# 4-D Geodynamic Modeling With Data Assimilation: Subduction and Continental Evolution

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## Executive summary

Subduction is a key geodynamic process governing the temporal evolution of the mantle and lithosphere. However, both the fate of subducted slabs and the accompanying continental evolution (deformation, topography, volcanism, etc.) remain poorly understood. This is because the relevant processes are complex and involve a large range of temporal and spatial scales. Techniques of data assimilation, including both the sequential (forward) and variational (inverse) approach, are promising in solving such non-linear problems by minimizing the number of model unknowns through prediction of observational constraints. We have obtained much experience from previous research in applying these data assimilation methods to geodynamic modeling. During the last year (2015-2016), we have applied these modeling methods to better understanding subduction and continental evolution in both North America and South America.

## Research activities and results

***Key challenges**:* Two main scientific challenges exist: 1) Origin of intra-plate volcanism, such as that in the Pacific Northwest including the Yellowstone volcanic field; 2) Causes and consequences of flat-slab subduction, such as that in South America. We use supercomputer models with data assimilation to address these two fundamental questions.

***Why it matters*:** Besides its apparent scientific merit, intra-plate volcanism also represents a major natural hazard on Earth. Therefore, understanding the mantle driving force of these hazardous tectonic events has important implications in both the scientific and societal communities. The formation and effect of flat-slab subduction, a process of plate tectonics that influences Earth geology the most, are another heavily debated topic in geosciences.

***Why Blue Waters*:** Both these research topics require large-amount of I/O and computation. Currently, Blue Waters represents the best platform for carrying out these calculations.

***Accomplishments*:**

1) On the formation of intra-plate volcanism, we tested the popular hypothesis that Yellowstone was formed from a mantle plume originating from the core-mantle boundary region. We built a computer model to simultaneously account for both the past subduction history and the present-day mantle seismic images. Our results suggest that a mantle plume is always subject to the dynamics of the sinking oceanic plate. As a consequence, the plume plays a very minor roll in the formation of surface volcanism. This work was published in the *Geophysical Research Letter*, which has obtained much media exposure. Figure 1 illustrates the key result of this paper.

Our more recent work suggests that, instead of due to a mantle plume, the formation of the extensive volcanism is directly controlled by the intruding hot asthenosphere from under the oceanic plate. This hot mantle was directed into the upper mantle below the western U.S. following the subduction-induced toroidal flow. Figure 2 summarizes the main results of this paper. We have submitted this work to the journal *Nature*.

2) For South America, we have developed a time-dependent 3-D spherical subduction model that starts from 100 million years ago (Ma). With this model, we systematically investigated the different mechanisms proposed earlier that are responsible for the formation of flat slabs. We found that the observed present-day slab geometry reflects a combined effect of several mechanisms (seafloor age, hydrodynamic suction, and buoyancy feature subduction), but the subducting buoyancy features play a major role. We also discover that the flat slabs are all internally broken, a result never expected before. Part of these results is published in the *Earth and Planetary Science Letters*. Figure 3 illustrates our simulated South American subduction at the present day. Figure 4 shows a new understanding of flat-slab subduction on Earth, as suggested by this research. Two more papers are in revision/preparation.

3) During the past year, we have made significant progress on two independent lines of research, both of which utilized Blue Waters. Two papers are currently being reviewed by the journal *Science* and *Nature Geoscience*, respectively. I will provide images when these papers come out.

## List of publications associated with this work (* denotes student author):

***Published peer-review journals:***

1. Leonard*, T., & **L. Liu** (2016), The Role of a Mantle Plume in the Formation of Yellowstone Volcanism, Geophys. Res. Lett., 43, doi:10.1002/2015GL067131.

2. Hu*, J., **L. Liu**, A. Hermosillo, & Q. Zhou (2016), Simulation of Late Cenozoic South American Flat-Slab Subduction Using Geodynamic Models with Data Assimilation, *Earth Planet. Sci. Lett*., 438, 1-13, doi:10.1016/j.epsl.2016.01.011.

3. Hu*, J., **L. Liu**, Abnormal Seismological and Magmatic Processes Controlled by the Tearing South American Flat Slabs, *Earth Planet. Sci. Lett*. in revision.

***Manuscript submitted/in preparation:***

1. Liu, L., & D. Hasterok, High–Resolution Lithosphere Viscosity and Dynamics Revealed by Magnetotelluric Imaging, *Science*, in review.

2. Liu, L., C. Chang, A. Kelbert, A. Anders, J. Bass, Stable Continental-scale drainage of North America: Implications for Deep Mantle Hydration, *Nature Geoscience*, in review.

