Astronomy 101

Planetary Geology

Background Photo by Serge B

Planetary Geology

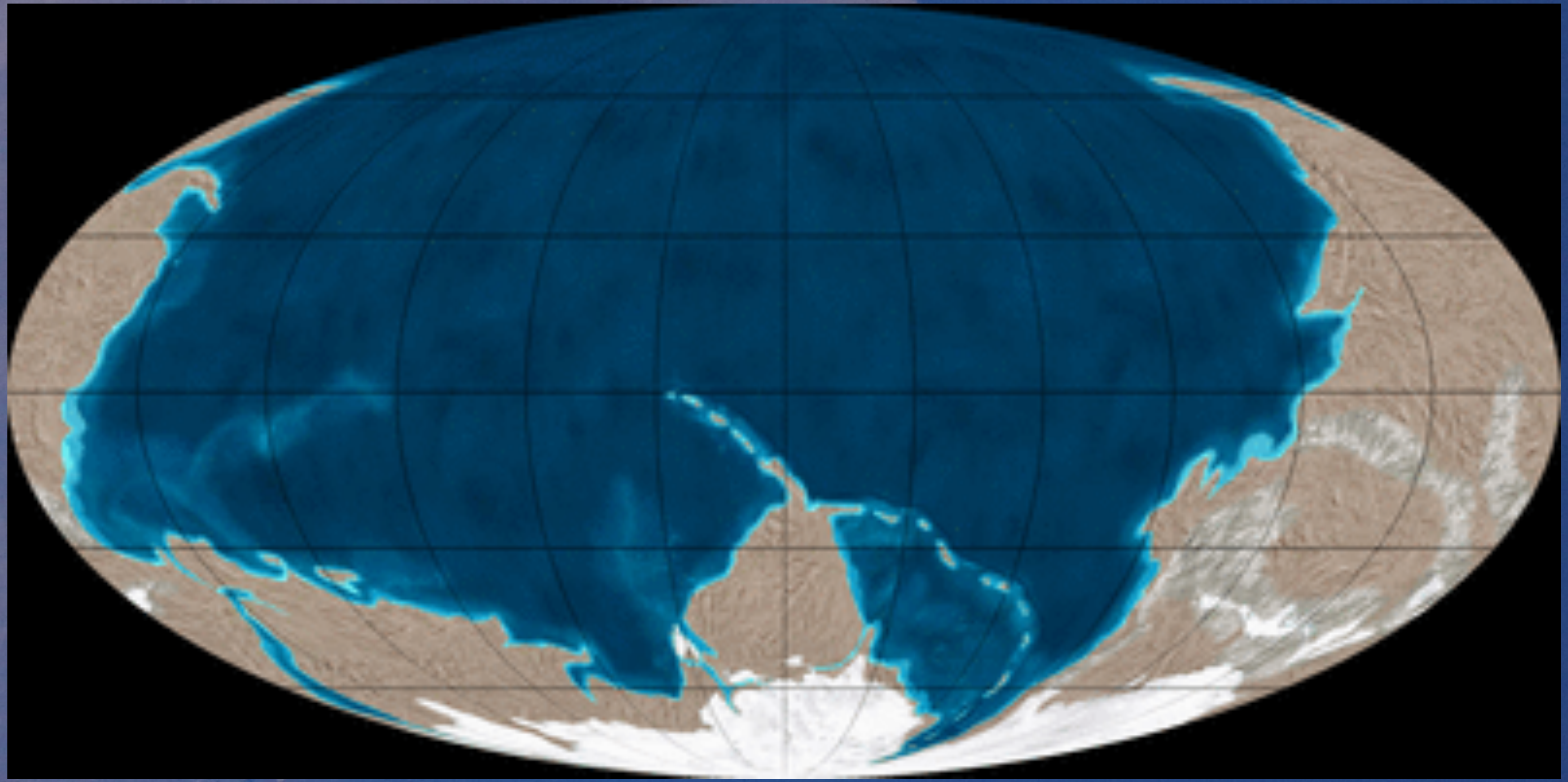
"Nothing is rich but the inexhaustible wealth of nature. She shows us only surfaces, but she is a million fathoms deep."

Ralph Waldo Emerson

Background Photo by Serge B

The Diversity of Worlds

Earth appears to be solid and steady, but anyone living in Alaska, California, or Hawaii will tell you otherwise!



On long time scales, even the continents slowly move about!

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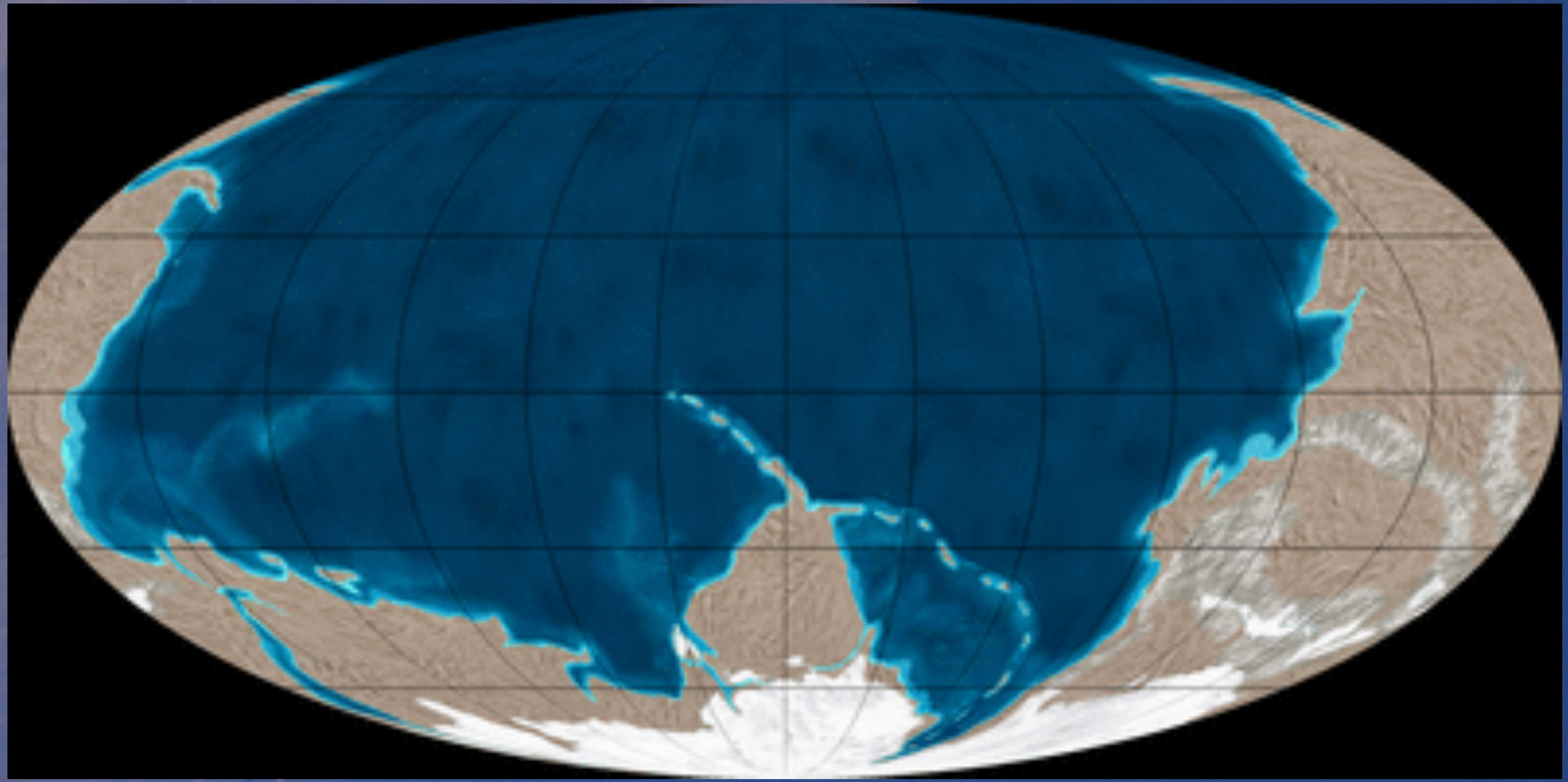
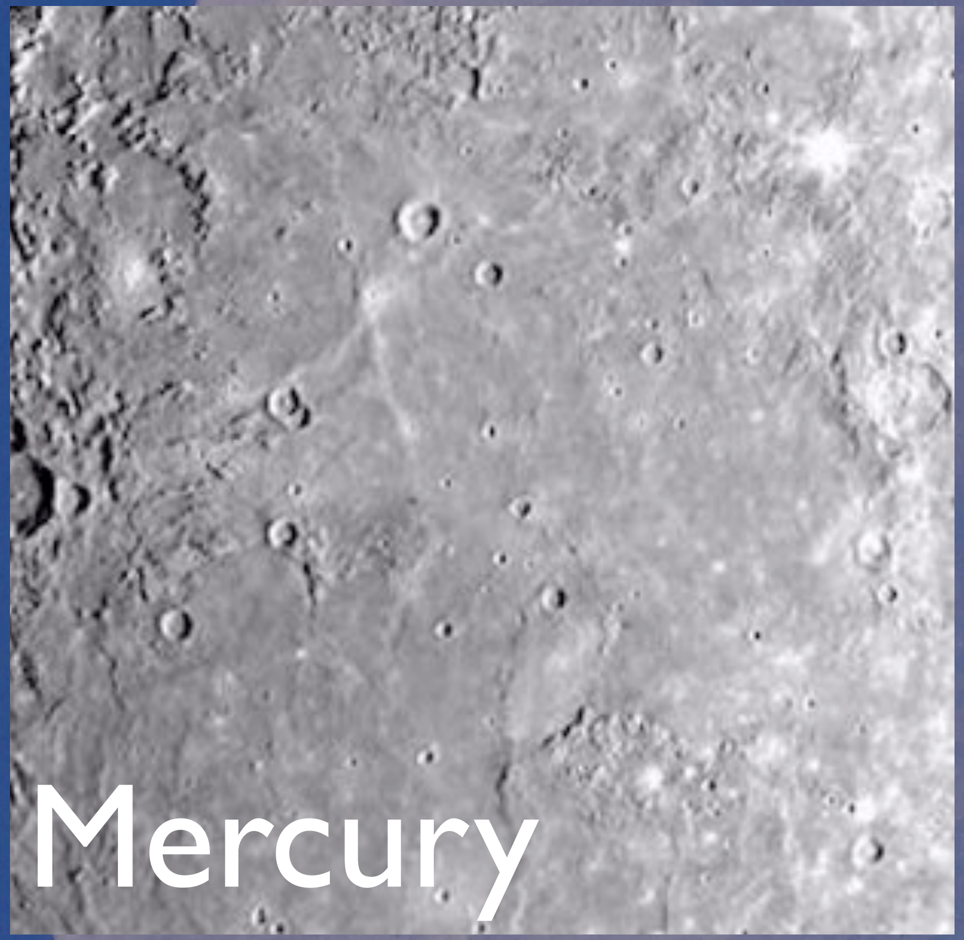
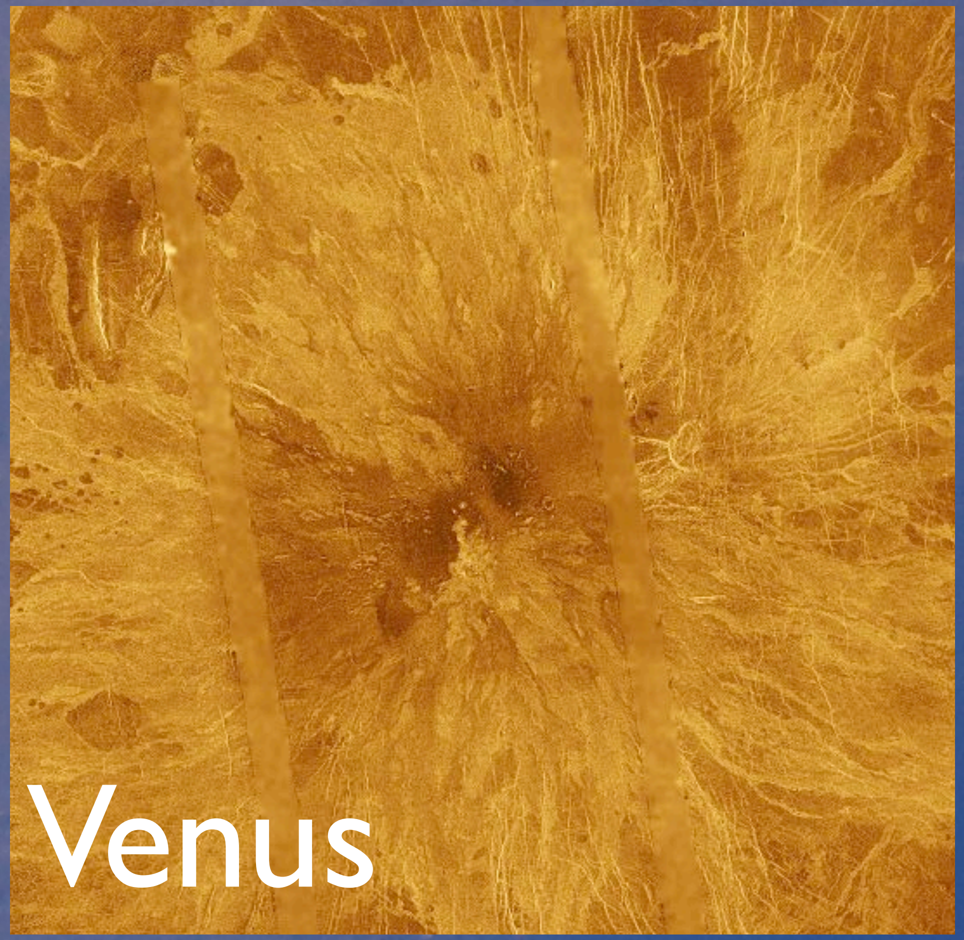


On long time scales, even the continents slowly move about!

The Diversity of Worlds

However, Earth is not alone in having undergone transformations of its surface; all of the terrestrial planets (and the Moon!) have undergone change

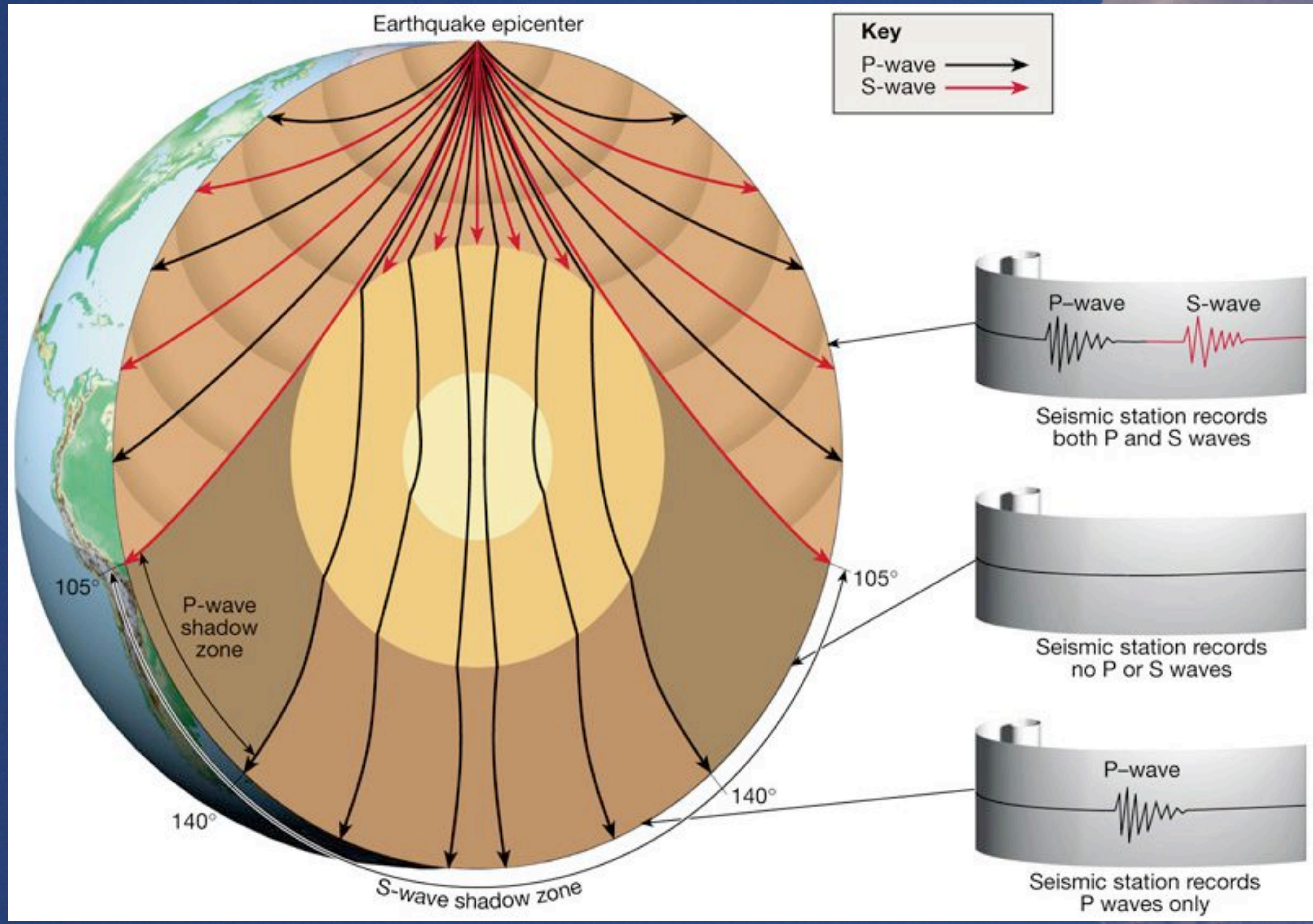




The goal is to understand how these differences among the terrestrial worlds came to be through the study of <u>planetary geology</u>

How do we know about the insides of planets?

For the Earth, most of what we know of its interior comes from seismic waves, the vibrations that travel through the interior and along the surface after an earthquake



We also have seismic data from the Moon thanks to the *Apollo* astronauts who left behind a seismograph and for Mars thanks to the *Mars Insight* mission

Less direct methods are used for other worlds: comparing the average density of the planet to the density of its surface rock tells us how dense it must be inside

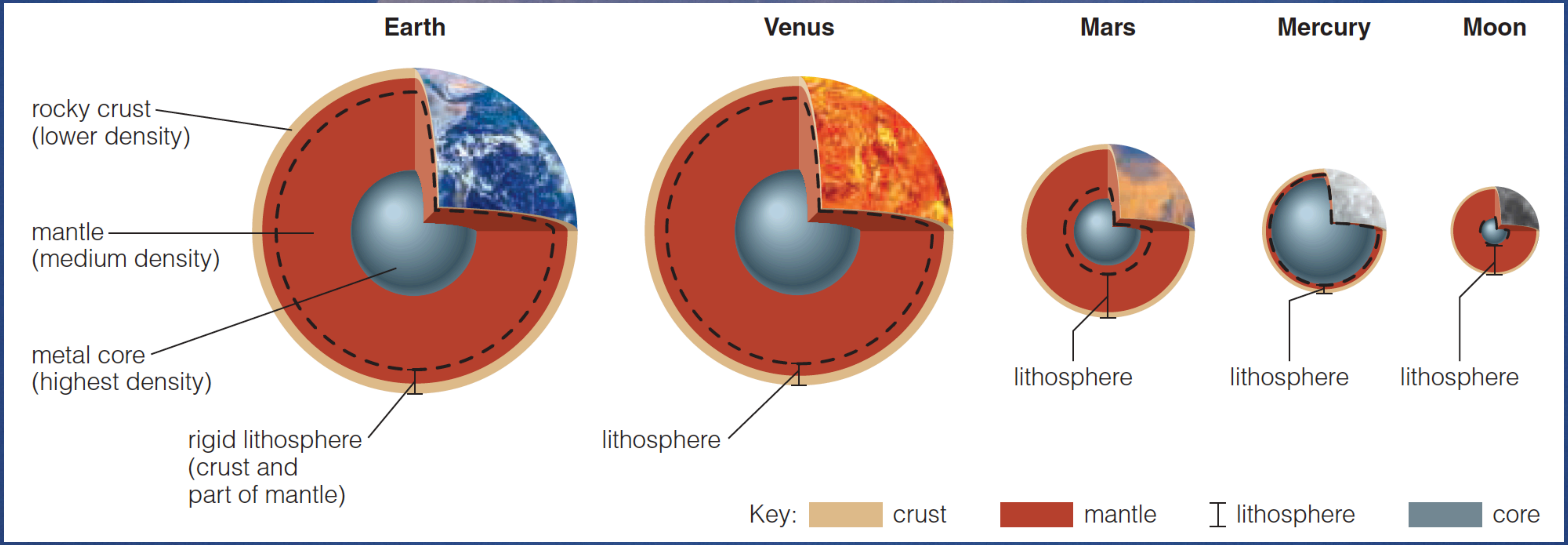
Planets are Like Ogres and Onions

Our studies have shown that all of the terrestrial planets have layered interiors:

Core: highest density, primarily metals like nickel and iron

Crust: lowest density, materials like granite and basalt; the world's outer "skin"

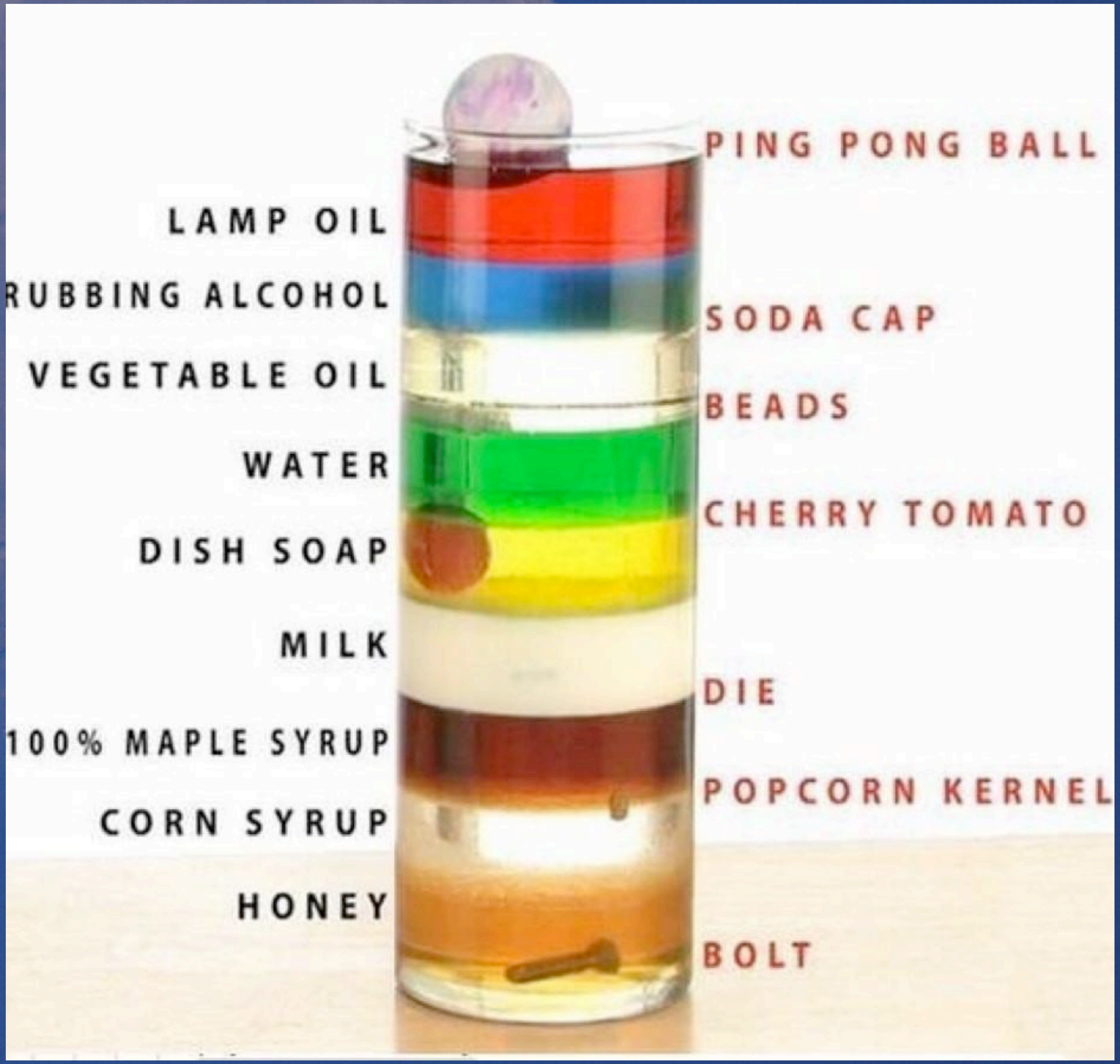
Mantle: rocky material of moderate density, mostly minerals containing silicon, oxygen; surrounds the core



Why are planets like ogres and onions?

