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## **Effects of Large Impacts on Crustal Structure and Basin Evolution: Example of the 65.5 Ma Chicxulub Impact Crater\***

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### **Abstract**

Large terrestrial impacts permanently modify local hydrology, mineral content, basin evolution and crustal structure. Modeling shows target material in a large impact, such as the Chicxulub impact 65.5 Ma, behaves as a fluid for 10-100s due to the 10-20 km/s impact velocity. Initially a transient crater forms 100 km in diameter by 35 km deep; rebound causes the center of the crater to uplift above the Earth's surface and then collapse forming a large basin containing a ring of elevated topography known as a peak ring. 3D seismic refraction data show that the Moho is upwarped ~1.5-2 km and the granitic basement remains uplifted by ~10 km within the center of the crater. Overlying this central uplift, and merging with the topographic peak ring, is an impact melt sheet that is imaged on seismic reflection data. As gravity becomes the dominant force, the transient crater walls collapse inward widening toward a final crater diameter that includes ring faults mapped at radial distances >125 km from the crater center. Interior listric normal faults move 5-10 km wide, intact blocks into the crater center; the blocks arrive prior to the final outward collapse of the central uplift and are emplaced partly beneath the peak ring. Above the slump blocks, the central basin of the crater is overlain with breccia from airfall and ground surge that was dominated ocean re-entry into the crater. This effect was enhanced at Chicxulub due to the impact being on a continental slope where the deep-water part of the crater never formed a topographic barrier to entry by tsunamis. The final crater floor remains topographically lower than the surrounding region forming a basin dominating the depositional setting for 10s of Myr. Remnant heat of the impact likely generated a vigorous hydrothermal system for up to 1-2 Myr into the Paleogene while the reformed crustal structure and high-porosity impactites continue to drive local hydrology today. The hydrothermal system and interaction of the

impact melt sheet with the peak ring breccias may result rich mineral deposits, such as those that found in other terrestrial impacts; this same environment likely fed a subsurface chemosynthetic biosphere. Consensus is that the pristine peak ring and melt sheet within Chicxulub are excellent targets for drilling to understand impacts as a geologic process.

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# Effects of large impacts on crustal structure and basin evolution: Example of the 65.5 Ma Chicxulub impact crater

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University of Texas at Austin

Institute for Geophysics

Jackson School of Geosciences



Notes by Presenter (for previous slide):

Before I can speak about the Chicxulub Impact Crater itself, I need to tell you about the concept that one of the largest extinctions of plants and animals on the planet occurred due to an extraterrestrial event. I am going to tell you a little bit about the organization that sent me here and specifically about ocean drilling. I will come back to that at the end of this talk because drilling in the impact crater is the next step of our research.

Image: A planetoid plows onto the primordial Earth, during the eons of time when conditions were ripe for the development of life. It is possible that life of kinds unknown to us appeared repeatedly only to be destroyed in collisions like this one which could 'rework' the entire surface. Fortunately, the average size of debris declined sharply through geologic time, but the supply of wayward rocks a few kilometers in size is by no means exhausted. Credit: Don Davis, NASA.

# With thanks to:

Gail Christeson



Jo Morgan, Mike Warner, Gareth Collins



Jaime Urrutia



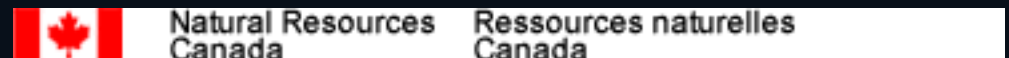
Penny Barton



Christian Koerberl



Richard Grieve





# CRATERING: A UBIQUITOUS PROCESS



Earth should have 25X more craters  
than the Moon

$3 \pm 2$ , 20 km or greater diameter  
craters every 1 Myr

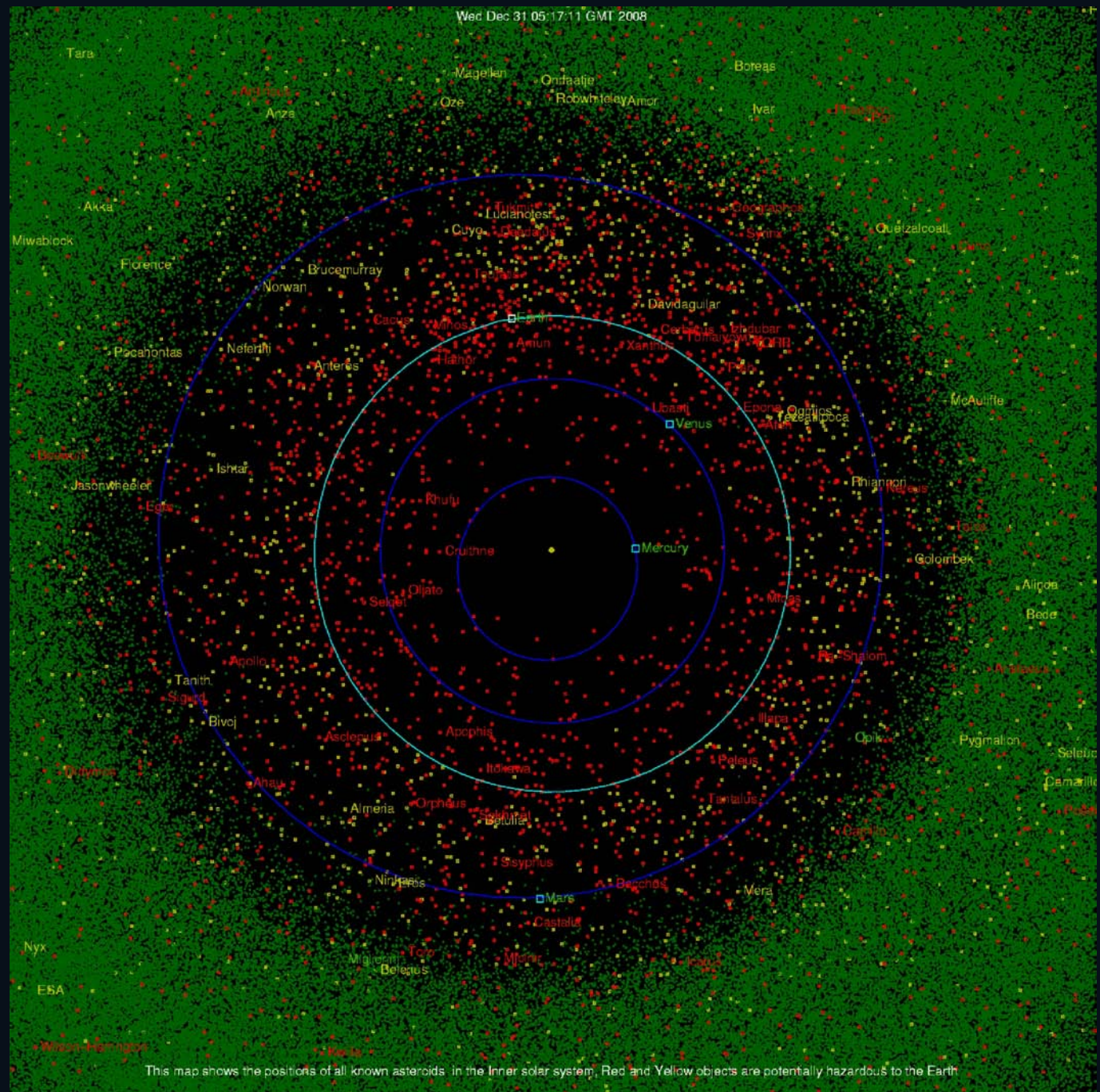


Only ~175 discovered (see <http://www.unb.ca/passc/ImpactDatabase/>)

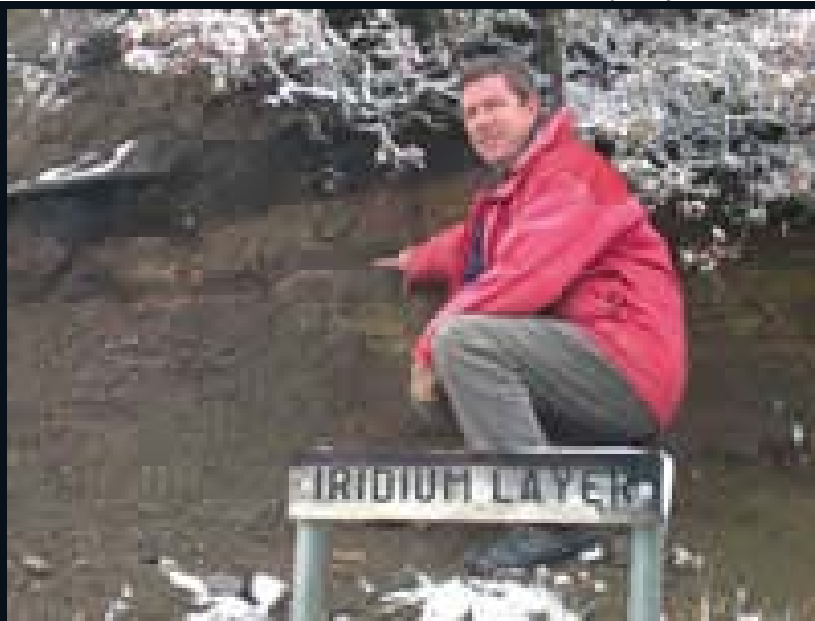
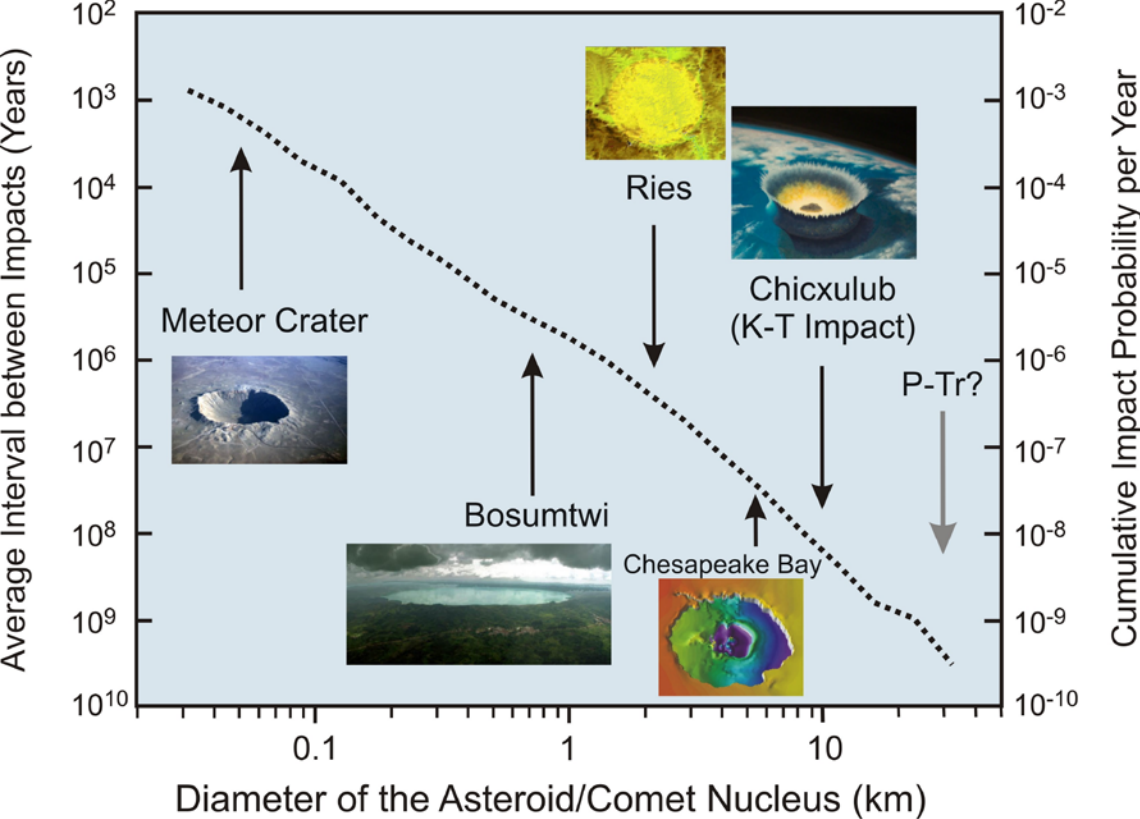


