Gale Crater in Context

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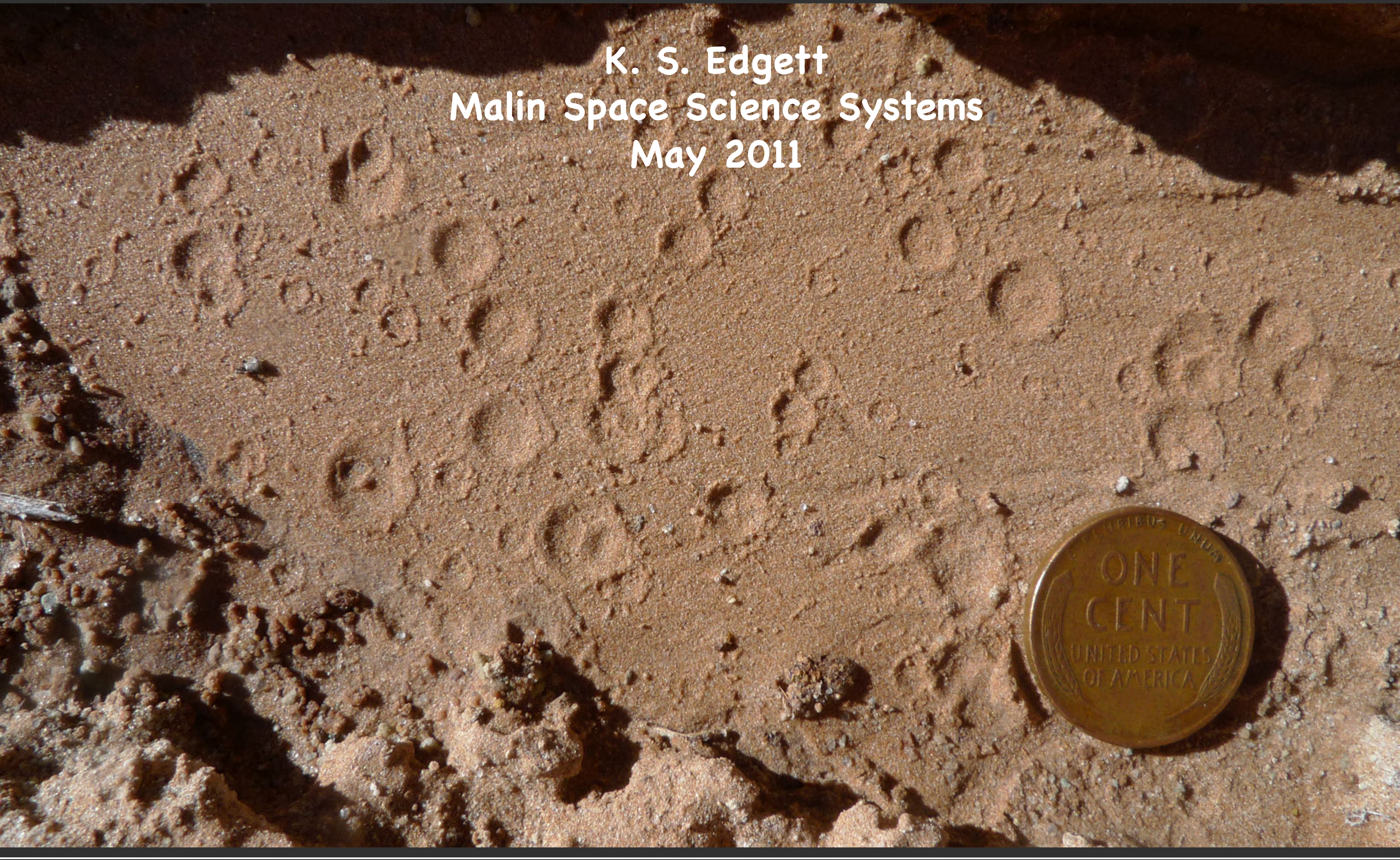