The process of differentiation makes the layers of the planets

Gravity pulls the denser materials towards the center, so dense materials like iron sank towards the center, leaving less dense rocky material at the surface



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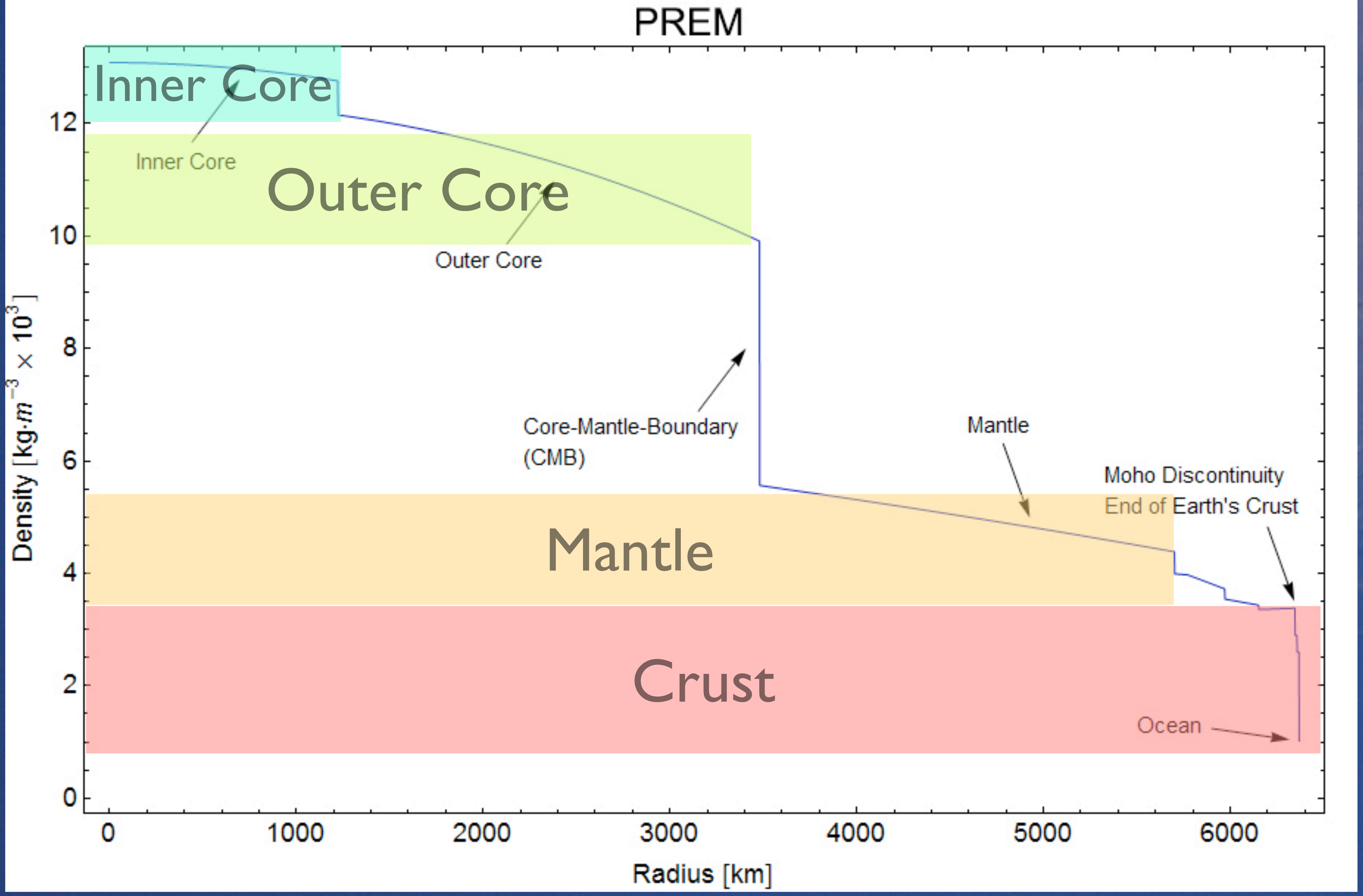
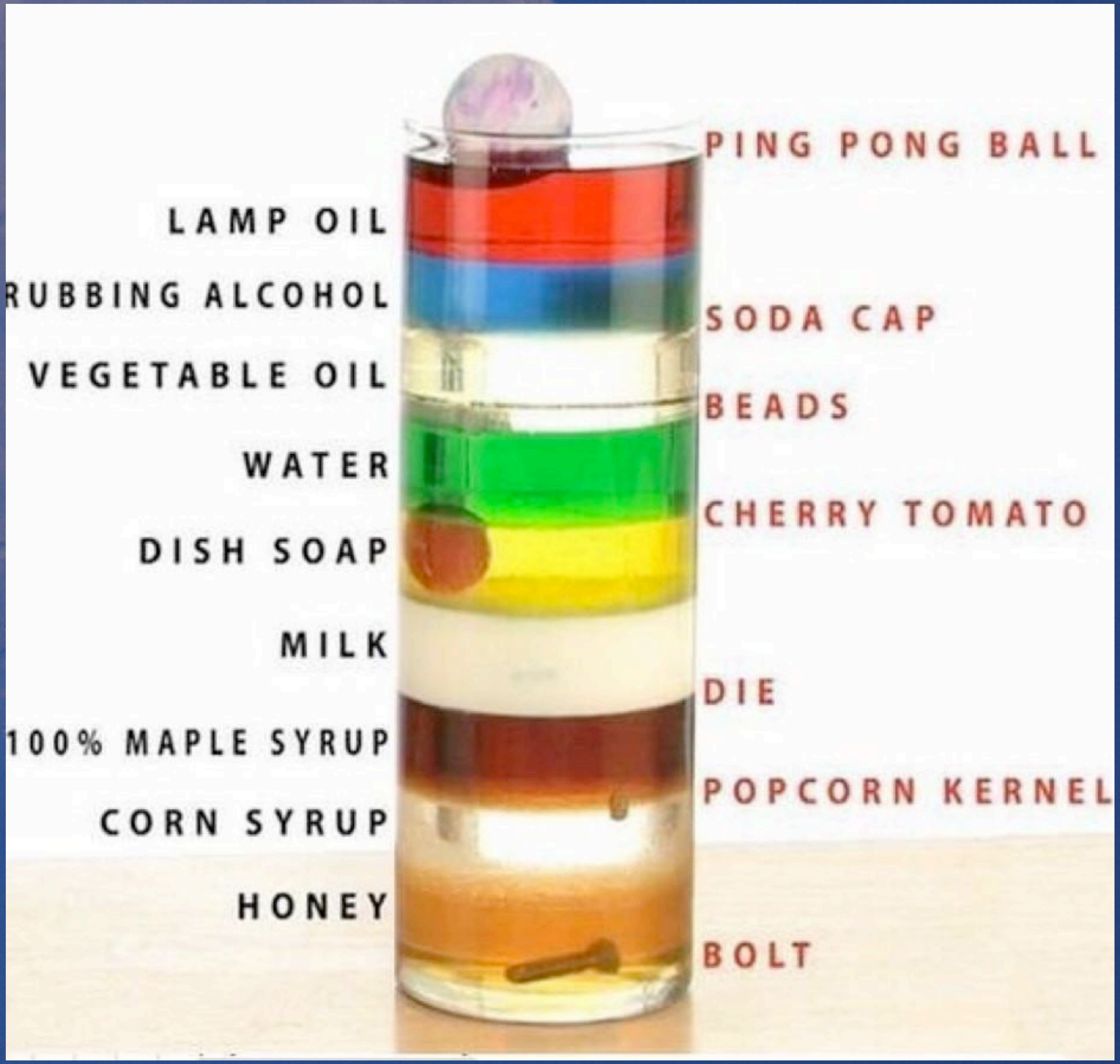
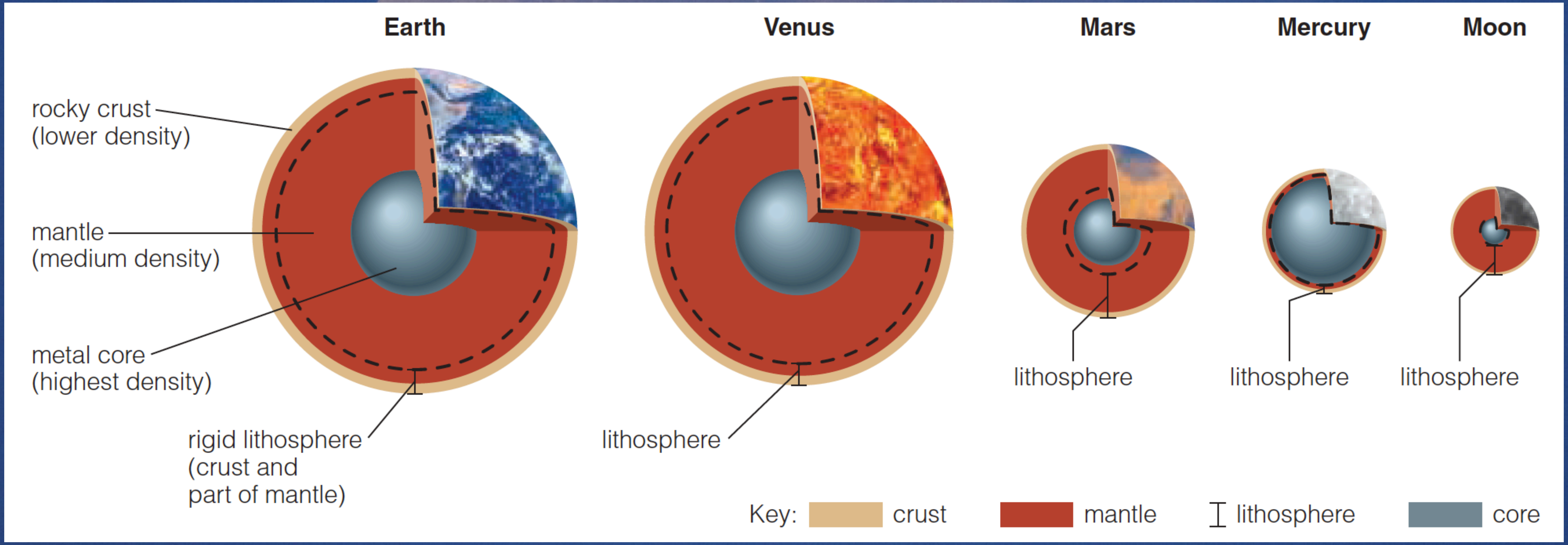




Why are planets like ogres and onions?

Often its more useful to categorize interior layers by rock strength than density: rocks can slowly deform when under stress and heat

In that way, a planet's outer layer of cold and rigid rock, called the lithosphere, essentially floats on the warmer, softer rock underneath



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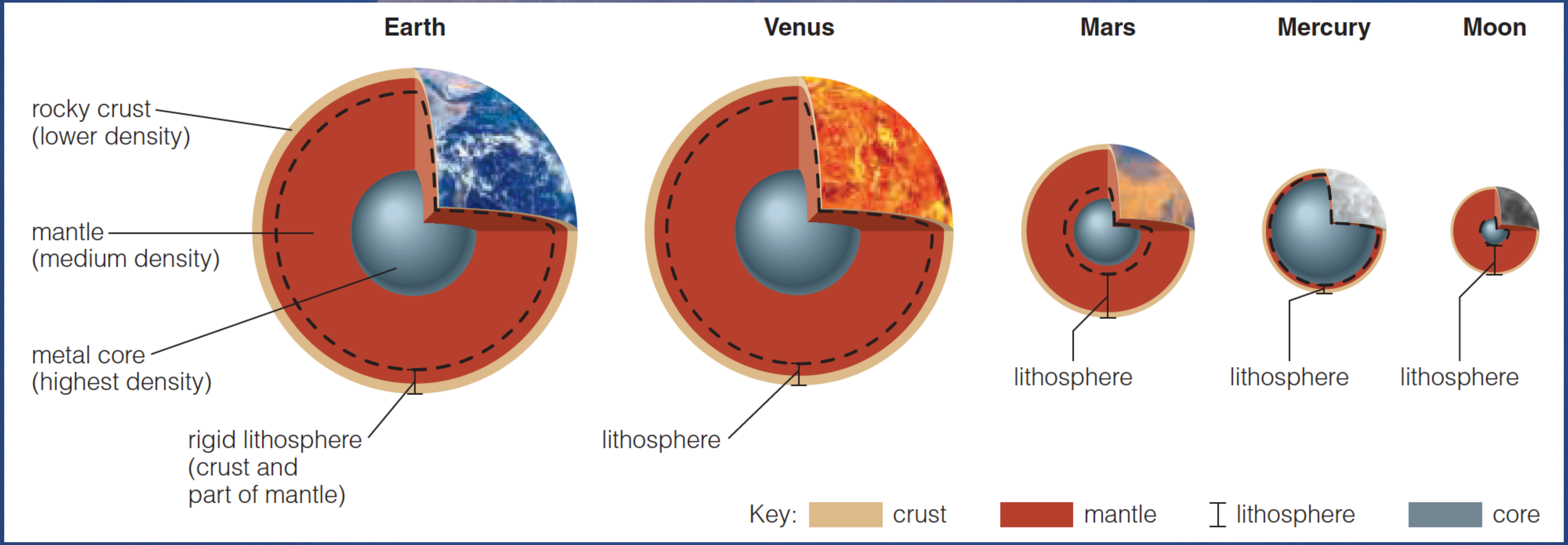
Note that lithospheric thickness is related to the size of the planet: smaller worlds have larger lithospheres



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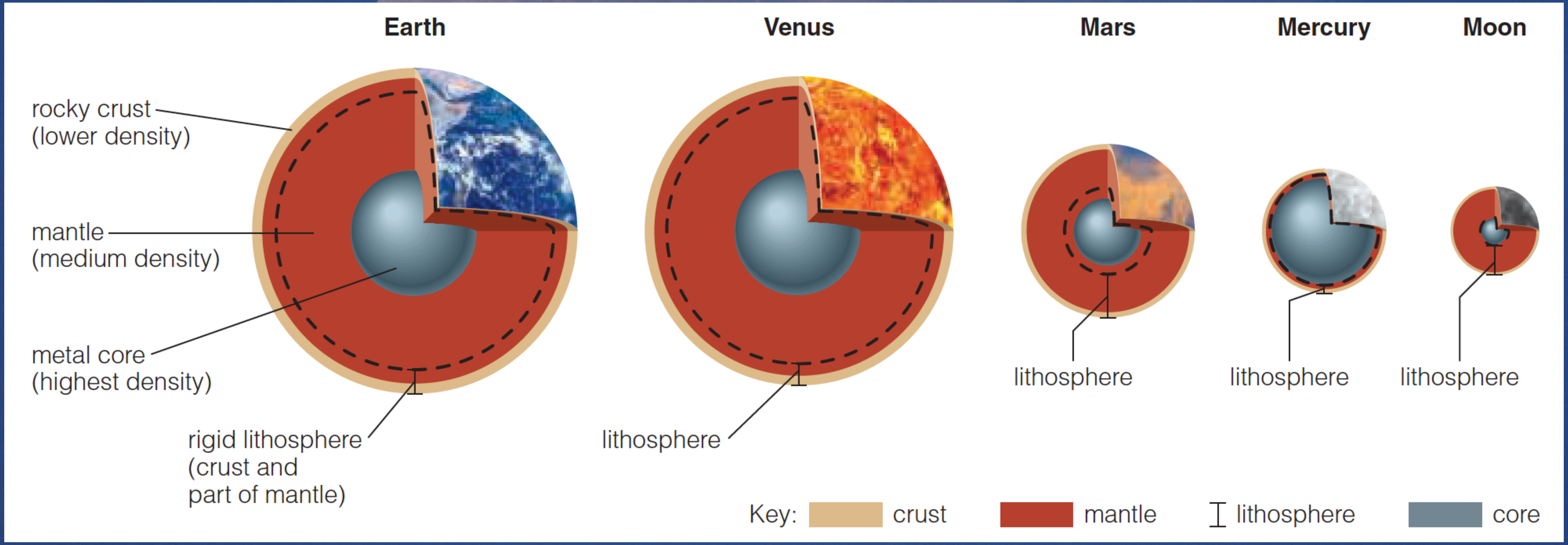
The thicker the lithosphere, the less likely molten rock can escape from below



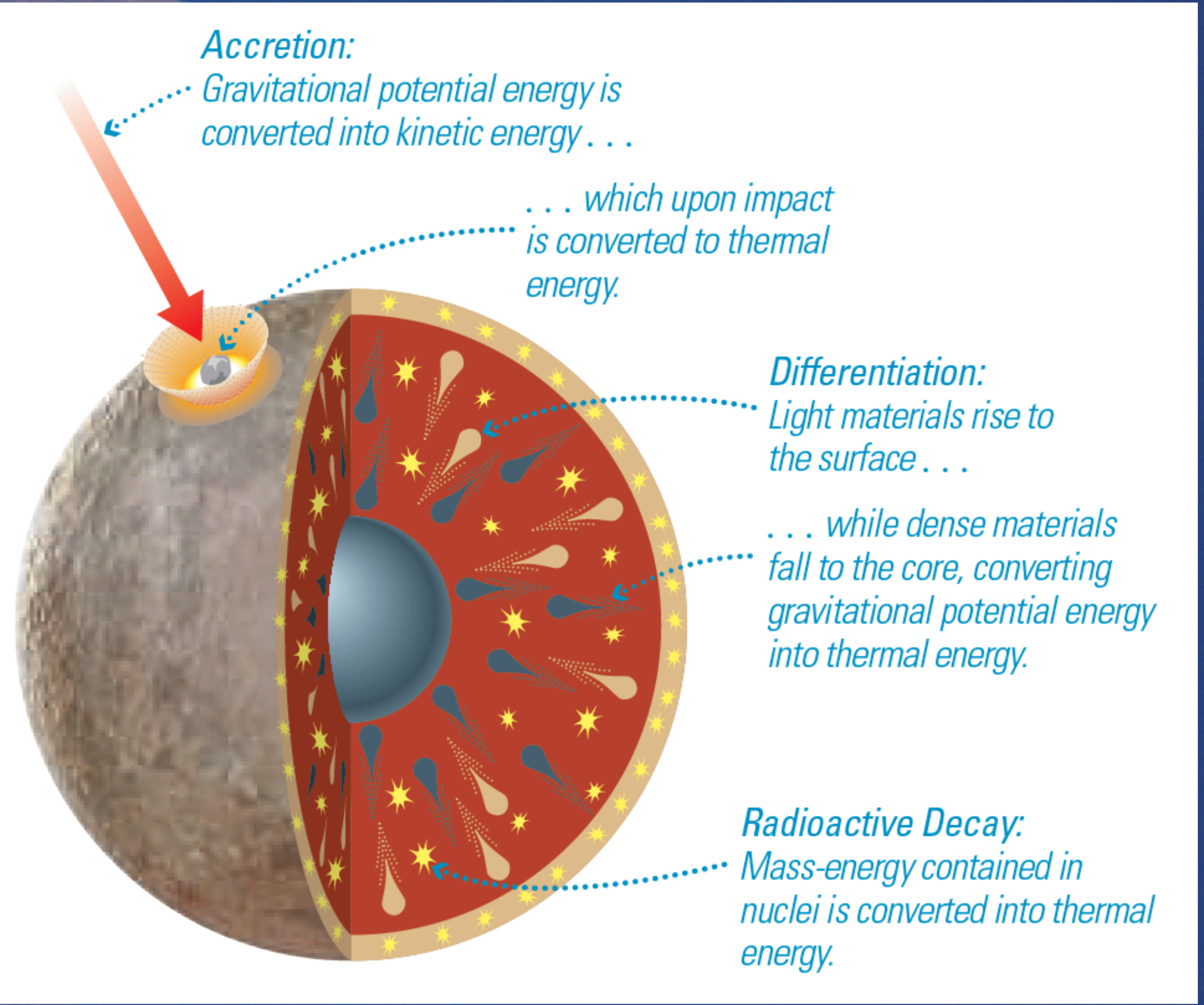
Heating a Planet Up

Most geologic activity comes from internal heat, and that heat can be generated from three sources:

Accretion: during its formation gravitational potential energy is converted into kinetic energy which is later converted into thermal energy

Differentiation: as the more dense matter moves inward, it loses gravitational potential energy and is converted into thermal energy via friction

Radioactive decay: as radioactive isotopes such as uranium, potassium, and thorium decay, subatomic particles fly off and collide with neighboring particles, converting some mass-energy to thermal energy

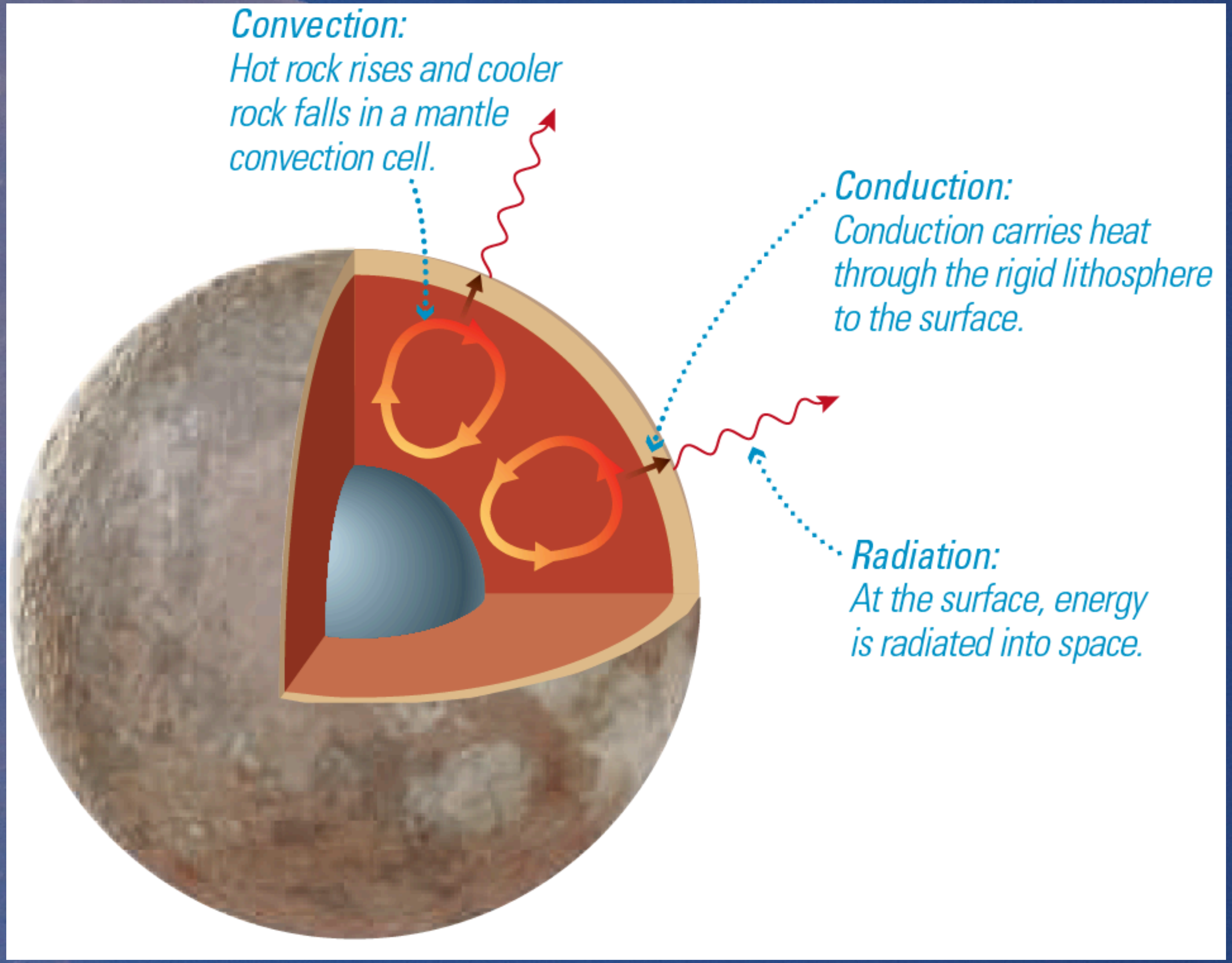


Note that accretion and differentiation were only sources of heat when the planets were young; radioactive decay is a continual source of heat

Cooling a Planet Down

Cooling a planet requires transporting heat outward, which also happens through three processes:

- <u>Convection</u>: hot material expands and rises while cooler material contracts and sinks
- <u>Conduction</u>: heat is transferred via physical contact of microscopic collisions of individual atoms or molecules
- <u>Radiation</u>: objects emit thermal radiation depending on their temperature, so light carries energy away



For the Earth, convection is the most important process until heat reaches the lithosphere; at that point, conduction dominates until the surface, where radiation takes over

Size Matters!

