



The role of water in connecting past and future episodes of subduction

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ABSTRACT

We investigate a weak, but persistent low *S*-velocity anomaly in the upper mantle beneath the US East Coast. This anomaly sits above the high-velocity lower-mantle *S*-velocity structure generally interpreted as relatively cool, subducted Farallon lithosphere. We argue that the most likely explanation for the lowered *S*-velocities is elevated water content, with hydrogen incorporated in defects and oxygen at regular lattice sites in the crystal structure of major mantle minerals olivine, wadsleyite, and ringwoodite. The subducted Farallon lithosphere is a potential source for this water while the lithosphere at the Atlantic North American margin is a likely recipient of the water. This water may be the *vital element* needed to allow the margin lithosphere to break and initiate subduction of the Atlantic lithosphere. In a broader geodynamic context we propose that a deep water cycle may be responsible for the longevity of plate tectonics in general and the Wilson Cycle in particular.

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1. Seismic tomography

Regional waveform tomography (e.g. [Nolet, 1990](#)) can detect structures within the upper mantle that are at least several hundreds of km across because of the way it extracts information from a combination of recorded seismic waves. [Nolet's \(1990\)](#) technique (Partitioned Waveform Inversion) relies on surface waves and various body *S* waves speeding up or slowing down in upper-mantle regions of anomalous rigidity. The information on wave velocity is extracted from seismograms of dozens to hundreds of earthquakes recorded at dozens to hundreds of seismic stations.

1.1. *S*-velocity structure and its resolution beneath eastern North America

Regional waveform tomography for North America ([Van der Lee and Nolet, 1997](#); [Van der Lee and Frederiksen, 2005](#)) reveals a region of low shear wave (*S*) velocities in the upper mantle beneath and roughly parallel to the eastern United States margin ([Fig. 1](#)). This zone of low *S*-velocity appears about 300 km wide and extends from at least a depth of 660 km to within the continental margin lithosphere, along the entire eastern USA continental margin, roughly parallel to the

Appalachians ([Fig. 1](#)). This enormous “dike” of low velocities slightly dips towards the interior of North America.

Independent seismic tomography that, like ours, includes multiply bounced *S* waves also show low velocities in the upper mantle in the general east-coast vicinity ([Grand, 2002](#), see Appendix A; [Marone et al., 2007](#)). The exact geometry of the enormous “dike” varies from model to model, in part because of differences in resolving power and choices in parameterization and regularization. Seismic tomography resolution tests (see Appendix A) show that the presence of such a “dike” can be resolved with the data set of [Van der Lee and Frederiksen \(2005\)](#), but that some of its details may be blurred. For example, several aligned vertical cylindrical features, would also be imaged as a fairly continuous-looking “dike”-shaped feature (see Appendix A), because of the horizontal smoothing power of the data and modeling parameters.

1.2. Anisotropy

Seismic anisotropy, which we do not explicitly account for, could affect the tomographic image. With fast ENE–WSW and E–W axes measured from SKS splitting in the northeastern US ([Fouch et al., 2000](#)), an apparent low-velocity feature could appear if our seismic tomography is dominated by waves from Central-American and Caribbean earthquakes to the eastern-US stations. Our data set probably contains enough such wave paths ([Fig. 1](#)) to affect the

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tomographic image and enhance its uncertainty but also contains enough waves at right and other angles to counteract those effects. Tests with our data set have shown that seismic anisotropy such as inferred by Fouch et al. (2000) and Gaherty (2004) can introduce artificial anomalies with similar velocities as interpreted here, but with a smaller spatial extent and in different locations than the “dike” feature interpreted here (Lloyd and Van der Lee, *in press*). Moreover, Marone et al. (2007) find that such azimuthal anisotropy does not significantly affect their isotropic S-velocity model.

The upper mantle beneath the eastern US not only stands out as anomalous in seismic tomography, but also in comparisons of observed seismic anisotropy and modeled mantle flow patterns. While most of the observed seismic anisotropy in North America appears compatible with large-scale mantle flow

models, matching observed anisotropy in the eastern US requires additional model adjustments (Conrad, 2006; Fouch et al., 2000).

1.3. Properties of imaged low-velocity structure

The anomalous S-velocity reduction in the imaged “dike” (Fig. 1) ranges from 40 ± 10 m/s in the transition zone, to 90 ± 20 m/s above 180 km, where the given standard deviations are from spatial averaging. Seismic tomographic resolution tests (see Appendix A) show that these velocity reductions could be underestimated, owing to regularization of the tomographic inverse problem. In the transition zone a hypothesized velocity reduction can be tomographically imaged with an anomalous velocity that is