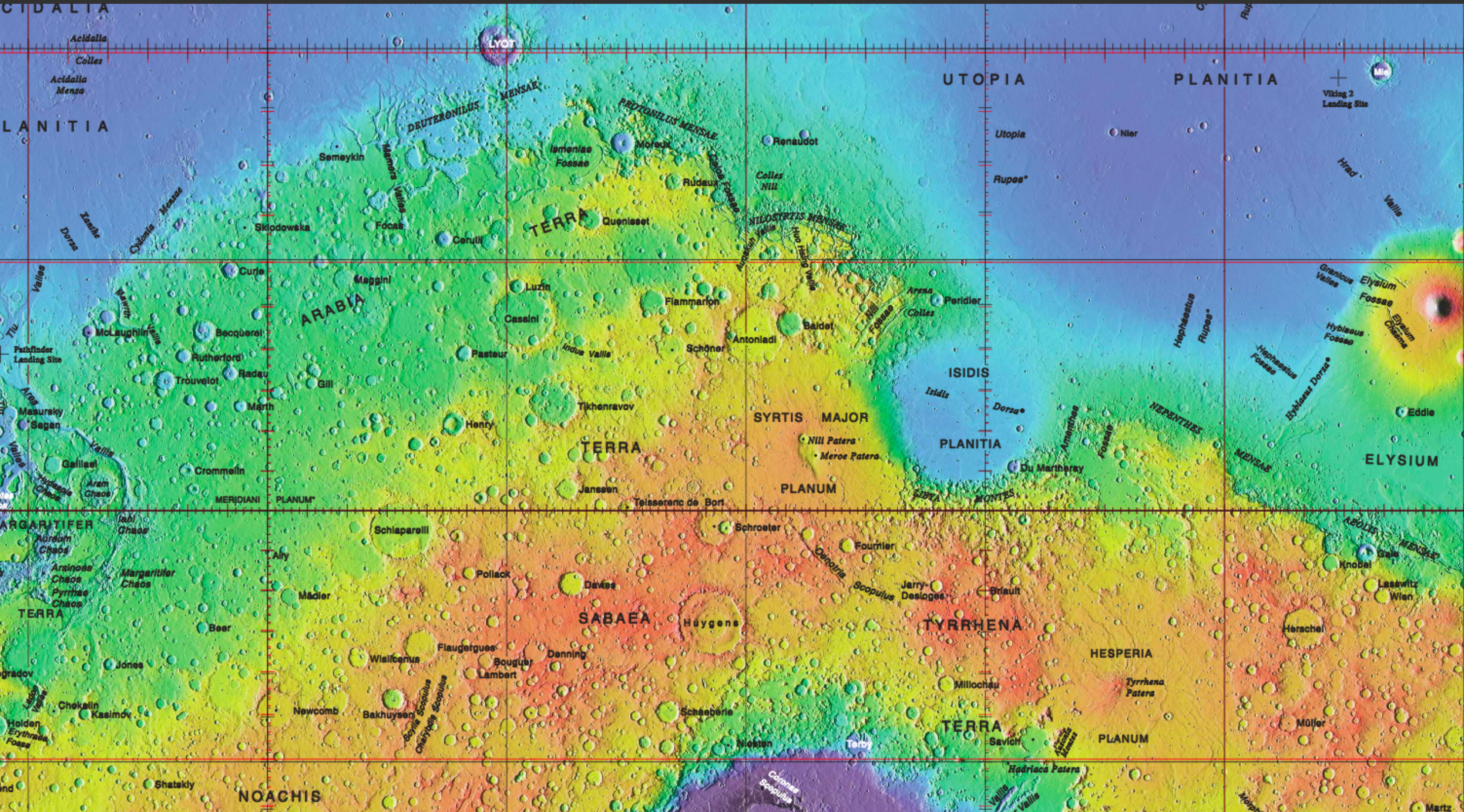
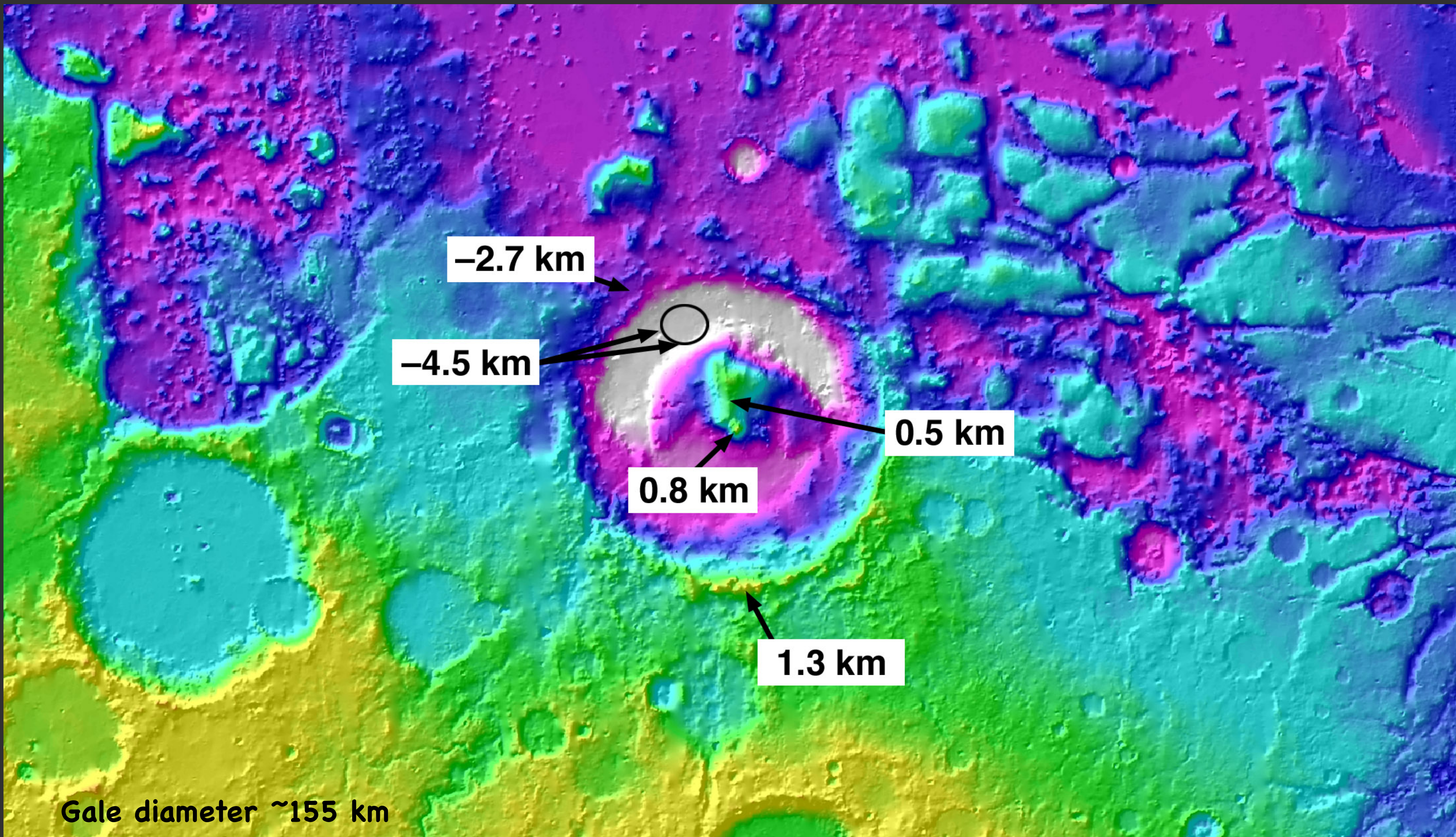


