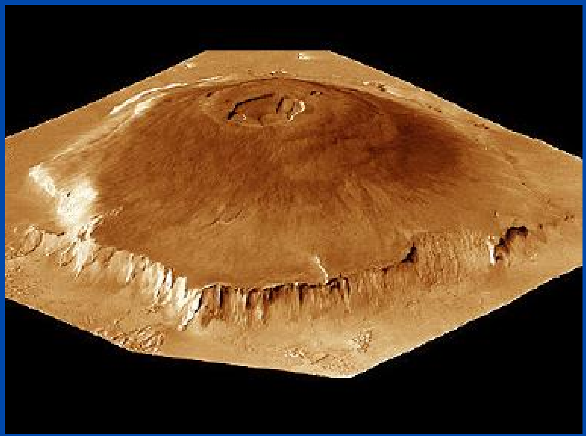
Lecture 11: Comparative Geology of the Terrestrial Planets

Please remind me to take a break at 12:45 pm!



Olympus Mons (Mars)
Volcanic caldera

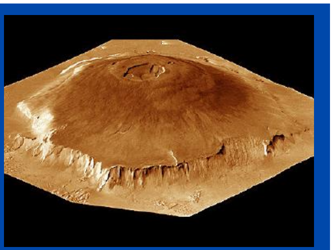
Claire Max

May 13, 2014

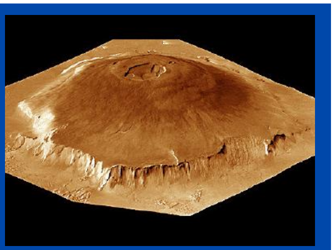
Astro 18: Planets and Planetary Systems

UC Santa Cruz

Planetary Geology: Earth and the Other Terrestrial Worlds

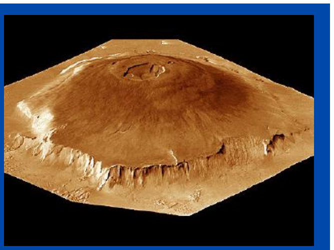


Comparative Geology of the Terrestrial Planets: Outline



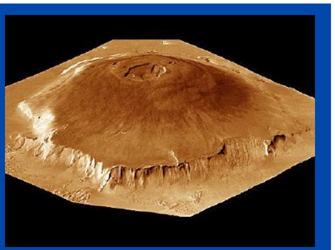
- Planetary interiors – what are the terrestrial planets like on the inside?
- Four processes that shape planetary surfaces
  - Cratering
  - Volcanism
  - Tectonics
  - Erosion
- Why do some planetary interiors create magnetic fields?

The Main Points

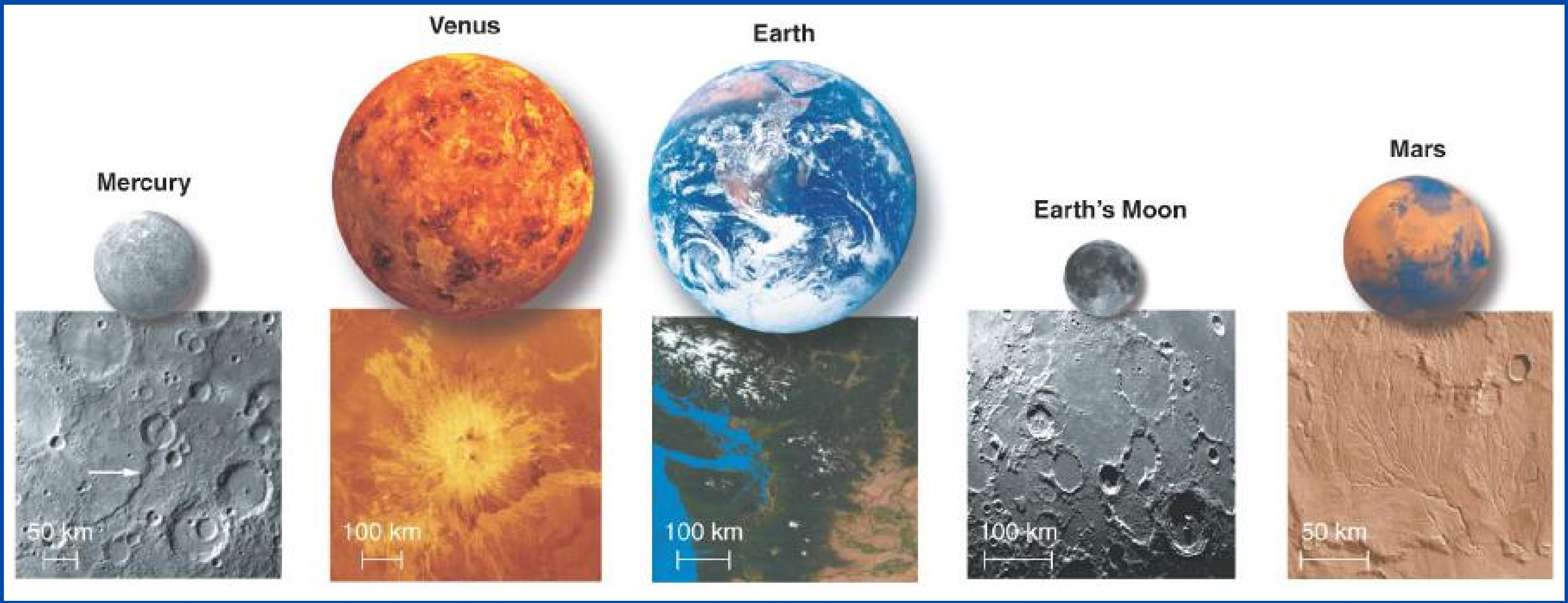


- **A few basic processes mold surfaces and interiors of terrestrial planets**
- **All terrestrial planets were once heavily cratered, but craters have since been erased on some**
- **Planet <u>size</u> influences volcanism, tectonics; <u>atmosphere</u> influences erosion**
- **General features should be same in other solar systems, not just our own**

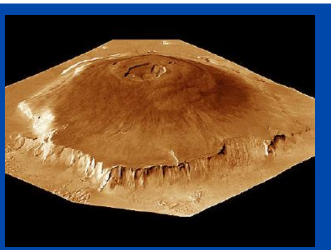
How can we make sense of the terrestrial planets?

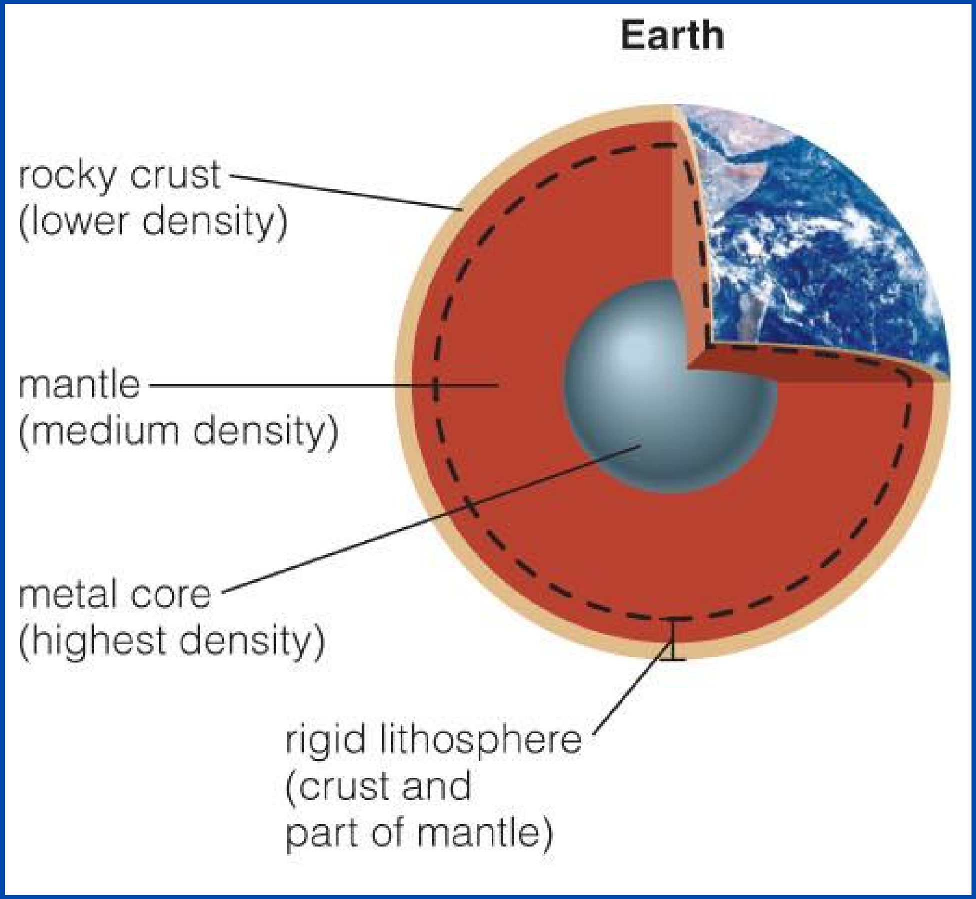


- **Look for the common basic processes that make them look the way they do**



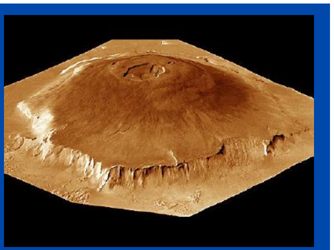
Earth's Interior



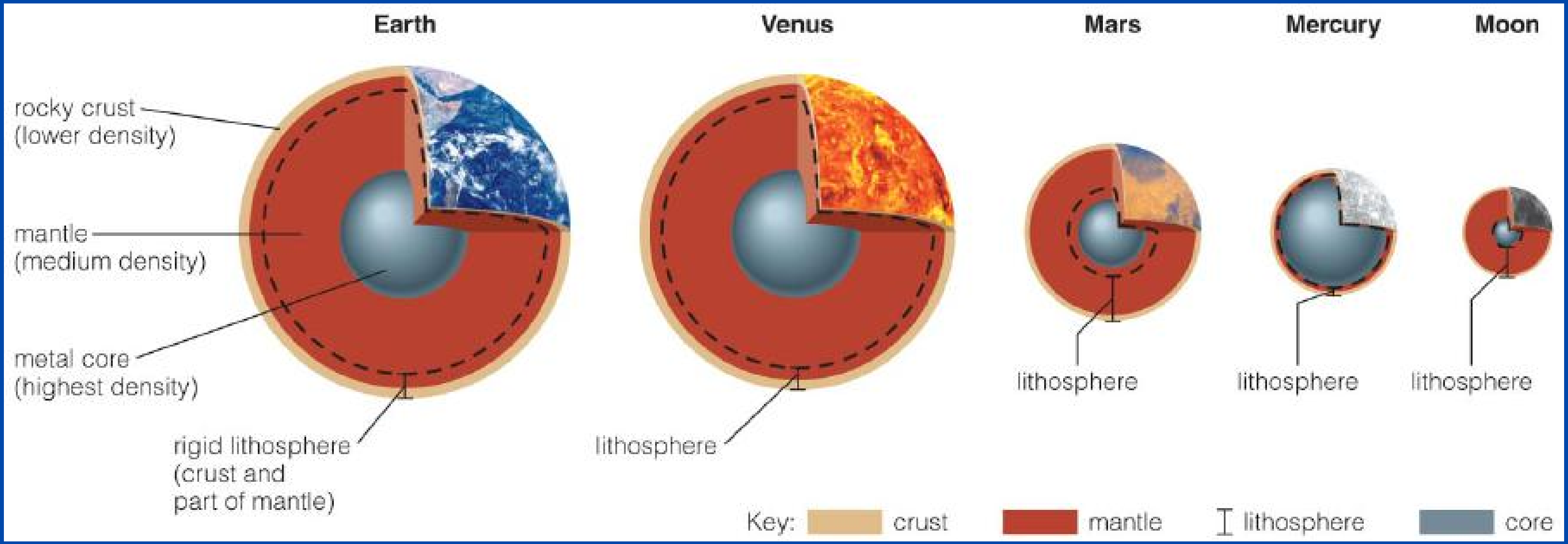


- **Core: highest density; nickel and iron**
- **Mantle: moderate density; silicon, oxygen, etc.**
- **Crust: lowest density; granite, basalt, etc.**

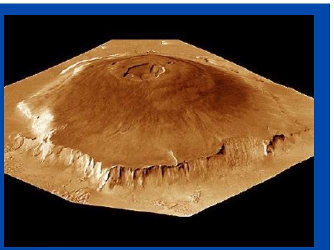
Variety in planet interiors

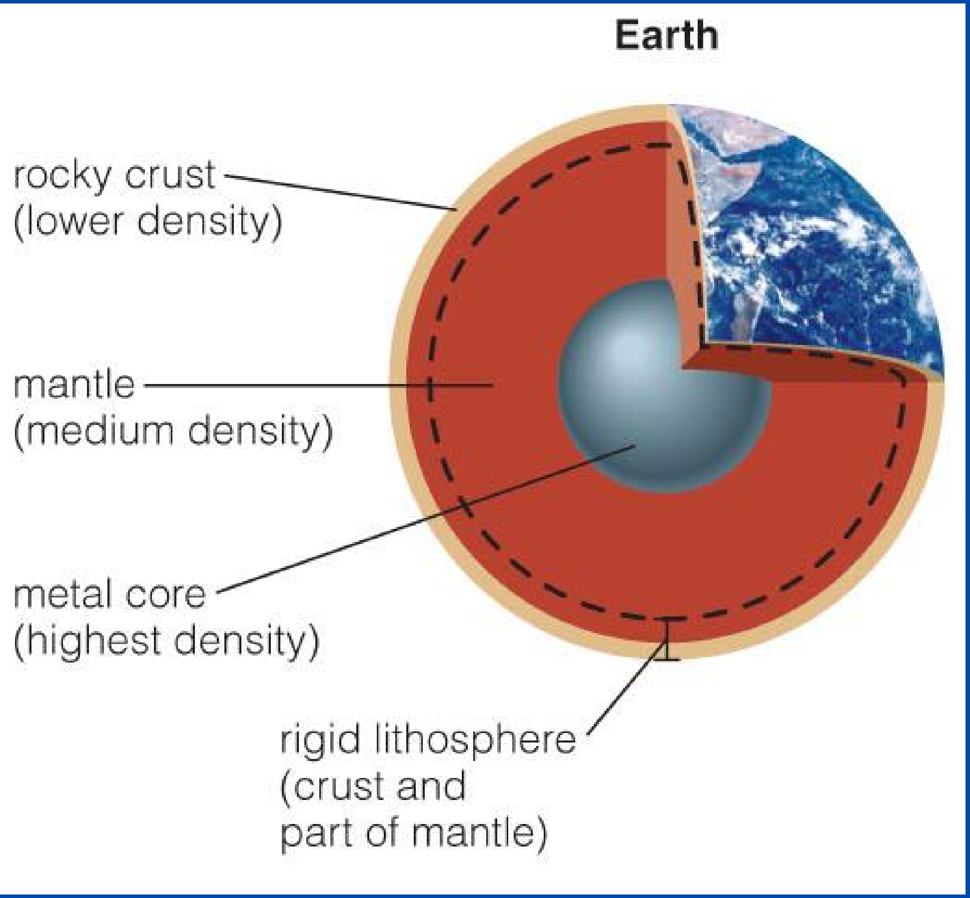


- Higher internal temperature ➡ rocks softer ➡ thinner lithosphere
- Thin lithosphere enables volcanism, continental drift



