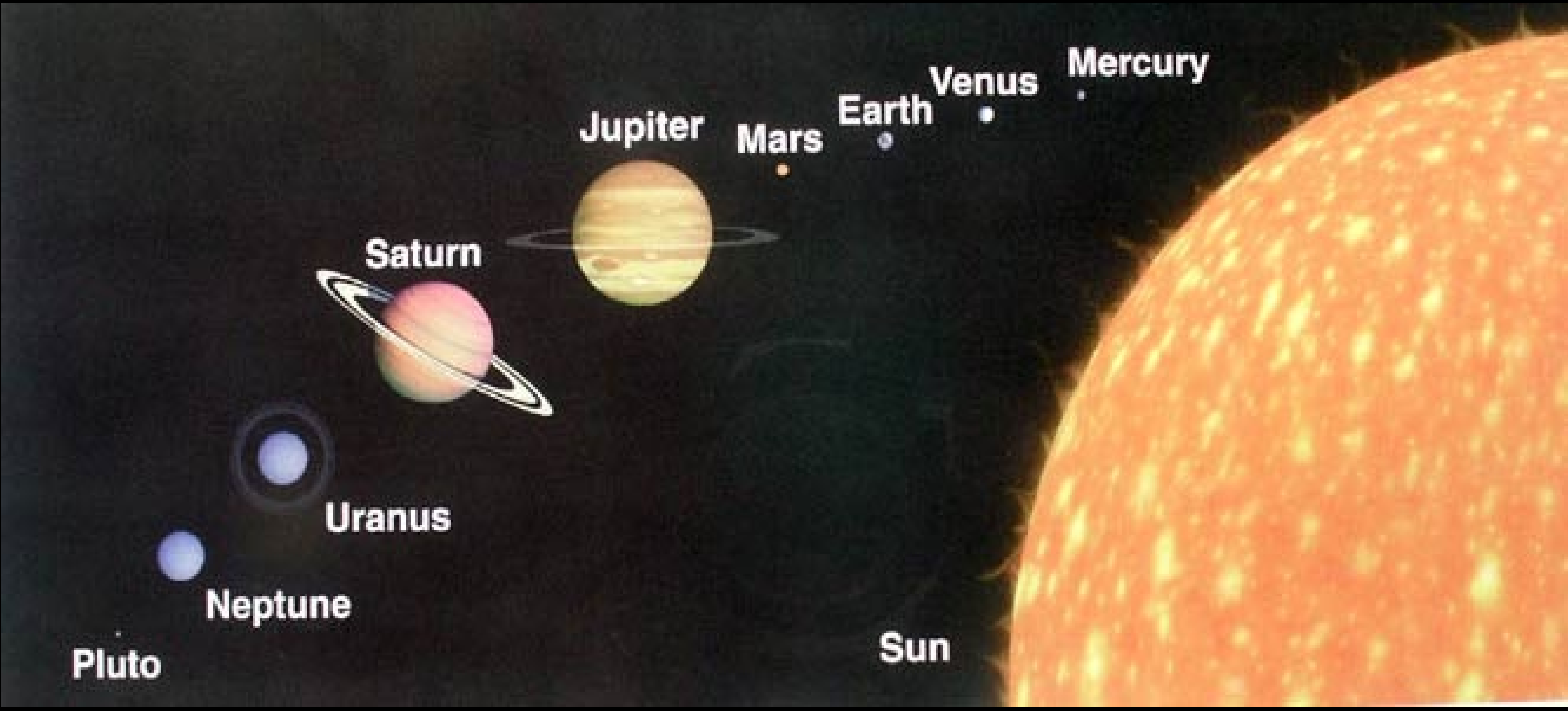
Chap 9: The Inner Planets: Geology

- Inner planets *vs.* outer planets
- Making surfaces
- Sources of heat
- Interiors, layering and why
- Surface Area to Volume ratio and how it controls cooling rate
- Plate tectonics *vs.* thickness of crust

Where Did the Rocky Elements Come From?

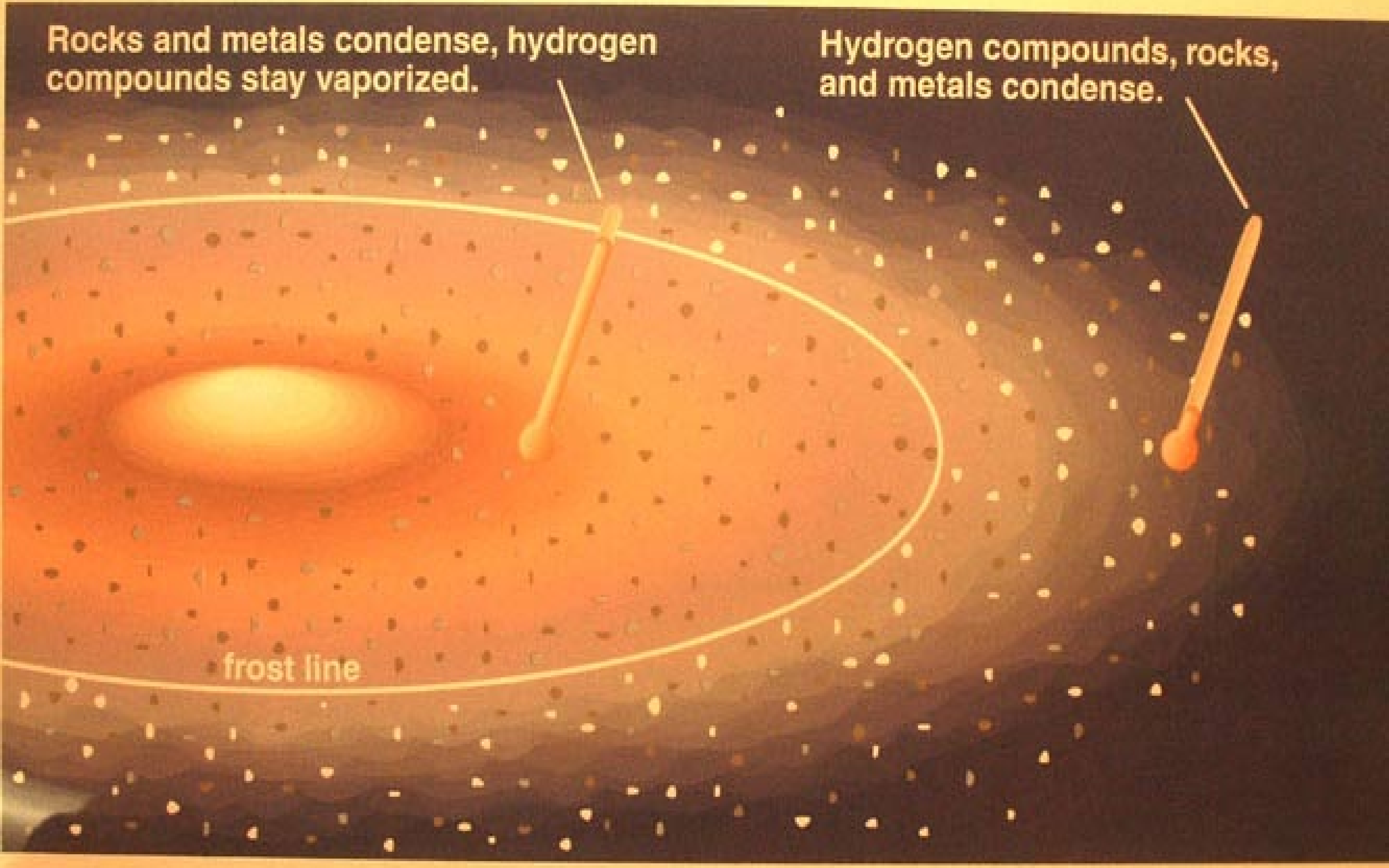
- All of the heavy elements that make inner planets (and our planet cores), were created in nuclear reactions in stars that lived and died before the sun was born
- During the death process, they ejected some of those created heavy elements into space, where they could end up in the proto-solar nebula and become part of our planets.

Little rocky inner planets, big hydrogen and helium-rich outer planets



Summary of Differences between the Inner and Outer Planets

Terrestrial Planets	Jovian Planets
Smaller size and mass	Larger size and mass
Higher density (rocks, metals)	Lower density (light gases, hydrogen compounds)
Solid surface	No solid surface
Closer to the Sun (and closer together)	Farther from the Sun (and farther apart)
Warmer	Cooler
Few (if any) moons and no rings	Rings and many moons


Rocks and metals condense, hydrogen compounds stay vaporized.
Hydrogen compounds, rocks, and metals condense.
frost line

Therefore, inside the Frost Line…

- It’s too hot close to the sun. No ices. So only the rocky material (~3% of the solar nebula) could collect. Not hydrogen and helium since their thermal velocities are high and escape velocities from these small planets are low
- Most plentiful component is iron (why? Because massive stars blow up when they develop iron cores, scattering it all over the place!)

Making an Inner Planet

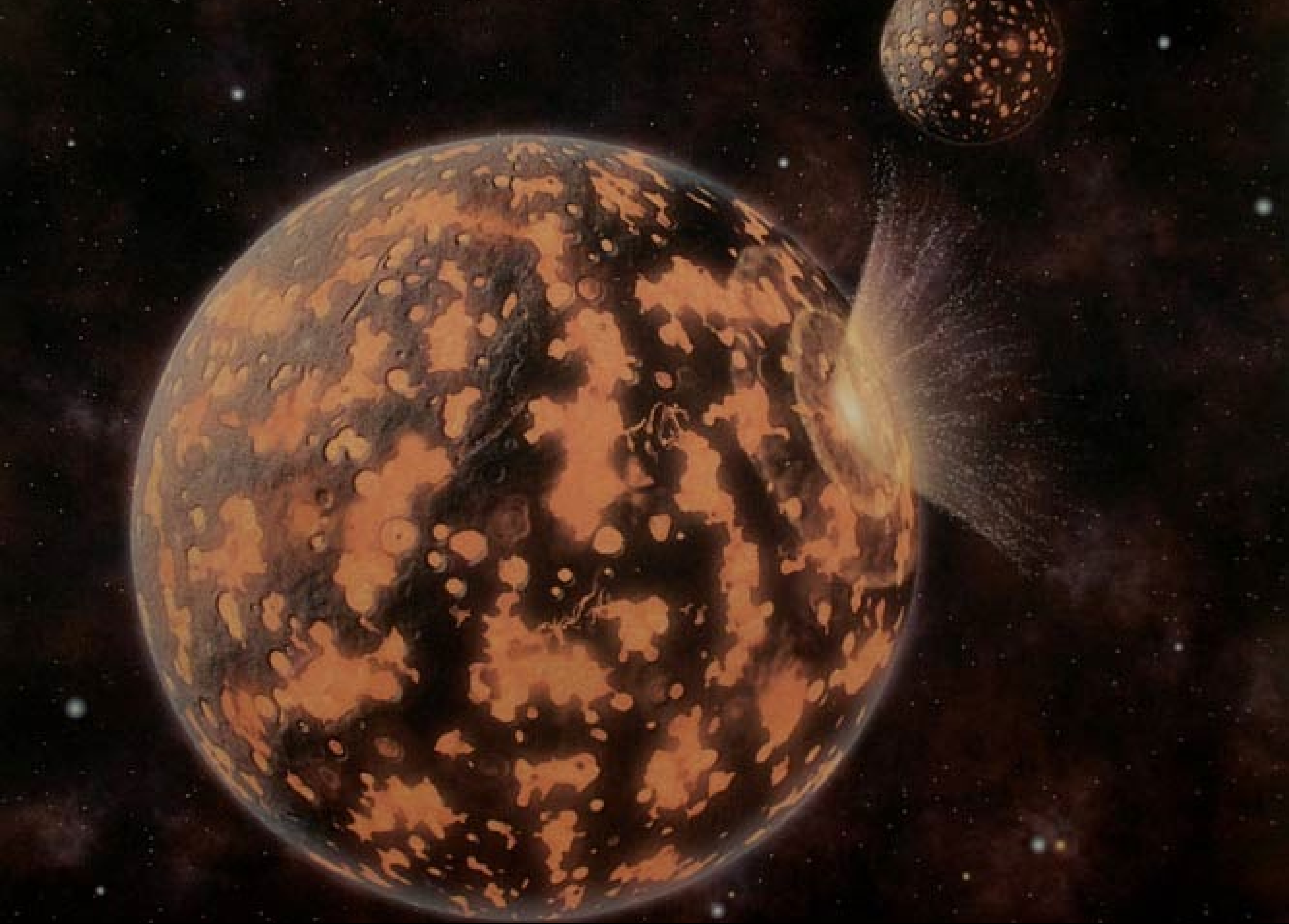
- After the heavier elements and minerals condensed into solid bits of dust and rock, they all orbited the Sun at about the same speed.
- Collisions between objects moving at the ~same speed are less destructive than those of objects moving at different speeds. Thus, when "dust bunnies" orbiting the Sun move close to one another, they can stick together more often than they destroy each other. Electrostatic force can provide the "glue", as we saw before
- These pieces gradually grow larger, into "dirt clods" and larger by accretion. Once they are larger than about ½ mile, gravity is strong enough to pull in more and pull them into spherical shapes.

Bringin' Heat: 3 Ways

- Initially the inner proto-planets are small and so self-gravity is weak and accretion is fairly gentle
- ***(1)*** Late stages, self gravity is substantial and the accretion velocities are bigger. The ***kinetic energy of impacts*** $\frac{1}{2}mv^2 = (3/2)k\text{T}$. Impact velocity is a few km/sec due to differential orbital speed, plus the velocity due to the gravity of the planet: about 10 km/sec. ~15 km/sec is 15 times faster and 200 times more energy per pound than a high powered rifle bullet! Easily gives enough temperature to melt rock
- ***(2) Radioactive decay of heavy elements, mainly U238, Th232, and K40 progressively into lighter "daughter" elements,*** supplies about half of Earth's outgoing heat today, mainly in the mantle and in the crust, where it's deep enough and hard to conduct or convect away. Even just a few dozen miles deep is enough for the time scale for conduction to be hundreds of millions of years
- ***(3) Differentiation:*** Incoming material is a mixture of densities, and as the heavy fraction falls and forces the lighter stuff to rise, the friction generates heat. Ultimately, this is more gravitational potential energy being turned into thermal energy (heat!)

Molten Inner Planets: Evidence?

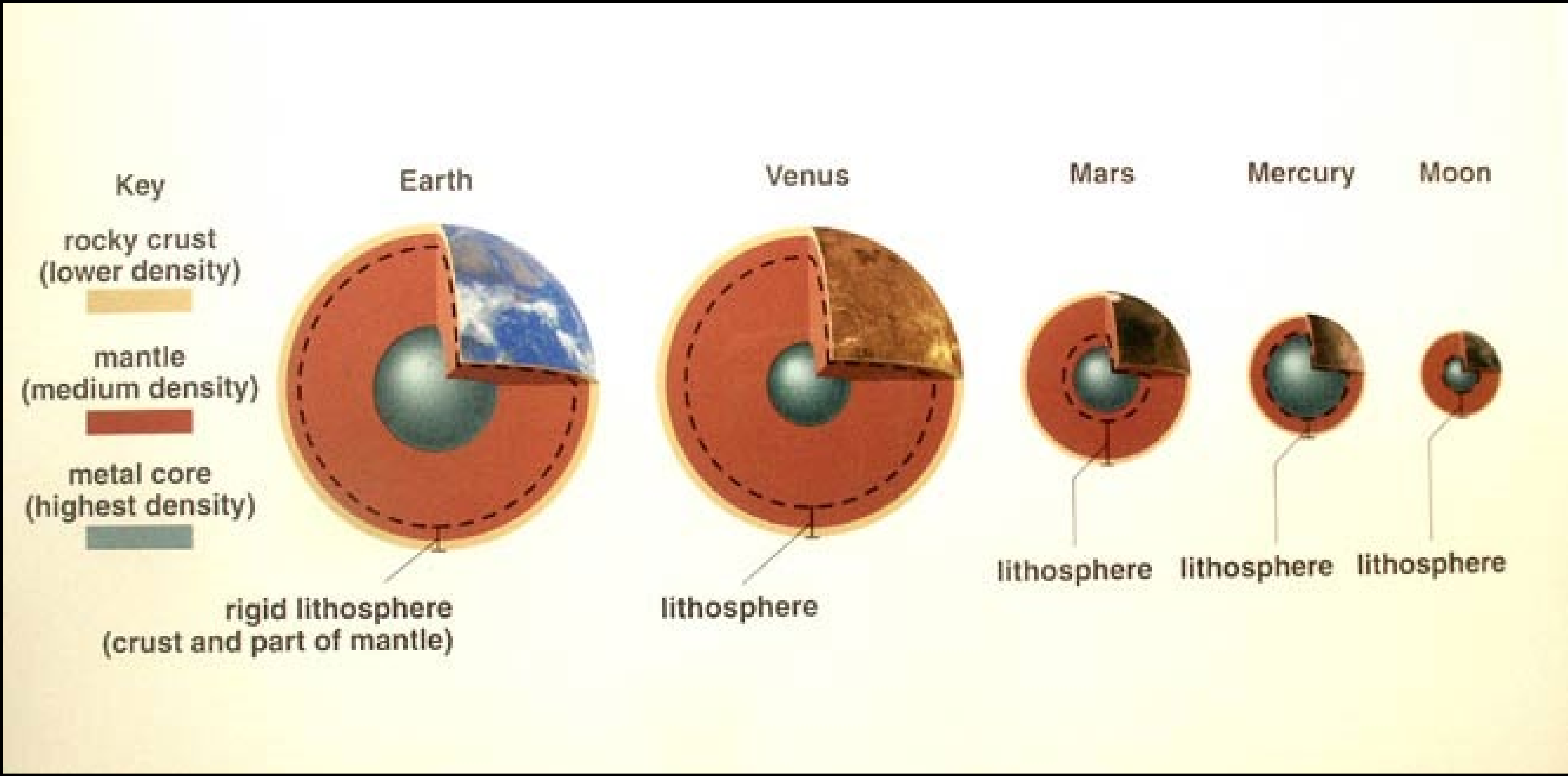
- If the planet is molten, the heavier chemical elements will sink towards the core, and the lighter elements will rise to the surface.
- **Layering – is proof of the molten history of the Earth, and other inner planets.**
- Indeed, we see surface elements are dominated by light rocky elements: silicon, aluminum, oxygen, magnesium, carbon…



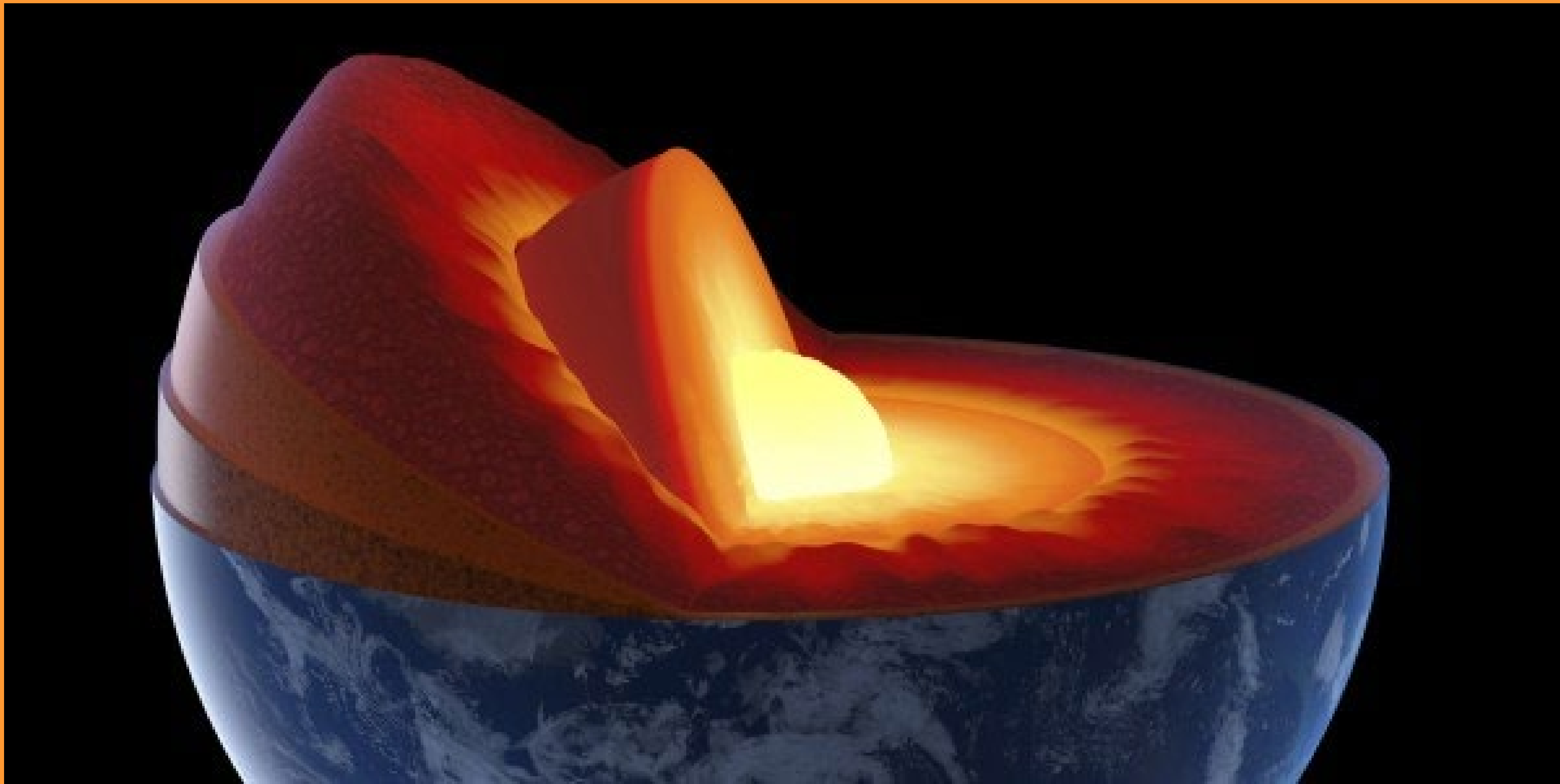
How Rapidly Does a Planet Cool?