Mounds, Layers, Filled, Buried, etc., Craters



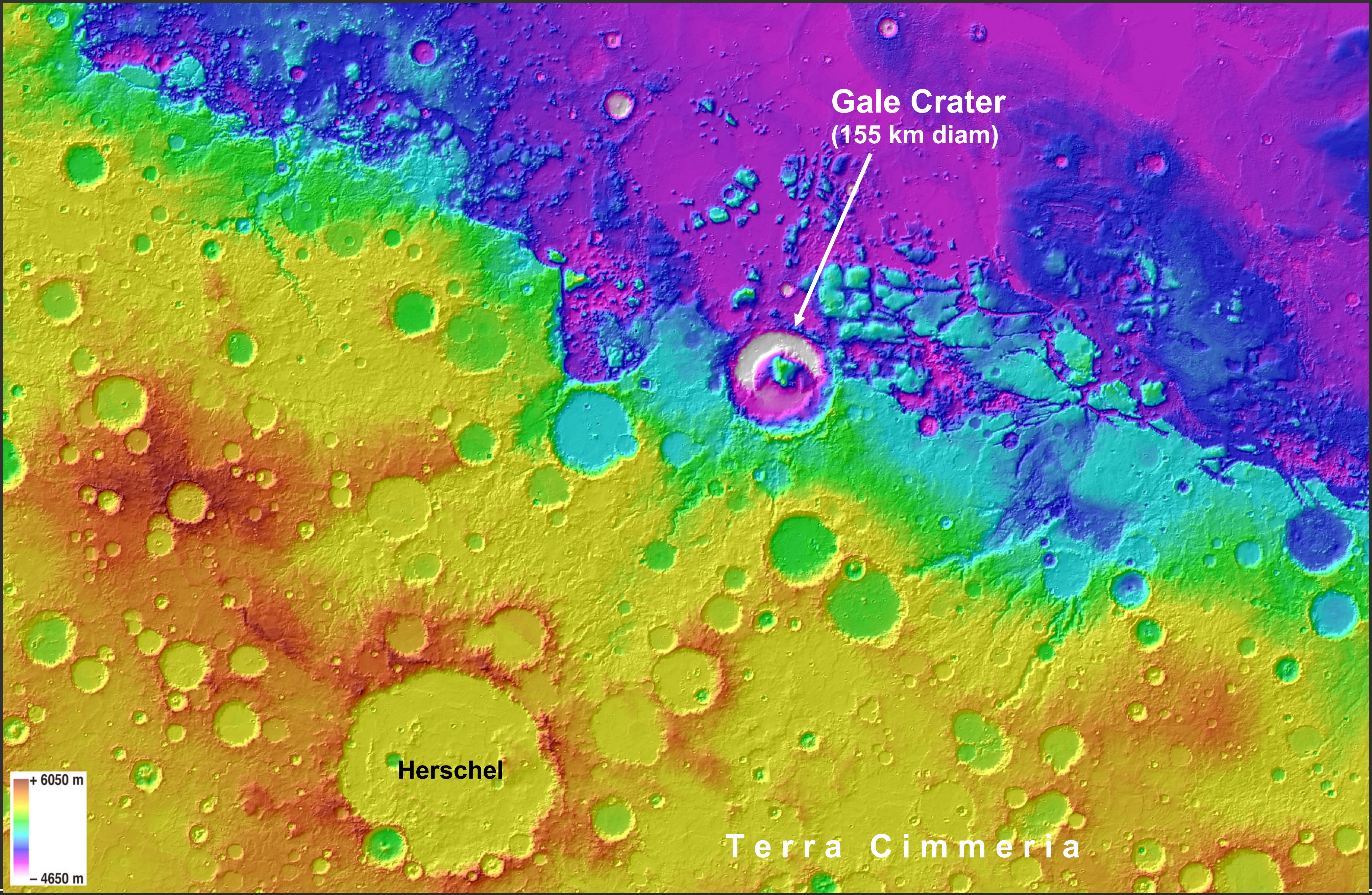
MOLA topography USGS Map

Deep! Not Many Places This Deep Outside of Hellas and the Northern Plains



MOLA topography

Did Water Run Downhill? Toward Gale?



