

FINESSE: Impact Cratering in the Solar System

By Dr. Gordon “Oz” Osinski

Moderator: Anita Sohus

July 29, 2015

2:00pm CT

Coordinator: Welcome and thank you for standing by. This call is being recorded. Thank you. You may begin.

Amelia Chapman: Great. Well I'd like to welcome everybody to the call. This is Amelia Chapman from the Museum Alliance. And we're going to be hearing a great talk today by Dr. Gordon “Oz” Osinski, who's an Associate Professor at the University of Western Ontario, Canada, where he also serves as Director for the Center of Planetary Science and Exploration and Principal Investigator of the Canadian Lunar Research Network. He's also the founder and first chair of the Planetary Science Division of the Geological Association of Canada.

He's going to be doing a talk today about cratering. And I hope everyone was able to get the presentation downloaded. If you didn't, you can give me an email. My email is Amelia.Chapman@jpl.nasa.gov.

I'd just like to remind everybody to make sure that you've muted your phone, which you can do with the mute button or star 6. Make sure you don't put us on hold or else we'll be hearing your hold music.

And if you have any questions, again, you can just give me an email or you can speak up. And let's ask Dr. Oz, is it Okay if people ask questions throughout your talk, or do you prefer to have them wait until the end?

Dr. Gordon Osinski: I'm happy to take questions anytime.

Amelia Chapman: Okay great. All right. Well without further ado, I think we'll just go ahead and get started.

Dr. Gordon Osinski: Slide 1: Okay well thanks for being online and on the phone everyone. And it's my pleasure to talk with you today about meteorite impact craters throughout the solar system.

And moving on quickly to the next slide, Slide 2, this is a poster which many of you may have seen from the Deep Impact movie in kind of the summer of 1998, so going a few years ago now.

But when we think about impact craters, I think most people will tend to think about the bad things that can happen. And while this is definitely the case, I would like to show you that there are also some beneficial effects of meteorite impacts that we're becoming more and more aware of -- in particular for astrobiology and the search for life on early Earth and other planets such as Mars. And we'll come to that later on.

Let's go to the next slide, Slide 3, which is an iconic image by NASA of our solar system. And this is a great image, because it really captures not only the eight planets -- plus some of the larger dwarf planets -- but it also shows us that we're not alone. In kind of the center between the orbits of Mars and Jupiter, of course we know there's an asteroid belt. So there are literally thousands of pieces of rock in a relatively stable orbit between Mars and Jupiter. But there are kind of some smaller objects and some larger objects that are not shown that are so sort of orbits closest to the terrestrial planets and other planets.

And of course also shown coming in from kind of the top right to the bottom left is a comet. And in the top right hand corner is an artist's rendition of

course of Pluto out there and some other large objects and also thousands of other objects, mostly comets out in the Kuiper Belt in the distant part of the solar system.

These comets are much less predictable. Many of them may only come into the inner solar system not in the span of humans. And so they can come in on a hundreds or thousands of years' time scale. And so those are almost impossible to predict.

Out there are comets and asteroids. We know they've struck various planetary objects from essentially the beginning of the solar system. And as we'll learn today and as I'm sure you know, they continue to strike objects in the solar system today and they will do basically I think until the end of the solar system.

So, the next slide, Slide 4, is the moon. Really you don't need a telescope. If you look up at the moon on a clear night, especially with a full moon -- which is coming up of course in a few days -- you can see that the moon is not a smooth surface. Its pot marked and pitted. And really all of these features that you're seeing on this image and if you were to look up at the moon, are meteorite craters or the expression and remnants of meteorite impact craters.

You can see some bright white specks, particularly in the lunar highlands, which is this brighter part of this terrain and these are relatively recent impact craters that have thrown debris out for sometimes hundreds of kilometers.

Of course, the other big feature of the moon are these dark kind of patchy, blotchy areas that we know are volcanic rocks, ancient lavas. And what they are basically showing is the expression of really large impact craters that formed early on in the moon's history. So you can see they're roughly circular

in outline. And so these are where lava flow has essentially flooded these giant impact craters. So the surface of the moon really is pockmarked and has been bombarded for millions of years.

And the thought that I want to ask yourself as a question is why this is. Why does the moon look like this? We're going to look at other planetary objects. Why do they look different or similar to the moon? And we'll come to the Earth, too.

Slide 5: Just a couple more pictures of the moon, kind of zooming in a little bit. And this is actually an image of a telescope image from Earth. And again, it just goes to show that the moon is pockmarked by literally thousands upon thousands of meteorite impact craters. So where asteroids or comets have struck the surface of the moon over the last four billion years, since it was formed.

Slide 6: The next image shows one of the Apollo astronauts. I think this is Apollo 16. One of the important things about impacts is that even if you want to study let's say the volcanic history of the moon, you have to contend with the fact that impacts have pummeled the surface of the moon over billions of years and so they can alter the rocks, the primary volcanic rocks on the surface of the moon.

So there's a lot of reasons to understand how impact craters are formed and how they alter rocks. They can literally melt and vaporize rocks because of the energies involved, and they can alter things in the solid state in a process called shock metamorphism.

So again, any questions as I'm going along I'm happy to answer.

Slide 7: The next slide, we're going to jump to the, just one slide on an inner solar system body. This of course is Mercury and some great, more recent images we've had from the Messenger mission. And I hope you'll agree with me that Mercury looks very much like the moon. Its surface is pockmarked by thousands upon thousands of meteorite impact craters.

There are smoother areas, which is highlighted perhaps best in the smaller image in the top left where again, some of the larger basins were flooded by lava flows early in Mercury's history.

And so Mercury and the moon are really dominated by impact craters. Their impacts are the dominant geological landform on these bodies.

Jumping to the next slide, Slide 8, is Mars -- and of course a body I'm sure most of you are probably familiar with. It doesn't show up -- excuse me -- terribly well here. But you can see quite a lot of impact craters. There are quite a lot of areas that don't appear to have impact craters. And so right away, that's telling us something about the geological history of Mars.

And it's actually showing up much better on the next image, Slide 9, which is a colorful digital elevation model. And so this is from the MOLA instrument aboard the Mars Global Surveyor Spacecraft. It's essentially showing us elevation. So blues and purples are low elevation, and reds and whites are high elevation. So you've got the scale there at the top.

Of course, Mars is a land of extremes, even more so than Earth, where we have mountains much taller than Everest and part of the lower areas that would be much deeper than the deepest parts of the ocean floor on Earth.

But what it also does, it shows us not just the differences in elevation, but the impact craters show up very nicely. And so you have this dichotomy that runs roughly, it starts off on the left-hand side. About the equator at zero degrees, we have the big, red area there where if you've got good eyes, you can see kind of four large, white, circular regions. Those are the volcanos of the Tharsis region.