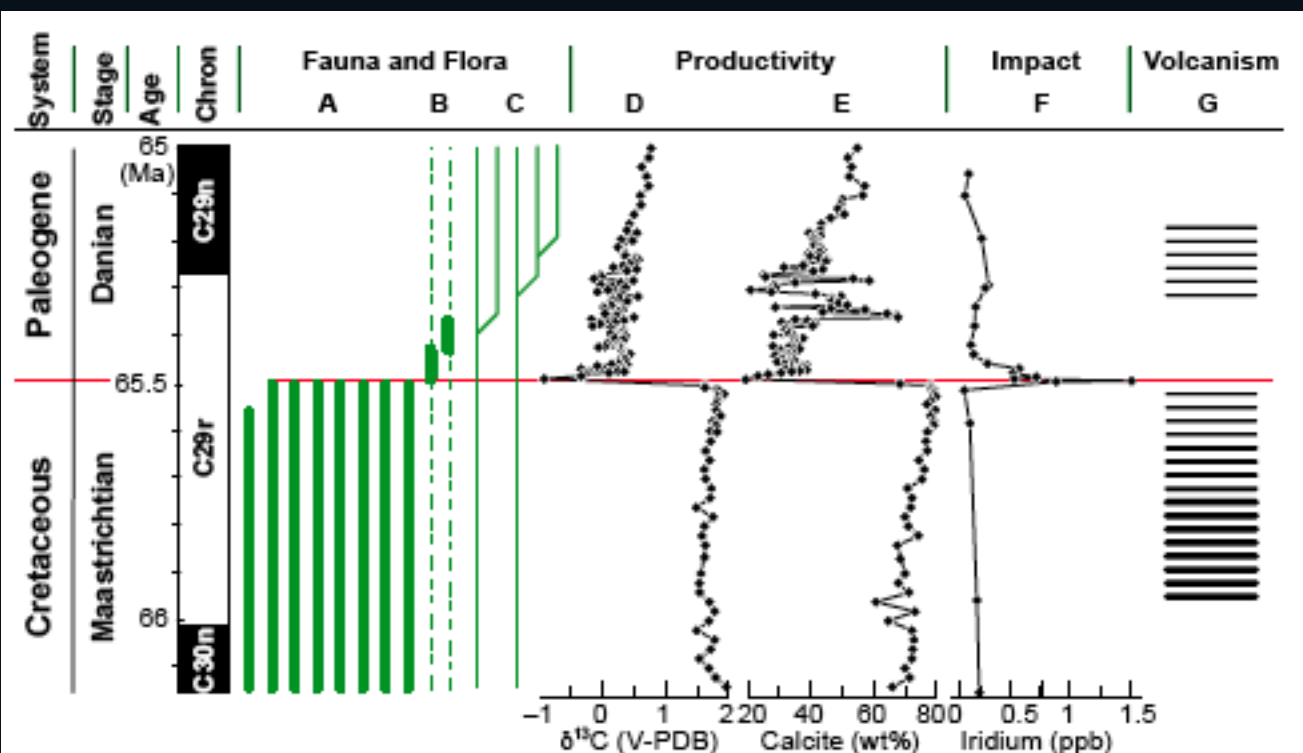
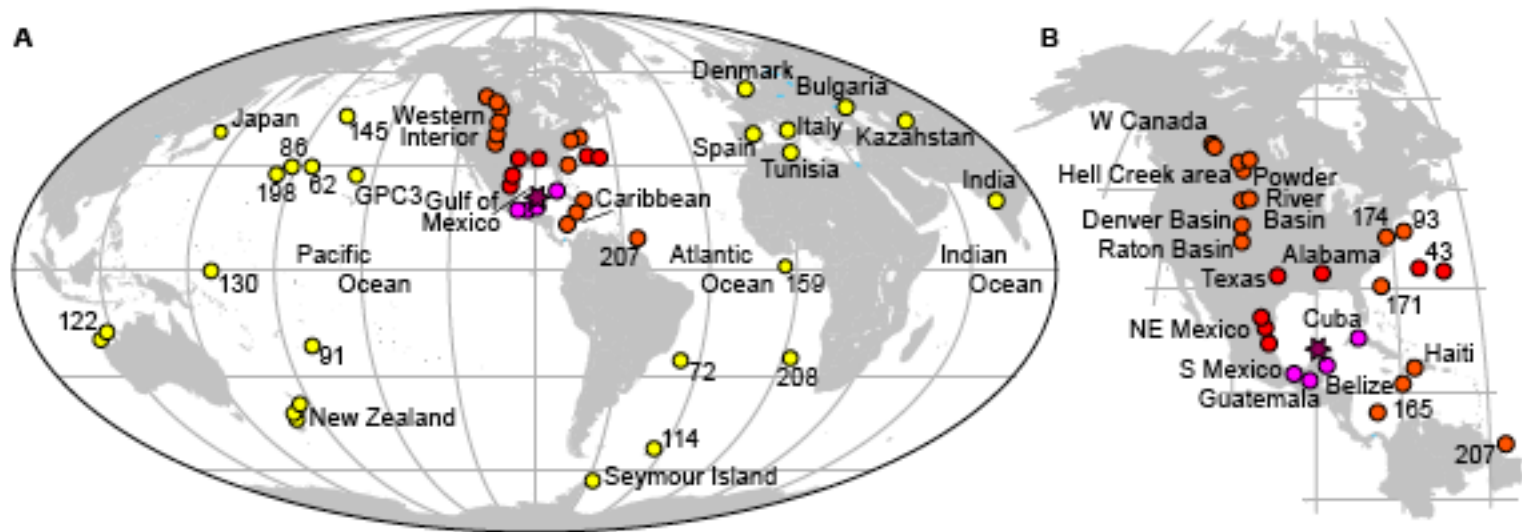
# Our Neighborhood

Lots of  
potential to  
leave a mark!

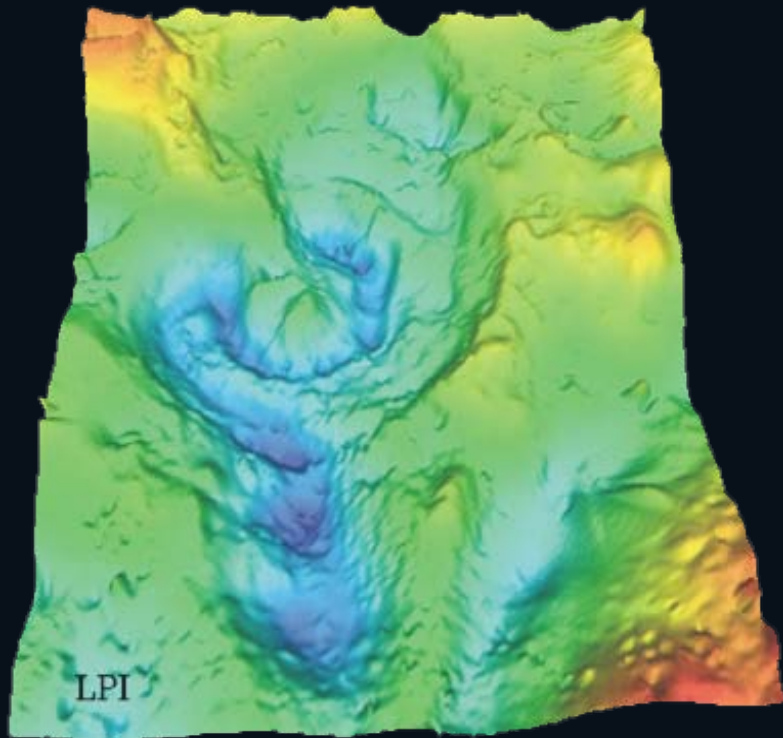












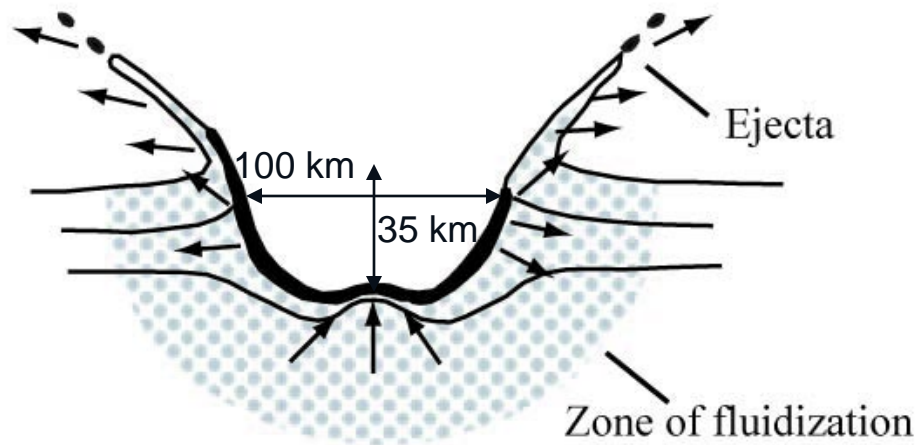
Notes by Presenter (for previous slide):

Shown here is an image of a gravity anomaly map over the top of the feature. This shows very slight differences in local gravity due to differences in rock densities. This was originally interpreted to be a volcano. It was discovered and drilled by the Mexican National Oil Company in the 1960's in the hope of finding oil. Instead, they found some odd rock and gave up on the site, forgetting about it for the next 30 years.