Size is the primary factor in determining geological activity: larger planets can hold on to heat longer

The small sizes of the Moon and Mercury means that their interiors cooled within a billion years of formation

- Their lithospheres grew, pushing the mantle deeper and deeper, and as a result, both are geologically "dead"

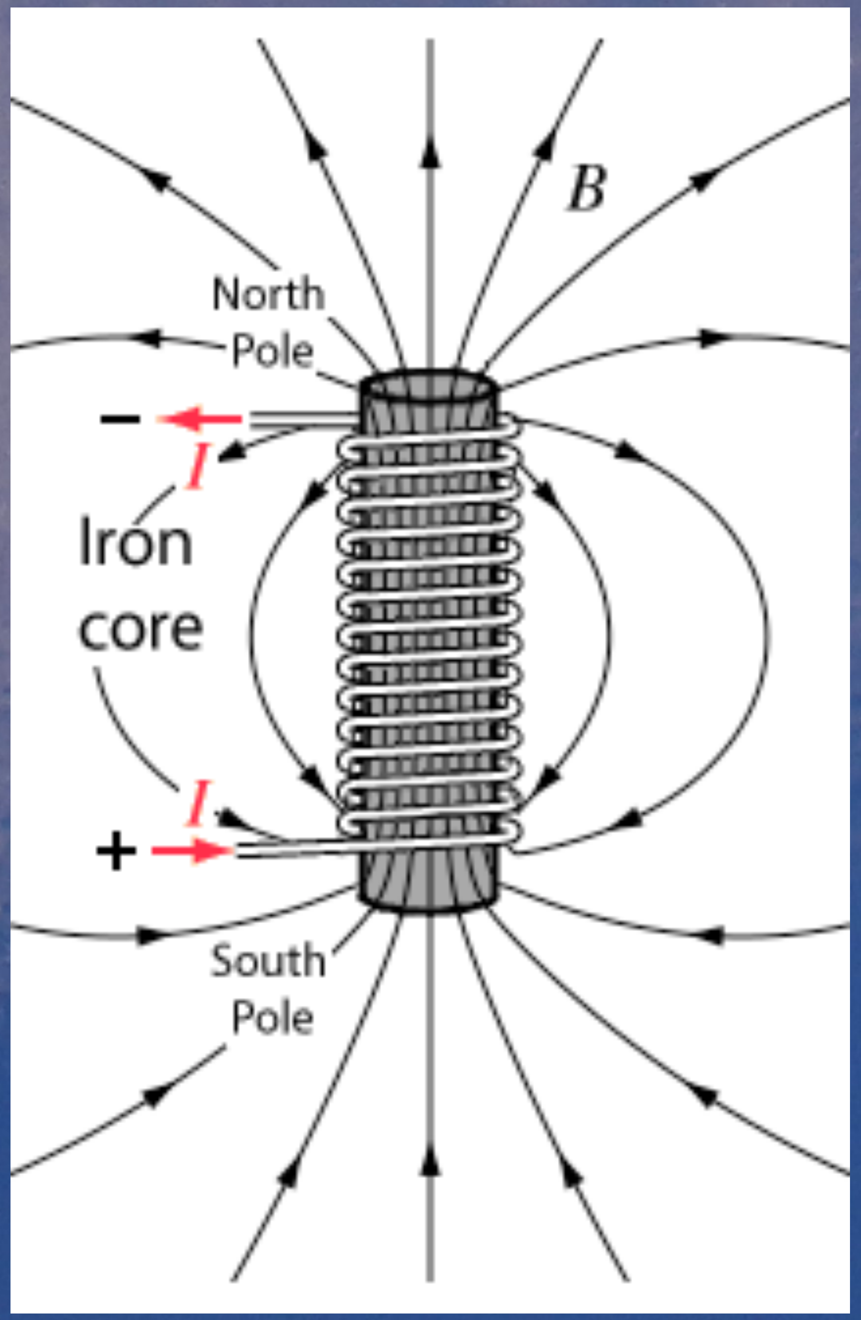
Earth is large enough to stay hot, and Venus probably is as geologically active as Earth

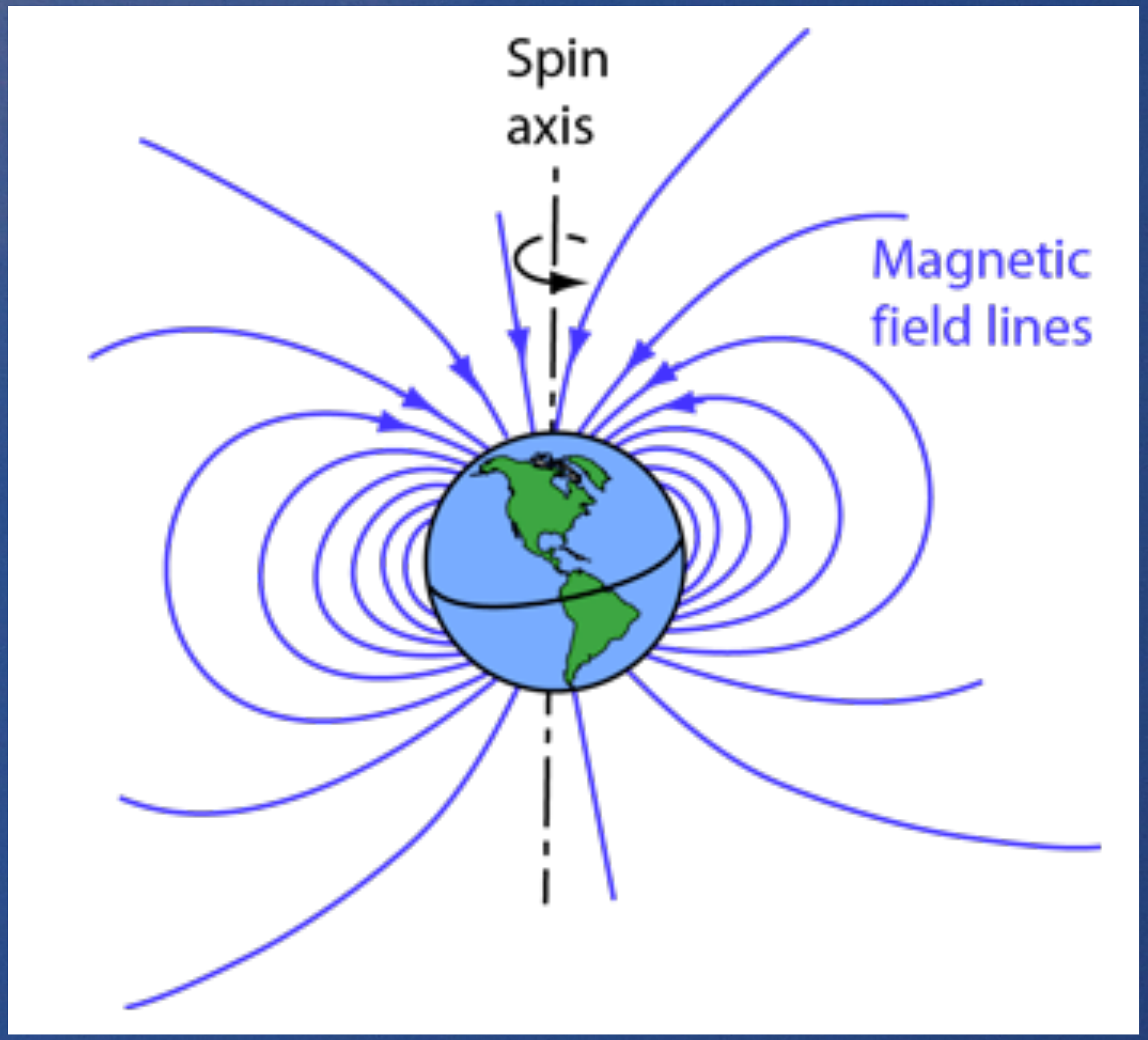
The intermediate size of Mars makes it act as an intermediate case: it has cooled significantly, but it probably still has some heat for some geological activity

It's what's on the inside that counts!

Interior heat helps create a global magnetic field which helps protect a planet from high-energy charged particles coming from the Sun

Earth's magnetic field is generated by charged particles moving around in the molten metal outer core, similar to an electromagnet





It's what's on the inside that counts!

There are three basic requirements for a magnetic field:

1. An interior region of electrically conducting fluid, such as molten metal

2. Convection in that layer of fluid

3. At least moderately rapid rotation

The Earth is the only planet that satisfies all of these requirements

The Moon has long since cooled and stopped convecting

Mars's core probably is still hot, but not enough to drive convection

Venus probably has a molten core, but either its convection or its 243-day rotation period are too slow to generate a magnetic field

Mercury is weird cause it still has a magnetic field

Shaping the Surface

Most surface features on the terrestrial worlds can be explained by four major geological processes:

Impact cratering

Tectonics

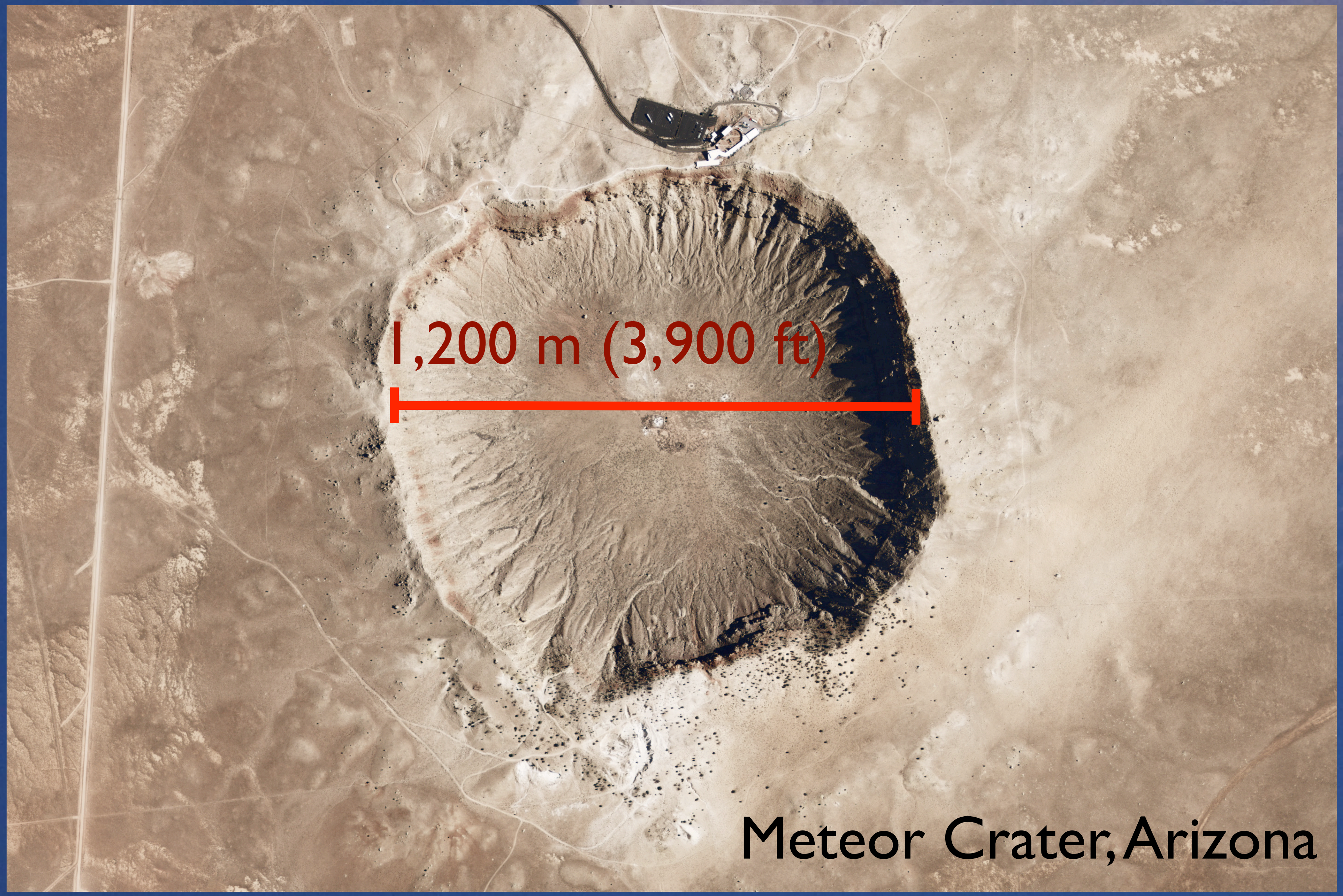
Volcanism

Erosion

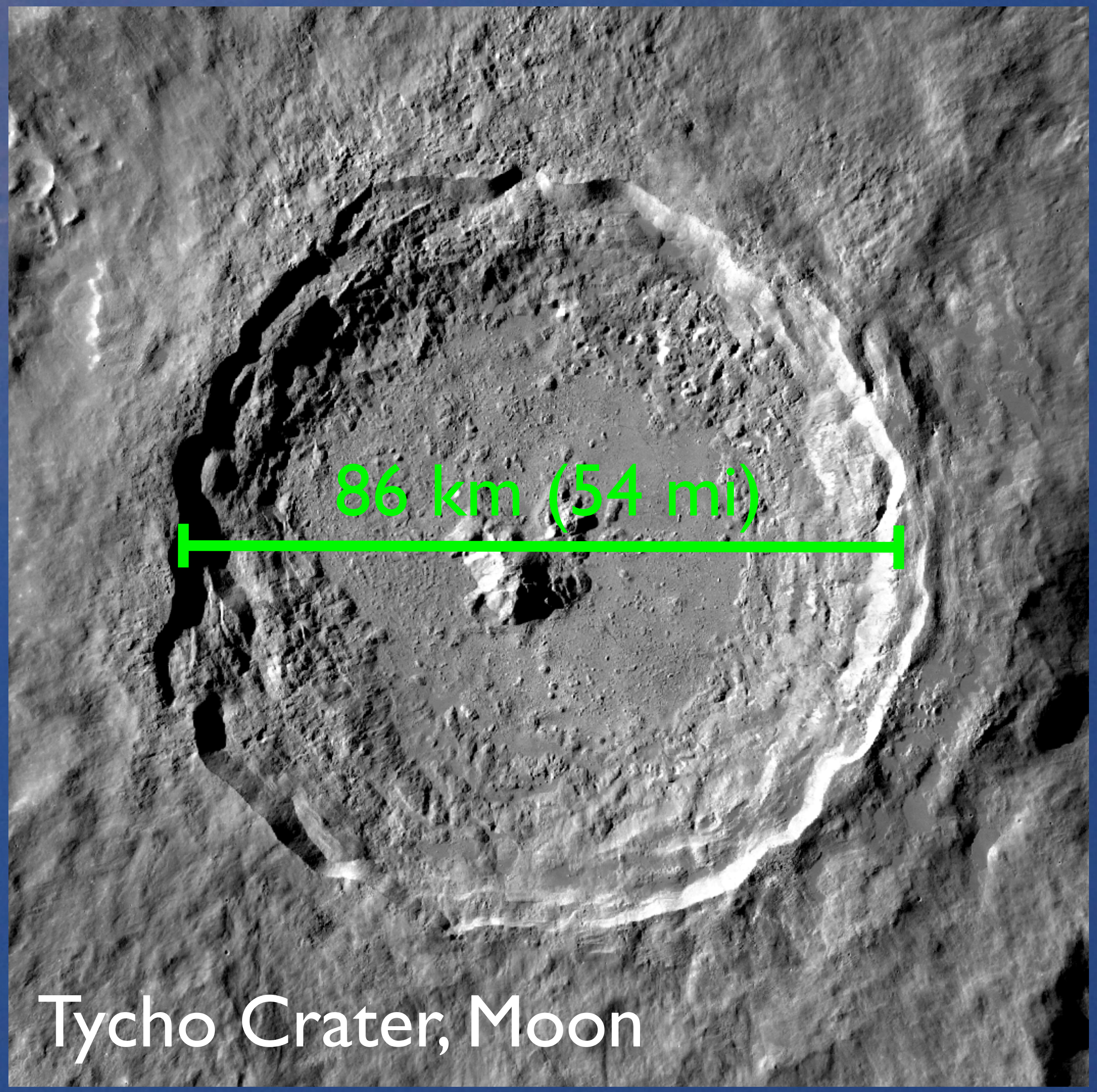
Impact Craters

An impact crater forms when an asteroid or comet slams into the solid planetary surface at speeds between 40,000 and 250,000 km/hr (25,000 to 155,000 mph), vaporizing solid rock and blasting out a crater, sending debris raining down over a large area

Craters are usually circular, regardless of the impactor direction, and about 10 times as wide as the objects that create them and might contain a central peak from the rebound



