LINKING SURFACE EVOLUTION WITH MANTLE DYNAMIC PROCESSES USING ADJOINT MODELS WITH DATA ASSIMILATION

Thesis by

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In Partial Fulfillment of the Requirements

for the degree of

Doctor of Philosophy

California Institute of Technology

Pasadena, California

2010

(Defended May 25, 2010)

ACKNOWLEDGEMENTS

First, I want to express my sincere gratitude to my advisor, Professor Michael Gurnis, for his patient guidance during the past five years. I thank Mike for his warm encouragement when I get frustrated on research, his careful and thorough suggestions on my scientific writing, and his incisive visions and prudent cautions on my thesis work. I cherish the days that I have learned so much from Mike and the convenience he provides for me to work on exciting projects using world-class computing facilities. I am grateful for all his help and all the rewarding collaborations we have developed.

I would like to thank several knowledgeable faculty members from whom I've learned a lot. Especially, I want to thank Professor Don Helmberger for all his kind help and stimulating discussions with me, which almost makes me a seismologist. I also want to thank Professors Joann Stock, Jennifer Jackson and Jason Saleeby for their generous help with my research. A special thanks goes to my academic advisor, Nadia Lapusta, who helped me a lot during the trying times. I also want to thank Hiroo Kanamori and Don Anderson, for their warm-hearted directions on spontaneous questions I came up with. I very much enjoy the academic atmosphere at the Seismological Laboratory. Meanwhile, I am also very thankful to our friendly and helpful Seismo Lab staff; without you these years would have been much more boring.

My thanks also go to the current and previous graduate students in the Seismo Lab. I'm grateful to Dr. Eh Tan and Dr. Eunseo Choi, who assisted me through the initial stage of geodynamic research with their experience and knowledge. I thank Dr. Ying Tan and Dr. Daoyuan Sun, who helped me extensively for seismological research. I also thank my fellow graduate students Sonja Spasojevic for earlier collaborations, and Dan Bower for carrying on interesting discussions. I have really enjoyed the times chatting and socializing with Shengji, Zhongwen, Dongzhou, and many other students, and I thank you all for your friendship.

Finally, my sincere thanks go to my beloved wife, Yun, and our families back in China. First, I am deeply thankful to my parents for raising me up and sending me to college,

which had been a big burden for a family with little income like mine. I want to sincerely thank my wife for her caring for me during the past years, which makes my life and work a lot easier. I am so lucky to have you with me while staying so far away from our families. I also want to express my thanks to my parents in law for their understanding and encouragement. Without all your enduring and absolute support, I would have accomplished nothing.

ABSTRACT

Quantifying the relationship between subsolidus mantle convection and surface evolution is a fundamental goal of geophysics. Toward this goal progress has been slow due to incomplete knowledge of the earth's internal structure and properties. While seismic tomography reveals details on internal 3D structure of the present mantle, evolution of the subsolidus mantle during the geological past remains elusive. This thesis attempts to solve the time inversion of mantle convection using the adjoint method based on present-day seismic images and geological and geophysical observations dictating the past evolution of solid earth.

The adjoint method, widely used in meteorological and oceanographic predictions, can be applied to mantle convection for the recovery of unknown initial conditions through the assimilation of present-day mantle seismic structure. We propose that an optimal first guess to the initial condition can be obtained through a simple backward integration (SBI) of the governing equations thus lessening the computational expense. By incorporating time-dependent surface dynamic topography in addition to present-day mantle structure, the adjoint method is improved so as to constrain uncertain mantle dynamic properties and initial condition simultaneously. The theory is derived from the governing equations of mantle convection and validated by synthetic experiments for a single- and two-layer viscosity mantle within regionally bounded spherical shells. For both cases, we show that the theory can constrain mantle properties with errors arising through the adjoint recovery of the initial condition. For the two-layer model, there is a trade-off between the temperature scaling and lower mantle viscosity.