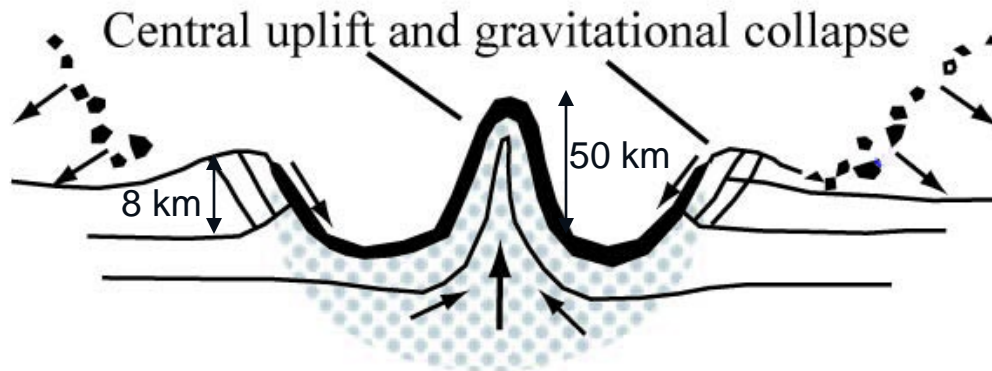
In the 1990's, Alan Hildebrand and his colleagues stated that this feature wasn't a volcano, and had the morphology of an impact. Some positions on the feature with incredibly low density are what you would expect with the creation of a lot of breccias (broken, crush-up rocks with porosity), which occurs in an impact. Kevin Pope noticed that the water-filled sinkholes, cenotes, where Mayans used to perform human sacrifice, have an interesting shape along the Yucatan Peninsula in Mexico, where they rim some kind of feature in the subsurface. This feature is a large control on the hydrogeology of the Yucatan Peninsula.



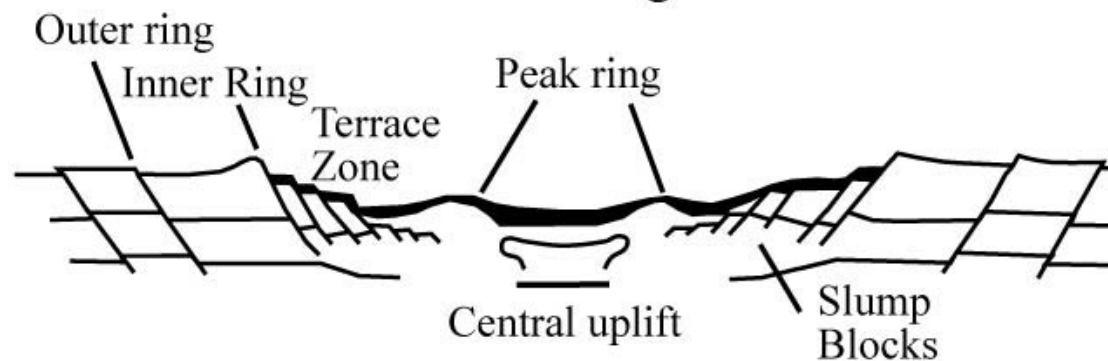
# A Excavation and formation of transient crater



# B Central uplift and gravitational collapse



# C Final multi-ring crater



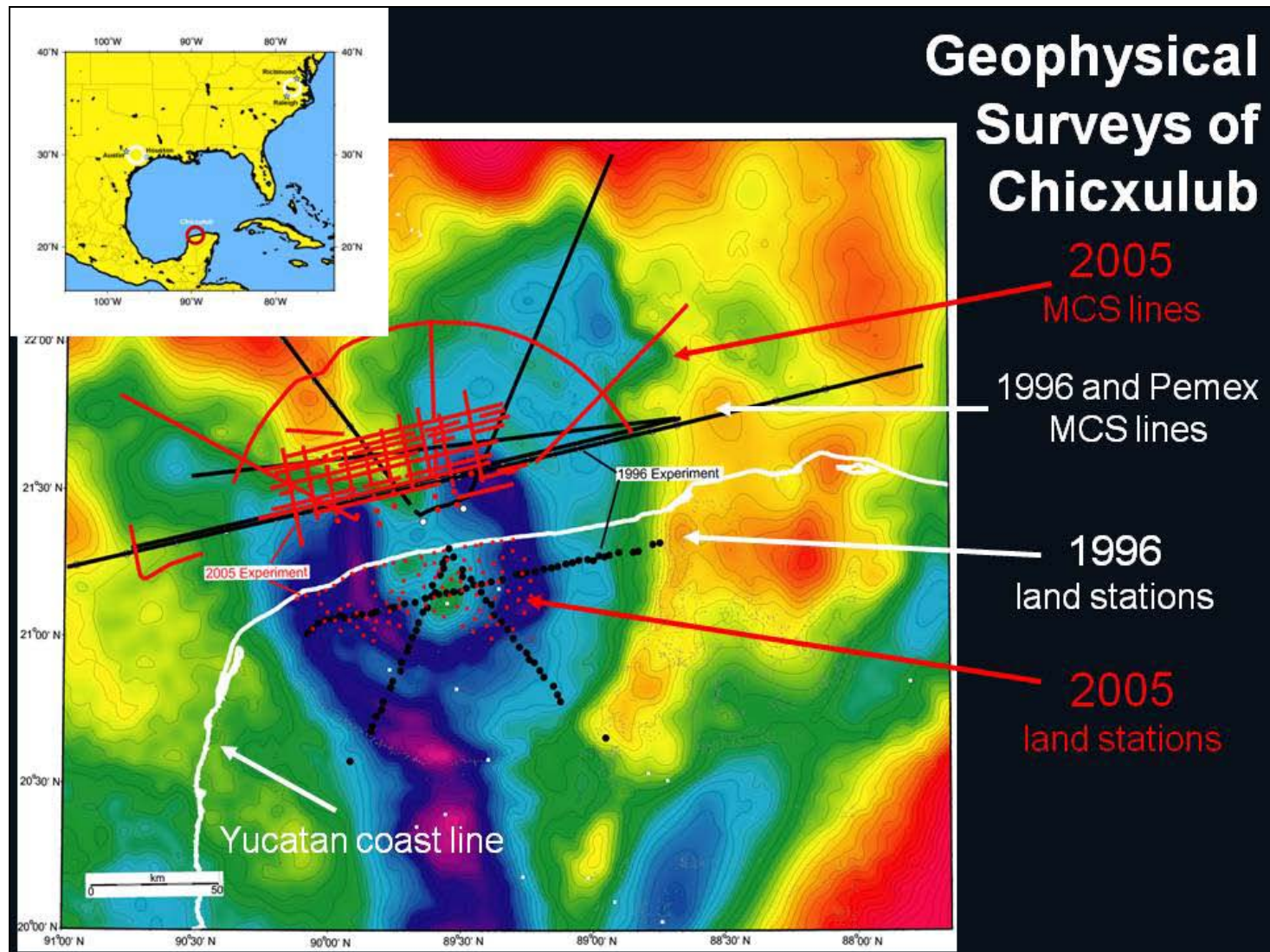
All in 300  
to 600 sec!

Notes by Presenter (for previous slide):

How do we get to that final structure with an impact? Because of the phenomenal speed of the impact, the meteor was traveling about 20 kilometers per second, anything they hit acts like a liquid. This is called acoustic fluidization. Basically, things are hit so hard that they flow like a liquid, effectively deforming in a brittle fashion at all scales.

Initially, it is very much like a rock being thrown into a pond. It first opens up a hole, the transient crater. It would have splashed up the rims of that initial hole, probably as high as 8 kilometers, the height of the Himalayas. This would have been temporary. The earth abhors a hole like that and it starts reacting. The center part, which is still moving will splash upwards, in this case 10,'s of kilometers into the air, the top of which probably reached escape velocity (it left the earth's atmosphere). The sides would now start behaving in a brittle fashion, forming big faults that would start collapsing inward to fill in the hole with these slumped terraces. Finally, this will collapse down and out and submerge back underneath, leaving a central uplift with a peak ring.

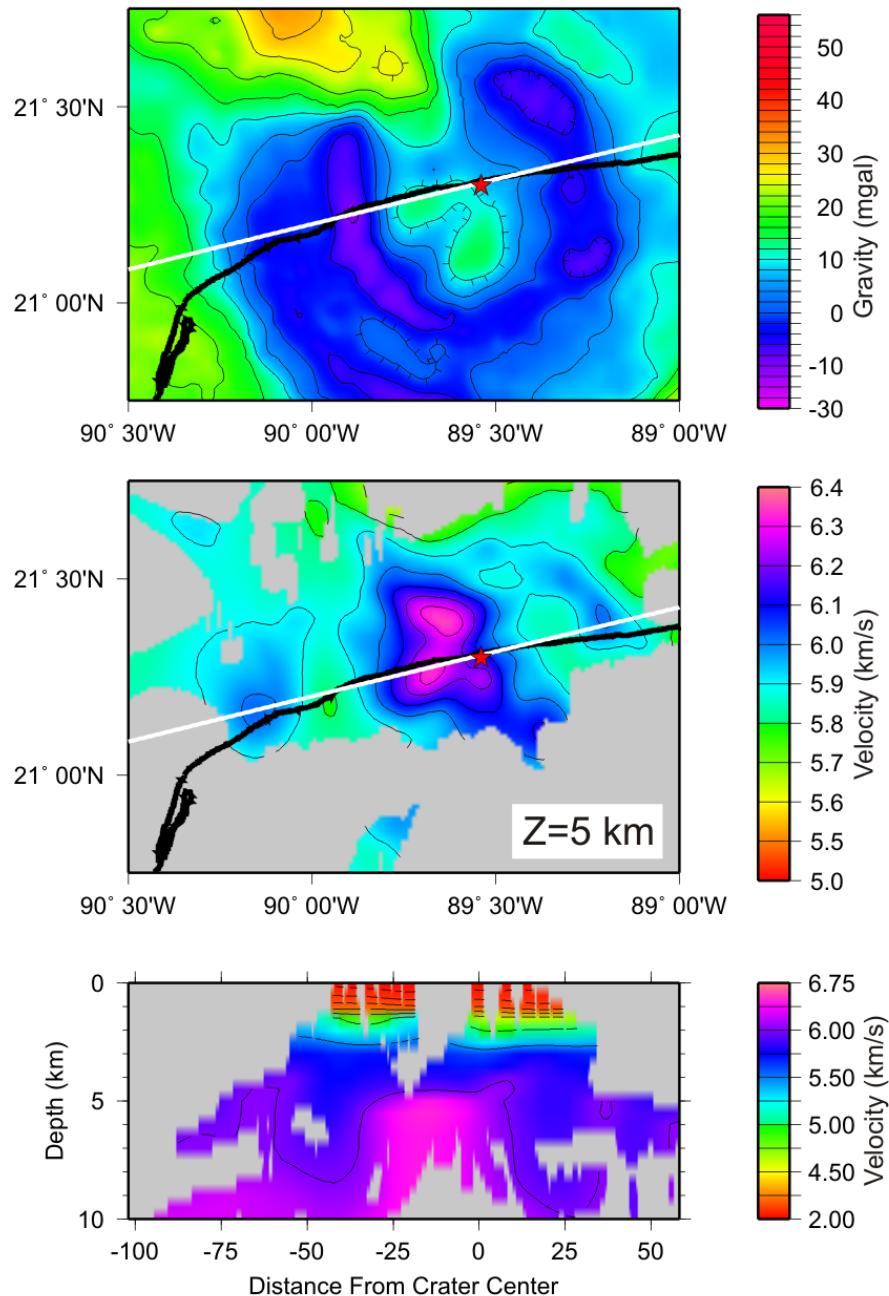
You will notice this is a big jump. That is because we do not actually know the processes from the models and the physical experiments to the actual crater structure, and those are some of the questions we still have. The amazing thing is this all happens in probably less than five minutes. It is an amazingly powerful phenomena.