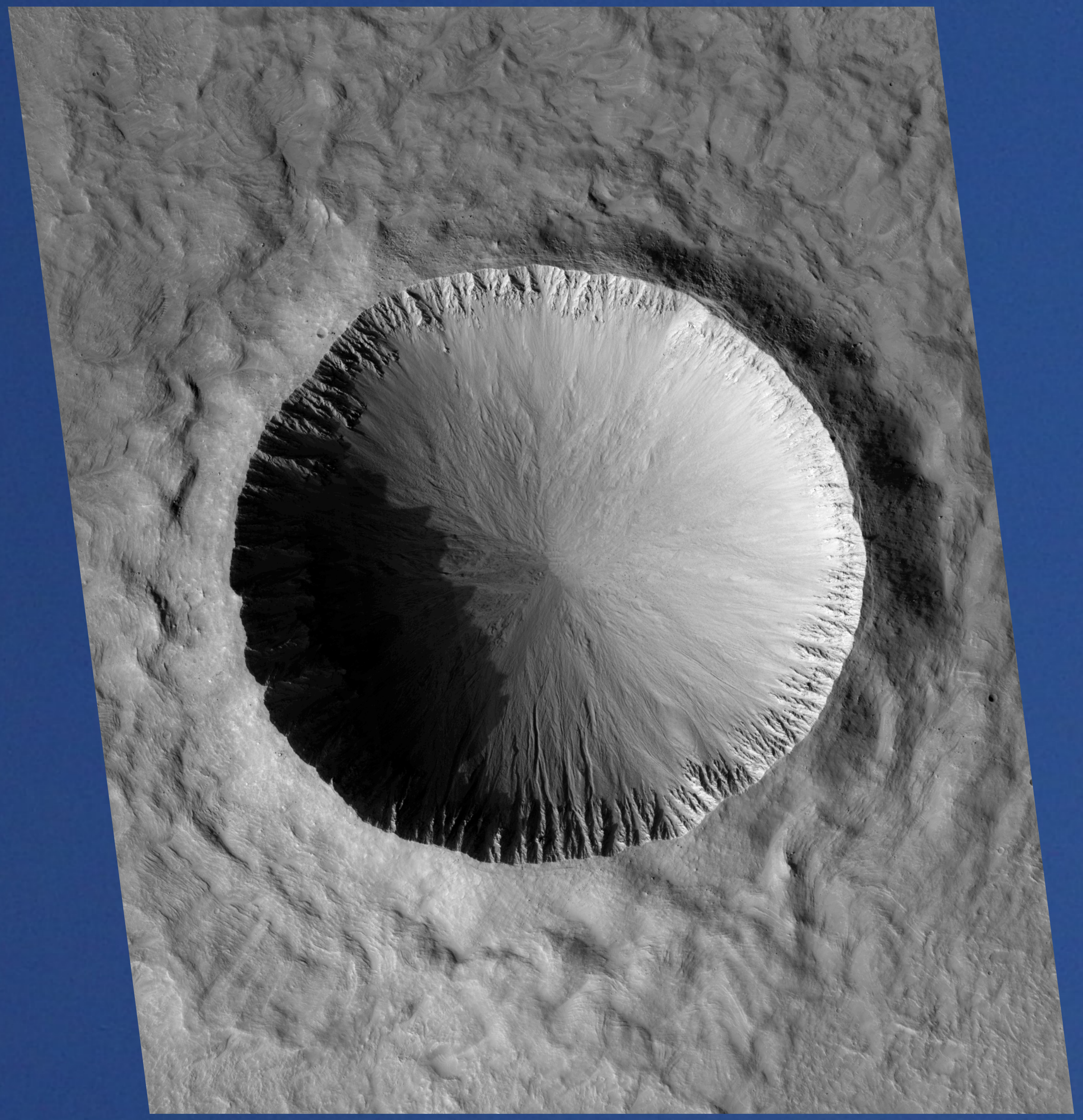
Meteor Crater, Arizona



Tycho Crater, Moon

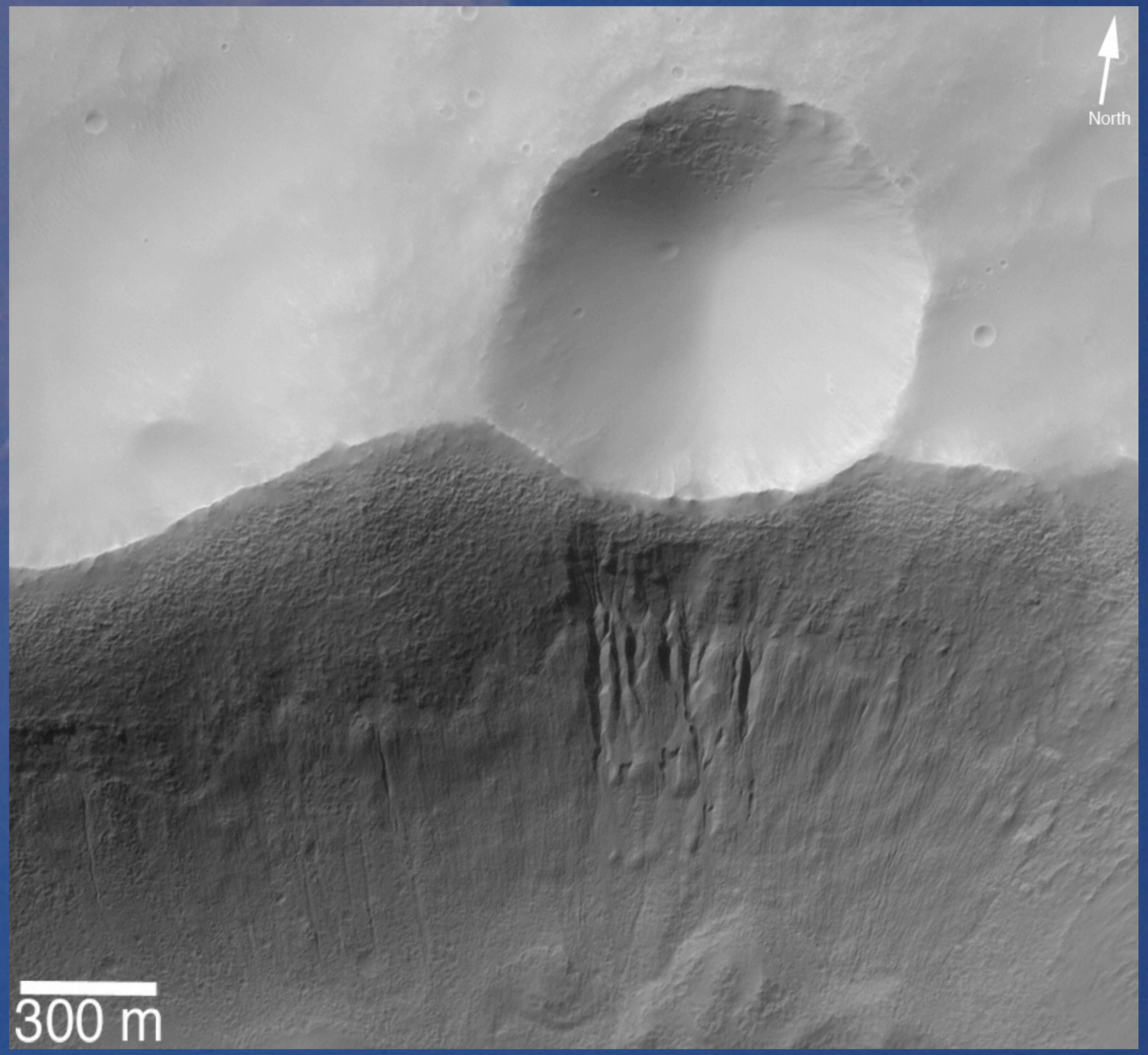
The Details of Craters

These three craters on Mars give us clues about geological conditions



Basic crater
Simple bowl shape

Crater surrounded by mud flows, suggesting underground water (or ice) melted on impact



Eroded crater
Lacks a well-defined bowl shape

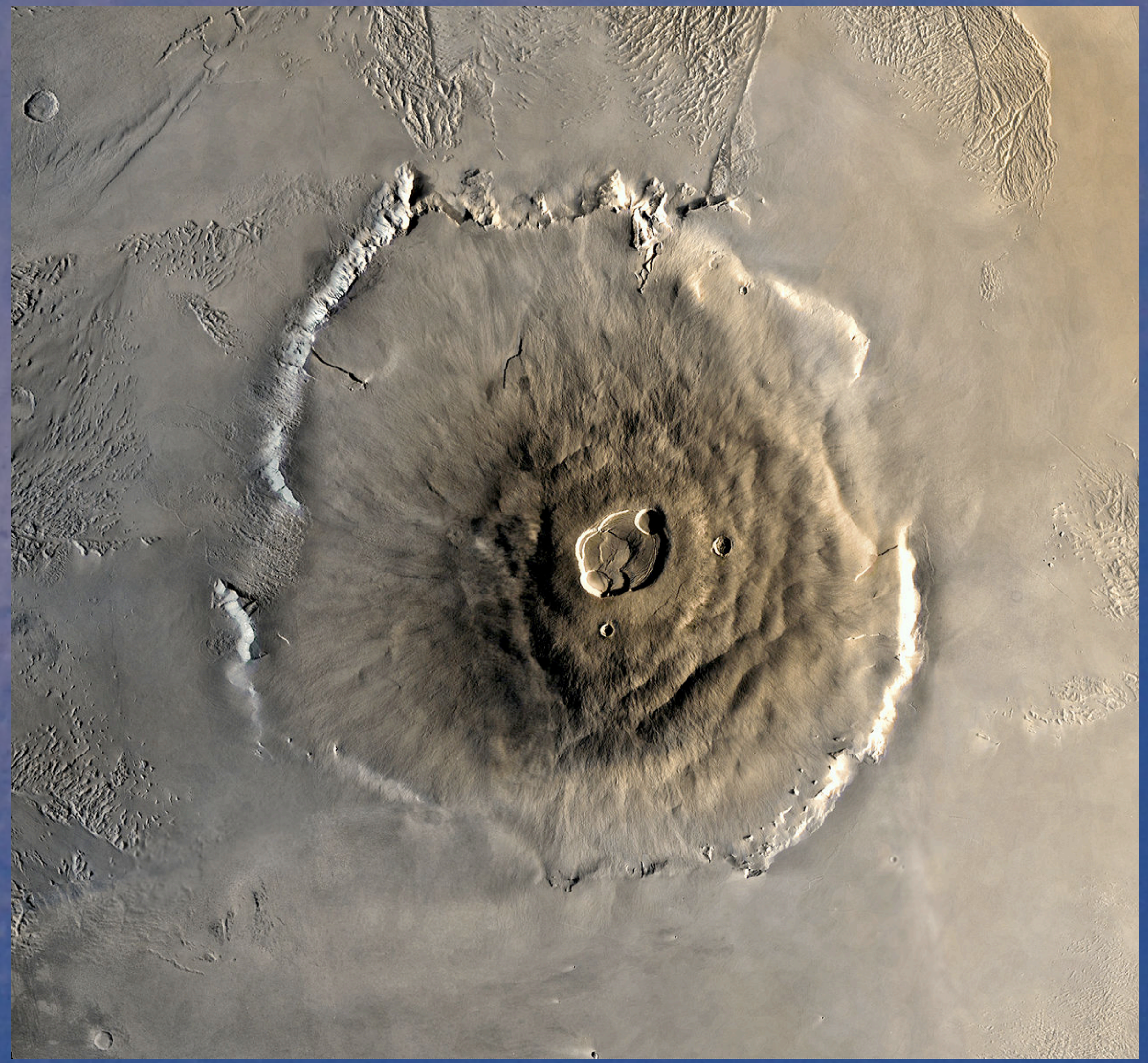
Volcanism

Volcanism occurs when underground molten rock finds a path to the surface

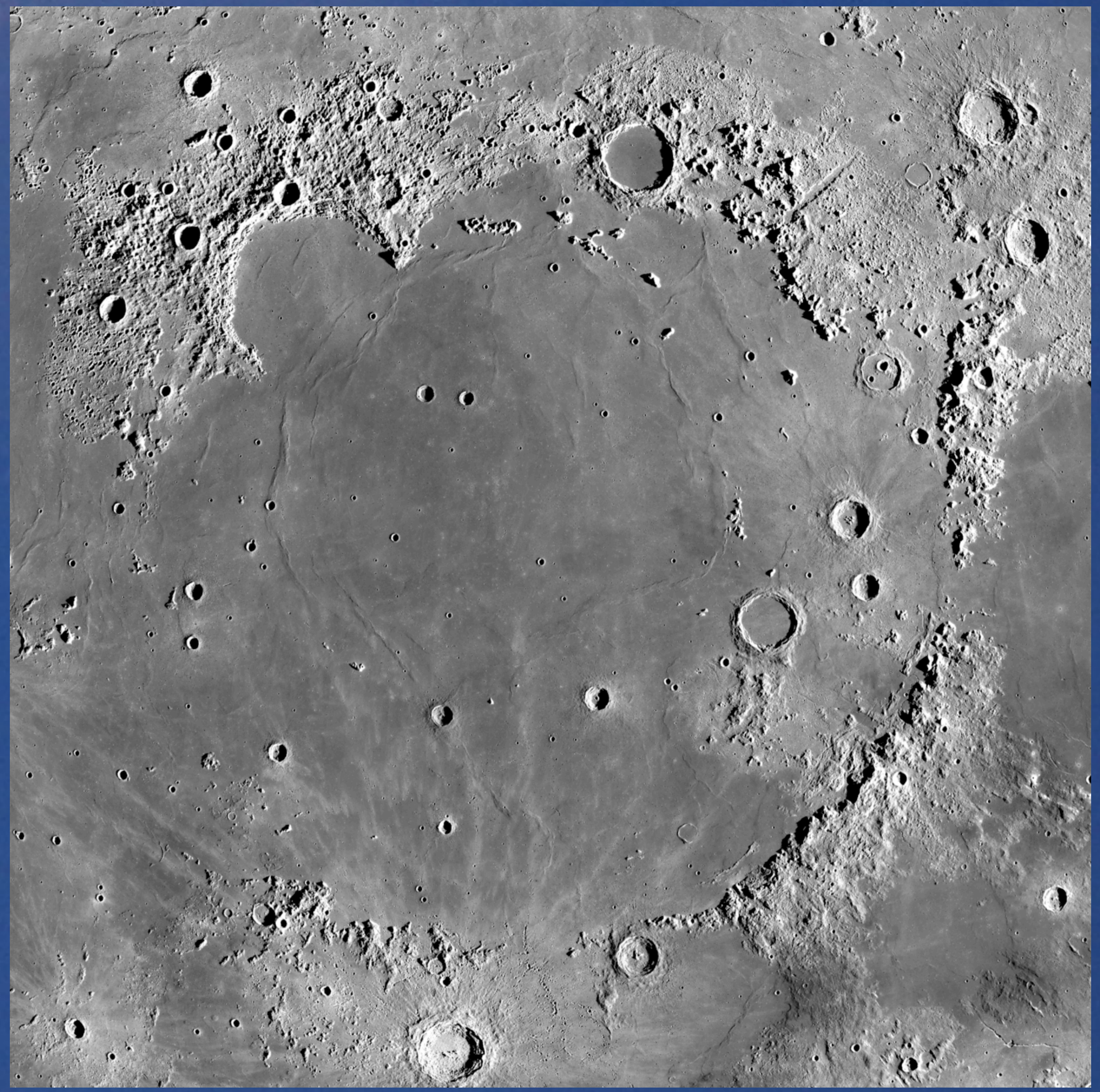
It does this because molten rock is less dense than the surrounding rock, the solid rock surrounding it exerts a pressure on the molten rock, and molten rock has trapped gases that make it want to rise

Volcanoes are also a source of <u>outgassing</u>: releasing gas from the interior of the planets

Mt. Fuji, Japan
Stratovolcano



Olympus Mons, Mars
Shield volcano

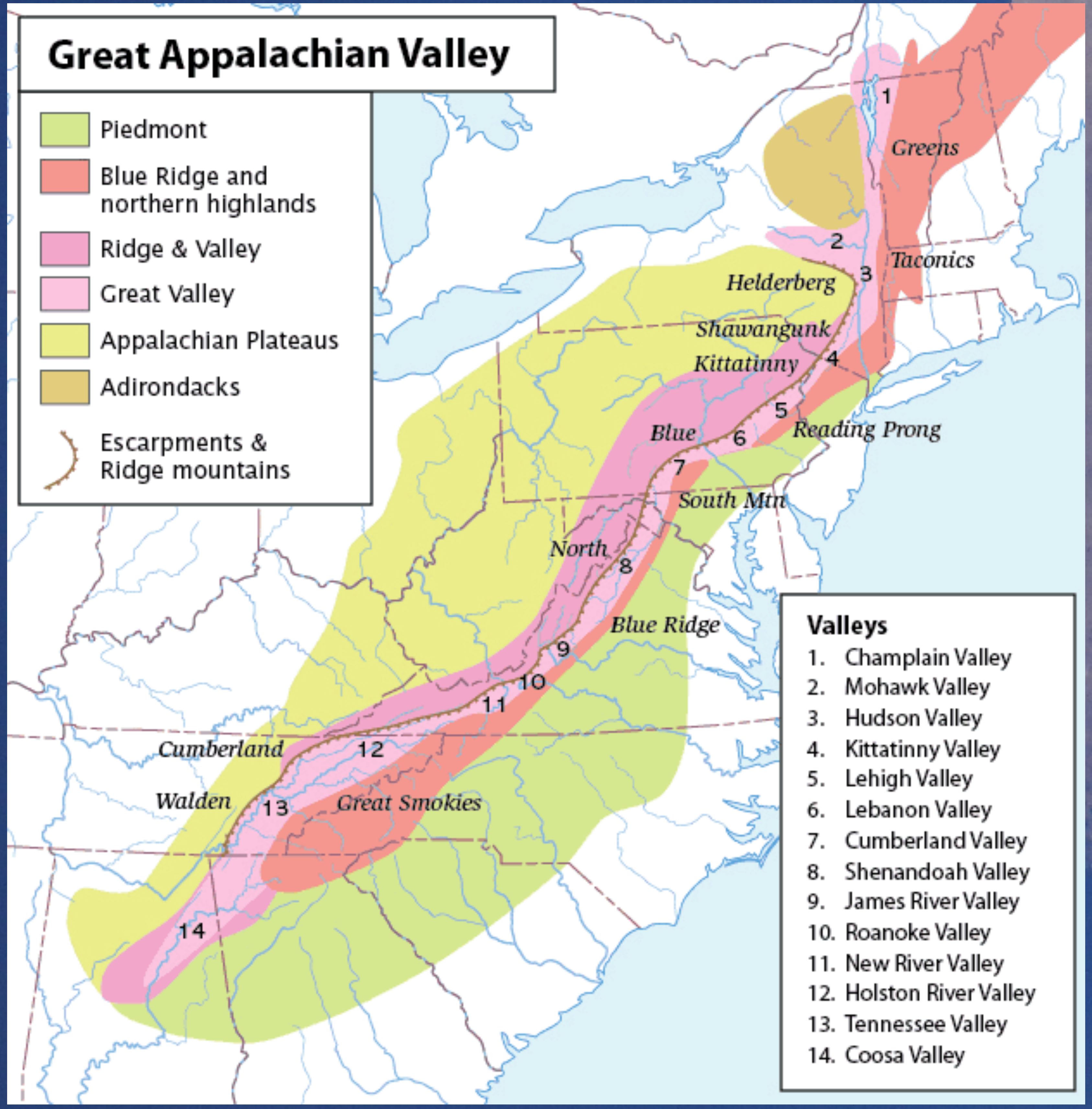


Mare Imbrium, Moon
Lava plain

Tectonics

Tectonic activity usually goes hand-in-hand with volcanism because both require a source of internal heat

Since the crust of a planet floats on the liquid mantle, movement of the mantle causes the crust to push together or spread apart



←Compression in the crust causes mountains like the Appalachians…

…while stretches in the crust can cause cracks and valleys like the Ceraunius Fossae on Mars→

Erosion

Erosion is the transport or breakdown of surface rock through ice, liquid, or gases

The Grand Canyon

© Clay Banks

Yosemite Valley

© Katie Hong

Lake Tekapo, New Zealand

© Jordan Heath

Sahara Desert

© Henry Dick

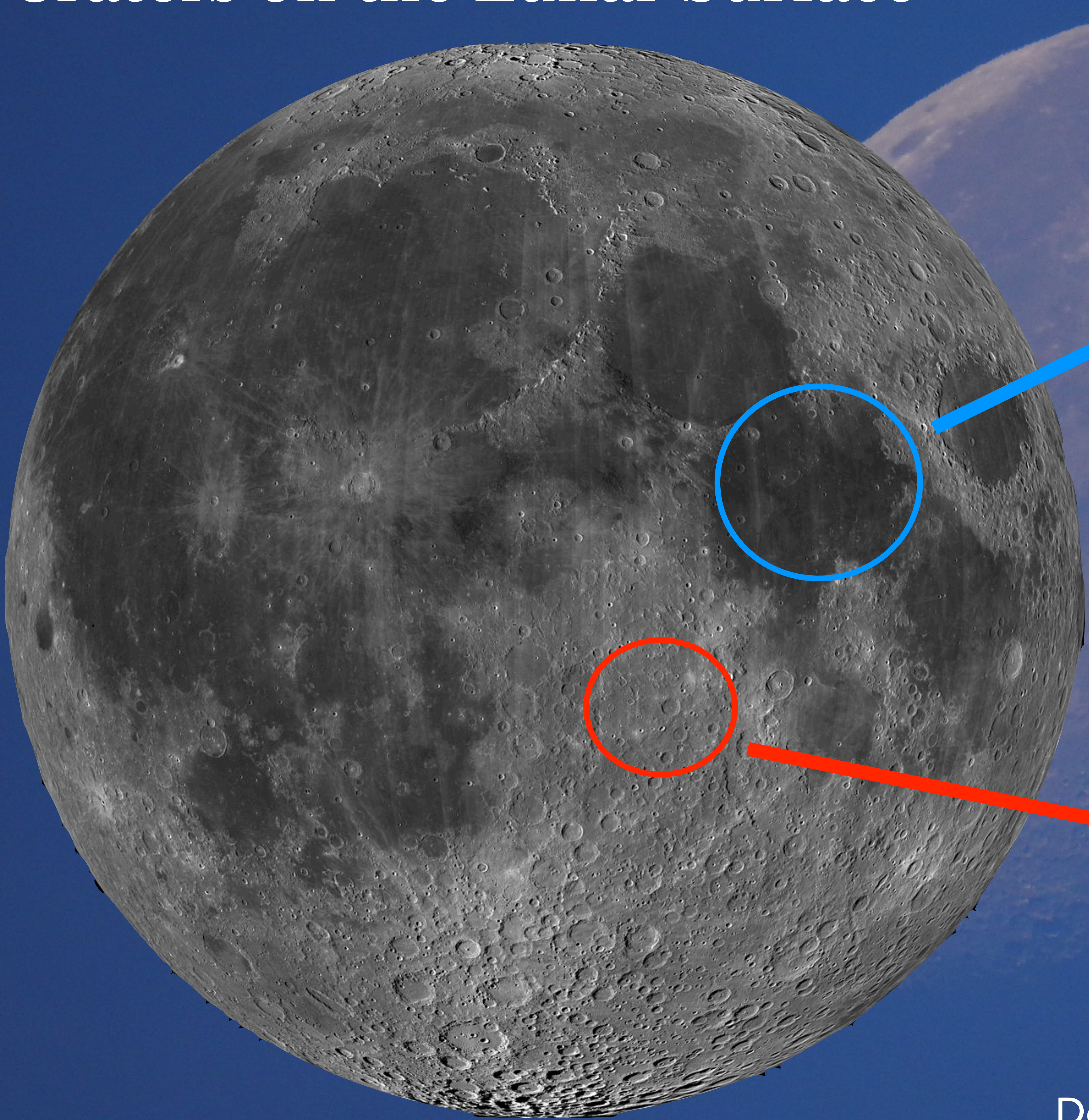
Learning the Age of a Surface

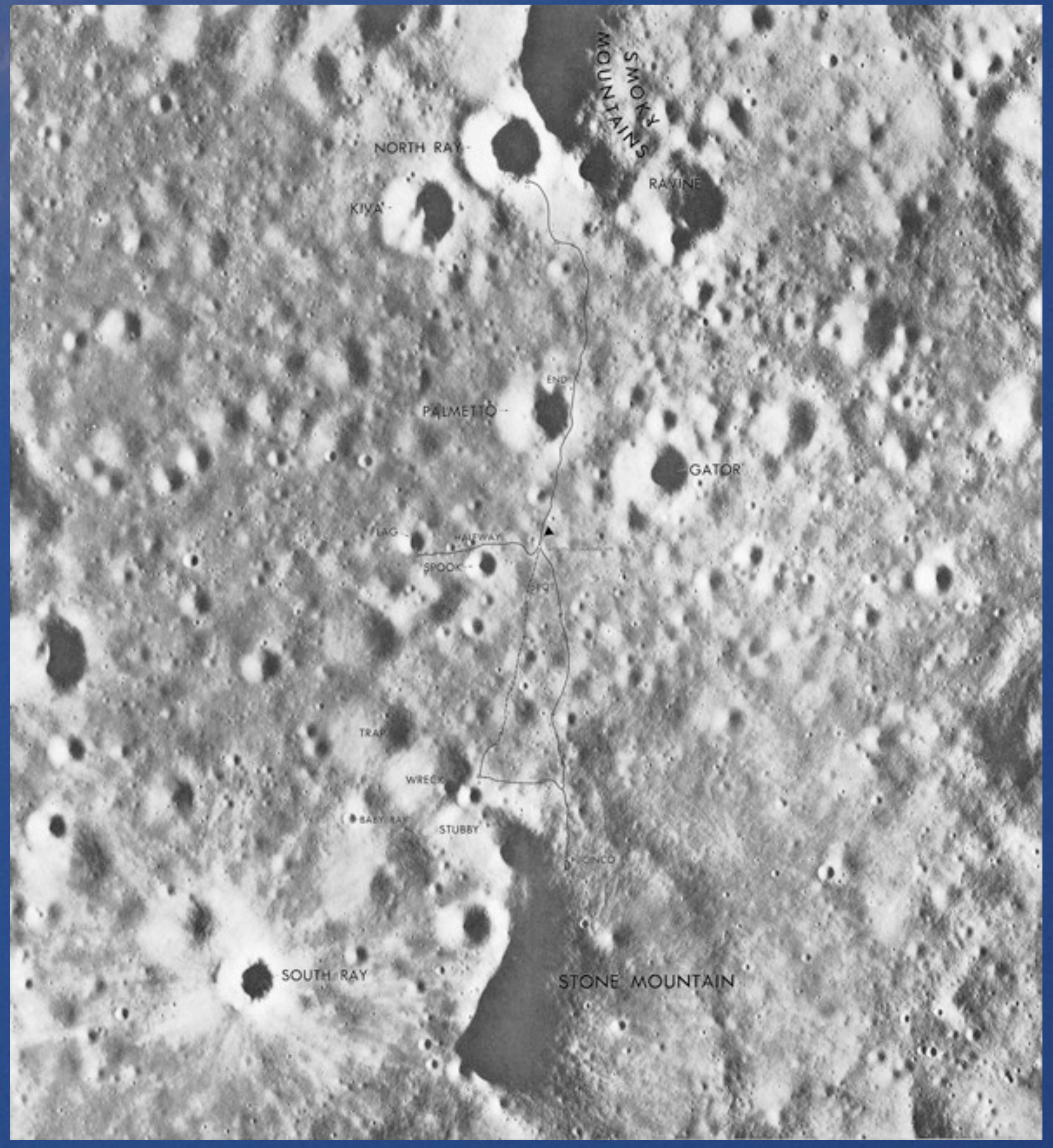
Impact cratering is the only process with an external cause, which leads to a very useful fact: *we can estimate the geological age of any surface region from its number of impact craters, where more craters indicates an older surface!*

For example, crater crowding varies from place to place on the Moon: the highlands have many craters while the maria have relatively few craters

> Radiometric dating of rocks brought back by the *Apollo* astronauts tell us that the rocks in the highlands are about 4.4 billion years old, while those from the maria are between 3 and 3.9 billion years old

Craters on the Lunar Surface





Descartes Highlands

Why do the planets have different geological histories?

