MODELING 4D EARTH EVOLUTION: FROM CONTINENTAL CRATONS TO THE YELLOWSTONE SUPERVOLCANO

Allocation: NSF PRAC/800 Knh
PI: Lijun Liu[1]
Collaborator: Manuele Faccenda[2]

[1]University of Illinois at Urbana-Champaign
[2]Università di Padova

EXECUTIVE SUMMARY

Many aspects of Earth's dynamic evolution remain poorly understood. Our research focuses on two projects: 1) what causes the most stable portion of continents—cratons—to experience dramatic elevation change and internal deformation; and 2) what is the ultimate source of heat that fuels the Yellowstone supervolcano. By positioning all known and unknown tectonic elements in a common evolutionary system model, we discovered novel insights regarding both questions. We found that the cratonic lithosphere is not as stable as previously thought and its lower part would delaminate when perturbed by mantle plumes from below, causing rapid surface uplift and crustal erosion. Our answer to the supervolcano question is rather surprising: The majority of the hot mantle maintaining past Yellowstone volcanism came from below the Pacific Ocean and not from the deep mantle plume right below as traditionally believed. Both works were recently published in *Nature Geoscience*, with extensive media reports.

RESEARCH CHALLENGE

The dynamic behavior of the deep Earth such as mantle flow and heat migration near a subduction zone as well as the resulting surface responses such as volcanic eruption, topographic changes, and drainage system migration are physically and numerically complex. A quantitative understanding of these processes, especially their past evolution, is vital for explaining the various geological, geophysical, and geohazards observations. The challenge we geodynamicists face is how to accurately reproduce the various activities within the inaccessible interior of the solid Earth and how to connect them with the geological records.

METHODS & CODES

In order to quantitatively understand the current and past dynamic processes within the deep Earth, we adopt multiple data assimilation techniques into large-scale geodynamic modeling. For example, we employ seismic tomography images to represent the present-day mantle temperature and viscosity profiles. We assimilate the motion of tectonic plates that is geologically reconstructed as velocity boundary conditions of a geodynamic model. We combine these data into a single physics-based numerical model using either sequential (forward) or adjoint (inverse) data assimilation techniques. The software package we use is a well-benchmarked finite element code, CitcomS [1]. We have tested the scalability and I/O performance of this code on Blue Waters. CitcomS is community-based software; it has been designed and tested on many supercomputers.

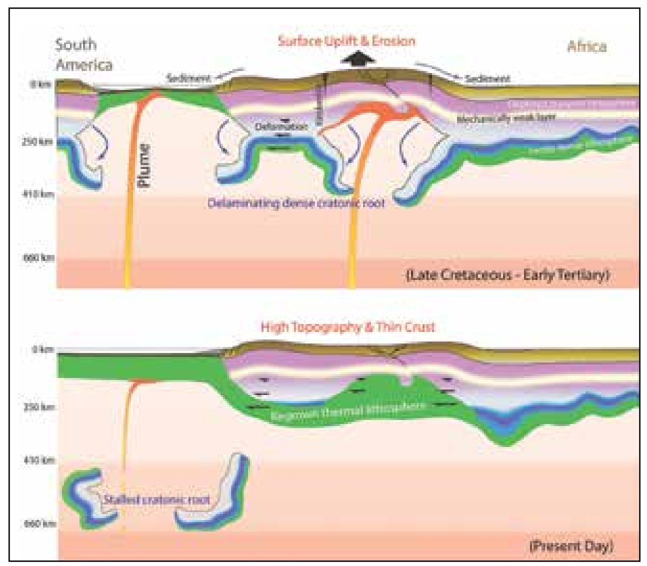

Figure 1: Illustration of craton evolution in Africa and South America. (Upper) The stable cratonic lithosphere was destabilized by underlying mantle plumes leading to delamination of the denser root in the Cretaceous era. (Lower) The missing roots thermally grew back toward the present, while recording this history in the lithospheric fabrics.