- Planets cool from their surface, and surface area goes as diameter *squared*
- But their heat content is proportional to their mass, which is proportional to their volume (assuming roughly similar chemical composition between inner planets), and volume goes as diameter *cubed*!
- **Therefore: Bigger things cool SLOWER!**
- **All planets have been cooling for the same period of time – 4.6 billion years. Therefore…**
- **Big planets will have thinner crusts!**

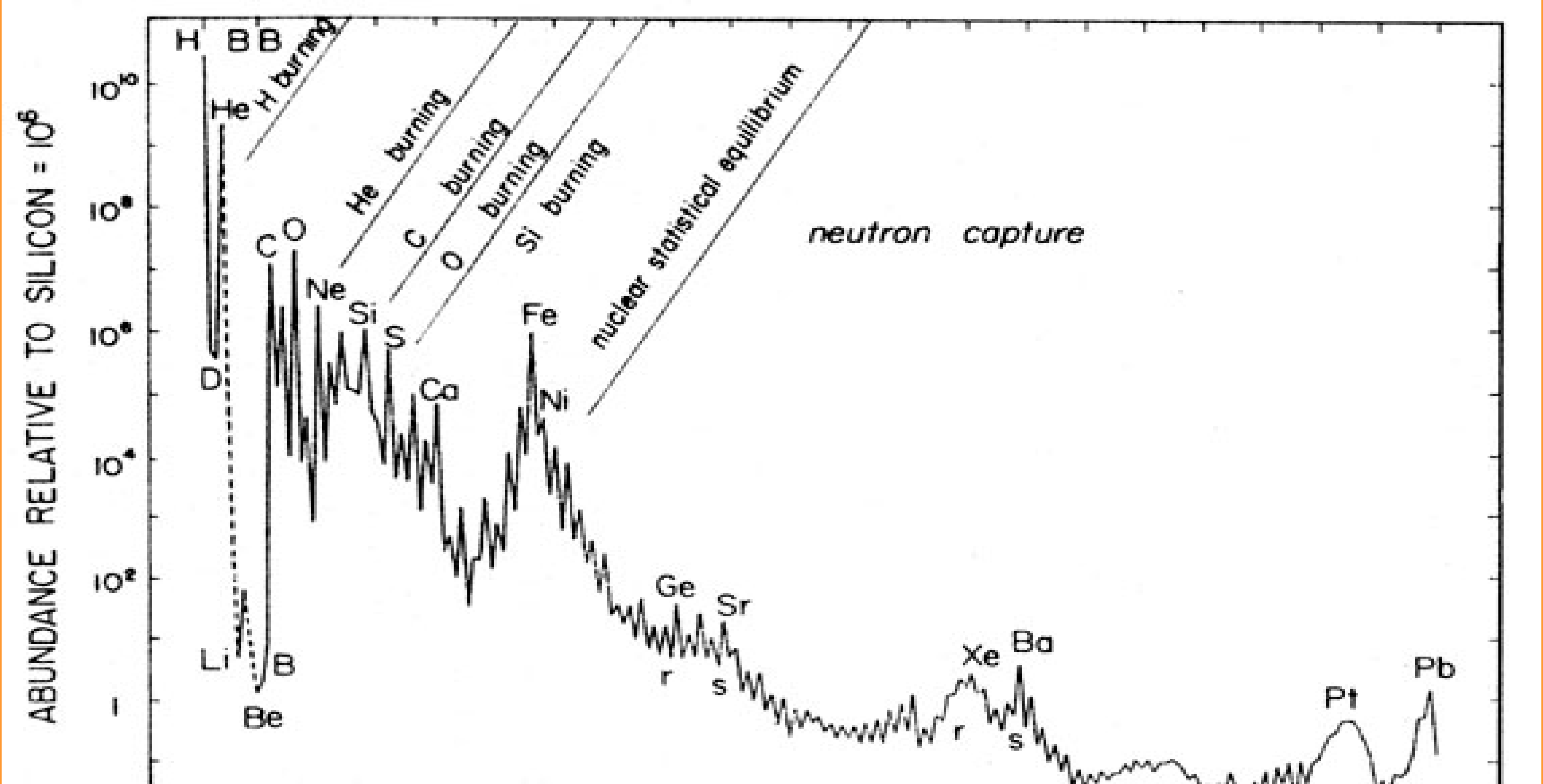
Inner planet interiors; summary. Mercury has a big iron core, moon not so much



Why so much Iron in those Cores?



Why so much Iron? High mass stars fuse light elements into heavy iron cores which then implode/explode, spreading the iron and radioactive nearby elements, everywhere. Below is the cosmic abundances of the elements. Note the strong spike around Fe (Iron), because of supernovae



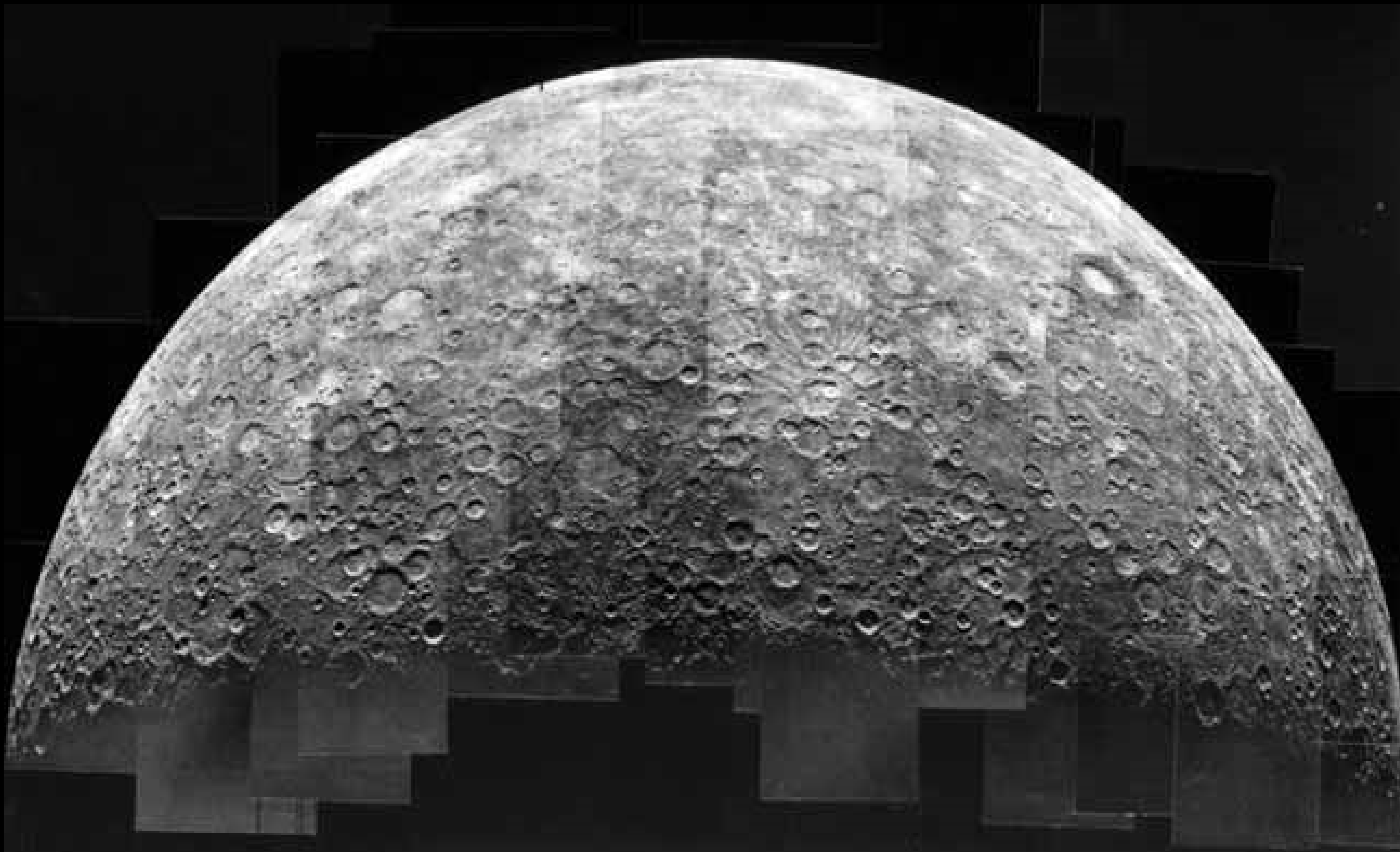
Mercury

- Smallest planet, only 3,000 mi across. About 40% of Earth’s diameter
- 600F on daylight side, too hot to retain any atmospheric molecules at all. Probably doesn’t help that the sun is so close and solar storms can rack the planet and carry off any atmosphere too.
- Cratering shows it hasn’t had atmosphere for most of the solar system’s history
- Also the densest planet – BIG iron core.

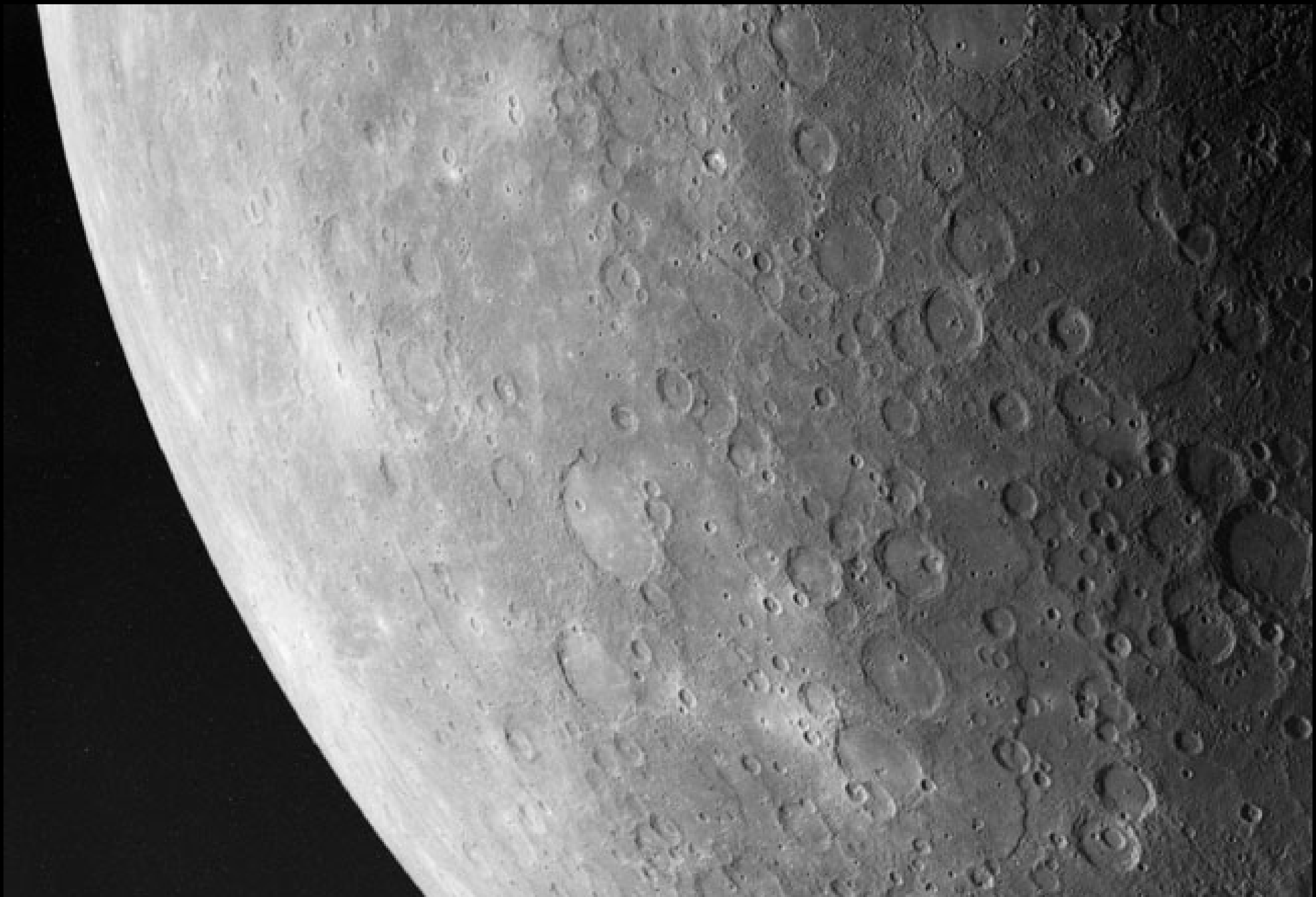
Why is Mercury so Dense?

- The early theory – initial sun was so luminous it vaporized much of Mercury's lighter elements in the crust
- **Messenger Mission** says **no** – large sulfur deposits – several percent of Mercury's crust by mass!, and large potassium-to-thorium ratio shows volatiles are much more common still today than this theory allows
- Probably Mercury condensed from iron-rich materials which may have predominated in the innermost solar nebula.

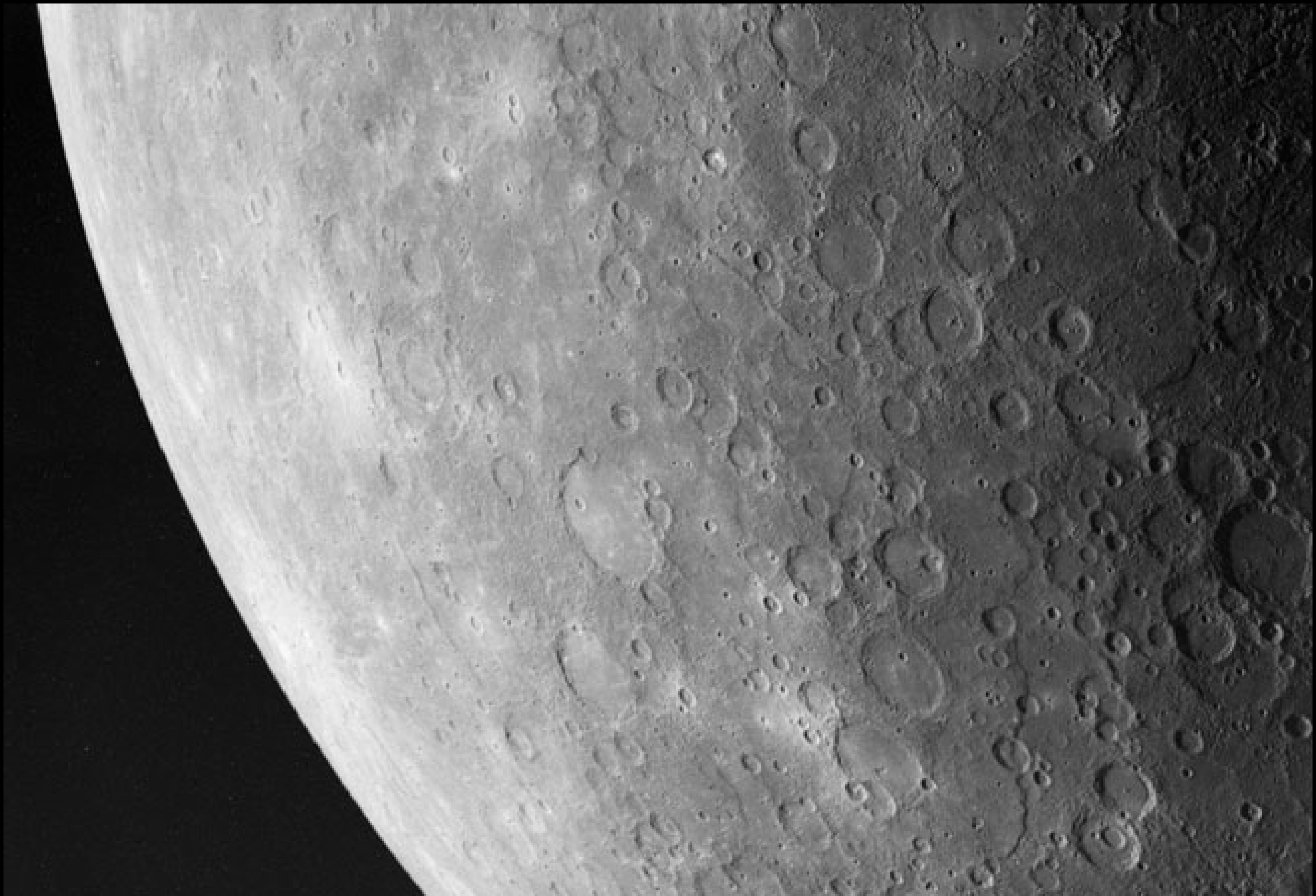
Mercury from Mariner 10 in 1975

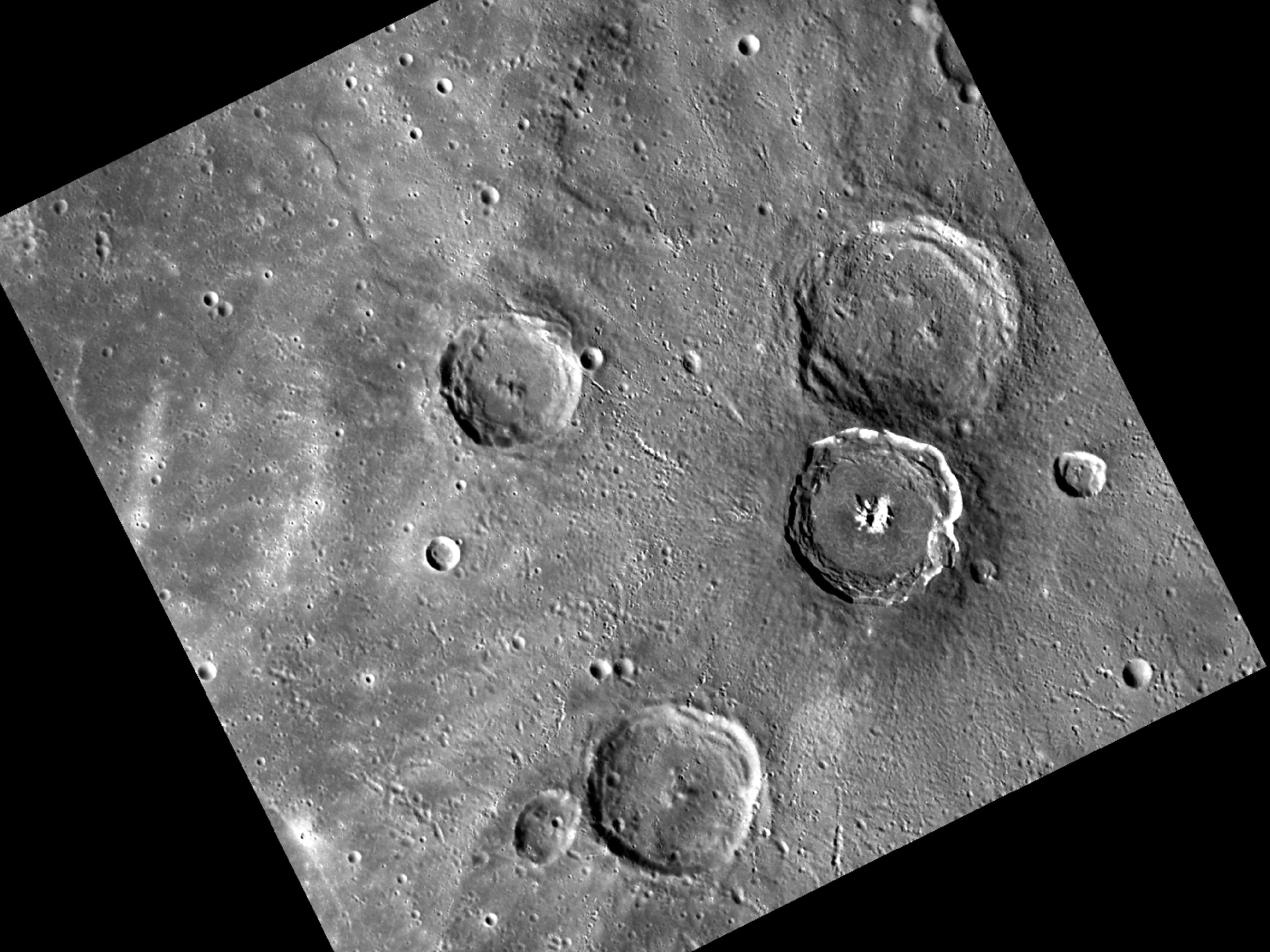


You've all seen lunar crater scenes… how do these Mercury craters compare? The same, or different?



Note that craters on Mercury look flatter, with lower rims than those on the moon. After impact, area is molten longer and stronger gravity likely why

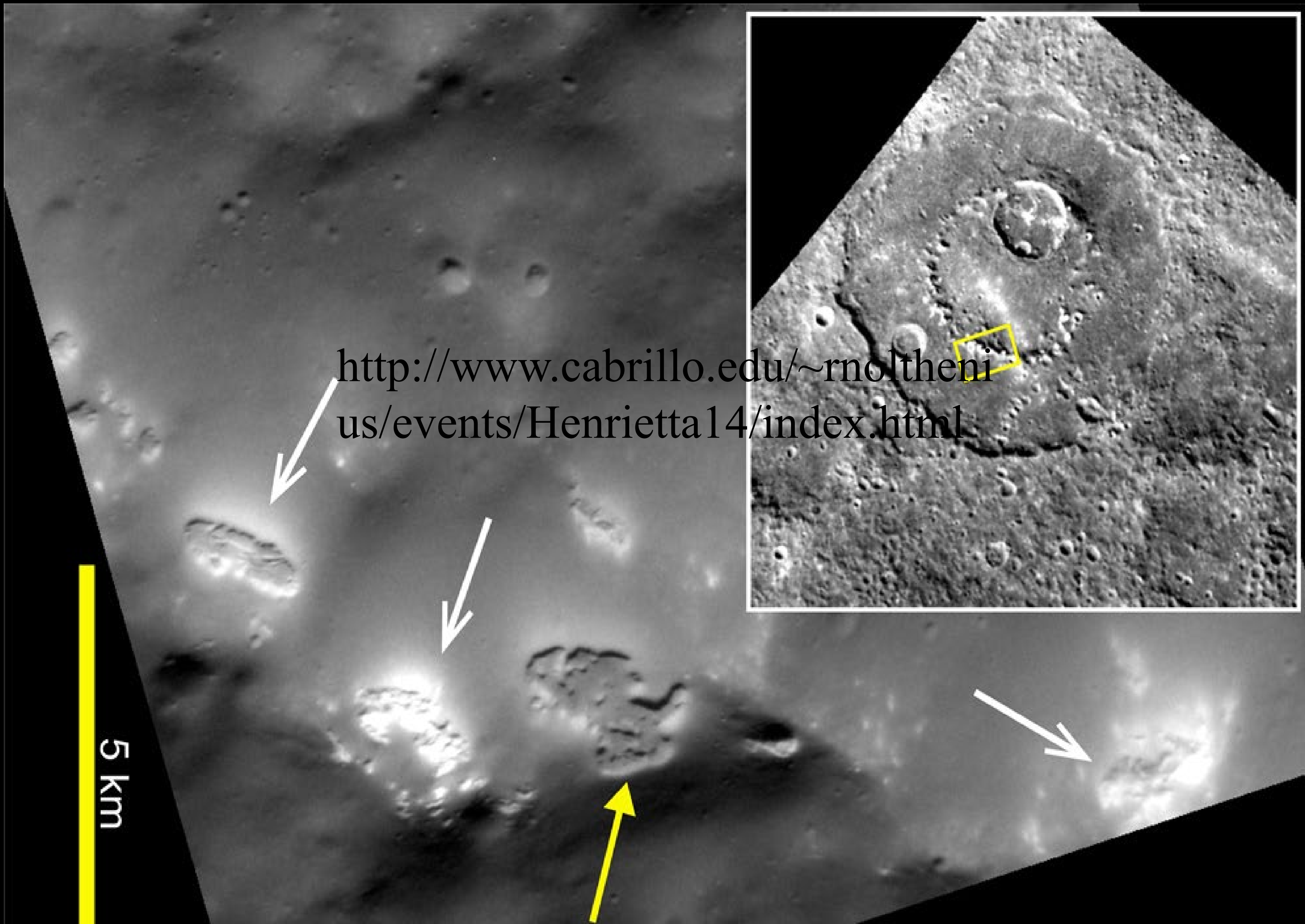




See anything unusual about this scene? You don't see this on the moon…

Evaporating volatiles (water?) look to have opened these cracks, like a drying mud puddle!