And so right away hopefully you're asking yourselves, well I actually don't see too many impact craters in that high elevation region. And as we go kind of from left to right, you can actually see that there's a big dichotomy between what we call the northern lowlands -- though they're not just low, but they really lack many impact craters. Whereas in the south -- we call that the southern highlands -- again, there's literally thousands upon thousands of impact craters. And so the south part of Mars looks more like Mercury and the moon. In the north, something happened.

And so without even putting a rover on the surface or a lander or stepping foot there ourselves, we can start to make some hypotheses about what has happened on Mars and its past.

And again, this isn't a talk about Mars. I'm not going to go it in too much detail. But suffice to say, the reason we can do this is that the rate of impacts through time is a relatively steady state affair. And so in the northern impacts that struck the south half of Mars more than the north half.

So really if Mars was just a geologically kind of relatively dead object like the moon is -- it hasn't been geologically active -- it should look like the south half of Mars all over it. But what its showing is that there's been something that has resurfaced these northern lowlands and one of the still controversial hypotheses is that there was flooding from a giant northern ocean that basically covered up all of those impacts that happened before it.

And of course in the red region there where we have the volcanoes, the idea there is that this is a younger area and these lava flows have covered up again the impacts that went before it. And so this actually gets onto one of the major uses really of impact craters is to give us a relative age of planetary surfaces. And again, it's not something I'm going to go into today but so-called crater counting is really the only tool that we have to date relatively speaking planetary surfaces throughout the solar system.

Of course Mars is fantastic -- we'll just jump to the next slide now, Slide 10, in that we really do over the past decade, we've had the rovers on the surface. And then in the next image is I think still one of my favorite all time images from the high rise camera of Victoria crater. And this provides images going down to 27 centimeters a pixel.

And so if you go to the next slide, Slide 12, which is basically the same again but another popup. This camera that I'm sure most of you have seen examples from, you can see the Opportunity rover there, something that's not much bigger than the desk in my here in Western.

Slide 12: So with Mars, we have this great opportunity to not just study impact craters from orbit, from spacecraft. We haven't gone there ourselves as humans, but we have the next best thing -- we've been able to look through the eyes of the rover and use the data we have from the spacecraft

Slide 13: Okay. So before we come to Earth and actually look at some examples of impact craters and talk more about impact craters are formed, I don't think I could give any talk right now about mentioning Pluto and showing one amazing image from Pluto that I think most of the world's been

enthralled with. And of course, this is the first time that we've been able to see the surface of Pluto in any resolution.

And so what are we seeing here? Well, it's also more interesting what we are not seeing. We're not actually seeing a surface that looks like the moon that is completely obliterated by impact craters. And so something -- some process or some processes -- are actually resurfacing Pluto on a geological time scale, which is of course incredibly exciting, given how cold it is there in the outer part of the solar system.

Now if you've got good eyes, you can see meteorite impact craters kind of more in the south and the darker regions of the left. And the interpretation currently is that big, kind of pale yellow area almost dead center, that's actually quite a large impact crater that has been then filled in by, again, some process. And so really yes, whether there are and whether or not impact craters are on various planetary objects does tell us a lot initially about how geologically active a planetary object is.

Man 1: Dr. Oz, could I ask you a question about Pluto?

Dr. Gordon Osinski: Absolutely.

Man 1: Terrific. Sorry, I've been having trouble downloading the slides here, so I'm just catching up with the slides, but I have been listening.

When the original photos came back, Stern and several of the others referenced how surprised they were at the complete lack of cratering. And yet when I look down near the Cthulhu region -- the one you pointed out at the bottom left there -- I see plenty of craters.

Is that what the older so to speak older surface of Pluto looks like?

Dr. Gordon Osinski: Yes. I think some of those very first images were a bit misleading because I think we'd all agree that there impact craters on Pluto. It's not a complete lack. But I mean, if again you just picture the Earth -- which will be on the next slide -- or kind of go back to Mars, there are I think far fewer than we expected. But there are definitely some. Yes.

Man 1: Thank you.

(Robert Bigelow): I also have a question. (Robert Bigelow), Solar System Ambassador. As far as cratering rates, would we expect the same rate of cratering in the very far outer solar system as we see in the inner solar system?

Dr. Gordon Osinski: That's a great question, and actually I do not know the answer for Pluto. They will be different, not drastically different I guess is the answer there. There are all sorts of subtleties anywhere in the vicinity of Jupiter. The cratering rates can change because there is big gravitational pull.

In the inner solar system, Mercury has a slightly higher rate because of kind of focusing into the sun. So yes, I don't know off the top of my head what the theoretical crater rates are for Pluto, but they really shouldn't be too different than they are here in the inner solar system.

(Robert Bigelow): Thank you.

Dr. Gordon Osinski: Yes.

Man 2: And if I could too, Dr. Oz. Earlier you stated that impact in cratering was sort of a steady state affair -- or the words you used. But haven't we seen variation over like eras like the period of early bombardment and that sort of thing?

Dr. Gordon Osinski: Yes, you're quite right. And I was going to add that to my statement, which is let's say the first half a billion years of the solar system -- so from about 4.5 to about 4. There's obviously controversy about how it dropped off. We do know, let's say at day one, impact rates were much, much higher because you essentially just finishing up the planetary formation process and all of those bits and pieces out there continue to strike the planets.

And then there's still an ongoing debate whether it was kind of an exponential drop off and we reach this - it's a relatively steady state for the last four billion years. Yes, so there's still a controversy over whether it kind of dropped off or whether we did have this spike at around four to 3.8 billion years -- as known as the heavy bombardment period -- or not.

But I think most would agree that really the last three and a half, and probably the last four, it's been relatively constant rate.

Man 2: Okay thank you.

Dr. Gordon Osinski: Okay so the next slide, Slide 14, and it's an iconic image of the earth, of course, courtesy of an Apollo mission. And, well, I would challenge anyone on the line to pick out an impact crater on the surface of this particular view.

As we'll see in a bit, there are a few impact craters that you can see from space on the Earth, but generally speaking we have a big lack of impact craters compared to most of the solar system bodies.

The next slide, Slide 15, shows it a little bit better and more schematically. And so this again, just like the Mars image I showed, is a digital elevation model, colored of course to highlight the oceans in blue. So blue is low elevation and again the reds and whites are high elevation.

So currently, we know of about 187 impact structures on Earth. I do use the word confirmed because there are many more that people have speculated about but where we don't have the diagnostic evidence in hand to unequivocally say they're an impact crater or not.

