Speaker 1 (00:14):

Andrew Dombard is a planetary geophysicist and professor in the Department of Earth and Environmental Sciences at the University of Illinois, Chicago. As a science team member on NASA's Europa Clipper mission. He specializes in the study of planetary lithospheres. The stiff outer layer of a planetary body that deforms in response to applied forces. Today, Andrew Dombard will be speaking about what the lunar lithosphere is and why it is important?

Andrew Dombard (00:45):

All right, Theresa, thank you very much for the introduction. Yes. I am going to be talking today about the lunar lithosphere. I want to cover the what, the why and the how. So, the first and most important question we need to ask is, what is a lithosphere? Well, you can think of a lithosphere as the bookshelf of a planet. It is mechanically stiff, outer surface of a planet and being mechanically stiff, it can support forces and loads that are applied to it. So, it's very much like a bookshelf. You put books on the bookshelf and that bookshelf is able to support those loads. Lithosphere does the same thing. If you put a big mountain on the surface of a planetary body, the lithosphere will support that load. If there are density variations within the subsurface, let's say you have a big or body on earth that represents a load on the lithosphere and the lithosphere needs to be able to support that.

Andrew Dombard (01:38):

Or if there are lateral forces, if you're squeezing on the lithosphere from the side, the lithosphere will resist those forces. We can look at this in a bit more applicable scenario instead of a bookshelf by looking at a cartoon schematic of a cross section of water, planetary lithosphere looks like. Again, we have this stiff outer region that is mechanically strong. And unlike the bookshelf where there is basically nothing underneath the bookshelf, there is actually material underneath the lithosphere, but it is very, very weak. And so, it can't really contribute to supporting the material that might be loading the lithosphere. Now, like a bookshelf, if you start applying loads to a lithosphere, it can start to deform in response to those loads. Here, I've dropped an isolated mountain on top of a planetary lithosphere and you see how the lithosphere is sagging under the weight of that load.

Andrew Dombard (02:41):

Now, this bookshelf analogy is actually quite useful for exploring the behavior of a planetary lithosphere. And here, I want to go back to that analogy again and show you a couple of examples of a bookshelf that's loaded down with some books. And hopefully this makes intuitive sense to you. When you have just a couple of books on your bookshelf, you don't have a lot of deflection of that bookshelf. That bookshelf is able to support those loads very well. But when you start to load up that bookshelf with a whole lot of books, now that bookshelf is starting to sag under the way. You're starting to see deformation of that bookshelf because you have a much broader load on the surface. A planetary lithosphere responds in exactly the same way. The responsible lithosphere to a load depends on the horizontal scale of that load, how wide it is. We will refer to that as the wavelength of the load. Is it long wavelength like this big stack of books, or is it short wavelength that we have right here?

Andrew Dombard (03:45):

So, looking at an example of how that plays out a planetary lithosphere may very well be able to support an individual mountain, but it may not be able to support an entire mountain range as well. However, mountain ranges still do exist. And so something must be helping to support those things because they do exist. And that's where our bookshelf analogy really starts to break down. Again, we have nothing underneath the bookshelf. It's just empty space under the bookshelf, but of course that isn't the case for a planetary body like the moon. If you look at the structure of the moon, you'll see something that looks like this. All the rocky worlds in the inner solar system have a structure that is essentially like this, where we have a metallic core that is surrounded by silicon rocky material. For the case of the moon, the metallic core is pretty small is then surrounded by mantle rocks.These are silicon rocks that are relatively dense. And then that is capped by a rocky crust. This crust is also silicon rocks, but these are rocks that are less dense than the mantle rocks that are underneath.

Andrew Dombard (04:58):

And so you can start to see a very definitive onion like structure, where you have stratification in the densely structure, dense stuff in the middle, less dense stuff at the surface. So, if you happen to have then a situation where that compositionally different crust is low density crust, is embedded within the mechanically stiff layer within the lithosphere, when you start to deform that lithosphere like in this situation, as we're deforming the lithosphere down, what we'll end up doing as well is we'll end up pushing lower density crust into the higher density mantle. And because there is denser stuff down here that induces a buoyant response. So, buoyancy starts to become an important term. And we can look at this in more detail by going back to a couple thousand years to Archimedes' principle.