Sub-surface cavities collapse, revealing some sort of white (sulfur-rich? Silica?) materials



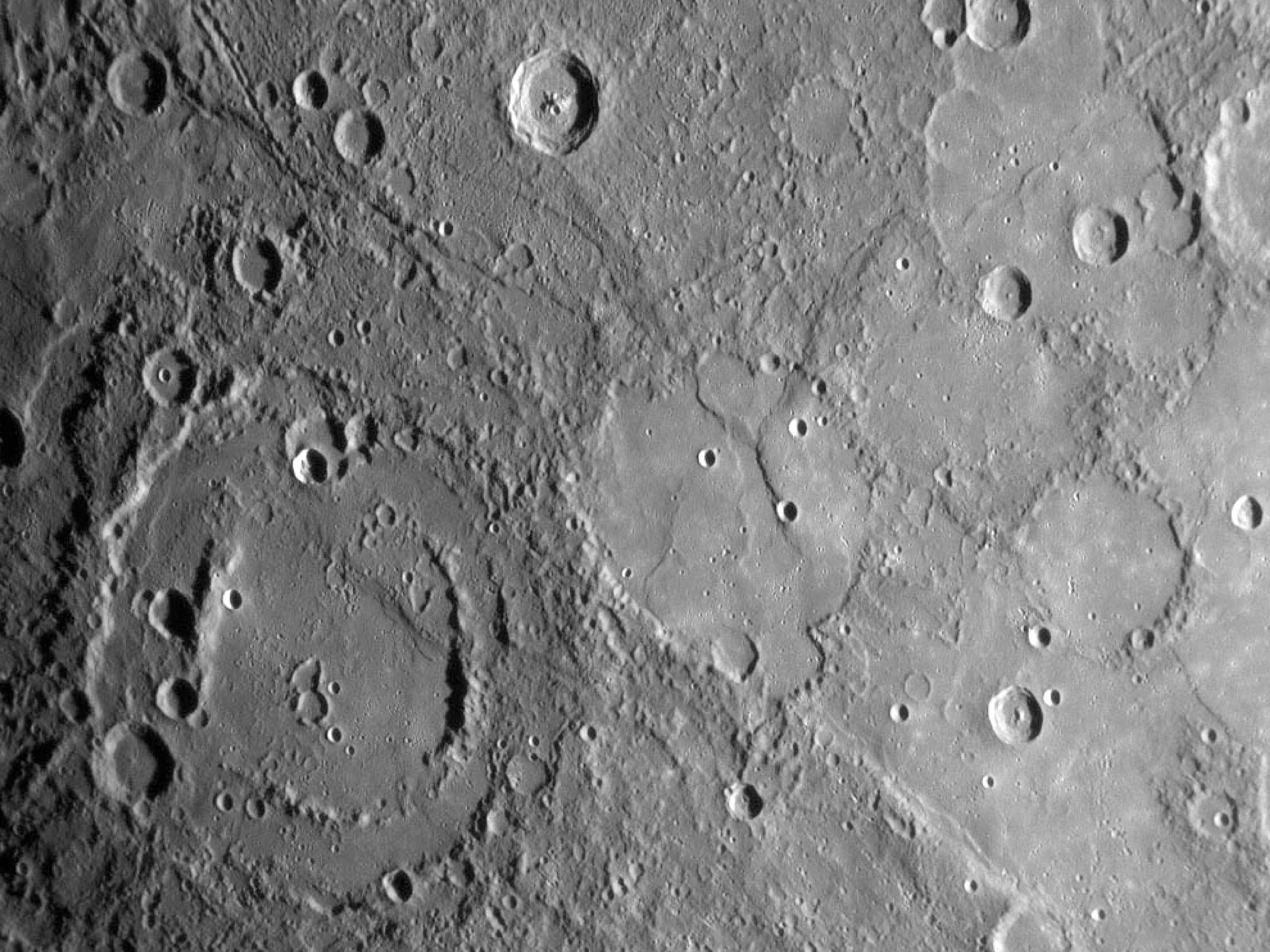
http://www.cabrillo.edu/~rnoltheni us/events/Henrietta14/index.html

Is/Was Mercury Geologically Active?

- Check out this picture, and then you tell me…

A fault line (A Lobate Scarp, to be specific)

- But notice how the fault is older than nearly every other crater it crosses.
- Apparently, and perhaps not surprisingly, Mercury appears to have geologically “died” as a planetary youngster
- Fits nicely with the rapidly thickening crust predicted by basic physics: cooling rate vs heat capacity
- Other evidence of geologic activity: large volcanic plains (thanks to Messenger, we know they’re volcanic because they are sloped, unlike non-volcanic plains which are level)
- Lots of volatiles have evaporated off the planet, shrinking it by about 1 mile of diameter, creating the many **scarps (next slide)**.



NASA / JHUAPL / ASU

Low-iron volcanic plains filling the Caloris impact basin make a large pale orange patch (marked "C") in this false-color image of Mercury. White arrows mark young smooth plains. Around the edg of Caloris and elsewhere lie small volcanic centers thought to form by explosive eruptions (black arros) Widespread dark blue areas are older rocks.

Mercury's Geologic History – Summary

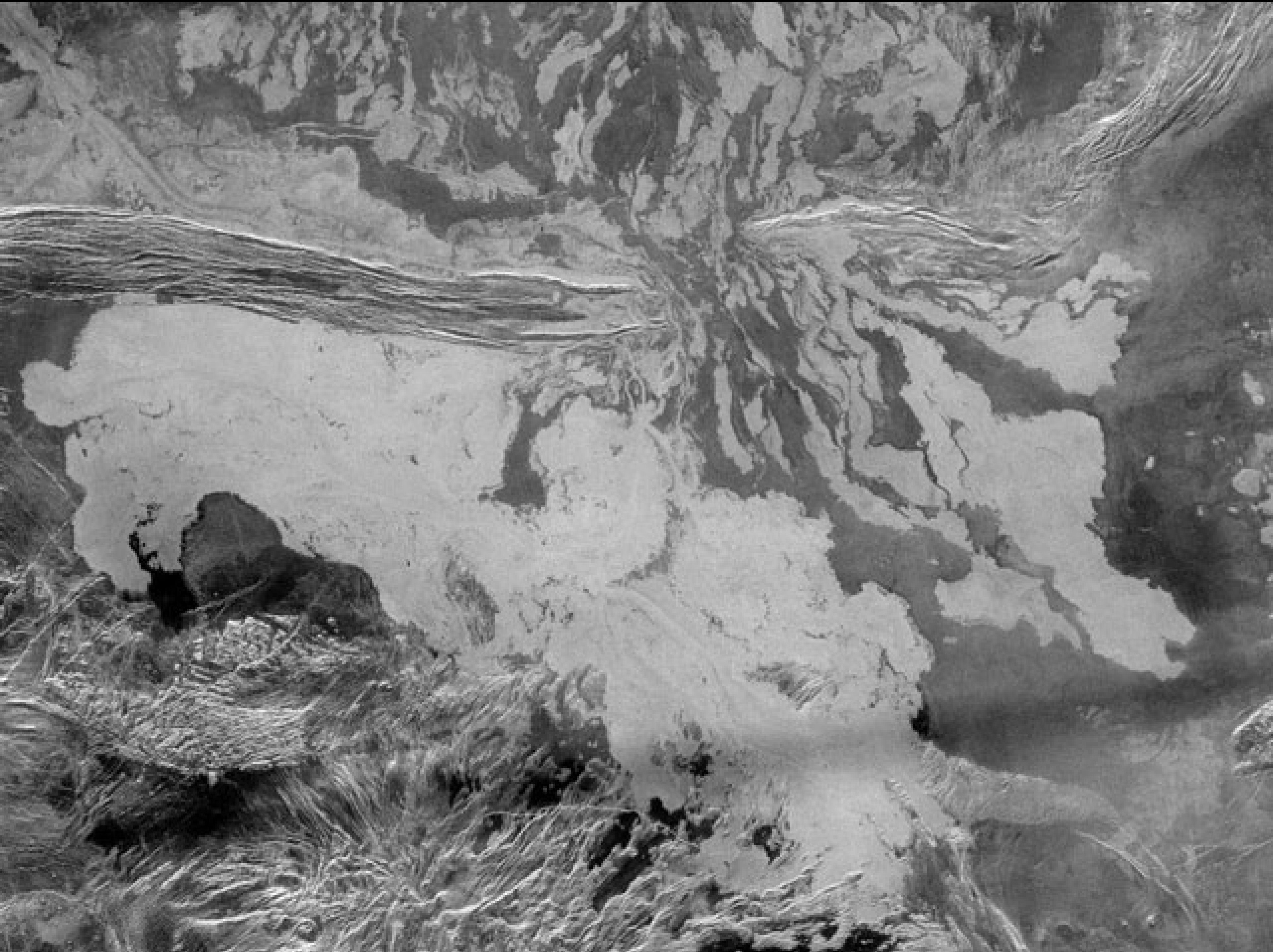
- Early Mercury had significant volatiles (likely water), enough that as they evaporated, Mercury shrank by about 11 km in diameter. Evidence is lobate scarps and evaporation cracks.
- Heavy cratering shows Mercury lost any atmosphere in the first few percent of its current age.
- It also has some long-dead volcanoes, but no evidence of the heavy volcanism that Venus shows

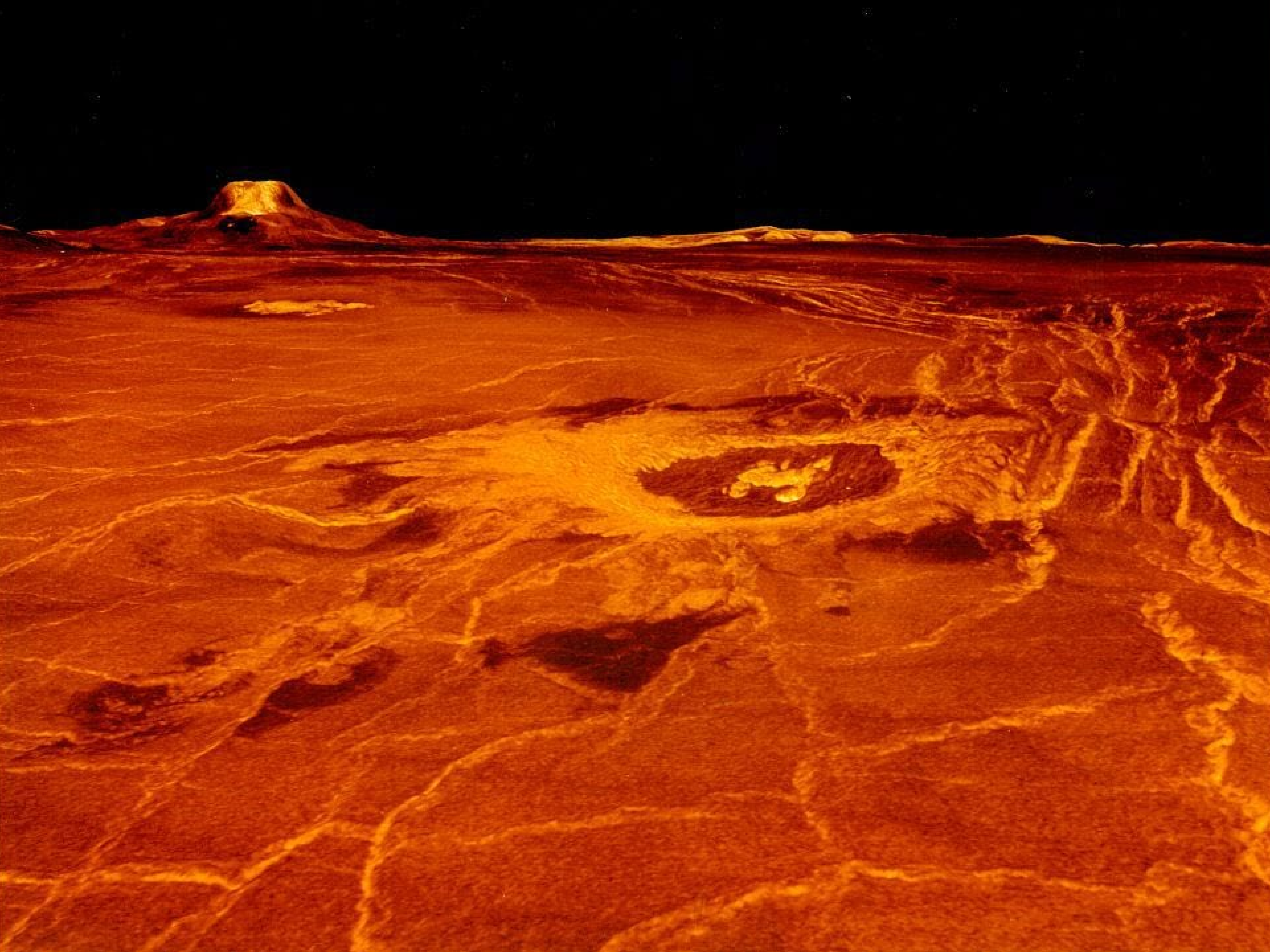
The Geology of Venus

- Almost as large as the Earth.
- Hot! From greenhouse gas CO2 atmosphere
- So you'd expect a thin crust and likely recent geologic activity.
- **You'd expect a thin atmosphere being it has less gravity than Earth and much hotter too. But, you'd be very wrong…**

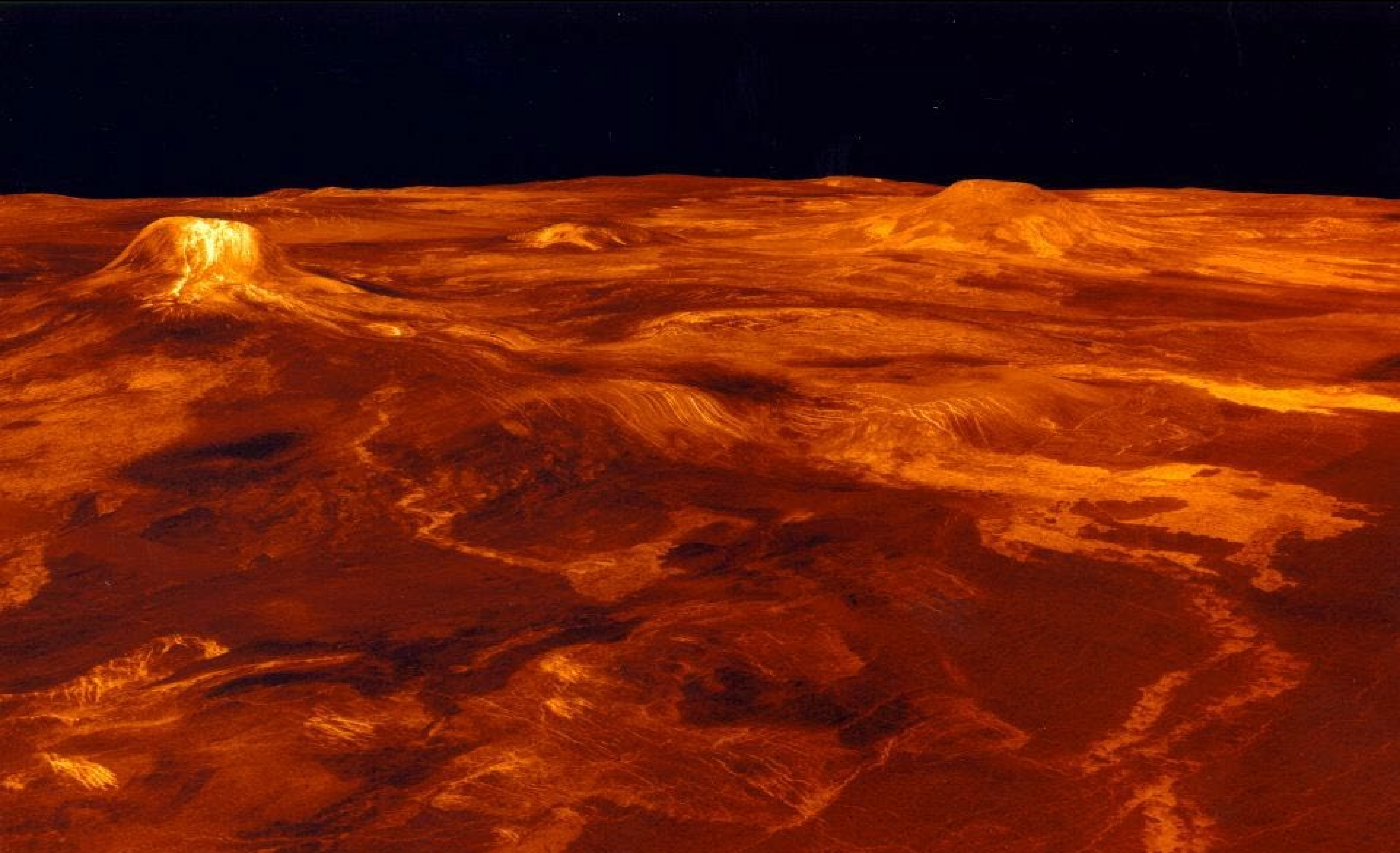
Sulfuric acid clouds cover Venus

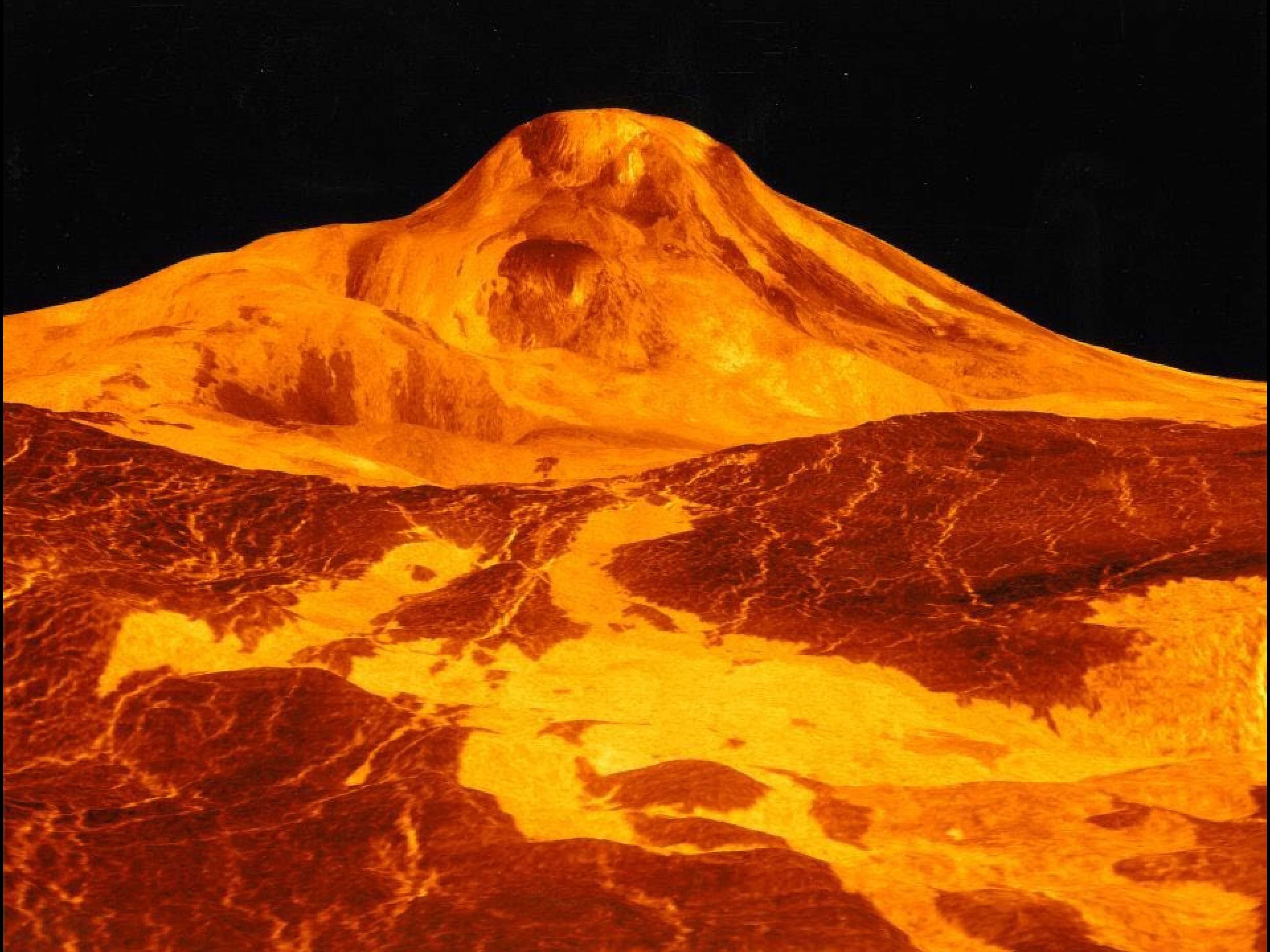
Magellan spacecraft radar-mapped right through the clouds. See volcanic mountains and flows





Radar-reflective smoother areas are brighter in this false-color rendition



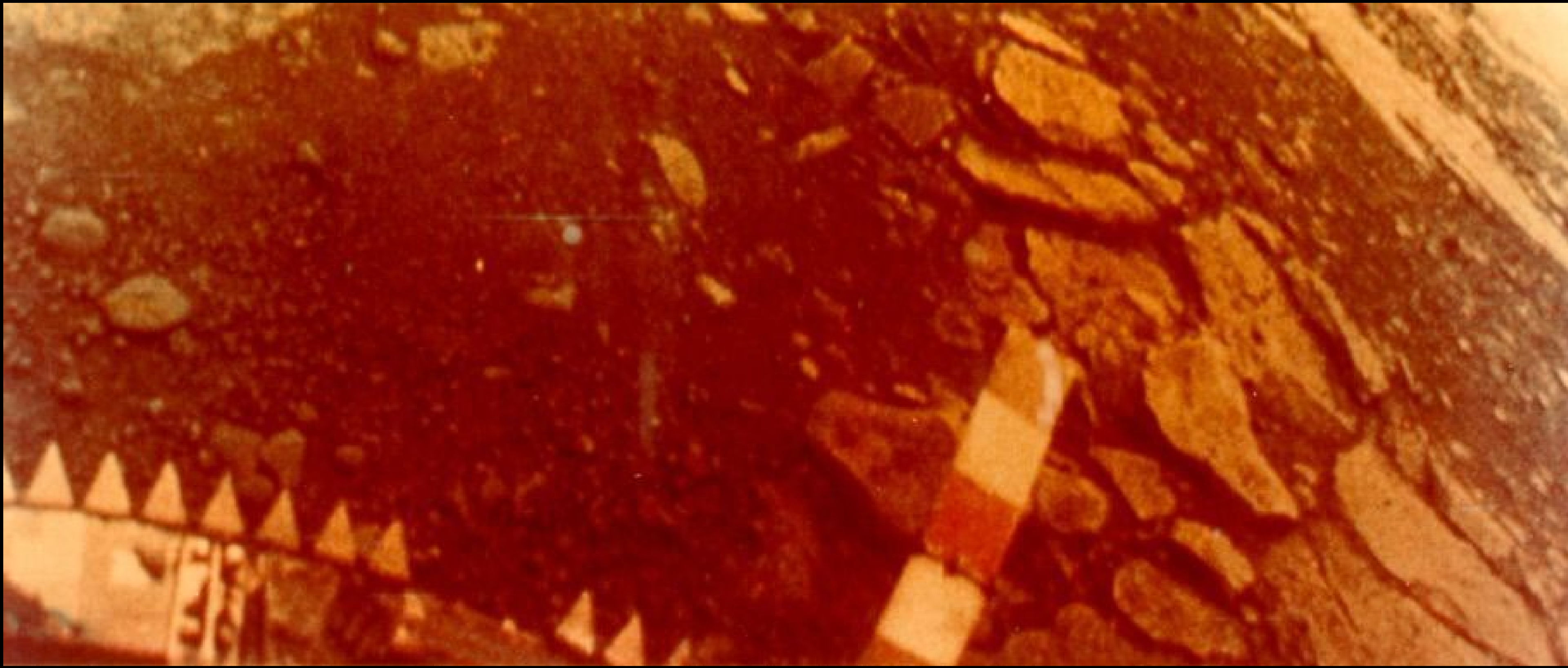


So we see on Venus…

- Volcanoes, up to 100,000 of them!
- Cracks in a thin crust
- A few BIG impact craters, but not much in the way of small ones.
- It may be that the surface rock is not very hard, but more like a very stiff plastic which can flow over time. Obliterating small craters? Wind erosion?