Notes by Presenter: In 2005, we collected a lot more geophysical data. Offshore, we collected seismic reflection data and we placed seismometers on the seafloor and on land, which are used to listen to earthquakes. The seismometers were used to gain information about the volume and the density of the rocks in the crater in order to understand the details of the impact.

# Refraction Results

- Structural uplift near the crater center (red star) is constrained by gravity and velocity data.
- The uplift is offset west of the crater center.
- Velocities of 6.3 km/s occur at a depth of 5 km. Outside the crater these velocities are found at a depth of 15 km, suggesting a vertical uplift of ~10 km.

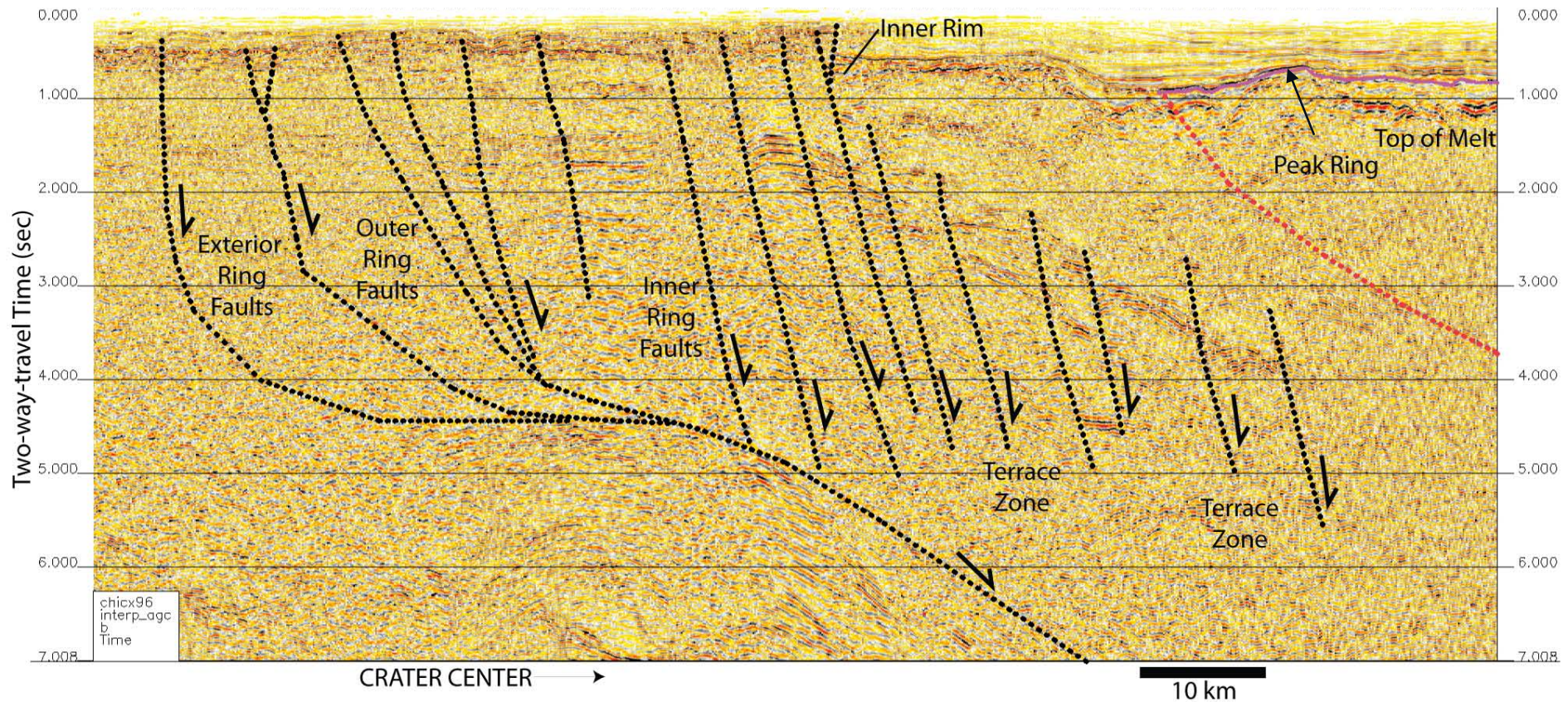




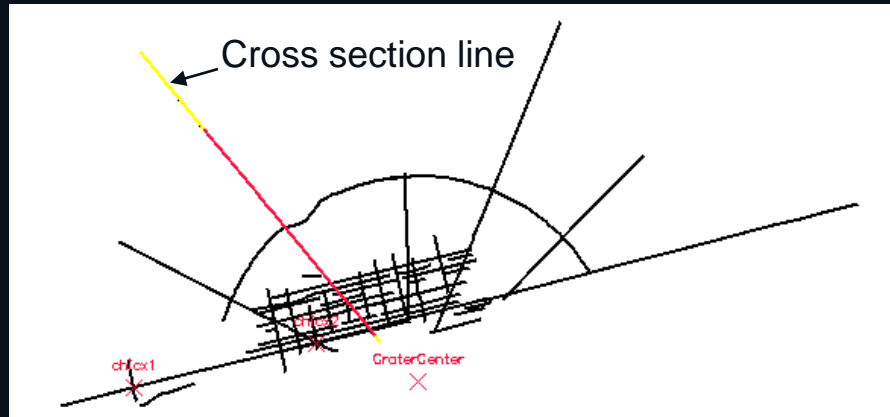
Notes by Presenter (for previous slide):

On the top, this shows a map of the uplifted part of the crater using models built from gravity data. The middle image is a map-view slice through our volumes of the earth, which we now know the velocities of, at about 5 kilometers depth. We see contours that show us very high velocities in the center of the crater. That may not seem impressive, but consider the velocities. 6.5 km/s is the velocity of granite at mid to lower crustal depths. Next is a cross section through that same volume. This shows that these velocities are normally around 10-15 km depth, but here they have been uplifted to 5 km depth. In other words, we have had about 10 km of vertical motion in the earth at the center of the crater, which is the “splashing up” that we see. This is direct observational proof that Chicxulub is an impact crater.

# NW Cross Section through Crater



## Reflection Results



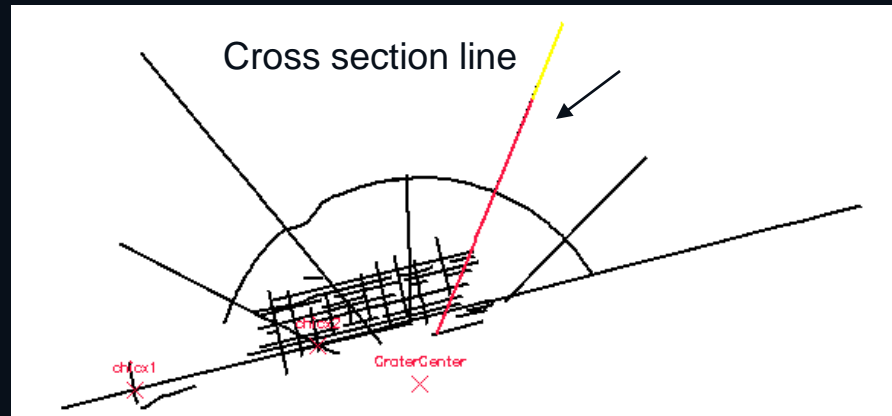
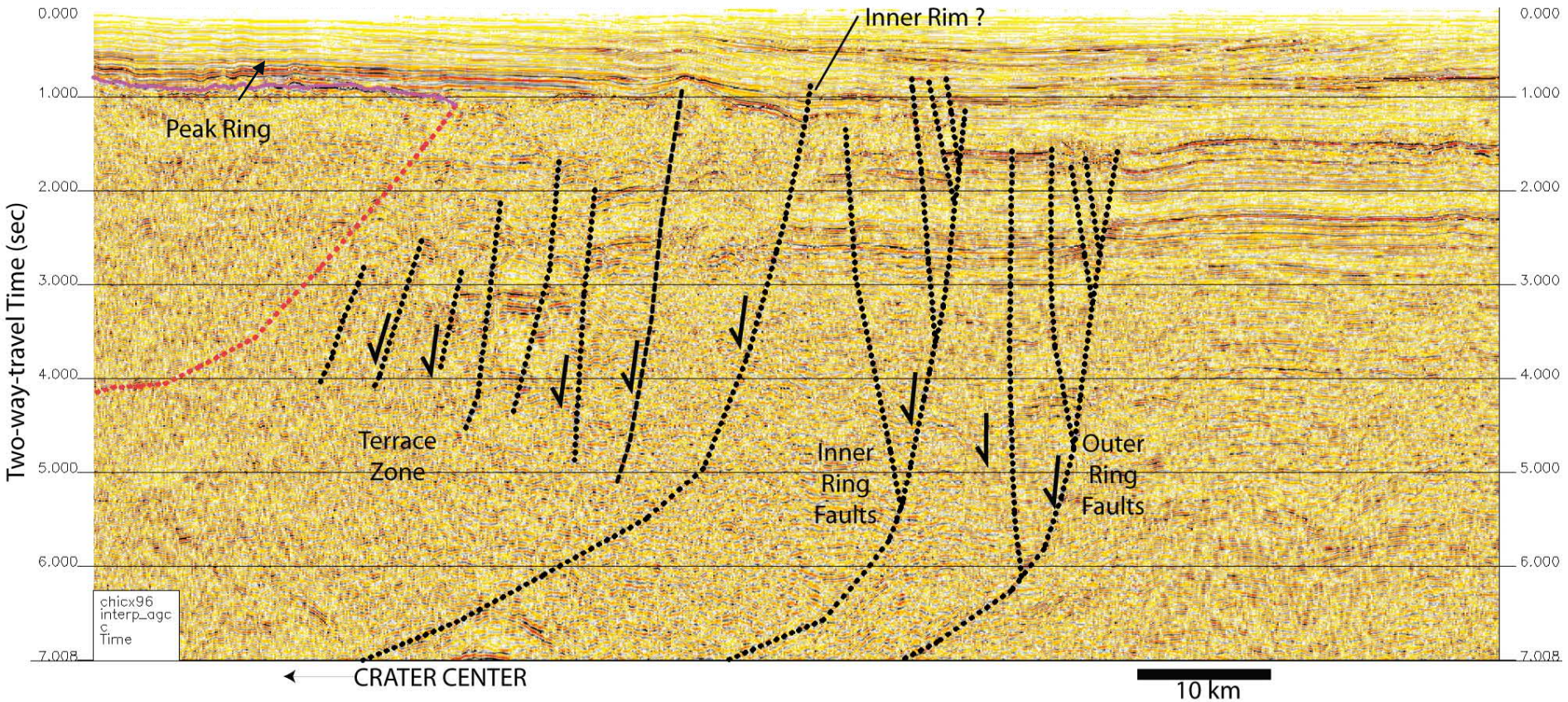
Gulick et al.,  
Nature  
Geoscience, 2008