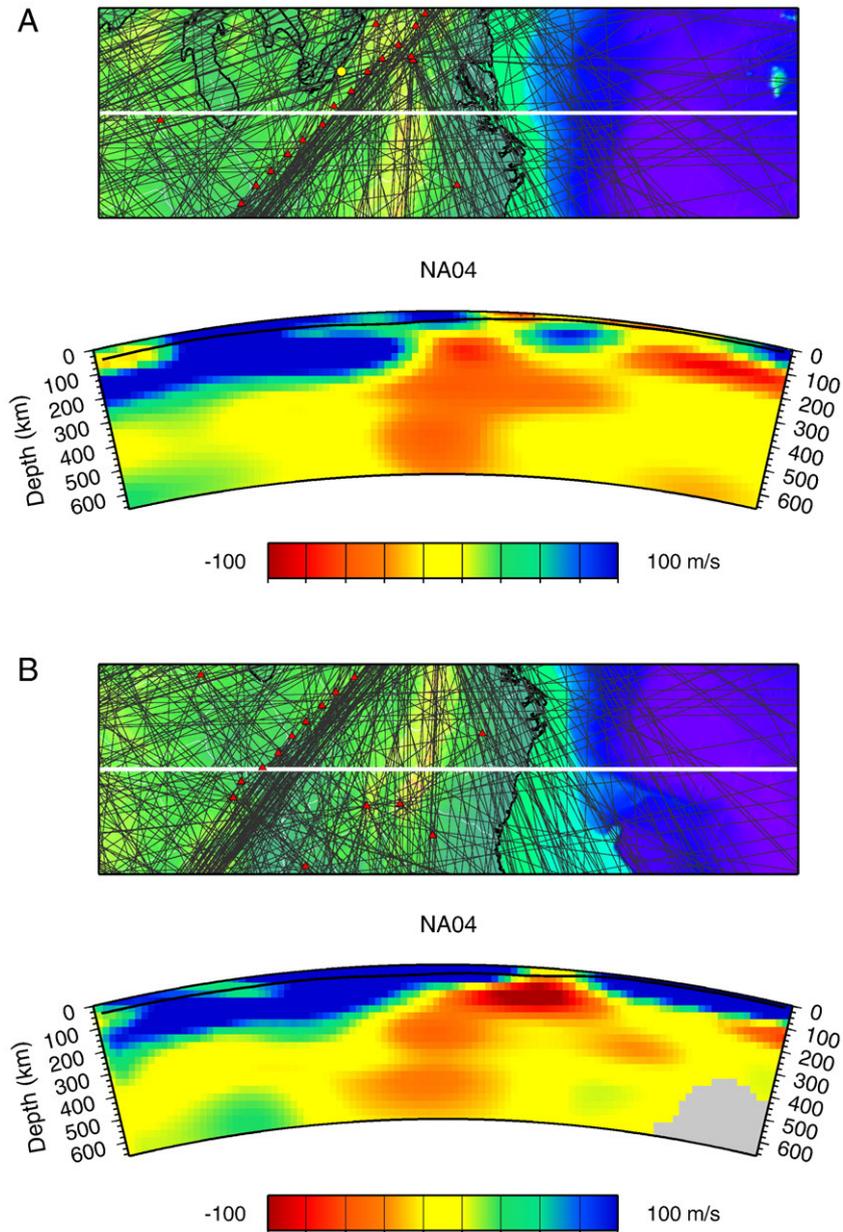


Fig. 1. Cross sections perpendicular (top) and parallel (left) to the “dike”, and maps (below) of 3-dimensional S-velocity model NA04. S-velocity is a proxy for rigidity. The red low-velocity region in the black ovals represents weak mantle material that we interpret as a hydrous upwelling. The color scale is oversaturated in the top half of the upper mantle in order to highlight the deeper, smaller-amplitude structures. Shown S-velocity is the difference from 1-dimensional model MC35, a modification of PEMC (Dziewonski et al., 1975).

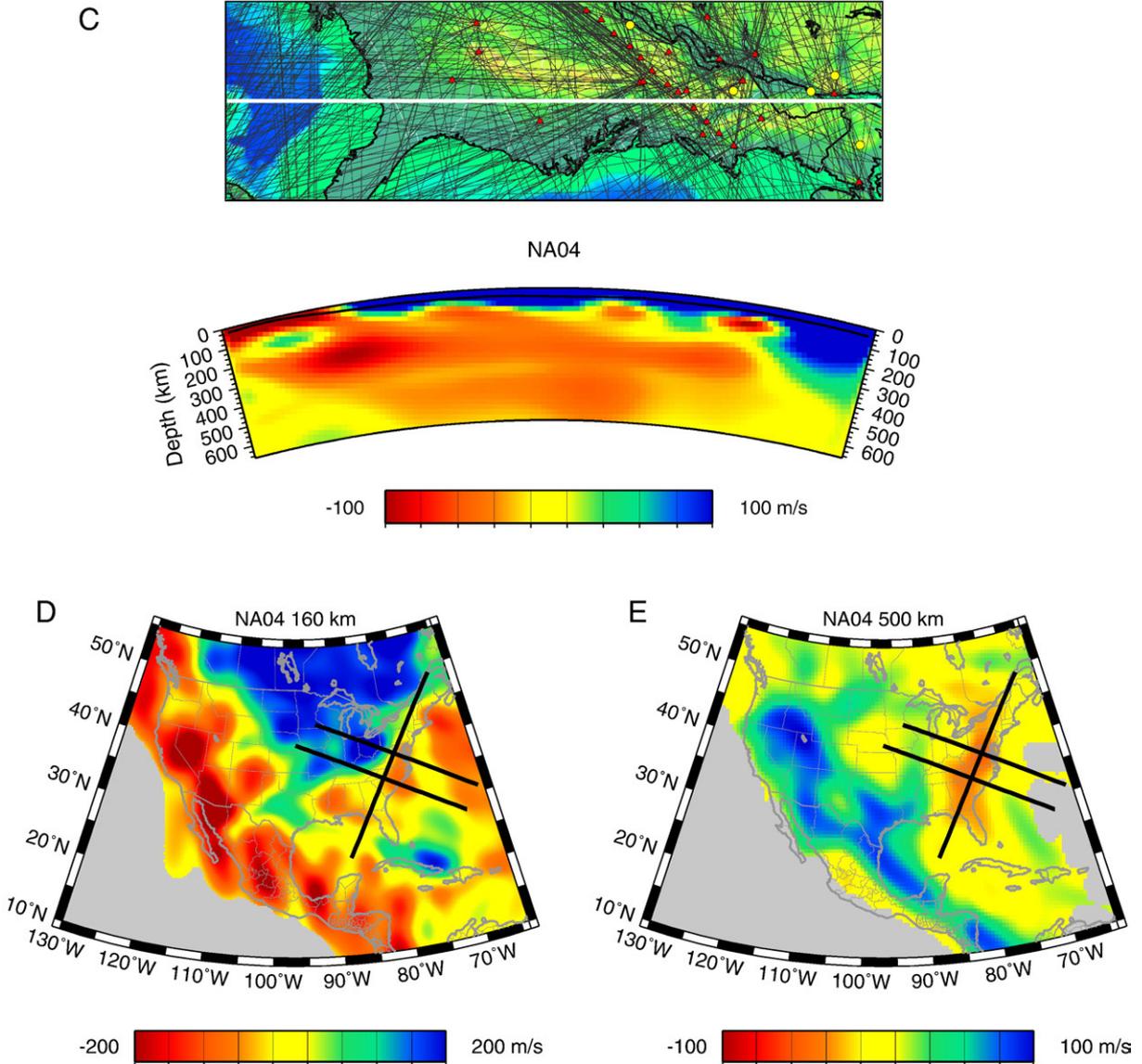


Fig. 1 (continued).

3.3 ± 1 times less than that of the hypothesized velocity reduction. Above 180 km, velocity reductions can be imaged 1.3 ± 0.3 times less pronounced than hypothesized. Taking these factors into account implies that the actual *S*-velocity anomalies with respect to 1D model MC35 (Van der Lee and Nolet, 1997) could be 130 ± 70 m/s in the transition zone (410 to 660 km), through 85 ± 60 m/s between 180 and 410 km, and 115 ± 60 m/s above 180 km. These anomalous velocity reductions are thus strongest in the transition zone and below the crust.

2. Nature of low-velocity structure

These velocity anomalies cannot be solely explained with anomalous major element composition, such as iron content (Jackson et al., 2000; Sinogeikin et al., 2001). A thermal explanation would require the low-velocity “dike” to be 200 to 300 °C hotter than adjacent mantle (Goes and Van der Lee, 2002; Cammarano et al., 2003). While such temperature anomalies are not unrealistic in general, the presence of a wide and tall hot zone is not corroborated by the circumstances:

We can neither identify a plausible source for such heat, nor are we aware of observations of other phenomena related to this heat, such as elevated surface heat flow at the eastern seaboard (Pollack et al., 1993), enhanced electrical conductivity (Wannamaker et al., 1996), or a thinned transition zone (Li et al., 2002; Courtier and Revenaugh, 2006). Elevated carbon content could substantially lower the *S*-velocity because it would exist in the form of carbonatitic melts (Hammouda, 2003; Dasgupta et al., 2004). However, below about 350 km carbonates would exist in solid form (Hammouda, 2003; Dasgupta et al., 2004) and their elastic properties are unknown. Although high-pressure carbonates could contribute to lowering the *S*-velocity, it is unlikely that they would lower the *S*-velocity by the entire inferred amount. Moreover, carbon has not been observed absorbed by major mantle minerals. At present there is thus no identified carbon-rich phase with the depth stability required to explain the low-velocity anomaly over the entire depth range recorded by seismic tomography. However, as discussed in the following section, a compositional source in the form of elevated hydrogen content both provides a reasonable explanation for the

inferred *S*-velocity anomalies, and is consistent with independent observations.