RESULTS & IMPACT

In the first project about the evolution of the cratonic lithosphere, we quantitatively reproduced the subduction and mantle flow below South America since 100 million years ago [2]. Based on these reproductions, we found that the widespread fast-mantle seismic structures below the South Atlantic region are stalled pieces of foundered continental lithosphere [3]. Further examination of the topography, gravity, geology, and seismic properties of the lithosphere reveals that large volumes of the cratonic lithosphere were delaminated into the underlying mantle during the Cretaceous era. This caused the surface to uplift and shed enormous amounts of sediment offshore, leading to thinned crust and deformed lithosphere. Our work, therefore, revised the traditional view that the cratonic lithosphere is neutrally buoyant and tectonically stable [4]. Part of this work was published in *Nature Geoscience*, and has enormous potential impact on other fields of geoscience, including seismology, geology, sedimentology, petrology, mineral physics, geomorphology, and the like.

In the second project about the heat source of the Yellowstone volcano, we developed a physical model that is consistent with all available geophysical and geological data constraints [5]. Our model reveals that most of the heat below the Snake River Plain and Yellowstone caldera originally came from under the Pacific Ocean [6]. This challenges the traditional hypothesis that the Yellowstone supervolcano has been fueled by a deep-mantle plume right below Wyoming. This result was also published in *Nature Geoscience*, with direct impact on many other fields.

WHY BLUE WATERS

The enormous amount of data processing and computation required for this work makes Blue Waters the best platform for our research.

PUBLICATIONS & DATA SETS

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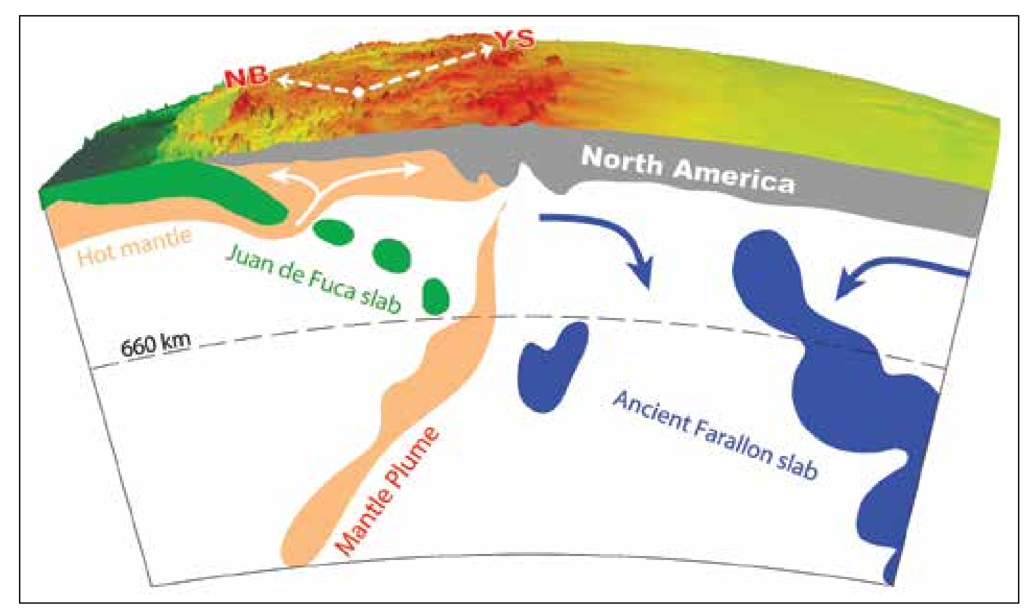

Figure 2: Schematic view of mantle dynamics below the western United States. The diverging motion of the hot intruding mantle, corresponding to the Newberry (NB) and Yellowstone (YS) tracks on the surface, is controlled by the sinking Farallon slab (blue) and the retreating Juan de Fuca slab (green).