Farallon Subduction Reconstructed by Inverse Dynamic Models: Stratigraphic Verifications and Geophysical Implications

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Abstract Using an inverse mantle convection model that assimilates seismic structure and plate motions, we reconstruct the Farallon plate subduction back to 100 Ma. Stratigraphy including paleoshorelines, sediment isopachs and borehole tectonic subsidence rate are used to constrain the depth dependence of mantle viscosity: Our best model has a lower mantle viscosity 1.5×10^{22} Pas, upper mantle viscosity 10^{21} Pas and a present-day effective temperature anomaly associated with the Farallon remnants at 160 ºC. In Late Cretaceous, the recovered Farallon subduction underneath North America was characterized by an elevated flat-lying oceaninc lithosphere surrounded by an extensive zone of shallow dipping slab emanating from the flat-lying slab farther east and north by up to 1000 km. Both shape and location of the flat-lying slab correlate well with the geologically inferred Laramide fault zone, and this limited region of flat subduction is consistent with the notion that subduction of an oceanic plateau caused the slab to flatten. Besides predicting the formation of the Western Interior Seaway, our model also suggests a three-stage postCretaceous uplift process for the Colorado Plateau, during which the Plateau changed its downward tilting direction from NE in Eocene to SW in Oligocene.

➤ **Forward model:** $\nabla\cdot\vec{u}=0;\ \nabla P+\nabla\cdot(\eta\nabla\vec{u})=\rho_m\alpha T_e\vec{g};\ \dfrac{\partial T_e}{\partial t}+\vec{u}\cdot\nabla T_e=\kappa\nabla^2 T_e$

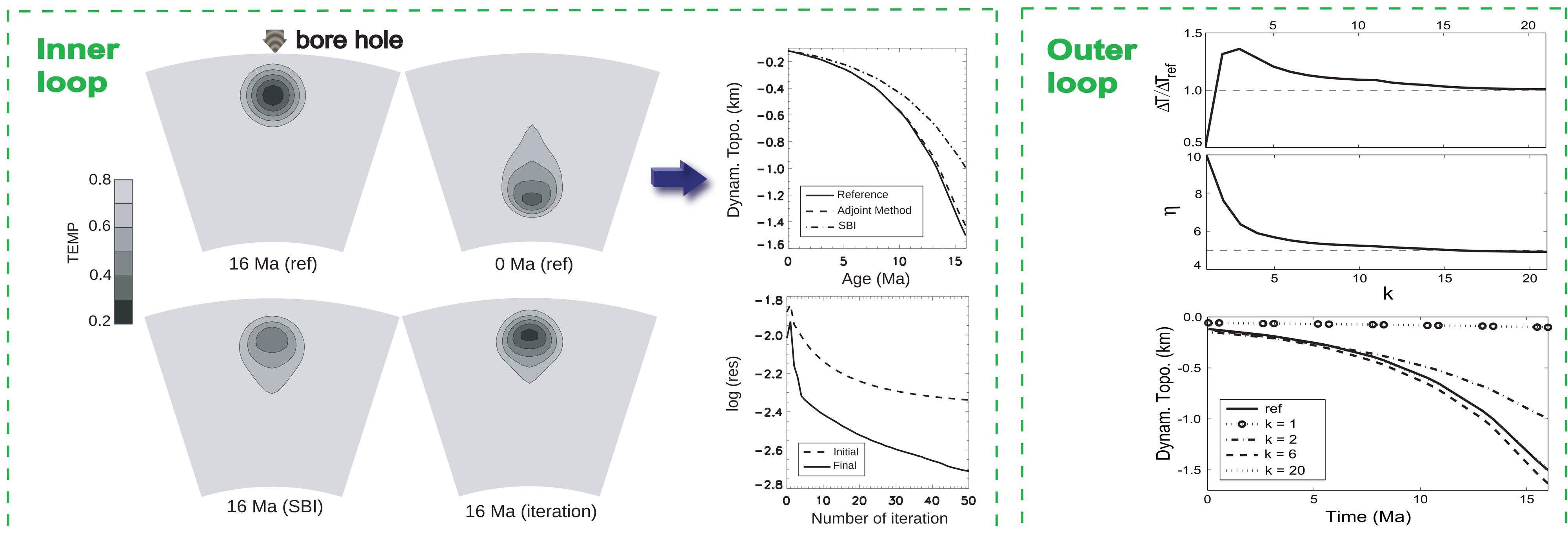
Adjoint model: $\dfrac{\partial\lambda}{\partial t}+\vec{u}\cdot\nabla\lambda+\kappa\nabla^2\lambda=0$