Soviet Venera Photo from ‘70s, Venus Surface

Another Venera photo – note strong curvature due to high atmosphere density refraction, and orange glow through sulfuric acid cloudy skies



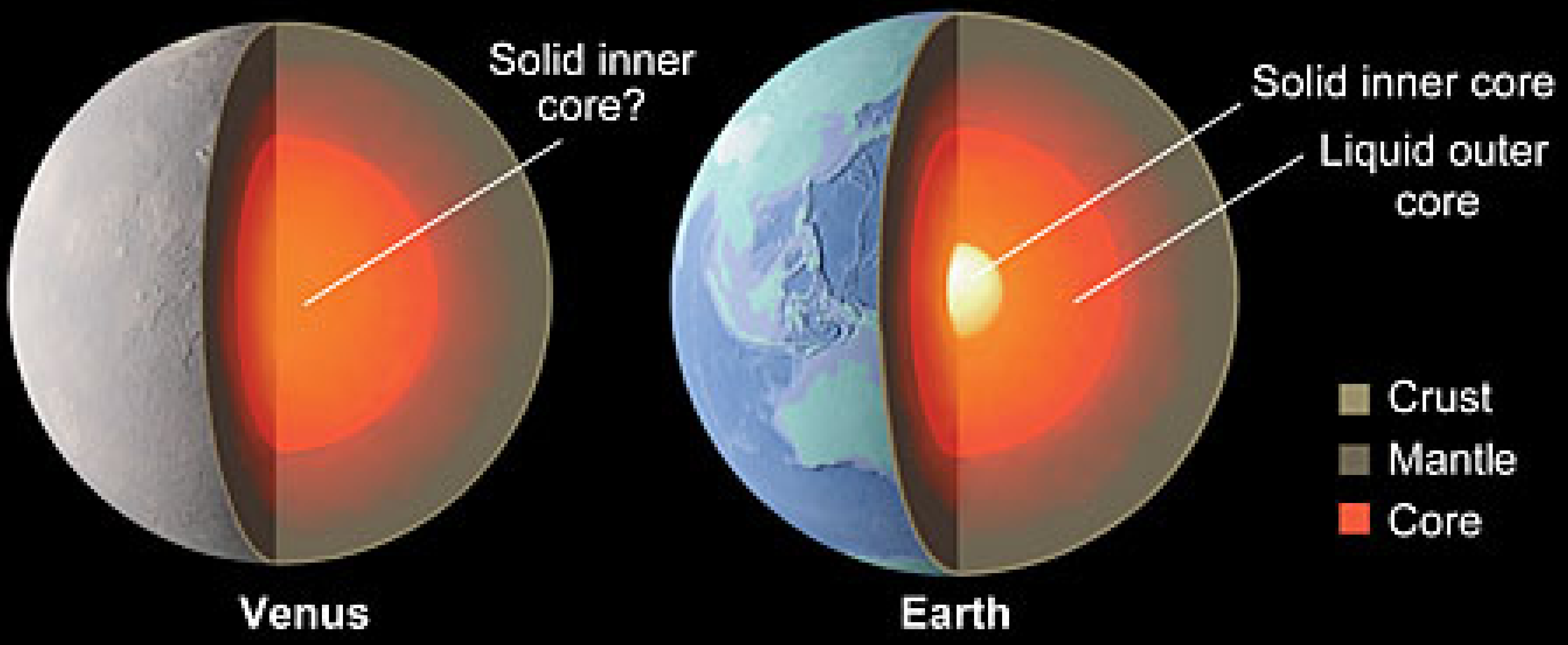
But Venus Has No Magnetic Field. Why?

- We'd long speculated it is because Venus rotates so slowly it doesn't provide the differential interior rotation to drive convection and hence the moving magnetic material to generate a field.
- Then for the past 20 years, the work of Nimmo goes further, concluding the mantle is too hot (perhaps helped by the hot CO2 atmosphere?) to permit a steep enough temperature gradient out of the core to support convection.
- But a new work (Jacobson *et al* 2017) builds on why the convection is missing (described here 2017) suggests that it is more typical for an inner planet to NOT have a magnetic field, and that the Earth is the unusual one.

The lack of a homogenizing impact would also explain why Venus has no tectonic plates

- Jacobson *et al* show that Nimmo's idea is valid and that indeed a stratified chemical composition is formed during the accretion phase. This is true right out to the crust, and gravitational stability between layers would shut off convection and hence tectonic motion.
- Helped no doubt by the hot CO2 atmosphere which keeps the mantle hotter than otherwise and hence lowering the temperature gradient from the core, which also inhibits convection.

Venus' core may be solid throughout, while Earth has a liquid convecting outer core.



Why Would a Homogenized Core Promote a Magnetic Field?

- Layering of lighter materials on top of heavier materials is gravitationally very stable against convection. Even with a strong temperature gradient from inner to outer, the density layering would kill convection, and hence the large scale moving charges to generate a field.
- But Earth was hit by a Mars-sized planet after it had formed layers and this impact scrambled those layers right to the iron core, allowing a liquid outer core with convection of iron-rich material and hence our strong magnetic field.

From Jacobson *et al.* 2017

- *"Here we show that the cores of Earth- and Venus-like planets should grow with stable compositional stratification unless disturbed by late energetic impacts. They do so because higher abundances of light elements are incorporated into the liquid metal that sinks to form the core as the temperatures and pressures of metal-silicate equilibration increase during accretion. We model this process and determine that this establishes a stable stratification that resists convection and inhibits the onset of a geodynamo.* ***However, if a late energetic impact occurs, it could mechanically stir the core creating a single homogenous region within which a long-lasting geodynamo would operate. "***

Venus Geology Summary

- Thick clouds prevent measuring by reflection the chemical composition of the crustal surface
- Venus appears to be still volcanically active, but no evidence of plate tectonics
- Both fit nicely with the thin crust expected, and the absurdly hot 800-900 F temperatures
- We'll see this is due to the Greenhouse Effect and Venus' 95% CO_2 atmosphere, later when we discuss planetary atmospheres

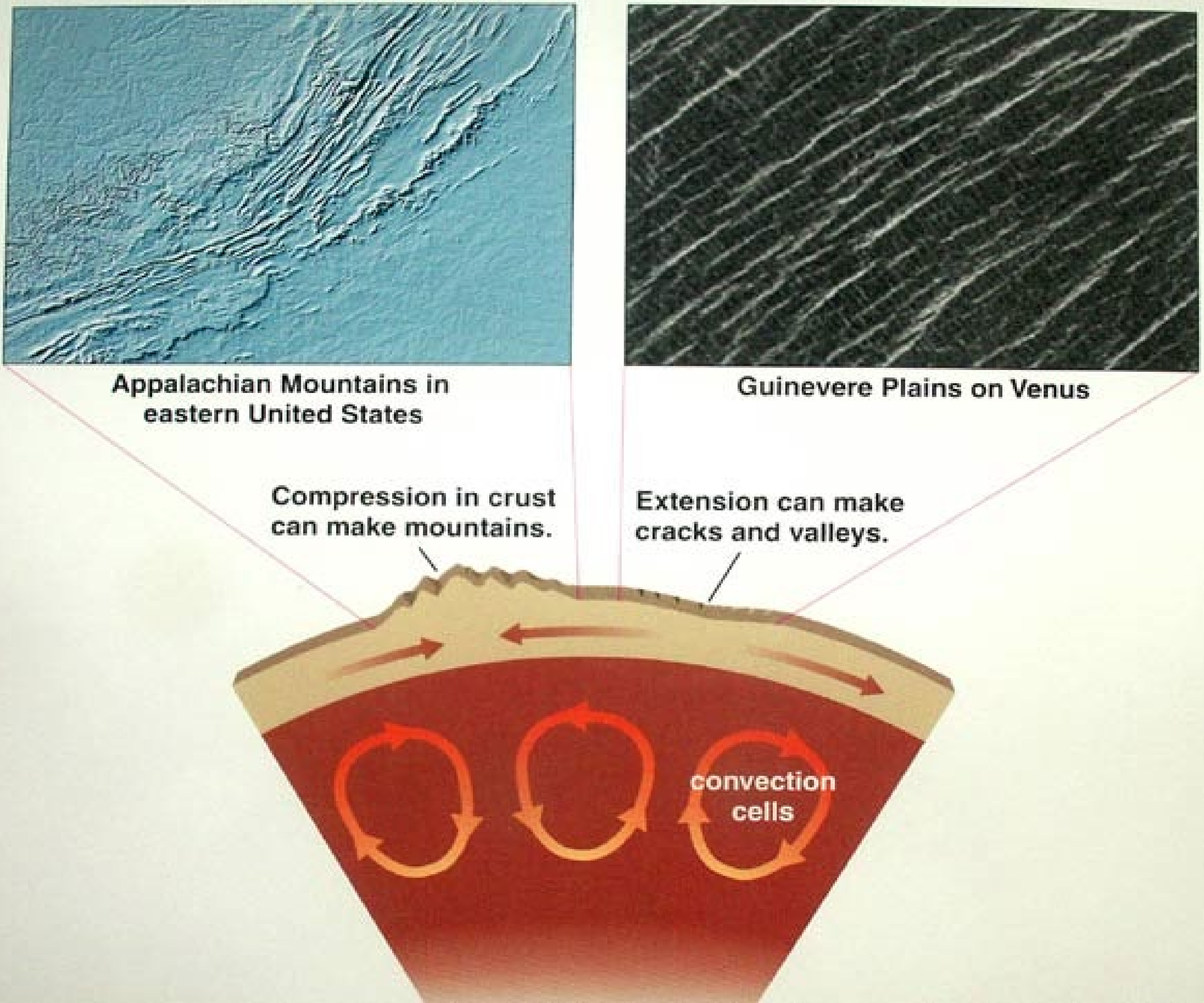
Earth – largest inner planet

- Crust divided into tectonic plates which move due to friction against the moving molten mantle underneath. Continental drift animation
- **Earth is the only planet which has clear tectonic plates. Jupiter's Europa is the only other solar system object which seems to have plates**

The Major Tectonic Plates of Earth

The Mid Atlantic Ridge – A Plate Boundary Spreading Zone

Earth's Ocean Basins and Continents: Spreading at one edge, subduction at the other. Spreading zones dark here



Appalachian Mountains in eastern United States
Guinevere Plains on Venus
Compression in crust can make mountains.
Extension can make cracks and valleys.
convection cells

Green aurora above Iceland volcano – Iceland sits on the mid-Atlantic Ridge spreading zone

But Why?

- We don’t see tectonic plates on the other inner planets. Why Earth?
- 1. The Earth is the most massive inner planet and so would be expected to have the thinnest crust, most easily broken.
- 2. The Earth has a rapid rotation…
- **The reason may be related to the origin of the moon….**

Our Moon is Weird

- No other inner planet has a sizable moon
- If our moon formed as part of a spinning proto-Earth, you'd expect it would orbit in the same plane as our equator. Instead it orbits close to the ecliptic plane
- It's got only a tiny iron core
- Its chemical composition is the same as the earth's outer mantle and crust
- And… the Earth spins much faster than Venus or Mercury, and faster than Mars too.

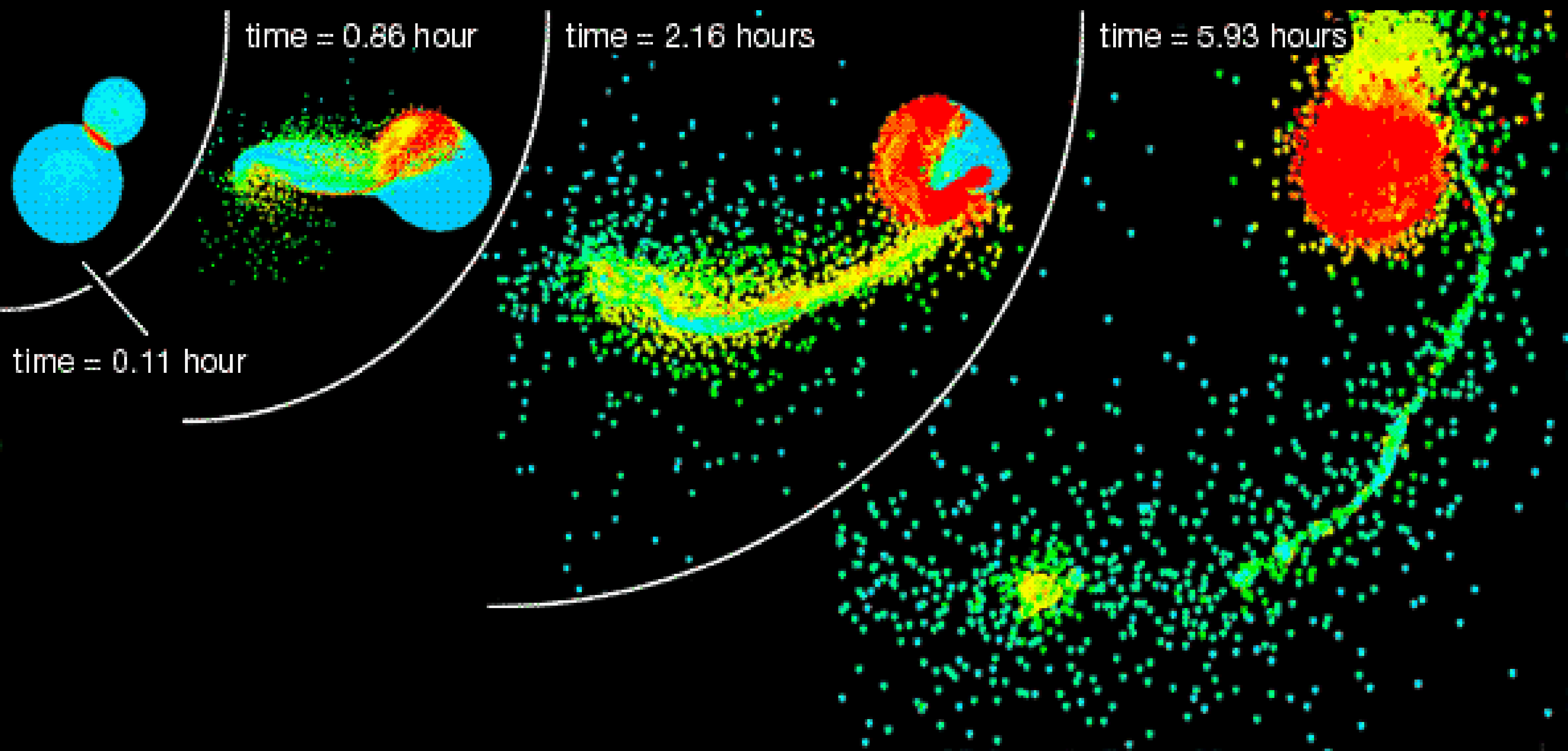
Putting These Clues Together Strongly Suggests…

- ***The moon was created as a by-product of a glancing blow; a collision between the early Earth and another planet.***
- How big a planet? We have run detailed numerical simulations, throwing all the relevant physics into numerical computer codes of different kinds (smoothed-particle hydrodynamics, adaptive mesh, finite-element…) numerically integrating it forward
- Here's an animation of such a simulation

Formation of Our Moon

- Looks like a ~Mars-sized planet hit the Earth with a glancing blow
- Spraying molten and vaporized material mostly made of the outer parts of both planets, outward and into a ring
- The heavy stuff of both planets settled by gravity to the bottom, giving the Earth a significant iron / nickel core
- The light stuff became the ring, 90% of which slowly spiraled back in by collisional friction and settled back onto our surface becoming our crust
- But roughly 10% of the ring was able to self-gravitate into the Moon before it fell back to Earth
- **The moon is only a little more than 1% of the mass of the Earth.**

Only 6 hrs after Impact, the moon has already formed at the end of the tidal tail of blasted-off material. Most lands back on Earth, but the Moon condenses quickly enough to escape tidal decay back onto the Earth. Impact creates great heat and liberates much internal volatiles

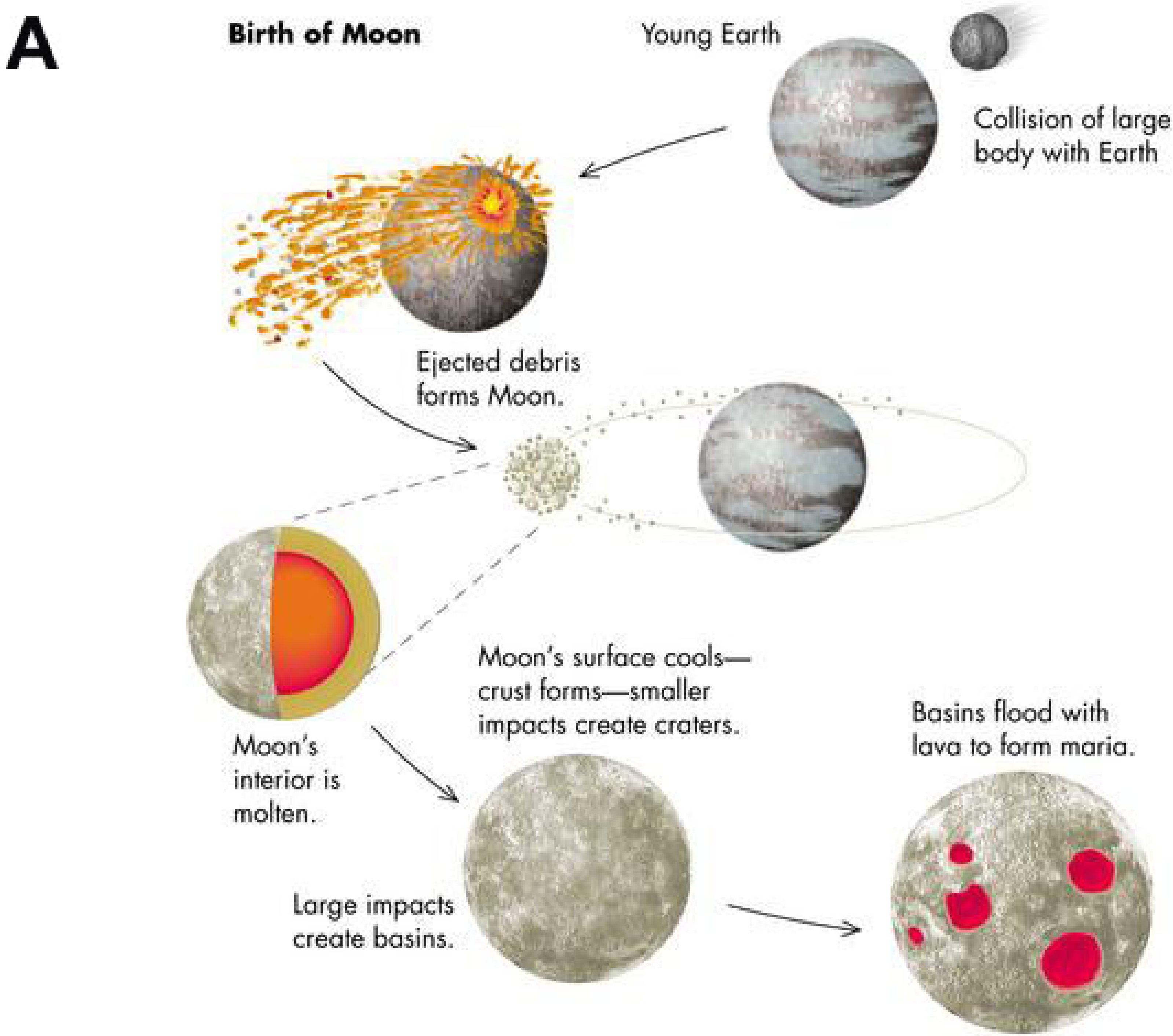


After it formed…

- We would then have a very rapidly rotating Earth, much faster than it currently is
- And a very close moon
- So we would get very strong tides – MANY times stronger than today's tides
- And tidal friction would rapidly transfer angular momentum from the spinning Earth to the orbiting moon, causing it to spiral outward
- Till today, when it is now 60 Earth radii away, and tidal stress is weak, but still slowly pushing the moon further away (about 1 cm/yr), and having slowed the earth to a 24 hour "day".

But then, why doesn't the Moon orbit exactly in the Ecliptic Plane? Why 5 degrees off?