2.1. Hydrogen from water

Elevated water (i.e. hydrogen) content would not only lower the *S*-velocity but also elevate and dampen (broaden) the 410-km discontinuity (Wood, 1995; Smyth and Frost, 2002; Van der Meijde et al., 2003). Elevated temperatures, on the other hand, would deepen and sharpen the 410-km discontinuity (Bina and Helffrich, 1994; Helffrich and Bina, 1994), implying that observations of the depth and width of the 410-km discontinuity can discriminate between heat and water as potential causes of the low *S*-velocities. A study of ScS reverberations reports an elevated 410-km discontinuity beneath the eastern US (Courtier and Revenaugh, 2006) and a receiver function study shows slightly weakened *P* to *S* conversion power at the 410-km discontinuity in this region (Li et al., 2002). These two independent results are consistent with the expected effects of a wet mantle but are inconsistent with a hot mantle. Likewise, the 660-km discontinuity would be deepened in the presence of water, while high heat would elevate it (Wood, 1995; Bina and Helffrich, 1994). The width of the 660-km is much less sensitive to these mantle conditions than that of the 410-km discontinuity (Higo et al., 2001; Helffrich and Bina, 1994). The low-velocity anomaly not only resides in the transition zone, as previously reported by Van der Lee and Nolet (1997), but extends upwards to mid-lithospheric levels. A recent high-resolution study of shallow mantle discontinuities in the northeastern US (Rychert et al., 2005) reveals that the lithosphere is indeed as thin as the tomography (Fig. 1) suggests. Rychert et al. (2005) further constrain the bottom of this lithosphere to be sharper than thermally possible and invoke a change in water content across it: A dry lithosphere above a more hydrous mantle.

2.2. Properties of a hydrous structure

Jacobsen and Smyth (2006) determined that at pressure the *S*-velocity decreases by about 135 ± 35 m/s for ringwoodite with 1 wt.% of water added into it. Although the effects of hydrogen on the shear modulus of wadsleyite and olivine have not yet been published, results from static compression experiments suggest that the magnitude of their softening by water should be similar to that for ringwoodite (Yusa and Inoue, 1997; Inoue et al., 1998). The *S*-velocity of ringwoodite could be reduced with the 130 m/s inferred from tomography by a water content near 1 wt.%. Since ringwoodite comprises only 60% of the mantle composition, its water content must be roughly 1.7 wt.% to explain the same velocity reduction, which is below the saturation limit (Ohtani et al., 2001). Above the 410-km discontinuity but below 180 km, the 85 m/s lowered *S*-velocities would imply 0.6 wt.% of water, using the same ringwoodite derivative for olivine, but likely somewhat less, anywhere between 0.2 and 0.6 wt.%, because at the lower pressures at these depths the effects of water are more pronounced (Jacobsen et al., 2004). It might also be possible that the effects of water on olivine rigidity are somewhat different than those for ringwoodite, yielding yet different water quantities. The previous amounts would imply 0.3 to 1 wt.% in olivine that comprises 60% of the mantle. This water concentration is above the originally published saturation limit for olivine (Kohlstedt et al., 1996) but in accord with the recently reassessed water solubility in olivine (Hirschmann et al., 2006). Our tomographically inferred *S*-velocities could thus imply that the upper mantle above 410 km is close to being saturated with water. Above 180 km, the *S*-velocity anomaly is stronger than below it but we infer much less water content because small amounts of water can induce partial melting at these depths, even at relatively cool temperatures (Gaetani and Grove, 1998). Such induced partial

melting very effectively reduces *S*-velocity (Hammond and Humphreys, 2000; Van der Lee et al., 2001, 2002; Gerya et al., 2006). Alternatively, or in addition, the *S*-velocity could be decreased by a larger percentage through the added effect of lowered elasticity, or *Q* factor, resulting from the elevated water content (Karato, 2003). Karato (2003) argues that this indirect effect of water content on *S*-velocities is strongest in the upper regions of the mantle where the average *Q* factor is low and may be less important in the transition zone where the reference *Q* factor is high. Either way, partial melt or lowered *Q* will lead to more strongly reduced *S*-velocities in the sub-lithospheric mantle, as observed here beneath the US East Coast. We thus infer that water content increases with depth within the observed giant low-velocity “dike”. However, we cannot rule out a water content that is constant with depth if the “dike” also has an anomalous iron content, which would lower the *S*-velocity by at most 50 m/s for realistic anomalies (<5%) in Fe content (Jackson et al., 2000; Sinogeikin et al., 2001), and if iron content increases with depth within the “dike” (Nolet et al., 2005). The inferred water content may be regarded as an upper estimate if anomalous iron and carbon also play a role in lowering the *S*-velocity in the deep upper mantle.

3. Dynamic implications

3.1. Effects on density and flow

At equilibrated mantle temperatures, ringwoodite with the 1 wt.% of water estimated here is likely less dense than dry ringwoodite and could thus be buoyant. The amount of buoyancy is uncertain, with estimates ranging from 0 to 0.6% for the mantle assemblage, depending on the depth (Inoue et al., 2004; Jacobsen et al., 2004). However, the effects of water on the density of olivine and wadsleyite would be similar to those for ringwoodite, with lower densities accompanied by higher pressure derivatives (Inoue et al., 1998). The combination of this depth-varying anomalous density of the hydrous “dike”, with phase transitions that are altered and offset from neighboring dryer mantle, and the inferred increase of water content with depth yields a strongly depth-dependent buoyancy profile. However, the net buoyancy of the enormous hydrous “dike” is likely positive under equilibrated temperature conditions, implying that the “dike” would represent an upwelling.

If the upwelling is a steady-state process, the decreasing water content with decreasing depth could indicate water loss during ascent. This loss could happen at the 410-km discontinuity (Bercovici and Karato, 2003), and again at sub-lithospheric levels where water would partition into melt. If the anomaly presents a non-steady state upwelling, the sub-lithospheric mantle, and eventually the overlying continental margin lithosphere itself, would become more and more hydrated with time.

3.2. Ascent velocity

Simple geodynamic estimates, such as Stokes' flow or faster-rising Rayleigh–Taylor instabilities, cannot capture the complete dynamics of the slightly buoyant hydrous “dike”, but can provide end-member constraints on its ascent velocity. As argued above, the buoyancy of hydrous mantle is heavily depth dependent and controlled by thermal as well as compositional factors such as the amount of water, but also anomalous iron and/or carbon could affect the buoyancy. We assume an average anomalous density of less than 0.5% and temperature-equilibrated conditions. For a slow end-member estimate of ascent velocity, we have applied Stokes' flow (Turcotte and Schubert, 2002) to an upwelling 100 km in diameter and obtain a velocity on the order of 1 km/m.y. For a fast end-member estimate of ascent velocity we have examined the evolution of a Rayleigh–Taylor instability from a widespread

hydrous transition zone (Bercovici and Karato, 2003) and obtain a considerably faster velocity of about 60 km/m.y. With these simplifying end-member calculations we thus constrain the average ascent velocity to range from somewhat below 1 km/m.y. to as much as 60 km/m.y.