3. Zhou*, Q., & L. Liu, Formation of the Yellowstone Volcanic Province due to Intruding Hot Oceanic Asthenosphere, *Nature*, submitted.

4. Hu*, J., L. Liu, & M. Faccenda, Origin of seismic anisotropy in South America, in prep.

**Figures:**

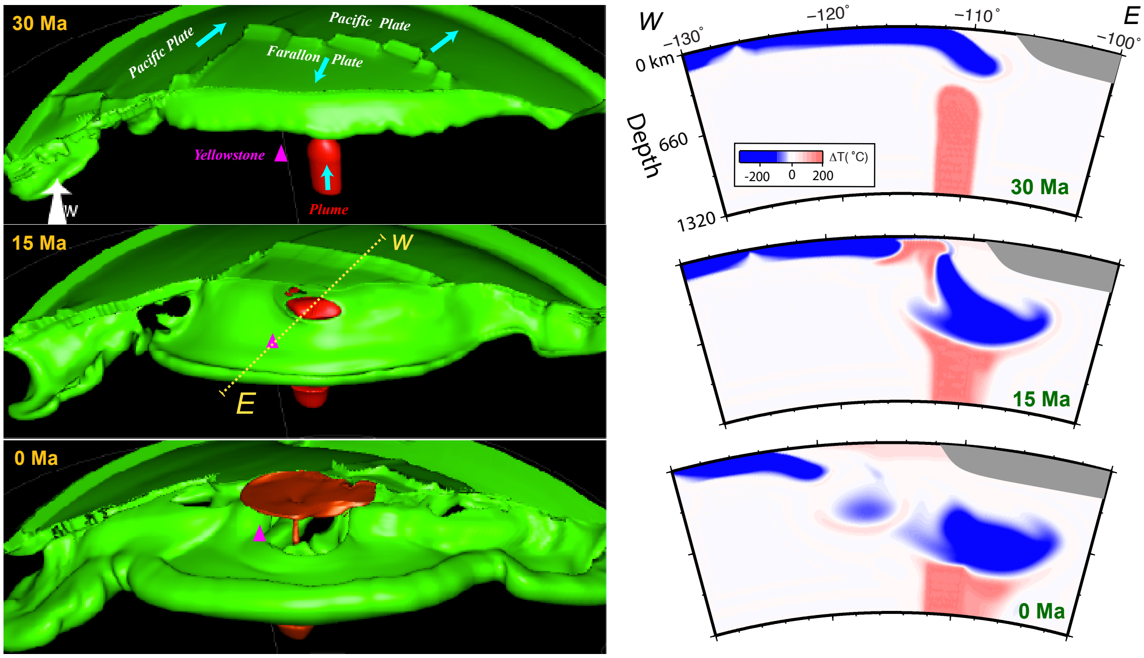


*Figure 1. Simulated temporal evolution of slab-plume interaction. (Left) 3D view of the time sequence showing the slab (green isothermal surface, at -50°C relative to the surrounding mantle) and the plume (red isothermal surface, at +50°C). (Right) Evolution along the east-west cross section.*