- The impactor's orbital plane can easily be within a degree or two of Earth's and still arrive at Earth from above or below the Earth and thereby have a collision plane tilted from the ecliptic.
- Also, the last collisions and near-misses before the end of planet formation …A 2015 published numerical study finds that if the latest collisions were large-sized objects, with many more near misses expected than actual collisions of course, then we could explain why the moon got gravitationally tweeked away from an initial ecliptic orientation, and also why the iron-affiliated elements gold and platinum are as common in our crust as they are.
- The idea is that they fell as part of these late collisions, after the Earth's crust had formed and provided a barrier preventing the new heavy stuff sinking to the core.


A
Birth of Moon
Young Earth
Collision of large body with Earth
Ejected debris forms Moon.
Moon's interior is molten.
Moon's surface cools—crust forms—smaller impacts create craters.
Basins flood with lava to form maria.
Large impacts create basins.

The Lunar highlands are only a little older than the lunar maria (dark basins)

- We know this because of the rocks brought back from the moon by the astronauts of the 1969-73 Apollo missions.
- The fact that the dark basins have so few craters tells us that the cratering rate in the solar system was high when the moon was very young, and then dropped dramatically.

Just a pretty picture: moon and Plieades star cluster

ancient and heavily cratered.

Lunar maria are huge impact basins that were flooded by lava. Only a few small craters appear on the maria.

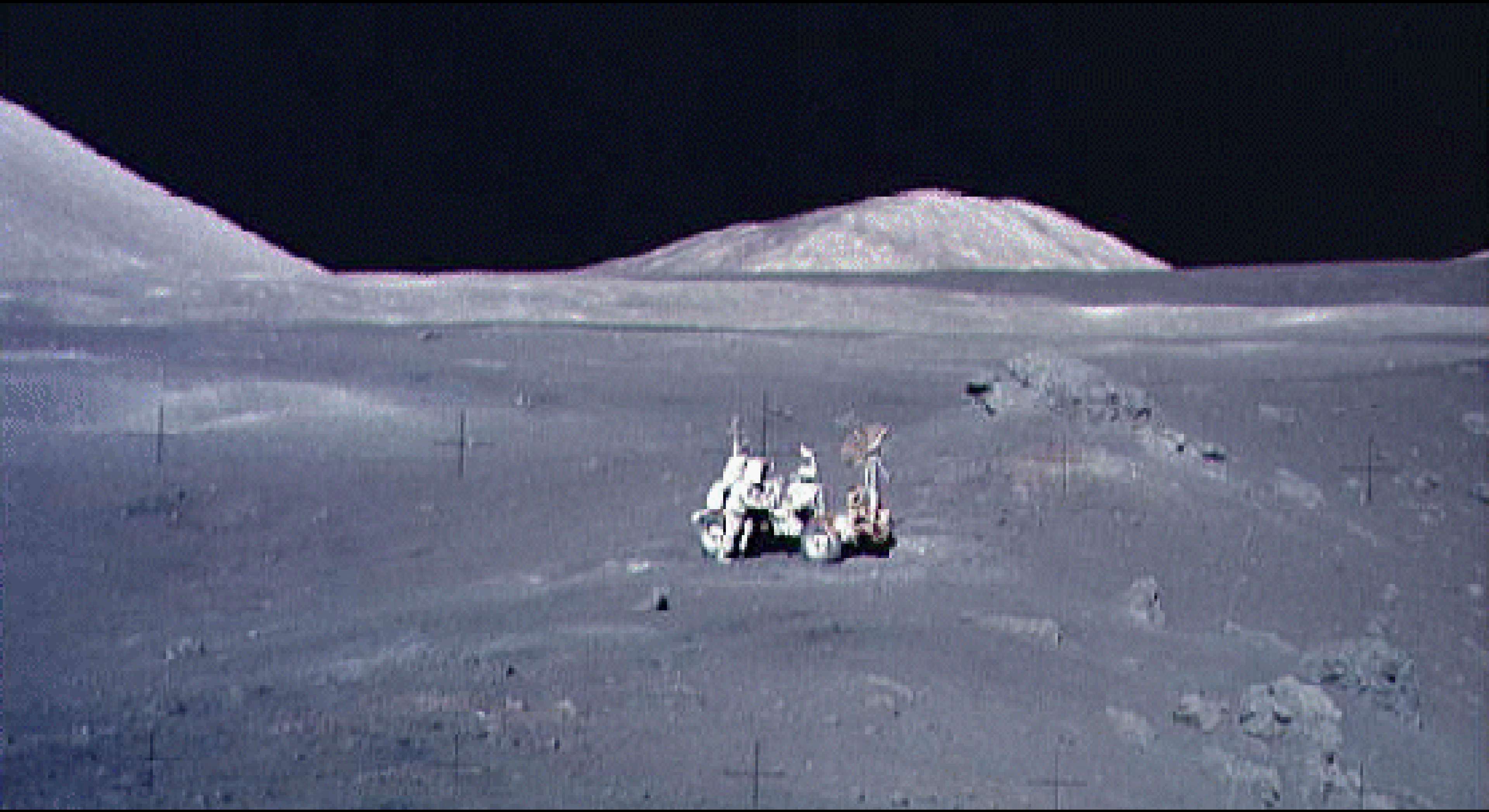
a

b

Age of the Moon

- Oldest meteorites are 4.57 billion years
- Oldest lunar rocks are 4.4 to 4.5 billion years ago, from lunar highlands. In '09, a zircon from an Apollo 17 rock dated to 4.42 billion years old. The crust of the moon should have formed within 90 million years of the impact creating the moon, putting the origin impact at ~4.52 billion years ago, agreeing well with the oldest meteorites.
- Oldest rocks on Earth are 4.0 billion years, from northern Canada, but zircon crystals imbedded in some rocks date to at least 4.3 billion years old


Gassendi
Mersenius
MARE HUMORUM
Hippalus
Doppelmayer
Rupes Kelvin
Campanus
Vitello



Summary on the Moon

- Inner planets don't HAVE moons – because they likely were not massive enough nor spinning rapidly enough to have a massive flattened disk which could condense into moons, like the bigger outer planets did. And, strong tidal pull from sun would also inhibit moon retention
- Now - We DO have a Moon! But it took a random (rare?) collision with a BIG (former) planet to make it, and it took a glancing blow to produce the massive ring required to make a moon which is still only 1% of our own mass, to spin us up.
- Then later smaller collisions tweeked orbit 5 degrees off
- The existence of the moon may be key to why life is possible on our planet, but more on that later in the course.

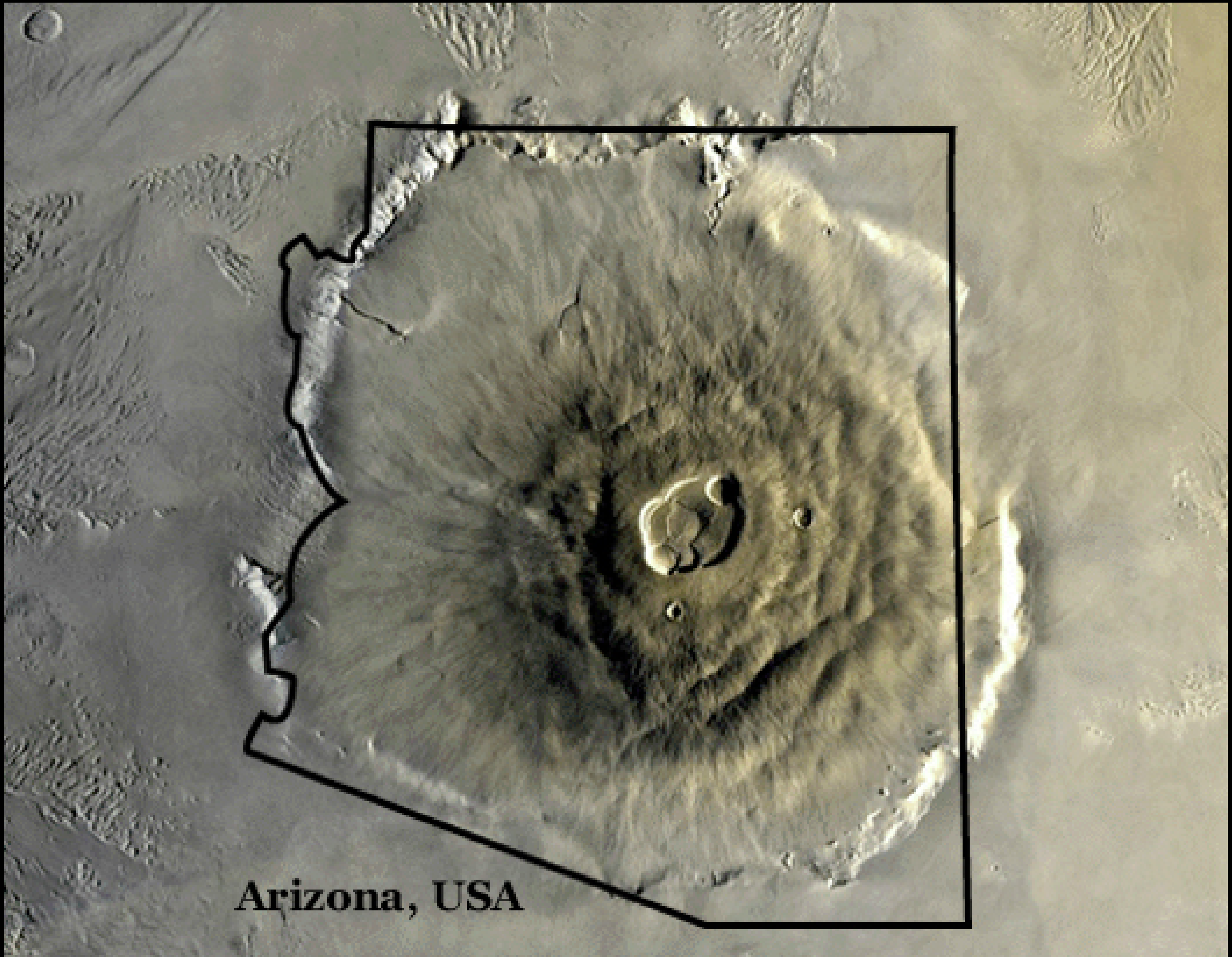
Key Points on Earth Geology

- Plate Tectonics requires (1) thin crust (therefore large planet), and (2) Rapid rotation. Earth is the only planet that qualifies!
- Plate tectonics dominates mountain building, weathering, re-surfacing of Earth.
- Water brought to Earth by comets, meteorites early on. Dominates the surface
- Earth unique in having a large moon. Moon stabilizes the Earth's rotation axis.
- Life and carbonates also essential to Earth geology, we'll talk about with Earth atmosphere and climate talk.

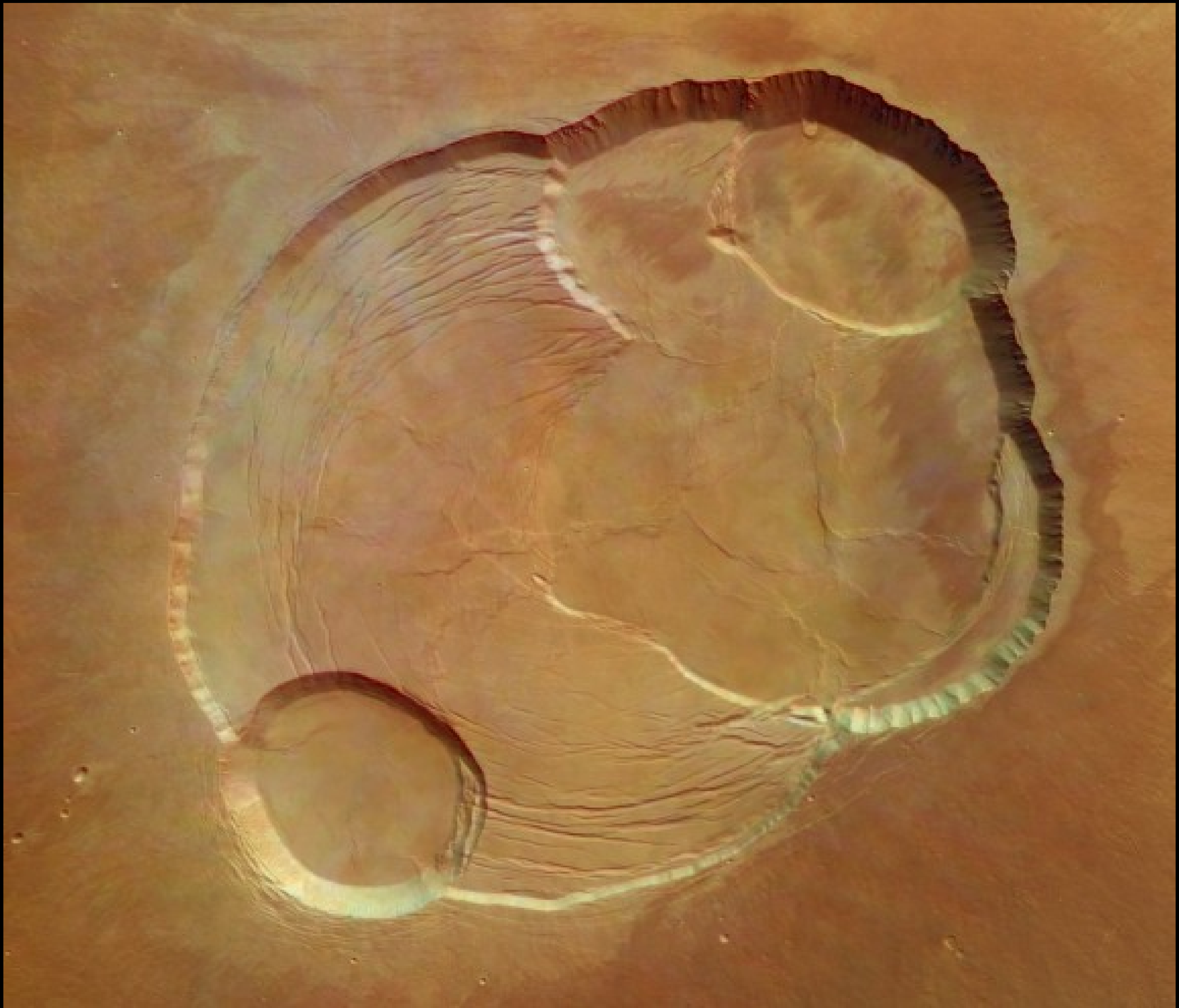
Mars – Half the Diameter of Earth

- Mars is small, cooled quicker than Earth, with much less radioactive decay heat contribution. Crust thickened up and yet…
- Huge volcanoes, with possible recent activity
- No moving tectonic plate evidence
- Ancient volcanoes but they do not appear to be active in the recent past

