Transcript for: DI022-01 A tectonically active early Earth driven by the tidal recession of the Moon

Simon Lock & Paul Asimow, California Institute of Technology

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Hi, I'm Simon Lock, and I will be describing how the rapid rotation of early Earth, and the subsequent tidal recession of the moon, shaped Earth's crust. /

It is thought that Earth had its first felsic rocks within approximately a hundred million years of the end of its accretion. Evidence for this comes from the early zircon record. / The Lu-Hf systematics of some zircons imply that they originated from an early-formed, enriched source. Furthermore, zircons as old as 4.4 billion years seem to have been derived from felsic, water-rich magmas. In order to form such magmas, it is necessary to take hydrated surface material and force it to depth within the Earth. At the present day, this is achieved in subduction zones, but we do not think that subduction as we know was possible on early Earth. / Various alternative to form the early zircons have been proposed, but there is no real consensus on the feasibility of these methods. However, previous work has neglected an important component of the dynamics of early Earth: rotation. /

The last event in Earth's formation is thought to be the Moon-forming giant impact, and this collision left the Earth very rapidly rotating. / In the canonical scenario, the impact set the present-day angular momentum of the Earth-Moon system and the Earth would have had a day of approximately five hours when the Moon first formed. / Recently, it has been found that there are various mechanisms that could have transferred angular momentum away from the Earth-Moon system during lunar tidal evolution. As a result, the Earth would have been initially rotating much more rapidly than in the canonical model, with a day as short as 2.3 hours. I will refer to such scenarios as high-AM scenarios. / Over time, the rotation rate of Earth was slow during lunar tidal recession. / Importantly, the timescale over which there was a significant change in the angular momentum of Earth (millions to 100s millions of years) is comparable to, or longer than, the timescale for freezing of the surface of the Earth, as calculated in magma ocean evolution simulations. Therefore, the first crust of Earth was likely formed while Earth was still rapidly rotating, and witnessed the slowing of Earth's rotation during lunar tidal recession. We must therefore consider the effect of rotation on the early crust. /

Due to its rapid rotation, early Earth would have been substantially oblate. To demonstrate the magnitude of this, I'm going to show you a series of cut throughs of planets of different angular momenta, corresponding to different Moon-formation scenarios. For reference, the present-day Earth will be shown in blue. / When the Moon first formed in the canonical scenario, the Earth would have been somewhat more oblate than at present. Although it might not look much at this scale, the difference in equatorial radius is still hundreds of kilometers. / As you would expect, the effect is more significant in high angular momentum models. For example, this is an example high angular momentum scenario where the Earth-Moon system initially has a total angular momentum of about twice the present day and the Earth has an equatorial radius that is thousands of kilometers greater than at the present day. / In the most extreme high angular momentum scenarios that have been explored, the Earth could have had an equatorial radius twice that of its polar radius. /

One effect of Earth's rapid rotation and oblate shape is that the effective gravity varied substantially across the surface. Here I am showing the surface gravity as a function of latitude for the four example scenarios I showed you on the previous slide. Even in the canonical scenario, the gravity can vary significantly across the surface, and the average gravitational acceleration is lower than that on the present-day Earth. /

Such variation in gravity with latitude can lead to significant differences in the crustal thickness of Earth's first crust. As an example, this figure shows the crustal thickness as a function of potential temperature in scenarios where the first crust formed by decompression or by extrusion of melt from the final stages of a non-fractionally crystallized magma ocean, calculated using the alphaMELTS thermodynamics model. Each of these bands is the range of crustal thickness that would be expected after the canonical Moon formation in green, and an example high angular momentum case in orange. And what you can see, particularly at the high potential temperatures we expect during the formation of Earth's first crust, the range in crustal thickness can be quite significant, on the order of a several kilometers in the canonical moon formation scenario and almost a factor of 2 in high angular momentum models. Also, combined with the higher potential temperature, the lower surface gravity at the equator in the high angular momentum models can develop crust that could be 10s km thick. /

The timescale for growth of the thermal boundary layer to base of this thick early crust is on the order of tens to hundreds of millions of years, comparable to the timescale of early tidal evolution. As a result, the early crust would have been partially lithospheric and partially asthenospheric: that is, the upper layer of the crust would have behaved rheologically as a solid, while the lower part of the crust, despite being of crustal composition, would behave rheologically as a fluid. This is not the situation that we have on the present-day Earth, where most of the compositionally crustal material resides within the lithosphere. / Therefore, early in Earth's evolution just after the formation of its first crust, there would have been a uniformly thick lithospheric crust, shown here in dark brown, but, as the asthenospheric crust would flow to reach an equipotential, a much thicker asthenospheric crust at the equator than at the poles, shown here in red. /

Now we must return to our old friend the Moon. / As the Moon tidally receded, Earth's rotation rate was slowed, and Earth returned to a roughly spherical shape within tens to hundreds of millions of years. / As a result, to accommodate this change in shape, Earth's crust must have been deformed significantly. Now, using the HERCULES planetary structure code, we have calculated the magnitude and rate of deformation of the surface during lunar tidal recession. /