MOLA topography

Additional Information, Not Presented on Screen at Workshop…

Notes

- What follows is a text written on 13 and 14 May 2011 that describes what I had been planning to say at the workshop; it is not a transcript and what would be said at the workshop would not likely be word-for-word the same as what is written here. But it would be similar.
- I had not planned to show any pictures; I had planned simply to talk about Gale and its context and big-picture setting.
- Instead, I presented the preceding "slides" at the workshop.
  - The cover picture shows rain-drop impressions in very fine sand and slit, Kodachrome Basin State Park, Utah, 11 October 2010; coin diameter is 19 mm. This picture has little to do with the talk.

Purpose of a MSL Field Investigation at Gale

- **Assess the Habitability of Early Martian Environments as recorded in a clear and distinct stratigraphic section.**
  - Habitability --> Environments --> Sedimentary Rocks --> Stratigraphic Section
  - The philosophical point for Gale is "the thicker the stratigraphic section, the longer and more varied the record of environments and environmental change is likely to be."

- **But, the record in Gale is not just about a stratigraphic column, it is also about investigating hard evidence for early Mars environments in which water (or a similar liquid) was present, flowing, and transporting and depositing sediment.**
  - There is a prominent channel — a former stream course — that enters the landing ellipse from the northwest. It comes down off the wall of Gale Crater. It deposited a prominent and obvious fan of sediment. This sediment will include clasts that were once part of Gale's wall... i.e., samples of rock that is older than Gale. And it was transported in a "wetter" environment than Mars has today... was that a habitable wetter environment?
  - Much of the rest of the northern 2/3rds of the landing ellipse also consists of older fans of sediment shed from Gale's north wall. As these pre-date the channel and fan I just described, then these, too, date back to a time when Mars was "wetter" and this liquid could still flow across the surface and do work upon the landscape.
  - The mound, itself, was eroded by streams. A liquid, perhaps water, beer, or vodka, cut deep canyons into the mound. This means
    - (a) those rocks cut by these streams were already rock at the time the erosion occurred — i.e., stuff was deposited in Gale, became lithified, then eroded to form a mound and then was cut by streams; and
    - (b) these canyon-forming events, too, indicate that the rocks we want to investigate in Gale — the very rocks cut by these streams — date back to a time when Mars was still this "wetter" place on which a liquid could flow and erode the landscape.

Gale's Setting

- Gale is a ~155 km diameter impact crater. To put that in perspective, the completely filled and buried Chesapeake Bay crater in North America is about 90 km in diameter; the filled and buried Chicxulub Crater is roughly 170 km in diameter.

- The deepest part of Gale, today, is at about -4.6 km below the martian datum; this is about the elevation of the proposed landing ellipse and there are very few places on Mars outside of Hellas and the northern plains that are at an elevation this low.

- Gale is near the present-day equator, at -5 South. It is due south of (presumably mafic to ultramafic) lava flow plains in southern Elysium Planitia. Being near the equator, it might be a decent place to observe — from the ground — the aphelion equatorial cloud belt that develops each Mars year.

- The crater straddles the so-called north-south "dichotomy boundary." That is, the troughs and mesas which mark the topographic boundary between southern cratered highlands and northern lowlands in this part of Mars was already in place the day the Gale-forming impact occurred.

- Gale has a neighboring crater that also straddles the "dichotomy boundary." It is located less than 1 Gale diameter to Gale's west-northwest and it, too, is about 155 km in diameter. This crater pre-dates the forming of the dichotomy boundary. It was filled or nearly filled with material which was then, along with the crater's north wall and rim, became broken-up into troughs, mesas, buttes, etc., when the mysterious boundary formed.

- Gale has two neighboring craters to its south-southeast, Lasswitz and Wien, that also pre-date Gale because we see Gale secondary craters superimposed on them.

- So, we can establish the relative age of Gale in comparison with its surroundings. It is not the oldest thing in the area, but Gale is still so old that it formed at a time when Mars was still much more geomorphically active than today, such that Gale became filled or partly-filled with the material that makes up the mound. And the rim was breached by a stream channel — to cut a stream through a raised crater rim requires superposition — i.e., that the rim was buried and thus not a barrier to the stream — and the walls of the crater were cut by streams, fans of sediment were deposited, and so forth. And the mound, too, was eroded by streams. So this all places Gale firmly in an "early Mars" setting when things were still wet and processes were still vigorous enough to bury kilometers-high crater rims and fill whole 155-km diameter craters with stuff. (Note: Holden and Eberswalde might be considerably "younger" in this regard... there is no reason to believe they were ever filled).

