# *Chapter 6*

# Broader Implications and Discussions

## 6.1 Subduction Evolution Beyond North America

In Chapters 4 & 5, we discussed the application of the adjoint models to the evolution of North America, including an initial inversion of Farallon subduction consistent with the WIS, model validation using vertical motion proxies from the Colorado Plateau and WIS basins, and a prediction of possible oceanic plateau subduction through comparison with plate reconstructions and structural geology. As noted earlier, these models were global but with the calibration restricted to North America. Therefore, the model that best fits the constraints from North America may also provide some useful directions on relating surface evolution to internal dynamics over other parts of the world.

Several snapshots of the recovered mantle structures from our preferred adjoint model are displayed in Figure 48. The map view display is centered over the Pacific Ocean, where different color contours outline the restored plates and slabs at different depths (Fig. 48). These solutions are obtained after five forward-adjoint iterations starting with an SBI first guess (Fig. 19), and incorporate the North American-restricted stress guide that mechanically couples the Farallon slab to the Farallon Plate. Model parameters including mantle viscosities and slab density are constrained by predicting the WIS stratigraphy (Chapters 4 and 5). During the conversion of seismic anomalies to buoyancy, we remove the low velocity signals and consider the high velocity anomalies as subducting oceanic slabs. Due to the uneven sampling of seismic ray paths for mantle structures, the slab image is not smooth and the recovered features near the surface are also irregular (Fig. 48). Most of the widespread sheet-like high velocity mantle anomalies are restored onto main oceanic plates especially the Pacific, Farallon, Nazca and Indian plates (Fig. 48), consistent with the oceanic origin of these slabs.

Overall, the surface high velocity anomalies pulled out along subduction zones to the west and south of the Pacific Ocean (against Japan, Philippines and Australia) are the most voluminous, consistent with the large area and fast subduction speed of the Pacific plate throughout the Cenozoic. Going backward in time, a clear Nazca anomaly is restored up at 30 Ma that keeps expanding in area until the Late Cretaceous, while the Farallon anomaly does not reach the surface until 70 Ma. Within the Indian Ocean, two separate segments of high velocity anomalies are restored, each at a different time: the anomaly against western Australia and Southeast Asia is subducting since ~50 Ma, while the subduction age of the segment to the south of India appears to be older than this time. Both the depth and lateral distance from subduction zones of the remnant slabs revealed by seismic tomography affect their mechanical coupling to the surface, and therefore, their recovered ages of subduction: slabs close to the trench with shallow depth are most strongly coupled to surface plate motions, and translate onto the surface the fastest, such as those surrounding the Pacific; slabs at larger depth are more loosely connected to the surface at present-day, whose recovery takes a longer time, such as the anomaly south of India; slabs that are both deep in the mantle and shifted laterally relative to the trench from which they were subducted are nearly completely decoupled from the surface oceanic plate at present, and an appropriate recovery to their original position on the surface has to be aided with a stress guide, which also takes the longest time, and one such example is the Farallon anomalies beneath North America.