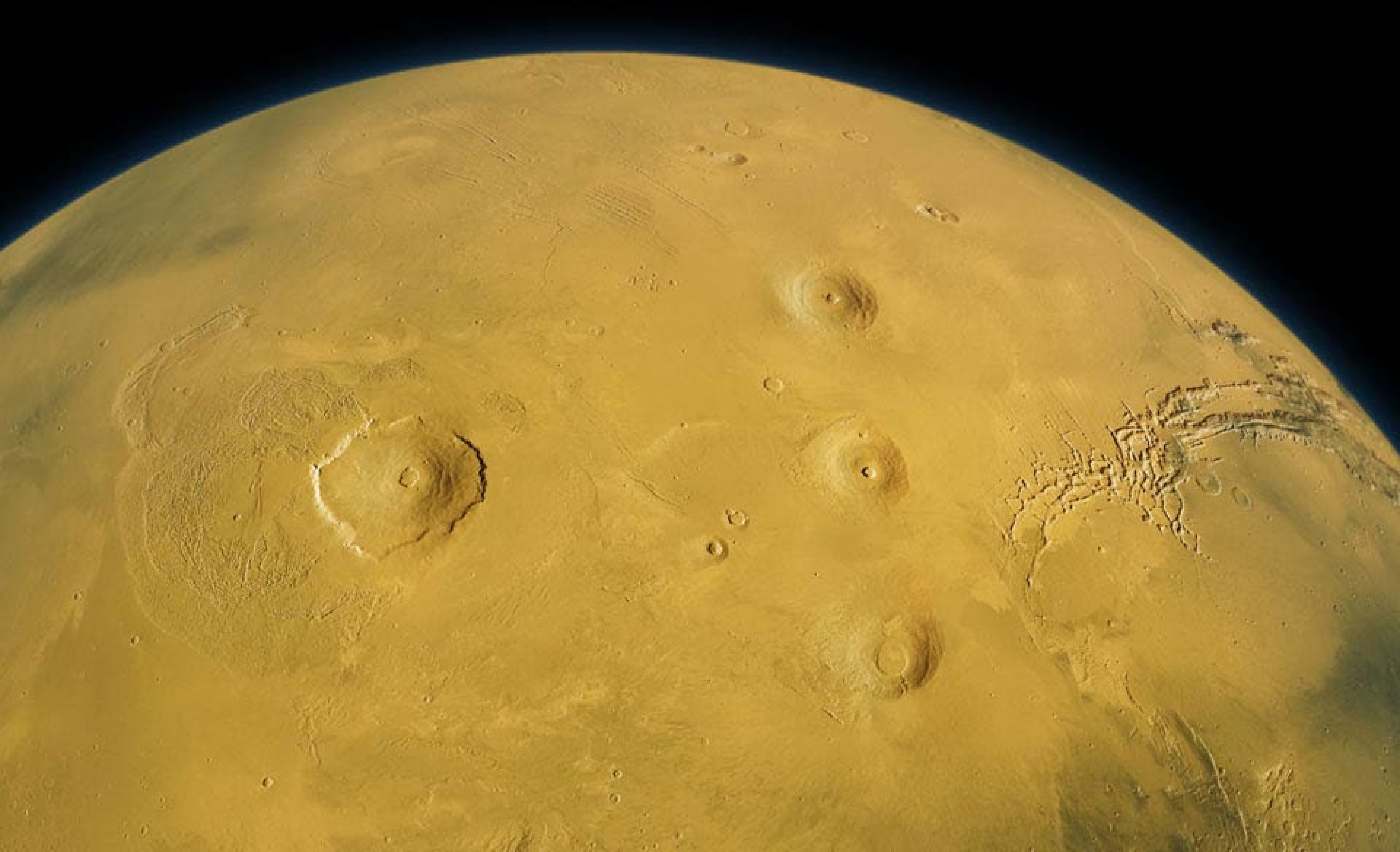
Olympus Mons *vs.* Arizona



Olympus Mons Caldera, showing multiple periods of magma, cooling nd solidifying

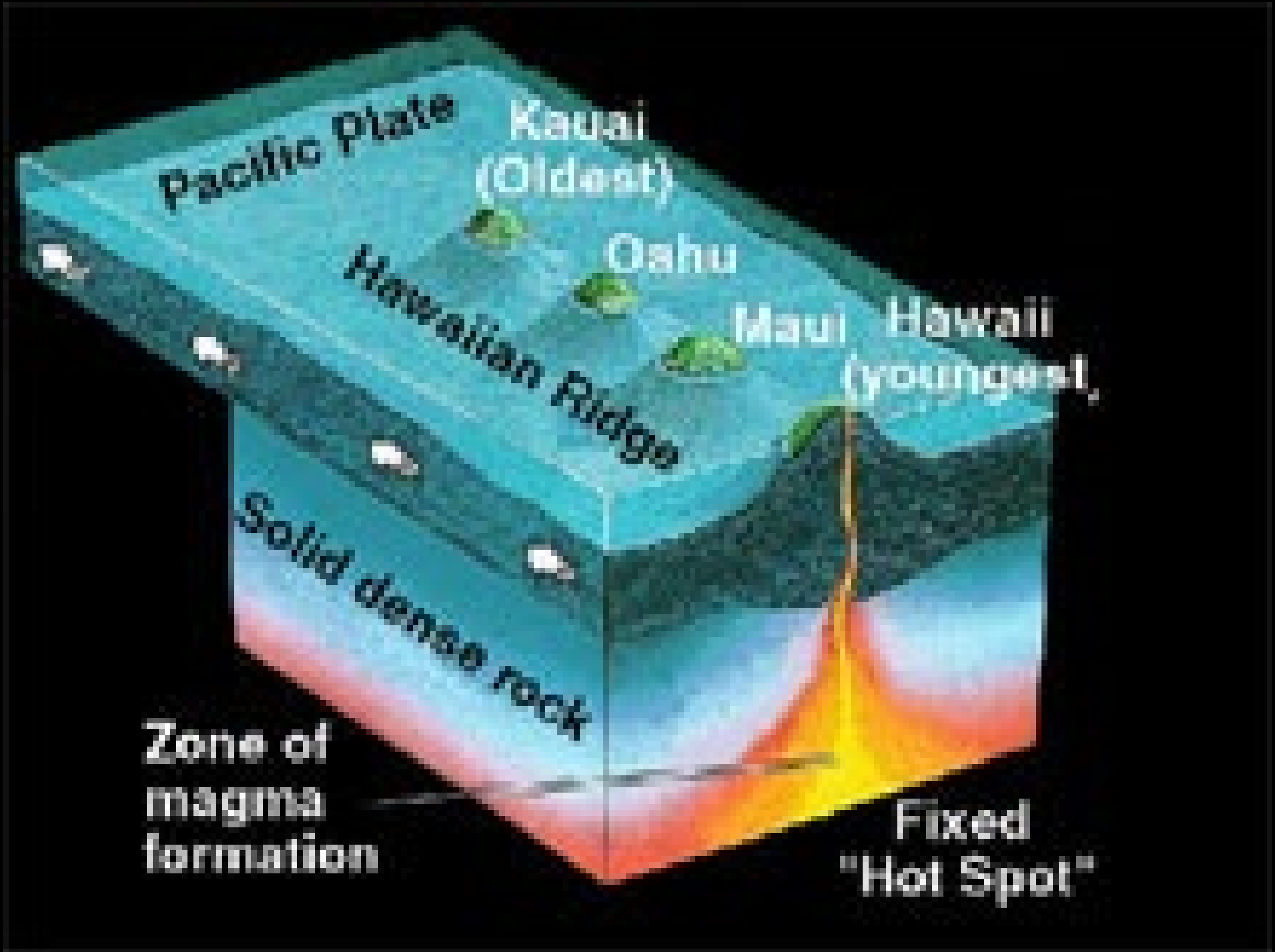


The Tharsis region – the Biggest volcanoes in the Solar System

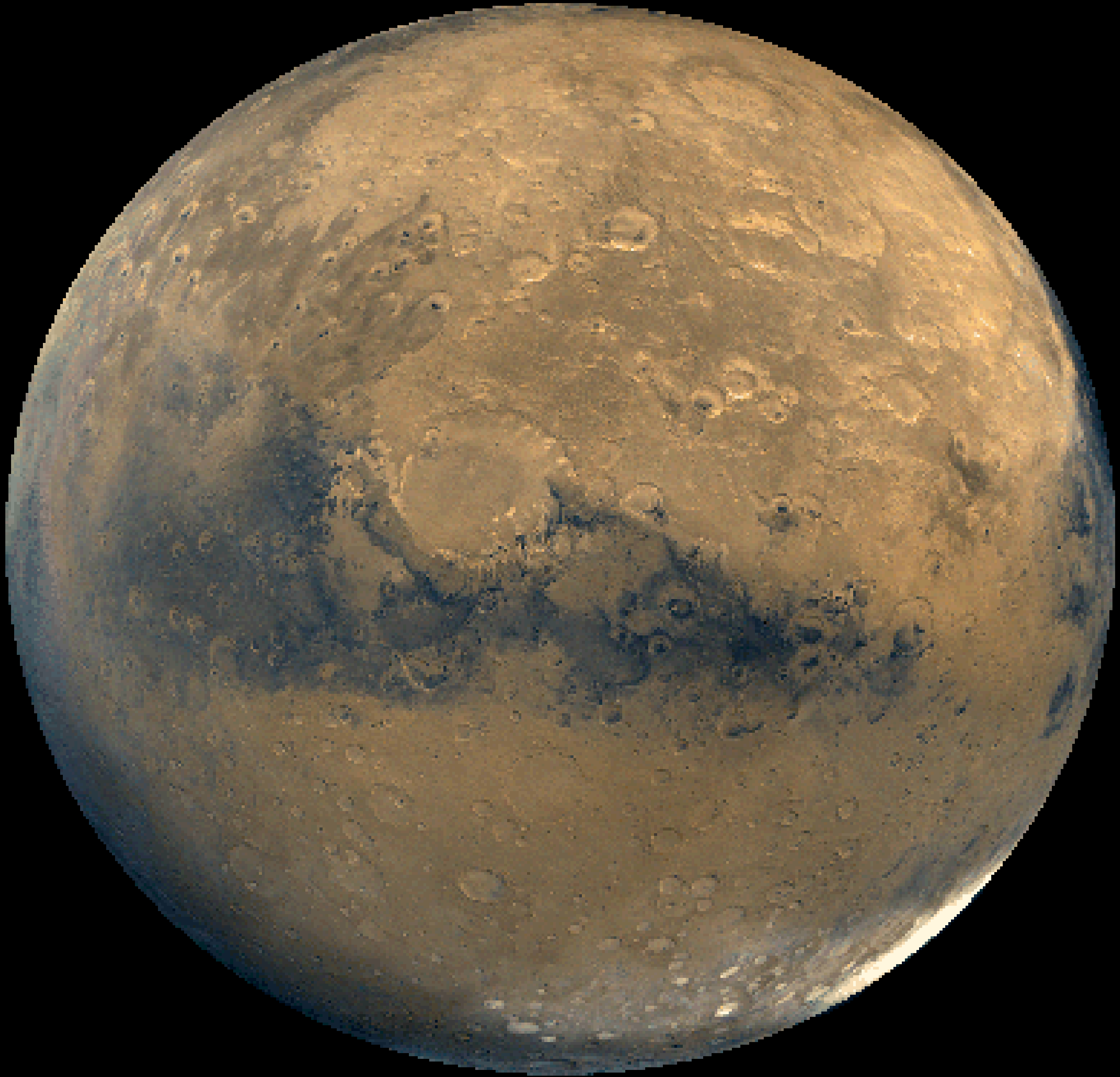


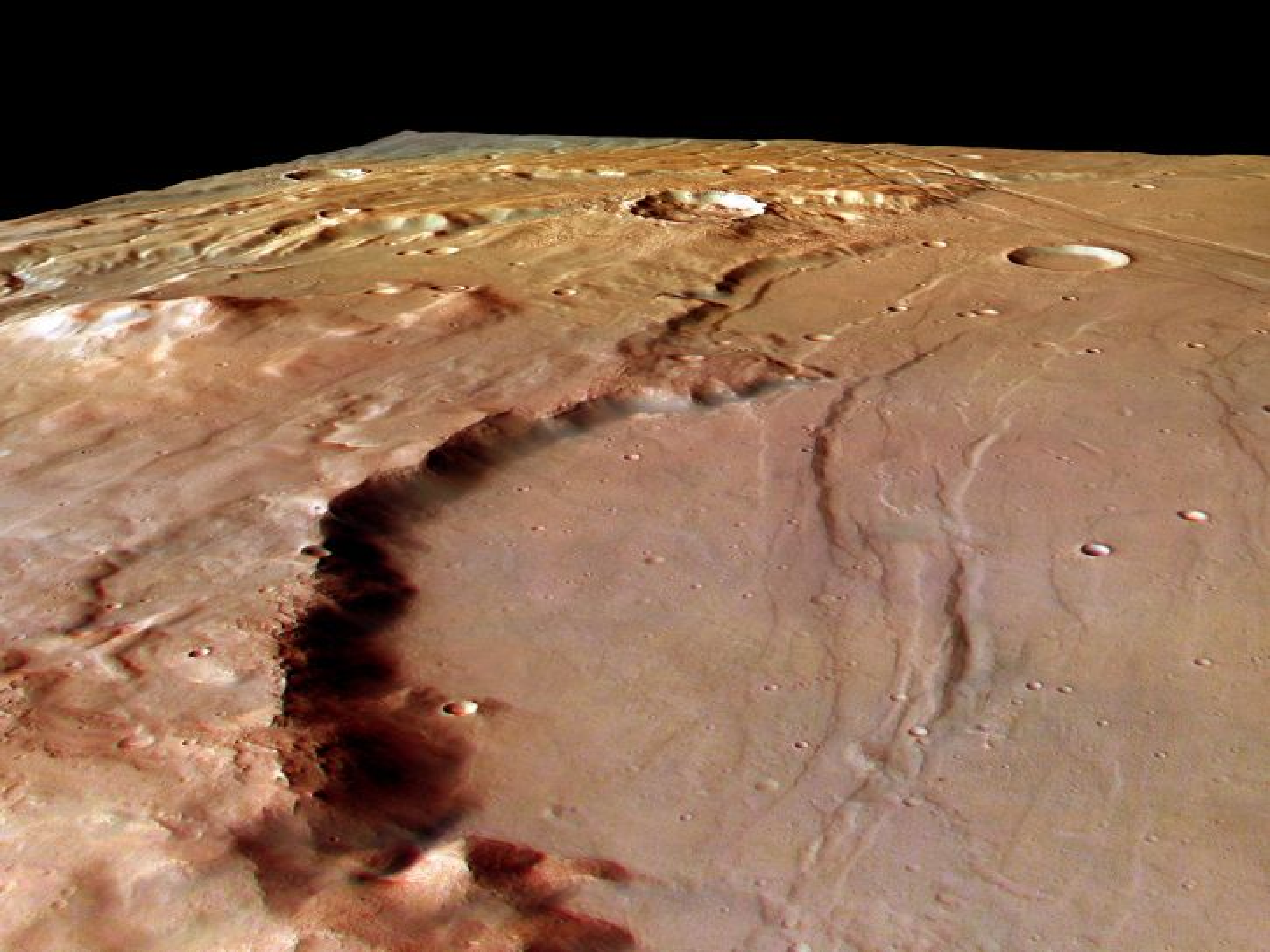
Mantle “Hot Spot” formation by convection

Hawaiian Islands String due to Plate Motion.

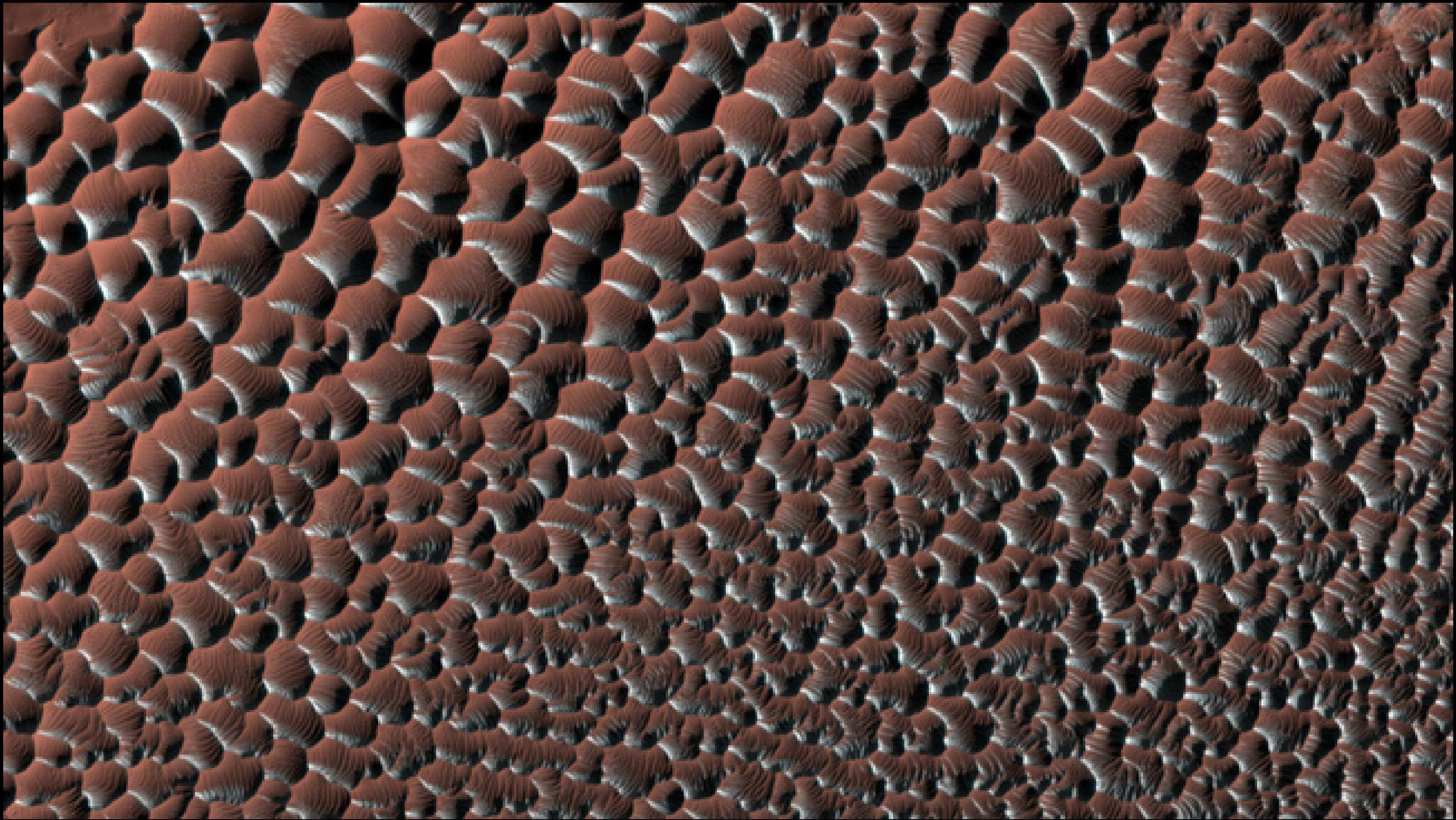


Impact Craters are Big – From Large Asteroids?

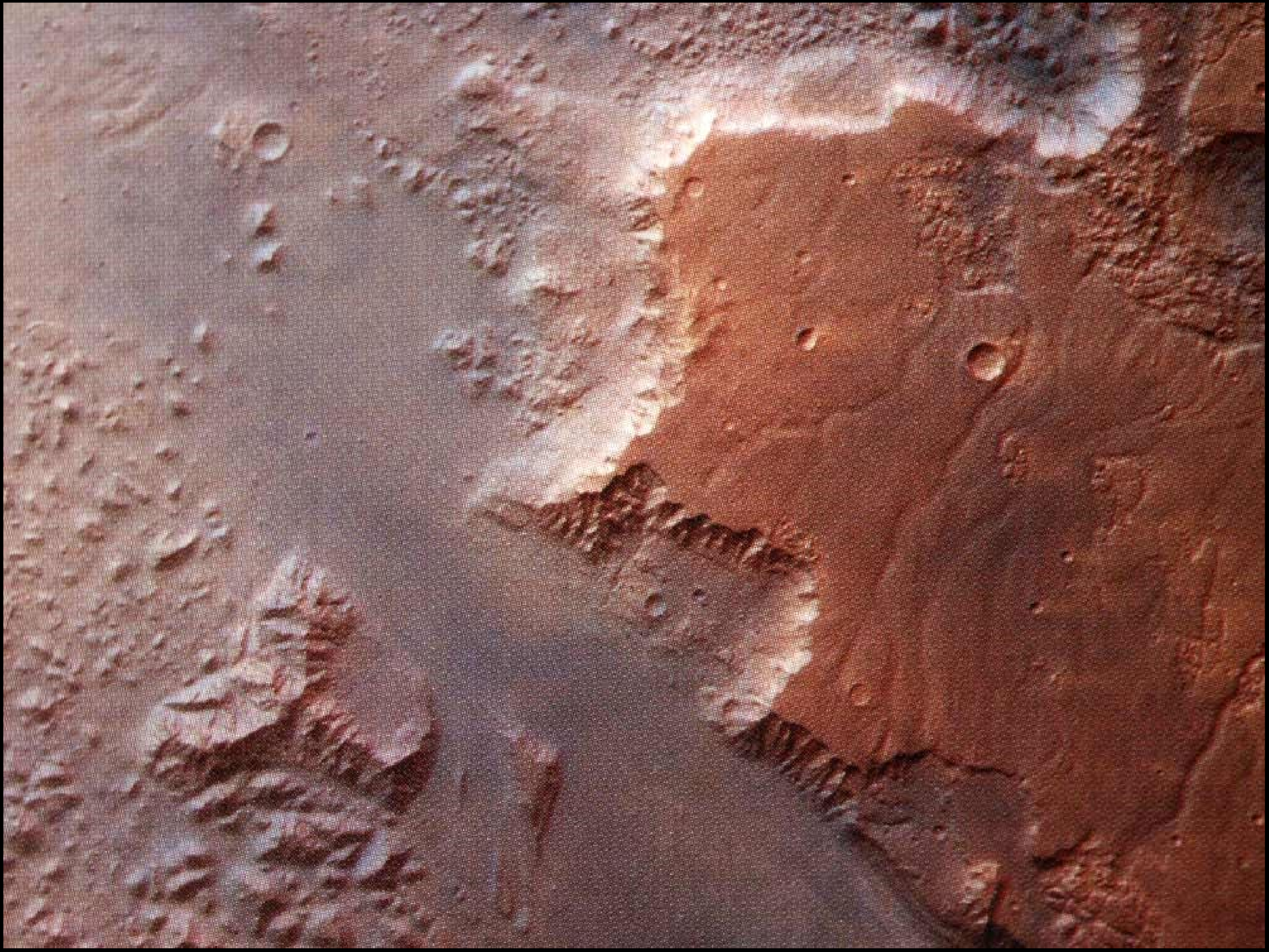




Martian Sand Dunes, with characteristic cresent pattern from wind deposition



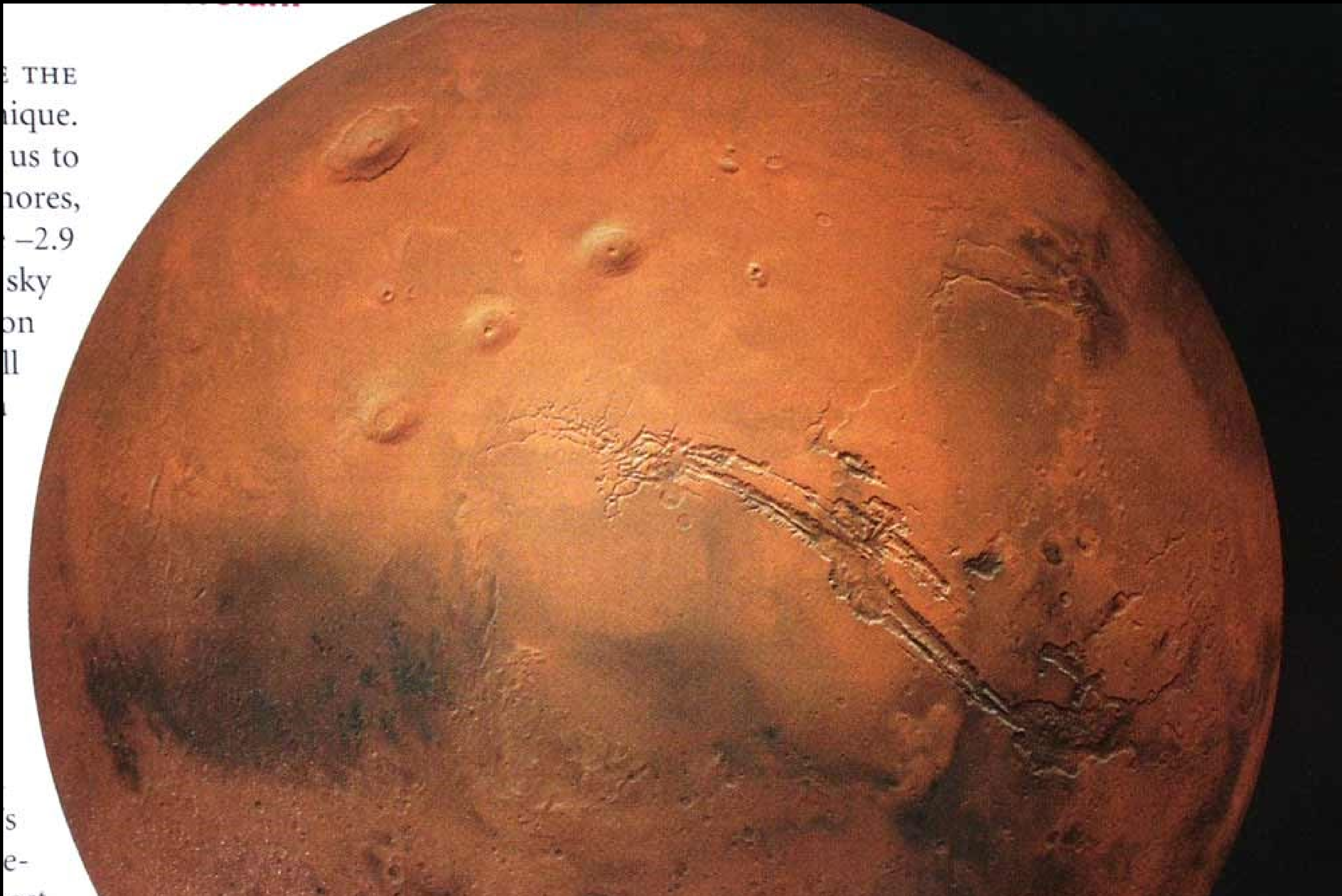
Martian continents, ancient ocean basin

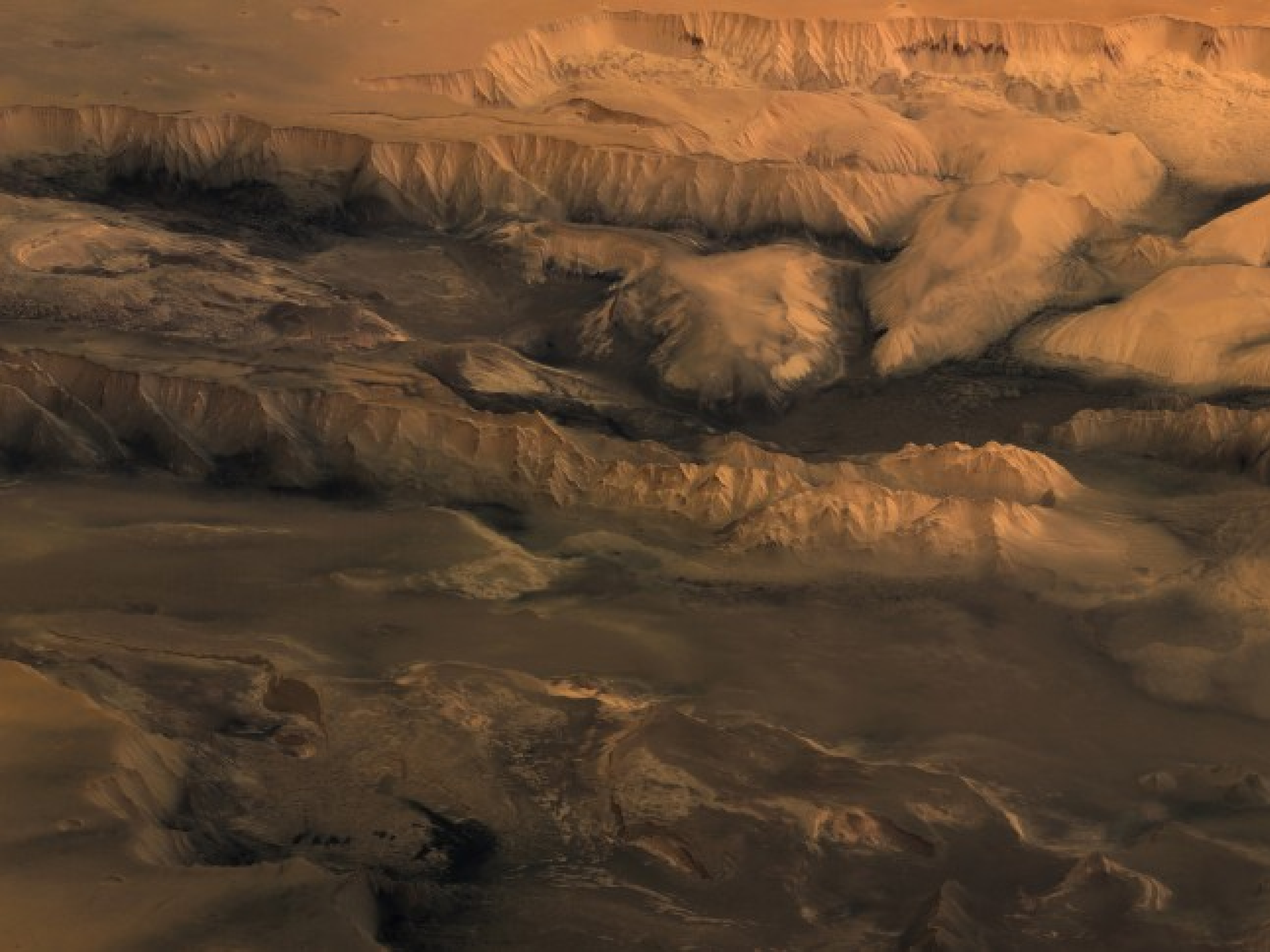


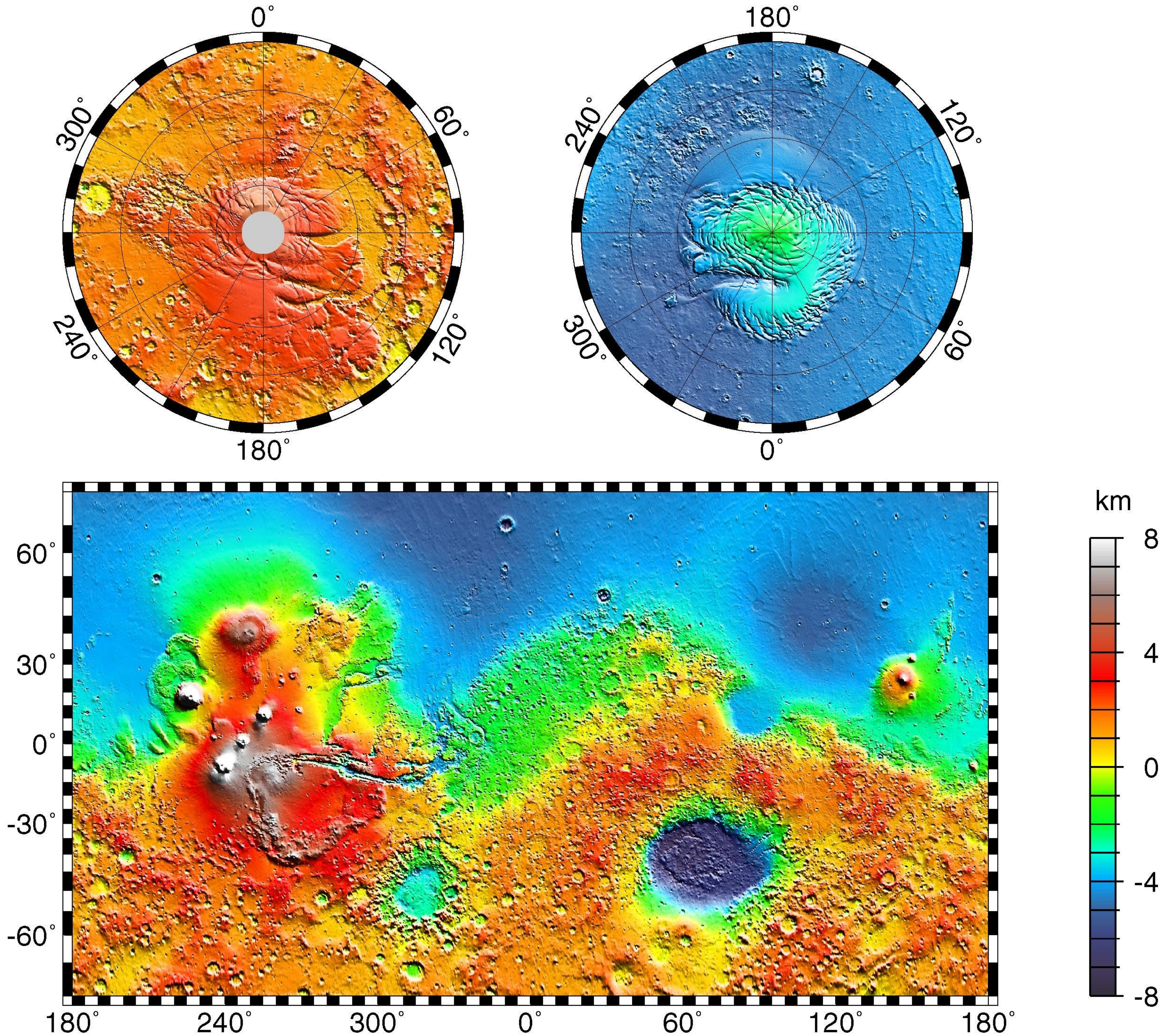
A Coastline? Fractal dimension of coastline matches those on Earth