Notes by Presenter (for previous slide):

What about the reflection images of the crater? Shown here is the peak ring that splashed outward and the top of the melt sheet in the middle. We see a layer of evaporites (salt deposits) stepping downwards into the center of the crater beneath the peak ring. We also see many faults breaking up the subsurface, up to a 250 km diameter distance away. On one side, the faults seem to merge into a low-angle fault, a feature that goes down towards the center of the crater. The other thing we notice is a well-defined rim of the inner crater, which we also saw on the gravity map. This is caused by the sediments filling in the center.



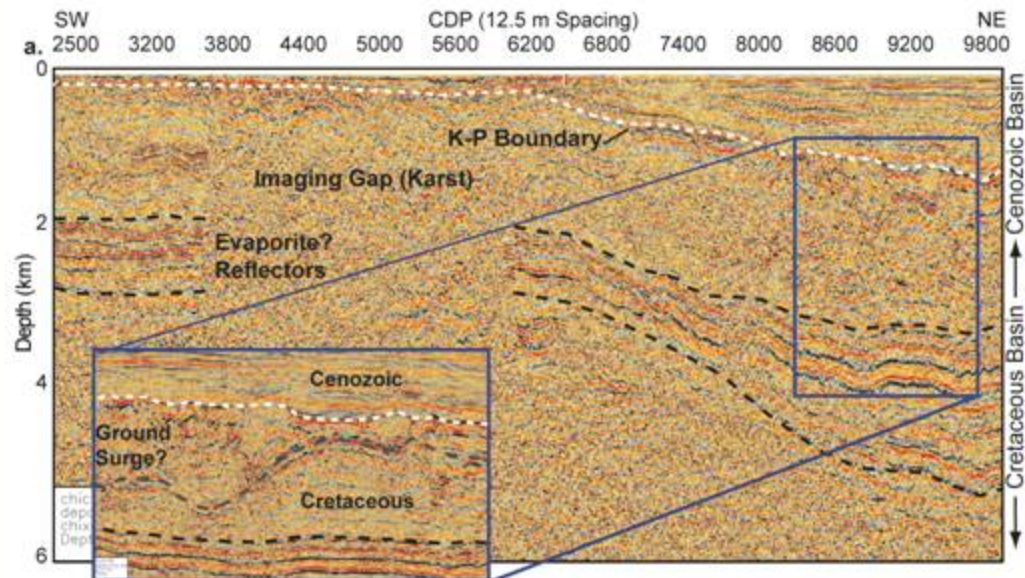
# NE Cross Section though Crater



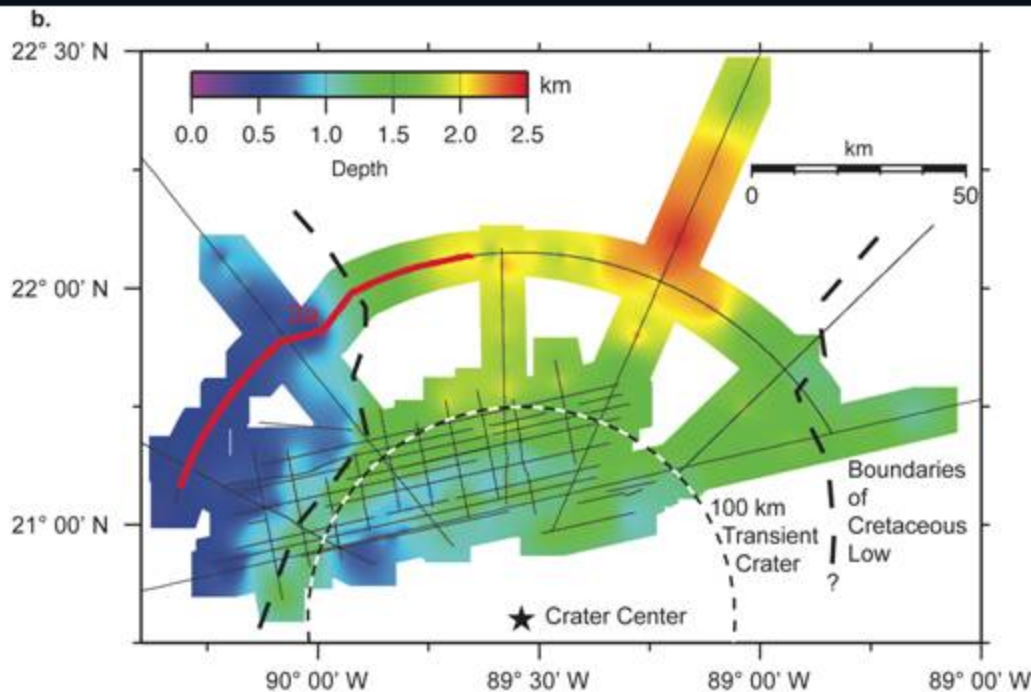


Notes by Presenter (for previous slide):

If we look at the northeast part of the crater, we see something very different. It still appears as a circle on the surface, but the subsurface shows it to be asymmetric. Here we do not see the crater rim, and the infilling sediments just keep on going towards the northeast. It looks like there was already some kind of basin providing a lot of sediment, and it simply continued to fill in after the impact. Also, notice that the material that slumps in towards the middle doesn't go nearly as deep as in the previous image, and the faults themselves have a different shape, similar to nested bowls rather than merging into one feature.



Cross-section of margin of Chicxulub crater

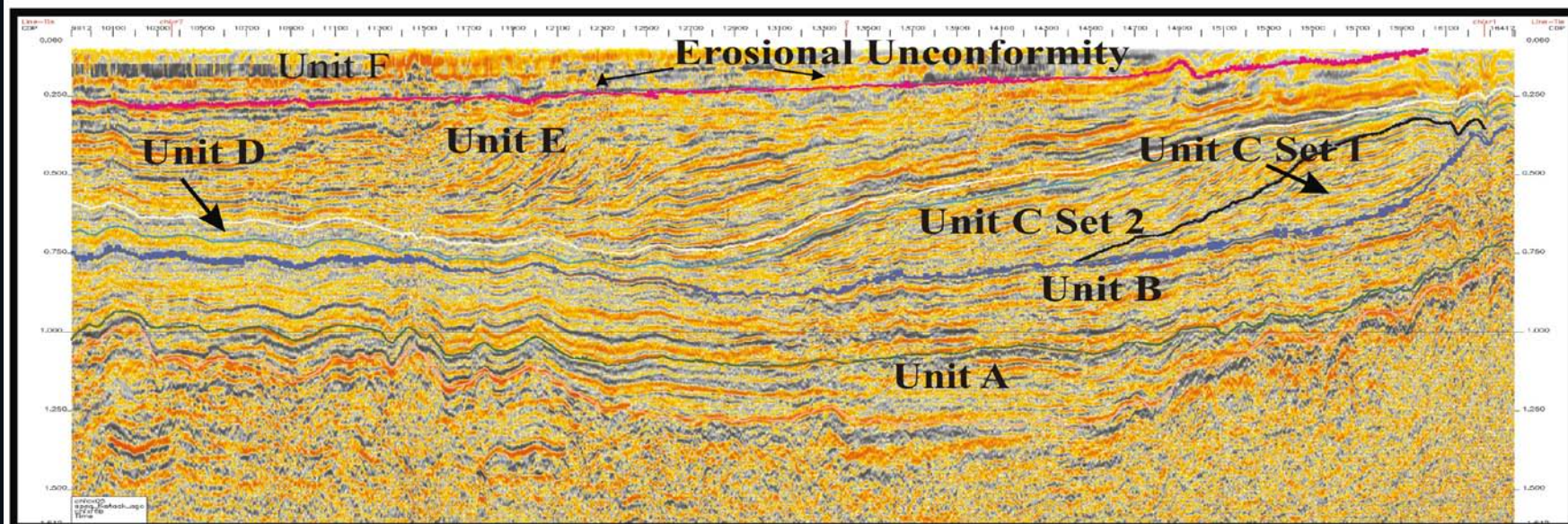
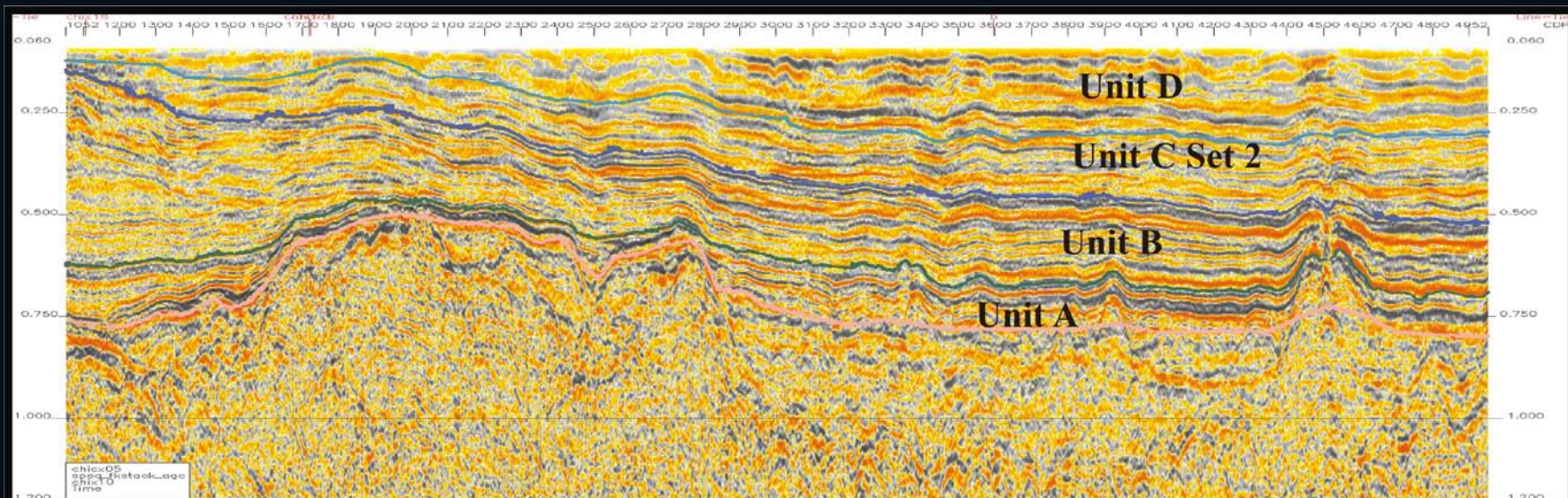