3.3. Effects of a hydrous upwelling on the surface lithosphere

The current proximity of the top of the upwelling to the surface and the thin lithosphere at the continental margin suggest that the wet upwelling hydrates the lithosphere from below. Hirth and Kohlstedt (1996) explain why lithosphere created by mid-oceanic rifting is fundamentally dry and thus very strong and resistant to shear. Regenauer-Lieb et al. (2001) show that the lithosphere needs to be hydrated in order to sufficiently lower its strength to allow it to shear through its thickness. Their self-consistent numerical model shows that a lithosphere with at least 200 parts per million (ppm) H/Si in the crystal lattice (Regenauer-Lieb et al., 2001), which is roughly 10 ppm of H₂O (water) by weight, can develop a shear zone whereas a dry lithosphere cannot. The effective viscosity in this shear zone dynamically drops to 10¹⁹ Pas. The hydrated lithosphere can yield along this weakened shear zone under less than 30 MPa (Regenauer-Lieb et al., 2001), breaking the lithosphere into two lithospheric plates. If one of these plates is negatively buoyant it could then subduct beneath the other (Hall et al., 2003; McKenzie, 1977). For our study area this implies that the margin-parallel hydration of the ocean–continent transitional lithosphere could initiate a new subduction zone in which the Mesozoic Atlantic lithosphere would subduct beneath the East Coast of North America in the next few million decades. In fact, Regenauer-Lieb et al. (2001) argue that hydration of dry lithosphere from below may be the only way to develop a subduction-allowing lithospheric shear zone as hydrating the lithosphere by downward porous flow of water from the overlying ocean is not viable because of the water's buoyancy and the brittle ductile transition essentially blocking porous flow (Hobbs et al., 2004). Recently, Sommer et al. (2008) presented evidence for multi-stage water enrichment process in garnet- and Cr-spinel-bearing lherzolites collected from the Colorado plateau. These observations suggest that because of the presence of 2-dimensional defects such as grain boundaries or cracks, the water mobility in the uppermost mantle may be far greater than previously thought, which further facilitates hydration of the surface lithosphere from below.

Incipient subduction at the US continental margin should cause strain within the ocean floor, eventually resulting in earthquakes. Moderate-sized on- and off-shore earthquakes are regularly observed in eastern North America (Mazzotti, 2007) and occasionally large earthquakes occur (Hough, 2002). The pre-seismometer timing of the large events and moderate size of the others have precluded a detailed quantitative analysis of their depths and focal mechanisms. However, with a growing event catalogue and rapidly increasing instrumentation, such as through the USArray component of Earthscope (Meltzer, 2003), such an analysis is imminent. The depths and mechanisms of these events will reveal whether they are related to plate-wide or post-glacial intraplate stresses acting at lithospheric weak zones (Mazzotti, 2007) or perhaps to the formation of a new plate boundary.

4. Hydrous upwelling from past episode of subduction

We have shown that the most plausible explanation for the dipping, giant “dike”-shaped low-velocity anomaly imaged beneath the eastern US margin is a hydrous upwelling. Presently this hydrous upwelling has not yet reached the surface but may be in the process of hydrating the lower lithosphere at the continent–ocean transition

(Fig. 1). A hydrated lithosphere can yield and shear through under less than 30 MPa (Regenauer-Lieb et al., 2001), implying that the Atlantic lithosphere could begin to subduct beneath the US East Coast within the next few million decades. Possible sources of the upwelling hydrous material are discussed in the following.

4.1. Origin of the hydrous upwelling

There are two possible origins for a hydrous deep upper mantle: 1) volatiles that co-accreted with the rest of Earth's building blocks and have not yet escaped the solid Earth, and 2) hydrous oceanic crust brought down by subduction. The first origin might have dominated in Earth's early history. It possibly caused the first occurrence of subduction on Earth in the Archean through lithospheric shearing after hydration by an upwelling volatile-rich plume. The second origin would dominate the Proterozoic and Phanerozoic as it sets our planet suitably apart from the other terrestrial planets on which plate tectonics does not operate (Beatty et al., 1999). The second origin has important implications for the apparent longevity of plate tectonics and the associated repeated closing of new ocean basins through geological time (Wilson, 1966). This origin requires that some water stays with the subducting slab after major dehydration in the upper 150 km (Zhao et al., 1997; Van der Lee et al., 2001, 2002; Gerya et al., 2004; Hasegawa and Nakajima, 2004), as is expected for relatively cold and the relatively cold parts of slabs (Frost, 1999; Komabayashi et al., 2004). The water would be transported predominantly by dense hydrous magnesium silicates (or alphabet phases) and released to major mantle minerals in few discrete depth intervals, notably near the top of the lower mantle where the alphabet phases are no longer stable (Frost, 1999; Komabayashi et al., 2004). Assuming that the subduction origin is now in play for the present US Atlantic continent–ocean margin we consider Paleozoic subduction of the Iapetus Ocean's lithosphere (see Appendix C) and Mesozoic subduction of the Farallon Plate as two different former episodes of subduction that could have supplied the inferred water to the deep upper mantle beneath the US East Coast. A systematic analysis of global plate motions over time might discriminate between the two but would require robust plate reconstructions, including locations and directions of subduction, for the Paleozoic and Precambrian. Nevertheless, the Iapetus hypothesis is associated with considerably more uncertainty than the Farallon hypothesis in terms of geodynamically plausible time scales for upwellings, in how the deep upper mantle could have stayed with the overlying continent as it drifted across hemispheres, and in the direction in which subduction occurred (Appendix C). Therefore, we deem the subducted Farallon Plate to be a more likely source for the inferred hydrous upwelling.

4.2. The subducted Farallon Plate

A fairly recent source of deep upper mantle hydration could be readily provided by Mesozoic subduction of the Farallon Plate. Most of the Farallon Plate subducted during the Mesozoic and has been detected tomographically in the lower mantle (Grand, 1994). Grand's (1994, 2002, see Appendix B) tomographic images show an ENE-dipping high-velocity anomaly in the top of the lower mantle close to the Appalachians, which is widely accepted to represent the subducted Farallon Plate. Fig. 2 shows a whole-mantle tomographic image composed of the global mantle S-velocity model of Grand (2002) for the lower mantle and the NA04 model for the upper mantle (Van der Lee and Frederiksen, 2005). The composite image shows a connection between the giant low-velocity “dike” and an independently imaged (Grand, 2002) low-velocity zone in the top of the lower mantle. The lower-mantle low-velocity zone sits directly adjacent to and on top of the high-velocity Farallon slab at 800 to 1000 km. The