First, let's consider the canonical scenario. I'm going to show you an animation, but to orientate you to what you're going to see, this is the final snapshot from that animation. On the left the top panel shows the semi major axis of the Moon as a function of time, and the bottom panel the angular momentum of the Earth. On the right, is a map of the rate of local deformation as seen by a distant observer in the equator. / As the surface of Earth is deforming, there is deformation in both the longitudinal and latitudinal directions. However, for simplicity, I'm just going to show you the longitudinal component, that is the deformation along lines of constant latitude and therefore accommodated in the longitudinal direction. / Because, as Earth's rotation is slowed, the pole sort of pops out, you get extension in the polar regions in both latitudinal and longitudinal directions. / Conversely, the equatorial radius is shrinking so you get compression in the equatorial region, and there's a point at about 40 degrees where the two transition. / So you can see the change in shape of the planet, I'm also plotting the original shape of the body from the start of the simulation as a black dashed line. / Now later I will show you integrated deformation rates, which will probably more intuitive to many of you, but to orientate you on this scale, the average deformation across the Himalayas today is about 2 times 10 -3. / The average rate for a subduction zone or a spreading ridge on the Earth today would be on the order of 2 times 10-4 if averaged around the circumference of Earth, / and that of a slow subduction or ridge would be a factor of a few lower. /

Let's now play the simulation. What you see is that initially the recession of the moon is very rapid, and so there are large surface deformation rates, but quite quickly the rate of recession decreases and therefore the rate of deformation also decreases, and eventually after millions to tens of millions of years, the deformation rate becomes smaller than the rates we see in tectonic features on Earth today. /

We can see this more easily if we look at integrated deformation rates. / As I said before, there is deformation in both the latitudinal and longitudinal directions so on the left here I am going to show you the latitudinal deformation, i.e., that along lines of constant longitude, integrated in both the polar and equatorial regions, as demarcated by the point of no deformation at about 40 degrees. / On the right, is the longitudinal deformation, as you saw in the previous animation, integrated along lines of constant latitude. We can compare these integrated deformation rates to common tectonic features on the Earth today. / A typical subduction zone or ridge is on the orders of a few cm's per year, / and a slow subduction zone or ridge is a factor of a few less. Therefore, in the canonical scenario, the integrated deformation rates are greater than, or comparable to, tectonic features on the Earth today for potentially millions of years after Moon formation. However, the high deformation rates are not sustained for long periods of time and so the effect of such deformation in the canonical scenario is likely to be relatively modest. /

Now let us consider an example high-angular momentum scenario. In the case I am going to show you, the Earth starts out with a high obliquity but during lunar tidal evolution the lunar orbit passes through an instability, the Earth's obliquity is decreased and AM is transferred away from the Earth-Moon system. This scenario was originally proposed by Cuk et al in 2016 but recently Tian & Wisdom have pointed out an error in that original paper. However, subsequent work has shown that this mechanism is still successful in reproducing the Earth-Moon system if the system started with even higher AM than considered by Cuk et al in 2016. As you can see on the left, in high AM models such as this the rate of change of the AM of Earth is quite variable. In this particular model, large changes in the rate of change of angular momentum are marked by crashes in the Moon's semi-major axis and we will see that these crashes can be quite significant for the surface deformation. /

As in the canonical model, the deformation rates are highest early on, when the Moon is close to the Earth. However, in the high angular momentum scenario the deformation rates are sustained at a higher rate for much longer. Also, the sudden increases in the rate of change of AM lead to very intense periods of surface deformation that last on order a million years or so. In such events, the deformation rate at the equator are comparable to those across the Himalayan convergence zone at the present day. However, those deformation rates are around the entire equator of the planet and are in both the latitudinal and longitudinal directions, so these are very dramatic events for the surface of the Earth. /

As before, we can look at the integrated deformation rates around the surface of the planet./ And, what we can see is that the deformation rates are both more variable but also of a lot higher magnitude than in the canonical scenario. Deformation rates that are comparable to tectonic features on the Earth today are sustained for 10s Myr. So what are the implications of this deformation for the early Earth? /

At the poles, extension would have led to thinning of the lithosphere, and therefore upwelling of parts of the asthenospheric crust and mantle, volcanism and degassing of parts of the silicate Earth. / Conversely, in the equatorial regions, convergence would have led to thickening of the lithosphere. Convergent tectonics could have driven surface material to depth causing melting and the production of evolved magmas. This could provide a mechanism for producing zircons derived from water-rich, felsic magmas early in Earth's evolution. / At the same time, the asthenospheric crust would have been thickened in the polar regions and thinned in the equator as it flowed to accommodate the change in gravitational potential of the more slowly rotating planet. / In addition, the increasing pressure within the body could have led to delamination of the bottom of the very thick asthenospheric crust. Therefore, the changing shape of Earth during its first 100 Myr or so would have had a significant impact on its crust, mantle and atmosphere. All of these processes would have occurred on top of a potentially quite active convective mantle dynamics and there is a lot more that needs to be done to understand the interaction between these different dynamical systems and we are starting to do that. /

In conclusion, rotation is an important aspect of early Earth dynamics that has been largely neglected. / For example, the distorted gravitational field of the rapidly rotating Earth would have led to crustal thickness variations across the planet. / The subsequent change of shape of Earth during lunar tidal recession would have driven significant crustal deformation on early Earth. Extension at the poles would have driven volcanism, degassing parts of the silicate Earth, and convergence at the equator would have forced hydrated materials to depth, producing water-rich, evolved magmas. / Therefore, tectonics driven by the change of shape of Earth during lunar tidal recession could explain the existence of zircons derived from felsic rocks within the first tens of millions of years of Earth's history. Thank you for listening.