But still, we have about 187. The number goes up by a few each year as we discover new ones. You can see a quite big concentrations in North America, in kind of Northern Europe, Scandinavia, in Australia.

I'm happy to answer questions as to why that is now or later, or maybe let people have a think first.

Of course, two thirds of our planet is ocean, and we see very few -- in fact, only really a couple on the true ocean floor. There's a few we know about on the continental shelf. But of course, Earth is geologically active and it's the major reason why we don't have more impact craters on Earth.

And in fact, just to emphasize that, our nearest neighbor, the Moon, is smaller than the Earth. And so actually the Earth, because of our bigger gravitational cross-section, should attract more asteroids and comets than the moon does. If the Earth was not geologically active, we'd look much worse off than the moon. And so this is down to Earth's active geology -- plate tectonics, volcanic resurfacing, and erosion is continually recycling the surface of the Earth, the plates and the crust of the Earth.

Woman 1: If I might ask a question, please?

Dr. Gordon Osinski: Yes.

Woman 1: Why would we be worse off than the moon if we didn't have our atmosphere and our geologic erosion and activity?

Dr. Gordon Osinski: So basically it's down to the fact that Earth is bigger and therefore kind of the gravitational (G) is higher. And so if let's say an asteroid was coming into the Earth's near vicinity, our gravitational field goes out further and so we can pull objects towards us -- more so than the moon. But kind of a maybe a bit simplistic explanation.

(John Conrad): Yes may I ask a question?

Dr. Gordon Osinski: Yes.

(John Conrad): This is (John Conrad), Solar System Ambassador. I've had occasion to use a Web site -- let's see, I'm looking at it here -- called the Earth Impact Database by the Planetary and Space Science Center in Canada, which is very useful.

I just wondered, based on the reference that I see on your slide here, is there one or another source that is viewed as the best source for the latest, fully accepted, certified impact crater map? Or are there several of them?

Dr. Gordon Osinski: There's several of them. And in fact, I'm in the process of kind of developing my own right now for both outreach and research purposes. It's actually a debate within the research community and many of us feel that - so many of you maybe know about and work with meteorites. And you'll know that the Meteoritical Society, which is an international organization, basically

you have to have their stamp of approval for a meteorite to be known and categorized as a meteorite.

But that doesn't exist for impact craters. And so this is why if you go to various different lists that people publish around the world, the numbers will be different. And so many of us feel that the Meteoritical Society or some other organization would be kind of best placed to have the one list where yes, if it's on this, the community feels it is an impact, or if it's not, it's not. But that doesn't currently exist.

(John Conrad): Thank you.

Dr. Gordon Osinski: Okay. So let's go on a little bit of a tour. Slide 16 is a picture of I'm sure a place many of you may have been to or at least familiar with, which is a Meteor Crater or Barringer Crater in Arizona. And so this is what we call a simple impact crater, which we'll get to in a second -- a relatively simple, bowl-shaped form that is 1.2 kilometers across. So by solar system standards, this is tiny. But if you've ever been there, you can see the black asphalt paved road that comes in from kind of the top left to the north. Well, in this image, the top rim of the crater and there's a museum there for scale. But I mean, it's a pretty substantial hole in the ground. But again, by solar system standards this is pretty small.

As we go to the next slide, Slide 17, this is actually Canada's meteor crater. This is now four kilometers across. It's up in northern Quebec, a place that's very hard to get to. And this is the New Quebec Crater. And again, this one's been filled by water, but if you took that water out, it would look just like Meteor Crater in Arizona.

Many craters on Earth, however, and on other planetary objects, don't have that simple bowl-shaped form. And we'll get to why that's the case in a few slides time.

Slide 18: So this is an image of what actually got me into impact cratering, and what brought me to Canada, which is the Haughton impact crater on Devon Island in Arctic Canada. So the image here is about 35 kilometers across and the crater is picked out by the kind of gray material in the center, that are rocks melted by the impact. And then you have all these kind of roughly circular valleys that show you where the crater rim used to be.

So this is a relatively young crater, only 23 million years old, and relatively well preserved. But it is obviously not a simple kind of hole in the ground.

Man 3: Excuse me doctor. Is that a false color image?

Dr. Gordon Osinski: This is almost true color land set. So it's been stretched a little, but we're up in the basically a polar desert environment. And so the rocks are not quite as red as this, but it's a polar desert. There's hardly any vegetation.

If you go to the far top right, you can see a lake there that is ice covered that's showing up in kind of turquoise.

Man 3: Yes.

Dr. Gordon Osinski: The gray is literally that gray, and I think I've got a slide later on that shows you what it looks like on the ground.

Man 3: Thank you.

Dr. Gordon Osinski: Slide 19: Just one more example before we get into why craters don't look the same. This is one of the few that we can actually see from space. And this is - I always get them mixed up. This is either the tailfin, one of the fins or the rudder from one of the space shuttles. And this is another impact crater here in Canada, which is the Manicouagan structure.

And what you're seeing here is there's a big circular lake that is there because it was dammed for hydro-electric purposes in the 70s. So the lake there is about 60 kilometers from kind of one side to the other of the circle.

This is a structure that's 100-ish kilometers across. The rim is completely lost because it's quite old. But the island in the center there is what we call a central uplift, which really typifies these so-called complex impact craters that I'll get into in the next slide.

So slide 20...

Man 4: (Unintelligible) SSA. I'm glad you raised this particular one. I wanted to understand. The central uplift is where the lake is well, it's where it was, where the lake is now. So wouldn't the glaciers just kind of pushed all the loose rock off and leave behind the melted rock, which solidified easier? Is that why the crater is shaped like this?

Dr. Gordon Osinski: A bit of both. So the island -- it's technically an island -- the island in the center is the central uplift that is draped in rocks. The lake is where - that would've been filled with all of these melts and brecciated that we call the crater-fill. And I can show that kind of diagrammatically in a couple of slides time. And so that's yes, where the glaciers have come around and scooped out those weaker, more broken up and brecciated materials.

Man 4: We have a professor here on campus, (Ed Patouk), who kind of looks at some of this stuff. And I bumped into him because I was learning a little bit about craters at one point, so I came across a piece of information and a map about aquifers across the United States. And the funny thing is the state of Michigan is these series of concentric aquifers, which almost looks like the land is kind of filled in, but the water is underneath and they kind of progress out with a function that mentions very similar to the craters.

And I was kind of wondering how many people have actually looked into things along that line, where you've got these concentric aquifers that might've actually been an ancient crater?