- Note, too, that only lower rocks in the Gale Mound were eroded by streams, not the upper mound rocks; this might mean that the Gale mound, itself, is recording the transition of Mars from an "early, wet Mars" state to the drier, modern Mars of today.

Gale in the Big Picture (part 1)

- Gale is of the family of craters on Mars that were filled or partly filled, buried or nearly buried, exhumed or partly exhumed. Some very big craters — bigger than Gale — suffered the same fate. Some are still buried.

- Many of the known impact sites on Earth are filled and buried structures. The Chesapeake Bay and Chicxulub impact sites are good examples on the larger end of the spectrum. There's even an impact crater buried beneath the Chicago O'Hare airport. One thing we know about these craters is that the stuff that fills them is, as you'd expect, a record of post-impact environments… in some cases, it might be the only record of environments that were otherwise not recorded or not saved, because of erosion, for the long-haul. Similar things are true for Mars.

- When one looks at the craters that were filled or partly filled and then eroded to expose the layered material that filled them — such as Gale — one finds that many of these cases form mounds in the crater. This is not always the case, but it is fairly common. Usually, the craters that exhibit this erosion — mound or no mound — are located at lower elevations in the martian cratered highland — such as in western Arabia Terra or, well, at Gale. This suggests that if one could start shoveling away the upper few kilometers of stuff in the higher cratered highlands, such as Noachis Terra, one would uncover many similar craters as we find in western Arabia or at Gale, or, for that matter, Spallanzani which is located way down at 58 degrees south, southeast of Hellas.

- Another thing we know about crater-filling materials is that they are not all the same, not all made of the same stuff deposited in the same types of environments. For example, in Henry Crater, a crater in west-central Arabia Terra that is about the same size as Gale, the mound that formed there has a fairly uniform erosional expression and uniform bedding thicknesses and expressions, suggesting its materials are generally the same throughout, whereas in Gale we see a wide variety of bed expression, erosional styles, and so forth. We also see in Gale this evidence of fluvial erosion of the mound-forming materials, but we do not see that in Henry and we rarely see that in any of the mounds or other layered-fill exposures.

Gale in the Big Picture (part 2)

- Another thing we know comes from looking at craters that are roughly of Gale size, say between 70 and 300 km in diameter, that are still filled or nearly filled – i.e., ones for which most of the stuff is still there and there is no mound. We see in cases like this that there are stream channels that come into the center of the crater or cut through the crater as if it weren't there; we see both negative-relief stream cuts and inverted stream sediments; we see places where there might have been eolian dune sediments – sometimes among inverted streams – but we're not sure if these are eolian sediments except that some of them erode into crescentic forms. We also see impact craters in the fill material. All of this tells us that when we look at Gale's mound, we have to consider not only what is there today, but was used to be there. If Gale was filled or nearly filled, then there could easily have been environments or micro environments – including streams that deposited material all the way out in the center of the crater or impact craters that damaged rocks deep below them – for which much of the evidence has been eroded away, leaving only traces and remnants… some of which we'll not know about or recognize in orbiter images until we (or MSL) goes there.

- Gale's Big Picture is more than the fact that it is of the family of craters with these layered fill materials. It is also of the family of landforms that have been cut by fluvial processes. And its landing ellipse and the terrain between where the rover might land and the mound we want to study provides us the opportunity to examine other features with planet-wide significance. In particular, there are the fans of sediment transported down the crater wall and deposited at the floor/wall interface. We see these kinds of deposits in craters all over equatorial and mid-latitude Mars and they are all telling us something about environmental conditions (including the amount of water needed to transport debris) on Mars in the so-called Noachian and perhaps Hesperian Epochs. We also have modern-day sand dunes between the landing ellipse and the mound; these are important… not just for eolian studies and remote infrared spectroscopy ground-truthing, but also to consider present-day water and cementation of grains… there are many places on Mars where it seems that sands are not as actively moving as we might expect if they were in terrestrial deserts… there is some evidence to suggest some of these sands are slightly crusted or indurated… what are the cementing agents, if any, and how are they formed? From moisture that comes and goes in these sands on diurnal or seasonal or obliquity-related time scales?

What is the Mound Made Of? (part 1)

- **I hear, from time to time, the voicing of a fear: What if all of the material in the Gale mound is eolian?**
- **That doesn't make much sense to me. It simply can't be. Not 5 kilometers of stuff that exhibits diversity of bedding features, erosional expressions, erosional events (from canyons cut by streams to eolian yardangs), and minerals (as best as we can detect from orbit).**
- **First, one has to consider the degree to which the mound-forming materials are clastic versus chemical sediment. If chemical, then we're talking about precipitation of minerals from solution… That would be <u>stunning</u> and <u>amazing</u> in and of itself. But I would imagine it is far more likely that the majority of stuff in the mound is clastic… Then one has to divide the issue of clastic sediment into four areas:**
  - how was a given clast produced?
  - how did that clast come to Gale?
  - what environment did the clast encounter upon arrival in Gale?
  - what happened to the clast after that?