u: velocity; P: dynamic pressure; η: viscosity; α: thermal expansion coefficient; T_e: effective temperature anomaly; ρ_m: mantle density; g: gravitational accelaration; κ: thermal diffusivity; λ: adjoint temperature.

➤ **Constrain mantle properties:** Application of the adjoint method to real geophysical problems requires a better understanding of mantle rheology and buoyancy which are crucial to mantle dynamics. This uncertainty can be overcome by assimilating surface dynamic topography associated with mantle buoyancy into the time-dependence of mantle convection.

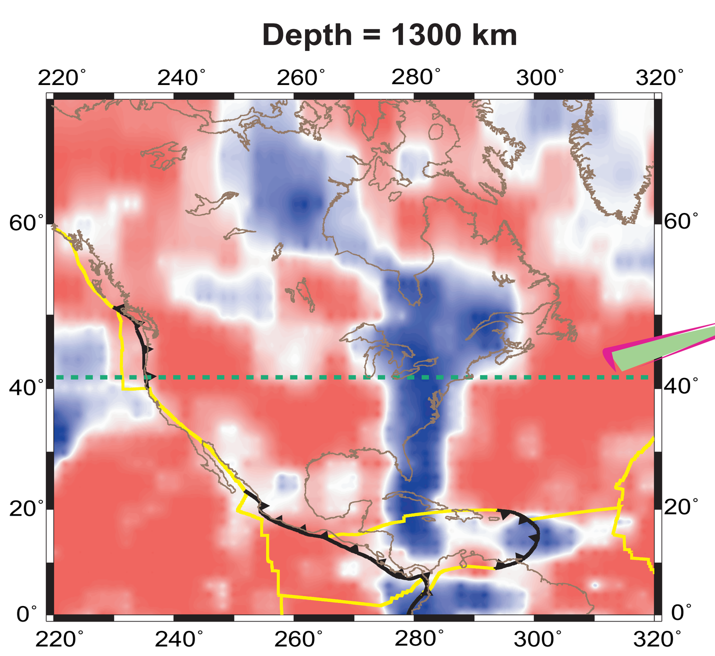
I.E. One layer mantle: $h(t)=\zeta(t)T_e;\quad \dot{h}(t)=\dfrac{\xi(t)}{\eta}h_1^{\,2}$

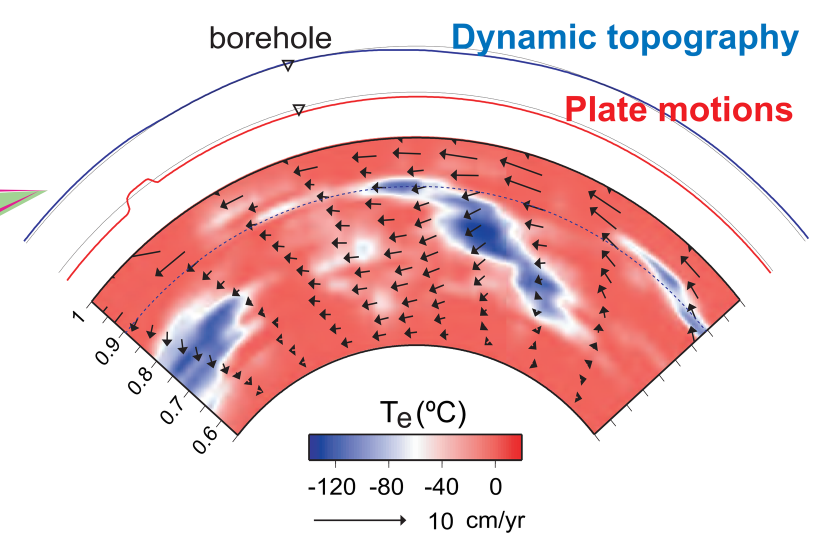
h: dynamic topography; ζ, ξ: numerical coefficients.