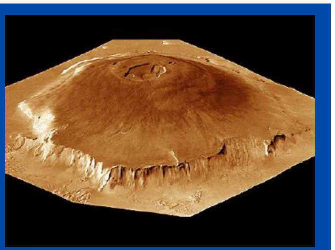
Differentiation

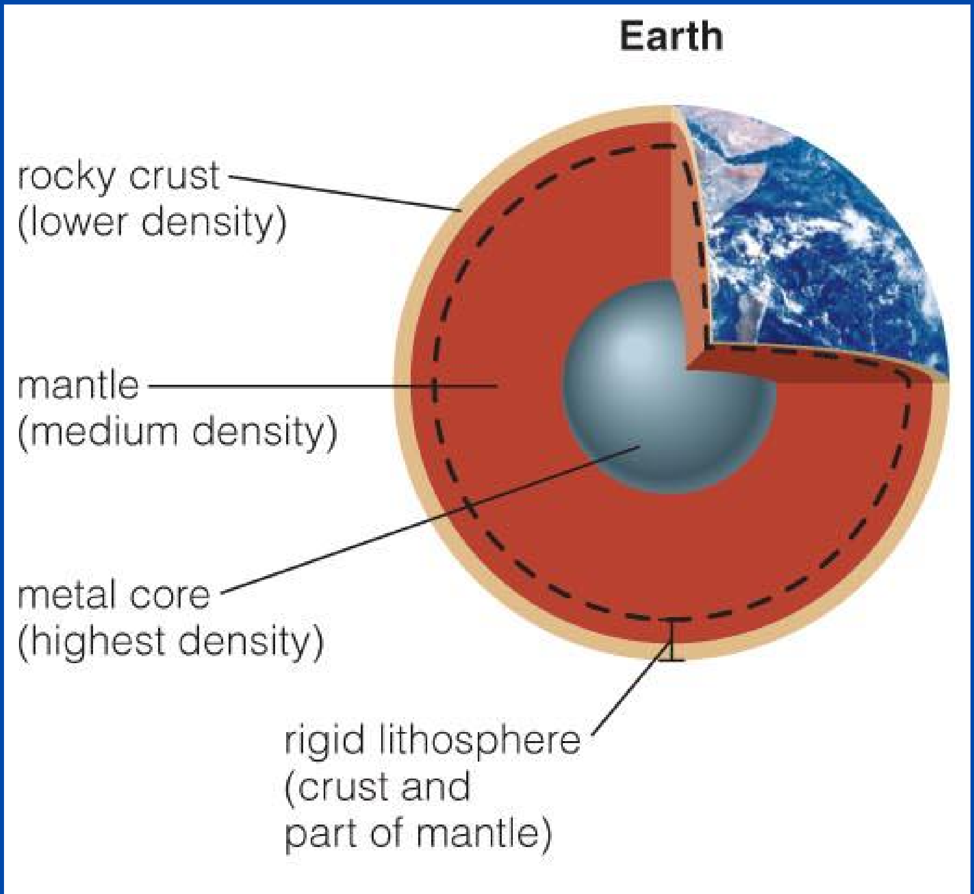




- Gravity pulls high-density material to center.
- Lower-density material rises to surface.
- Material ends up separated by density.

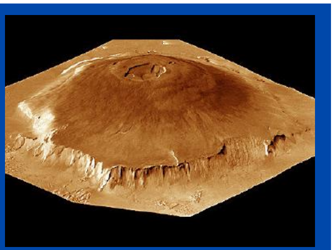
Lithosphere

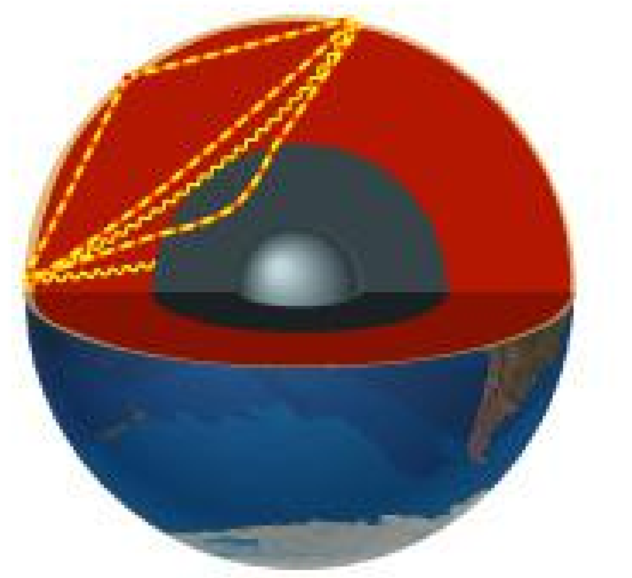




- **A planet's outer layer of cool, rigid rock is called the *lithosphere*.**
- **It "floats" on the warmer, softer rock that lies beneath.**

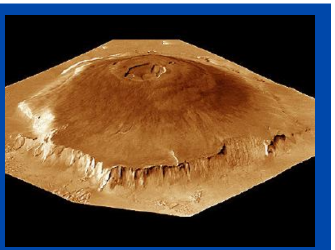
Seismic Waves tell us what's inside

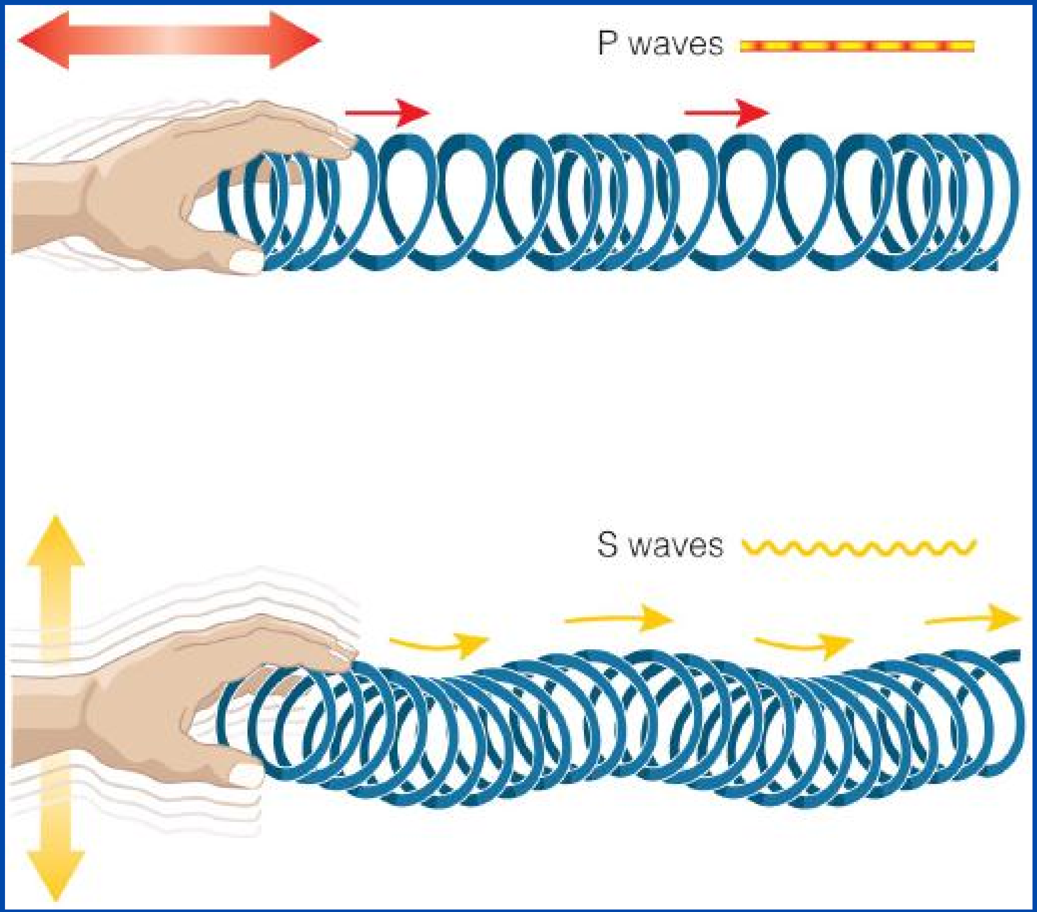




- **Vibrations that travel through Earth's interior tell us what Earth is like on the inside**
- **Source: earthquakes!**
- **Detectors: seismographs**

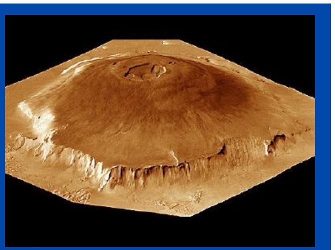
How do seismic waves tell us what's inside Earth?



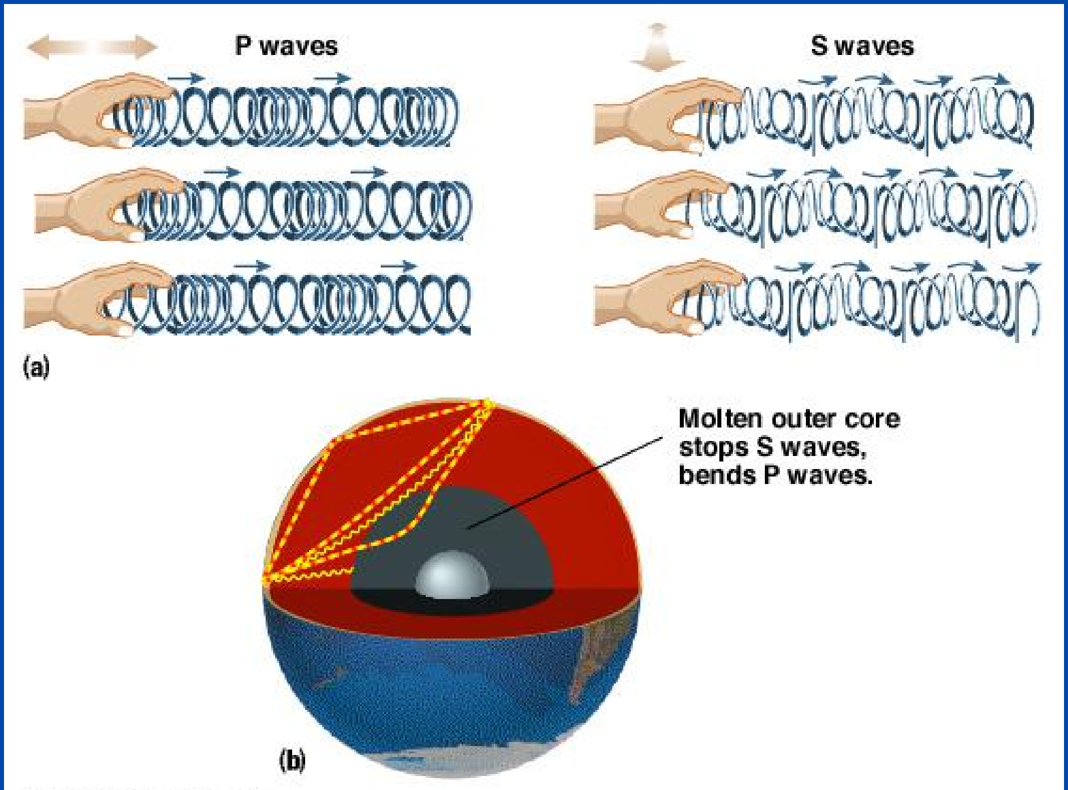


- **P waves push matter back and forth.**
- **S waves shake matter side to side**

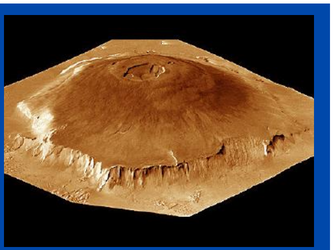
Seismic waves tell us about planetary interiors

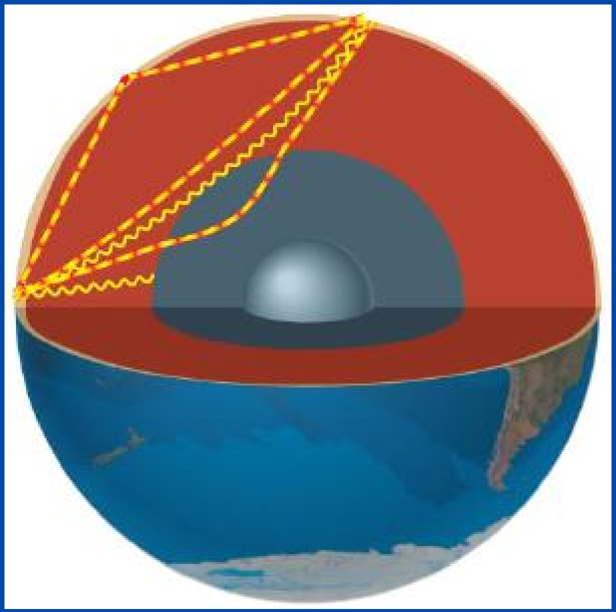


- **Measure travel paths of seismic waves from earthquakes**
- **Combine with physical models of materials**
- **Has been done on Earth (a lot), Moon**



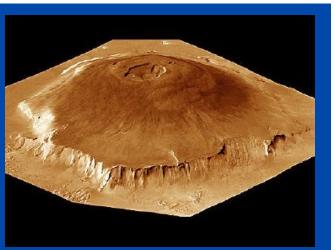
How do we know what's inside Earth?





- **P waves go through Earth's core, but S waves do not.**
- **We conclude that Earth's core must have a liquid outer layer.**

Thought Question



What is necessary for *differentiation* to occur in a planet?

a) It must have metal and rock in it.