What is the Mound Made Of? (part 2)

- One of my favorite places on Earth is eastern Christmas Lake Valley, Oregon. This valley has a wonderful, active eolian dune field. You might have seen it in the 1967 Kirk Douglas movie, "The Way West," which was also Sally Field's first film. Unlike the majority of dune fields on Earth, there's almost no quartz there. These are largely volcaniclastic sands. Some of the grains arrived as tephra from the terminal eruption of Mt. Mazama some 6700 years ago. Those included sand-sized plagioclase and pyroxene crystals, most of which have adhering glass; they also include grains that are glass. There are also pumice fragments from Mt Mazama; because of their lower density, they tend to be larger than the average sand grains in these dunes. Some of that pumice arrived by falling from the sky, some of it arrived later by floating across shallow lakes. But not all of the sand is from Mt Mazama's tephra. Much of the rest of the sand comes from eolian erosion of the substrate beneath and upwind of the dunes. This substrate is mostly lacustrine sediment from deep Pleistocene lakes; there were, of course, dry periods in this record, as well. And most of the grains that make up this lake sediment, too, are volcaniclastic. There are basalt lithic fragments that were transported into the lakes by streams that eroded the surrounding terrain — which is entirely basalt. There is tephra from other eruptions in the region, such as from the Newberry Craters. Some of this teprha is very fine and forms ash beds — the ash fell from the sky, so it was volcanic material transported by an eolian process but, when it arrived in Christmas Lake Valley, it settled into a lake and became mud at the bottom of that lake. Later, some of these ash beds were sufficiently cemented that the dunes include some grains which are aggregates of cemented ash. The sediments also include diatomaceous earth and various other fossils of once-living organisms.

- Going back to Gale, then...

- First, there is the issue of where a given clast came from. We know from the many filled and buried or partly buried craters on Earth that, as you might expect, most of the filling material comes from outside the crater. Eroding the rims and walls and terraces and central peaks does not provide enough material to fill a 155 km diameter crater.

What is the Mound Made Of? (part 3)

- So, some clasts will have come from Gale's rims, walls, and central peak. Most of those, we know from terrestrial examples, will be breccias and conglomerates reworked by subaerial streams and/or subaerial or subaqueous debris flows/turbidity currents.

- We can get some handle on the nature of Gale's wall and rim rock by looking at the fan materials in the MSL landing ellipse. These are important to understanding the provenance of what we'll eventually find when we get to the mound; they are also important because we'll be examining rocks that pre-date Gale and pre-date the "dichotomy boundary" — what is this material that forms cliffs, mesas, buttes, etc., along this boundary, yet was sufficiently destructible to form the boundary? This is actually very important to understanding Mars as a whole and it would be really neat if we were able to get some clues about this.

- Then there's the rest of the clasts in the mound. Where did they come from and how did they get there and what did they find when they arrived?

- I want you to imagine, now, that you are one of these clasts. You are a particle. Be the particle.

- Ok. So where do you come from? Were you created by the shattering of bedrock in an impact event somewhere else on the planet? Were you created by an explosive volcanic eruption? Were you created by the weathering and erosion of crystalline bedrock? Lava flows? Are you a meteoritic particle, coming in from outer space?

- And how do you come to Gale Crater? There are really only two ways: either in suspension or by some combination of saltation and traction (well, those and the meteoritic arrival, I guess). Which way are you arriving? If you are suspended, what are you suspended in? An ocean that once covered Gale completely because either the ocean was really really deep or the crust at Gale was depressed and later elevated to its present position? Perhaps, more likely, you are suspended in air. What's that air like? This is early Mars. Is it more dense than now? Is it warmer? Wetter? More dust storms than today? Less? Rainy? Foggy? What's it like? And how did you become suspended? Ejected by an impact? Thrown up in a pyroclastic eruption? Picked up in a dust storm?

What is the Mound Made Of? (part 4)

- And how do you leave suspension? Do you fall from the sky, into Gale, as the winds die down? Water vapor or ice crystals nucleate on you and you fall as rain, hail, or snow?

- Or were you transported by saltation and traction? How? Were you part of a sand dune that marched up over the Gale's raised rim? Were you carried along in a stream? By the way, you might have been transported in suspension in a stream, too. Your stream carried you into Gale because it didn't "know" Gale had a raised rim — the rim was buried — you flowed downhill from the south because Gale is down-hill from Herschel, for example. Perhaps, years later, all evidence of your stream was removed from the martian surface... the rock through which your stream cut was eroded away, perhaps leaving an inverted channel, or not, but eventually that, too, left the scene.