Tomography

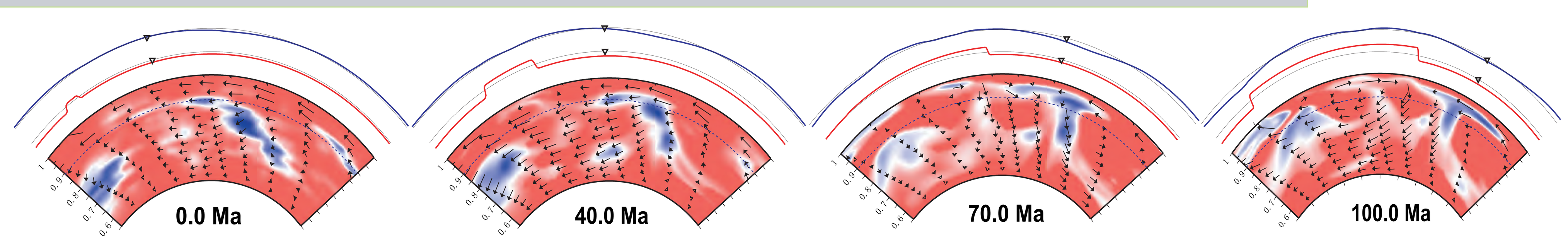
Global shear wave sesimic tomography [Grand, 2002].





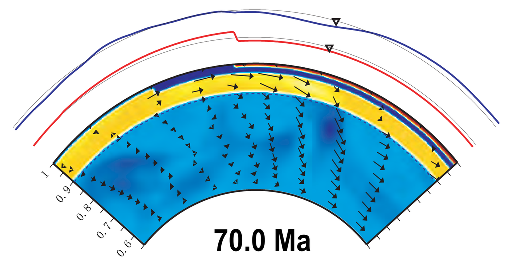
Dynamic models I:

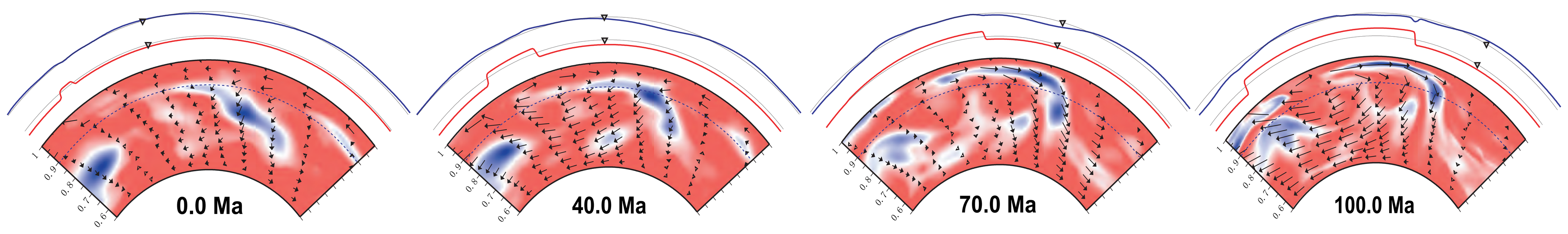
A standard convection model with imposed plate motions will not lead to a geophysically reasonable subduction geometry. This problem can not be overcome either with a different radial viscosity structure or with more adjoint iterations.