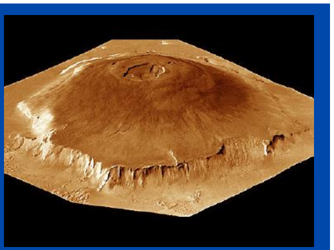
b) It must be a mix of materials of different density.

c) Material inside must be able to flow.

d) All of the above

e) b and c

Thought Question



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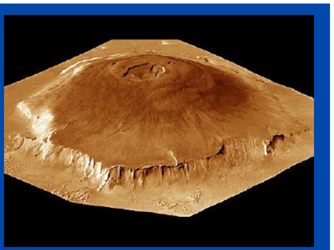
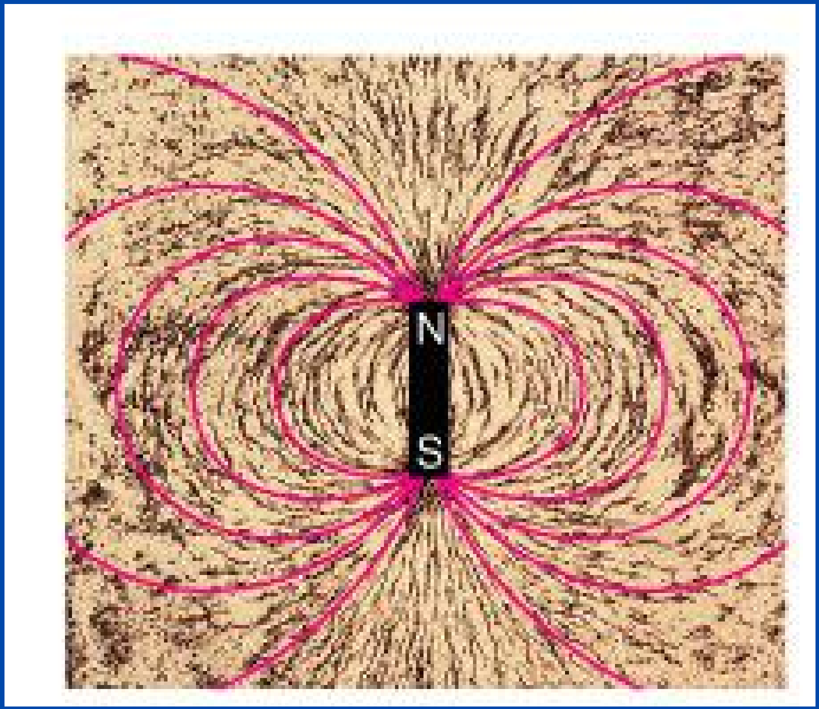
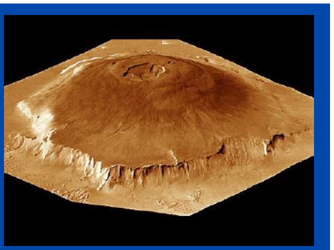
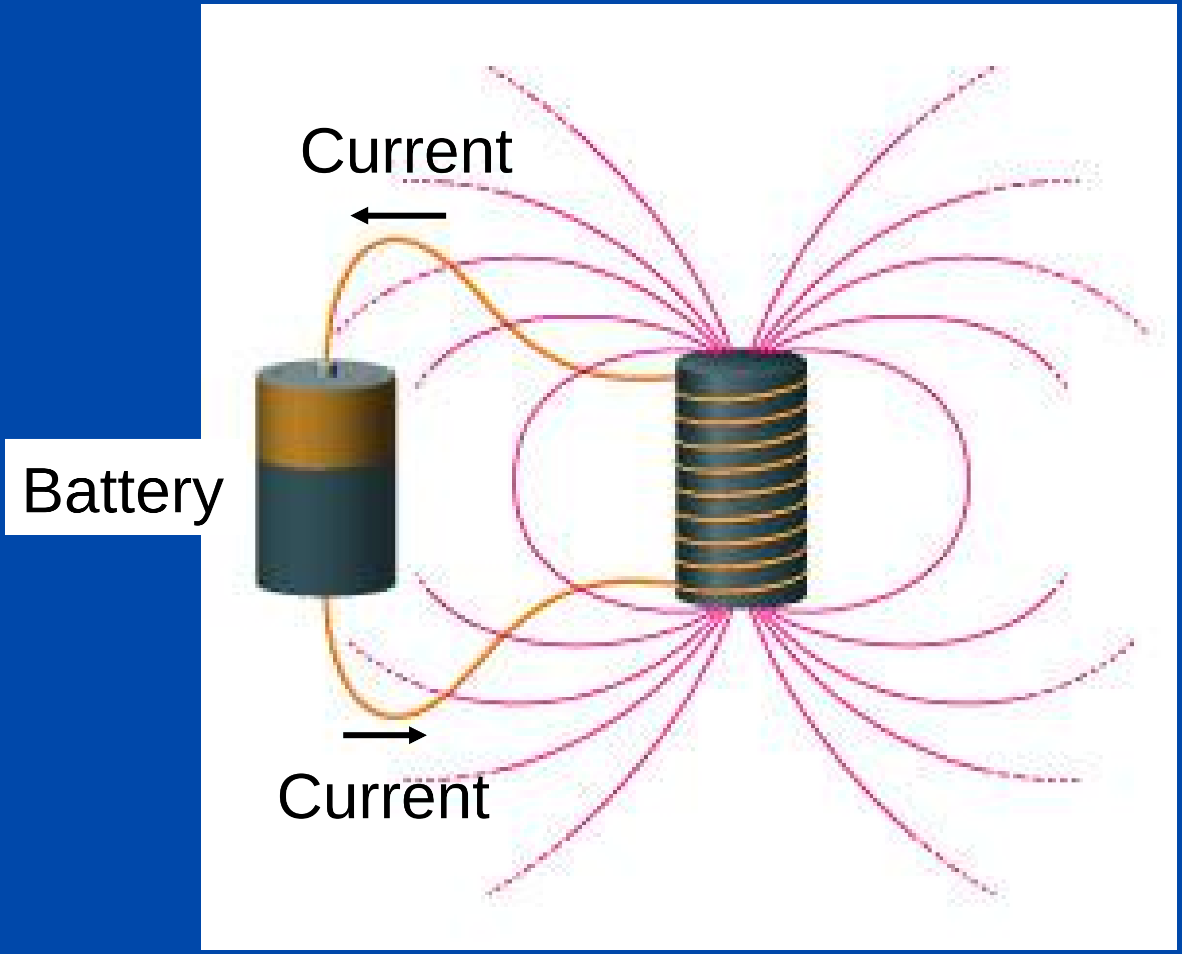
Why do some planetary interiors create magnetic fields?





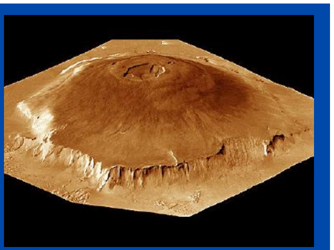
Sources of Magnetic Fields in the lab

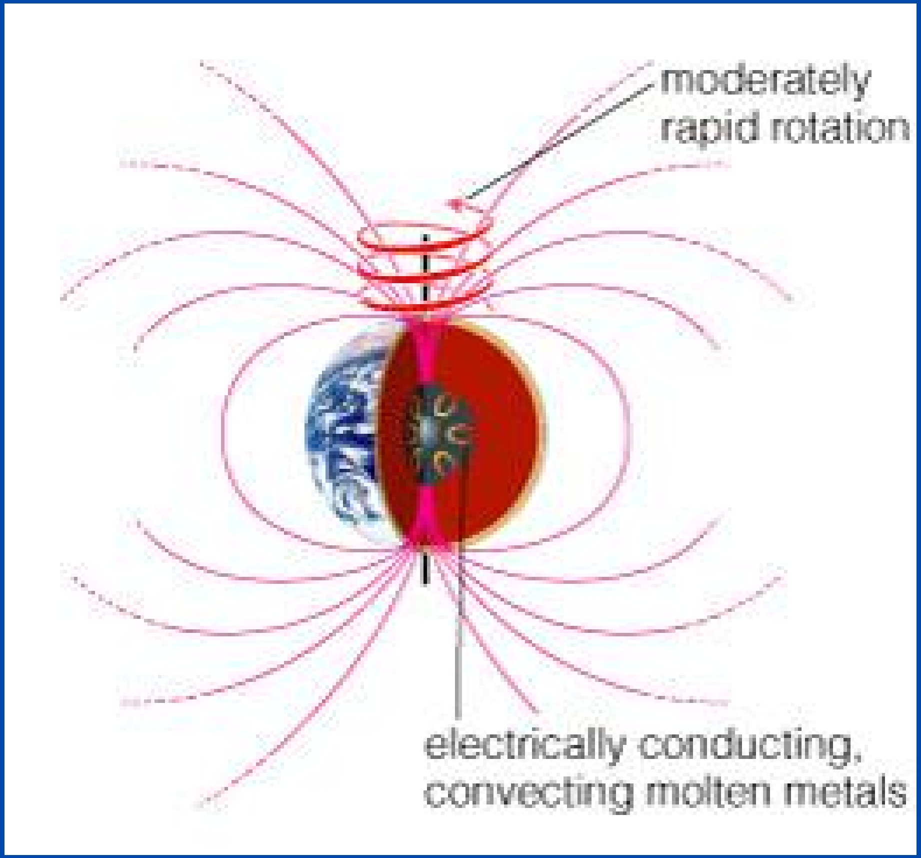




- **Motions of charged particles are what create magnetic fields**

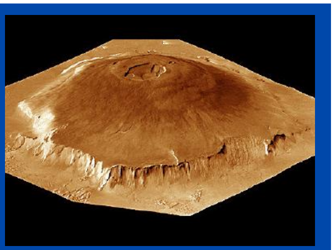
Sources of Planetary Magnetic Fields



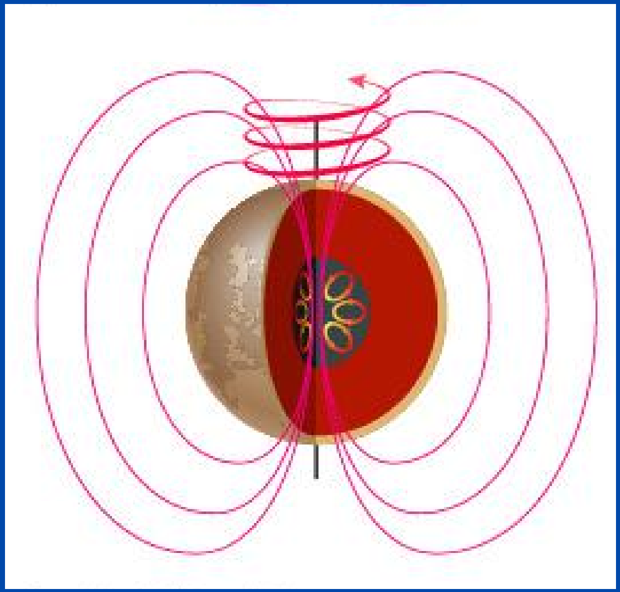


- **A world can have a magnetic field if charged particles are moving inside**
- **3 requirements:**
  - **Molten interior**
  - **Convection**
  - **Moderately rapid rotation**

Planets with molten cores have magnetic fields

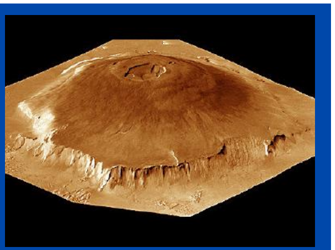


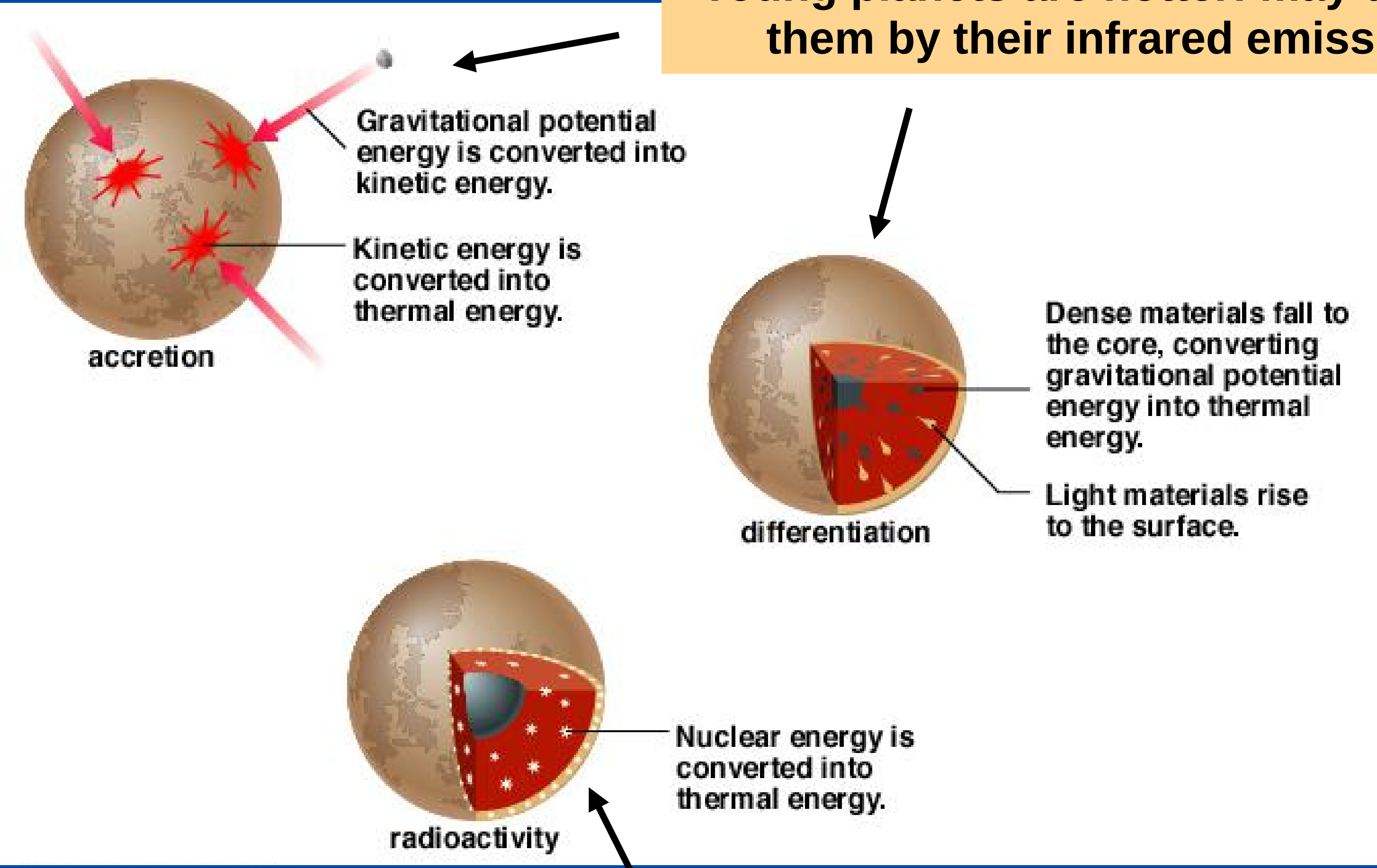
- "Dynamo process"
  - Convection within molten core
  - Convection + rotation causes electric current
  - Electric current makes magnetic field (as in electromagnet)



- Earth: molten core, fast rotation ➔ strong magnetic field
- Venus: molten core, slow rotation (or small convection) ➔ no field
- Mars and Moon: much smaller, cooled faster, solid core ➔ no field
- Mercury: has magnetic field ➔ is its big metallic core molten??