Dr. Gordon Osinski: I have not heard of that, in particular the Michigan aquifers. But it would be quite interesting. Sort of makes me think that people haven't looked into that question in detail. But of course if you go back to the map of craters on Earth, a good third of them are buried.

Man 4: Yes.

Dr. Gordon Osinski: And so I mean, there's quite a few on the continental US that are buried that we know from drill cores and from geophysics. Many of them were discovered because they actually produce oil and gas. Others - and the best example that has exerted a big influence on ground water and aquifers that I know of is Chesapeake Bay.

So of course on the eastern sea board, Chesapeake Bay is the site of a 40-ish kilometer diameter impact that is mostly buried. But in that instance, it's actually a bad influence because apparently what's happening is that kind of circular basin is letting seawater encroach onto the I guess the

land, or into the land, so that you're getting kind of marine salty water going into the freshwater aquifers.

But, I mean, we'll come to it maybe in the next couple of slides, but of course these larger craters fracture and fault the Earth's crust to many kilometers deep and many kilometers wide. And so it does make sense that they will exert a control for potentially millions of years on groundwater flow, on hydrocarbons, and things, too.

Man 4: Thank you.

Dr. Gordon Osinski: Okay so onto slide 20. So just in these next couple of slides, I just wanted to talk kind of very briefly about how impact craters are formed before we kind of move on again.

So we split the formation of a crater into three main stages -- contact and compression, excavation, and modification. And so the contact compression stage is definitely the shortest. It occurs when a projectile -- that again can be an asteroid or a comet. We usually don't know what -- it strikes the surface of a planetary object.

And one key thing about these early stages of cratering is that it is really a geological process governed by physics. And in these early stages, it's all about kinetic energy. So kind of back to high school physics and the half mass velocity squared, it differs on different planetary objects in terms of what we call the impact velocity.

But on Earth, for example, a typical asteroid will hit the Earth at around 15 to 20 kilometers a second -- can be slower, can be a bit faster. Comets can come in anything upwards of 70 or 80 kilometers a second. So

you're always - even I who have been studying these impacts for a long time have to kind of pause and just think about that for a while.

I mean, humans cannot generate anything close to those speeds. And a high powered kind of sniper rifle, these experimental guns that NASA has for simulating impact experiments, we can't get into double figures of meters per second. And so that plus you're dealing with sometimes hunks of rock clumped across releases immense amounts of energy that are simply kind of mind boggling.

And the other key thing is that unlike other geological processes, it's an instantaneous release of energy. Geologists typically work on kind of things that happen over the millions of years of time scale. And it's sort of very concentrated single points in the Earth's surface.

So this contact and compression stage lasts only a few seconds. Essentially the projectile hits the surface, burrows in we think about one or two times its diameter, and then essentially meets resistance and comes to a stop.

And then what happens is a shockwave radiates out into the surface of the Earth and back into the projectile.

So one of the key kind of misunderstood things about impacts is that it's not like firing a shotgun or a handgun into the sand and you form a crater or a hole not much bigger than the round. That's basically just mechanical excavation.

What is happening here is that it's the shockwave that is forming the crater, not necessarily the mechanical excavation for the projectile. And that's shown here kind of schematically as we move into the excavation stage.

So, the shockwave compresses material and behind it, we get this release or refraction wave that is tensional. And the interaction of the shockwave and the subsequent release wave forms what we call a transient crater. And if we take a projectile one kilometer across, it's not an exact science but you can end up with a transient crater ten times that in diameter. And so the hole that is formed in the ground is much larger than the actual projectile.

During this excavation stage is when all sorts of things happen to the rocks, and the atmosphere for that matter, but because of the intense kinetic energy, the temperatures can be several thousands of kelvin and several thousands of gigapascal. So we're talking about pressures and temperatures on the surface of the Earth that are hotter and higher pressure than in the Earth's core. And so this will melt and vaporize cubic kilometers of rock in an instant of geological time.

So for relatively small craters on Earth, around two, three, four kilometers across, these so-called transient craters are relatively stable. And so that's what we call simple impact craters and we get this relatively small, simple, bowl-shaped form.

Slide 21: For the larger diameters, we move into what we call the modification stage. And this is where literally the hole is unstable and in this case, gravity then comes into play.

And so just like if you were to dig a big whole in your backyard, there's a point where the walls become unstable and they would collapse inwards. And so two things happen and the kind of competing mechanism that's shown more on the bottom half there, which is collapse of the crater walls.

And then we get shown in the arrows in the middle there, we get upward movement of the crater floor. And this forms what I mentioned earlier which is a central uplift. And shown in red here is kind of these sort of crater-fill deposits that are a mixture of essentially melted rock and broken up rock.

So moving onto slide 22...

Man 5: Dr. Oz?

Dr. Gordon Osinski: Yes?

Man 5: Back at slide 20 where you show the projectile coming in, you mentioned it's about a ten-to-one difference with the size of the crater. How would that change if we changed the mass of the projectile or if we change the velocity? Is it still one for one?

Dr. Gordon Osinski: That's a good question. I actually have a post-doc doing some modeling of that right now, because it's something we tend as a community to ignore a little bit. We tend to assume - so I guess one of the big challenges is that -- and it's also of course something we're pleased about -- is that we've not witnessed a large impact event. And so we're left with studying the end product and studying these large - these early parts of the process from essentially computer modeling or small scale experiments.

But we generally assume that you can change the parameters in the equation for kinetic energy and the outcome is more or less the same. So you could have a small, let's say small, dense, very fast projectile versus a big, slow, maybe porous asteroid. The energy is the same and the crater size will be the same.

We don't actually quite know if that's the case, but I think kind of broadly speaking it will be. So let's say you had a comet impact coming in at 70 kilometers a second. You would need a smaller comet with those higher velocities than an asteroid coming in slower to form the same size final crater, if that answers your question.

Man 5: Yes, you did. And is there a speed of sound, for lack of a better word, or a propagation speed through the lunar regolith that there's sort of a limit, like a sonic barrier where if you hit it too fast no you have a bounding up of the shockwaves? And does that change the morphology?

Dr. Gordon Osinski: So how the shockwave - the shockwave is traveling faster than the speed of sound. How it traveled through rocks does vary depending on the rock. It's quite complicated and it's something that we're I'd say only in the last decade we're getting stuck into. If there's more space in the rock, such as a lunar regolith or in sedimentary rocks that does change how quickly the shockwave propagates through it and how the energy dissipates. Those are kind of questions that might have to answer offline.

Man 5: Okay.

Dr. Gordon Osinski: Yes.

Man 5: Not to carry this topic out too far, but I was associated with the weapons labs who did a lot of buried nuclear device tests. And they have probably 1000 staff years of research into how to pack the channel that leads down a mile in some cases, what kind of materials to put into it in order to keep that shockwave from exiting the surface and creating a blowout.