There are three fundamental properties that control to what degree each of our four processes affect each planet

- Volcanism and tectonics both require internal heat, which means they depend on planetary size
- Erosion requires an atmosphere, so planetary size is important; the planet needs to be cool enough for gases to be attached to the planet, so distance from the Sun is important; rotation rate is also important as it is the primary driver for weather
- Impact craters are an external random event, so planetary factors aren’t *as* important, but volcanism and tectonics cover up craters so planetary size is important

The Geology of the Moon and Mercury

What geological processes shaped the Moon?

The bright, heavily cratered regions are the lunar highlands, while the smooth dark regions are the lunar maria

However, the entire surface of the Moon must have been covered in craters during the Late Heavy Bombardment period, so what happened to the craters in the maria?

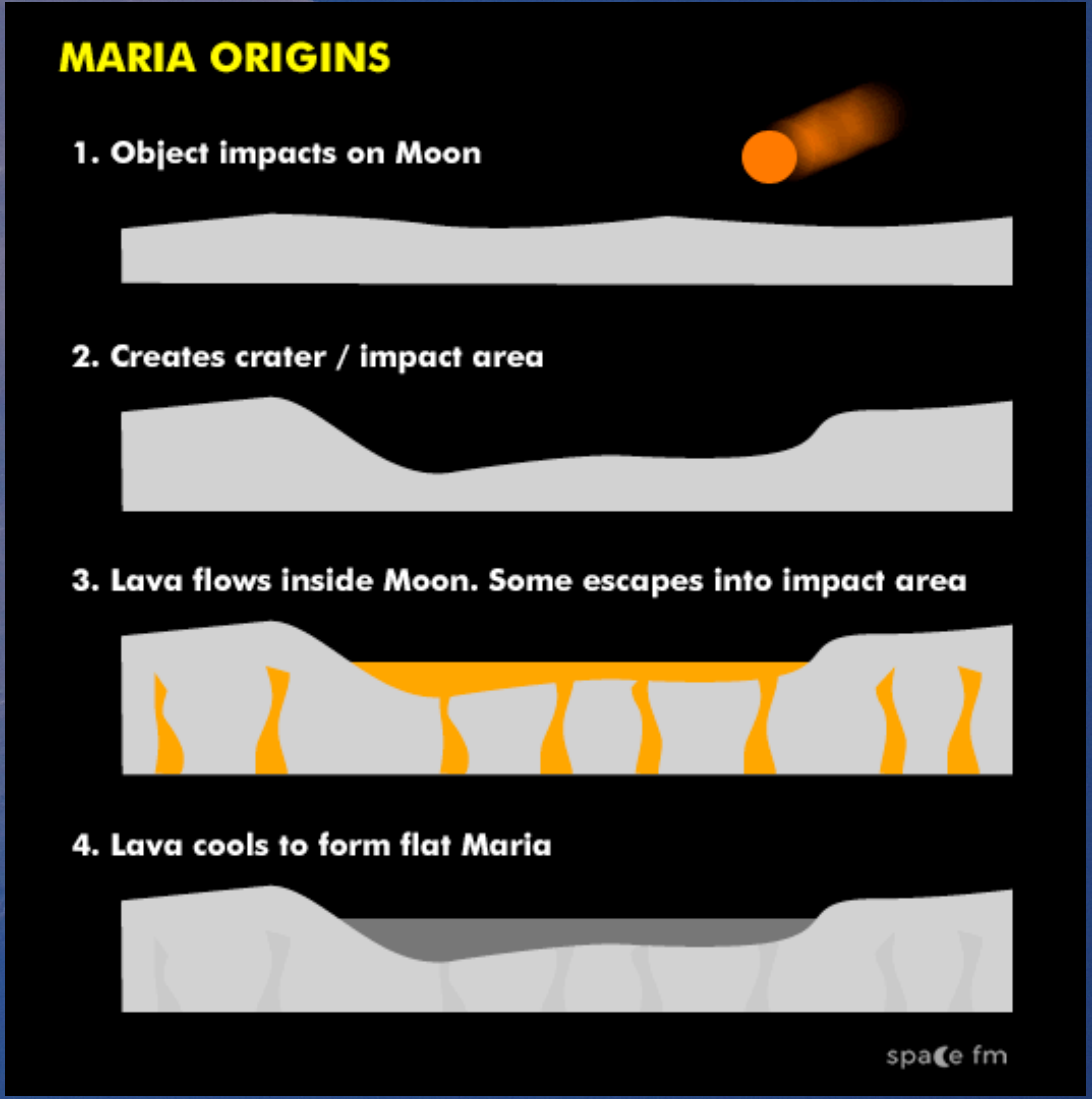
The Formation of the Maria

During the Late Heavy Bombardment period, craters covered the entire surface, and the largest impacts were likely strong enough to fracture the Moon's lithosphere underneath the craters

However, the Moon had already cooled, so no molten rock filled the craters until millions of years later thanks to heat from radioactive decay

The maria are giant filled-in craters! Their dark appearance comes from the basalt that rose up from the interior as lava, and that lava must have been very runny because the maria are very flat

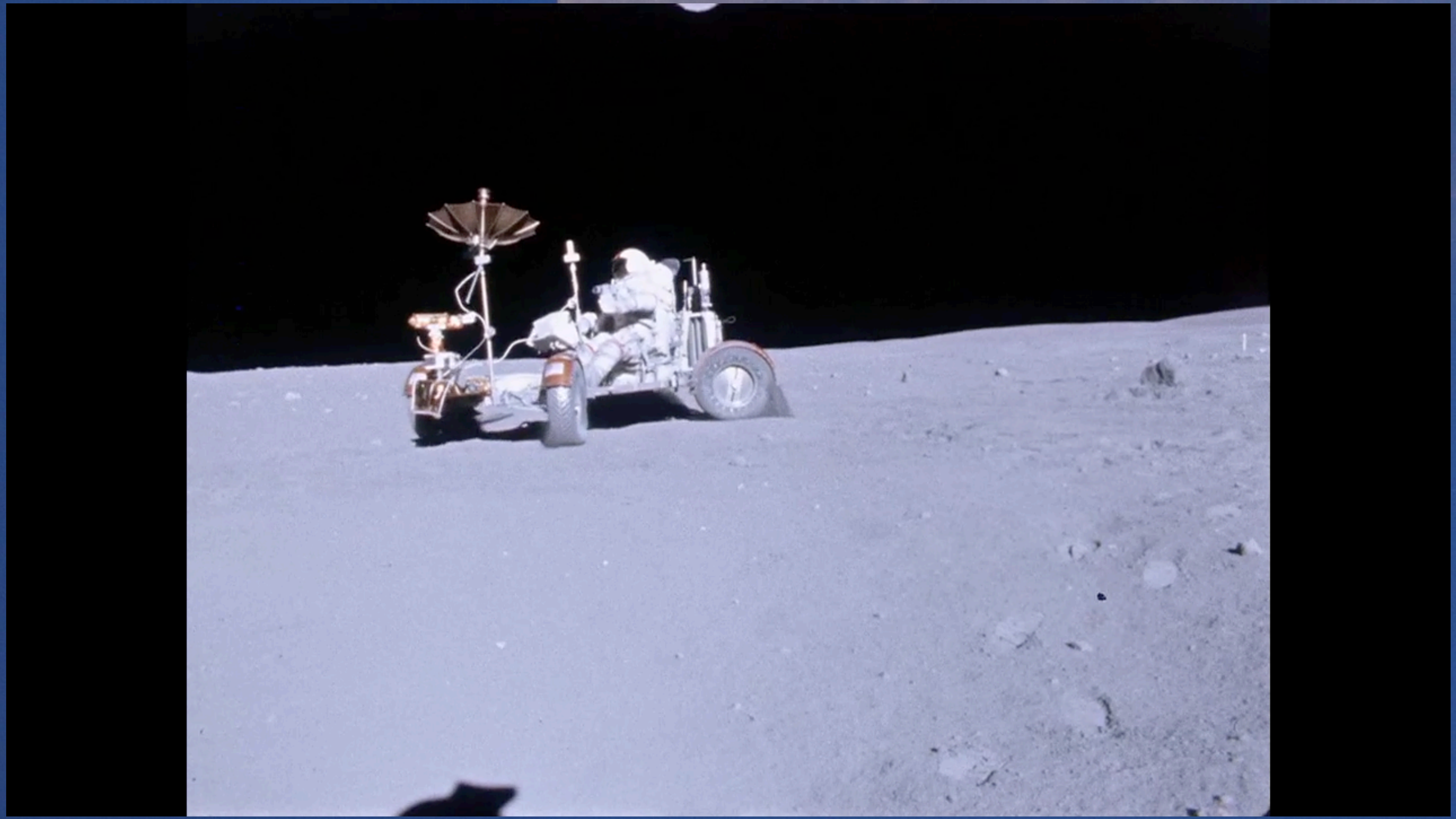
Relatively few impacts have happened since, which is why the maria are relatively crater-less



The Moon Today

Most of the geological activity has stopped since the formation of the maria, although a few small eruptions may have occurred as recently as 50-100 million years ago

The only ongoing geological activity is the slow “sandblasting” of the surface by micrometeorites, giving the surface a thin layer of powdery “soil”



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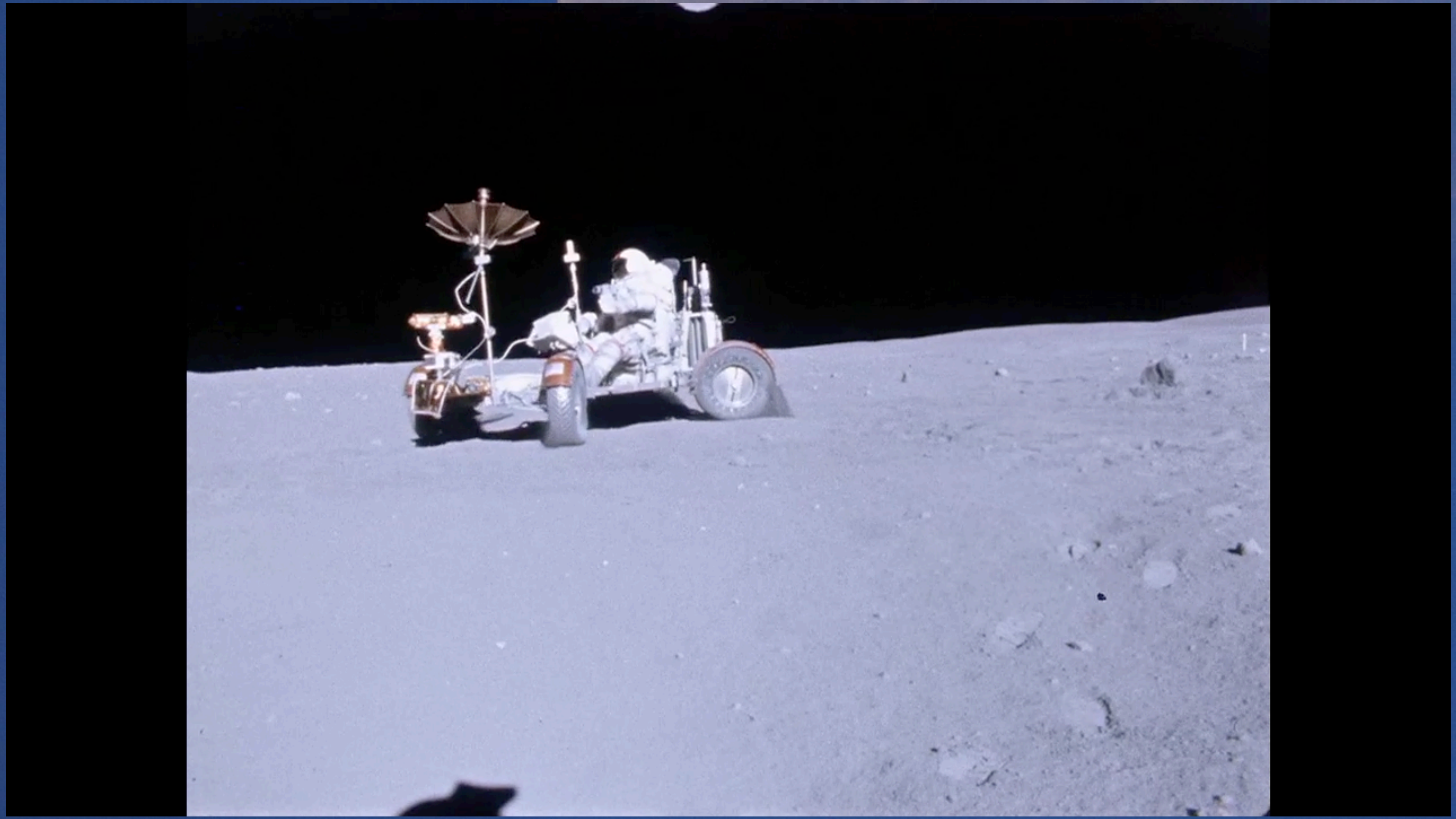
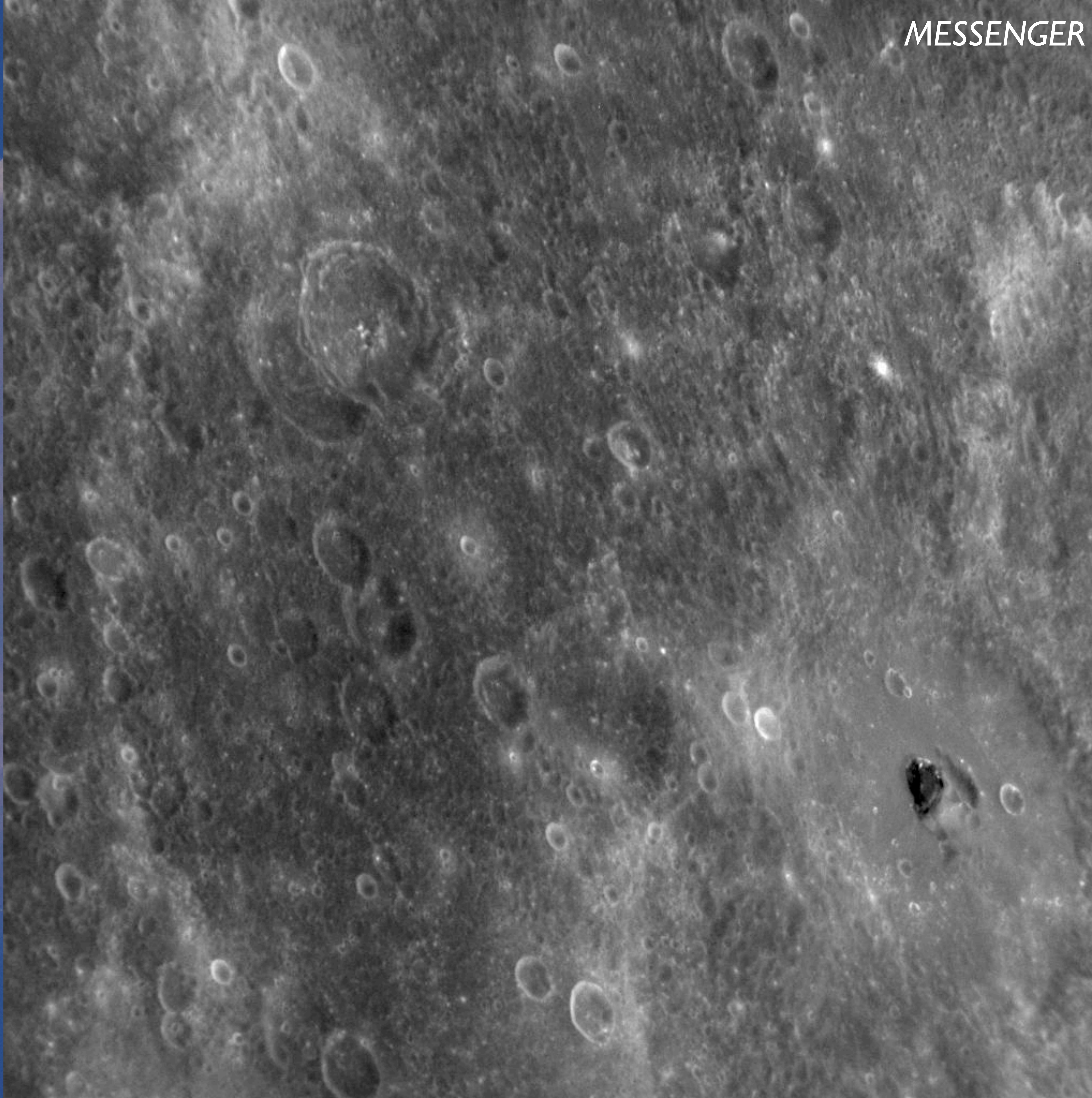


What geological processes shaped Mercury?

Impact craters are visible everywhere on Mercury, indicating an ancient surface; however, they are less crowded than on the Moon, suggesting that lava covered up some of the earlier craters



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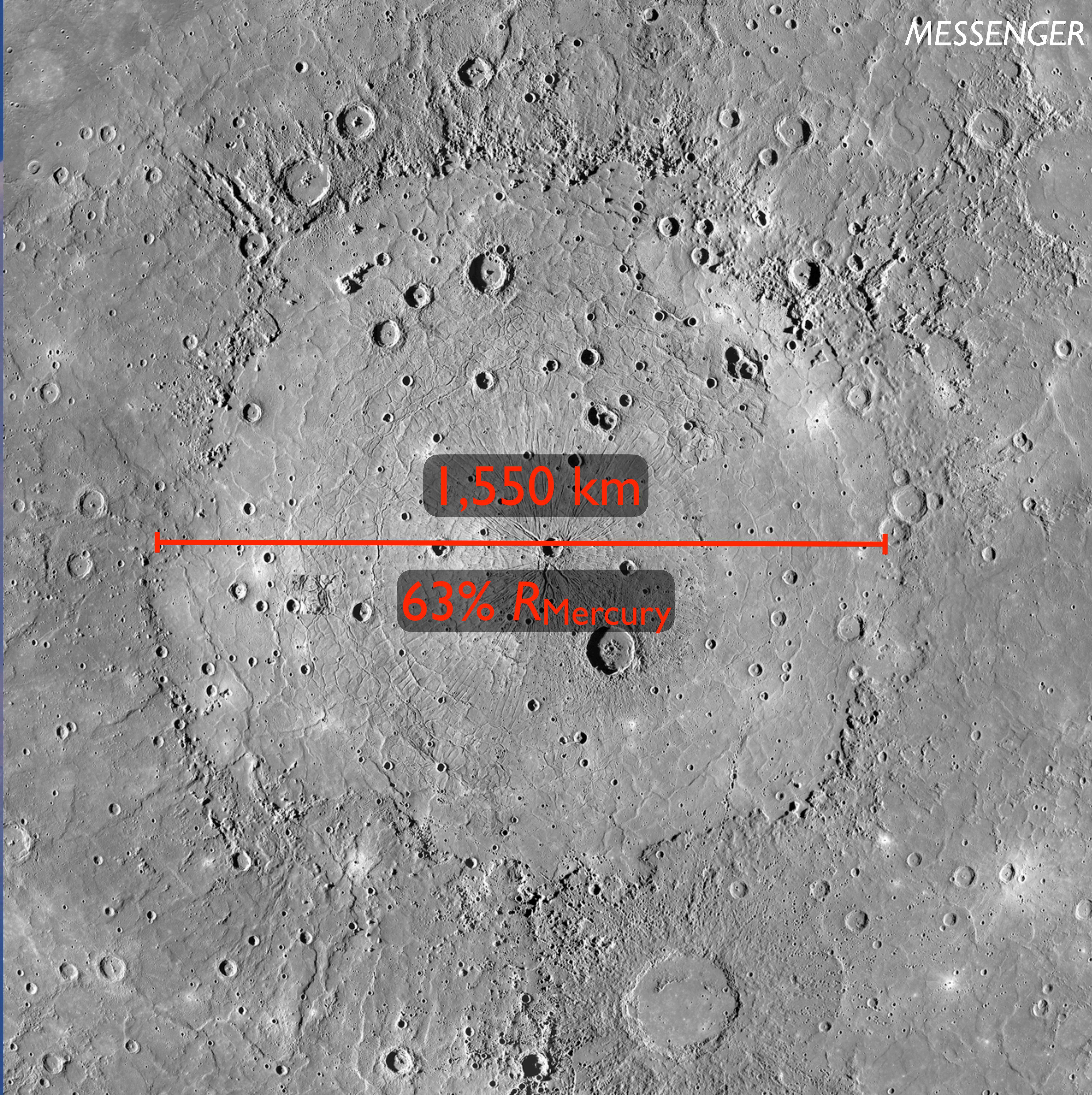
Mercury's largest impact craters are called *basins*, formed from impacts so large and violent that they melted surface rock that then filled up the crater

The largest is *Caloris Basin*, spanning more than half of Mercury's radius!