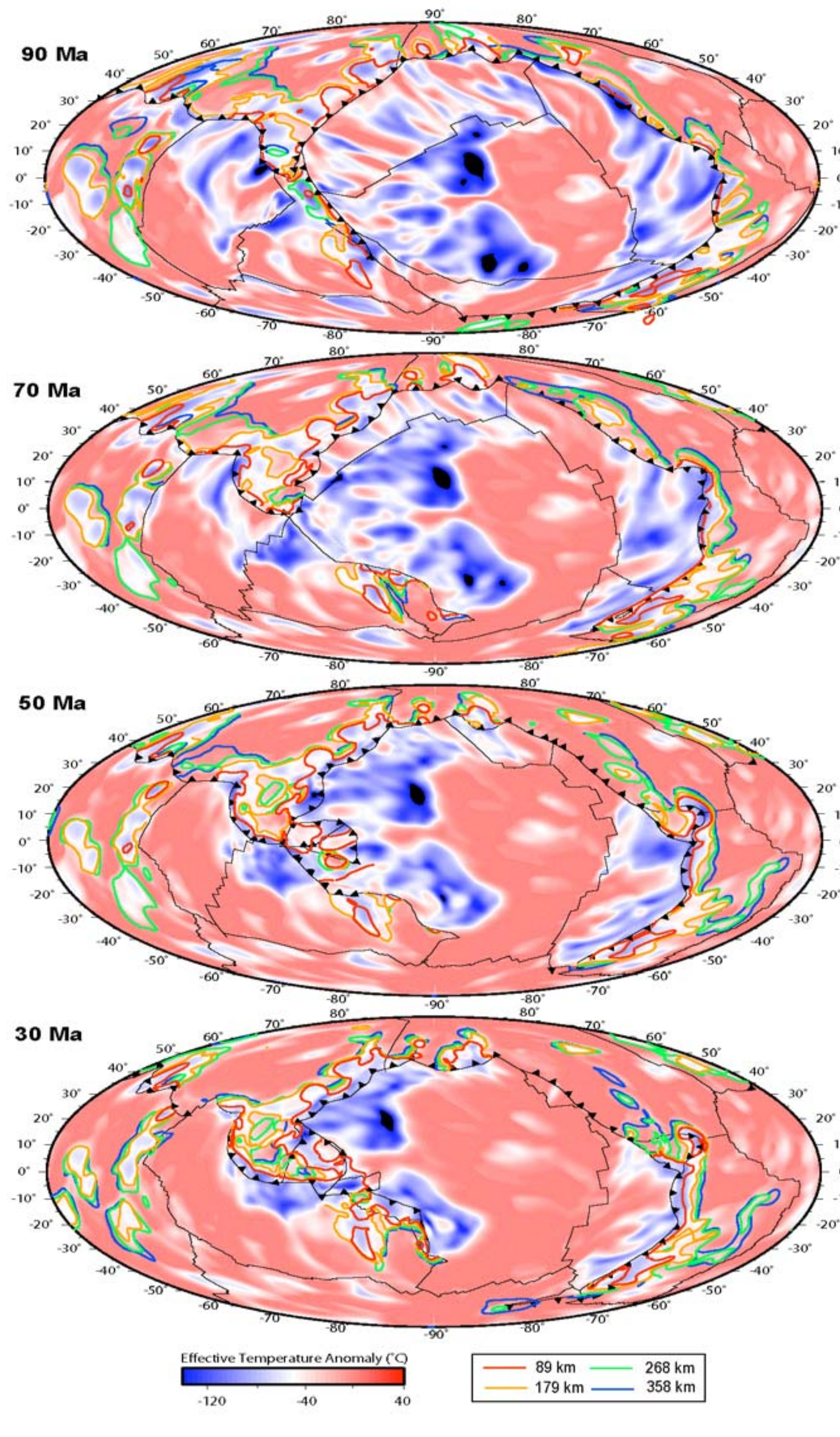

**Figure 48**. Reconstructed global subduction systems from the adjoint model at four different geological times. The background temperature is at 179 km depth, with color contours indicating slab edges at different depths.

The area of the Pacific Ocean decreases since the Cetaceous due to the retreat of trenches along its western and eastern margins (Fig. 48). During the subduction of oceanic plates, continents move toward the trench, override previously subducted slabs, and experience dynamic subsidence. As can be seen from the discussion in Chapter 4 and 5, North America has been such an example where the westward migration of the continent over the subducting Farallon slabs has led to a dynamic subsidence sweeping from west to east across the entire continent. Since a westward motion also occurred on South America, the continent may have experienced similar vertical motions. Recently, in collaboration with the research group at Sydney University, we analyzed dynamic topography output from the inverse model over South America, and the predicted vertical motion along the Amazon River (Fig. 49). The eastward migrating subsidence center followed by regional uplift in northwest South America, due to the continent's progressive overriding of sinking slabs with the decrease in age of the subducting plate partly responsible, provides an explanation to the reversal of the Amazon River drainage system during the Late Miocene [Shephard *et al.*, 2010]. Possible future study areas could include Australia and Southeast Asia where trench retreat also occurred (Fig. 48).