And I'm just wondering do your research people take advantage of that particular community that was especially active probably in the '60s, '70s, and '80s?

Dr. Gordon Osinski: I'd say yes and no. Actually some of the big names in cratering in the 60s and 70s, one in particular was Dave Roddy, who worked for the USGS but also participated in a lot of the nuclear tests. So yes, I mentioned modeling and small scale experiments earlier. But definitely the large scale nuclear tests, in particular the buried ones, are where actually a lot of our knowledge of how impact craters or how we think impact craters form comes from.

One of the things that we run into is that a lot of that's in the kind of so-called gray literature and not necessarily out there in the public domain.

Dr. Gordon Osinski: Absolutely. There's enough out there that we have gleaned a lot of information from those earlier tests, yes.

Man 5: Okay. Thank you.

Man 6: Another question, you talked about the speed of asteroids hitting the surface. I'm thinking of that, forgot what it's called but I think it was over the Rocky Mountains back in the '70s. There was a movie of an asteroid that skimmed the Earth's atmosphere. And it seemed to be visible for I don't know, some seconds at least. But it came sort of at an angle just tangential to the Earth and it was caught on film by a family. It was at the Tetons, near the Grand Tetons. Do you recall that?

Dr. Gordon Osinski: I'm not sure I was around but I do - I'm pretty sure I've seen images of it, yes. And we'll look - yes it's a famous one right over the Tetons where you're looking at a fireball trail there that, yes, was very oblique.

Yes, so did you have a specific question about that event or?

Man 6: I was thinking that if they're traveling at that speed, if you're the unfortunate observer where you're right underneath the impact of this thing, you wouldn't even visually see much because it would pass through the atmosphere in a matter of a few seconds. Do I have that right?

Dr. Gordon Osinski: Absolutely. I mean, not even a few seconds. Yes.

Man 6: Okay.

Dr. Gordon Osinski: So again, yes that one was oblique which is why it was witnessed for so long. Yes.

Man 6: Great. Thank you.

Dr. Gordon Osinski: You could, I mean if you think about it, yes 50 kilometers a second, I mean if you blink its gone 50 kilometers, so yes.

Man 6: So the way it's sometimes depicted in movies and some of our planetarium shows, we get this elegant little streak of light in the sky before it hits the ground. That doesn't happen?

Dr. Gordon Osinski: I would tend, yes, to say no. I mean if you're witnessing it striking let's say on the other side of the state or continent, then you would witness it for longer. But if you were at ground zero, yes I would say yes. It would be over pretty quickly. Yes.

Man 6: But I think what we're talking about here, large, large impacts. What we see are much smaller objects that tend to burn up. So your analogy here could be (unintelligible) where...

Dr. Gordon Osinski: Yes.

Man 6: ...people witnessed it for a long time but large pieces of it never made it to the ground. It didn't crater. If something's the size of Barringer yes, for miles, people wouldn't have survived.

Dr. Gordon Osinski: Yes. Okay. In the interest of time because I do believe we only have until 4:00 Eastern, I'm now on slide 22. And this just shows you this progression of what happens as you increase basically the energy of the impact and therefore increase the diameter of the crater.

And the Moon really is the best place to look at this because it's, again, once they form, craters are relatively well-preserved. And so on the top left you have a nice, simple crater seven kilometers across (unintelligible) to the bottom right we have kind of prototypical so-called complex crater in the form of Ulugh that has this uplifted rim, a relatively flat floor that if we were to zoom in would be filled with melt, and then literally a mountain in what we call a central peak.

And then as we scale up even further to the famous Schrodinger crater, which is now 300 kilometers across, we lose the single peak and instead we get a circular ring of mountains that we call a peak ring structure. And so again, this is reflected in how craters form and how things change as we increase the diameter.

I would say as a community that we're still understanding why you get this difference in morphology. So it's definitely controversial in particular how these peak ring craters form.

Okay. So the next slide, slide 23, is kind of an iconic image now by (Unintelligible) Davis, kind of a large impact striking the Earth. And so I'm just going to dwell very briefly on the next two slides on so again the kind of destructive effects of impacts.

And so on slide 24, there's another artist rendition. Of course is maybe what most people out there in the general public think about impacts is the extinction of the dinosaur and many other forms of life on Earth about 65 million years ago.

And moving quickly onto slide 25, this just puts it in a great plot by a book called *Traces of Catastrophe* by Bevan French of a plot on the - so the x-axis is essentially energy. And you'll see here that is in tons of TNT equivalent, actually megatons. And on the y-axis is the impact interval -- so how frequently these events occur.

And so really the take home message of this is that as you increase the diameter of the crater, the kind of things go off the scale. And even meteor crater as you'll see is already about two or three times orders of magnitude more powerful than the atomic bombs dropped on Japan at the End of World War Two.

As you get to Chicxulub, which is associated with the extinction of the dinosaurs, at about 200 kilometers or 180 kilometers across, we're looking at something on the order of 10^7 to 10^8 megatons of TNT. And so the numbers don't really mean anything to me. But just to emphasize the fact

that this is an incredibly energetic geological process that really is unlike any other geological process.

But I kind of wanted to move into the last sequence of slides on this by kind of ending I guess on a bit more positive note, which is so-called beneficial effects of impact events that I think have become more apparent in the last decade, last couple of decades.

Slide 26: This was actually an article I wrote for the New Scientist quite a few years ago. I didn't get to choose the title or the cover caption or image, but basically how impact events have benefitted microbial life in particular.

And so slide 27 -- and this is a lot of my research area now -- is it turns out impact events after they form yield a lot of benefits for, again, microbial life. And this is important when we're thinking about where and how life originated on Earth and also potentially where to look for evidence for life on Mars and other planetary objects.

And so one of the key things that impacts do is that they create habitats for microbial life that were not there before the impact, such that an impact crater is actually a beneficial kind of a protective niche for organisms after they form.

So these are a few different ones, and I'm just going to focus in for this talk on impact generated hydrothermal systems. And so what I mean by hydrothermal system? Well just kind of picture Yellowstone National Park, New Zealand, Iceland in your head. And it comes from two Greek words -- I mean hydros and thermos. Heat plus water.

And so if you have hot rocks and water in contact with each other, the water will heat up. Hot water can dissolve rocks and minerals in one area. As it rises to the surface by convection, it will cool and then it will precipitate out new minerals and hot springs and steam vents. And that's a general, kind of simple concept of a hydrothermal system.