By assimilating seismic structure and plate motions in the inverse mantle convection model, we reconstruct Farallon plate subduction back to 100 Ma. We put constraints on basic mantle properties, including both the depth dependence of mantle viscosity and slab buoyancy, by predicting proxies of dynamic topography evident in the stratigraphy of the North American Cretaceous western interior seaway. Models that fit stratigraphy well require the Farallon slab to have been flat lying in the Late Cretaceous, consistent with

geological reconstructions. The models predict an extensive zone of shallow-dipping subduction extending beyond the flat-lying slab farther east and north, while the limited region of subducting flat slab resembles an oceanic plateau. In order to test the hypothesis of oceanic plateau subduction and its relationship to the Laramide orogeny, we compare the inverse convection model with plate reconstructions. Two prominent seismic anomalies on the Farallon plate recovered from inverse models coincide with paleogeographically-restored positions of conjugates to the Shatsky and Hess plateaus when they subducted beneath North America. The distributed shortening of the Laramide orogeny closely tracked the passage of the Shatsky conjugate beneath North America, while the effects of Hess conjugate subduction were restricted to the northern Mexico foreland belt. We find that Laramide uplifts were consequences of the removal, rather than the emplacement, of the Shatsky conjugate, and we predict that these subducted plateaus should be detectable by the USArray seismic experiment.

The inverse convection models predict a continuous vertical motion history of western U.S., which is further validated by constraints on the vertical motion of the Colorado Plateau since the Cretaceous. With the arrival of the flat-lying Farallon slab, dynamic subsidence swept from west to east over the western U.S., peaking at 86 Ma within the Colorado Plateau. This eastward migrating dynamic subsidence is consistent with a recently compiled backstripping study that shows a long-wavelength residual subsidence shifting to the east, coincident with the passage of the flat slab beneath North America in our inverse model. Two stages of uplift followed the removal of the Farallon slab below the Colorado Plateau: one in the latest Cretaceous, and the other in the Eocene, with a cumulative uplift of ~1.2 km; the former represents the Laramide uplift which also marks the initial uplift of the entire western U.S. Both the descent of the slab and buoyant upwellings raised the Colorado Plateau to its current elevation during the Oligocene. A locally thick lithosphere enhances coupling to the upper mantle so that the Colorado Plateau has a higher topography with sharp edges. Our models also predict that the plateau tilted downward to the northeast before the Oligocene, caused by northeast-trending subduction of the Farallon slab, and that this northeast tilting diminished and reversed to the southwest during the Miocene in response to buoyant upwellings.

Overall, this thesis shows that the adjoint models with data assimilation are useful in linking surface evolution to deep mantle processes both over North America and areas beyond. While more research is clearly needed to construct a more earth-like model, this thesis presents an important advance in data-oriented geodynamic models.

CONTENTS

LIST OF FIGURES

Number *Page*

LIST OF TABLES

Chapter 1
Introduction

One of the ultimate goals of geophysics is to understand subsolidus mantle convection and its relationship with surface observables, both geophysical and geological. Steady progress has been made as we increase our ability to image the earth's internal structures. Development of seismic tomography has provided significant insights into mantle convection. From global seismic tomography, we see not only large-scale low-velocity anomalies rising from the CMB and high-velocity belts correlated with ancient subduction zones [*Su et al.*, 1994; Li and Romanowicz, 1996; Masters *et al*., 2000], but also structures like subducted oceanic slabs extending into the lower mantle [Grand *et al*., 1997; Van der Hilst *et al*., 1997; Ritsema *et al*., 2004; Li *et al*., 2008]. Deep-rooted columnar low seismic velocity structures, associated with surface hot spots, may have been detected and could be indicative of active mantle plumes [Montelli *et al*., 2004, Zhao, 2004; Nolet et al., 2007]. Closer to the surface, regional tomography has imaged active subduction zones showing high seismic velocity slabs overlain by low velocity mantle wedges [Zhao *et al*., 1997; Huang and Zhao, 2006; Sigloch *et al*., 2008; Roth *et al*., 2008]. Although very informative, tomographic images only provide a snapshot of mantle convection, the final instant of an evolving system.