In addition, the morphology and geographic distribution of recovered seismic structures may provide constraints (or feedback) on the imposed plate motions in places where direct measurement from paleo-magnetic data is unavailable. For example, because the seafloor at the active spreading center has zero age, this part of the oceanic plate represents a discontinuity in the thermal structure of lithosphere, with the part closer to the ridge having less negative buoyancy. Morphology of the recovered Pacific thermal anomalies does not seem to follow this character of a spreading center: in the vicinity of the imposed Izanagi-Pacific ridge, the restored anomalies on the Pacific side shows a strong signature continued from the older part of the plate (Fig. 48, at 70 Ma), instead of giving rise to a weaker-than-ambient signal due to decrease in the age of the lithosphere. Several possible reasons can lead to this inconsistency between recovered thermal anomalies and assumed plate motion history. First, the seismic image beneath East Asia, especially at small scales (~200 km), may still not be well resolved, although increasing agreements among different models are obtained [Grand, 2002; Zhao, 2004; Li *et al.*, 2008]. Second, the dynamic properties of the inverse model, including the scaling from velocity perturbation to density anomalies and the depth-dependence of mantle viscosity, may vary geographically, such that the values constrained in North America (Chapter 4) are different from those beneath East Asia; consequently, the recovered Pacific subduction process is not appropriate. A third possibility is that the imposed plate motions are not accurate; in fact, the timing of subduction of the Izanagi-Pacific spreading center against Japan was inferred based on a sequence of idealized assumptions that may not hold true [Whittaker *et al.*, 2007], while the mismatch between the restored Pacific anomalies with imposed ridge positions (Fig. 48) may suggest that this ridge could have subducted earlier than assumed. These speculations, of course, are subject to future study with a systematic investigation on the compatibility of the imposed plate motions with recovered seismic anomalies associated with past subduction.

Apparently the inverse models still need further improvement, especially better realizations of the convergent plate boundaries, which is crucial for recovery of subduction zones. Overall, the model shown in Figure 48 seems to have recovered subduction geometries along most of the trenches reasonably well, but small-scale artificial features along subduction zones exist (i.e., cold anomalies get entrained under the overriding plates, where in reality subducted slabs only come from the oceanic plate). This is not the case for North America where its boundary with the Farallon plate is explicitly parameterized as a low-viscosity zone overlying a high-viscosity stress guide, so that the thermal anomalies can become completely restored onto the Farallon plate. Future models should seek a better treatment of all the plate boundaries, especially subduction zones, as expanded on below.