On Earth today, all active systems are in volcanically active areas driven by heat from magma. But it turns out, impact craters actually generate hydrothermal systems, which today I think is fairly intuitive but a couple of decades ago really wasn't recognized. Because if the intense energies that we've talked about before, you can melt larger volumes of rock and so right there is your heat source.

So onto slide 28. I'm actually going to take you back to this Haughton crater in the Arctic that I talked about very briefly earlier on. So it's up in the high Arctic, well above the Arctic Circle. And this is where I cut my teeth looking at impact craters.

Slide 29: So this is this land set image again. Some of you may be familiar with this site because it's where NASA and the Haughton project have done a lot of work. And it was also known as Mars on Earth for a while too. But first and foremost, it's an impact about 23 kilometers in diameter and formed about 23-24 million years ago.

And slide 30 now is an image just of this. It really is unbelievable terrain that does not look like Earth. These gray hills in the foreground are the rocks that were melted by the impact event. And so there is your heat source for this hydrothermal system.

Slide 31: And I just threw in kind of a couple of images just because many people don't ever get to go up to Arctic. Kind of what it's like doing field work up there. So this is our base camp and the rim was kind of set on the northwestern rim of the crater there.

And of course being on slide 32, this is July in the Arctic and so it can be nice, but it can snow every month of the year up there. So sometimes it's a challenge doing geological field work.

But over the course of three summers, I was able to put together this map that is shown on slide 33. And so this is a simplified geological map of the Haughton crater. And so the orange in the center there, the bull's eye, these are these crater-filled melt rocks. The kind of purple-y color is the central uplift, so rocks that were uplifted from depth. And the pale blue are the rocks that have formed kind of the rim region. All of the black lines are faults that formed when the impact crater happened.

And so on the bottom left where the arrow, this is a picture. Hope you can see it. There's a rock camera for scale. This is what we call a vug. It's essentially a cavity in the melt (unintelligible) and rocks that is aligned by you can see a green mineral that is marcasite, which is iron sulfide just like pyrite. And you can see some popcorn-like yellow material. These are all minerals, hydrothermal minerals that were formed as fluids flowed through here after the impact and driven by the heat of the impact.

The next kind of slide -- slide 34 -- is the same, but the image in the bottom left as changed. Of course, you actually need three things for a good hydrothermal system. You need the heat, you need the water, but you also need fractures for the fluid to flow through. And of course, impact events by

now I hope you recognize are very energetic and they fault and fracture large volumes of the rocks.

The pale material here is calcite, calcium carbonate that is along these vein systems around the edge of the central uplift.

And slide 35 is just another image from the field. And it's what all these little red dots are around the rim of the crater. And this is one of the most exciting findings. Not much to look at in the field. It's these kind of two streaks of orange running from top to bottom in this image of what we think are basically fluid flow paths and where we had hot springs when the crater was first formed.

And so the next slide -- slide 36 -- capture schematically if you were to kind of cut in half and take a pie slice through any impact crater really from let's say five to 200 kilometers across and what it would look like. And where you would find these hydrothermal systems.

And again, I think the most exciting for astrobiology is the fact that we think anyways that we would have had hot springs -- and there's one there shown from Yellowstone -- just around the rim of these impact craters.

So onto the next slide -- slide 37 -- why am I excited and why others excited about this is really because of the origin of life on Earth and other planetary objects. And so we know that -- we talked about it. There's a question slide earlier on -- that -- and we know from looking at the Moon -- that impacts cratering rate on earlier, the first half a billion years was 10 or 20 times more common and higher than it is today.

And coincidentally, it's around this time of this proposed so-called late heavy bombardment that life appeared on Earth. So it's almost paradoxical in that we have life appearing at a time that was literally Hades on Earth, hell on Earth.

And so when we go through kind of ideas of where life originated, you probably get taught in biology that we think that hydrothermal systems, maybe the so-called black smoker smokers at the bottom of the ocean floor was where life originated.

Slide 38: Twentieth century scientists will not be the first. I mean, Charles Darwin basically conceived of this idea in the Origin of the Species and he called it this warm little pond idea where you have the heat, you have all of the nutrients where life can get going again. So it's still debated, but we do think that one of the most likely places where life on Earth originated is in hydrothermal systems. And therefore one of the best places to look for life on Mars is on hydrothermal systems.

And as I mentioned earlier, and now that we know that impacts can create these, this really kind of opens the door to really any object in the solar system that has even ice and a surface that could be melted, potentially could generate a hydrothermal system. Because unlike volcanism, where you need a relatively large planetary object and kind of heat from within to generate geological activity, any object out there can be hit by asteroids and comets.

So I think I'm running out of time, but if you just go to slide 40, which is essentially the same as slide 39 just to kind of justify this a little further in terms of a hydrothermal origin of life. This really does conform and is backed up and supported by the terrestrial tree of life, which in this great rendition here is color-coded.

And so in red, the oldest forms of life that we know of on Earth are these thermophiles, these organisms that are heat loving and in fact will only grow at temperatures above 90 degrees Celsius. Unlike humans, these kind of bugs like the heat. They in fact need the heat. And so this drives this idea of a hydrothermal origin of life.

And I will end on slide 41, which is an image from a structure I've just returned from, actually, the Tunnunik structure up in the Canadian Arctic where we have rocks that were originally flat uplifted and upended by the power of these meteorite impact events.

And I'd be happy the rest of the time to take any questions.

Man 7:: Doctor, that slide on, the image on slide where you have the structure of the cratering, is it really that symmetrical or does that depend on the local geology?

Dr. Gordon Osinski: Sorry I missed the beginning there because I think someone else was talking. On which slide was this?

Man 7: Slide 40. The picture at the top right.

Dr. Gordon Osinski: Yes, the counter cross section is definitely schematic. But really, craters are - so there was a question earlier about something I haven't really talked about is the angle of impact. So because craters are formed in the shockwave as opposed to kind of mechanical excavation, they're roughly circular and therefore roughly symmetrical down to angle - it takes angles of kind of below about 20 degrees or so, so variably impact to get kind of varying symmetric craters.

So the vast proportion will be roughly symmetrical in terms of kind of outline and structure.

Man 7: Okay. And looking around the Moon we see in that picture you've got the central uplift. Looking around the Moon, we see craters of similar size, some with a central uplift and some without. What accounts for that?

Dr. Gordon Osinski: So without looking at specific examples, really when you get the so-called smaller size, we get transitional craters where kind of the central uplift is only getting going. And that's probably driven in part by the energy and maybe it was a slightly lower energy impact.

But we do know that the target plays a difference, too. So you could take a crater of exactly the same diameter in the (Mary) regions in the volcanic regions and in the highlands and we know that central uplifts form at smaller diameters in those volcanic regions than in the highlands.