Dynamic models II:

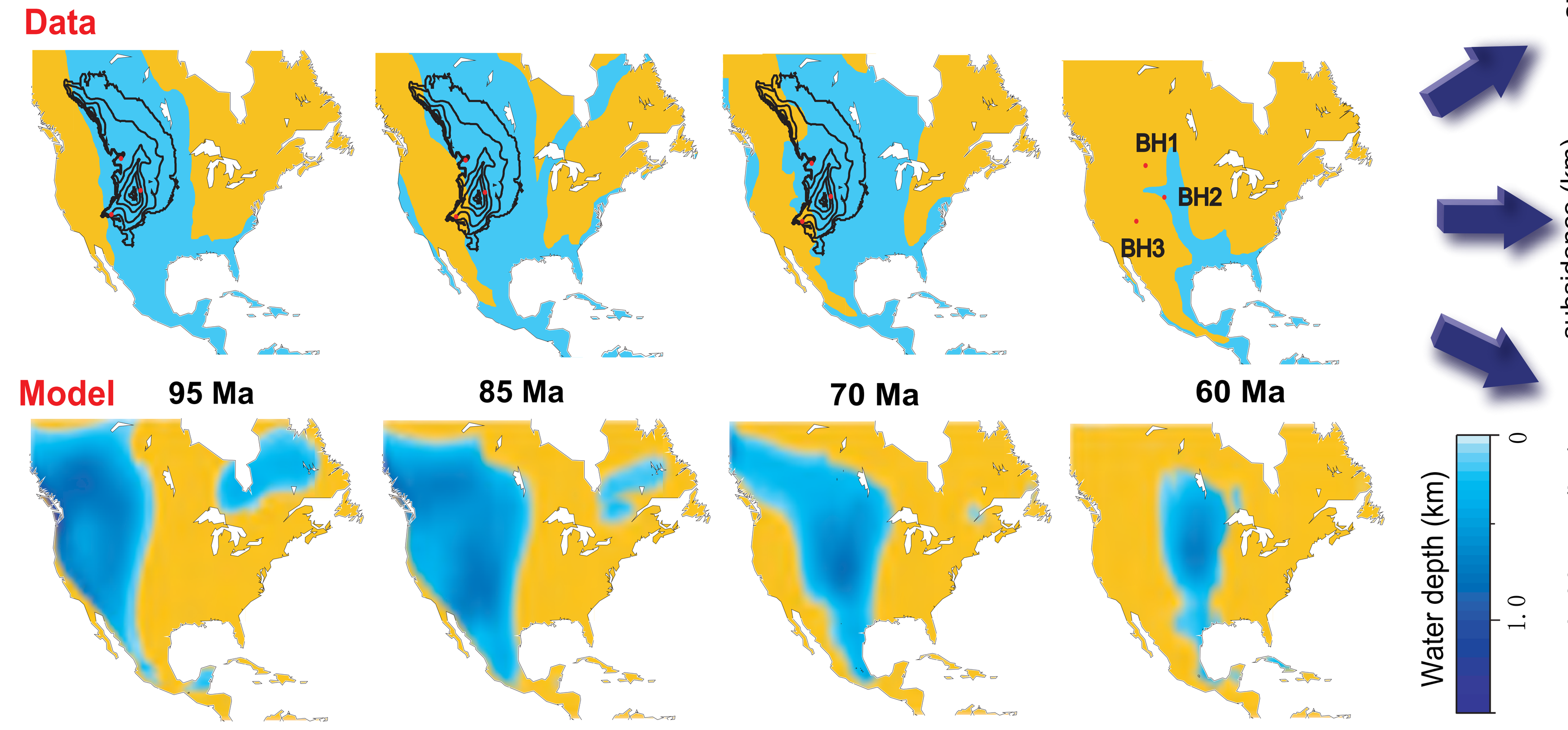
Since we hypothesize that this problem is due to a missing upper mantle slab that connects present day lower mantle Farallon remnants to the oceanic plate on the surface, we implement a simple stress guide under the North American plate in which the Farallon slab preferentially attaches to the oceanic plate as it rises up to the surface. This leads to a reasonable subduction geometry.