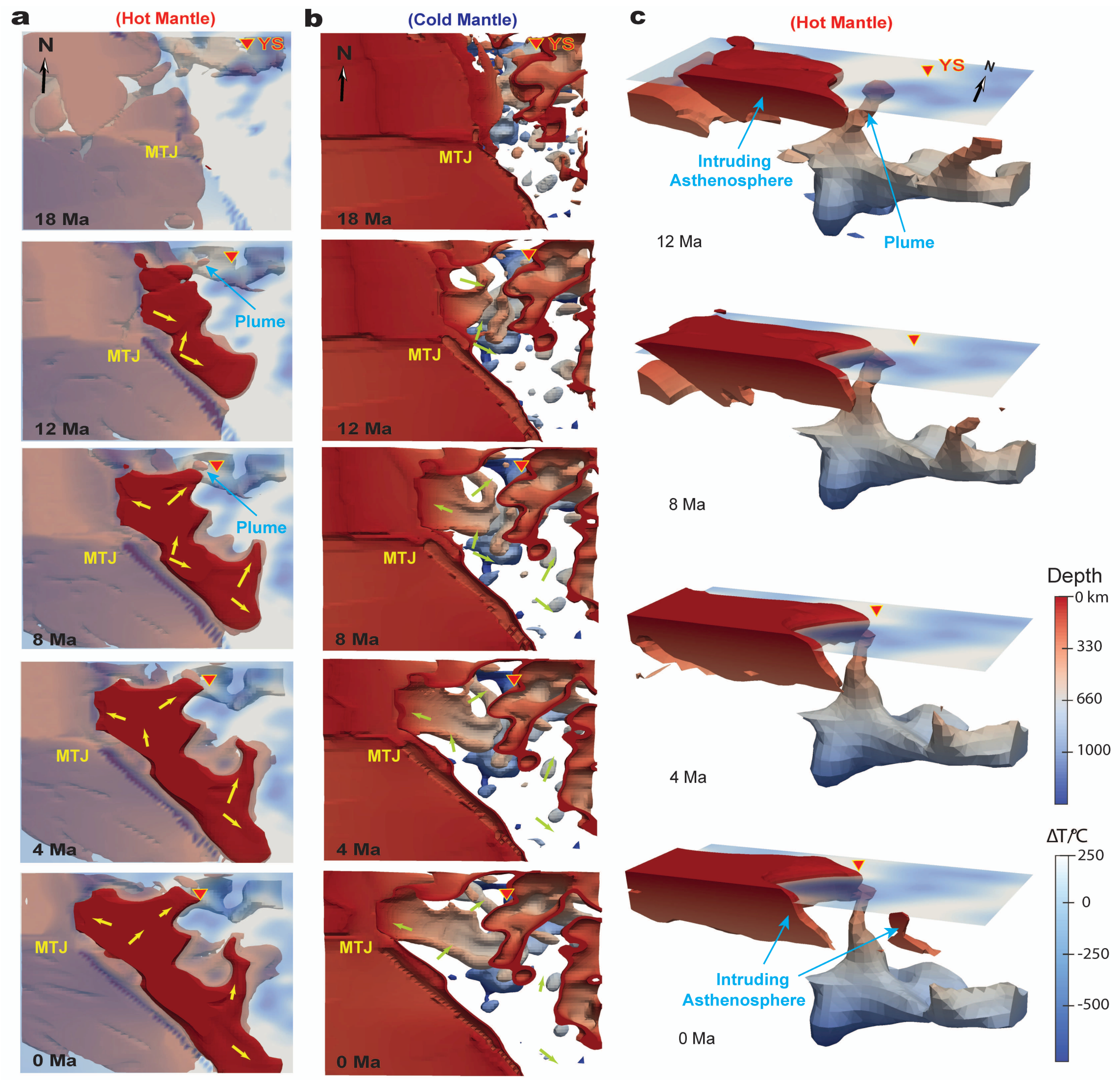


Figure 2. 3D representation of mantle evolution in the preferred model. (**a, b**) Top-down view of the temporal evolution of hot and cold mantle anomalies, respectively. In **a**, both an isosurface (at a temperature anomaly of +50 °C; color indicates depth of the isotherm) and the temperature at 60 km depth (the translucent map slice, with color indicating temperature) are shown. In **b**, an isosurface of the -100 °C anomaly is chosen to represent the cold mantle. The red triangle marks the projected past location of the Yellowstone caldera, and yellow (in **a**) and green (in **b**) arrows represent the mantle flow. At 18 Ma, most of the hot anomalies are under the oceanic plate. Subsequently, the hot asthenosphere enters the western U.S. through the slab hole below Oregon and around the southern slab edge. The plume never reaches the surface in this model. (**c**) A close-up view on the evolution of the intruding hot oceanic asthenosphere and putative YS plume. Color definitions are the same as those in **a**.