Three processes that heat planet interiors

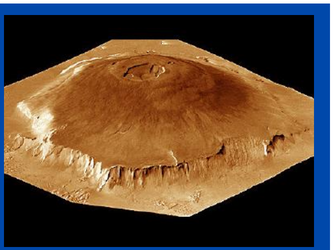




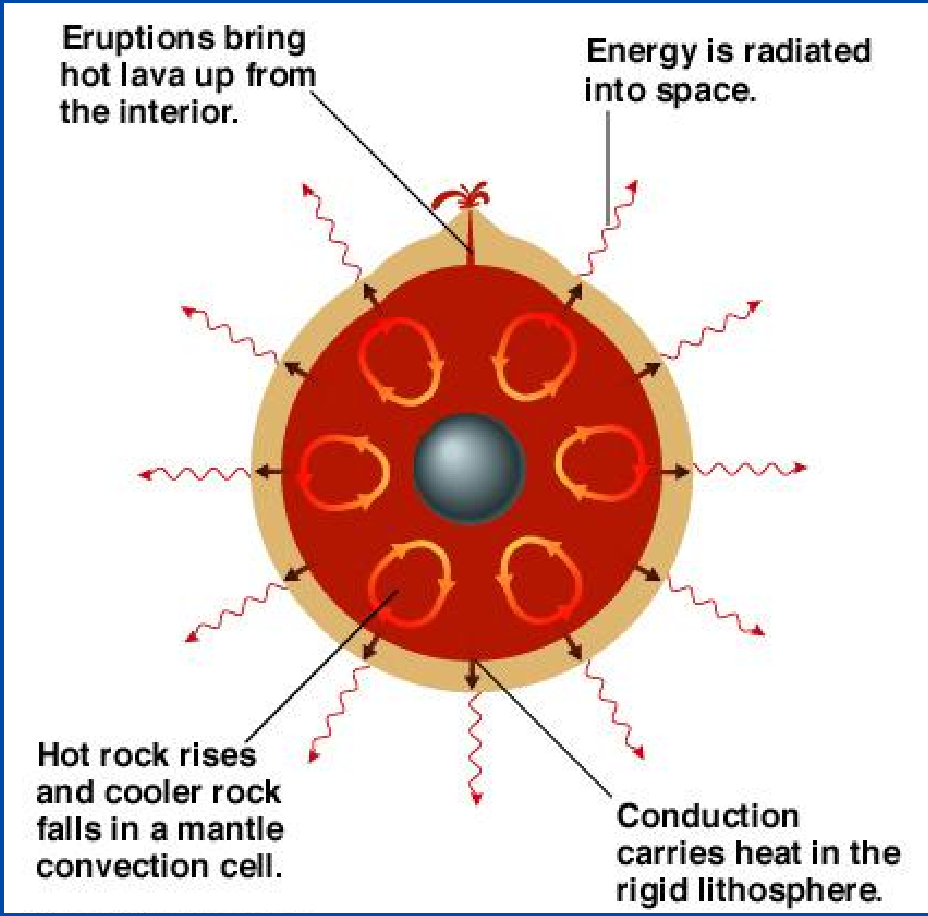
Young planets are hotter: may detect them by their infrared emission

The biggest heat source for Earth today

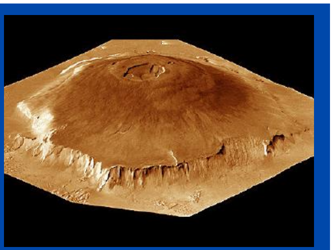
How do planet interiors cool off?



- Size is critical factor
  - Larger planets stay hot longer
  - Smaller planets cool quicker
- Why?



Smaller planets cool more quickly



- **Heat content depends on volume (total amount of hot material)**
- **Loss of heat through radiation depends on surface area**
- **Time to cool depends on surface area divided by volume**

surface area of a sphere $= 4\pi r^2$

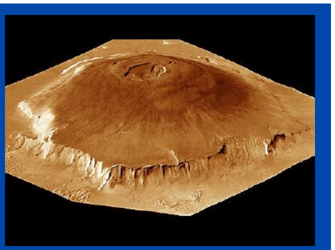
volume of a sphere $= \frac{4}{3}\pi r^3$

ratio of surface area to volume $= \frac{3}{r}$

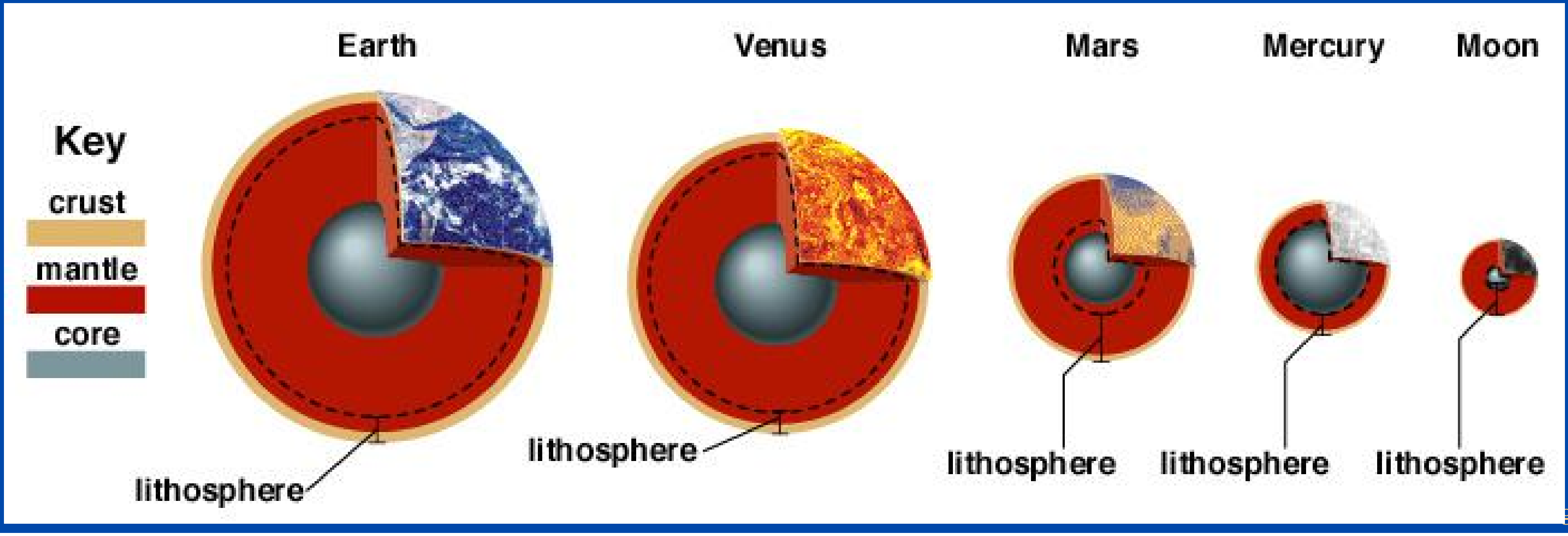
cooling rate increases with surface to volume ratio

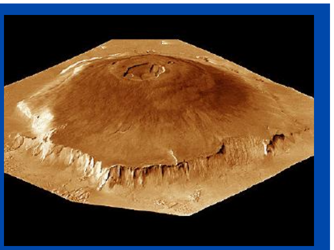
$\Rightarrow$ cooling processes are faster for small planets

Size influences internal temperature



- Earth and Venus are biggest, interiors are hottest, lithospheres are thinnest
- Moon and Mercury are now geologically (almost) dead. Smaller bodies cool off faster.
- Another way to see this: larger planets have more mantle material to provide insulation, slow cooling processes

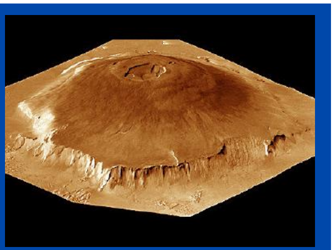




Concept Question

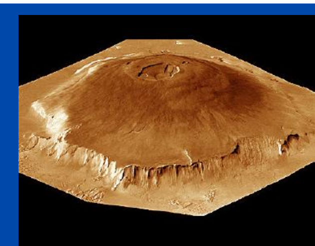
- A small planetary object, like the Moon, is most likely to be
  - a) solid on the inside, with little magnetic field
  - b) liquid in the inside, with little magnetic field
  - c) solid on the inside, with a strong magnetic field
  - d) liquid on the inside, with a strong magnetic field

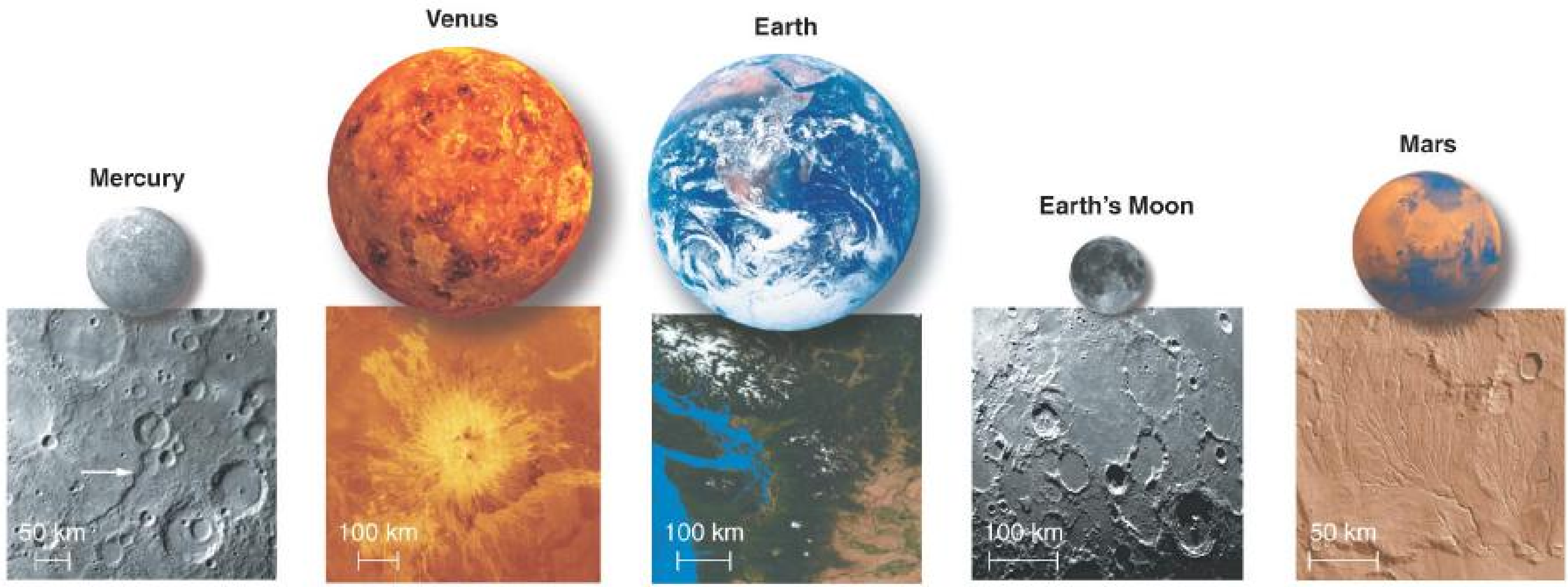
What have we learned?



- What are terrestrial planets like on the inside?
  - All terrestrial worlds have a core, mantle, and crust.
  - Denser material is found deeper inside.
- What causes geological activity?
  - Interior heat drives geological activity.
  - Radioactive decay is currently main heat source.
- Why do some planetary interiors create magnetic fields?
  - Requires motion of charged particles inside a planet

What processes shape planetary surfaces?





Heavily cratered Mercury has long steep cliffs (arrow).

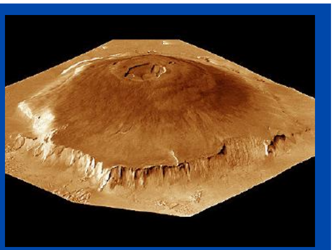
Cloud-penetrating radar revealed this twin-peaked volcano on Venus.

A portion of Earth's surface as it appears without clouds.

The Moon's surface is heavily cratered in most places.

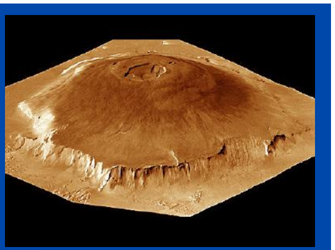
Mars has features that look like dry riverbeds; note the impact craters.