If you're up in the hundreds of kilometers range, though, really all impact should have a central uplift. So it's telling you that maybe this crater was then filled by volcanic material or something.

Man 7: Thank you.

(Ed Mahoney): (Ed Mahoney), Solar System Ambassador. I'm looking at slide 29, the Canada map. I'm looking at Hudson Bay. It's a beautiful semi-circle on the right. Could that be an impact crater?

Dr. Gordon Osinski: Yes slide 28. It's a question I often get, and I wish there was a firm answer. But people have gone up there. In fact the Geological Survey of

Canada, which at one time actually had an impact geology group, they've gone up there and searched around and there literally is not a single speck of evidence for it being an impact.

And so the idea is that it's mainly due to isostatic rebound after the last glaciation but yes, definitely intriguing. It just goes to show that all circular structures are not impact craters, which we sometimes tend to forget when looking at other planetary objects.

(Ed Mahoney): Thank you.

(Chris Thompson): (Chris Thompson). I'm a Solar System Ambassador as well. I understand one of the ways you can determine an impact crater is through discovery of shatter cones. Could you help us understand how shatter cones are formed?

Dr. Gordon Osinski: Yes, to a certain extent, because like many aspects of impact cratering, we're still actually trying to figure out how they formed.

Unfortunately I don't have an image in here, but I'm sure if you just put shatter cone into a search engine, you'll come up with something.

So, it's the only - it's a shock metamorphic effect. So it's something that's formed in the solid state without melting. And it's the only one that's visible with the naked eye without the aid of a microscope, so it's not the shock quartz that you may have heard of.

So essentially they're conical and they have these striations that radiate to the point on the cone. And they're formed - still the best model is that it's basically is the shockwave radiates out from the point of impact. It will come across with some inhomogeneities -- so a bubble or something of different

density. And that will cause the shockwave to kind of scatter from a point. And if you can imagine a shockwave radiating out from a point, you can generate this conical shape.

It's not universally accepted, and there's little things we don't quite understand. And in fact, I have some research ongoing on how shatter cones form but that's kind of broadly speaking how we think they form. And one of the...

(Chris Thompson): (Unintelligible) analogy of a BB hitting a plate glass window and popping out a cone on the other side. Is that roughly analogous?

Dr. Gordon Osinski: Roughly I would say, yes. One of the key things though about shatter cones and like things like circle planar deformation features in quartz is that they cannot be generated any other way, even in - so shatter cones have only been formed in meteorite impacts and in the nuclear test craters of the 1960s because you need pressures that aren't seen. Even the most violent volcanic explosion can't generate.

Man 8: A question about the Pluto image. One of the craters that really stands out is down at sort of the 8:00 position right at the edge, that dark region and it...

Dr. Gordon Osinski: Yes.

Man 8: ...the sun's hitting it quite well, I guess. But it looks like it has a very high, almost concentric series of rings, like a central ring of something -- mountains or another wall. What do you think that is?

Dr. Gordon Osinski: Yes if it's the same one I'm looking at, my guess -- again, without looking at it in detail -- is that you're looking at a complex crater. And so the feature

that looks kind of maybe casting a shadow in the center could be a central uplift. And then if you were to go to the slide of lunar craters, slide 22, you'll notice that in Ulugh and Schrodinger is that we get this terrorist region where the walls of the crater collapse inwards.

And so, my best guess would be that that's what we're seeing there. On Pluto, too.

Man 8: More a wall collapse than any kind of central peak.

Dr. Gordon Osinski: Again, it's big enough. Given Pluto's smaller gravity, we would expect kind of craters, such as Ulugh crater here on slide 22, to form on Pluto. We see it on other icy bodies. Some of the moons of Saturn and Jupiter we see craters that look just like this, even though they form in ice. Because ice can pretty much behave as a rock under these circumstances.

Man 8: Right. Thank you.

Man 9: Doctor can I ask you a question about slide five?

Dr. Gordon Osinski: Yes.

Man 9: In that picture of the Moon there, some of the craters like Plato have always amazed me. They've got a big broad circle, but then a completely flat bottom as though at one point, lava oozed up and filled in the crater.

Was that - as you've got some of those examples there in that slide there, and in that picture on slide five, does that happen during the impact and is it a result of impact? Or does that happen later on in the geological time where that lava oozes up and fills in the basin?

Dr. Gordon Osinski: That's a great question. In fact, there's been ideas that kind of come back and forth in the research community that impacts can initiate volcanic eruptions. I think the pendulum is back more or less in the realm of unless it's incredibly exceptional circumstances, impacts will not initiate any kind of volcanism.

And so, most of these -- and I think it's been borne out by kind of age dating from crater counting and things -- that the age of the lavas filling the majority of craters is any numbers of millions or hundreds of millions of years after the impact. And so really it's magma that is taking advantage of kind of the fractures formed from the impact is why we kind of see these filled-in craters.

Man 9: Excellent. Thank you.

(Carla): Hi this is (Carla). I'm a Solar System Ambassador. And I was hoping you could talk more about slide 41 and tell us specifically what portion of this crater that we're looking at? Because the rocks, you know, to the left of center are almost at a 75 to 80 degree angle, whereas the rocks on the right hand side are horizontal.

Dr. Gordon Osinski: So yes, slide 41 is actually - when did I get back? Two weeks ago. I spent - I was up there in the Canadian Arctic. So these are all sedimentary rocks. It is a little deceiving because of the angle, but the rocks on the right-hand side are also still, they're not at 75 but I'd say at least 45 or 50 degrees.

So we're actually within the central uplift. So one of the unique things is that there's a canyon carved which will be right through where you have this central uplift in one of these fresh lunar craters. So it's really allowing us to study how these uplifts form.

And it really is, again, it's one of these somewhat mind-boggling things where we still think in the space of a couple of minutes you can bring rocks that used to be two, three kilometers down in the crust of the Earth or on other planets. You bring them from that depth to the surface. These rocks were initially flat and its part of the Arctic and so you've upended them, tilted them, and brought them in towards the center of the crater. So it's really quite a spectacular scene.

(Carla): Thank you.

Woman 3: I'm sorry sir. Could you please explain Gale Crater? Why it looks so different?

Dr. Gordon Osinski: Yes I can answer that question and then I think there was a previous question about to be asked. So Gale Crater on Mars, where Curiosity is. It looks like it should be a central peak crater, so again I'll go back myself to slide 22, where you have kind of the lunar example of Ulugh.