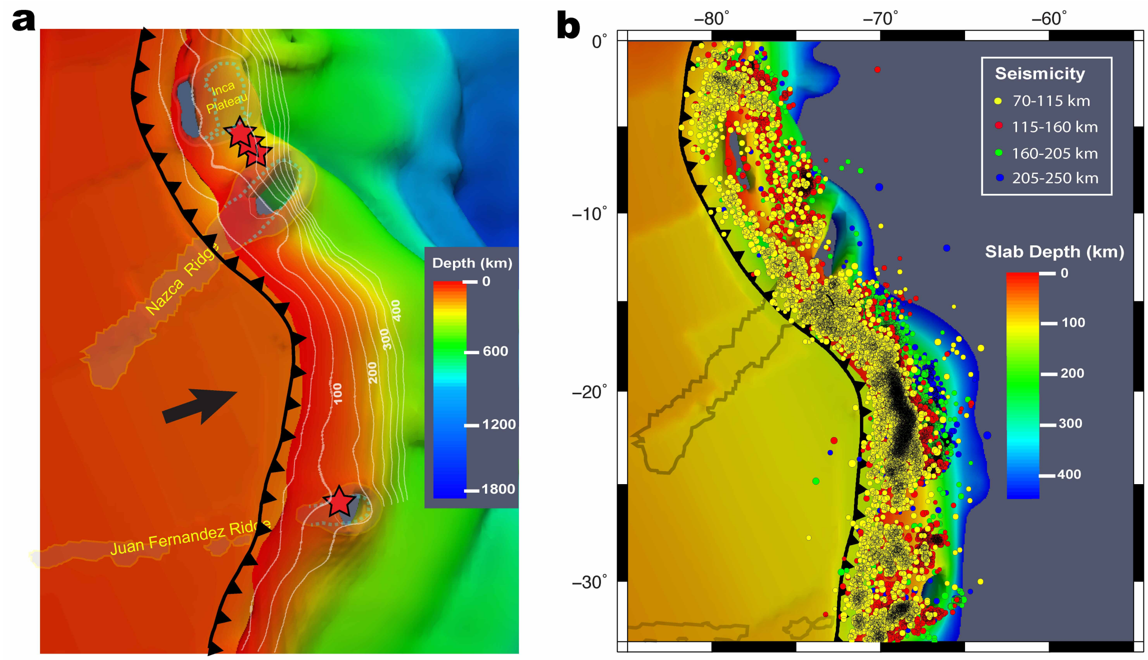


*Figure 3. The geometry of the predicted present-day slab beneath South America and the Naca Plate west of the trench (outlined using an isotherm of 300 °C cooler than the ambient mantle). (**a**) 3D aerial view of the subducting Nazca Plate (temperature isosurface), with colors representing the depth of the slab upper surface on the right side of the trench and that of the plate lower surface on the left side of the trench. The slab tears are illustrated with both the isosurface of temperature and the evolution of buoyancy features (filled gray areas). Since we use a relative cold temperature isosurface, which shows the inner part of the slab, the actual slab tears are slightly smaller. Thin white lines are the interpolated Benioff zones from Hayes et al. (2012). Dashed lines within the subducting buoyancy features outline their original intact geometry. Red stars indicate the locations of adakitic eruptions. (**b**) Spatial comparison of the slab geometry with the distribution of intermediate-depth seismicity (Mb>3.0 from ISC seismic catalog).*

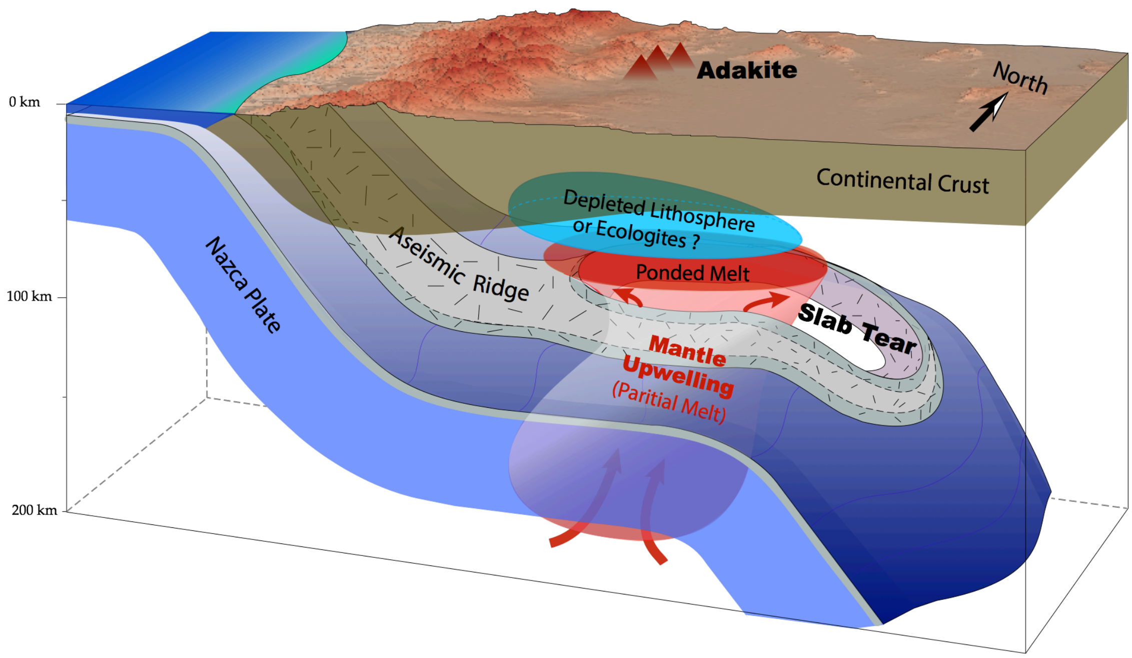


Figure 4. A schematic representation of the broken flat slab during aseismic ridge subduction. In the overriding plate, only the crustal layer is shown. The vertical axis is exaggerated in scale.