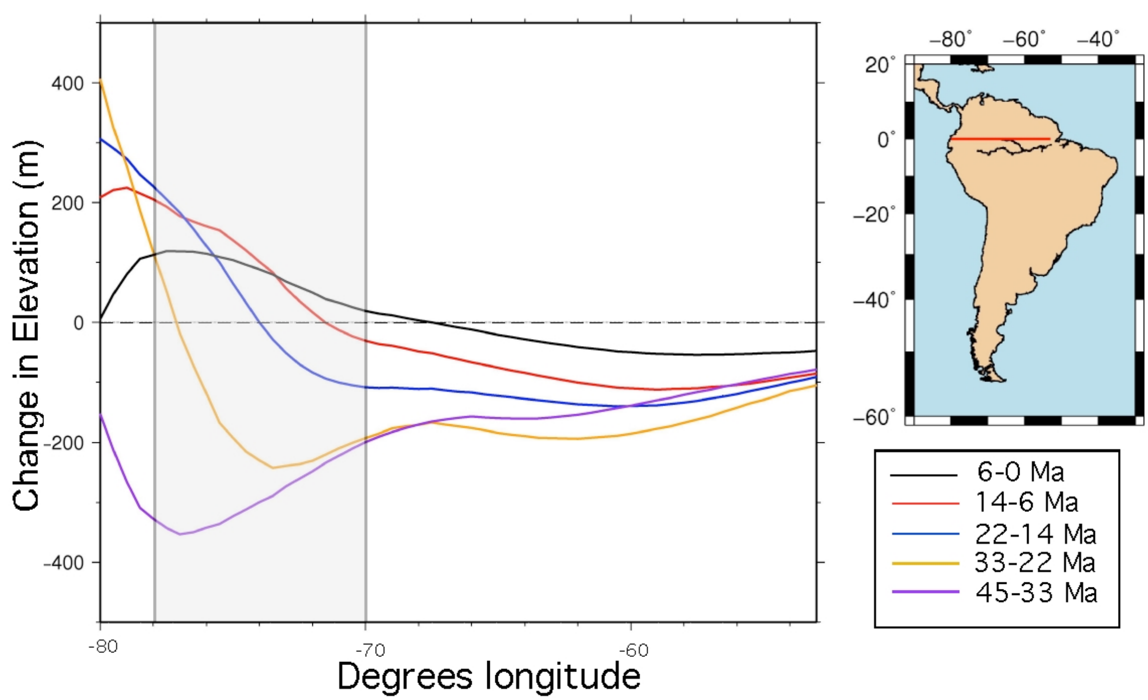

**Figure 49** Modeled change in continental elevation of South America at the equator for five stages (from Shephard *et al*., in review). Note the eastward propagating change from subsidence to uplift in the Pebas Sea area after 33 Myrs ago, accompanied by an accentuation of subsidence at the mouth of the evolving Amazon River. Gray band indicates the approximate longitudinal extent of the Pebas Sea at this latitude (adapted from Marshall and Lundberg, 1996).

## 6.2 Limitations of the Current Adjoint Models

In this thesis, I explored the adjoint data assimilation techniques applied in mantle convection. Stitching together various observational constraints, including both static and time-dependent ones, the adjoint inversion has been shown to be useful in solving geophysical and geological problems. Several important problems have been explained by inverting the present-day seismic tomography image of mantle subject to forced plate motions on the surface. Although promising, the models are still primitive due to both simplifications in physics and limited model resolutions. The major limitations of the adjoint models are as follows.

### 6.2.1 Poorly Resolved Boundary Layers

In the adjoint models purely based on seismic tomography, the surface and lower (core-mantle boundary) thermal boundary layers (TBL) are not entirely appropriate. Because seismic velocity anomalies revealed by tomographic inversion represents perturbations relative a reference one-dimensional velocity model (e.g., Grand [2002] used a hybrid model where the upper mantle is based on Grand & Helmberger [1984] and lower mantle PREM [Dziwonski & Anderson, 1981]), the resolved seismic image tends to fail in delineating the exact configuration of the upper and lower mantle boundaries. Compositional differences between continental and oceanic lithosphere further complicate the interpretation of tomography image. Consequently, the structure of the adjoint models, converted from seismic velocity anomalies, does not have a realistic lithosphere, both for oceanic plates whose thermal structure is dominated by secular cooling, or continental whose vertical temperature gradient is more gradual than that of an oceanic plate. In practice, we removed the upper 200 km of mantle from the seismic image, resulting in a "hot" surface (Fig. 48). The models, therefore, did not properly simulate the thermal evolution of the lithosphere or the core-mantle boundary. A possible solution is to prescribe a top TBL before running the inverse model (Fig. 50), as we will discuss later [Section 6.3.1 & 6.3.3]. The same issue for the bottom TBL arises in dealing with lowermost mantle dynamics and heat transfer across the core-mantle boundary (CMB), where a reasonable expression of the temperature jump from the mantle to the core is essential [Bunge, 2005; McNamara and Zhong, 2005; Leng and Zhong, 2008].

Besides the thermal evolution of lithosphere, mechanical deformations are also of great interests. Future models based on the adjoint method could attempt to assimilate a proper definition of continental structures in order to model geological processes within the subducting and overriding plates during active subduction. Recent developments in this direction with forward models include simulating backarc basin evolution [DiCaprio *et al.*, 2009], mantle wedge process and orogenic deformation [Farrington *et al.*, 2010; Rey and Müller, 2010], and fracture of subducting plate inducing possible slab dehydration [Faccenda *et al.*, 2009]. Toward a prediction that can be compared directly with geology, rather than making inferences based on qualitative correlations as we did for explaining the Laramide (Chapter 5), future adjoint models must be improved in representing lithosphere structures.