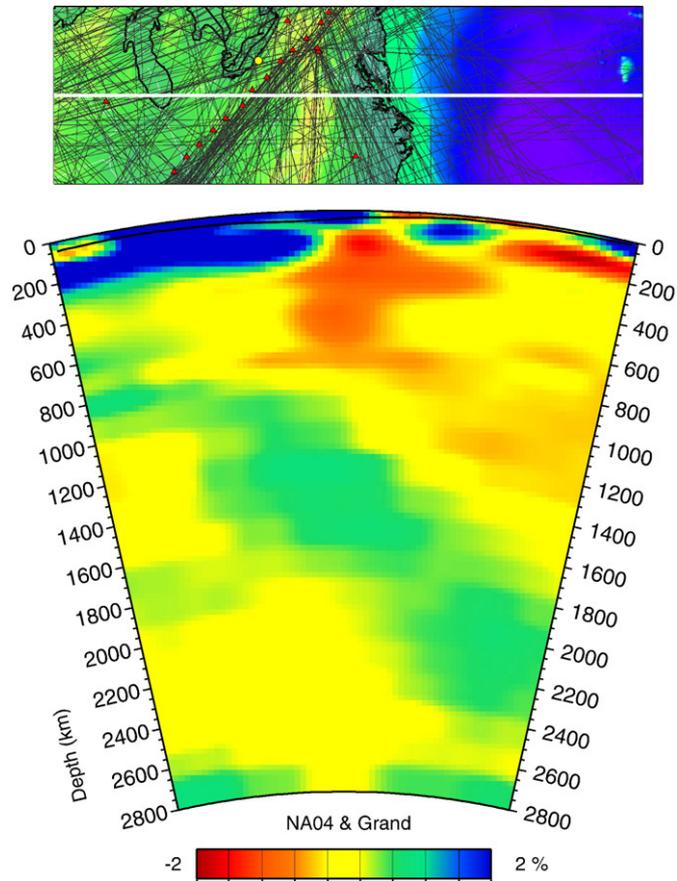


Fig. 2. Composite tomographic image (Grand, 2002; Van der Lee and Frederiksen, 2005) along one of the same trajectories as shown in Fig. 1. The velocity anomalies are with respect to a slightly modified PEMC. The color scale is over-saturated in the top half of the upper mantle in order to highlight the smaller-amplitude deeper mantle structures. These deeper features contain the ENE-dipping high-velocity Farallon anomaly showing subducted lithosphere of the Farallon Plate and the slightly W-dipping enormous low-velocity “dike” anomaly discussed in the text. The two anomalies meet at the top of the lower mantle.

strike of the Farallon slab at these depths is remarkably sub-parallel to the US East Coast (Grand, 2002), mainly because of a major episode of flat subduction beneath the western US during the Tertiary. If the inferred enormous “dike” results from dehydration of the subducted Farallon lithosphere at the top of the lower mantle, the implied average ascent velocities would be within and at the low end of the geodynamically inferred range in Section 3.2. Because thermal diffusion would have a retardation effect on the rise time, the ascent velocity may be nil during the Mesozoic and larger than average in more recent geological times. Such an inferred dehydration phase of the Farallon slab in the top of the lower mantle thus geometrically explains the enormous low-velocity “dike”. More importantly, mineral physicists expect cold subducting lithosphere to experience a dehydration phase near the top of the lower mantle where water-transporting dense hydrous magnesium silicates break down (Komabayashi, 2006).

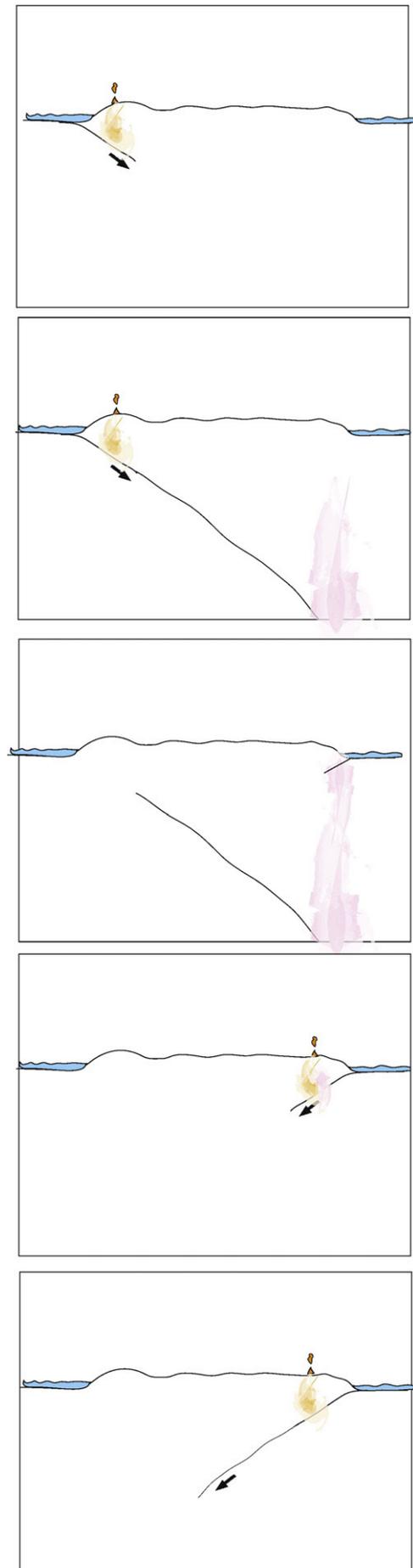


Fig. 3. Cartoon illustrating how subduction on one side of a continent could trigger subduction on the opposing side of the continent 200 to 300 million years later. The bottoms of the frames represent the bottom of the upper mantle at 660 km. The orange colors represent a typical hydrous mantle wedge and the pink colors represent a (much less) hydrous upwelling from the top of the lower mantle or transition zone.

4.3. General applicability in time and space

Given the correlation between many continent widths and horizontal offsets between trenches and the lower-mantle positions of material subducted at the trenches, the mechanism of lower-mantle slab dehydration beneath an opposing continental margin need not be rare. Moreover, thick, stiff cratonic lithosphere beneath continental cores would deflect lower-viscosity upwellings beneath it to its sides, preferably towards the side in the direction opposite to plate motion (Fouch et al., 2000). The subduction initiation mechanism proposed here may thus apply more broadly, though not everywhere and always, in space and time than at the present US eastern margin. Perhaps the same mechanism could have triggered the relatively young subduction of the Atlantic lithosphere beneath the Caribbean Plate through Farallon (now Cocos) Plate subduction at the Middle America Trench. However, if a subduction-triggered hydrous “dike” welled up far from a continental margin beneath an unusually wide continent such as Asia, it would not trigger new subduction but instead could be responsible for intraplate tectonic phenomena, such as rifting and volcanism (Zhao, 2004). On account of its width and western-margin subduction history of the Nazca Plate, a hydrous upwelling might be expected beneath the eastern margin of South America. In fact, tectonically stable easternmost Brazil has experienced some surprisingly recent magmatism (Mizusaki et al., 2002). A vertical low-velocity feature has been imaged beneath southeastern Brazil, but was interpreted as a fossil feature rather than an active upwelling (VanDecar et al., 1995).

Our proposed mechanism implies that it would take several hundreds of millions of years for Farallon subduction to trigger Atlantic subduction. If this mechanism is indeed fairly common through geological time, hydrous upwellings with a subduction origin could represent a mechanism for the Wilson Cycle: Hydrous upwellings from lower-mantle slab dehydration would trigger new subduction zones hundreds of millions of years after the earlier episode of subduction.

