A TECTONICALLY ACTIVE EARLY EARTH DRIVEN BY THE TIDAL RECESSION OF THE MOON.
S. J. Lock1 and P. D. Asimov1, 1Caltech, 1200 E. California Blvd., Pasadena, CA 91125. (slock@caltech.edu)

Introduction: How and when Earth developed the dichotomy of felsic continents and mafic seafloor is an enduring mystery of Earth’s history. At the end of the main stage of accretion, Earth likely had a basaltic crust covered by a global ocean [1], but evidence from ancient zircons suggests that the first felsic crust developed early. Zircons as old as 4.4 Ga seem to have been derived from felsic rocks [2]. Earth therefore likely had its first felsic rocks and perhaps a dichotomous crust within ∼100 Myrs of the Moon-forming impact. Today, felsic crust forms at subduction zones, but it is thought unlikely that modern-style subduction occurred early enough to produce the first felsic materials [3]. Mechanisms have been proposed to form felsic crust in the absence of modern subduction [e.g., 4] but there is no consensus on their ability to explain the early zircon and rock record.

However, previous studies have neglected an important component of Earth dynamics: rotation. After the Moon-forming giant impact, Earth was rapidly rotating with a day between about 5 and 2.5 hrs [5,6]. Earth was significantly oblate, with a ratio of polar to equatorial radii of 0.9 in the canonical model [5] and as low as 0.5 in recently proposed high-angular momentum (AM) models [6-8]. Earth would have had a very different physical structure (i.e., internal pressure, temperature, etc.) than at present [9,10]. As the Moon receded from Earth, the planet’s spin period increased and its shape changed dramatically, becoming roughly spherical within a few 10s Myrs [6,11-13]. Such a rapid and substantial change in shape had significant consequences for Earth’s crust, atmosphere and interior.

Here we use petrological models and planetary structure calculations to determine the effect of Earth’s distorted and changing shape on the early crust.

Formation of primary crust: The first long-term stable crust was likely formed by decompression melting of upwelling mantle either driven by thermal convection or cumulate overturn. Earth’s surface froze, and the first crust formed, within 10^4-10^6 years of the giant impact [14], while the planet was still rapidly rotating. To determine the effect of rotation on crust formation we use the HERCULES planetary structure code [15] with the same parameters and equations of state as used in Lock & Stewart (2019) [9].

Due to the distorted shape of the planet and the substantial centrifugal force, the internal pressures in Earth would have been lower than at the present day and the effective gravity would have been stronger at the poles and weaker near the equator [9]. Compared to the formation of mafic crust on Earth today, the lower pressures would have increased the depth at which the adiabat crossed the solidus, and so increased the volume of mantle that experienced melting. The thickness and composition of the crust would have varied latitudinally due to the variable gravity. Simple mid-ocean ridge-like decompression models imply that crustal thickness varies as g^2 [3]. The surface gravity following a canonical impact could vary by as much as 10%, leading to similar variations in crustal thickness. The crust formed at the equator after a high-AM giant impact could be 100s of km thick, with crust an order of magnitude thinner at the poles (Fig 1A). We are working to accurately quantify the variation in crustal composition and thickness using the MELTS code [16].

The high heat flow and very thick crust of this early epoch led to a reversal of the modern situation in which the crust is embedded within the thermal boundary layer. The timescale for the thermal boundary layer to grow to the bottom of the crust is on the order 10^6-10^8 yrs, depending on crustal thickness. Much of the change in Earth’s shape likely occurs over less than a few 10s Myr [6,11-13]. Throughout this period, there is therefore a substantial fraction of the crust that is within the asthenosphere and will respond to forcing viscously.

Crustal deformation during tidal recession: As the Moon tidally receded and Earth’s rotation slowed, the crust would have been deformed (Fig 1). Fig. 2 shows the extent of deformation of the surface assuming the change in shape was accommodated locally at each latitude. At high latitudes, local surface area increased, resulting in extensional tectonics, volcanism and volatile degassing. In the equatorial regions, crustal shortening would have led to compressional tectonics. The lithosphere would have been thickened near the equator and thinned at the poles. Conversely, the asthenospheric crust would have flowed to occupy an equipotential and been thinner at the equator than at the poles. As Earth’s rotation rate slowed, internal pressures would have increased [9]. The increase in pressure at the base of the crust could have stabilized denser phases (e.g., garnet) in the lower crust and led to the lower crust becoming denser than the mantle and delaminating.

The potential for deformation varies significantly between Moon-formation models. In high-AM models, the change in local area is on the order of 10s% and convergence rates at the equator could have been comparable to those building the Himalayas today (assuming that most of the change in shape occurred in 10^7 yrs as suggested by tidal evolution models [6,12,13]). Significant deformation is also possible in the canonical model but is on the order of a few percent.
Conclusions: Earth’s early crust was strongly influenced by rapid rotation. In particular, the change of shape due to lunar tidal recession drove extensive tectonic activity. Hydrated crust and/or sediments could have been forced to depth and melted to produce evolved magmas and felsic rocks. We suggest that such rotationally-driven tectonics produced topography and felsic crust in the first ~10 Myrs of Earth’s history. This process may explain the observation that zircons as old as 4.4 Ga were derived from felsic magmas which incorporated hydrated surface material [2].


Figure 1: A schematic showing the effects of lunar tidal recession on Earth’s crust. The depth of the crust and ocean are exaggerated, but the oblateness of Earth is to scale for a high-AM Moon-forming impact [D].

Figure 2: Surface deformation as a function of latitude as Earth’s rotation was slowed to its present-day rate, given varying initial AM (x-axis). Panels show the fractional change in the length of the surface in the latitudinal (A) and longitudinal (B) directions and the change in surface area (C). Note that the gradients of the colorbars are not constant; values close to zero are more finely resolved (±4% in A & B, and ±10% in C). The change in the colorbar is marked by the dashed black line. The solid black line marks net zero deformation. The vertical white line corresponds to the AM of Earth when the Moon was at the Roche limit if the AM of the Earth-Moon system was the same as the present-day as in the canonical giant impact scenario [C].