In order to constrain the time dependence of mantle convection, other geophysical observations beyond seismic imaging and gravity that extend into the time domain are needed. An important constraint comes from the velocity of plates and their time dependence that can be predicted in global flow models [Lithgow-Bertelloni and Richards, 1998]. Another possibility comes from surface topography (through stratigraphy and relative sea level) that has been used as a constraint on time-dependent models of mantle convection [Gurnis, 1993; DiCaprio *et al*., 2009], some with assimilated plate motions [Gurnis *et al.*, 1998]. Furthermore, predicting the present-day mantle seismic structures through forward models also helps to constrain past geologic events [Bunge and Grand, 2000] and explain uncertain mantle anomalies [McNamara and Zhong, 2005].

However, previous models of mantle convection have all faced the difficulty of incorporating reasonable initial conditions. For example, Bunge *et al*. [1998] assumed a quasi steady-state mantle structure achieved by imposing the Cretaceous plate motion for a relatively long time before allowing time-dependent plate kinematics to start. This assumption is potentially problematic since plate motions change continuously. Gurnis *et al*. [1998] used an initial condition at 140 Ma in a model of the Australian region based on the earlier geological evolution. These initial conditions cannot reproduce the exact structures of present-day mantle.

On the other hand, Steinberger and O’Connell [2000] and Conrad and Gurnis [2003] utilized a simple backward integration of the convection equations to predict past mantle structure by advecting the current mantle structures back in time, while neglecting thermal diffusion. This method, however, limits its application, because neglecting thermal diffusion will lead to the accumulation of artifacts at thermal boundaries with time [Ismail-Zadeh *et al*., 2004]. Inferring the initial condition of a diffusive process through a simple reversal of time is problematic because it leads to exponentially growing numerical errors, which is called an ill-posed problem.

A promising approach to recovering initial conditions is through the use of an adjoint method widely adopted in meteorology and oceanography [Talagrand and Courtier, 1987] and recently introduced into mantle convection [Bunge *et al*. 2003; Ismail-Zadeh *et al*., 2004]. The method constrains the initial condition by minimizing the mismatch of a prediction to observation iteratively in a least-square sense. Through synthetic experiments, Bunge *et al*. [2003] and Ismail-Zadeh *et al.* [2004] separately demonstrated that the initial condition could be effectively recovered with iterative solver schemes. However, the application to geophysical problems remained limited, because earlier tests all assumed that the initial condition is the only unknown in the system, which is obviously not true. In fact, both the rheology and effective Rayleigh number of the mantle, two key parameters governing the vigor of convection, are still uncertain, and this prohibits a unique recovery of the past mantle structure since the solution strongly depends on these mantle properties. On the other hand, the computational expense of earlier adjoint algorithms is high, especially for large- 3D models.

In this thesis, I will summarize our work on improving the adjoint method by expanding the category of data constraints for assimilation and applying the method with real data. In Chapter 2, we describe the theoretical basis of the adjoint method in mantle convection and its implementation in computational software. By bringing in time-dependent observations, i.e., surface dynamic topography, the adjoint method can be used to constrain uncertain mantle dynamic properties, while simultaneously recovering the unknown initial conditions of mantle, as we show in Chapter 3. While in Chapter 4, with the improved adjoint inversion technique, we perform the first inversions of mantle convection based on data (including seismic tomography, plate motions, and stratigraphy as proxy for dynamic topography). The model was tailored for recovering the Farallon plate subduction back to the Late Cretaceous. In Chapter 5, by combining the adjoint models with plate reconstructions and structural features, we argue that the mechanism causing flattening of the Farallon slab was subduction of two oceanic plateaus, whose passage beneath North America had led the formation of the enigmatic Laramide orogenic event. This chapter also discusses the vertical motion evolution of the western and eastern U.S. accompanying the Farallon subduction, and implication of the inverse model on quantifying evolution of the western interior basins. In Chapter 6, I first provide a broader discussion on subduction evolution during the past beyond North America based on the adjoint model we have developed, followed by a summary of limitations of the current inverse models and some possible future improvements.