### 6.2.2 Uncertain Interpretation of Seismic Tomography

Conversion of seismic velocity anomalies into buoyancy is crucial for the dynamic evolution of the inverse models. During the past decades, increasing consistencies emerge from different tomography models, especially on structures with large spatial scales (>500 km) in areas with good data coverage [Van der Hilst *et al*., 1997; Grand, 2002; Zhao, 2004; Ren *et al*., 2007; Li *et al*., 2008]. However, existing tomography models still show considerable discrepancies in resolving mantle structures at small scales (e.g., features with a dimension of a couple hundred kilometers), due to both the uneven seismic sampling and different resolving powers of inversion techniques [e.g., Grand, 2002]. By comparing different tomography inversions, we find that the Farallon remnant slabs in the lower mantle beneath North America are well resolved, with both the dimensions and magnitude of anomalies consistent among different models. However, the agreement on upper mantle Farallon slabs is much worse, especially among global tomographies. In fact, even the recent high-resolution regional tomography models based on the USArray seismic experiment still show substantial disagreements [Roth *et al*., 2008; Burdick *et al*., 2008; Tian *et al*., 2009], but this situation is likely to be improved given the fact that the surface coverage of USArray is still expanding to the east coast. Consequently, the results we present based on the adjoint models are mostly dealing with the North American evolution prior to the Oligocene time, when the present-day lower mantle Farallon slabs were close to the surface. Because the poorly resolved upper mantle structures do not form a coherent tabular slab system that could allow stresses to transmit along the length of the slab, we had to implement a parameterized stress-guide in order to bring the lower mantle slabs back onto the surface. A comprehensive study exploring the recent tectonic and geologic evolution during the past 30 million years will require a better-resolved upper mantle image beneath North America, especially those related to the subducted Farallon plate.

Another issue is how to appropriately interpret the low velocity anomalies from seismic inversions. In our models, we removed all the low velocity anomalies from the seismic image when converting into density, essentially assuming that these structures are neutrally buoyant. This assumption is not necessarily valid, given the putative role mantle upwelling plays in terms of driving convection, both in enhancing the long-term mantle-scale flow velocity by forming a ‘superplume’ above the CMB [e.g., Zhang *et al*., 2010] and in generating focused plume conduits that may form surface hotspots [e.g., Smith *et al*., 2009]. Although the bulk of the large low velocity provinces above the CMB is considered to be chemical in origin based on their seismic properties [Ishii and Tromp, 1999; Masters *et al*., 2000; Ni *et al*., 2002] and their stability in the lower mantle [McNamara and Zhong, 2005; Torsvik *et al*., 2008], they seem to also possess some extra buoyancy driving mantle flow [Lithgow-Bertelloni and Silver, 1998; Gurnis *et al*., 2000; Simmons *et al*., 2007]. Similarly, the low velocity anomalies beneath North America also seem to be thermal-chemical in origin. On the one hand, prediction of the present-day topography of the Colorado Plateau (Chapter 5) requires extra buoyancy associated with the low velocity anomaly beneath the western U.S. On the other hand, magnitudes of dynamic subsidence inferred from regional vs. global sea-level curves suggest that the low velocity anomaly below the U.S. east coast should have little thermal buoyancy, implying a composition-dominant origin of this anomaly. We suggest that a quantitative understanding of the extra buoyancy associated with the low velocity anomalies beneath North America is subject to future research.

In fact, most tomography models agree better on the high velocity structures than the low velocity ones [Grand, 1997; Li *et al*., 2008], and this indicates that the nature of mantle upwellings is less well understood than that of downwellings. Special attention is needed in dealing with upper mantle structures, where melting may also occur. One good example is the low velocity anomalies revealed by recent regional tomography models beneath western U.S., including the structures below Yellowstone [e.g., Burdick, 2008; Sun and Helmberger, 2010] and Colorado Plateau [Wang, 2007]. A quantitative estimate of composition and properties of these anomalies based on an inverse approach may require an extensive constraining process such as investigating the resulting dynamics on the surface including topography and geoid, heat flow, and a detailed history of magmatism and regional geology. An alternative approach is to simulate melting with forward models following laboratory or petrological empirical relations. Recent work focuses on subduction zones [Kincaid and Hall, 2003; Gorczyk *et al*., 2007; Hebert *et al*., 2009; Zhu *et al*., 2009] and mid-ocean ridges [e.g., Katz *et al*., 2006; Katz, 2008; Ito and Behn, 2008], while a trend is also observed in modeling sub-continental melting processes [Hernlund *et al*., 2008; Conrad *et al*., 2010].