5. Further implications

If the hydrous upwelling we infer from the seismic tomography indeed exists and interacts with the surface lithosphere in ways that would promote future subduction, we might expect, in addition to seismic activity at the margin, future magmatism at the margin, uplift and subsidence of the eastern margin, and a thin layer of melt atop the 410-km discontinuity, as discussed briefly in this section.

A thin layer of dense melt might be present on the 410 km discontinuity (Bercovici and Karato, 2003; Karato et al., 2006) beneath the eastern US if the tomography reflects a steady-state process rather than a vertically inhomogeneous distribution of water. Hydrogen can be present in wadsleyite and ringwoodite in different forms, one of these being free protons. If a significant portion of the hydrogen is present as free protons rather than bound to the crystal structure of ringwoodite, a hydrated transition zone could lead to reduced electrical resistivity (Huang et al., 2005).

The hydrous upwelling inferred here might increase surface elevation beneath the Appalachians and continental margin. Recent (Neogene) uplift has indeed been observed in the Appalachians and its cause has not yet been identified (Pazzaglia and Brandon, 1996). Gurnis et al. (2004) note that four recently initiated subduction zones in the Pacific underwent rapid uplift and then subsidence prior to subduction initiation. According to data from the Global Positioning System the USA East Coast appears to be subsiding at present (Sella et al., 2007). The subsidence might be caused by a negatively buoyant lithosphere that is weakening as a result of being hydrated by the inferred enormous hydrous “dike”.

The hydrous upwelling in our mechanism for subduction initiation would further predict anomalous magmatism during the early stages

of subduction, with a strong influence of water-induced partial melting of upper mantle with a complex history. Perhaps the presence of sub-lithospheric hydrous melts even before the initiation of subduction plays a role in the development of a back-arc basin during early stages of subduction (Gurnis et al., 2004), and the associated production of rare boninites (Wilson, 1989; Crawford, 1989).

6. Conclusions

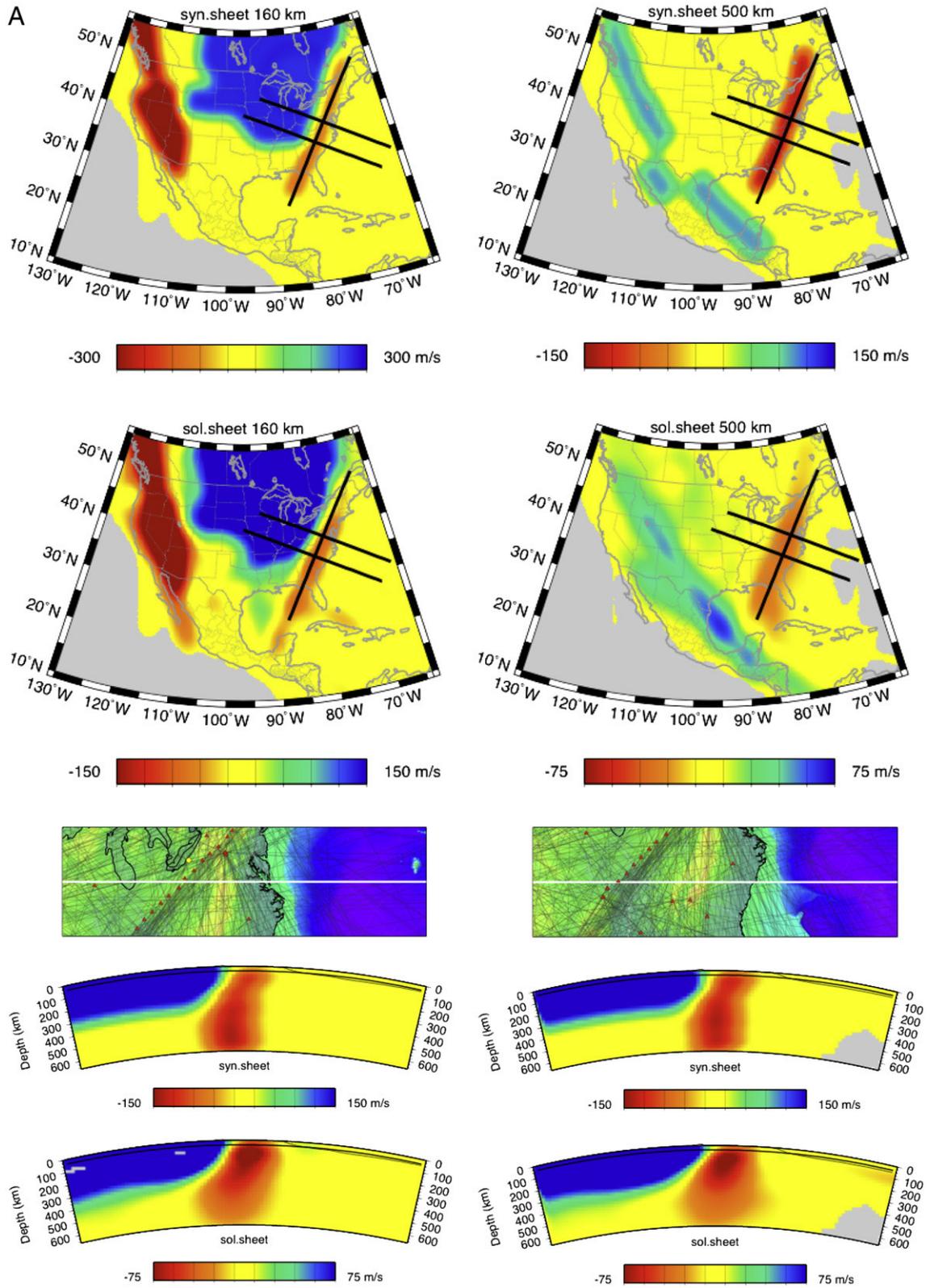
Seismic waveform tomography with North American seismograms reveals an unfamiliar zone of low *S*-velocity. Here, we have interpreted this weak zone as a margin-parallel line of discrete, columnar hydrous upwellings or an along-strike continuous upwelling (enormous “dike”). The hydrous upwelling likely originates in the top of the lower mantle and/or transition zone. These regions of the mantle would be hydrated by past episodes of subduction of oceanic crust beneath North America, in particular subduction of the Farallon Plate. We propose that past episodes of subduction can initiate present or future subduction because of the way the hydrous upwelling would interact with the lithosphere at the surface. A lithosphere that is hydrated by an underlying upwelling could develop a low-viscosity, dipping shear zone, along which the plate would yield and subduction of negatively buoyant oceanic lithosphere could begin. This cycle has been illustrated in Fig. 3. The seismic-tomographic model suggests that this mechanism could be ongoing beneath the US East Coast and that a new subduction zone could form there in a few million decades.