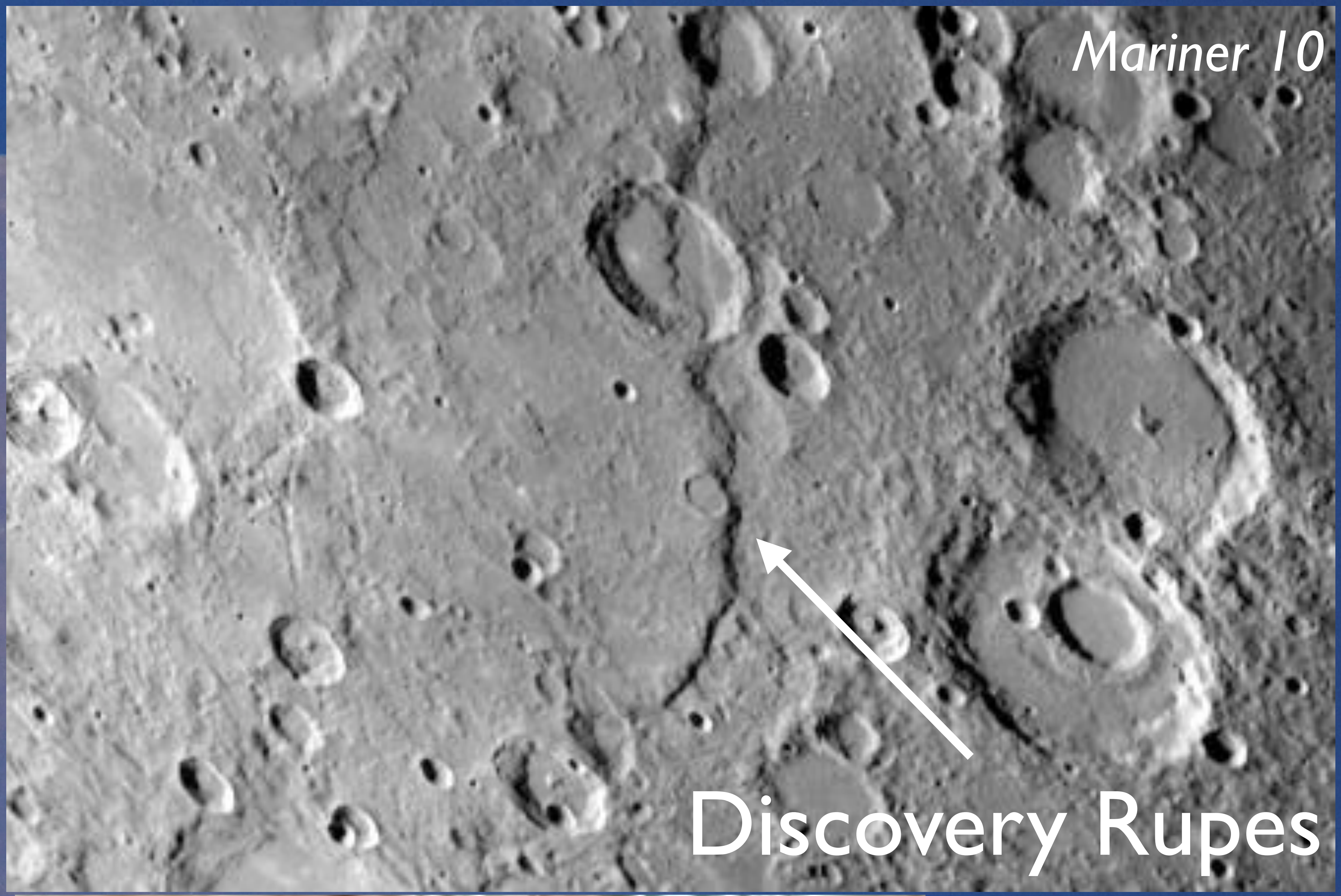
Honey, I Shrank... Mercury?

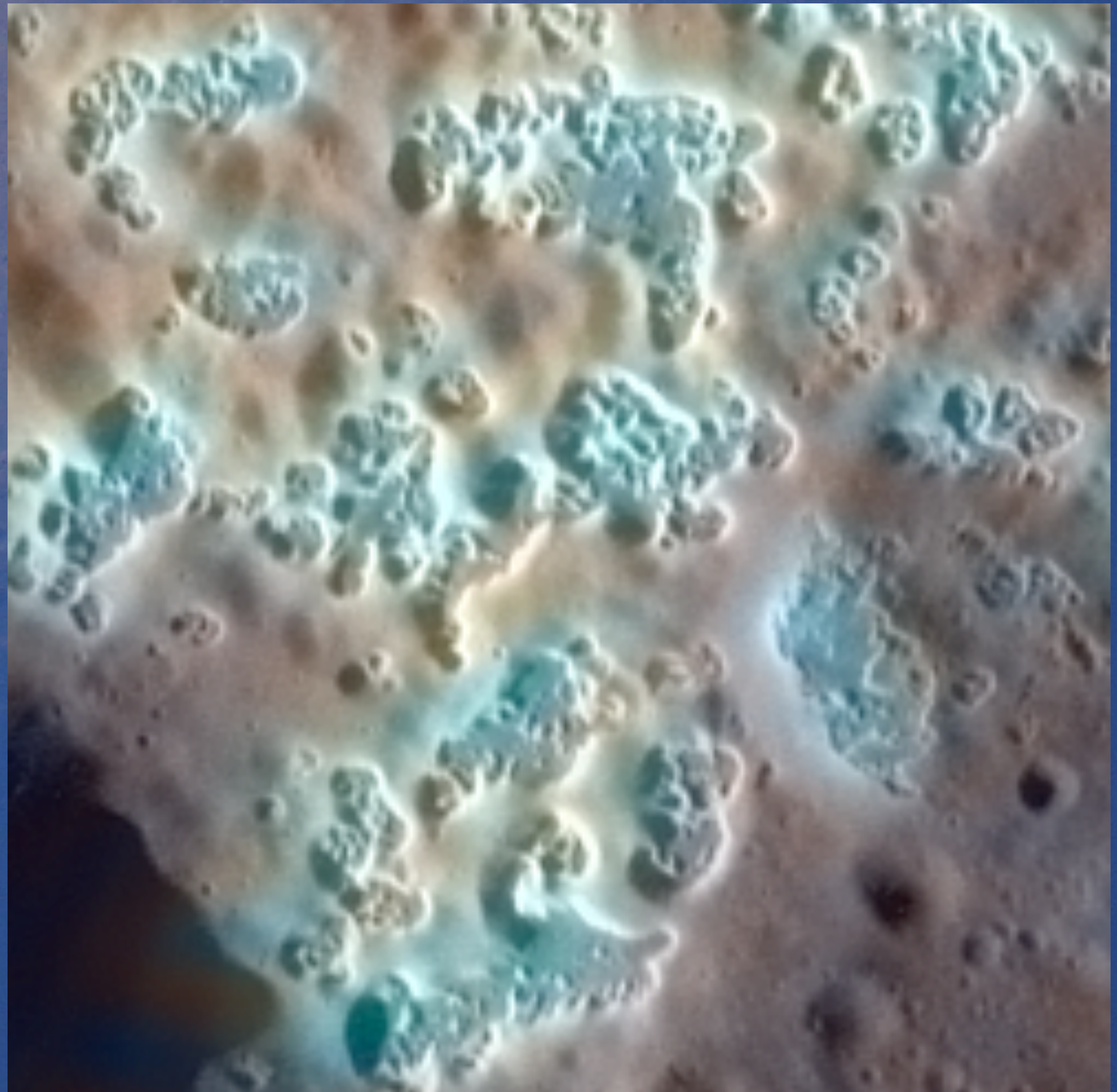
Mercury is covered in cliffs that stretch 3 km (1.9 mi) high or more and run for hundreds of km across the surface

They probably formed when tectonic forces compressed the crust, causing these "crumples," evidence for Mercury shrinking in the past!

Mercury is also thought to have retained internal heat longer than the Moon, confirmed by crater counts, but most activity ceased between 1-2 billion years ago

Despite that, some crater floors appear to be leaking vaporized material, causing the rock to crumble and make "hollows"





Raditladi Crater

MESSENGER

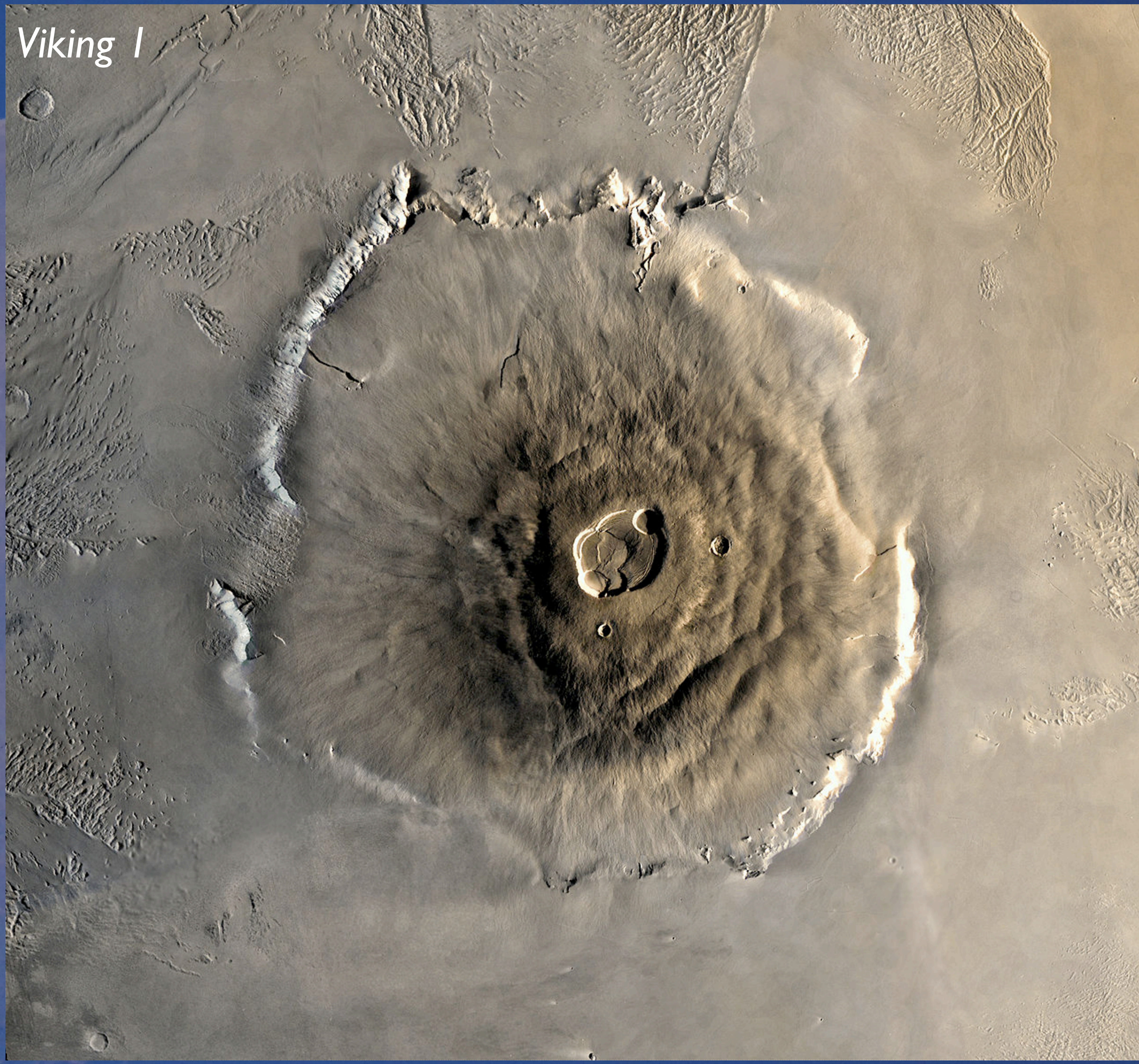

The Geology of Mars

The Surface of Mars

Martian Volcanoes

Volcanism was probably the most important process in erasing craters in the northern plains, although we’re unsure why it had a bigger effect in the north than the southern highlands

One volcano, Olympus Mons, is the largest mountain in the solar system, with a base 600 km (380 mi) across and a peak 26 km (16 mi) high



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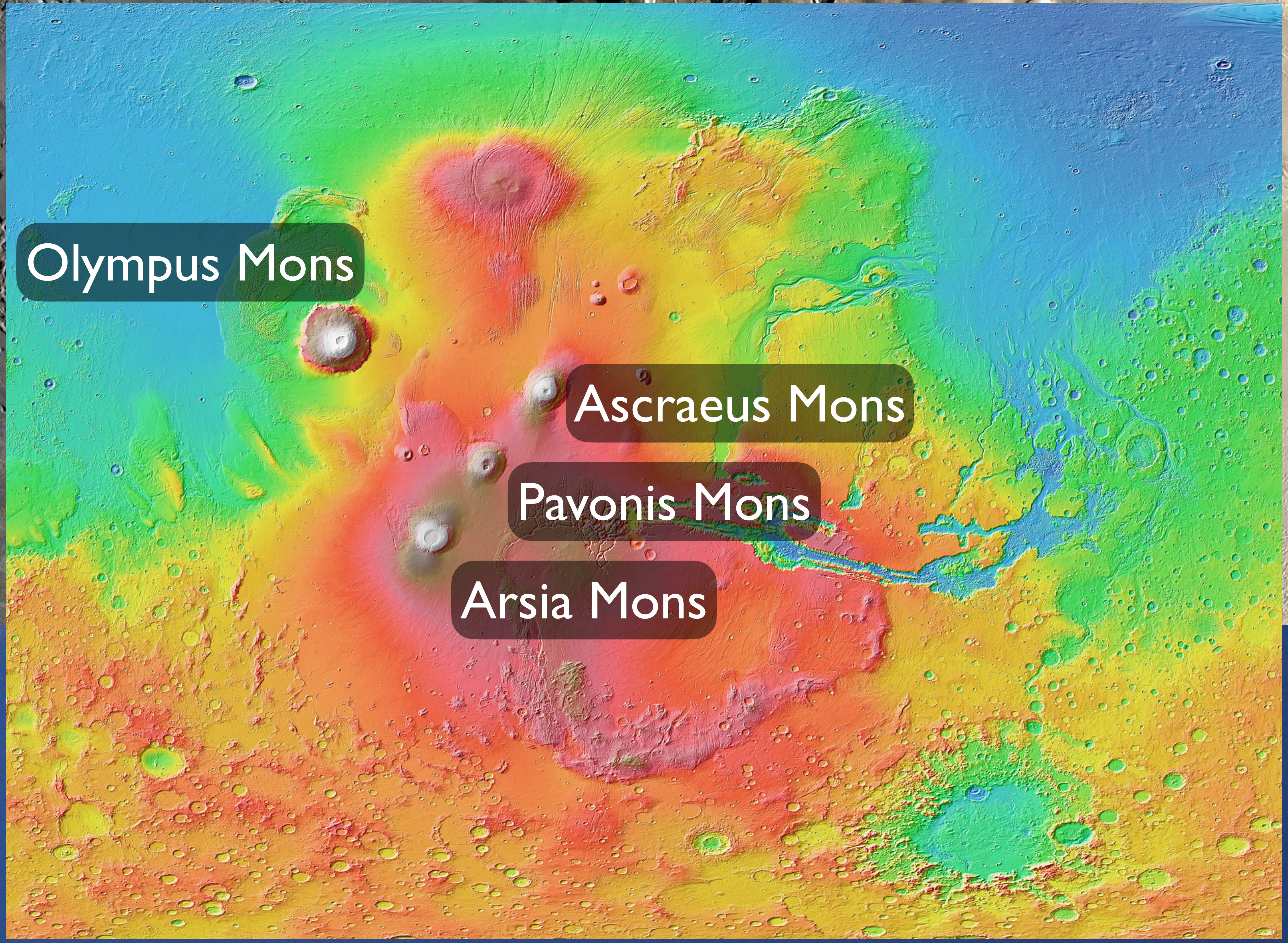
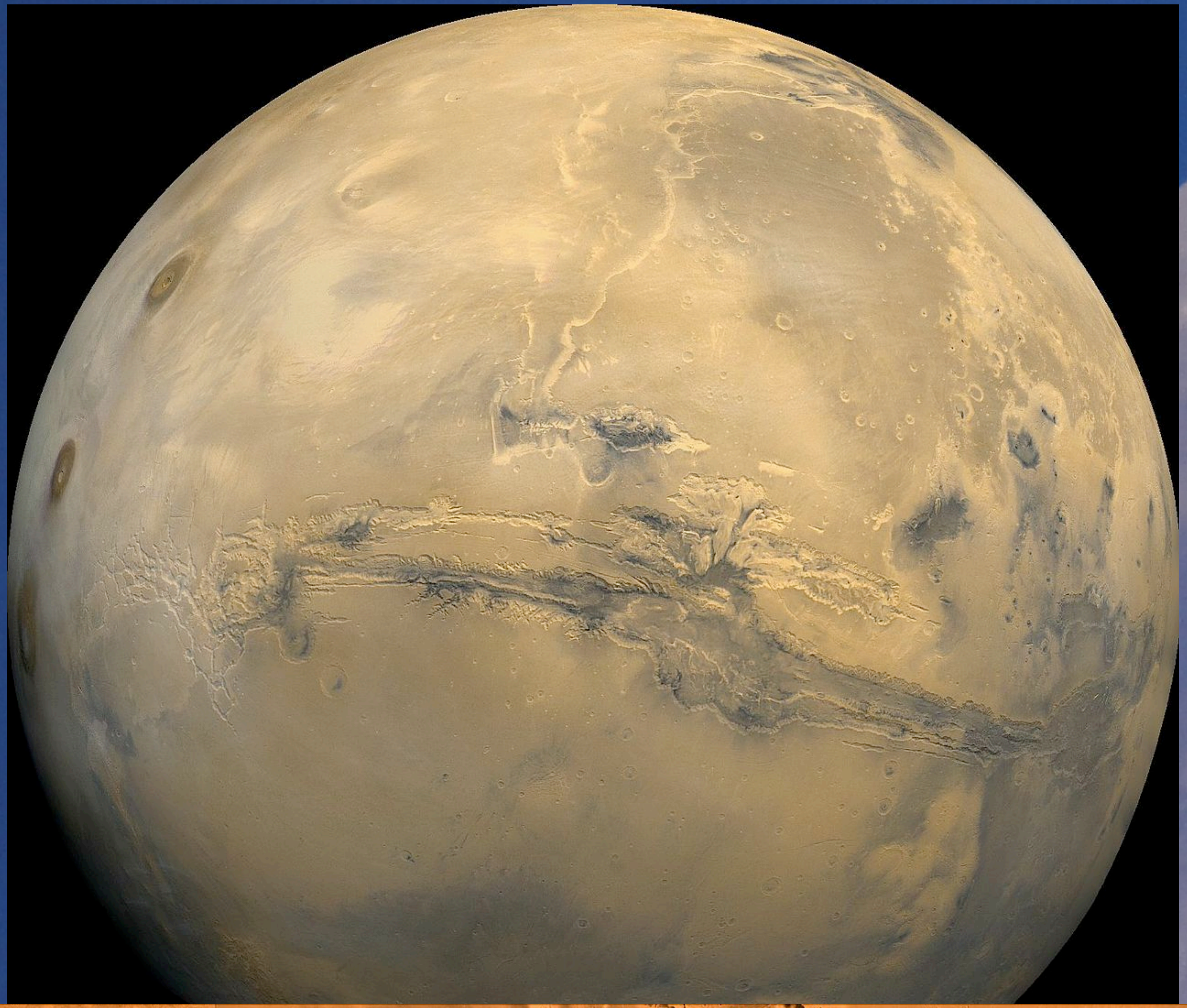
Along with Olympus Mons, several large volcanoes can be found on the Tharsis bulge, a region some 4000 km (2500 mi) across, likely created by a long-lived plume of rising mantle material that bulged the surface and provided the lava for eruptions

Mars had volcanic activity as recent as tens of millions of years ago, and might erupt again in the future

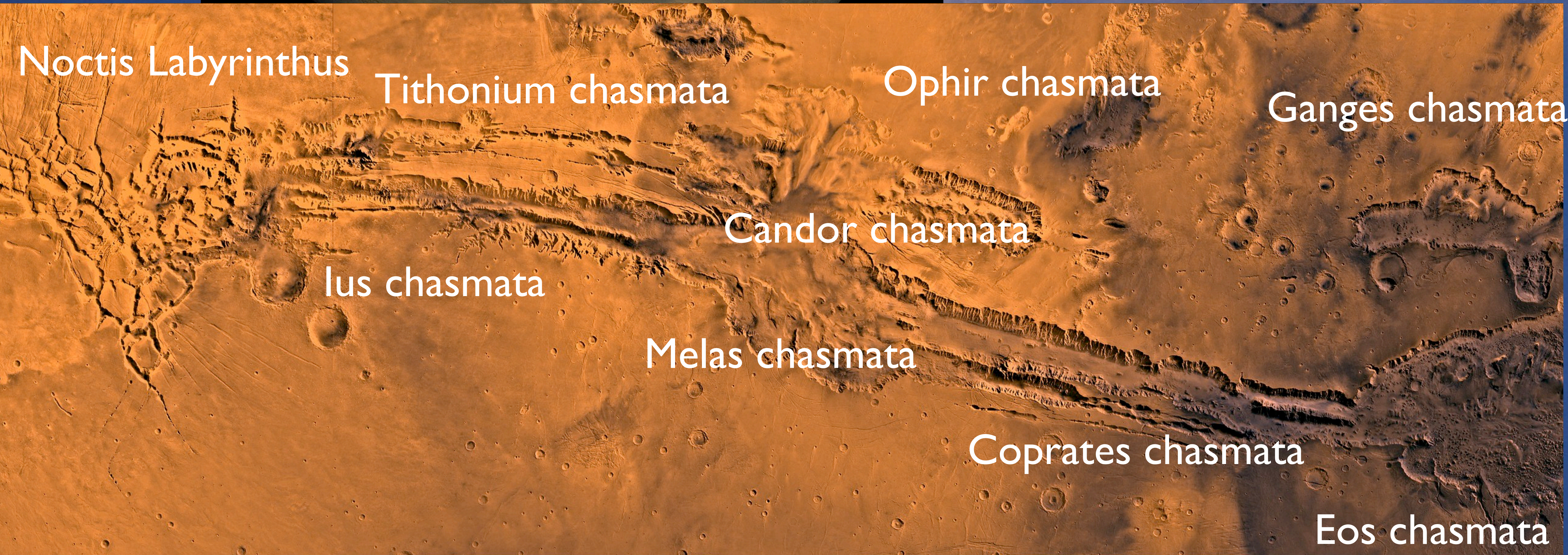


Tectonics and Valles Marineris



Mars' most prominent tectonic feature is the deep system of valleys called *Valles Marineris*

Stretching a fifth of the way around Mars' surface, it is about four times as deep as the Grand Canyon and no one knows exactly how it was formed



Parts of the canyon are enclosed by high cliffs on both sides, so neither flowing water or lava could've formed it, but its western end is at the Tharsis Bulge, so maybe there's a connection?

Water on Mars?