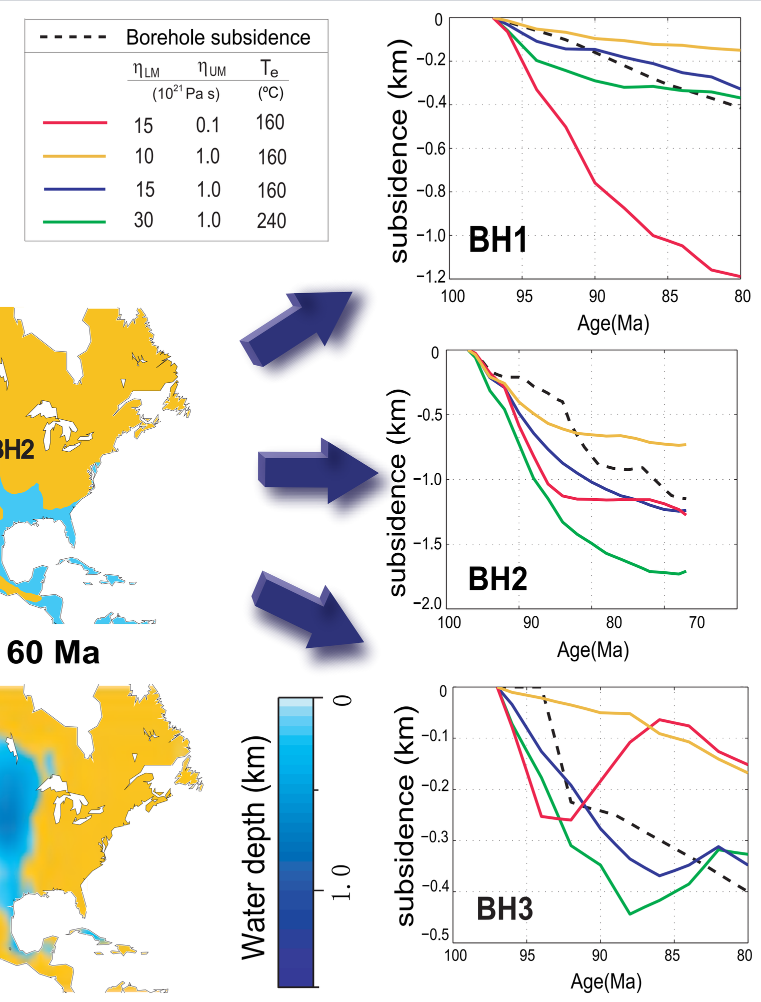




Stratigraphic constraining:

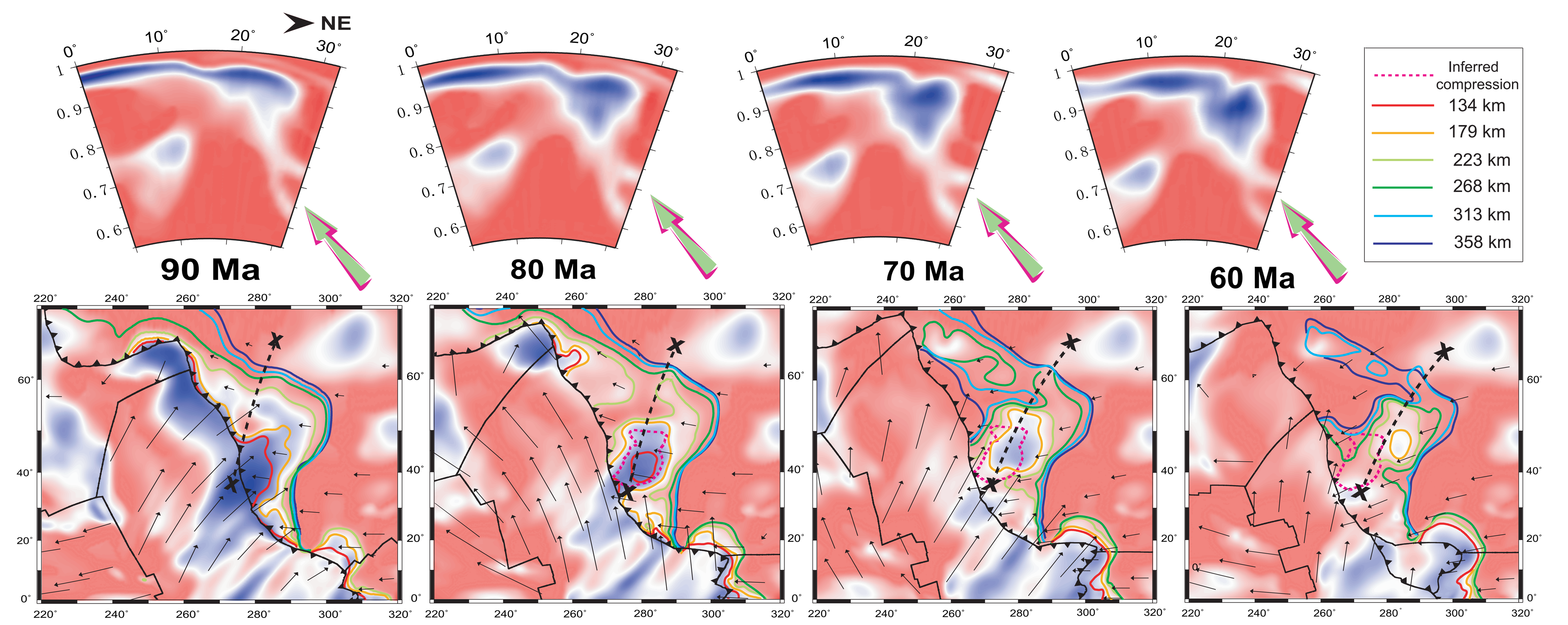
Predicting the Late Cretaceous paleo-shorelines and borehole tectonic subsidence rates in western U.S. constrains both mantle viscosities and slab buoyancy: the best fit model has $\eta_{LM}=1.5\times10^{22}$ Pas, $\eta_{UM}=10^{21}$ Pas and $T_e=160$°C.