Andrew Dombard (05:51):

And let's look at the flotation of an iceberg in the ocean. We have three materials here. We have the atmosphere here, we have the ice and we have the water down here. And again, you see a gradation in the density. The atmosphere is less dense, the ice is intermediate density and the water is the highest density. So what we have here above the water line, we effectively have ice that has replaced the atmosphere. This represents excess mass that has a downward directed weight that is pushing down on the iceberg. However, underneath the water line, you have effectively replaced water with lower density ice. This lower density material here is now positively buoyant. And so there is an upward directed force on the system. And the balance between the two, the flotation point of this iceberg is when the downward weight of the stuff above the water gets matched by the buoyancy force of the stuff underneath the water.

Andrew Dombard (06:56):

Exactly the same idea applies to a planetary lithosphere, except here we call it airy isostacy. So, let's go back to our bookshelf analogy and start thinking about what's going on here. Again, we have denser stuff underneath, so we might have a buoyancy term if we have a lot of displacement, but start by looking at this short wavelength load. We're only putting a couple of books on our bookshelf. Because it's only a couple of books, this bookshelf is able to support the load just fine. A lithosphere would be able to support a short wavelength load just fine without much deflection. And so, it is supported entirely by the strength of the lithosphere. However, in this situation, because the load is a lot broader, it's a much longer wavelength, you get more displacement of the lithosphere, you're pushing lower density crustal material into the higher density mantle, which generates a buoyancy force. That buoyancy force will add to the strength of the lithosphere. And so it'll be some combination of lithospheric strength and buoyancy that in general supports a load on a planetary lithosphere.

Andrew Dombard (08:05):

All right. So that's the, what? Let's transition to the why and the why actually has two parts to it. First of all, where do lithosphere come from? How do they form on a planetary body? And the second question is why do we even care? All right, let's start with that first part. The why the lithosphere form. It has to do with the mechanical behavior of geological materials. Also known as rocks. Rocks are a collection of minerals and minerals are crystal and solids. The atoms within that mineral are arranged in a very definitive crystal lattice and that crystal lattice has strength to it. So, a rock will hold its shape just fine. You can use rocks to build a building. Rocks can be put across the span and hold their shape as well, such as these arches out in Arches National Park.

Andrew Dombard (08:56):

However, of course, if the stresses get too big on this material, you start overwhelming that elastic strength and the rock can break. This gets expressed as brittle behavior within the rock. And the last thing that might happen to a rock is viscous behavior. Even though the rock is in a solid state, it has a definitive crystal in structure. When a geological material like a rock reaches a temperature of at least 50% of its melting point when measured on an absolute temperature scale, you start seeing viscous behavior. It starts flowing like a liquid. Therefore, it becomes mechanically weak, and it can no longer support loads because instead of supporting those loads, it's now flowing to try to relax those stresses on the system. This is exactly the same mechanism by which glaciers flow. Glaciers flow like a liquid, even though they are a crystal and solid. Now, all three of these properties will determine the properties of the lithosphere.

Andrew Dombard (09:57):

Again, going back to our cartoon schematic of the system, where we have the strong layer at the surface, the lithosphere and the weaker stuff underneath. The reason that we have this type of behavior is because temperatures tend to increase as you increase depth within a planetary body. The material near the surface is cooler. This stuff is going to be at a relatively low temperature. And so the elastic behavior is going to dominate, but as you get to greater and greater depth, the material gets warmer. Eventually, you'll reach the point where it can no longer support stresses over geological time scales because that viscous behavior is starting to kick in. And so what the lithosphere is, is primarily a reflection of that elastic strength of the rocks in the cooler surface. While that strength goes away in the subsurface where the rocks are warmer and viscous behavior starts to dominate.