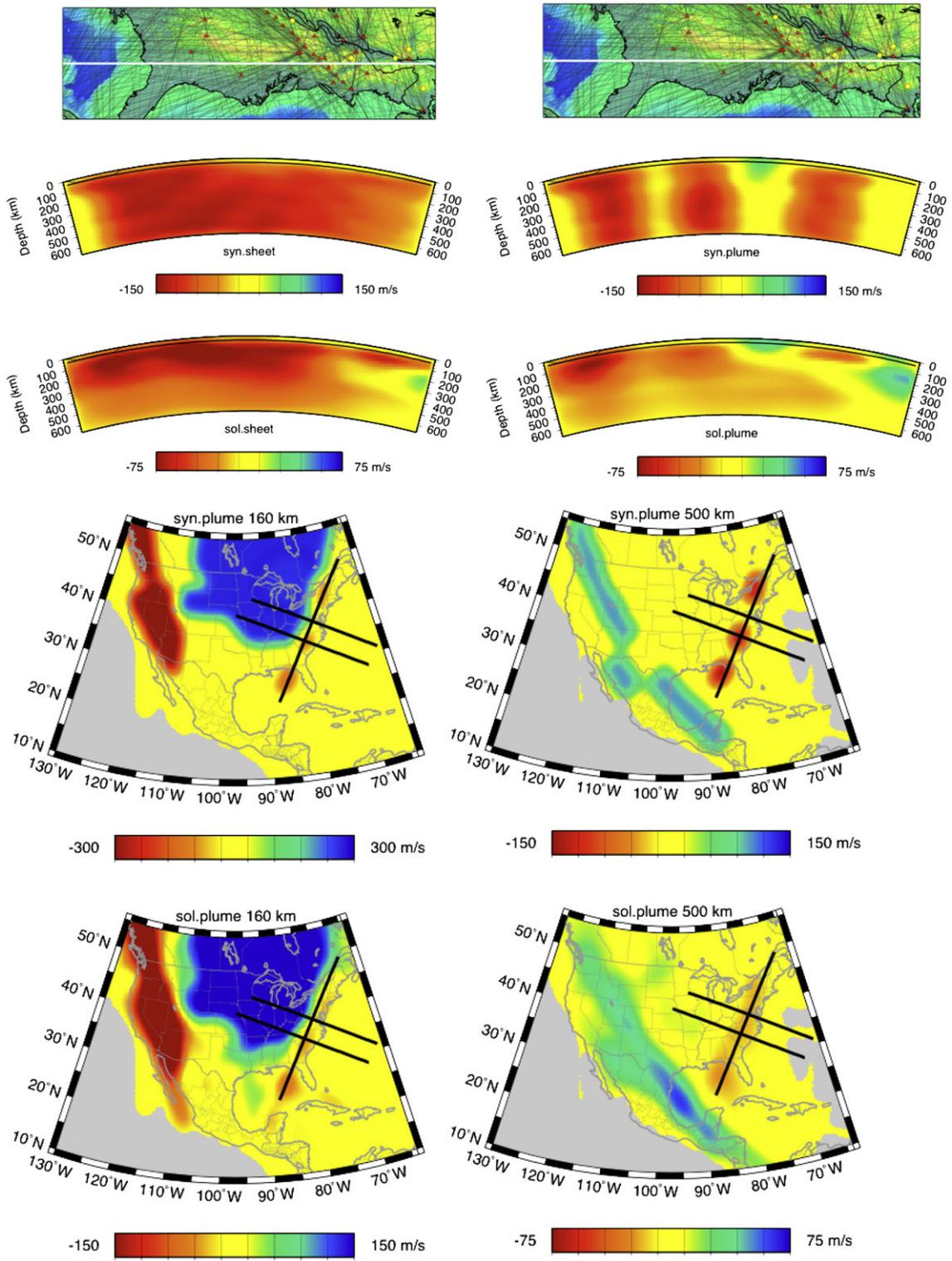
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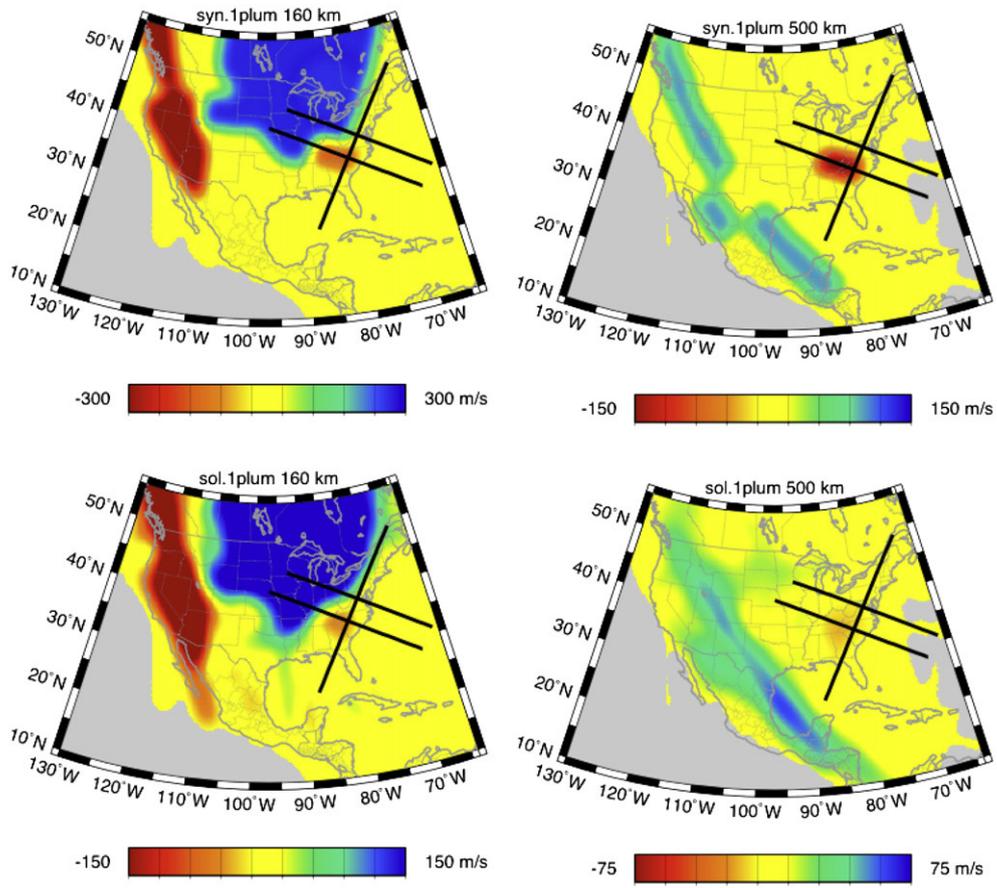
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Appendix A. Resolution tests

This appendix illustrates the resolving power, and smearing associated with limitations therein, of the seismic data for a giant dike, a lineament of mantle plumes, and a single plume. The top frames (labeled “syn”) in the figures represent hypothetical Earth models for each of these structures. The bottom frames (labeled “sol”) show how the hypothetical models are imaged by the data set of Van der Lee and Frederiksen (2005). The maps show that resolving power for the east coast decreases with latitude north of 43N. The cross sections show that resolving power decreases considerably with depth; the velocity reduction of the anomalies is underestimated by a factor of about 1.3 ± 0.3 above 180 km to a factor of 3.3 ± 1 in the transition zone. Maps and cross sections labeled “sheet” reflect resolving power for a “dike”-shaped anomaly as imaged in model NA04 from data. Maps and cross sections labeled “plume” demonstrate that a series of cylindrical anomalies could also be imaged as a relatively continuous anomalous band. Maps and cross sections labeled “1plum” show that a “dike”-shaped anomaly is unlikely to result from lateral smearing of a single isolated low-velocity anomaly. Resolving power for the east-coast low-velocity anomalies is tested in conjunction with that for larger-scale anomalies, such as the much better resolved central craton-like high-velocity anomaly in the uppermost mantle. A smooth version of this large structure is resolved partly at the expense of resolving the adjacent smaller low-velocity east-coast feature.