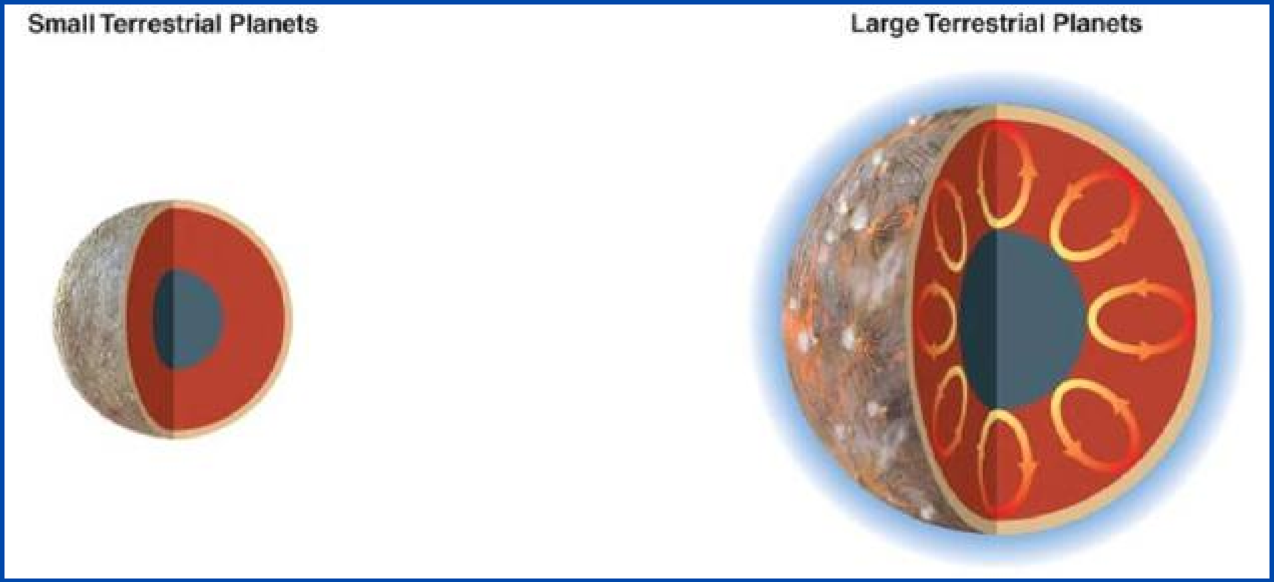
Four processes that shape planetary surfaces



- **Impact cratering**
  - excavation of bowl-shaped craters when asteroids or comets or small meteorites hit a planet's surface
- **Volcanism**
  - eruption of molten rock (lava) from planet's interior onto its surface
- **Tectonics**
  - disruption of planet's surface by internal stresses
- **Erosion**
  - wearing down or building up of geological features by wind, water, ice, other weather effects

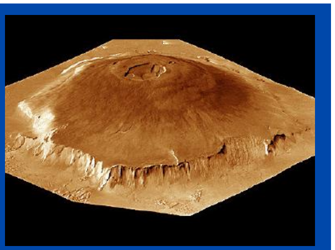
Role of Planetary Size

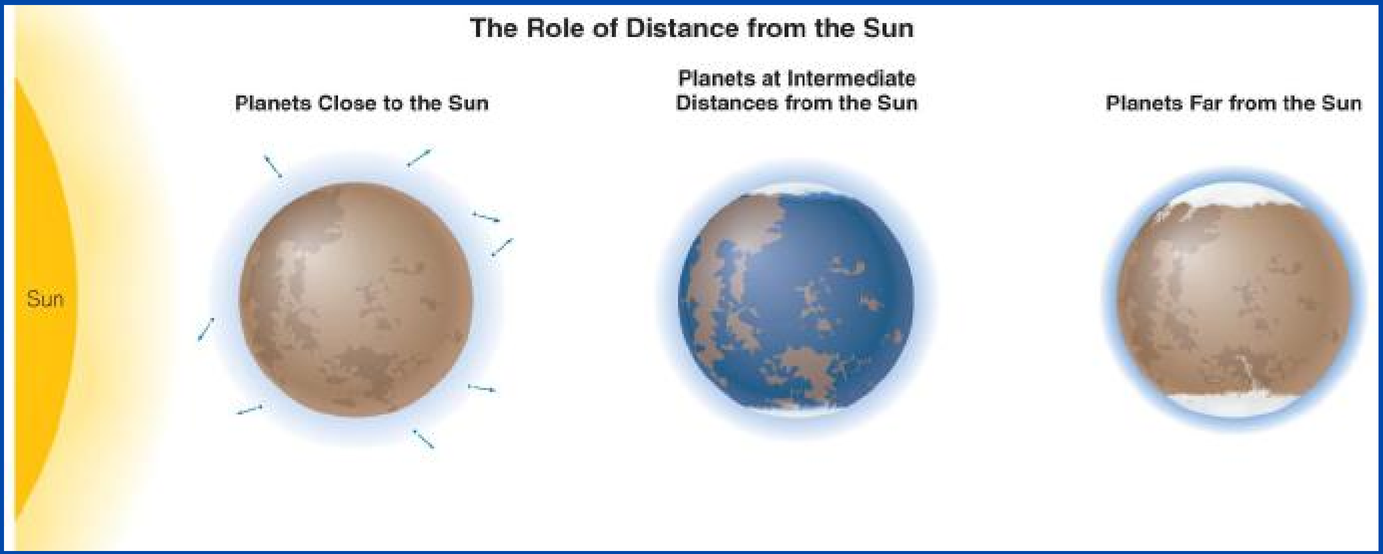




- Smaller worlds cool off faster and harden earlier.
- Larger worlds remain warm inside, promoting volcanism and tectonics.
- Larger worlds also have more erosion because their gravity retains an atmosphere: water, wind

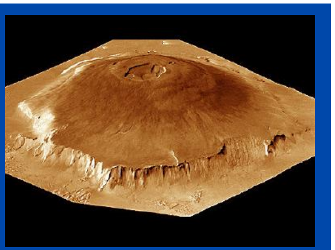
Role of Distance from Sun





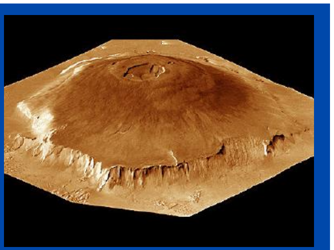
- Planets close to the Sun are too hot for rain, snow, ice and so have less erosion.
- Hot planets have more difficulty retaining an atmosphere.
- Planets far from the Sun are too cold for rain, limiting erosion.
- Planets with liquid water have the most erosion.

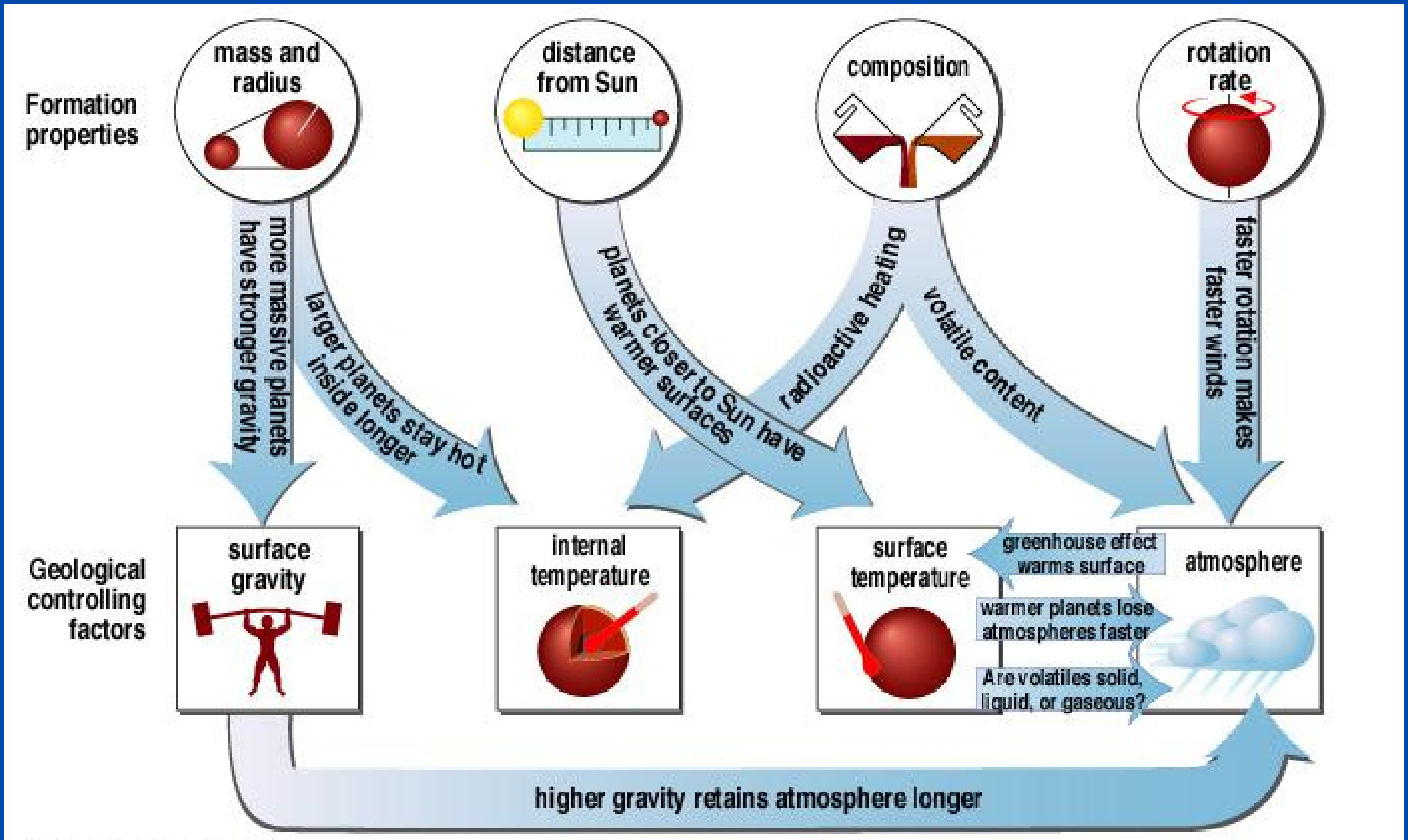
Role of Rotation



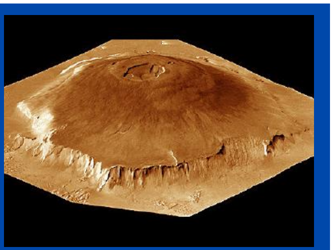
- **Planets with slower rotation have less weather, less erosion, and a weak magnetic field.**
- **Planets with faster rotation have more weather, more erosion, and a stronger magnetic field.**

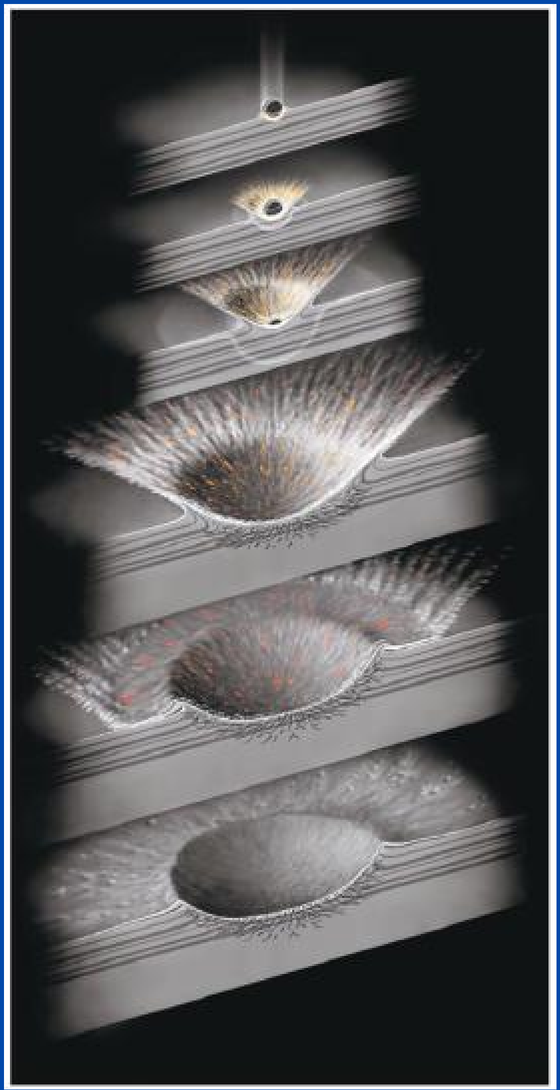
Planets' formation properties influence geology





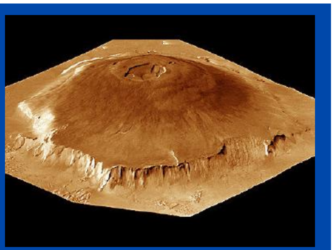
Impact Cratering

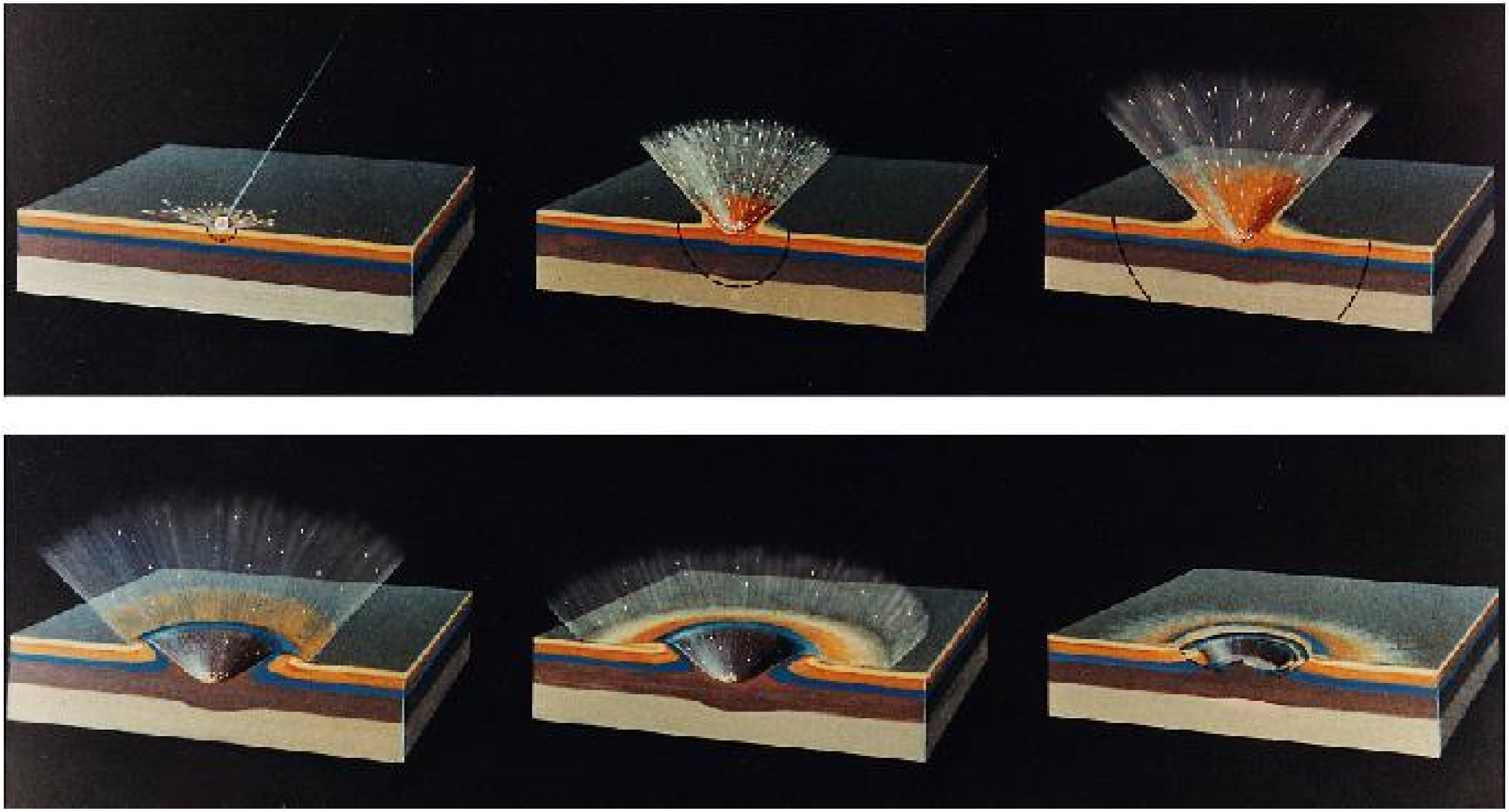




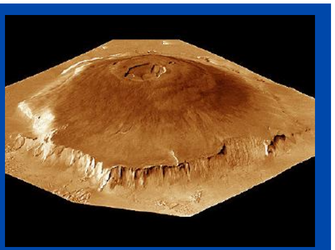
- Most cratering happened soon after the solar system formed.
- Craters are about 10 times wider than object that made them.
- Small craters greatly outnumber large ones.