But it's again, this is a lesson that you have to - nature complicates things. So in this instance, we had a large crater, about 150 kilometers across. It must've had a central peak, a central uplift in the center, but it was either completely eroded or partially eroded and then the crater was filled up with sediment, with sedimentary rocks that are relatively flat lined. And then there was erosion.

And so this mound, Mount Sharp in the middle of Gale Crater, is not actually the central uplift. It's the remnants of sediments and sedimentary rocks that infilled that crater and that were later eroded, to give us kind of a false central uplift.

Woman 3: Thank you.

Amelia Chapman: This is Amelia just checking in. I know we've gone past our official end time. Are you Okay still answering a few more questions?

Dr. Gordon Osinski: Yes. I think I have to run in a couple of minutes, but I can definitely take, yes, a couple more questions.

Man 10: Okay I was asking a couple minutes ago about the slide 15, the database that you have shown graphically of the Earth and the impact craters.

Dr. Gordon Osinski: Yes.

Man 10: And I wondered if any of the dots on their corresponded to the one you just visited there at slide 41?

Dr. Gordon Osinski: You've caught me out on this one, because I haven't updated this. This Teutonic structure is actually newly discovered I guess a year or two now. It would be - so if you go to kind of Canada and Hudson Bay, the high latitude one is the Haughton Crater I talked about.

Man 10: Yes.

Dr. Gordon Osinski: The Teutonic structure is in Victoria Island, which is almost due west of that one.

Man 10: Okay. So it's not shown. But Haughton Island, the one you talked about, that's the upper left, the northernmost Canadian dot there on the left?

Dr. Gordon Osinski: The northern most Canadian one and then kind of the furthest dot out to the left is the Avak structure in Alaska, which is below the Arctic Circle I think. Yes.

Man 10: Okay. Thank you.

Dr. Gordon Osinski: Yes.

Man 11: Doctor the clustering they have in Europe there and also in Australia. Do we know, since they're so packed together, do we know if they're related at all?

Dr. Gordon Osinski: So the reason the main answer as to why there is a clustering -- also in North America to a certain extent -- is because that's where we find the oldest rocks on Earth. So these are shield areas where the rocks are two and three billion years old and it's more that you - there's just a longer record that hasn't been destroyed for us to find.

Now, there are subtleties in this too because there are large areas of let's say, let's take Central Africa where it's too dangerous to go. And so no one is looking for impact craters. Or in the tropical rainforests, you've got much less chance of seeing something for more that's a few different things, but it's really driven by kind of the geology of these regions more than anything .

Man 12: Sure.

Dr. Gordon Osinski: Yes.

Man 11: You said earlier that you didn't think that the craters on the Moon would actually kind of cause volcanic activity. But there are some things called concentric ring craters, which are rather small considering other craters nearby

but they do have a central inner ring itself that's not like an uplifted reflection ring form a regular crater basin.

And according to what I was reading, this February in Sky and Telescope, they're suggesting that there was a lunar - excuse me, a lava plug that kind of welled up from the inside of the crater and then kind of collapsed like a soufflé in the middle, creating this central, very unique crater that can even be seen from telescopes, which afterwards I had to go look for myself and see it myself. But they're there.

And do you agree with that, or do you think there's something else going on?

Dr. Gordon Osinski: So I'm not too familiar with the term central ring. I believe maybe what was discussed there is the so-called multi-ring craters which Orientale for example on...

Man 11: No the Orientale is like 900 kilometers across.

Dr. Gordon Osinski: Yes.

Man 11: These guys are really small. These are only in the size of regular, simple craters, but they have this obvious ring that can be seen. I'm looking at one from the far side, which they say is only 11-1/2 kilometers in diameter.

Dr. Gordon Osinski: I will maybe reserve my skeptical-ness and have to go check this out, actually. I would say unless, again, having magma kind of well into a crater long after it formed I think has definitely been shown to be the case.

But a crater that small kind of causing that, I'm a bit skeptical of. But I'll maybe have to go and dig out this article or you can find my email and send it to me. I'll be interested to read.

Man 11: Sky Telescope February this year, 2015.

Dr. Gordon Osinski: February this year, Okay.

Man 11: Bob King is the author.

Dr. Gordon Osinski: I will take a look.

Amelia Chapman: Maybe we can have just one more question. Then we can let our speaker head off to his next engagement.

Dr. Gordon Osinski: Yes.

(Adrienne Provenzano): Hi this is (Adrienne Provenzano). I'm late joining, so I'm sorry this is a repeat question. But I'm wondering - I had a chance to see the (unintelligible) crater up close earlier this summer, which is great. And I'm wondering to what extent are there still undiscovered craters on Earth?

Dr. Gordon Osinski: That's a great question and it actually - I've still got this slide of the map of craters on Earth -- slide 15.

(Adrienne Provenzano): Okay.

Dr. Gordon Osinski: One of the great - so the Scandinavia if you go this clustering literally in Sweden, Finland, and Norway, if I was to show this map from about a decade ago or maybe 15 years now, there was I think half a dozen, maybe a dozen

craters known. They had a systematic program to go out and find impact craters. And they found another 20 or so.

And so they're quite eroded, quite difficult. They don't show up very obviously in satellite images. But if you translate that distribution just to the shield areas, for example, of kind of Canada, there should be quite a few more to be found. Several tens of craters I would expect are still out there, kind of on the surface of the Earth, and of course many more -- probably hundreds -- that are buried that it would take a random drill core to come across it.

So yes. And I mean, well in this year so far there's another new crater discovered in Sweden and one I can't quite remember where. So we're adding a few a handful of craters each year. And there should be more.

(Adrienne Provenzano): And are there many that are generally accessible? Because it's great to just stand on the rim of a meteor crater, but how many others could somebody do that at?

Dr. Gordon Osinski: Yes I mean I think we've found the easy ones, the obvious ones.

Accessible to a certain extent, I think the best example of that is in the US, actually, is this Santa Fe structure, not far outside Santa Fe, New Mexico. It's a very old structure and there's no kind of visible circular form, but I've seen pictures of beautiful shatter cones. And apparently it's on hiking trails that have been used for kind of decades and someone at some point just decided to take a bit of a closer look.

So that's an example where - that was I want to say maybe five years ago it was discovered. But it's eroded and you need things like shatter cones to find them.

(Adrienne Provenzano): Thank you.

Dr. Gordon Osinski: Yes.

Amelia Chapman: Well I'd like to thank everybody for joining us today, and most especially like to thank Dr. Osinski for sharing his wonderful stories and answering all of our questions today.

Man: Yes great presentation. Thank you

Men: Thank you.

Woman: Thank you.

Dr. Gordon Osinski: Thank you. Been a pleasure joining you.

Woman: Very much.

END