Map view of depth to Cretaceous ocean floor

Notes by Presenter (for previous slide):

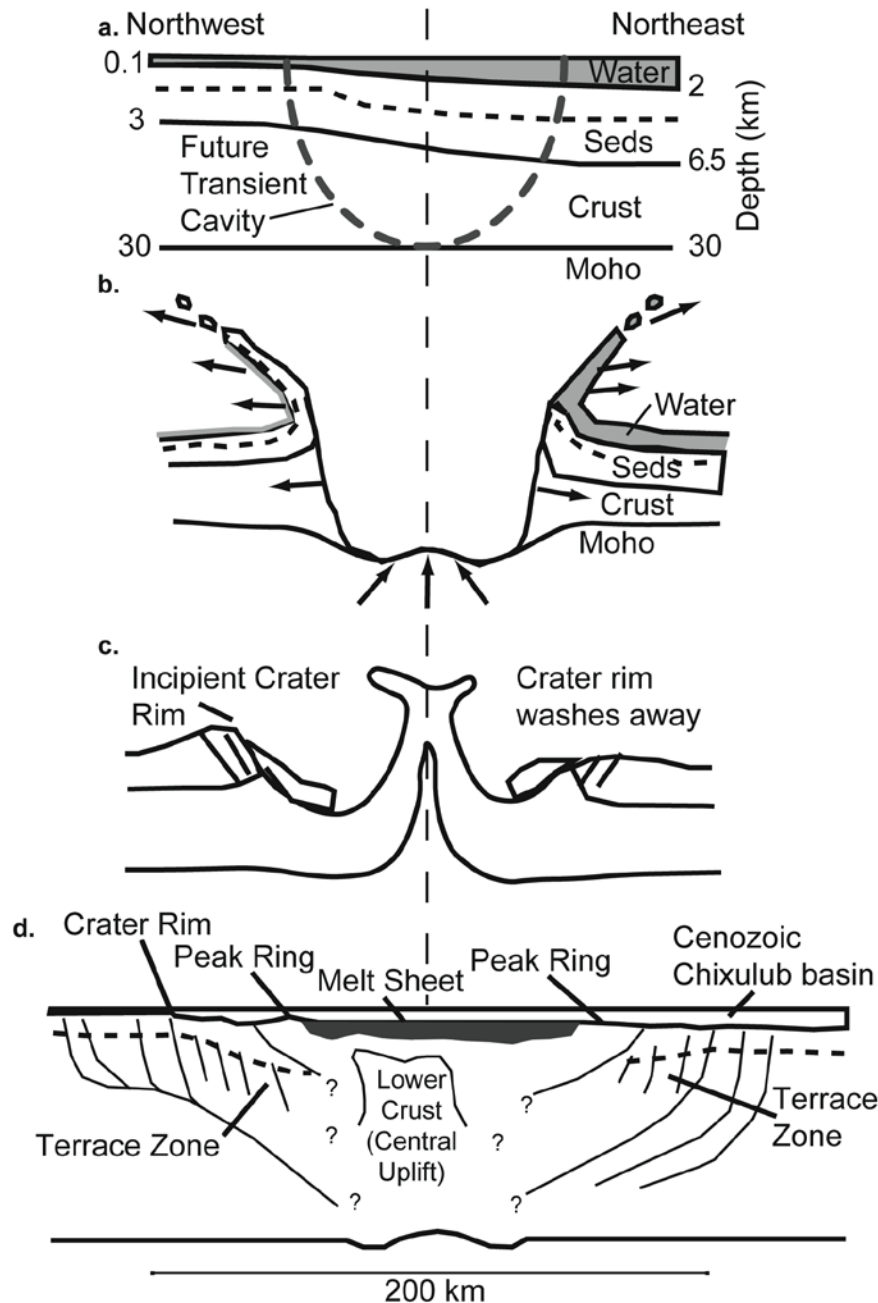
So what do the Chicxulub observations tell us? What do all these asymmetries in the subsurface tell us about the impact itself? Here is a seismic reflection line that wraps around the edge of the crater, but outside of the transient crater, the area initially blown open. What you see are evaporite reflectors that thicken as you go to the northeast. That is another way of saying that a basin was already present, as we see the continued thickening of the deposits in that direction. The white, dashed line is the interpretation of where the seafloor was at the K-T boundary. It also deepens into that same position. The seafloor was not flat, and the lower image shows the depth of the reconstruction of the seafloor at the end of the Cretaceous. We can see that west of where the impact struck the depth was as little as 100 meters. To the east, it was as deep as 2.5 kilometers. So the area the impact hit was a slope. That means that the area that was vaporized and ejected may have had as much as 650 meters of water in it, not the shallower depth we thought before.







# Structure



- Impact resulted in a 100 km transient crater that collapsed into the 200 km final crater
- Asymmetries result from target structure rather than meteor trajectory
- Ring faults mapped at distances up to  $> 125$  km
- Basin forming event that governed stratigraphy until Oligocene

Notes by Presenter (for previous slide):

It could be that these shallow target products, these heterogeneities in the target, are driving some of the asymmetries we see in the final crater structure. On the left side of the model, we see almost no water and thinner sediments. On the right side, there is deeper water and much thicker sediments. So if that is the transient crater, on one side we see what we would expect, but on the other side much of the material that splashes out was actually made just of water. When an impact hits, anything it strikes is going to act like a liquid. However, after the impact is over anything that is a liquid is just going to wash away. In other words, if the uplifted edge was mostly made of water, it would just wash off. That means there would be no ring to observe on one side of the crater.

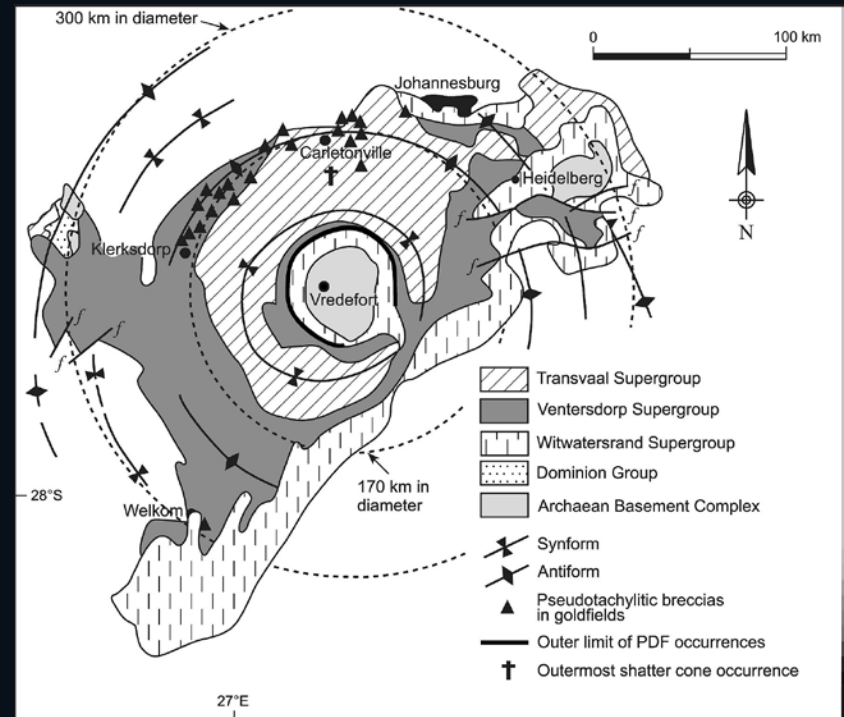
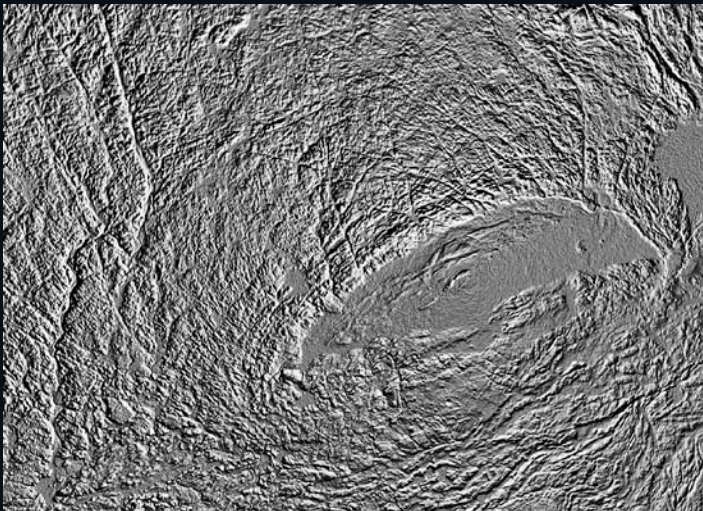
Things can also be deposited at different depths based on how thick the sediments are on one side of the crater or the other. Therefore, if you have heterogeneities in the target you can actually form very different features in the final crater structure. This tells us nothing about the way the impact hit it.