Impact processes



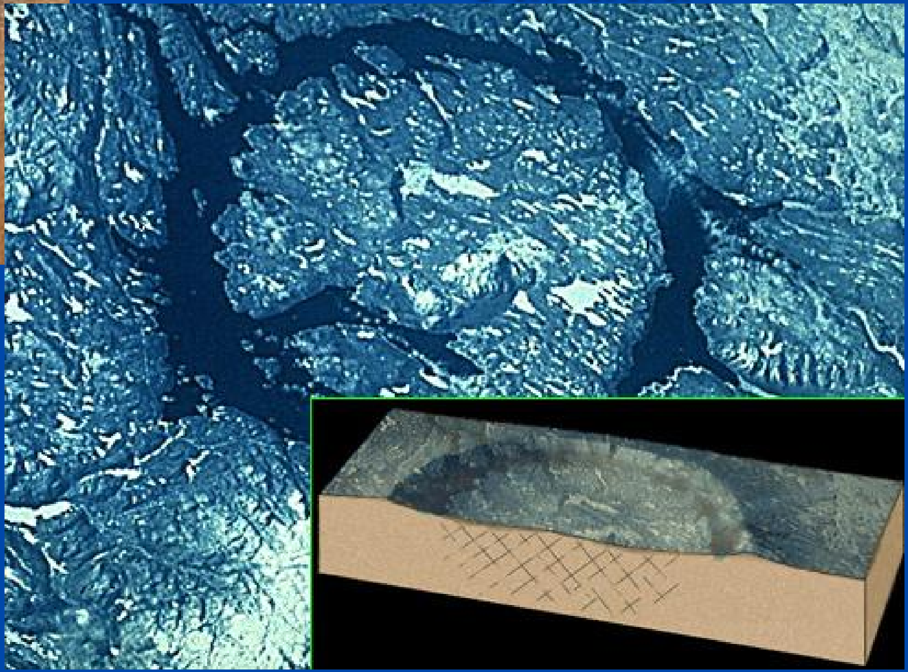


Impact cratering on Earth

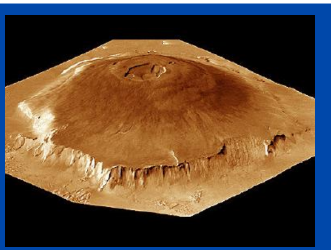


Barringer Meteor Crater Arizona

Manacouagan Crater Canada

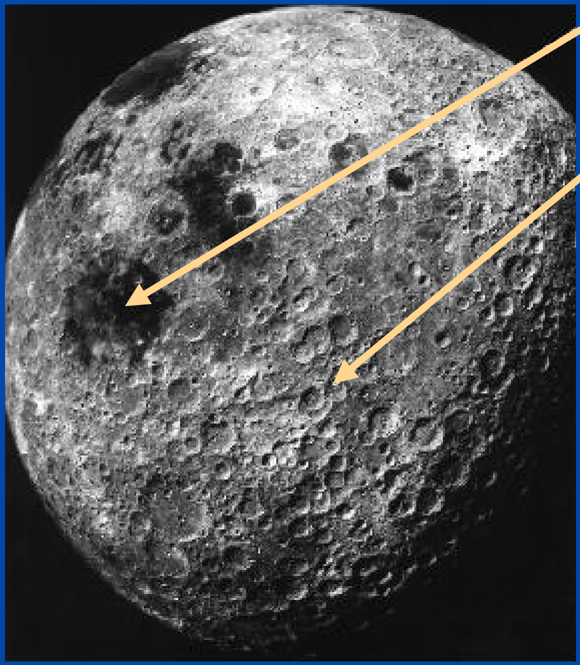


Craters on Moon, Mars



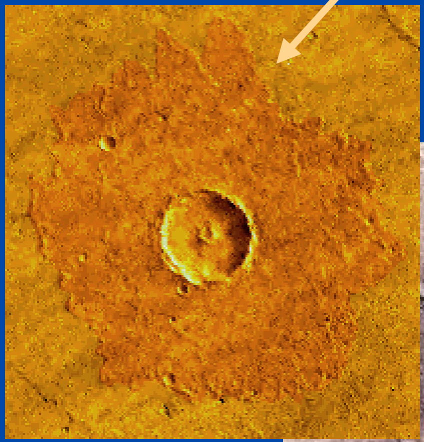
Maria: impact basins filled in with lava

Highlands: ancient and heavily cratered



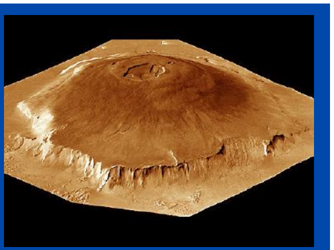
Moon craters

Impacts into icy ground may produce muddy ejecta

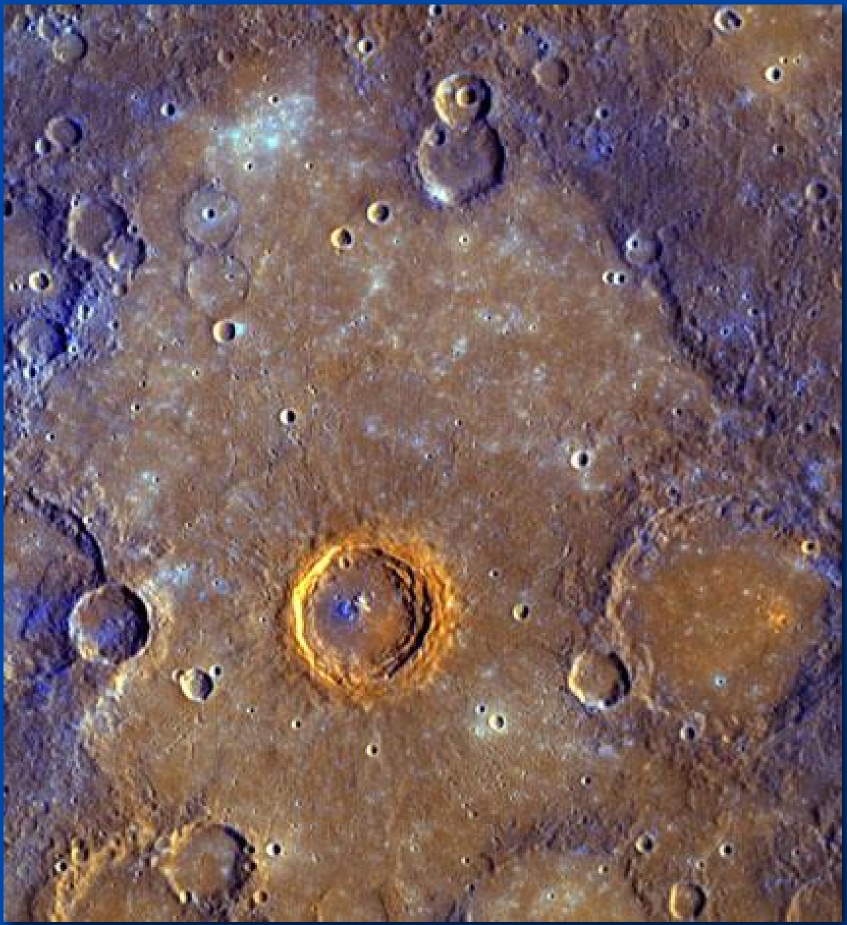


Mars craters

Craters on Venus, Mercury

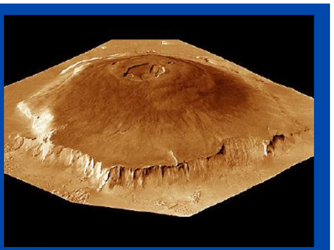


Venus
(from radar altimeter)

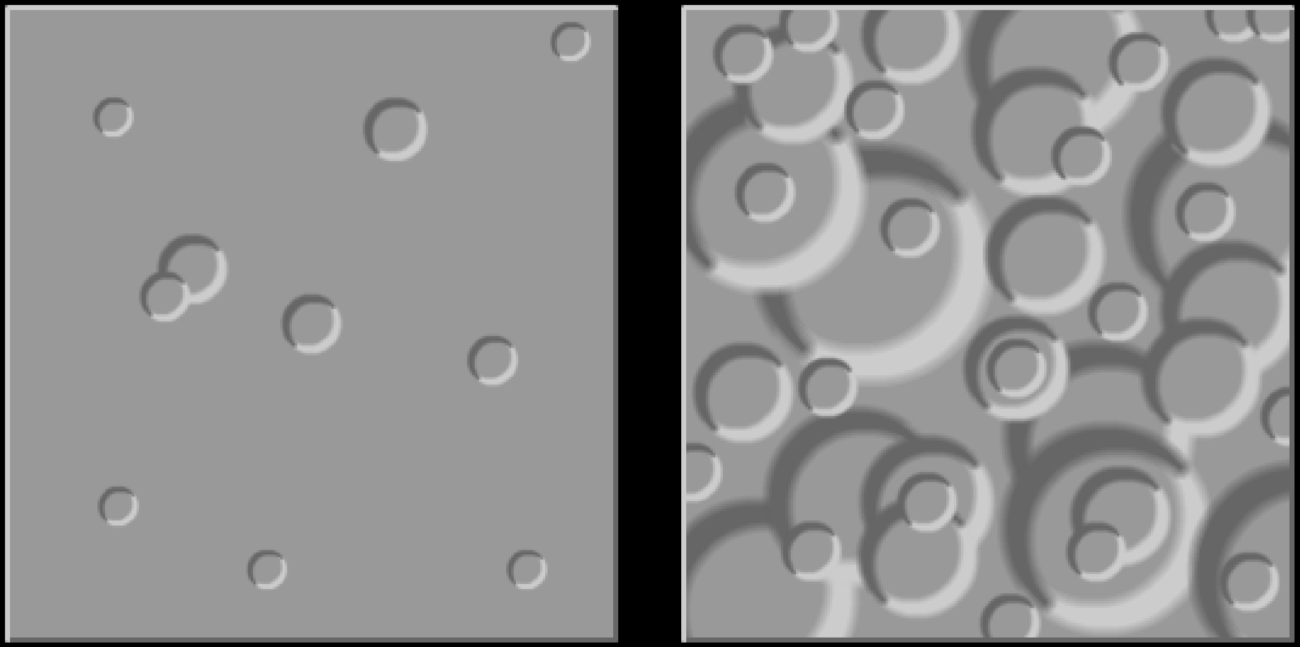


Mercury
(from MESSENGER spacecraft)

Concept question



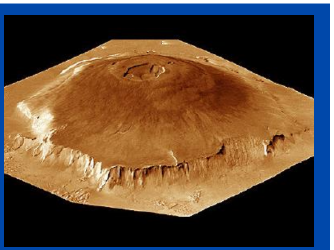
The maps below show regions on a terrestrial body. Which of these regions is the oldest?

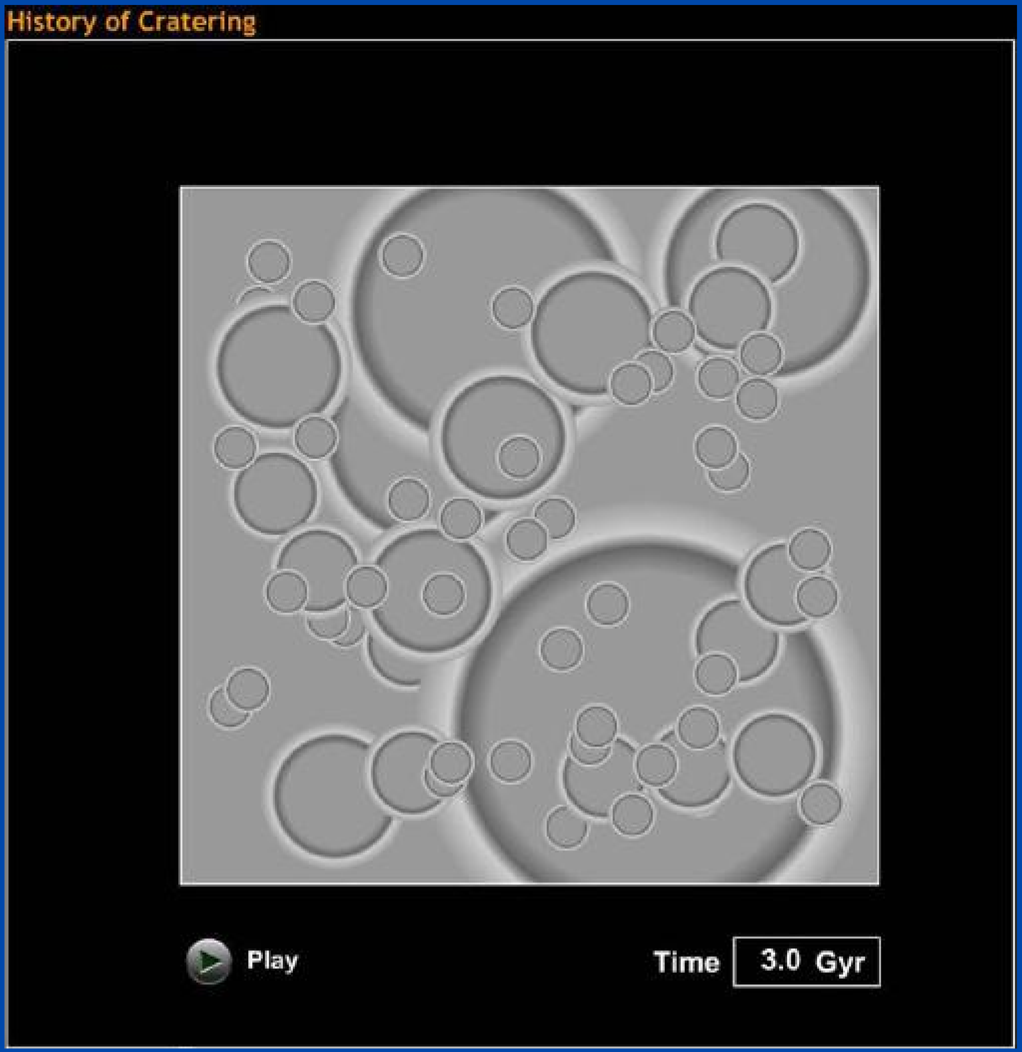


(A) (B)