Liquid water is *unstable* on the Martian surface: most of the surface stays below freezing, but the few areas that get above freezing still have very low air pressure, so any liquid water evaporates

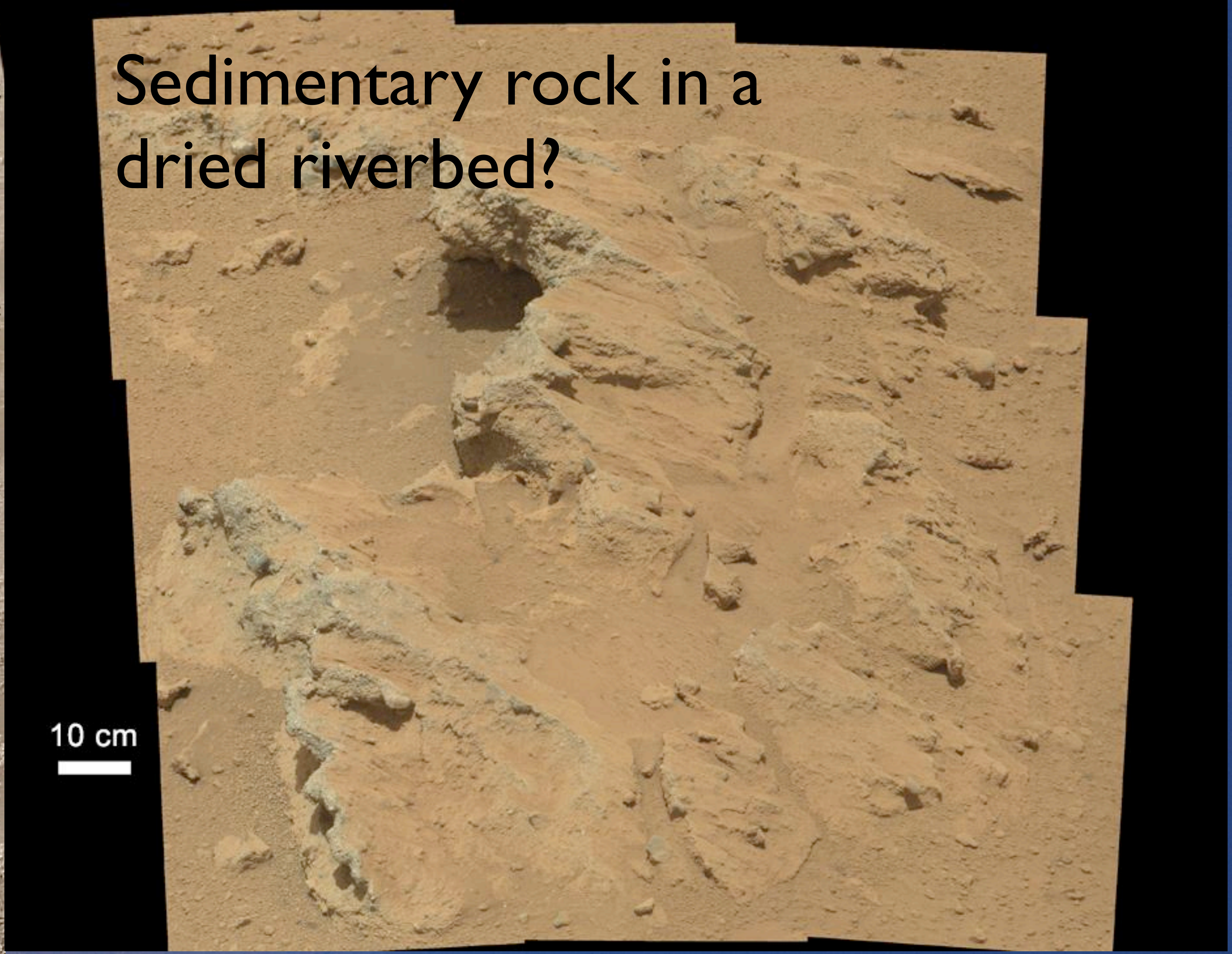
However, there are features on Mars that can only be explained with the presence of water long ago, about 3 billion years ago

The lack of small craters suggests erosion; features exist that look like river deltas; rovers have found mineral evidence of liquid water in ponds or lakes; *Curiosity* is heading towards Mount Sharp, where layers exist that might be sedimentary rock!

There is even evidence for recent water flows as the temperatures warm during the year!

River deltas in Eberswalde Crater?

Sedimentary rock in a dried riverbed?



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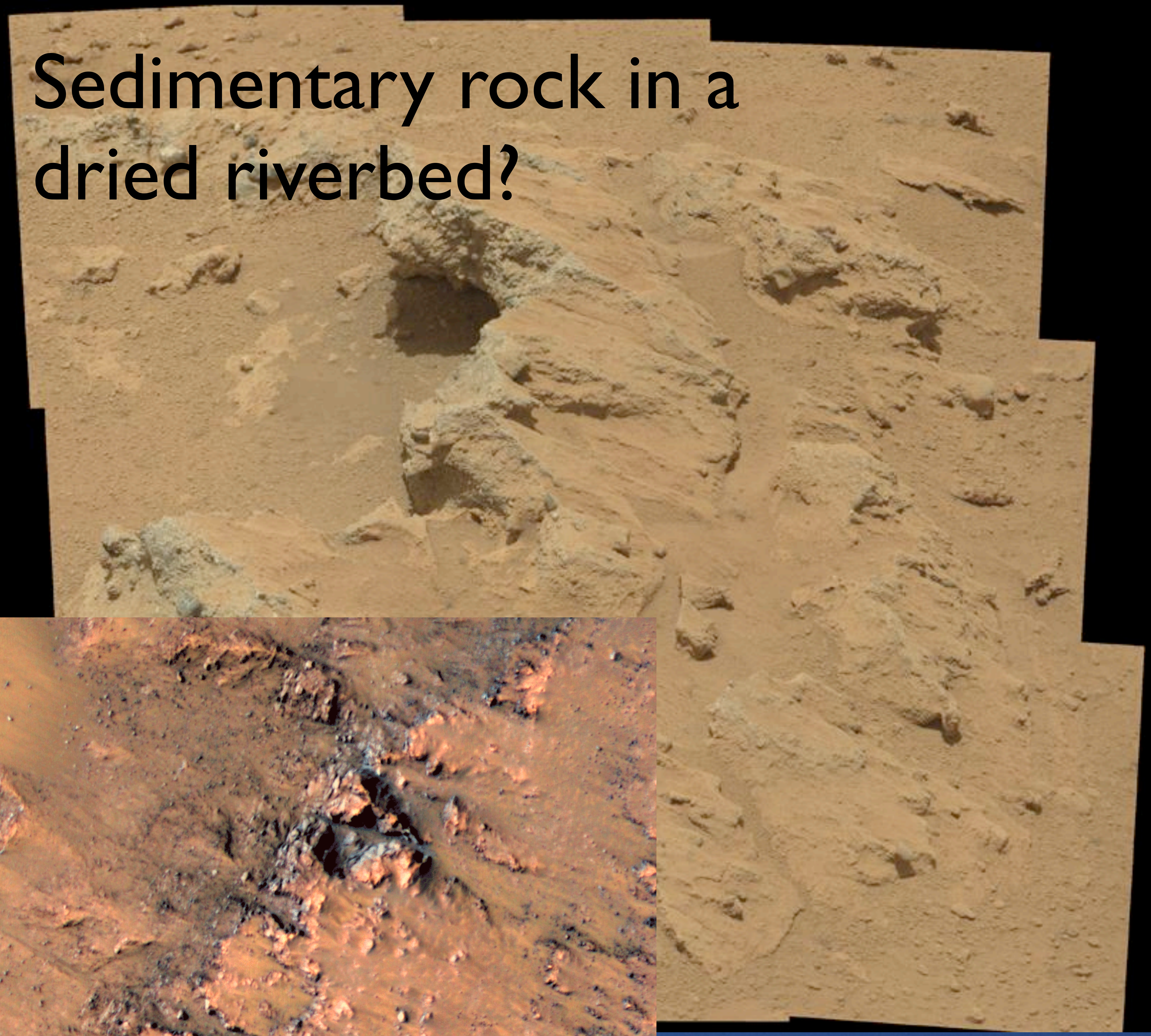
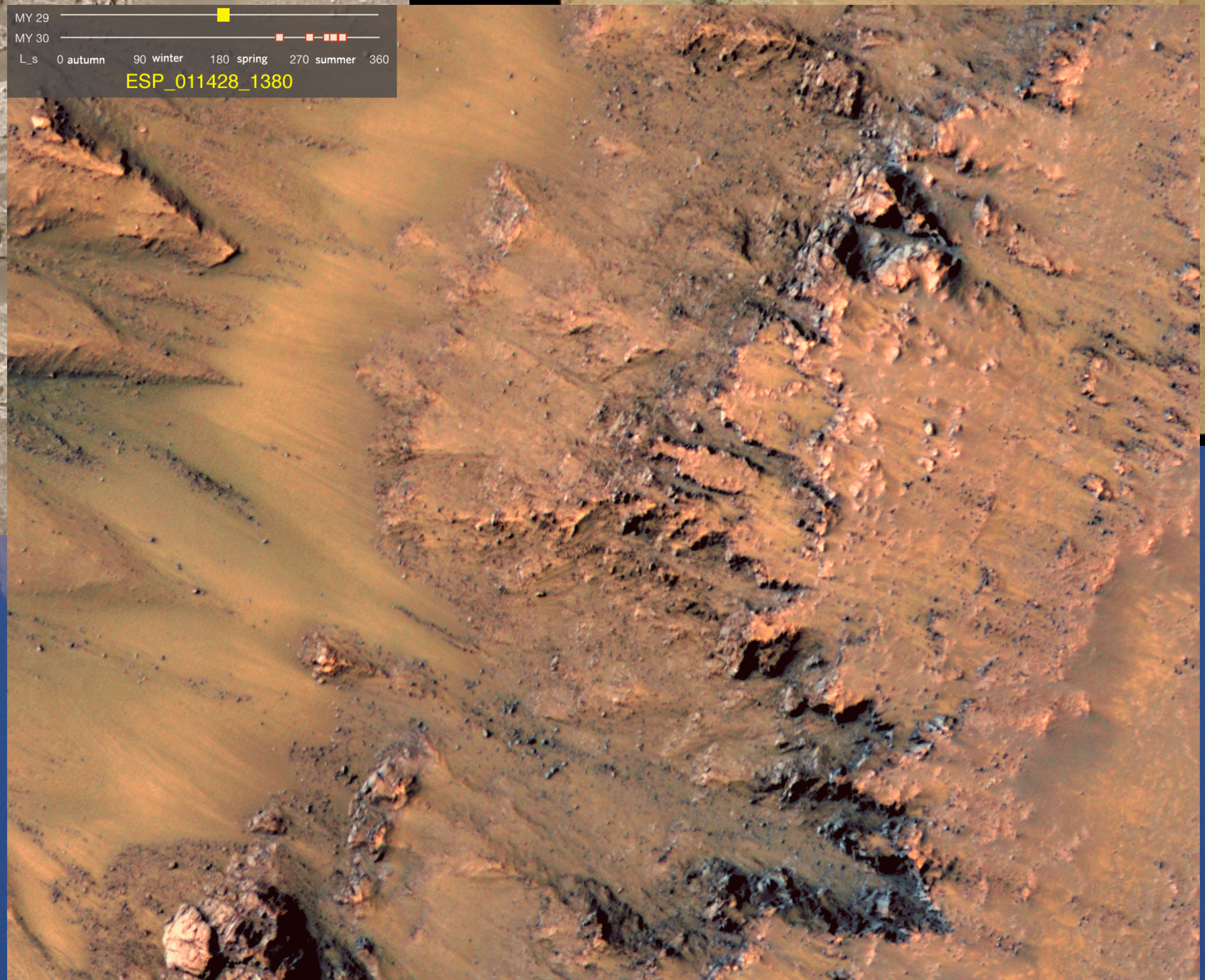
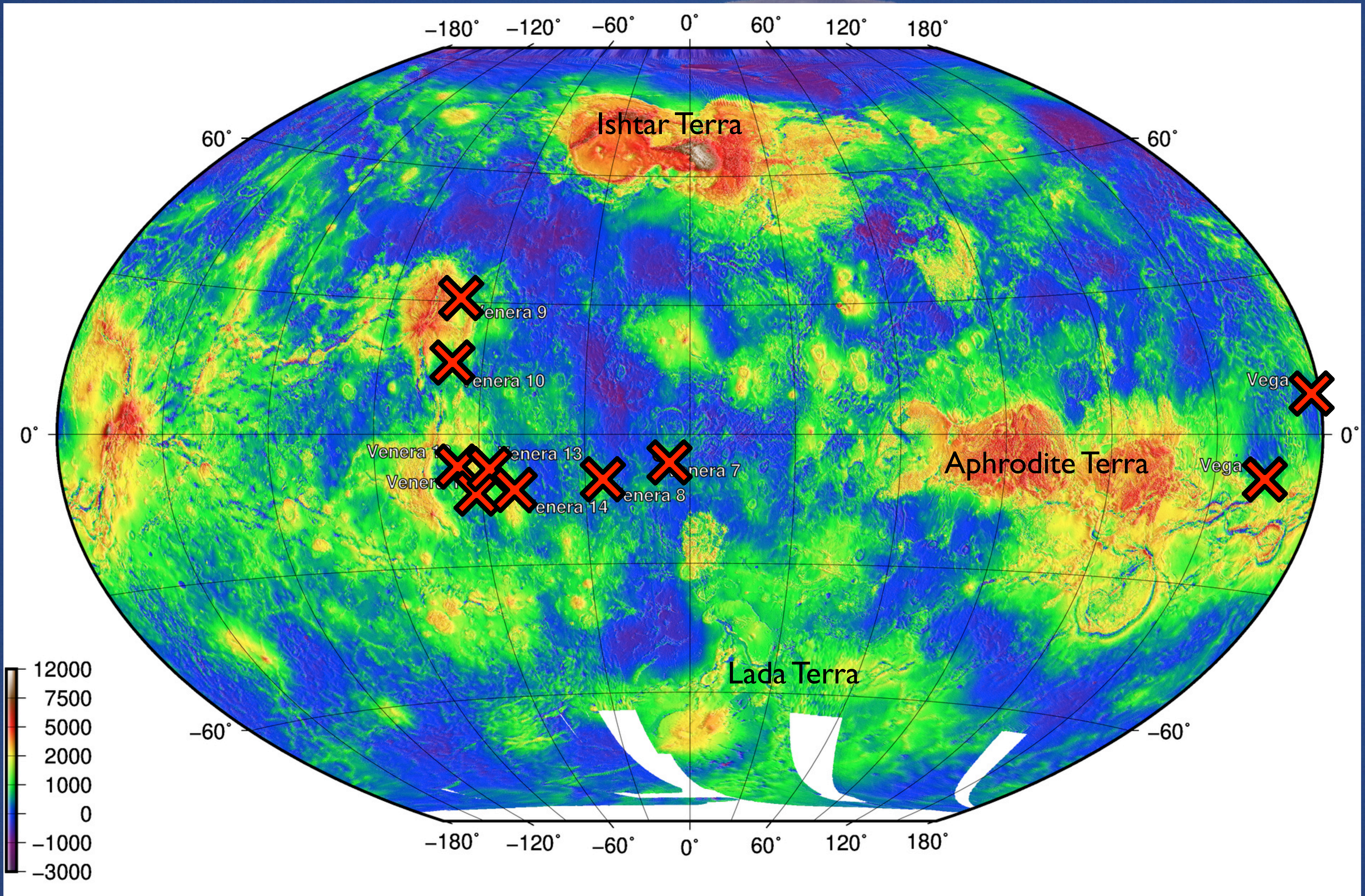





Curiosity's view of
Mount Sharp


The Geology of Venus

The Surface of Venus

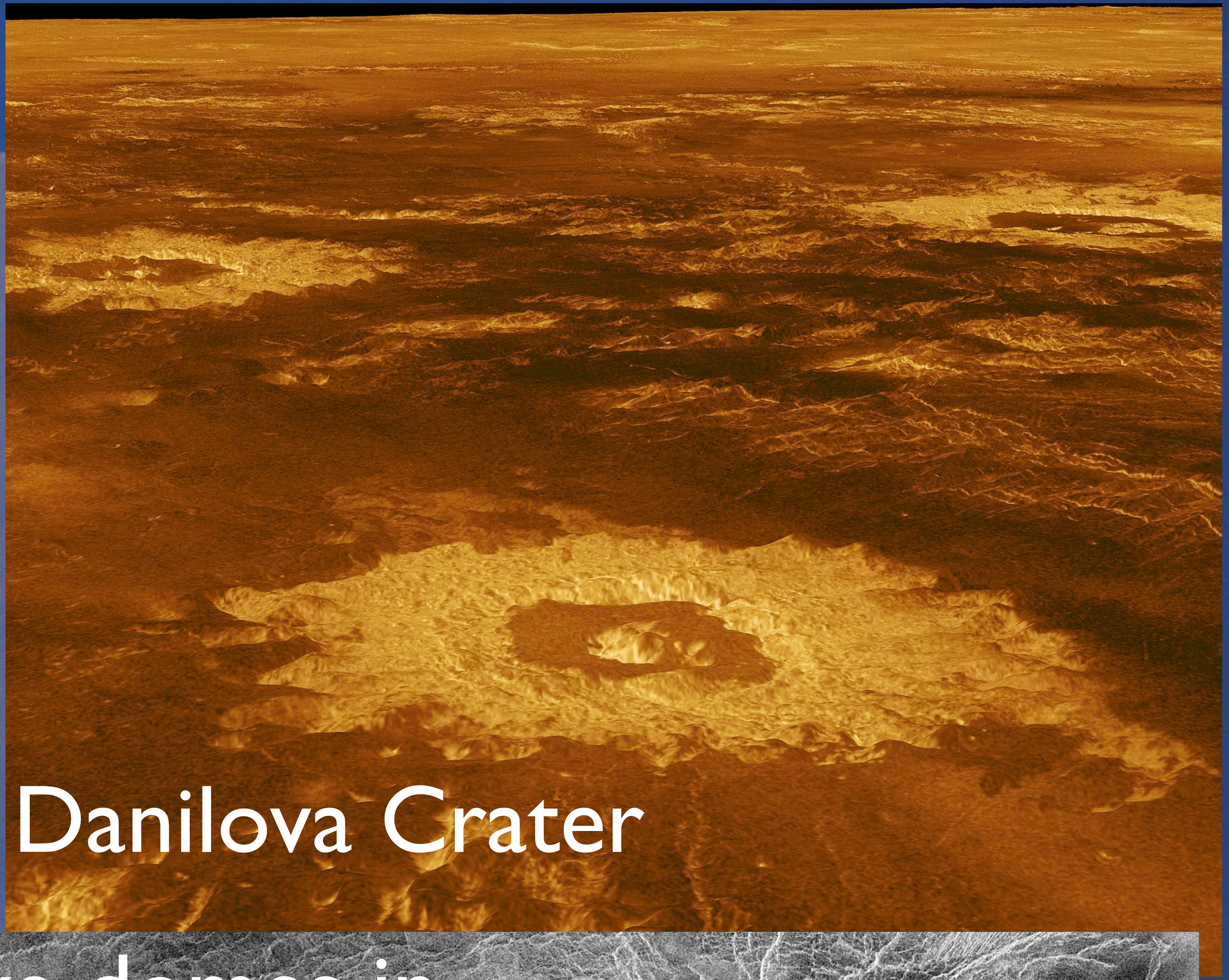


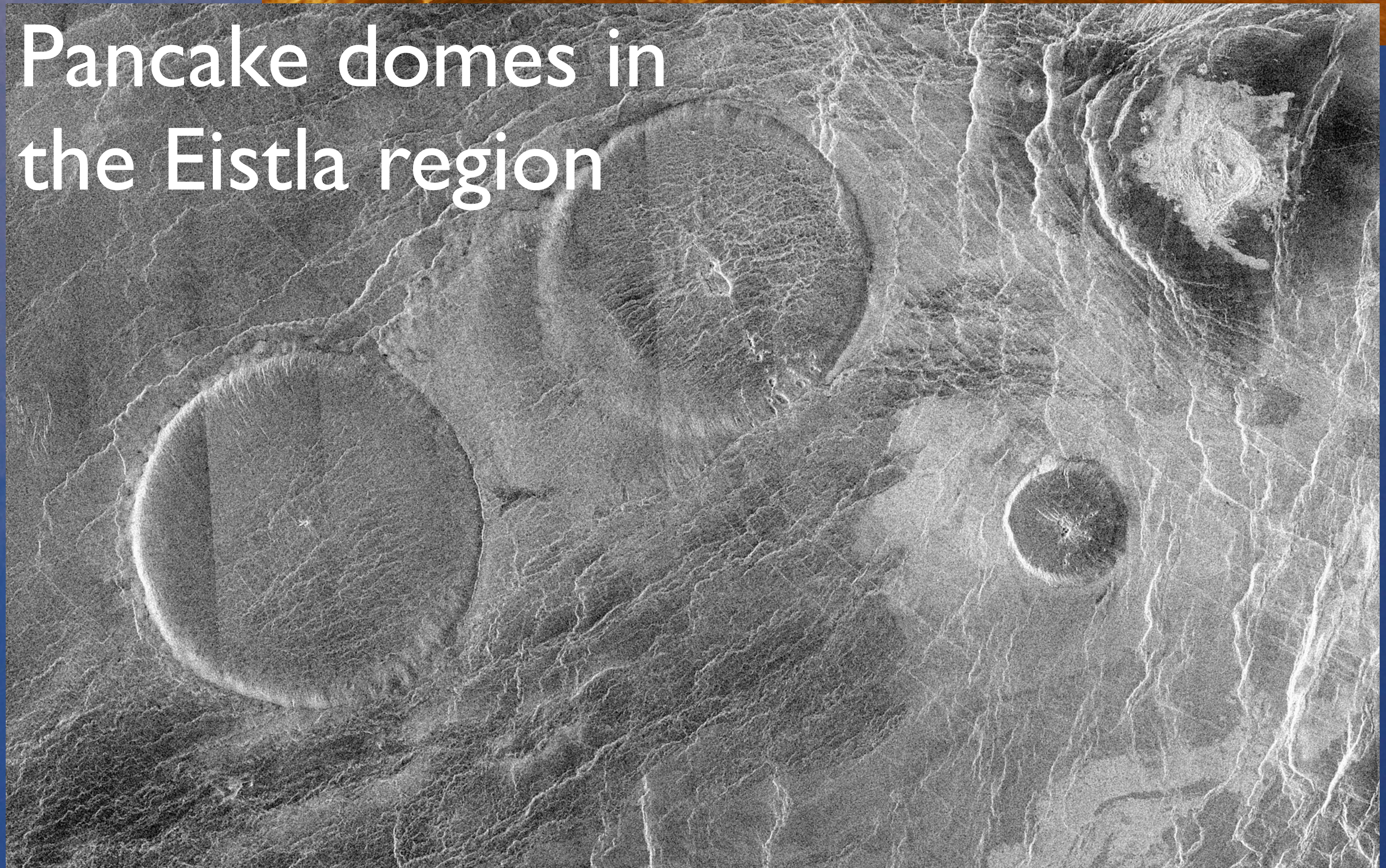
Craters and Volcanic Activity on Venus

Venus has a relatively small number of impact craters, indicating that its craters were erased by other processes; it also lacks lots of large craters, probably because the impactors burned up in Venus's thick atmosphere

Venus is covered lava plains and volcanic mountains and shows evidence of tectonic activity in the past

It should retain as much internal heat as Earth does today, so it is likely still geologically active; the ESA *Venus Express* mission detected evidence of volcanic activity as recent at 250,000 years ago





Venusian Erosion… or lack thereof

You might expect Venus to have strong erosion with that thick atmosphere, but images from the surface say otherwise

Venus is far too hot for any rain or snow to fall on its surface, and its slow rotation means there is very little surface wind

Venera 13, 1982

Does Venus have plate tectonics?

