A GIANT IMPACT ORIGIN FOR THE FIRST SUBDUCTION ON EARTH Q. Yuan[1,2], M. Gurnis[1,2], P.D. Asimow[1]. [1]Division of Geological and Planetary Sciences, California Institute of Technology (qyuan@caltech.edu), [2]Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

Introduction: As planetary exploration continues, Earth emerges with a so far unique signature: plate tectonics. Although the timing and mechanism of the start of plate tectonics remain under debate, a satisfying model ought to link its onset to the initial conditions of Earth's evolution, which are widely believed to have been set by the Moon-forming giant impact [1]. The collision of a protoplanet called Theia with the proto-Earth at ~4.51 Ga is expected to cause an uninhabitable surface condition for a significant period due to global-scale melting [2, 3]. However, geological records, in particular some Hadean detrital zircons with heavy oxygen isotopes and low crystallization temperatures, argue for a clement surface by 4.3 Ga [4, 5], resembling the modern Earth with granitic crust and oceans. Generation of granite, in turn, is thought to require subduction. However, the mechanisms of subduction initiation in Earth's earliest period remain elusive.

Subduction initiation has been systematically studied previously [6] and more than 10 mechanisms have been proposed (see review [7]). But among those scenarios, there are only two that do not need a pre-existing weakness in the lithosphere to initiate subduction from a stagnant lid mode. Those mechanisms are plume-induced [8] and impact-driven [9] subduction initiation. However, the subduction induced by both mechanisms is short-lived. Plume-induced subduction is also impeded by the requirement for strong plumes, which are unfavorable in the hot ancient mantle. The impact-driven hypothesis, on the other hand, is only likely during the Late Heavy Bombardment (4.1-3.8 Ga), too late to explain the Hadean detrital zircons record.

Here, we propose that the conditions created by the canonical giant impact can naturally give rise to subduction initiation ~200 million years after Moon formation (Fig. 1). Recent studies show that Earth's lower mantle remained solid after the giant impact [10, 11] and our previous study indicates that some Fe-rich and dense Theia mantle materials (TMM) should have sunk to the base of the mantle. We have suggested that TMM are candidates for the origin of the two seismically observed large low shear velocity provinces (LLSVPs) [12]. Here, we apply whole-mantle convection models to show that strong mantle plumes could arise from thermochemical piles of TMM, weaken the lithosphere and eventually cause subduction initiation. If LLSVPs are primordial [13], we argue that their associated mantle plumes may also cause sporadic subduction events until subduction becomes self-organized. After that time, the cold lithosphere would inhibit further plume-induced subduction. Our model links the Moon's formation to incipient subduction, hinting that the search for large rocky exomoons may assist in finding an Earth-like host exoplanet.

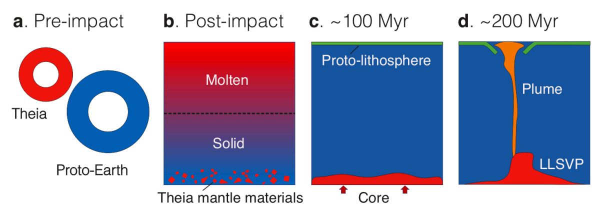

Figure 1. A schematic illustration of the path from the giant impact to plume-induced subduction in the early Hadean. A canonical giant impact (a) leads to a two-layered mantle structure (b) [10, 11]. After solidification of the upper magma ocean (~100 Myr, [14]) a proto-lithosphere formed [15], which was then destabilized and segmented by impact of a mantle plume from an LLSVP made of the Theia mantle remnant (d).

Methods: We have computed a series of 2-D whole-mantle convection models to explore subduction initiation driven by LLSVP-related plumes. The conservation equations of mass, momentum and energy were solved under the Boussinesq approximation for a viscously dominated fluid with the finite element method using the *Underworld* package [16]. The models contain 4 compositional components: crust, lithosphere, Theia mantle materials (TMM) and background Earth mantle. A layer of intrinsically dense TMM was introduced at the bottom of the model at the beginning of each calculation. Geophysical observations require that LLSVPs have a distinct bulk modulus, so we use a depth-dependent density profile within the LLSVP [17]. The CMB temperature is set at two times of its current temperature, in agreement with simulated conditions after the giant impact [11]. The viscosity is both nonlinear and temperature-dependent with plastic failure and weakening processes [18].