Show Answ

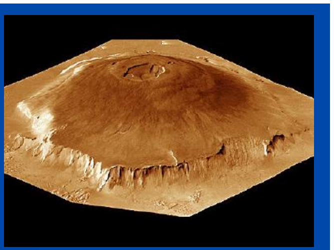
History of Cratering on the Moon



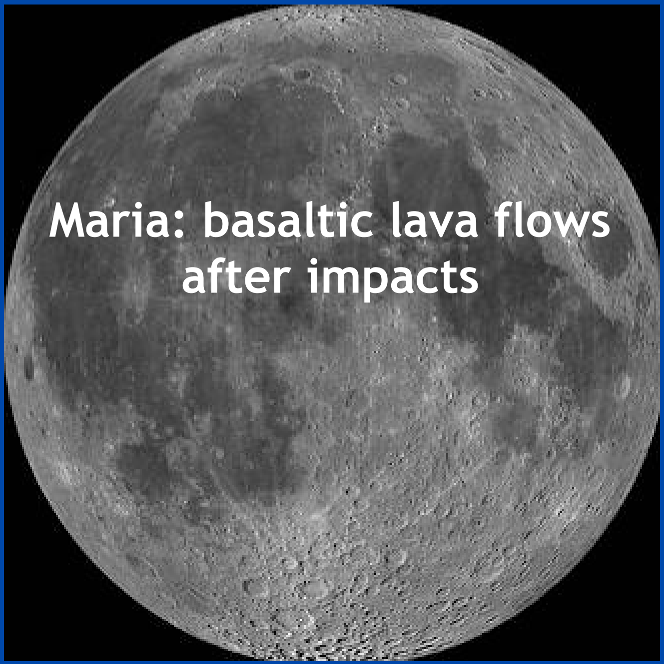


- Most cratering happened in the first billion years.
- A surface with many craters that has not changed much in 3 billion years.

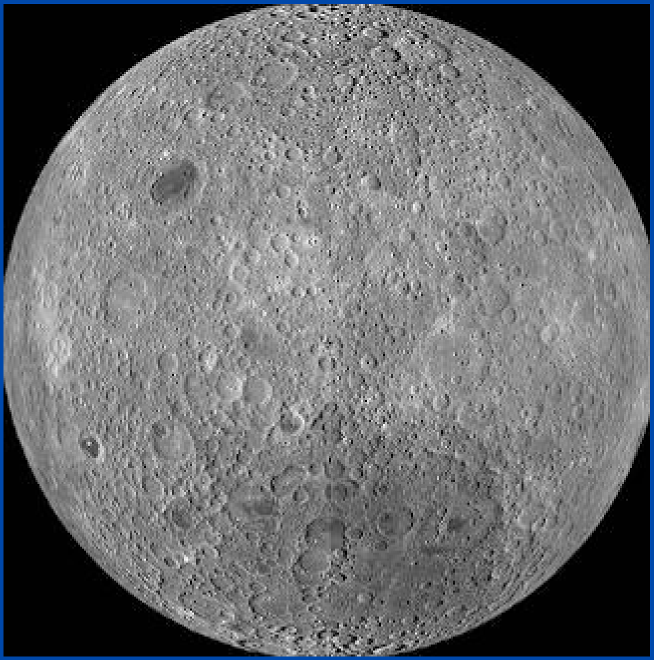
Why are front and back sides of moon so different?



Front side

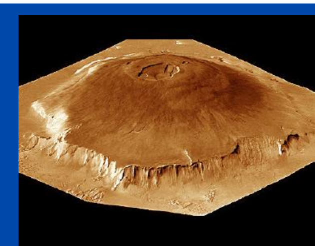


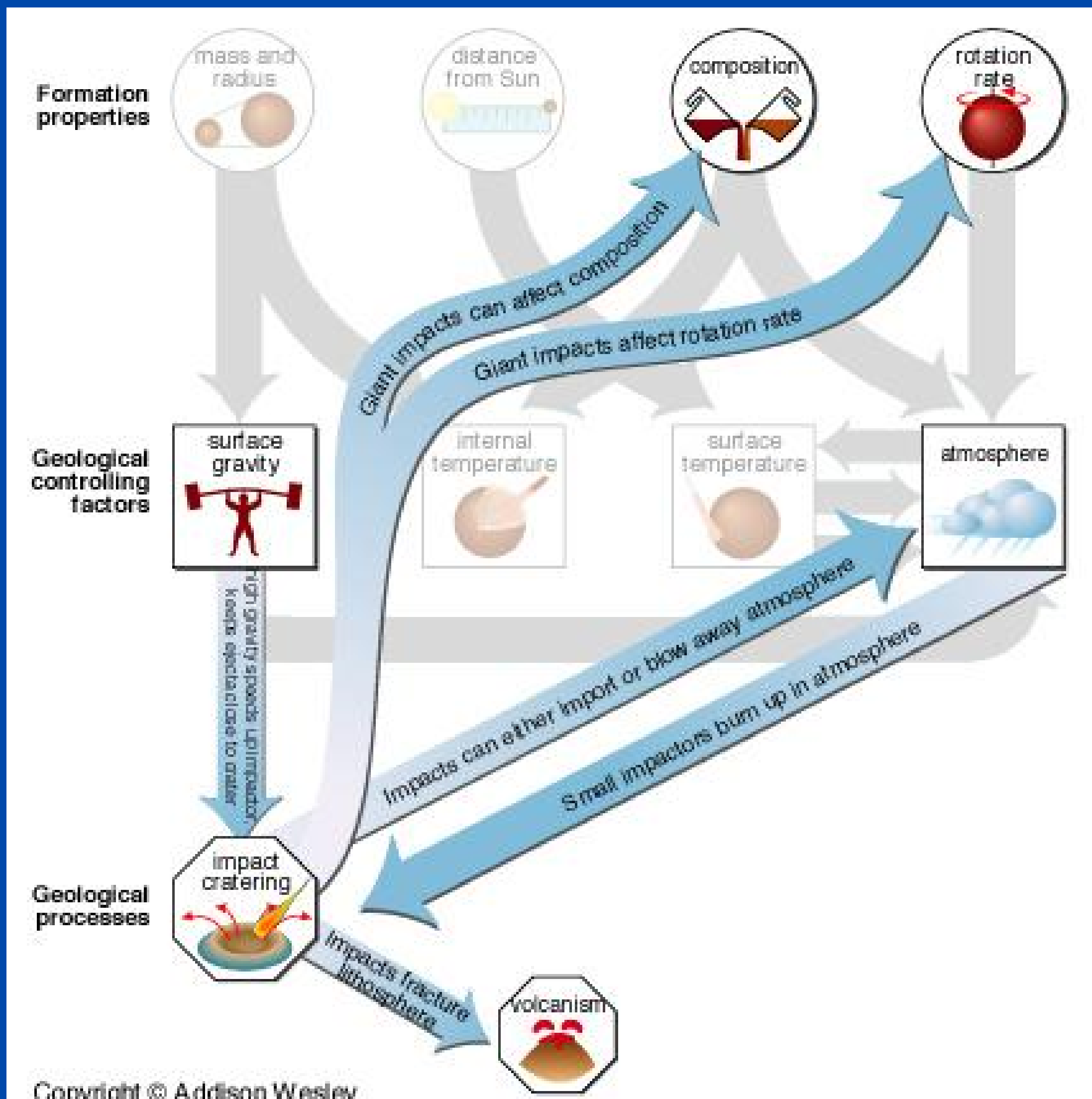
Back side



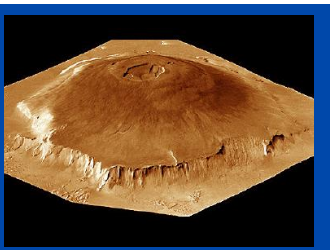
- Thicker far side crust may keep magma from surface.
- Heat released by radioactive decays is larger on near side; hot magma flows to surface more readily.

Concept Map for cratering



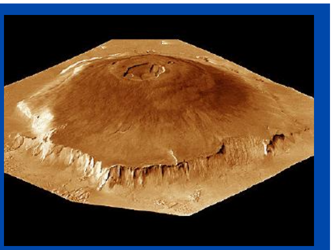


Four processes that shape planetary surfaces

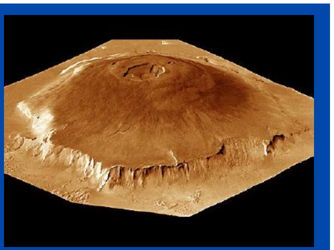


- Impact cratering
- Volcanism
- Tectonics
- Erosion

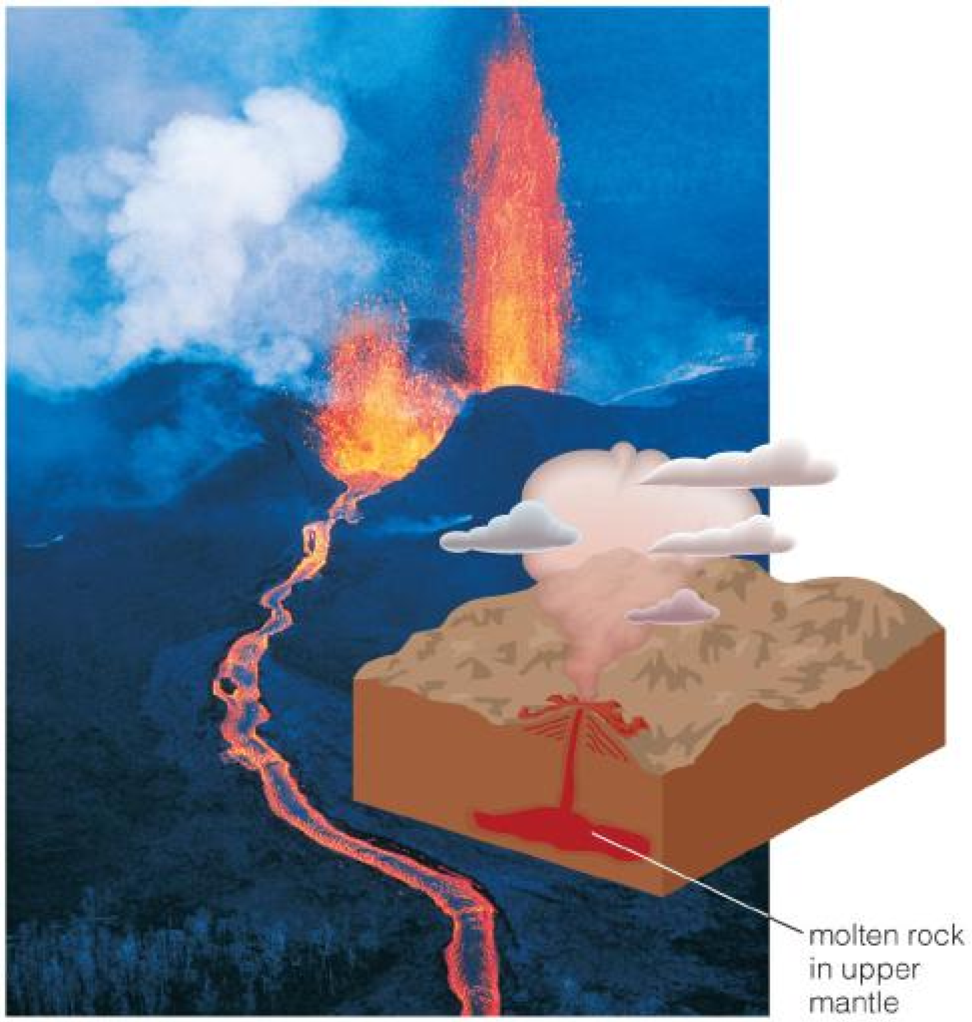
Volcanism: Viscosity of magma (lava) plays big role



- **Viscosity describes a fluid's internal resistance to flow (a measure of fluid friction)**
- **The less viscous the fluid is, the greater its ease of movement (fluidity)**
- **Honey is more viscous than water**

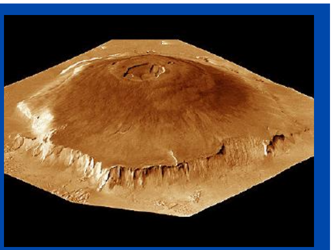


Volcanism



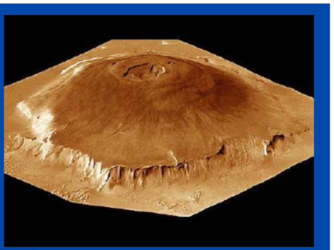
- **Volcanism happens when molten rock (magma) finds a path through lithosphere to the surface.**
- **Molten rock is called *lava* after it reaches the surface.**

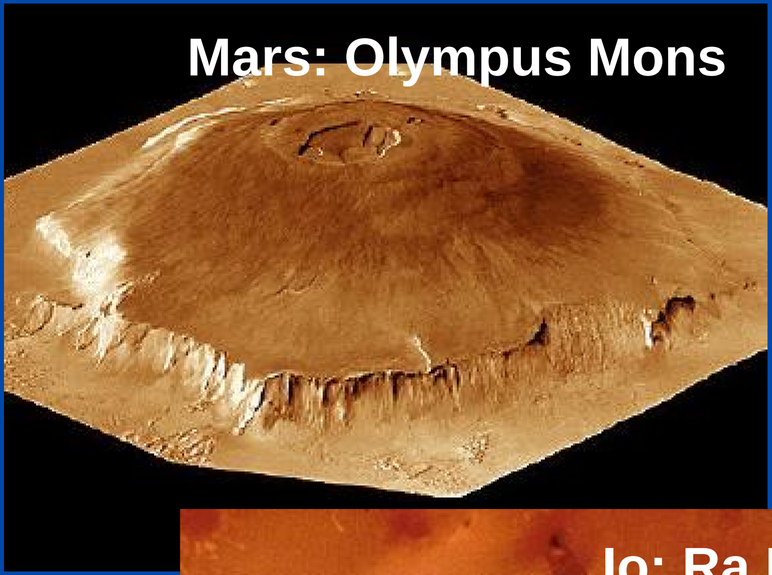
Volcanism and viscosity



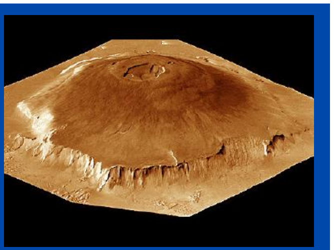
- **Lowest-viscosity lava: flat lava plains**
  - **Maria on the Moon**
- **Shield volcanoes: medium viscosity lava**
  - **lava is still “runny”**
  - **produces volcanoes with shallow slopes (<10 deg)**
- **Composite or strato-volcanoes**
  - **lava has high viscosity (“goopy”)**
  - **makes steep sloped volcanoes (>30 deg)**