Venus shows no evidence of Earth-like plate tectonics; instead Venus shows the same age surface everywhere, about 750 million years old

We think Venus doesn't have any tectonic activity because its lithosphere is thicker and stronger than Earth's, so it doesn't fracture as easily

It might be thicker and stronger because Venus's high temperatures have baked all of the water out of its lithosphere

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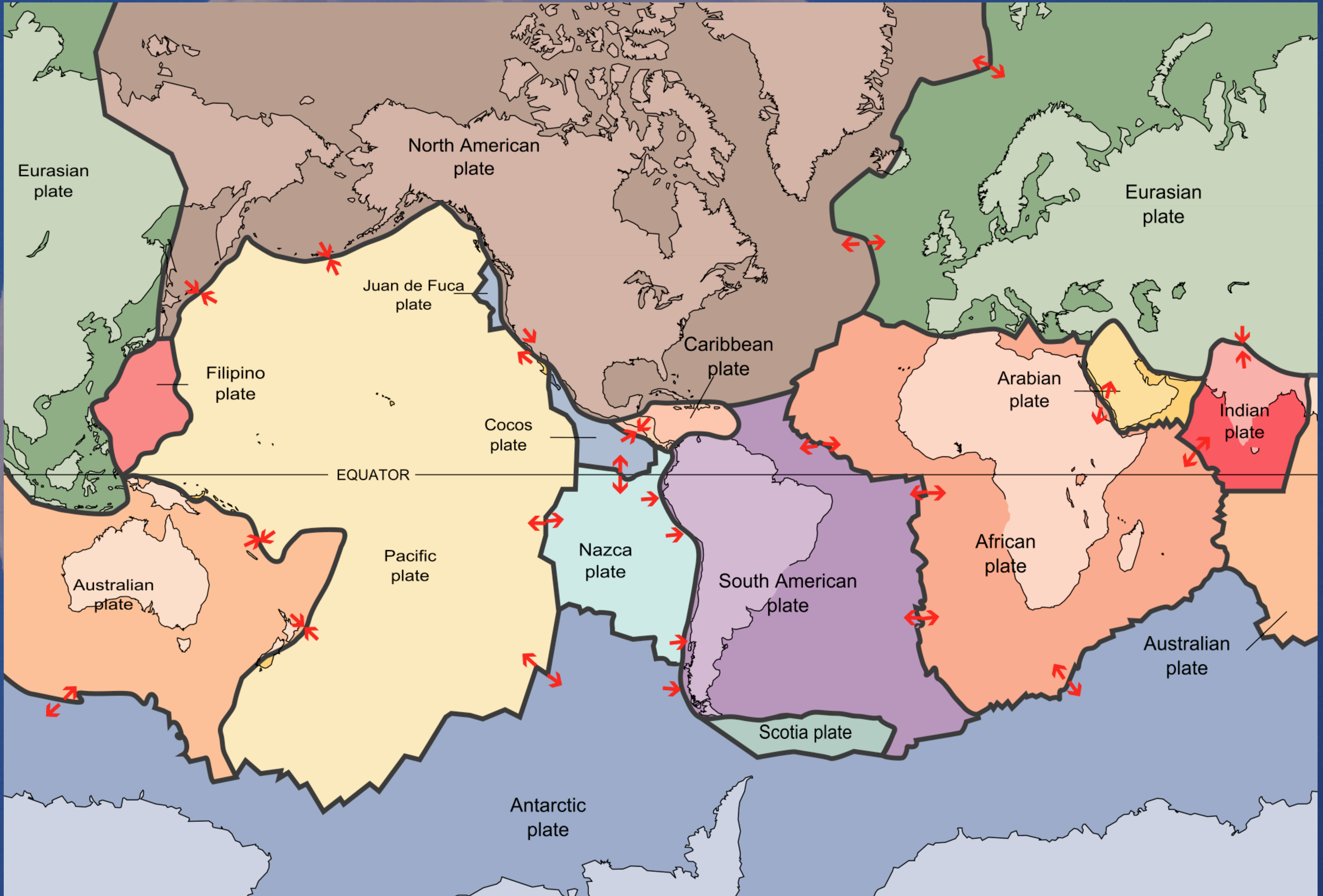
The Unique Geology of Earth

Earth's Plate Tectonics

Plate tectonics traces its origin to Alfred Wegener in 1912 who posed the idea of *continental drift* by noticing that South America and Africa seem to fit into each other

His idea gained traction when geologists discovered *mid-ocean ridges* from which the seafloor grows, causing the continents to drift apart

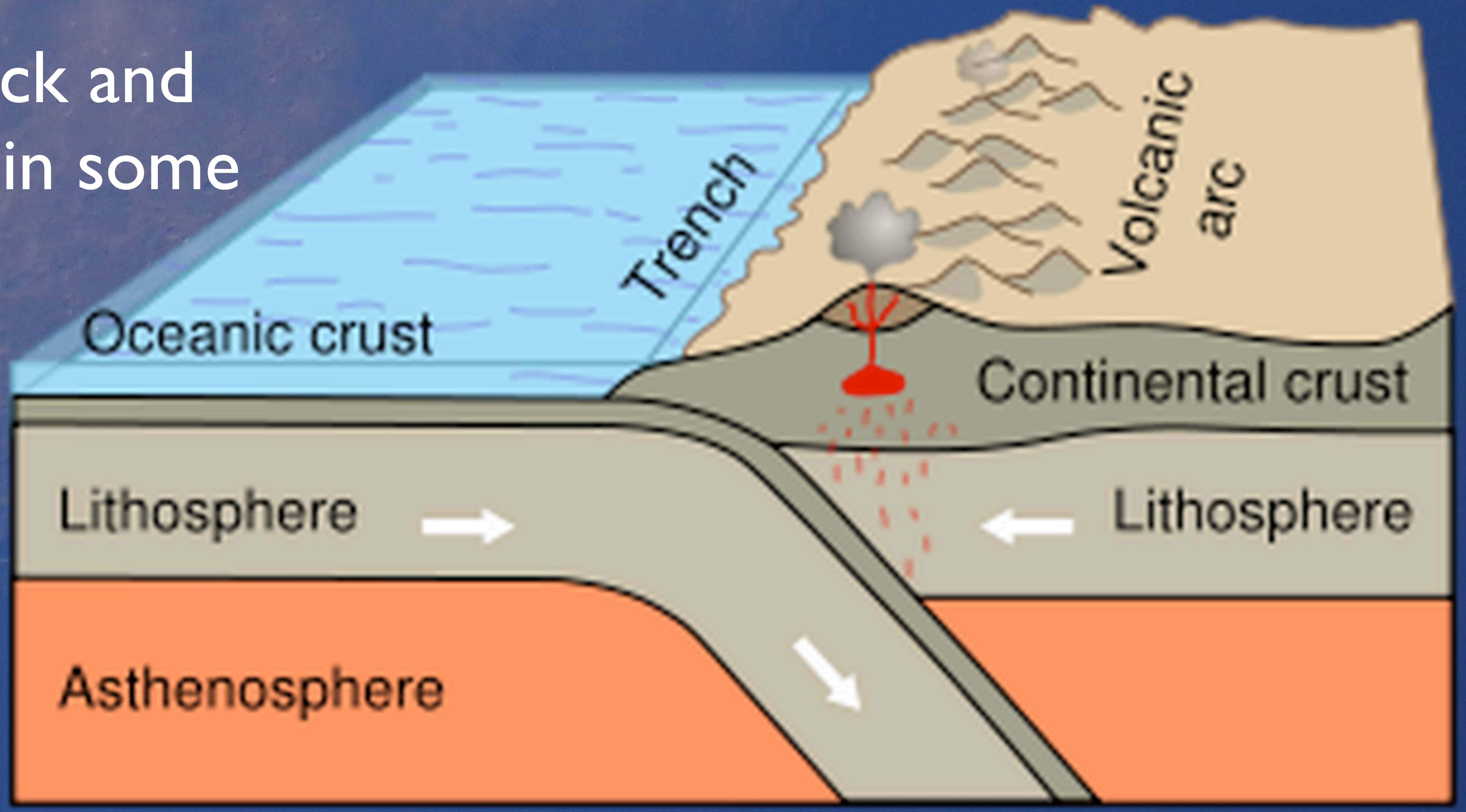


Two Types of Crust

Earth is unique among the terrestrial planets in that is has two types of crust: seafloor crust, which is thinner, denser, and younger than continental crust

Seafloor crust is typically 5-10 km thick and made of high density basalt rock and radiometric dating has shown that it is less than 200 million years old

Continental crust is typically 20-70 km thick and made of low density rock like granite and in some places is around 4 billion years old!



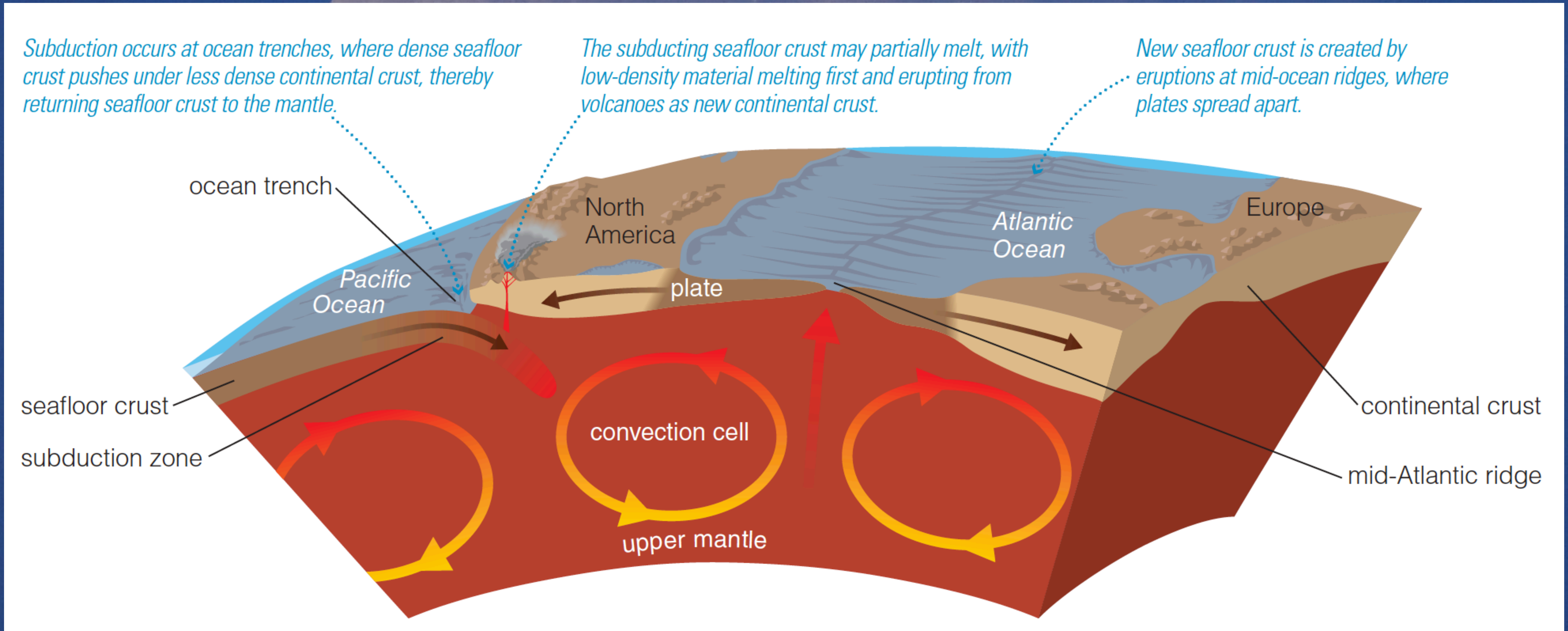
The Conveyor Belt of Plate Tectonics

Mid-ocean ridges occur at places where mantle material rises up, creating new seafloor crust and pushing plates apart

Over millions of years, the crust gradually makes its way towards a subduction zone, where seafloor meets the continent, and the denser seafloor slides underneath the continent back into the mantle

As the seafloor crust slides into the mantle, if enough material melts, then the molten rock may erupt upward as a volcano

Plate tectonics is clearly driven by the heat flow from mantle convection, making internal heat very important!



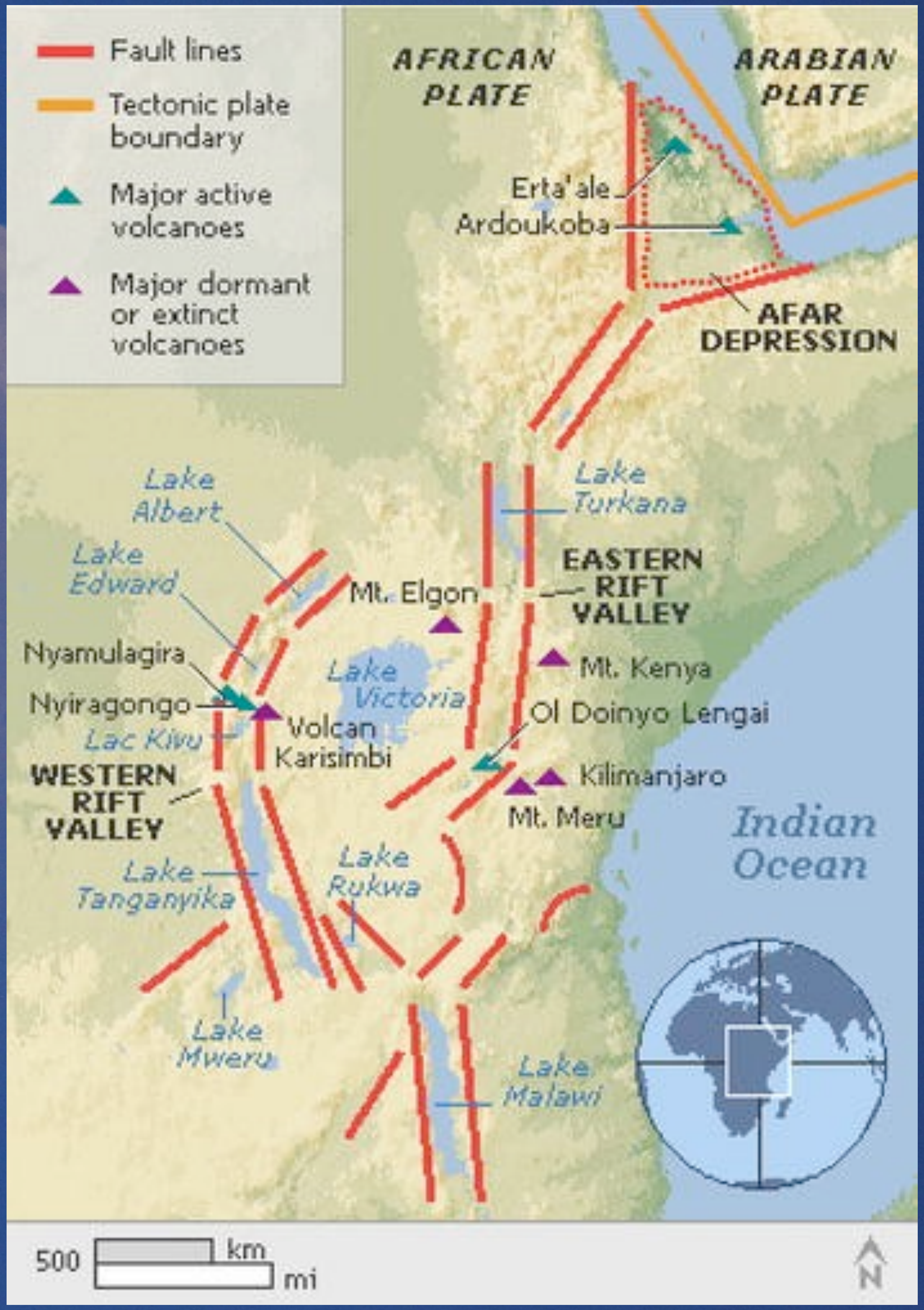
Building Continents

…and tearing them down!

Continental plates build each other up when the collide, but they can also pull apart or slide relative to each other

When continental plates pull apart, we get *rift valleys* that will eventually tear the continents apart and form an ocean

When continental plates slide past each other, we get <u>faults</u>, where the stress is sometimes so great that earthquakes happen



Hot Spots


SAND ISLAND
1117 ACRES
EASTERN ISLAND
366 ACRES
SPIT ISLAND
15 ACRES
Miles
0
1
2

Hot Spots

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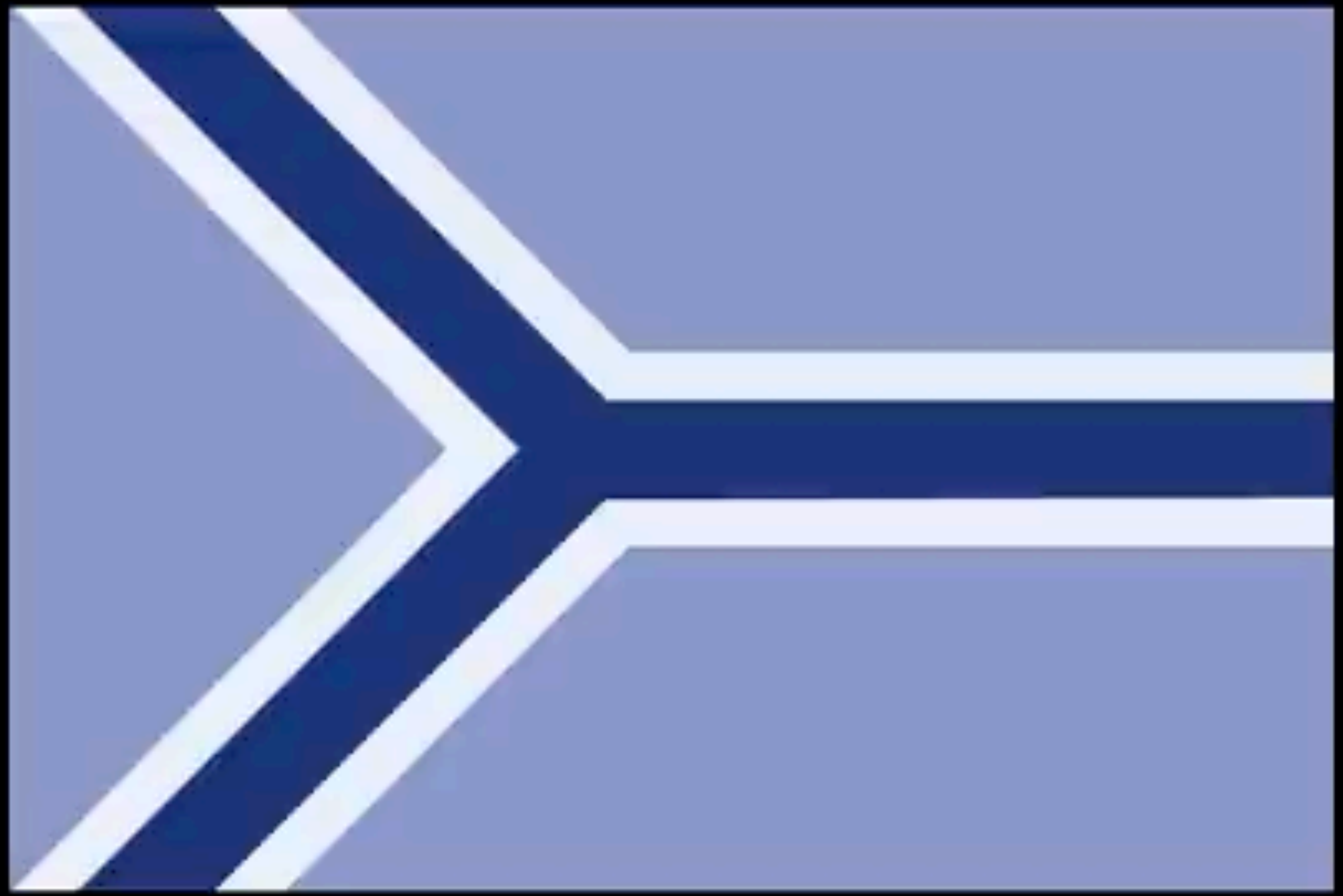
300 Million Years of the Future World

(Pangaea Proxima Model)



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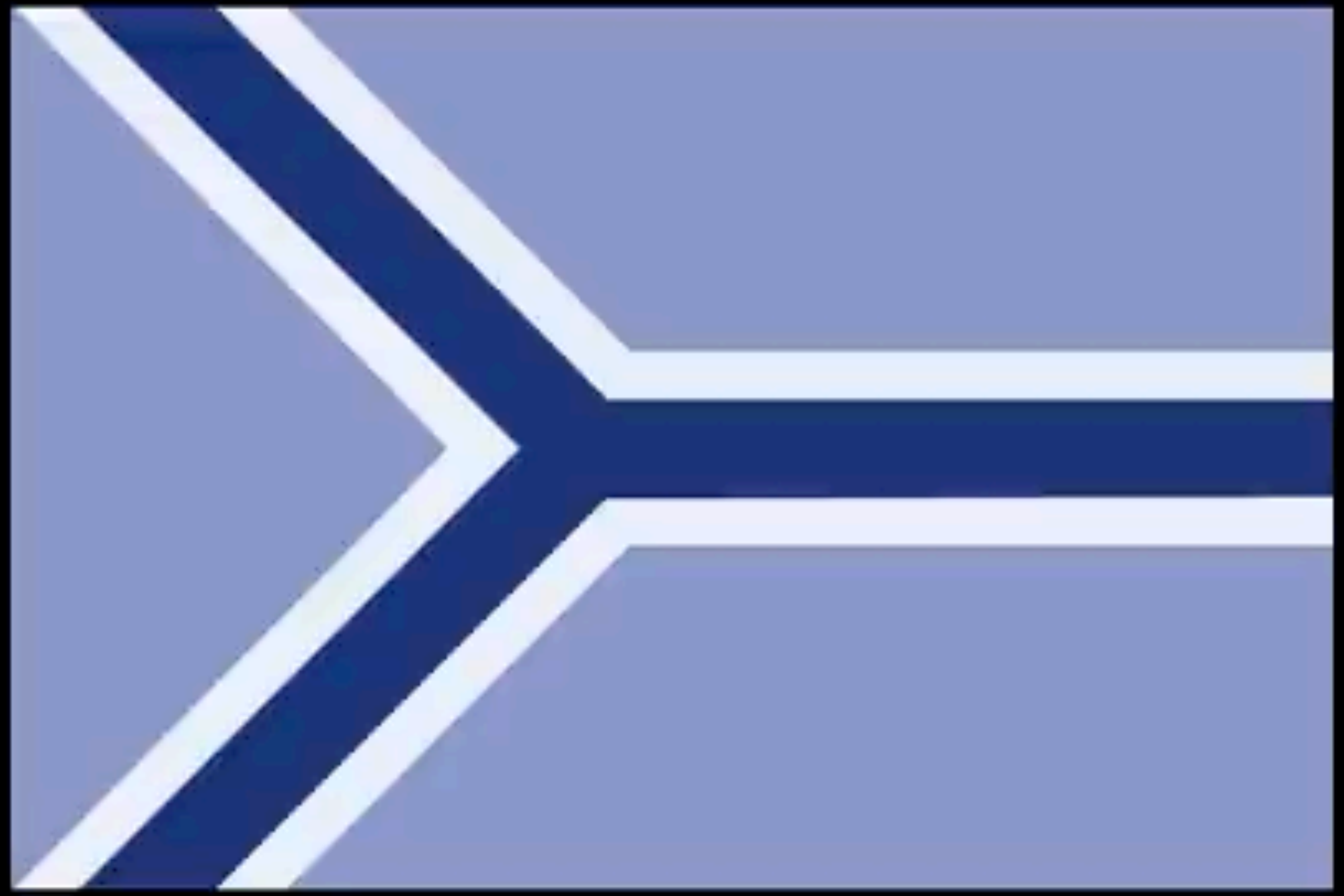
300 Million Years of the Future World

(Pangaea Proxima Model)



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Topics Going Forward

- Intro to the Universe ✔
- The Night Sky ✔
- History of Astronomy ✔
- Motion, Energy, and Gravity ✔
- Light and Matter ✔
- Telescopes ✔
- Solar System Overview ✔
- Formation of the Solar System ✔
- Geology of the Inner Planets ✔
- Atmospheres of the Inner Planets
- The Jovian Planets
- Asteroids, Comets, and Dwarf Planets
- Exoplanets
- Space and Time
- Spacetime and Gravity
- Building Blocks of the Universe
- Our Star
- Surveying the Stars
- Star Birth
- Star Stuff
- The Stellar Graveyard
- Our Galaxy
- Galaxies and Modern Cosmology
- Galaxy Evolution
- The Birth of the Universe
- Dark Matter, Dark Energy, and the Death of the Universe
- Life in the Universe