### 6.2.3 Simplification in Physical Assumptions

In order to keep the number of unknowns small, we have assumed a simple mantle structure during the inversion of the Farallon subduction. For example, the model has a three-layer viscosity structure, without any phase transformations or possible chemical anomalies. Through forward models, we find that the phase change at 660 km depth plays a smaller role in controlling Farallon plate subduction, compared with the total buoyancy associated with the slabs. Since the Olivine-Spinel phase transformation at ~410 km depth tends to enhance subduction while the Spinel-Perovskite phase change at 660 km depth tends to slow down the subducting slabs, the net buoyancy effects of these two competing phase changes is playing a minor role controlling the overall speed of subduction, given that the slab is strong enough to transmit thermal buoyancy along the length of the slab [e.g., Billen, 2008]. Phase transformations will affect the morphology of slabs when the slab rheology varies along its length and thermal buoyancy diminishes (say, due to young slab ages). Because these phase changes occur at different depths (above and below the mantle transition zone), the down-going slab will experience a torque that can deform the flow pattern locally by causing slab thickening or buckling within the transition zone [e.g., Christensen, 1996; Tetzlaff & Schmeling 2000; Cízkova *et al*. 2002]. Therefore, in a more realistic model, these physical processes still need be incorporated. Other phase changes may also be considered in future models, including a possible post-peroviskite transformation at the core-mantle boundary [Sidorin *et al*., 1999; Hernlund *et al*., 2005] and the basalt-ecologite transformation at the base of the lithosphere [Ringwood and Green, 1966], which may affect subduction dynamics through changing the density and rheology of slabs [e.g., Ji and Zhao 1994].

Although the influence of phase changes may be secondary compared to the overall buoyancy of thermal anomalies, both the adiabatic compressibility of the mantle with depth and the decreasing thermal expansion coefficient at higher pressures can affect convection [e.g., Hansen *et al*., 1994]. Another factor that influences slab morphology is rheology: with varying slab strength relative to the surrounding mantle, the subducting slabs will evolve into different geometries [e.g., Billen, 2008; Stegman *et al*., 2010]. It is, therefore, important to explore the effects of rheology on the style of subduction and generation of surface plates [Zhong and Gurnis, 1996; Tackley, 2008; Stegman *et al*., 2010], especially for the development of fully dynamic inverse models (i.e., the prediction rather than the imposition of surface plate motions, see next section for more discussion). However, we realize that, within the adjoint models, a sophisticated realization of complex slab rheology as that used in forward models [e.g., Billen, 2008] is limited by the intrinsically low resolution images obtained by seismic tomography. A possible solution is through a hybrid model with explicitly defined upper mantle slabs embedded in the adjoint models (see section 6.3.3).

### 6.2.4 Limited Applications with Forced Convection

As mentioned in the previous section, the adjoint models we developed use prescribed surface velocities rather than predicting them by the internal convection of the mantle, i.e., a forced convection. With surface plate motions imposed as boundary conditions, mantle flows close to the surface (e.g., within the lithosphere) are largely passive, while convection at larger depth is more subject to internal buoyancy forces. Consequently, these models have limited applications in exploring the driving mechanism of motions of tectonic plates, which has been an import unresolved question. Potentially, uncertainties or errors associated with plate reconstructions can be mapped into model results, although some of these artifacts can be ruled out through comparisons with tomography image [Bunge and Grand, 2000] or together with geology [Van der Meer *et al.*, 2010].

While imposed velocity boundary conditions take plate motions as constraints, a fully dynamic model treats them as predictions, which, by comparison to the observed values, inform us of the driving mechanism of plate tectonics and mantle convection [e.g., Stadler *et al.* 2010]. In order to construct a fully dynamic model, special attention must be paid to slab rheology and numerical resolution. The essence of plate tectonics is that the surface shell of the earth can be divided into quasi-rigid pieces that are moving relative to each other with most of the deformation occurring at their boundaries. This requires a proper rheology that generates plate-like kinematics with either prescribed weak zones between strong slabs [Zhong and Gurnis, 1996] or yielding stresses that allow certain parts of the rigid plate to weaken [Tackley, 2008]. On the other hand, mesh resolution and computational cost are additional limitations for large-scale numerical models. This is especially the case in models with a more realistic parameterization of plate boundaries including faults or orogenic deformations. More discussion about this issue can be found in the next section.

## 6.3 Some Thoughts on Future Model Development

Given the limitations of the current models and possible developments of data and techniques, future geodynamic models with data assimilation may be improved in the following aspects.