Another issue is that there was a lot of water, 650 meters, much more than the expected 10-20 meters that turned to vapor. While the water turned to water vapor, the sediments below it got vaporized or ejected as well. These sediments included the layer of evaporites (salt and sulfate) highlighted earlier. In this case, as much as 25% of these evaporites that got vaporized had very high sulfur content. If you combine sulfur and water, you get sulfate aerosol. Sulfate aerosol in the lower atmosphere will wash out as acid rain. We now have another mechanism for extinction. The acid rain could directly affect both the terrestrial and marine organisms. There has been a suggestion that those organisms that did not make it past the Cretaceous were those more susceptible to changes in the acidity (pH) in the marine environment. Sulfate aerosols in the upper atmosphere are an excellent way to cool the atmosphere. They reflect the sun's solar radiation and so have a net cooling effect on the planet.

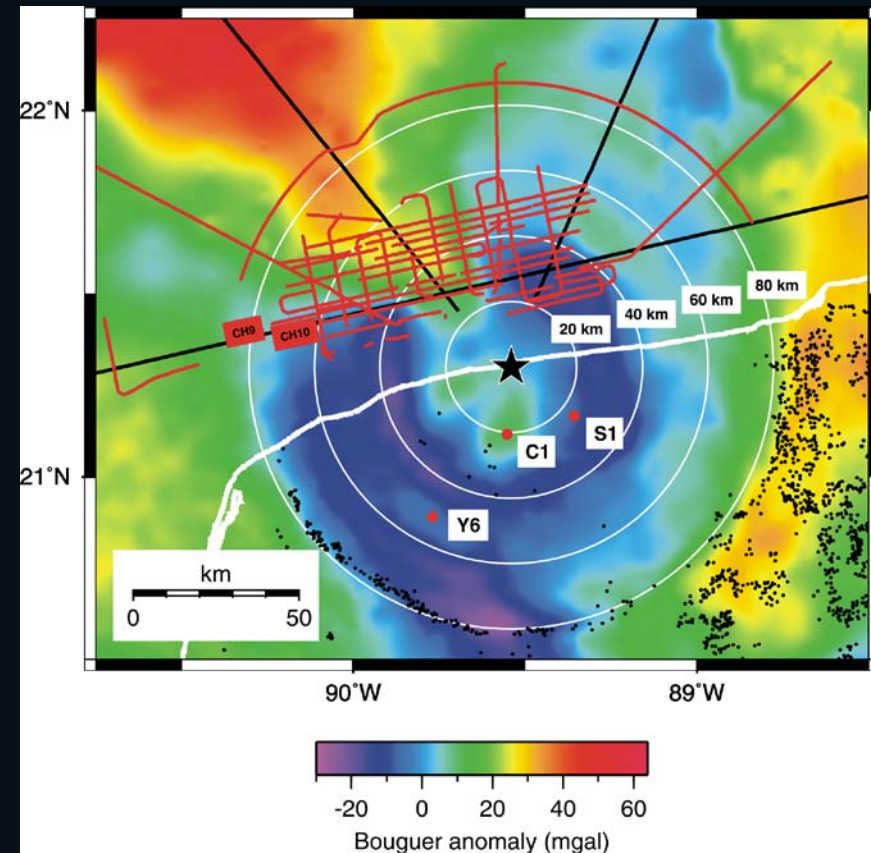
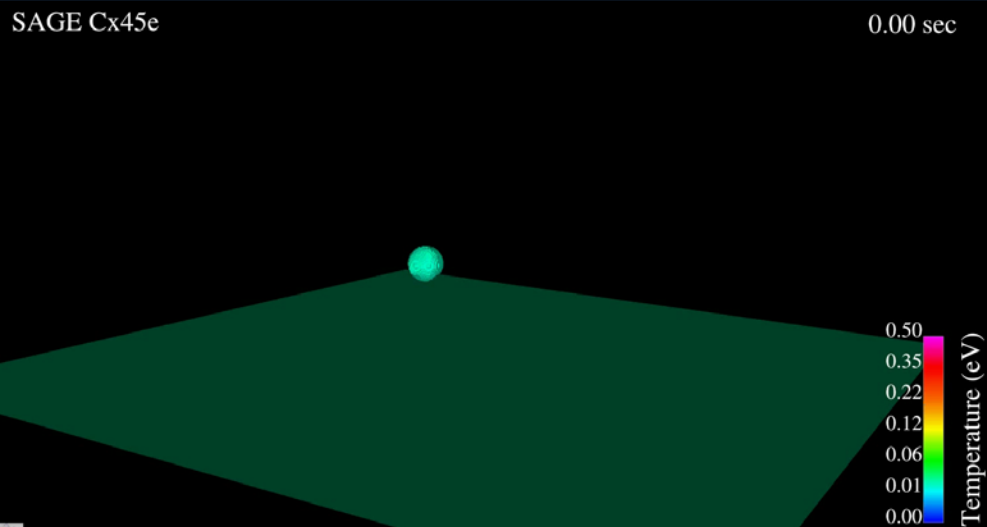
Right after this theory arose, another idea came up that the impact made dust travel all around the world and caused a "nuclear winter" that lasted a long time. This is wrong. There just was not enough dust blown out of that one spot to wrap the entire planet and make it go black and cause that mass extinction. This was figured out very quickly after the theory was advanced. What the impact may have done was kick off a chemical experiment that caused a cooling effect with a change of chemistry in the ocean through acid rain. It shows you the concept that if you kick the system you can change climate very rapidly so that it cannot respond quickly enough.

# Resources

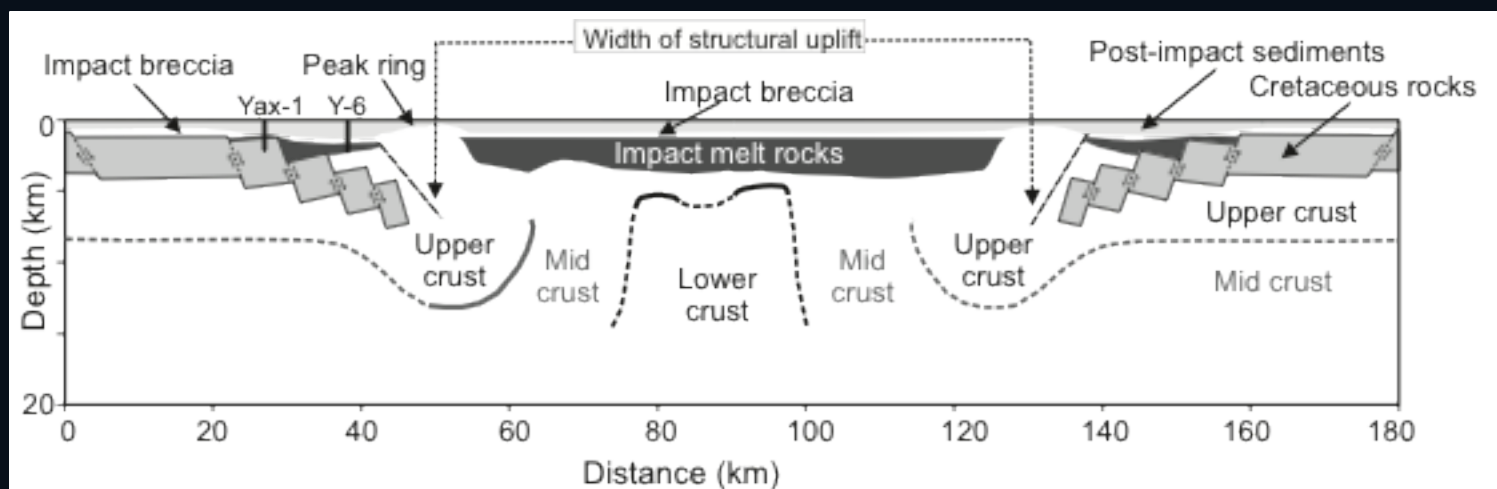
- Thermal perturbation & hydrothermal aftermath
- Ejection & Uplift
- Brecciation

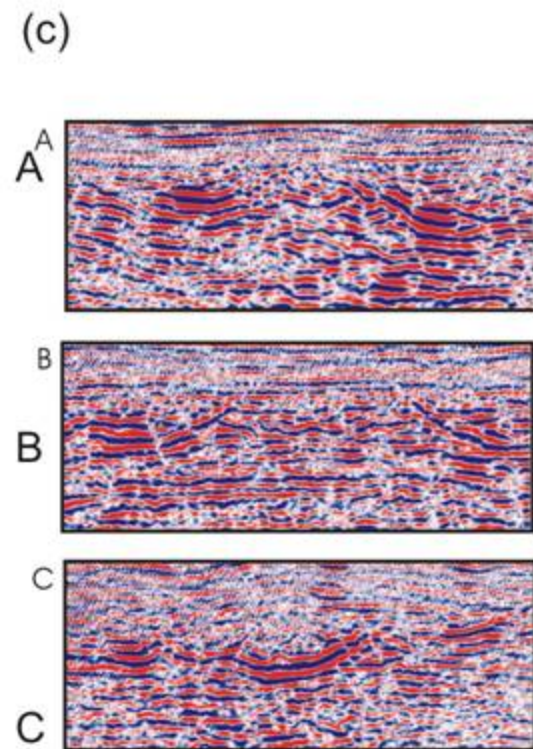
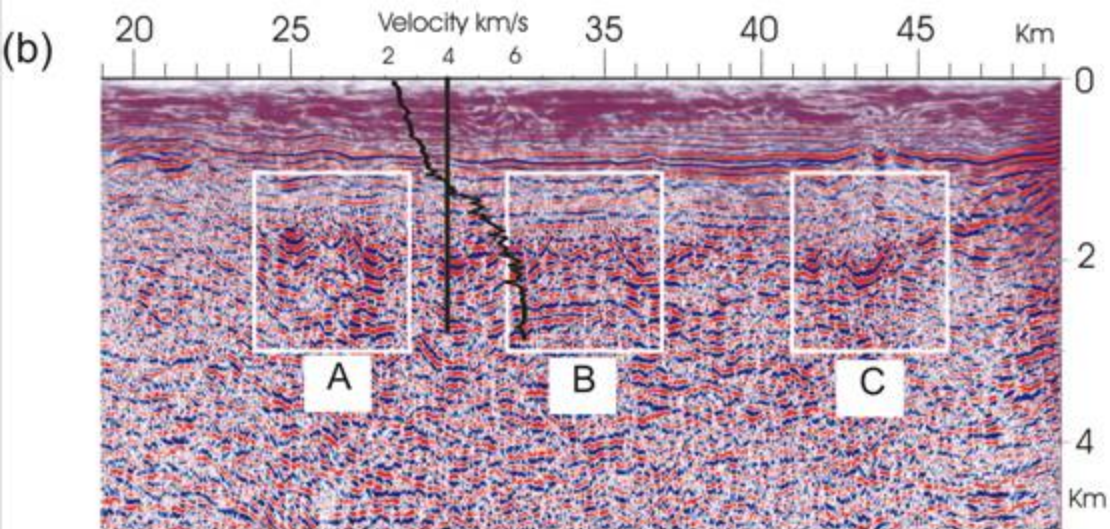
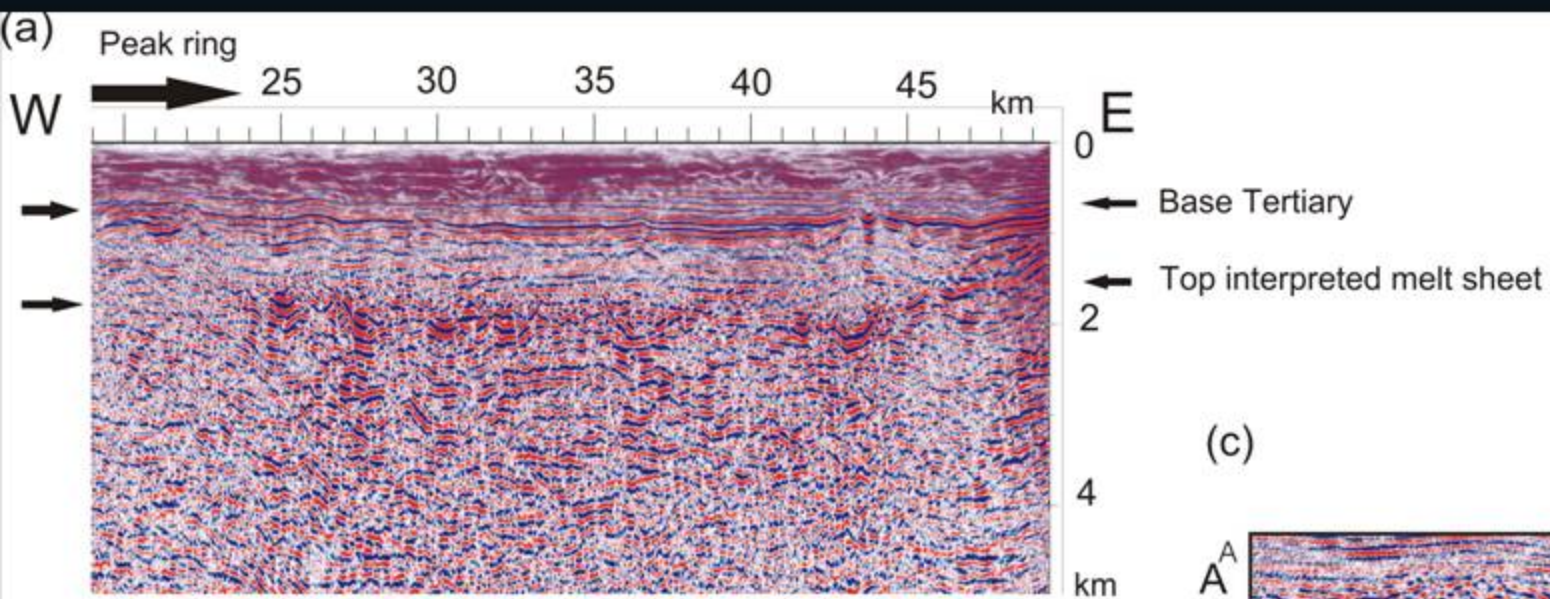