Andrew Dombard (10:52):

And of course, if you put too much deformation on this lithosphere, if you put two big bending stresses on it, the material can actually break. And this will get expressed as false on the surface where you'll have a plane of weakness in the rock, and you'll have slip along that plane of weakness. And that's what a fault on the surface is. All right, well, let's go to part two of that wide question. Why do we even care? Well, how a lithosphere deforms, how much deflection you see and what the style of that deflection is, the stress is associated with, all of that is primarily tied to how thick the lithosphere is. We can go back to our bookshelf analogy game. If you put a healthy stack of books on a bookshelf, if the bookshelf is really thick, you'll have much less displacement of that bookshelf than if that bookshelf is really thick. It's the thickness that controls how much deformation you see. And in turn the thickness of a planetary lithosphere is most strongly controlled by the heat flow. How much heat is coming out of a planetary body.

Andrew Dombard (11:55):

Again, I've already talked about how temperatures increase with depth, and this is driving heat out of the interior. When the heat flow is high, the temperatures increase relatively rapidly with depth. Like I have schematically shown here in this red curve, and you reach that transition from elastic behavior to viscous behavior at a relatively shallow depth. However, when the heat flow is low, temperatures increase much more slowly. And so that transition point, which determines where, how thick your lithosphere is at a deeper depth. And so you end up with a thicker lithosphere when the heat flow is low and the thinner lithosphere when the heat flow is higher.

Andrew Dombard (12:35):

And why that is important is because thermal evolution is really key to understand the history of a planetary body. For geophysicist like myself, this is the holy grail that we're going after. And the reason that's the case is because geological activity stuff that is happening to this planetary body is largely driven by the thermal energy in that planetary body that is trying to get out. Plate tectonics on earth is a wonderful example of that for the earth. Every earthquake, every volcano that we have on the earth is largely an expression of plate tectonics, which is how the earth is trying to get it teed out. So, by studying a planetary lithosphere, by looking at different features, scattered across the surface and of different ages, it provides a tracer for this thermal evolution and really helps us understand how this body has evolved through time. And so this is critical information for trying to understand the history of the moon.

Andrew Dombard (13:36):

All right. So since the lithosphere is so important to study this, how do we go about studying this? How do we take our observations? What observations do we use to try to determine what is the [inaudible 00:13:48] lithosphere and how has it evolved? Well for this, we need three observations. We need to have imagery. We need to have topography and we need to have gravity. And let's look at each of these in turn. The imagery, you basically put a camera near the planetary body that you want. A wonderful example of this is the LROC camera on the Lunar Reconnaissance Orbiter. We have wonderful high resolution images of the entire moon that has revealed a lot of detail that we didn't see previously. And what these images can show is tectonic structures on the surface. Tectonic structures is just a fancy word for faults. These are the faults that we're talking about. These faults record, the stresses associated with the deformation of a lithosphere.

Andrew Dombard (14:37):

I got a nice example here taken by the astronauts on Apollo 10, a side view of Rima Ariadaeus. What you see here is this valley that is running across the surface of the moon covering long distances and running relatively straight... In a straight line across the surface of the moon. The reason this valley is here, is this is a type of geological structure known as a graben. A graben I forms in a tensile environment where you pull horizontally on the system. You end up generating a fault that's going like this and a fault that's going like this. And as you stretch this apart, the block in between the two sinks down and you end up with this fault bounded valley on the surface. And by looking at the style of the fault, here we know that it formed in a tensile environment. And by looking at the orientation of this feature, we also know in which direction those stresses were at their maximum.

Andrew Dombard (15:31):

And so we can tie what type of stresses and what orientation they had into studying a planetary lithosphere. The background that I've been using in this talk the whole time is a view of Mare Serenitatis. Mare Serenitatis is one of the big impact basins on the moon that's covered with a lot of relatively high density basaltic rocks. These basaltic rocks were in place in big volcanic flows. And so this is material that's added to the surface, and it represents a load on the lithosphere. And so the lithosphere is going to sag under the weight of that load. And as it starts to curl in on itself, it starts squeezing the material on the surface. So, all these wrinkles that you see in this dark patch right here, they're called wrinkle ridges. They are an expression of thrust faults. Faults that form in a compressive environment. And that's associated with the squeezing that you get of the surface as this material is sagging under... As it is based sagging under the weight of all these volcanic flows.