Results: Figure 2 shows a successful computation where a mantle plume from the LLSVP-like piles initiated subduction after ~130 Myr. The initial layer of dense TMM started to form individual piles by its depth-dependent density and bottom-heated internal convection. Meanwhile, the lithosphere grew thicker due to inefficient cooling while in a stagnant lid mode of convection. At 123 Myr, a strong mantle plume developed from the top of the central TMM pile (Fig. 2a). This mantle plume quickly rose to the upper mantle, becoming narrower due to the viscosity decrease at the transition zone. At 133 Myr, the rising plume reached the lithosphere and formed a plume wedge, cutting the lithosphere (Fig. 2b). Following this, the plume started to spread at the surface, overcoming the yield strength of the surrounding lithosphere segments and eventually forming shear zones along the subducting plate boundary that promoted self-sustaining and retreating subduction (Fig. 2c). As slabs continued to subduct, partial melting of the subducted basaltic crust in the garnet stability field gave rise to buoyant melt that rose to the surface at ~150 Myr (Fig. 3). Such slab-derived melts could have evolved to form the early felsic rocks in agreement with geological records.

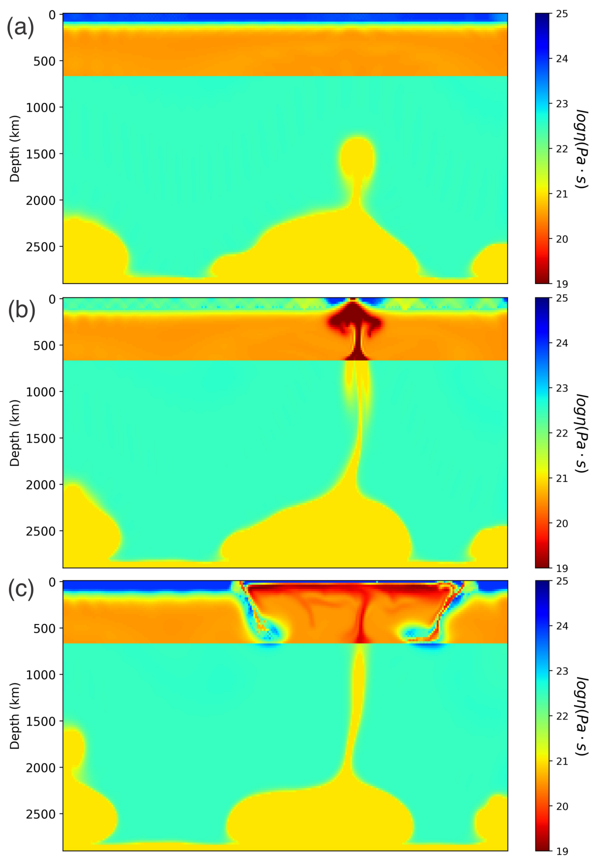

Figure 2. Viscosity field of the reference case showing a LLSVP-sourced plume induced subduction initiation. (a) Plume rising from the LLSVP at 123 Myr; (b) Development of a plume wedge at 133 Myr; (c) Slab retreat and melting of crust at 149 Myr.

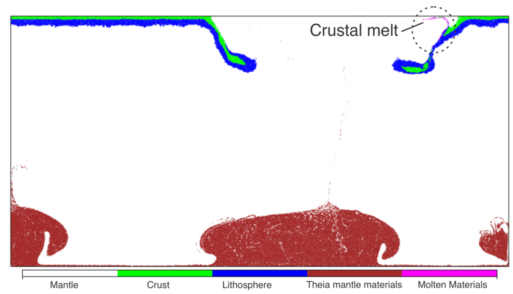

Figure 3. Compositional field shows ascent of the slab-derived crustal melt at 149 Myr.

Discussion: Plumed-induced subduction has been systematically explored in previous studies both in 2D [8] and 3D [19]. The plumes in previous models were manually introduced close to the lithosphere. A recent 3D model study examined self-developed mantle plumes from the CMB [20], but the thermal model lacks the LLSVP materials, which has been linked to strong mantle plumes, large igneous provinces, and intense hotspot volcanism in the last few hundred million years [21]. To our knowledge, we present the first self-consistent dynamic model with LLSVP-sourced plumes that induce subduction in a stagnant lid convection state. However, the work shown here is 2D and the plume-lithosphere interaction is expected to be more complex in 3D. Previous 3D experiments have shown that strong plumes can induce subduction but only when the lithosphere is relatively weak [19, 20], so we expect to find similar dynamics in future 3D models as long as LLSVP-launched plumes form before the lithosphere becomes too strong.

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