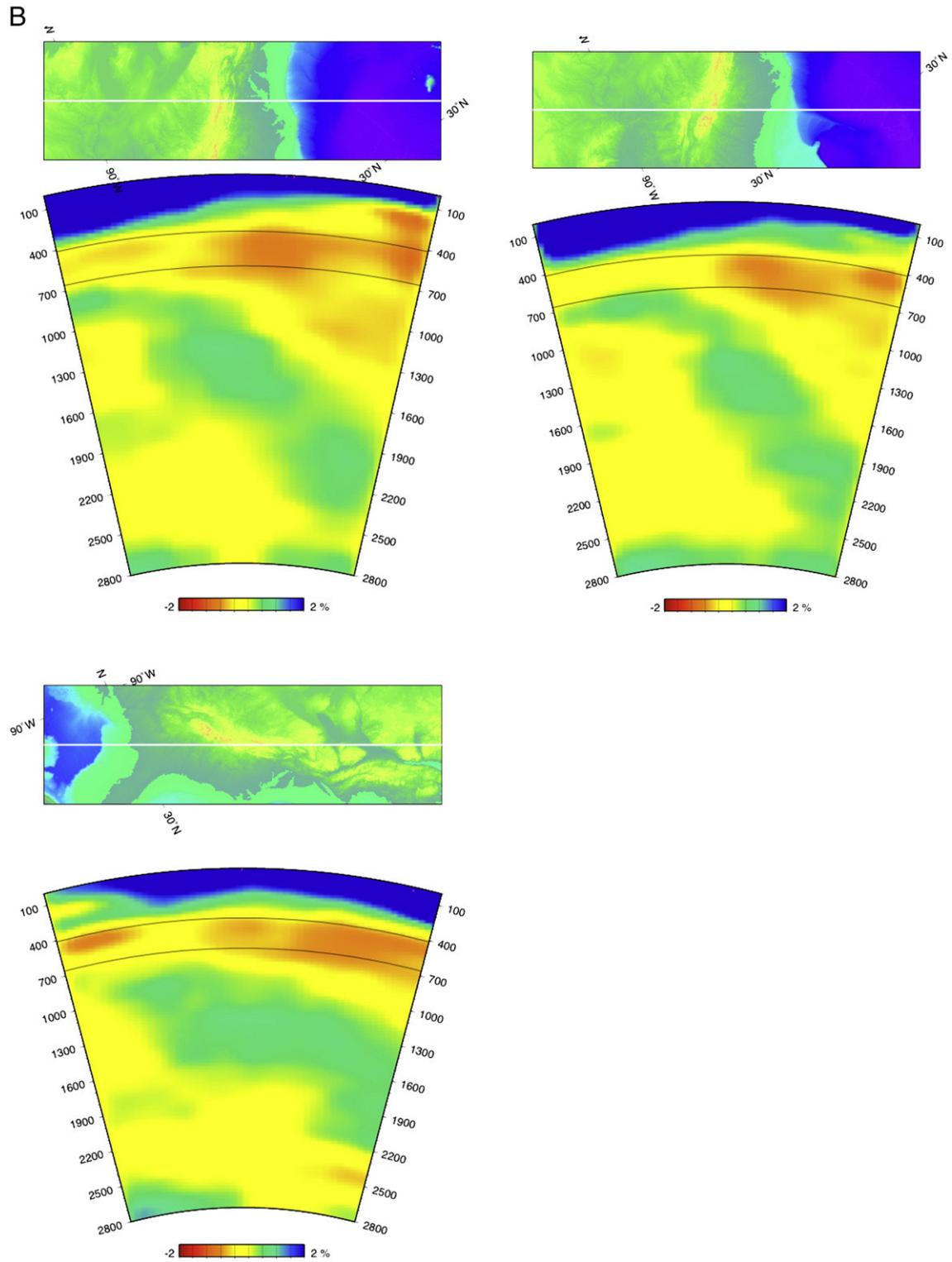






Appendix B. Grand's whole-mantle tomographic images

Whole-mantle tomographic image along the same profiles as in Fig. 1, entirely through Grand's (2002) model. The black lines are at depths of 410 and 660 km and mark the transition zone.



Appendix C. The subducted Iapetus Ocean

The Iapetus Ocean closed during the Paleozoic, forming the roughly east coast-parallel Appalachian Mountains (Hatcher et al., 1989) in the southern hemisphere (Van der Voo, 1993). It is unclear which portion of the mantle will stay with a continent that moved as much as North America has since the Paleozoic. However, VanDecar et al. (1995) argue that the entire upper mantle might stay with the overlying continent for at least 100 m.y. If this applies to North America, the deep upper mantle that was hydrated by subducted crust from the Iapetus Ocean would still sit near the Appalachians in their present location. Van der Lee and Nolet (1997) imaged a component of the enormous, low *S*-velocity “dike” presented here and suggested that it could represent mantle hydrated by lithosphere of the Iapetus Ocean.

The Appalachians formed in several stages of which the Permian Alleghanian orogeny was the most recent and pervasive stage for the central and southern Appalachians (Hatcher et al., 1989). The preceding Acadian orogeny, however, involved much higher convergence rates peaking in the Devonian (Lawver et al., 2002). Most of the hydrous oceanic crust was likely subducted beneath North America during this period, dipping towards the North American interior (Hatcher et al., 1989; Jurdy et al., 1995; Lawver et al., 2002; Van der Voo, 1993). Assuming Acadian-associated upper mantle hydration between 400 and 660 km during 350 to 300 Ma implies an average ascent velocity to presently lithospheric depths of 0.9 to 1.7 km/m.y., which is on the slow end of the wide range of possible ascent velocities. However, the hydrated upper-mantle region would have been less or even negatively buoyant during its formation in the mid-Paleozoic because the subducting Iapetus lithosphere would have cooled the mantle beneath the Appalachians, increasing rather than decreasing average density. In fact, we believe that the Mediterranean region is currently in such a stage. A relatively high volume of high-velocity material, interpreted as subducted lithosphere from the Tethys Oceans, has been imaged in the Mediterranean transition zone (Marone et al., 2004), which is accompanied around 400 km by what appears to be an anomalously hydrous mantle (Van der Meijde et al., 2003). Only temperature re-equilibration over geologic time will allow this cold hydrous material to warm up and become positively buoyant because of its anomalous composition. In the case of Paleozoic subduction of the Iapetus Ocean, sufficient time has passed to allow the effects of hydration on density to overtake the opposing effects of low temperature on density.

Appendix D. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.04.041.

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