- Edge erosion suggests ancient water
- Requires Martian atmosphere to be thicker and warmer than it is now.
- Atmospheric loss, more on that later.
- Remarkable asymmetry of Mars – Northern Hemisphere all deep ocean basin. Southern hemisphere all continental highlands…
- Huge impact basin in North??

Valle Marinaris: As Long as the U.S., 5x deeper than Grand Canyon. Erosion draining from Tharsis Region to polar lowlands?







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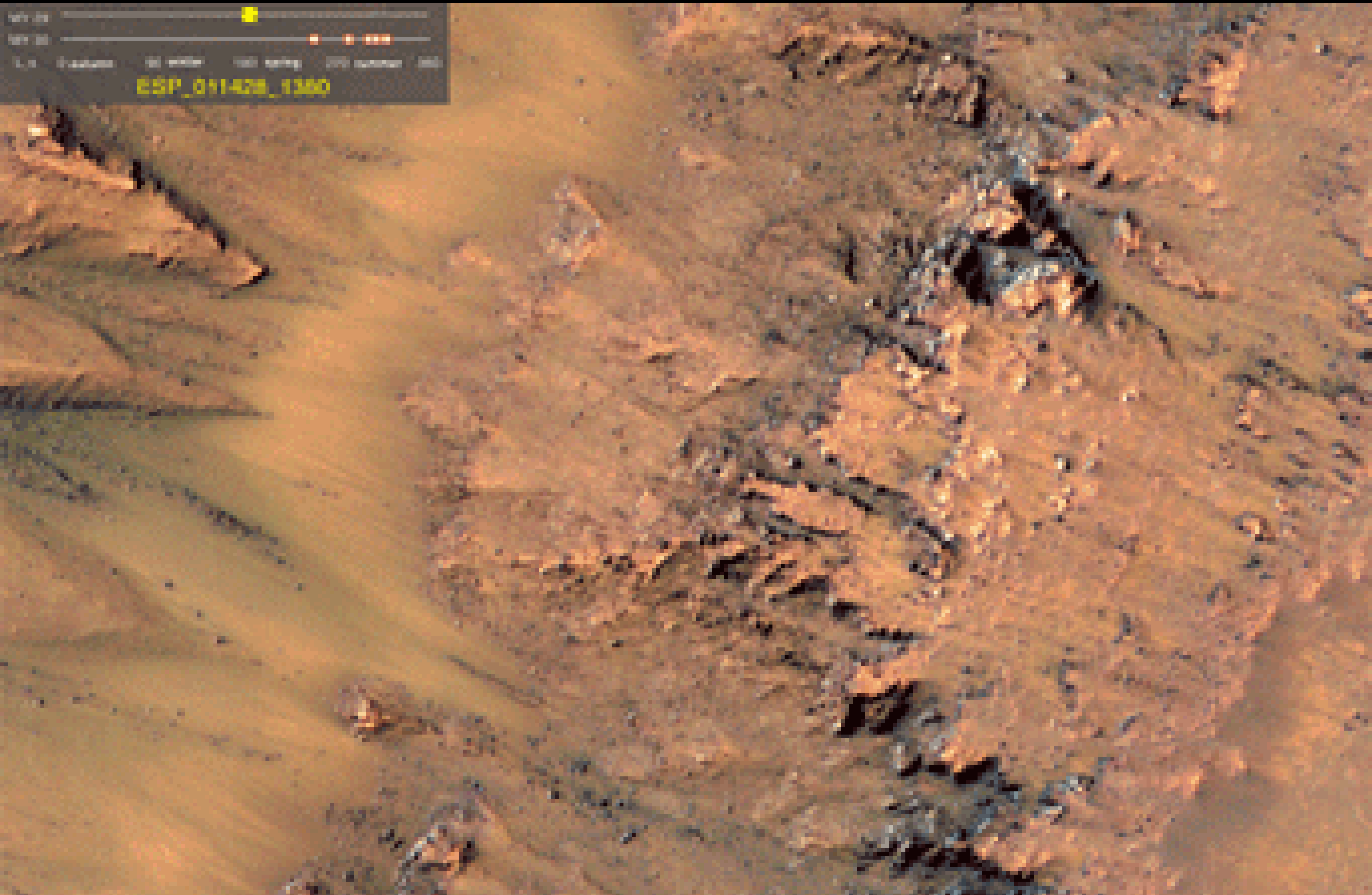
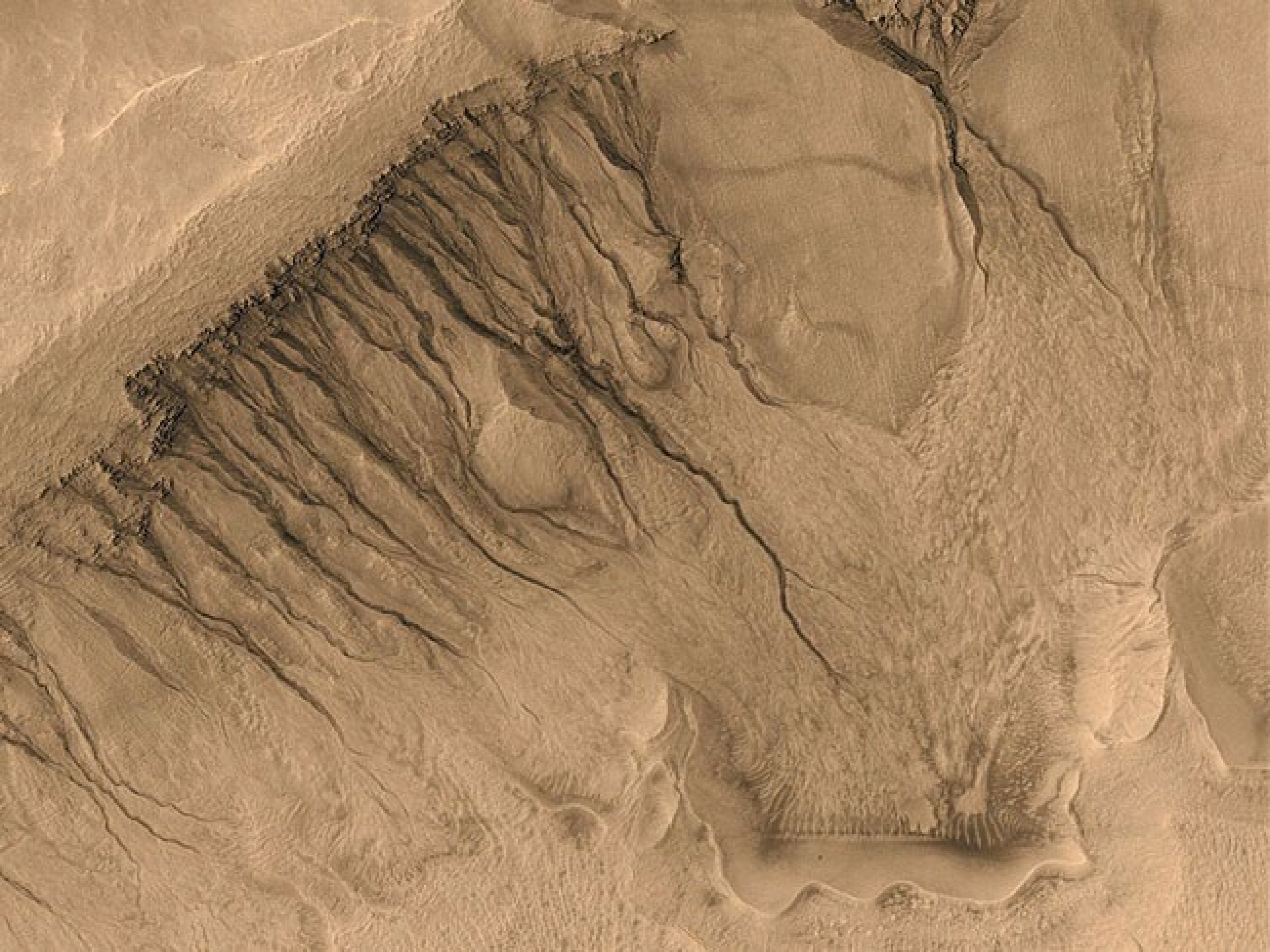
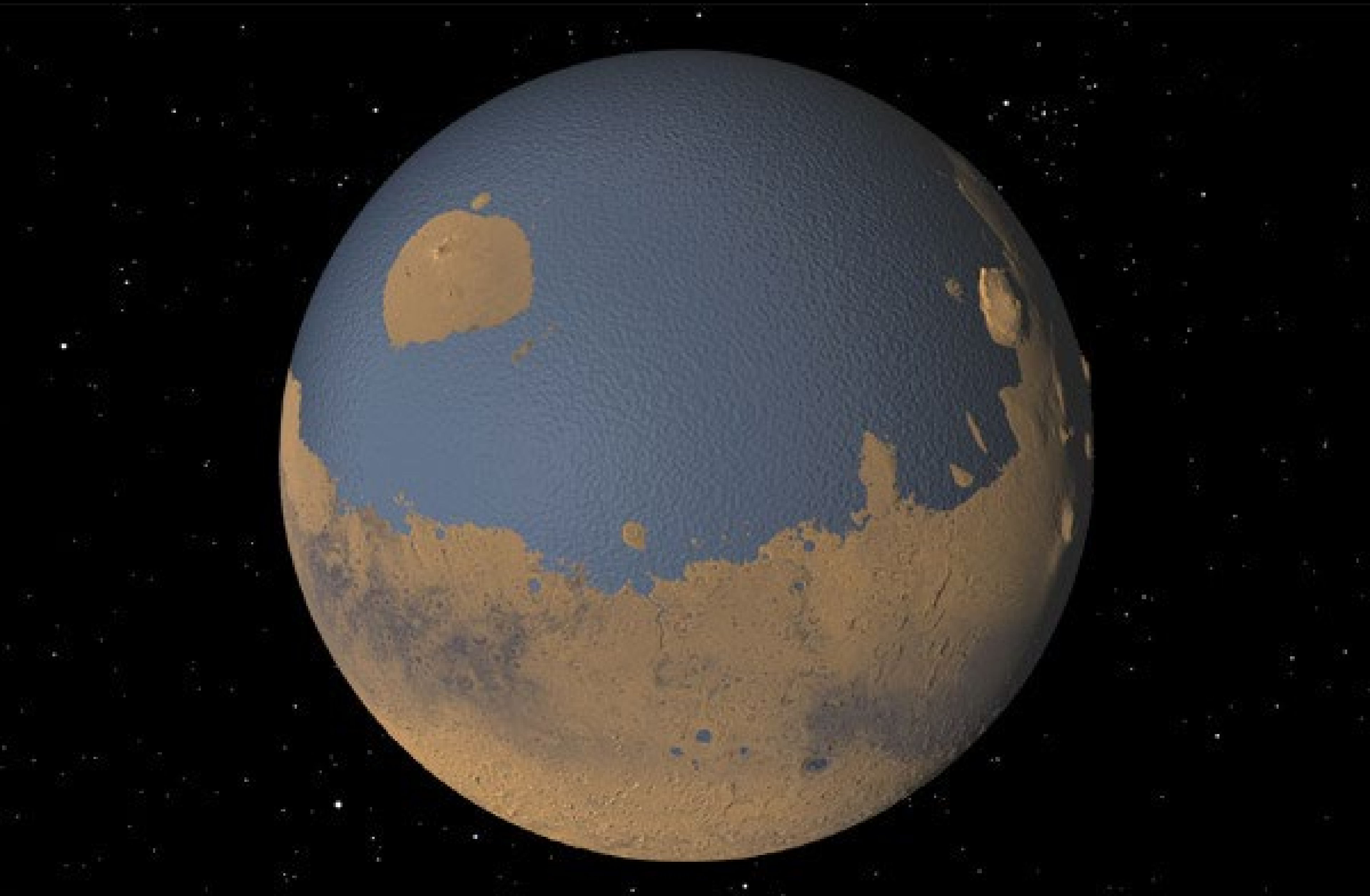
In Newton Crater: Shadow time lapse suggests flowing…. Something. Brine? Sand?

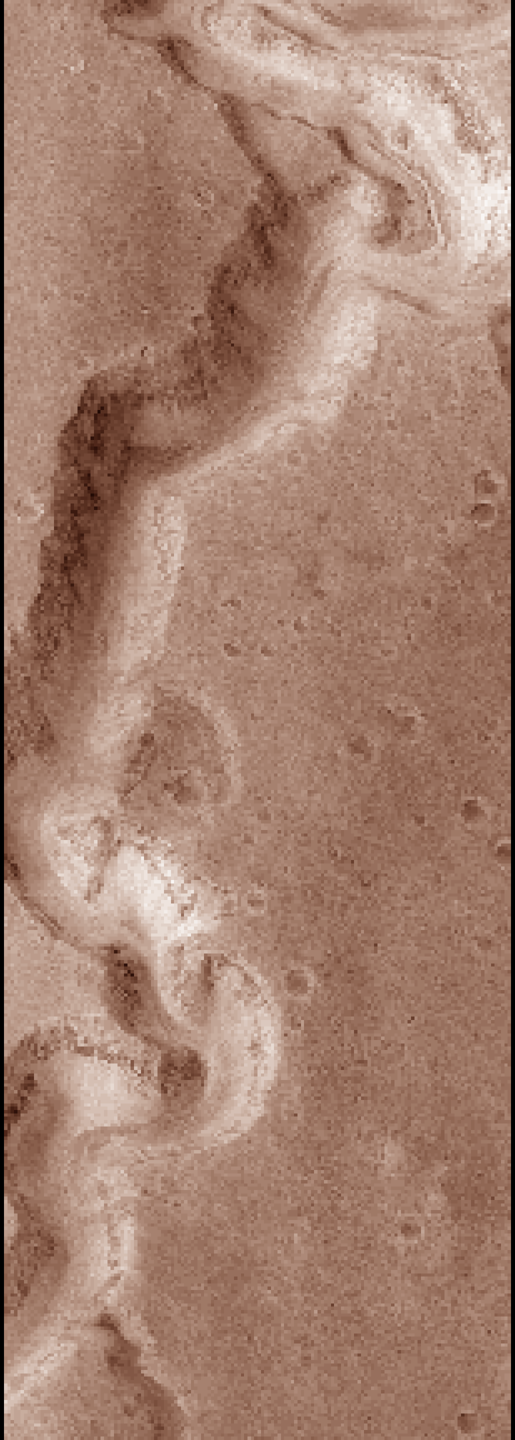




A Little Photoshop work, and we can visualize… An Ancient warm and watery Mars!



A dry riverbed, meandering through ancient crater fields



Ancient hot springs (inactive now), may get a closer look in a 2020 Mars mission

WHILE AN UNDERGRADUATE planetary-science student, I applied for a research position with a professor on campus. During my interview the professor looked at me and asked plainly, "What's your favorite planet?"

I was startled by the question but promptly answered that my favorite was not really a planet — I was fascinated by the planetary wannabes that make up the asteroid belt and the Kuiper Belt.

"Good," he replied. "I never hire any-

With the advent of the telescope came Earth's first Martians — those who dedicate their lives to understanding the red planet. In 1644 the first Martian surface features were recorded. By 1659 Christiaan Huygens had identified a prominent feature — now known as Syrtis Major — in a sketch. From that point on, Mars observers abound. No perihelic opposition (closest approach to Earth) came without a legion of Martians, armed with powerful telescopes, observing the red orb.

As telescopic technology advanced, so too did our understanding of Mars. The

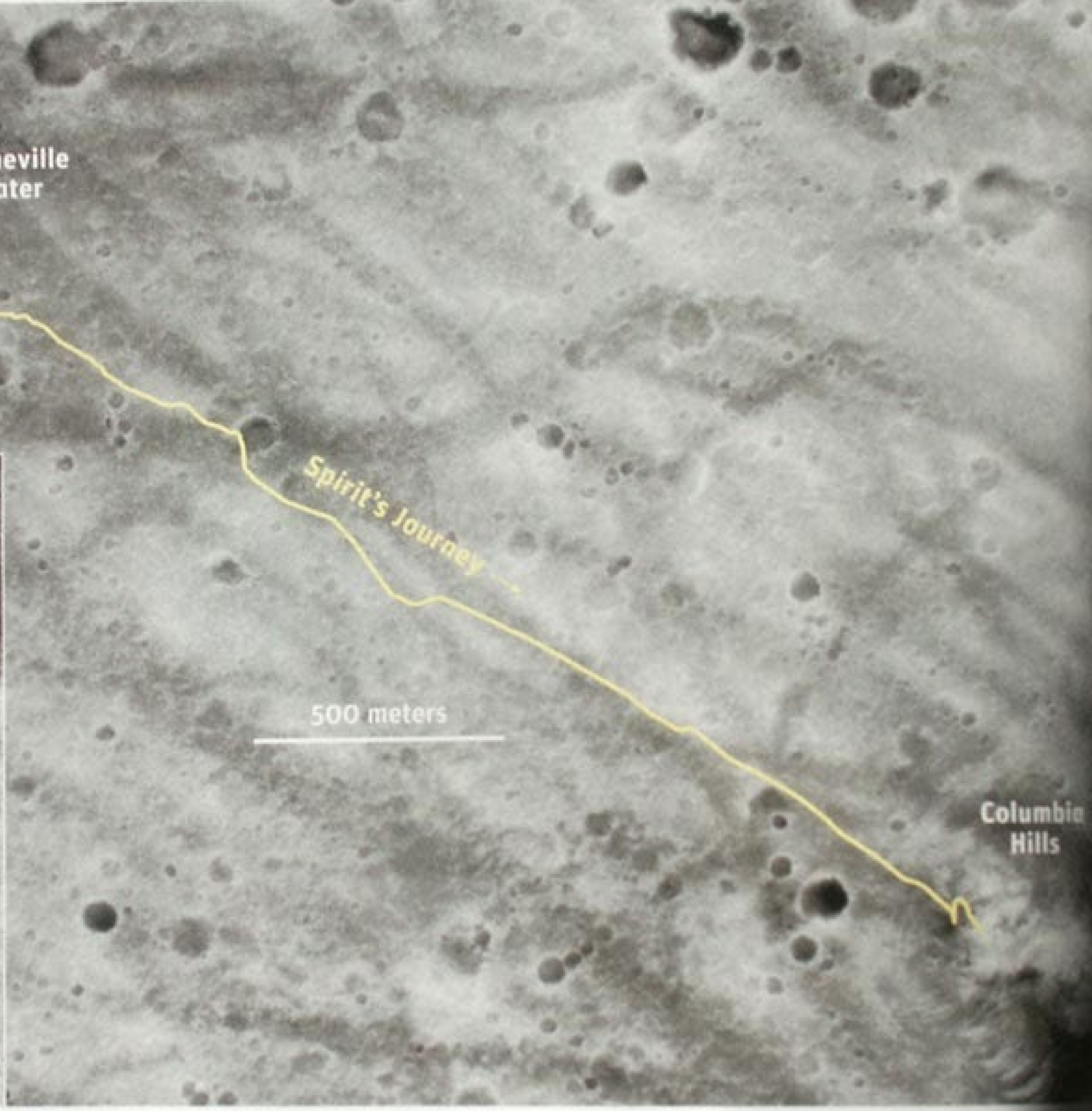
Italian, can mean artificial or natural channels). Lowell is portrayed as the passionate observer, always steadfast in his support of Martian canals and the civilizations, past or present, that must have