Andrew Dombard (16:38):

All right, the next thing we would like to have to study lithosphere is topography. Again, we can go back to the schematic here where we've put a big mountain on the lithosphere, but you see how the lithosphere is sagging under the load. And the characteristic shape of this deformation is very characteristic of a top loaded lithosphere, where it's sagging under the weight. And so you end up with these negative spaces here, but you can also raise up these positive flexural bulge on the periphery of this thing. This deformation can be very characteristic of how a lithospheric is deformed. And so measuring the topography is very important information to have. Now, there are several ways you can get planetary topography. A lot of them are based on just using images again. There are several techniques you can use there using images. You're using one of those techniques right now, you're taking two images of a scene with your eyeballs, separated by a short baseline. And your brain is interpreting the parawax that you have between those two images to try to reconstruct the three dimensional aspect of the scene around you.

Andrew Dombard (17:44):

You can do the same thing for the moon, with stereo imagery of the surface. You can also use an active system where you send a electromagnetic wave from a spacecraft down to the surface, and you simply measure how long it takes for that wave to go down and return to your spacecraft. You can do this with radio waves and radar. You can do it with visible light, with a LiDAR. You shoot the surface enough time with your little laser beam or your radio wave, and you can piece together what the topography of a planetary body is. And thanks largely to the efforts of the LOLA laser altimeter, The Lunar Reconnaissance Orbiter again, we now know that topography of the moon far better than we know the topography of the earth, because on the earth, we have silly things like forests and oceans getting in the way. Don't have those confounding factors on the moon. And so we really understand the topography of the moon really, really well.

Andrew Dombard (18:43):

And the last observation we would like to have to study a planetary lithosphere is gravity. Now, when you're taught planetary gravity in your introductory physics classes, they always give you the nice Newtonian gravitational formula for the gravitational acceleration or the acceleration due to gravity around a planetary body is the universal gravitational constant times the mass of the planet divided by its radius squared. That is exactly the term you would use for a perfectly spherically arranged body, but every mass density anomaly that is deviations away from that perfect spherical structure yields deviations in the strength of gravity. Imagine you had a big hill over here. This hill would represent excess mass. And so gravity would be a little bit stronger over here. Let's say you had a big valley over here. This valley would represent missing mass. And so gravity would be a little bit weaker here.

Andrew Dombard (19:41):

Now, these gravity anomalies are very, very subtle. They're only about one part and 10 to the four, one part and 10 to the five to that GM over our R square term that you learn in your intro physics classes. But these gravity anomalies are big enough that orbiting spacecraft can actually detect these very subtle gravity variations. And so we can map out the gravity structure of the moon. And this is what the gravity field of the moon looks like, where all the red colors are relative gravity highs and all the cooler colors are relative gravity lows. And again, the reason that is important is because the deformation of a planetary lithosphere displaces a lot of boundaries away from that perfectly flat... Hysterically flat structure that you have here.

Andrew Dombard (20:27):

Again, we can go back to this cartoon schematic here. Everything that exists above these dash lines, which represents a flat surface. And I show here with these red arrows, is a mass excess. Gravity will be a little bit stronger because of these mass excesses, everything in a blue that exists below these dash lines and whether that's the flexural trough here or the displacement of low density crustal material in the higher density mantle represents deficient mass. Gravity will be a little weaker. So, in addition to looking at the surface, looking at the topography and looking at the images, which might record stresses on the surface by way of fault on the surface, you can also look at what the subsurface is doing below this lithosphere. And therefore you can try to understand piece together, how is this lithosphere deforming? How thick is that lithosphere and start to piece together the thermal history of a body?

Andrew Dombard (21:22):

So the last thing I want to cover is a very brief example of how this all works. The most common land form you see on a planetary body is an impact basin. The moon has been collecting craters for four and a half billion years. An asteroid comes in, smacks in on the surface, boom, makes a big hole. A comet comes in, smacks on the surface, boom makes a big hole. These holes are all over the place on the moon. They have a wide range in ages and they're distributed across the entire surface. When you look at the largest of these impact craters, we call these impact basins, these are the craters that are greater than about 200 kilometers in diameter. The oldest of these impact basins have a very muted topography and a very subtle gravity anomaly map relative to younger impact basins. And so we can interpret that as the ancient lithosphere of the moon was not able to support this basin topography as well as it could for younger basins.