### 6.3.1 Tomography: Push the Limit of Resolution

Global tomography models usually have poor resolving power for fine-scale features, because both their long ray path inside the mantle and coarse data coverage on the surface cause smoothing of the inverted seismic image [e.g., Ritsema *et al*., 2007]. Regional tomography, with shorter ray path and denser coverage of receivers, reveals the local structures better. Recent development of tomographic inversions based on finite-frequency sensitivity kernels using multiple frequency bands may resolve structures better [Sigloch *et al*., 2008; Li *et al*., 2008]. Toward a realistic representation of mantle structure, the most promising approach is adjoint tomography, which avoids the blurring effect of seismic inversion by solving for the seismic wave field in a domain with full 3-D seismic velocity anomalies. Such model have increased wave speed variations up to several tens of percents, much larger than the standard perturbations expressed in traditional tomography [Tape *et al*., 2009]. The adjoint tomography, however, is computationally expensive, and has only been applied locally.

With the continuing deployment of the USArray seismic network across the U.S., several high-resolution tomography models have appeared in the literature [Sigloch *et al*., 2008; Burdick *et al*., 2008; Roth *et al*., 2008; Tian *et al*., 2009]. Various features have been detected beneath the western U.S., including a parallel-subducting slab doublet related to the Juan de Fuca plate subduction [e.g., Burdick *et al*., 2008; Roth *et al*., 2008], a controversial high velocity anomaly below Nevada [West *et al*., 2009], and plume-like low velocity anomalies around Yellowstone [Sigloch *et al*., 2008; Burdick *et al*., 2008; Roth *et al*., 2008; Sun and Helmberger, 2010]. These new generation of regional tomography models provides a chance for the adjoint convection model to recover the recent evolution of subduction along western North America.

I have started to develop such a high-resolution inverse convection model based on the tomography of Burdick *et al*. [2008] to reverse the subduction process beneath western U.S. since the Miocene. The effective temperature anomalies scaled from tomography is shown along a east-west profile at 41°N (Fig. 50). A temperature-dependent viscosity with lateral variations by four orders of magnitude is used, and a thermal boundary layer on top is included. Inversion to the past based on this model is still ongoing research.

Regional high resolution tomography models below the western U.S. based on either different datasets [Burdick *et al.*, 2008 vs. Tian *et al*., 2009] or different inversion techniques [Roth *et al*., 2008 vs. Burdick *et al*., 2008] show significant consistency for the major features, especially the upper mantle slab structures. Eventually this will help to construct a coherent image of the Farallon subduction by connecting the upper and the lower mantle structures. This may also provide a chance for a more realistic reconstruction of the Farallon subduction, where the stress-guide discussed in Chapter 4 is no longer necessary.