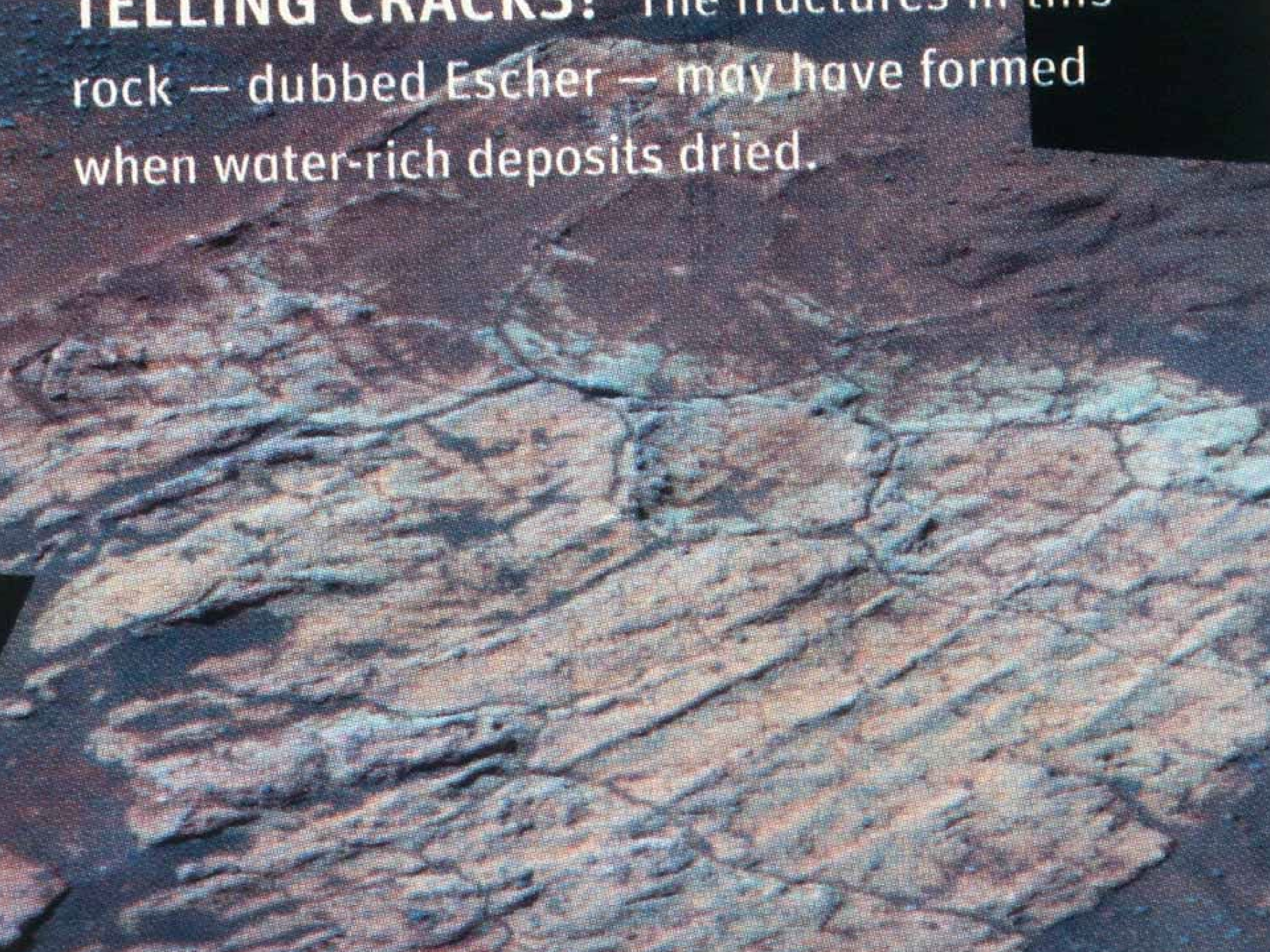
Two decades after the Viking spacecraft went to Mars, another lander finally snapped images of the planet's surface on July 4, 1997. The Mars Pathfinder mission was deemed a tremendous success; however, two subsequent missions failed. This Mars-scape was assembled from a mosaic of images from Pathfinder's camera. Courtesy NASA/JPL.

The Martian rover "Curiosity" – a mobile lab for drilling, sniffing, baking-and-shaking, photo'ing

And off it goes…dune-buggying across Mars

MARS TREK Spirit has traveled more than 4 kilometers across Gusev Crater and is now set to explore the Columbia Hills. *Inset:* The keen eye of Mars Global Surveyor's Mars Orbiter Camera captured the rover's tracks during its first 93 days *(sols)* on the planet.

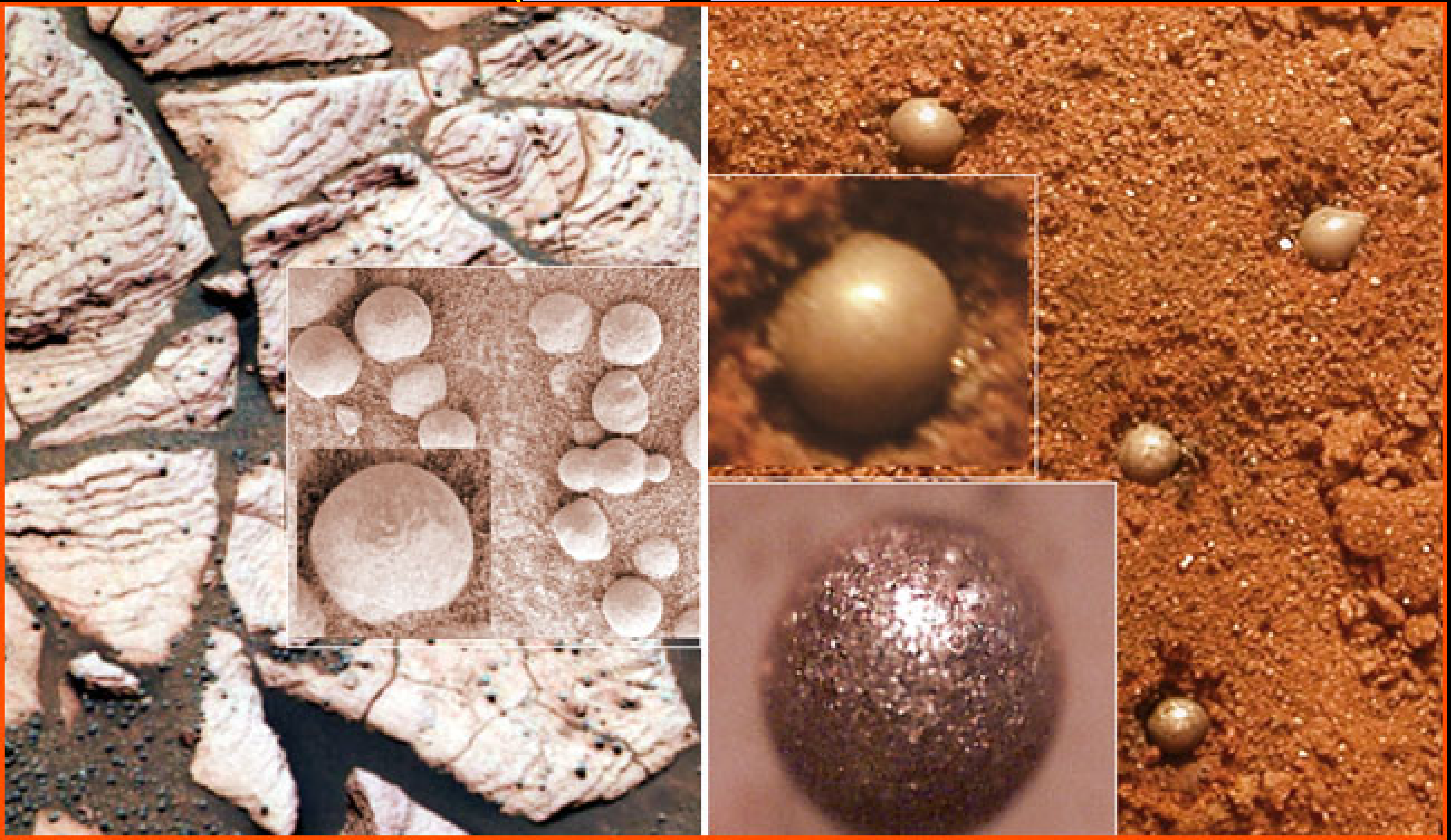




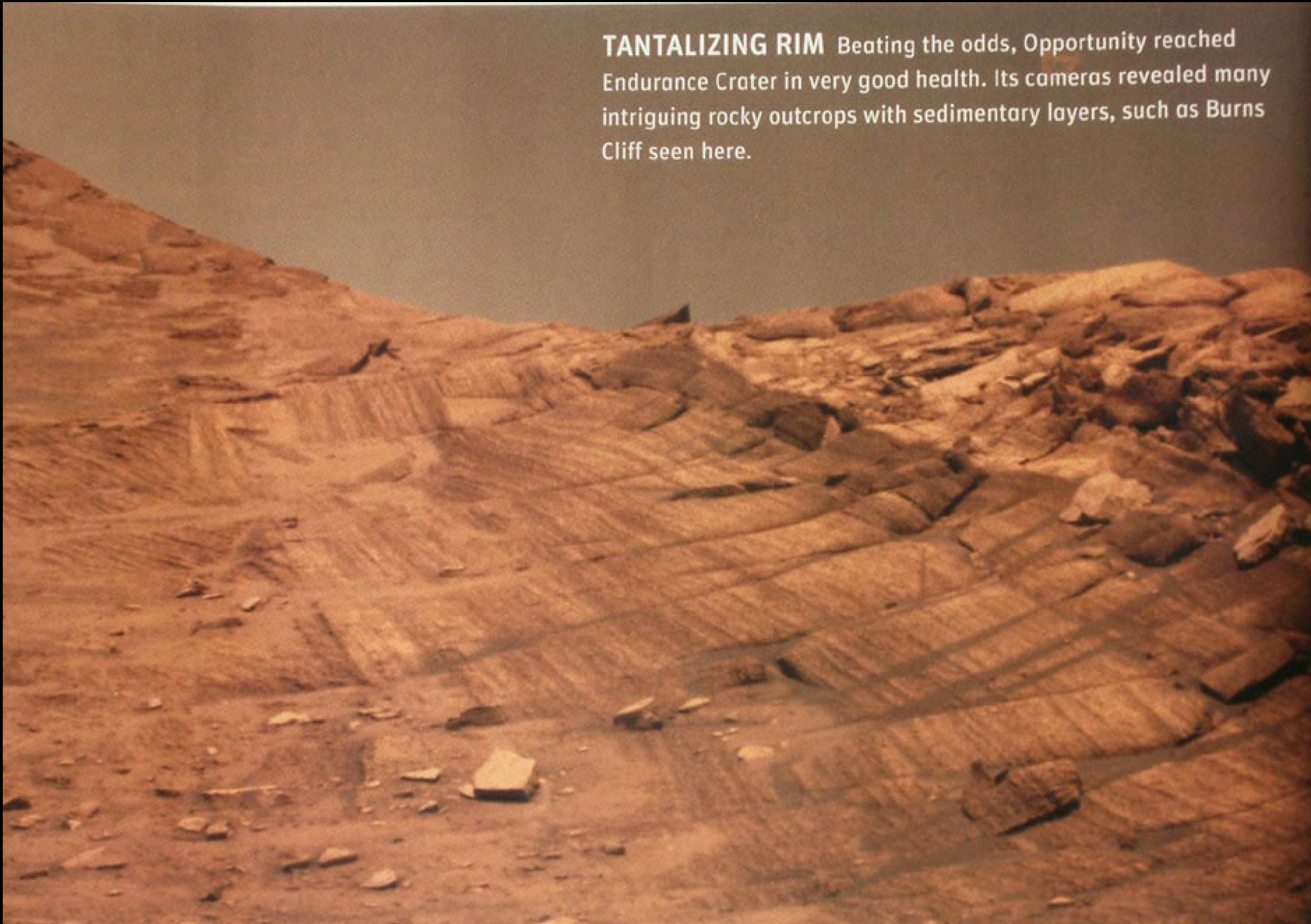
TELLING CRACKS! The fractures in this rock — dubbed Escher — may have formed when water-rich deposits dried.

These “blueberries” are controversial. They are primarily made of hematite – an iron-rich mineral which only forms in water. A competing, newer theory: they’re from a meteorite impact

(source , discussion.



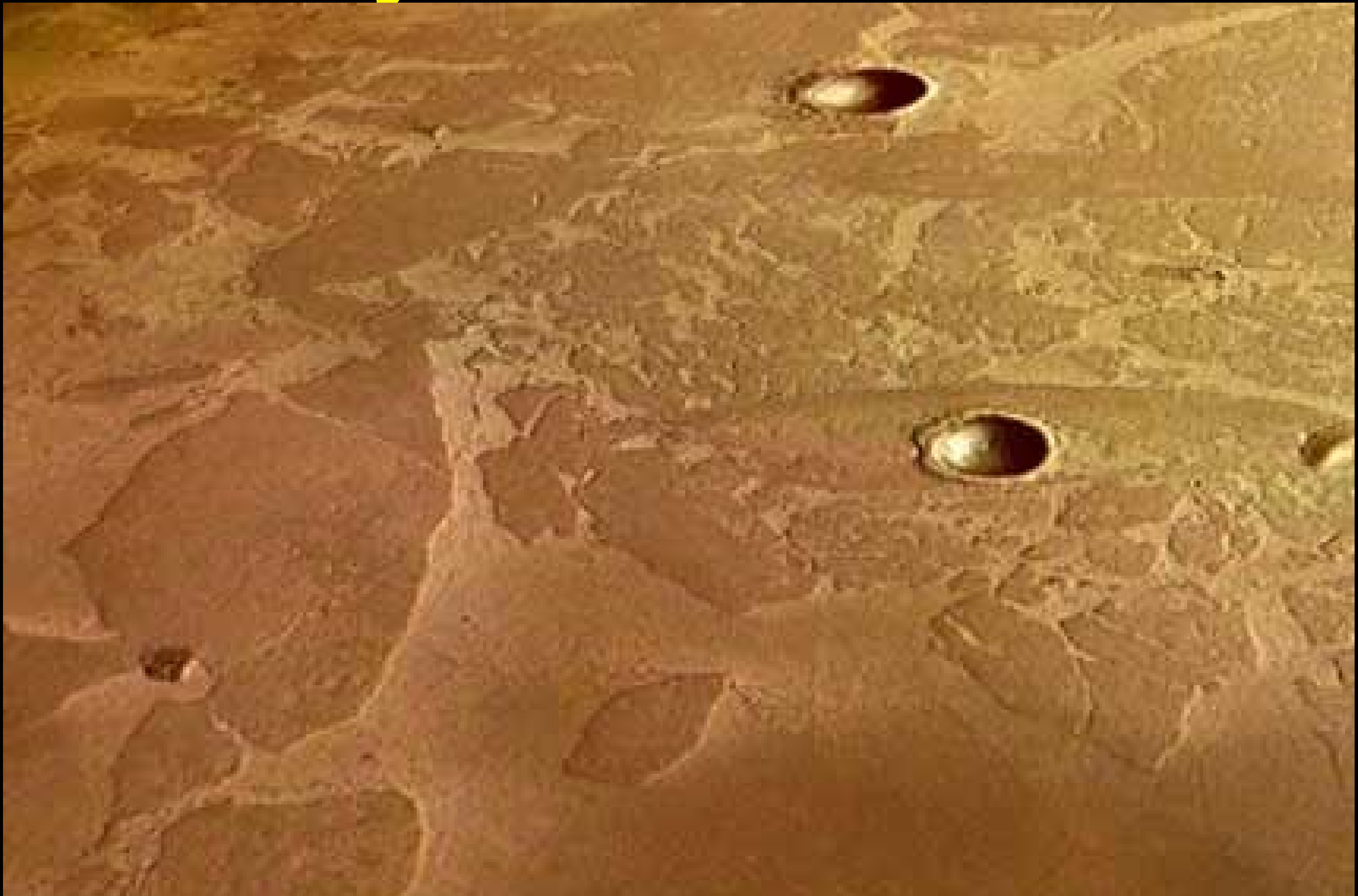
Sedimentary layers exposed on Crater wall



TANTALIZING RIM Beating the odds, Opportunity reached Endurance Crater in very good health. Its cameras revealed many intriguing rocky outcrops with sedimentary layers, such as Burns Cliff seen here.

Close up of (reddish) hematite, drill marks into Martian sediments show bluish less oxidized iron minerals underneath

Frozen water ice floes covered by eons of dust?



Martian South Polar Cap, of CO_2

Close up of south polar cap

The Happy Face Crater

Just for fun

Mars has two tiny ~15km moons

- Phobos, and Diemos
- Probably captured asteroids, orbits do not indicate they formed as part of Mars.
- Mars also spins in 24 hours, convection in the mantle?
- May have been geologically active early on, but crust is now likely to be too thick to allow plate motion. And…
- Mars has no magnetic field, indicating that there is little movement of a molten interior.
- What do you notice about features on this Moon??

“Strafing” lines, or Stretch Marks?

- Subsurface cracks filled over with accreted dust?
- Or perhaps due to a plane or ring of debris orbiting Mars in the plane of the orbit of Phobos?
- Or perhaps stretch marks from tidal force; Phobos orbits only 6,000 km above Mars’ surface.
- Perhaps Phobos came from the asteroid belt, richochette’d off of Mars, losing energy and being captured in orbit, and debris kicked up slowly over the eons fell back on Mars and on Phobos

Phobos (from Mars Orbiter)

Diemos, from Mars Reconn Mission 2008

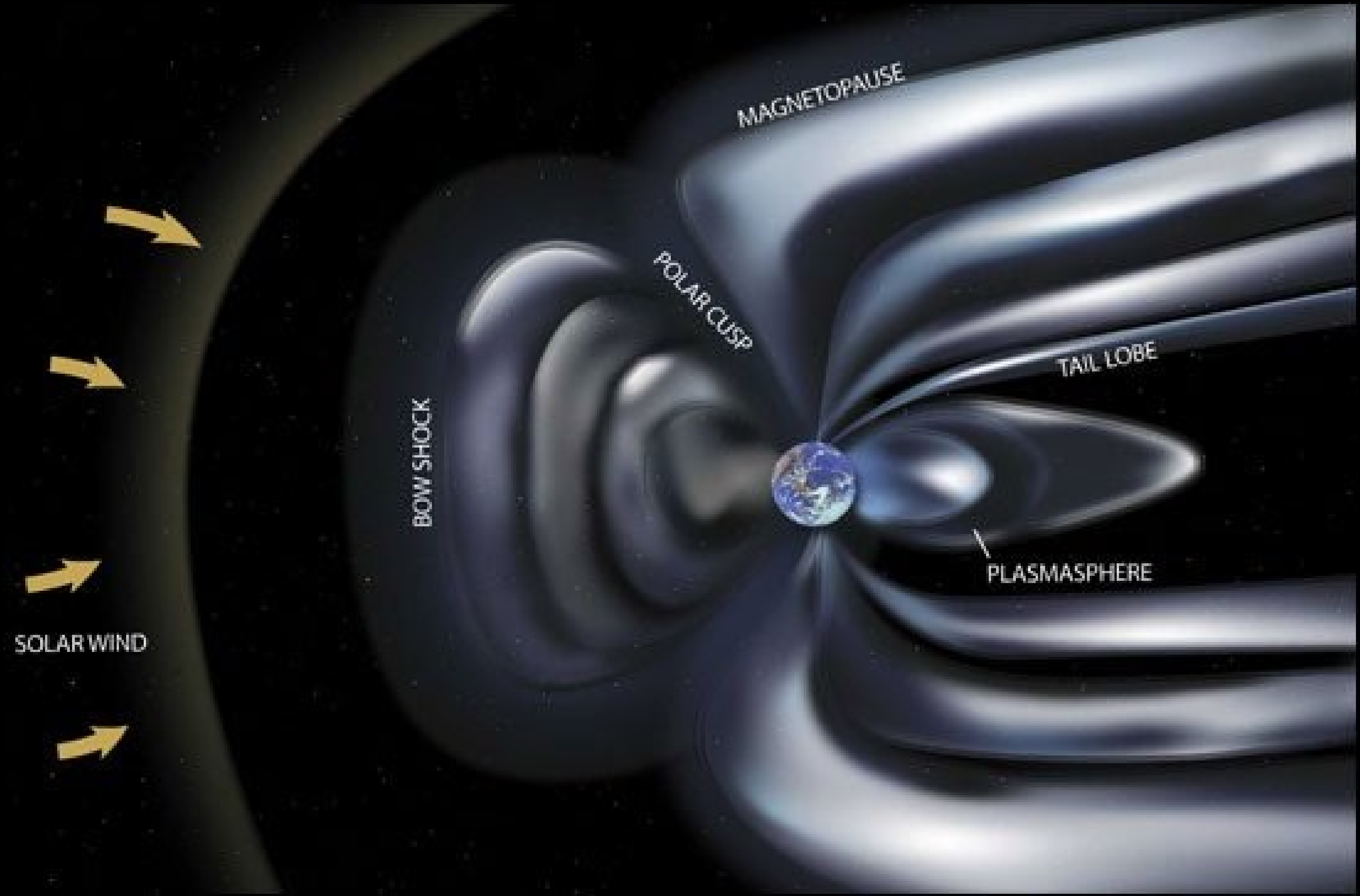
- Earth’s inner core is solid due to high pressure. Earth’s magnetic field arises from the liquid outer core and perhaps some from the mantle as well.
- Evidence in 2003 is that Mars has a liquid core, at least in the outer parts, as well. So why Mars has no magnetic field today is a puzzle.
- A new mission to Mars is planned which will set up seismometers and hopefully allow us to probe the interior better and answer these questions

Note What Causes a Magnetic Field for a Planet

Caused by moving charges, which create an electric current. Circulating electric current creates a magnetic field. A planet needs two conditions to have a decent magnetic field

- --1. Beneath the surface, an ***electrically conducting liquid interior*** material (metals are great for this, iron especially)
- --2. ***Significant rotation,*** to generate differential rotation amplifying the circulating motion of the conducting material to help produce a global dipole field

Magnetic Fields Important for Evolution of Atmospheres – Our Next Topic…



Chap 9: Key Points - Inner Planet Geology

- Bigger planets cool slower, therefore have thinner crusts
- The 3 ways planets inherit/generate heat
- Cratering rate: high at beginning, rapidly dropped.
- Lunar maria formed during Late Bombardment, likely formation of Asteroid Belt material
- Mercury shrank by 1 mile as volatiles escaped
- Venus covered with volcanoes. Hot due to Runaway Greenhouse Effect, freshly repaved surface, almost no craters. Thick atmosphere of CO2.
- Earth only planet with thin crust and high rotation -> **plate tectonics**
- Moon formed by collision with Mars-sized ancient planet right after Earth formed, gave us high rotation rate and moon, pushed away gradually by tidal friction
- Mars – no magnetic field . Had thicker, warmer atmosphere and ocean early on. Giant impact hit North hemisphere creating ocean basin. Evidence of ancient rivers
- Mars has largest volcanoes in Solar system, size argues against moving plates