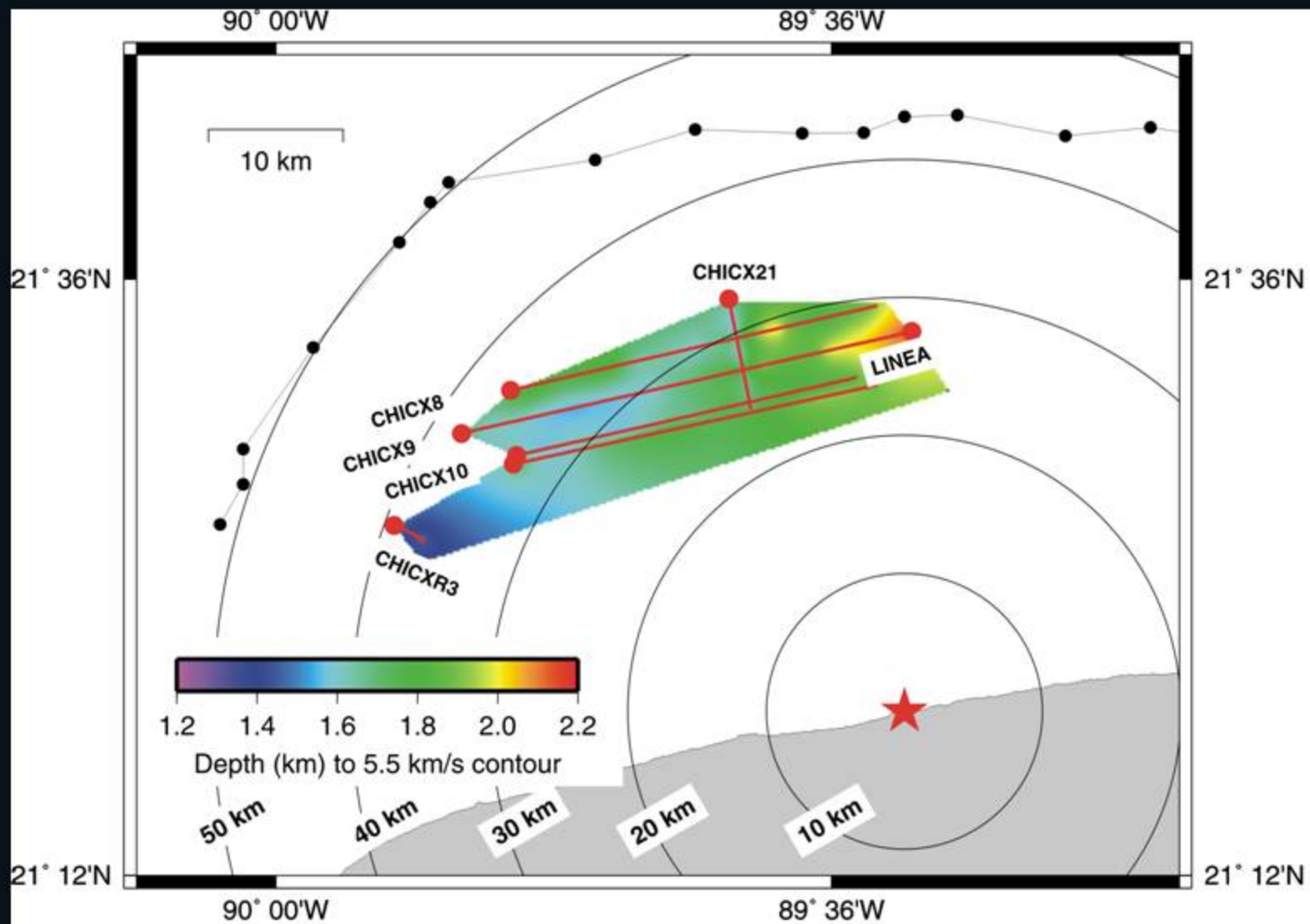
Vermeesch  
&  
Morgan  
2008





Barton et al in press





Barton, Figure 4, cdr

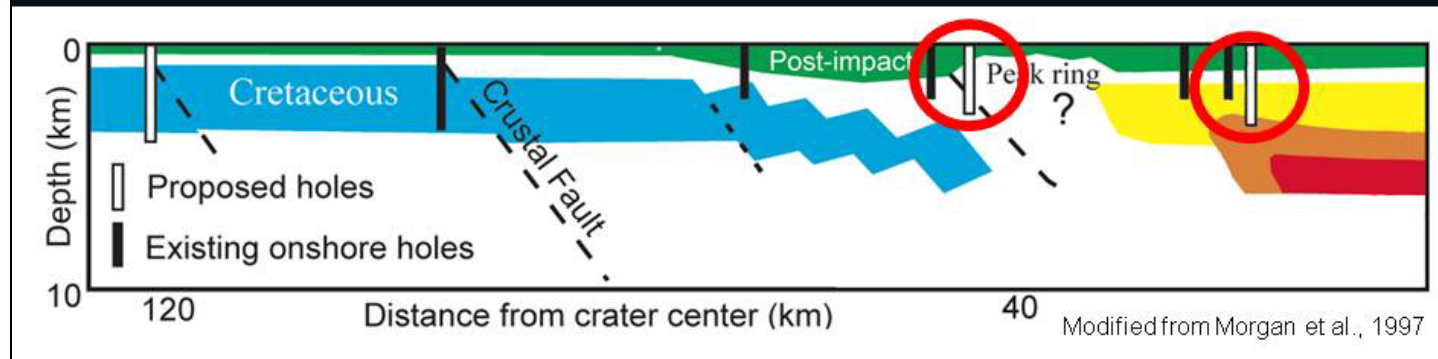




# Resources @ Chicxulub

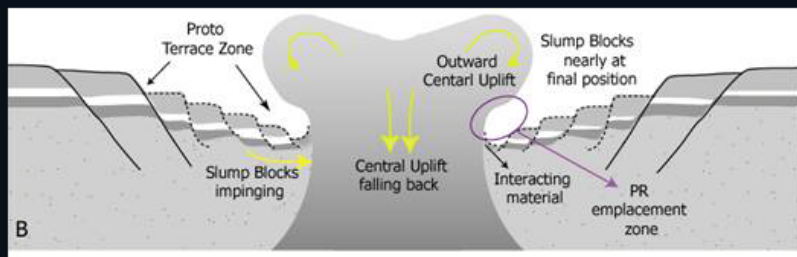
- Thermal effect at impact site likely rendered removed local hydrocarbons while basin isolation prevented migration
- Breccia from impact important reservoir rock at Campeche Oil Fields
- Peak Ring potential target for PGE or other hydrothermal mineral deposits
- Central uplift and overlying melt sheet unknown in terms of potential

# Future Research: IODP Drilling

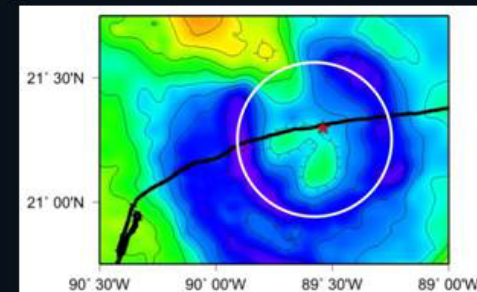


What are the dimensions of the melt sheet? (Proxy for energy release)

Is the peak ring associated with a thickened layer of melt-rich impact breccia? Is it formed by collapse of the central uplift?



Mendoza et al. (2007)



Notes by Presenter: The plan is to drill a transect of holes across the impact. We will drill in the annular trough and learn what life looked like as it came back after the impact. We can drill in the peak ring and actually figure out what the ring is made of.



# Thanks for listening!

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