Andrew Dombard (22:21):

And what that's telling us is that we had a transition from very thin, very weak lithosphere to up until about 3.9 billion years ago, in which case the lithosphere was now thick enough that it was able to support this basin topography. And this supports the idea of secular cooling of the moon. We expect that the moon started off a lot warmer than it is, and it has been cooling through time, but by studying these basins and looking at how the lithosphere might be supporting this basin topography, now we can start to put quantitative constraints on how this is actually occurring. And so this is why planetary geophysicists like myself study lithosphere. And with that, I thank you very much for your attention. And I am happy to answer any questions.

Speaker 3 (23:07):

Yes. We have a question from Isaac. Can you talk more about how you classify a lithosphere? Can it only be made out of one material or more and does it have to stay above a certain depth?

Andrew Dombard (23:20):

So, the answer is no, it doesn't have to be one material. In fact, to some degree, the material really doesn't matter. It can be made up of multiple materials that could have a vertical stratification or even change horizontally. What really matters is the mechanical behavior here again, because rocks near the surface are mechanically cooler. They are stronger than the warm stuff underneath. So yeah, it can be made up of different materials. I've already talked about how we have the crust of the moon. And if that crust gets embedded within that lithosphere, if the crust is a certain thickness and that lithosphere is a little bit thicker than that, then that lithosphere is going to be made out of the crustal material, as well as the lithospheric mantle material that exists underneath it. It can also vary laterally. Usually when you see a lithosphere drawn schematically, I've done in this talk, they show a definitive layer, a flat bottom, that's just following what the surface is doing, doesn't have to do that either.

Andrew Dombard (24:26):

You can have all kinds of different factors, which can result in the lithosphere being a little thicker here, a little bit thinner here. And the transition from that elastic behavior to the viscous behavior. I drew it as a straight line, but in actuality, it's a lot more gradational. So yeah, lithosphere can actually get really complex. So they are not quite as simple as the cartoons that I've shown here in this talk.

Speaker 3 (24:52):

Okay. Thank you.

Andrew Dombard (24:54):

Okay. So, how do lithospheres factor into my research and into my teaching? Well, in terms of my teaching, when I teach, in my planetary science course, I do spend one lecture talking about lithospheres. When I teach a hardcore geophysics course, we spend a lot of time talking about lithospheres. The engineers in the audience will appreciate the fact that we go into very gory detail of the beam equation, the nice fourth order differential equation to understand how lithosphere is deforming. In terms of my research, I have dedicated my career to the study of planetary lithospheres, as a primary thing that I do with my research. I am very interested in the processes.

Andrew Dombard (25:45):

So, therefore I usually don't focus on a single planetary body. I've done research on the moon. I've done research on Mars, on Venus, Mercury. I've basically worked my way around both the inner and outer solar system, but the common theme to what I'm working with here is I'm trying to use that lithosphere and how it might be deforming with response to loads and forces applied to it to really try to unravel what is the history of this body, really is a powerful tool for exploring the past of these planetary bodies.

Speaker 3 (26:21):

Great. We have another question. What's the coolest fact, most interesting piece of information when learning about lithosphere?

Andrew Dombard (26:29):

Hmm. How amazingly complex it is. I have drawn the system here, you got an elastic layer and then you got the stuff underneath. And of course it isn't simple because again, all three of those mechanical processes, I talked about the elastic behavior, the brittle behavior and the viscous behavior, all three of them have the potential to happen at once. It's just a question which one is dominating. And so these nice little simplified elastic lithosphere like I doodled in the schematics here is really a very coarse representation of it. And when you really get into the nitty gritty of the mechanics of this, it is for people like me, it is a lot of fun.

Andrew Dombard (27:20):

And what we do in my lab is we actually go beyond this very simple representation of lithosphere of a definitive elastic layer. And we'll actually use finite element analysis. We use a commercial finite element, mechanical engineering code to study planetary lithosphere. So, that's always a fun thing to do is to take a code that is used to explore gaskets and airplane wings, and really push its boundaries to investigate upwards of an entire planet. So, how using those types of numerical techniques to really get into the nitty gritty of how these things deform, for me, that's really interesting.