Saturation would likely result in partial melting, which could have a variety of effects on seismic velocity and Q depending on the geotherm, type of melting, and geometry of flow [*Karato and Jung*, 1998]. The lack of a strong velocity anomaly suggests that there is likely not much melt present, so the anomaly is not over-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) would be needed to distribute the water efficiently. Such increased water levels would have enormous, if poorly understood, implications for convection due to the strong dependencies of viscosity upon water. Water content usually 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, high fluid flow rates would be required to explain the broad distribution of water.

Another unanswered question regarding the fate of dehydrated water is whether water in the lower mantle would interact 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. Either the water concentration would 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. The attenuation in the transition zone seems to be low [e.g., *Durek and Ekstrom*, 1996], suggesting that added water there has little effect on attenuation. 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 could

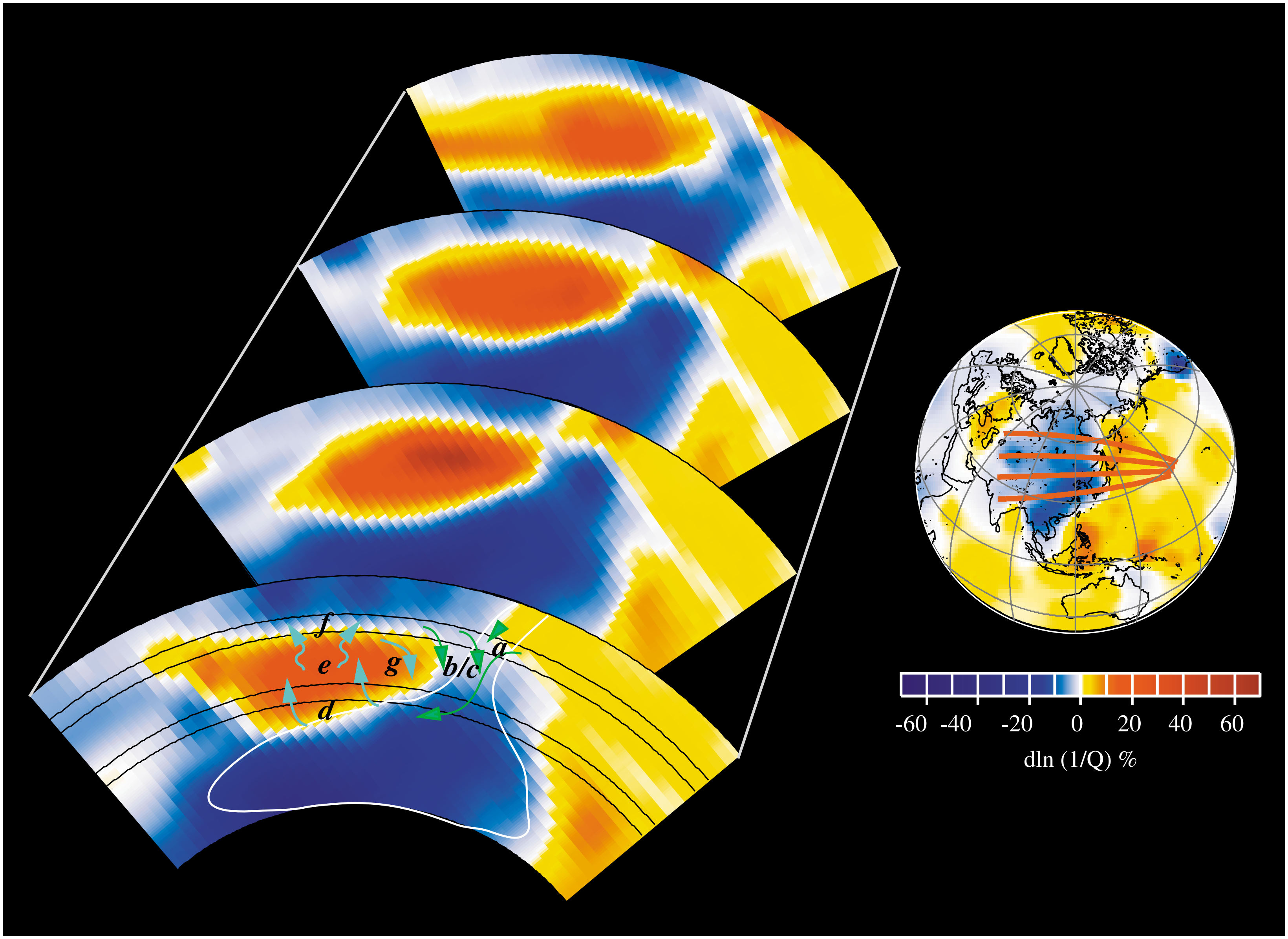

Plate 4. Tomographic slices through the high-attenuation anomaly, with some possible flow paths for the water that could be entering the lower mantle via subduction of oceanic lithosphere. a) Water can enter the deep mantle in hydrous phases contained within a cold slab. b) Hydrous transition zone minerals 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.

play 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], and the interpretation of our seismic attenuation anomalies as the result of high water content remains highly speculative, but one that could prove to be very important in understanding the mechanisms of convection within planets.

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