- Ok, now you, the particle, have arrived in Gale. What's it like? Let's say you were suspended in a dust storm or ash cloud and you fell from the sky. What did you find when you got there? Did you fall to a dry, desert surface, like you'd find in any equatorial crater on Mars today? Did you fall to the surface of a lake — whether shallow or deep — and settle to the bottom? Are you an aeolian deposit, or a lacustrine deposit, now? And what if you fell to the surface of an ice-covered lake, and there was some time period on which you floated on a little iceberg, along with some cobbles, say, that were torn from the shore? That ice melted and then you and the cobbles and pebbles settled to the bottom — those larger guys are now drop stones, they made impressions in the sediment like, well, kinda-like a volcanic bomb sag.

- And, after you arrived in Gale and encountered some environment, what else happened to you? Were you reworked by wind? Picked up and moved again by a stream that was flowing across the interior of a partly-filled Gale? Transported by a mass movement, a debris flow? Eventually you became buried, cements clung to you, you became part of a rock. What happened, then? Did you or your cementing agents or your neighboring clasts become altered or completely changed by soaking in some groundwater of some new and different pH? Did you get warmer? Colder? Wetter? Drier? Were you part of the material that is still there, in the mound, or were you caught up in the erosion that created the mound? Were you one of the particles in the rock that had to have been disintegrated and removed from Gale, leaving behind the mound?

How Was the Mound Made? (part 1)

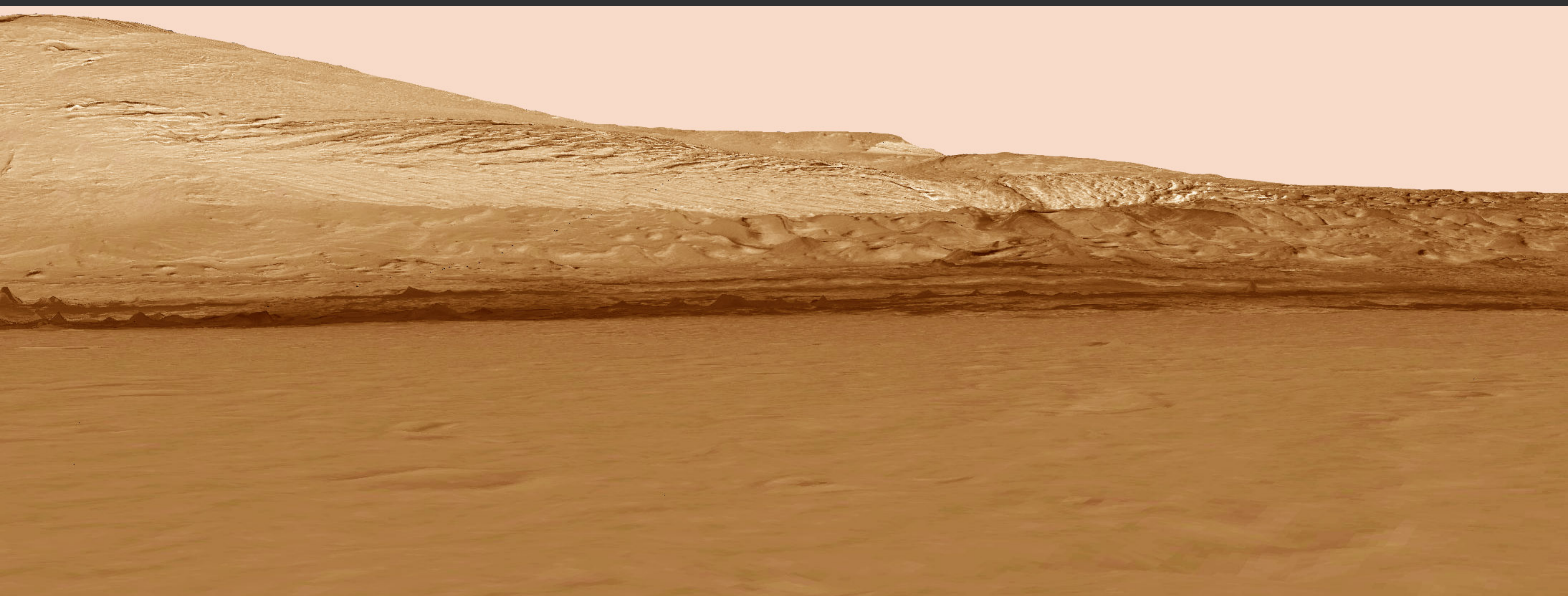
- I've already mentioned that the Gale mound is complex. Perhaps some of the other speakers will shows some of that complexity, but suffice to say that our main science objectives for the MSL Primary Mission are focused on the least complex aspect of the mound — the nature of the lower mound layered rocks, the sulfate-bearing and clay-bearing materials. But there's all kinds of weirdness in the Gale Mound — rock units of different layering and erosional expression in the upper parts of the mound, a mound-skirting unit which is, in part, made of material shed from some earlier episode of erosion of the mound; the fluvial canyons and their inverted channel fill materials that cut the mound — and in a few cases there are fans of their sediment (e.g., some decent examples on the SE side of the mound). And the east half of the mound is really odd, with some lobate forms that could be mass movement or salt glaciers or something; with large blocks oriented every-which-way in landslide deposits; with mantles that seem to be younger than all the mound rocks but still, themselves, seem to be sufficiently lithified as to retain small impact craters. And of course there are craters that were interbedded within the mound, craters that formed on the mound and were eroded down to nubs of their former selves, and so on.