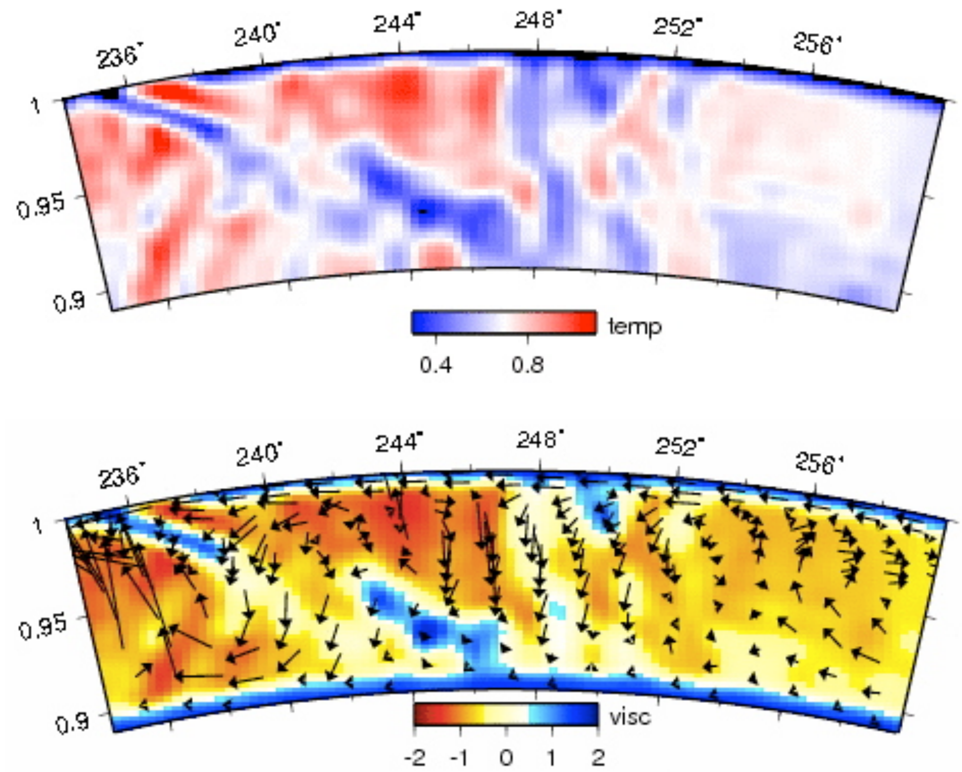


**Figure 50** E-W cross-section along latitude 41°N in western U.S. upper mantle, showing its present-day buoyancy field. (Top) Temperature anomaly converted from seismic image of Burdick *et al*. [2008]. A thermal boundary layer is added, and the Juan de Fuca slab redirected to its surface plate at the trench (~236°E longitude). Vertical axis shows normalized radius. (Bottom) The viscosity structure based on a temperature-dependent rheology (relative to $10^{21}$ Pa s) and the density driving flow field (arrows) with the plate motion imposed as boundary conditions on top.

### 6.3.2 Constraints: Multiple Datasets

So far, we have attempted assimilation of several different datasets into the inverse model, including seismic tomography, plate motions and surface dynamic topography. We also adopted qualitative constraints from structural geology after the fact for further model validation, but have not established a formal algorithm allowing strict assimilation of these datasets.

In theory, any observation related to the dynamics of the mantle could constrain the model. On the other hand, application of these constraints is restricted by limitations of the numerical models. As more powerful and adaptive algorithms are created in future simulation software, more types of data can be brought in, which will make the model more earth-like. With the current computational ability of the software CitcomS, other observations like the geoid [Zhong *et al.*, 2008] can be extended into our predictions. Future inverse models with data assimilation should follow this trend, as is the same path the general circulation models in meteorology and oceanography have covered.

As every single simulation approach has its own limitation in terms of assimilating data and representing the earth, mutual consistencies between different modeling techniques are an important alternative measure of the validity of a physical model. The adjoint models, by satisfying various data with distinct natures, have the potential to better explain the evolution of solid earth than traditional means. With the several existing limitations improved, such as realistic boundary layers, more complete physical assumptions and higher numerical resolutions (Section 6.2.1), the adjoint models will gradually move toward this goal.

### 6.3.3 Algorithm: Hybrid Models

By purely assimilating seismic images, the inverse model cannot represent the thermal boundary layers of the mantle properly. This is because tomography inversions based on body waves (representing the majority of such models), especially for global tomography, have little sensitivity to shallow structures like the crust, because the ray paths are largely vertical at shallow depth [e.g., Grand, 2002; Burdick *et al*., 2008]. Therefore, the adjoint convection models converted from tomography also do not have a realistic lithosphere structure. Since most geophysical and geological observations are recorded at the earth's surface, an appropriate representation of the lithosphere is important, especially for future high-resolution models with extensive data assimilation. A possible way to solve this problem is to prescribe the lithosphere via traditional forward modeling techniques and maintain this constraint during the adjoint iterations, so that not only are major mantle structures captured based on scaled seismic images, but that fine features along boundary layers can also be expressed through explicit definitions with forward modeling (e.g., Fig. 50). In this case, the iterative procedure of the adjoint inversion will need to be updated so that it does not overwrite the forward constraints.

Another advantage of hybrid models is to help increase local numerical resolutions. As global models based on traditional uniform meshing are computationally expensive, and regional models suffer from artificially imposed vertical boundaries, new mathematical concepts for more efficient calculation must be generated. One approach has been to use a nested model where a coarse global model contains a finer regional one [Tan *et al*., 2006]. An alternative means is adaptive mesh refinement and coursing (AMR) techniques, which allow realization of local features with high resolutions while maintaining the total number of mesh grids largely the same [Burstedde *et al*., 2008; Stadler *et al.* 2010]. Implementation of these techniques is likely to improve the power of future geodynamic models greatly.

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