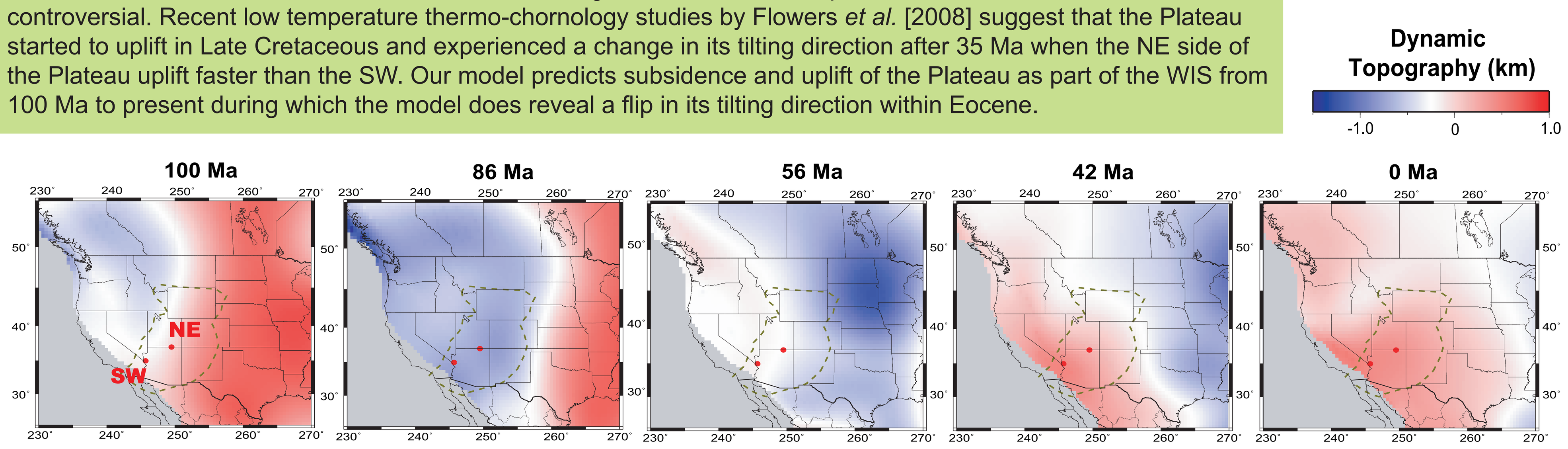
Farallon subduction

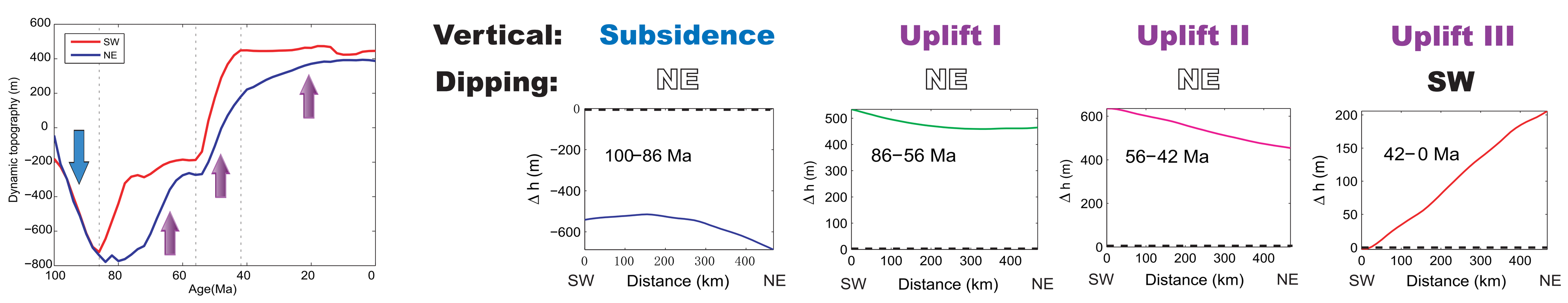
Our model reproduces a flat-lying slab that is shallower and thicker than surrouding structures; the morphology of this structure correlates well with faulting associated with the Laramide orogeny, and is consistent with the assumption of an oceanic plateau subducted underneath the continent, leading to formation of a large area of flat subduction. A vast halo of shallow subduction is inferred beyond the flat slab, which, as sinking, produces a broad region of dynamic subsidence that creates the Western Interior Seaway (WIS).



Colorado Plateau

Cause and timing of subsidence and uplift of the Colorado Plateau have been controversial. Recent low temperature thermo-chornology studies by Flowers *et al.* [2008] suggest that the Plateau started to uplift in Late Cretaceous and experienced a change in its tilting direction after 35 Ma when the NE side of the Plateau uplift faster than the SW. Our model predicts subsidence and uplift of the Plateau as part of the WIS from 100 Ma to present during which the model does reveal a flip in its tilting direction within Eocene.





Conclusions

1. Inverting for Farallon subduction with the adjoint method provides a new way to constrain basic mantle properties, including viscosity and mantle buoyancy.
2. The Farallon flat subduction is a natural result of inverting tomography while predicting various stratigraphic observations. The flat slab reconstructed by adjoint models correlates well with the flat slab inferred from basement cutting Laramide-type faults in the western US. Morphology of the recovered flat slab is consistent with a subducted oceanic plateau.
3. During the Late Cretaceous, beyond the flat portion of the Farallon slab, vast range of shallow dipping slab segments emanate east and northward with an extent up to 1000 km, which has caused a much broader range of dynamic subsidence over the North America Craton than previously thought to be within Colorado and Wyoming.
4. Our model quantitatively explains the subsidence, uplift and tilting associated with the Colorado Plateau suggested by recent low temperature thermochronology study.
5. Inverting seismic structure from present day mantle to the past provides unexpected insights to tectonic events.