- But let's think about the lower mound for a minute; the stuff that is proposed to be the main focus of an MSL investigation at Gale. How do you get a mound, in the first place? One thing to do is to consider how craters like Gale could become filled-in with sediment.

- After the impact occurs, which forms the crater, you're first going to have a lot going on — fall-back breccia, melt, adjustment of the substrate, and so forth. But after the dust settles and things calm down, then the local environment and gravity are going to start doing their thing. Sediments are going to be shed from the crater walls and, if there is one, its central peak. If this is a wet environment, this shedding will likely be in debris flows, alluvial fans, etc. If it's all underwater, the debris flows might be thought of as turbidity currents. But, basically, you're going to get coarser sediments — forming breccias and conglomerates, in the facies adjacent to the walls, central peak, etc. If there are streams and/or this is a lake, finer sediments will be carried farther into the basin. There will be a sandy facies farther from the wall than the conglomeratic facies, then there will be a silt and clay facies at the center.

How Was the Mound Made? (part 2)

- Now, if you take this simplified model – coarse facies, sandy facies, and silt/clay facies – and bury it, lithify it, then you get a crater filled or partly-filled with sedimentary rock. Now let's say the water table drops, faults and impacts cut the fill material, and pretty soon these materials are exposed to wind erosion. What's going to go away first and the fastest is the sandy material. And, we know in these craters that something had to be removed… this stuff is in a hole in the ground, but it has up and left that hole. So you can imagine it leaves in the form of dunes that climb up and out of the crater, because it was the sandy facies, the stuff most easily eroded and transported by wind. The finer grains mixed in with these sands also blow away because the impact of saltating sand helps set this stuff in motion, too.



Simulated view from Curiosity rover in landing ellipse looking toward the field area in Gale; made using MRO CTX stereopair images; no vertical exaggeration. The mound is ~15 km away in this view. Note that one would see Gale's SW wall in the distant background if this were actually taken by the MSL Mastcams on Mars.

Gale's Equatorial Setting

- Gale sits near the present-day equator of Mars.
- How long has it been near the equator? A billion years? Three billion years? I don't know. But probably a long time.
- Perhaps it was near the equator back at the time when materials accumulated in Gale to form the layered mound. Perhaps it was still near the equator when streams cut and formed canyons in this material.
- Ok, so let's say Gale has been near the equator for as long or nearly as long as Gale Crater has existed... since the times of so-called "Early Mars."
- Are you one of those folks who believe early Mars was warmer and wetter, or at least wetter?
- Do you think, based on your research or the work of others, that there's geomorphic evidence for rainfall on early Mars? If so, wouldn't an equatorial setting be more likely to have experienced this rainfall? Could we even ponder finding raindrop imprints in Gale's fine-grained sedimentary rocks?
- Or maybe it didn't rain at the equator, even on this early Mars... perhaps it snowed... Wouldn't it be more likely, near the equator, that this snow would sometimes melt and run off, forming streams, ponds, perhaps even lakes?

Gale Mound Records the Transition of Mars from "Wet" to "Dry"?

- One last thought.
- The mound in Gale is roughly 5 km thick. It is not simply a layer-cake stack of sediments, it is a record of environmental change, including events that interrupted the deposition of this stack and, even, eroded parts of it away.
- The lower mound rocks are cut by canyons formed by streams. Some of the material that filled the stream channels are still there; some of these cuts look just like river- and stream-cut canyons on Earth.
- This fluvial erosion occurred some time after the lower mound rock-forming sediments were deposited and lithified.
- Fluvial erosion did not occur, or, at least, did not cut canyons into the uppermost Gale Mound rocks.
- Does this mean that the record of deposition and erosion in the Gale Mound is also a record of environmental change as the planet, Mars, transitioned from its early, wetter climates to its more modern, dry climate?
- The Gale Mound might record the manner in which Mars transitioned from "early, wet" conditions to "modern, dry" conditions. Although the MSL rover could probably not investigate this transition in a 1-Mars-year mission, this would certainly give us some interesting things to investigate if the mission were to be extended to 2, 3, or more Mars years after that.

Conclusions

- Gale has a lot to tell us about equatorial settings on Early Mars.
- An extended mission on the Mound might also tell us about how early, wetter Mars transitioned to the more modern, drier Mars.
- Further, a field investigation in Gale could, potentially, also tell us something about the rock that was damaged by whatever processes formed the "dichotomy boundary"
- and it can certainly give us clues, applicable to many other places on Mars, about how craters became filled and buried,
- about fans of alluvium we find shed from many crater rims and walls,
- and even about modern sand dunes.
- But, most importantly, there is this mound and its 5 kilometers-thick record of environmental change and the fact that some of it definitely dates back to a "wetter" time when streams flowed on the surface of Mars.
- And we'd get to examine that record in the order in which the environmental changes occurred.