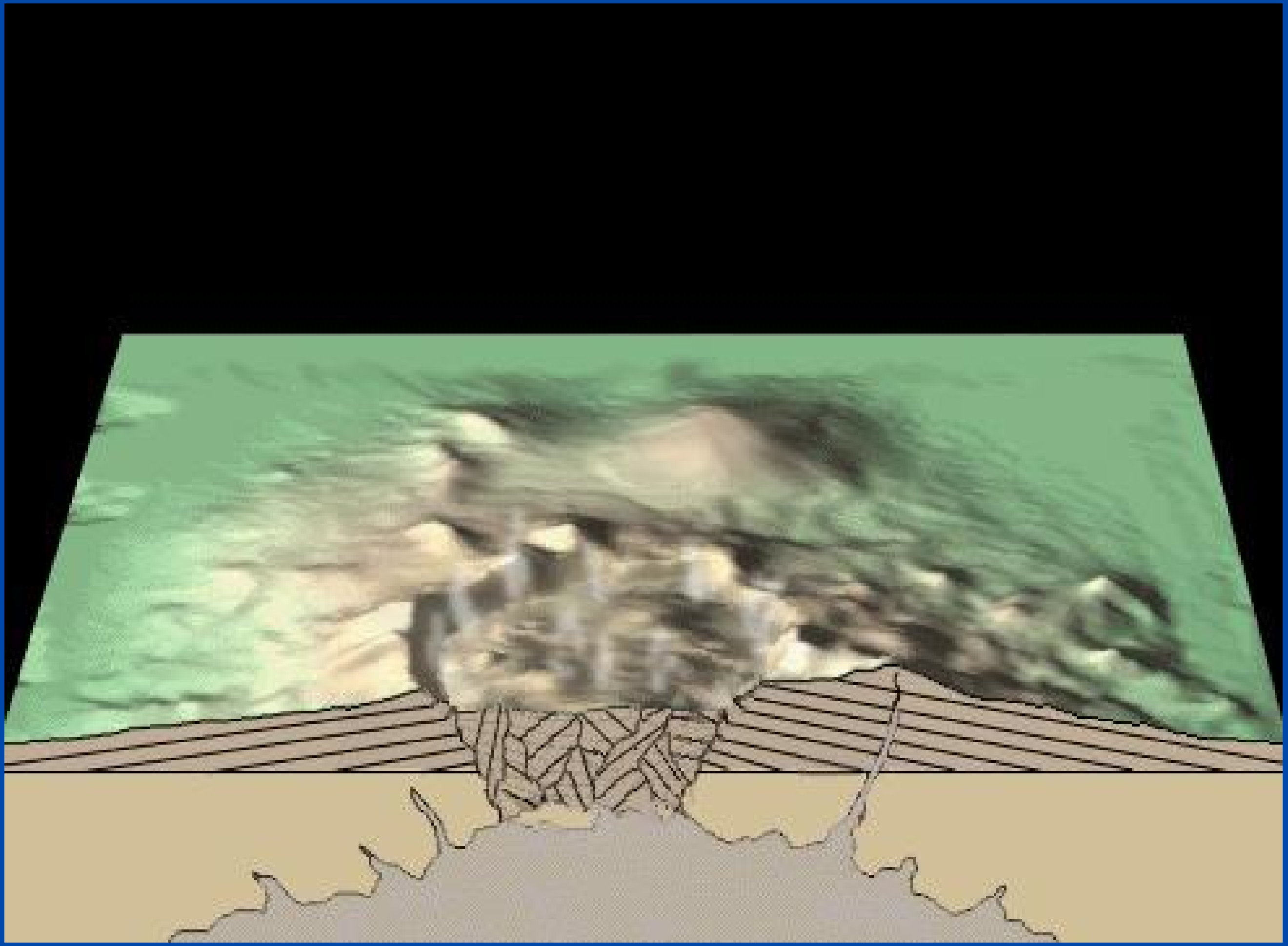
Shield volcanoes on Earth, Venus, Mars, Io



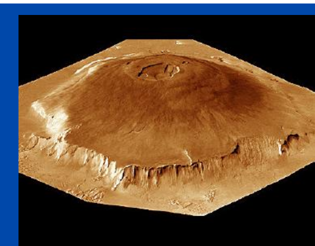


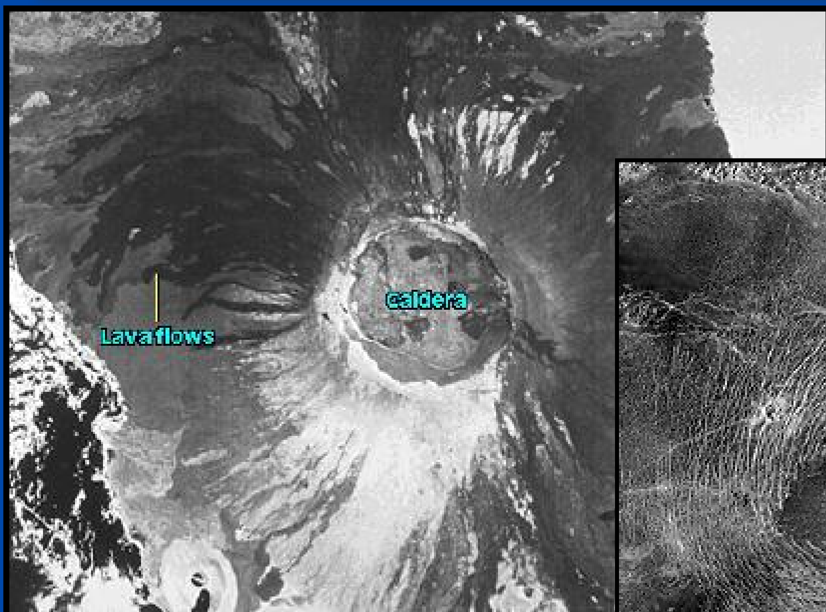
Caldera: when vent of volcano collapses



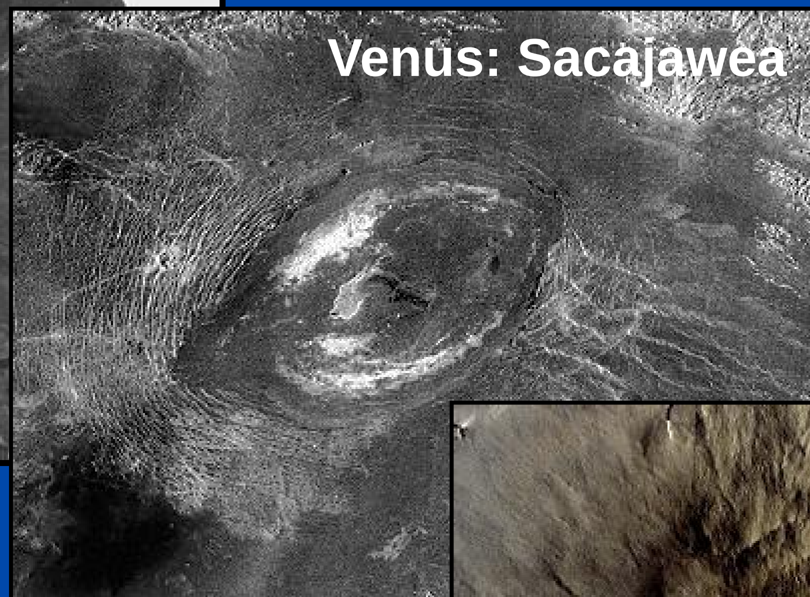


Calderas on Earth, Venus, Mars

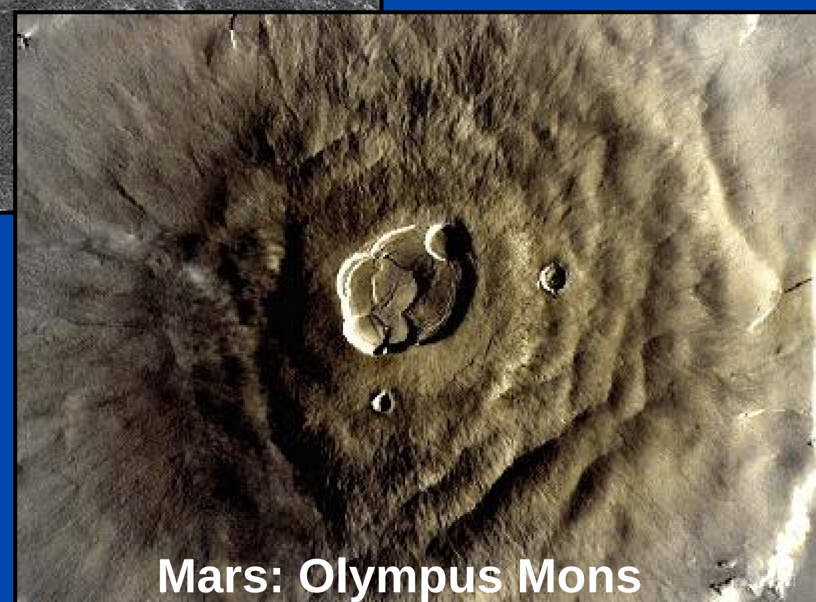




Earth: Galapagos Islands

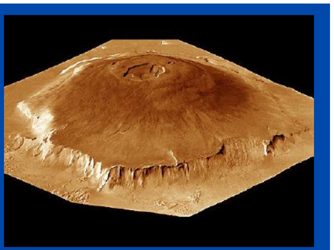


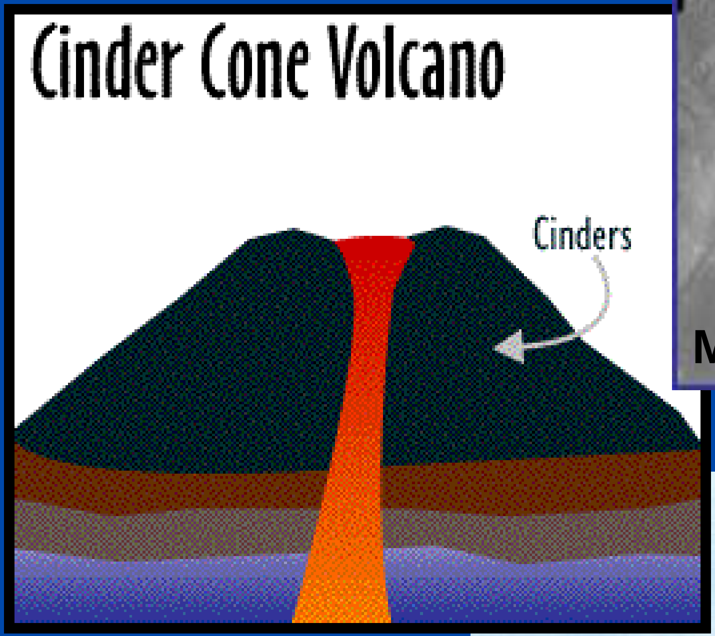
Venus: Sacajawea

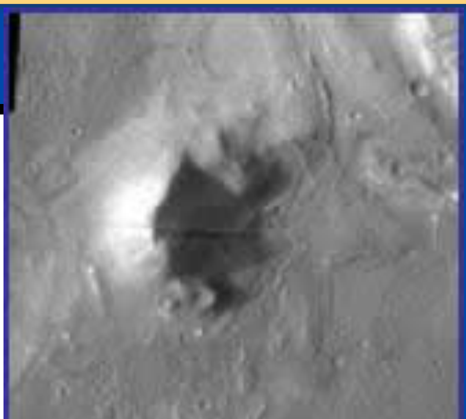


Mars: Olympus Mons

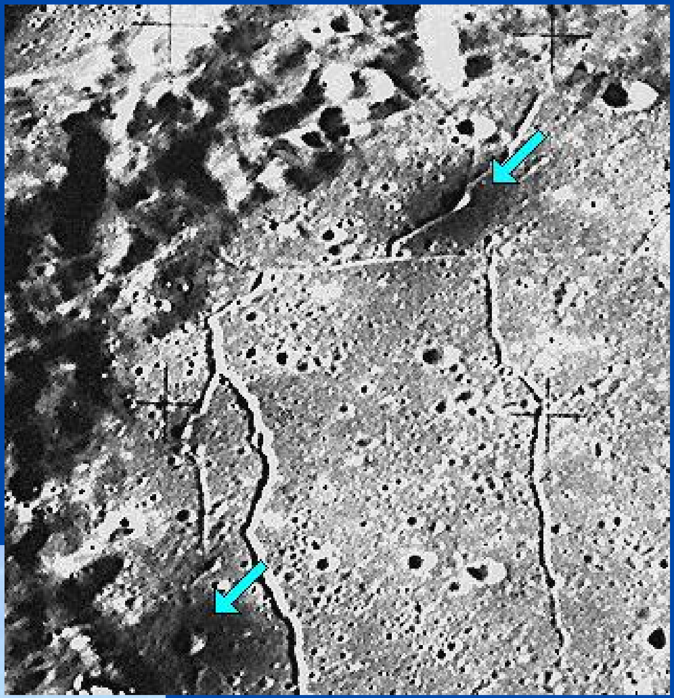
Cinder cones on Earth, Moon, Mars







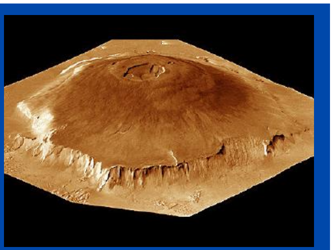
Mars: Syrtis Major



Moon (2)

Earth: Pu’u O’o

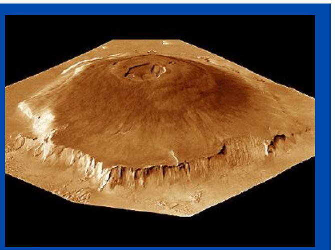
Volcanic outgassing releases gases into atmosphere

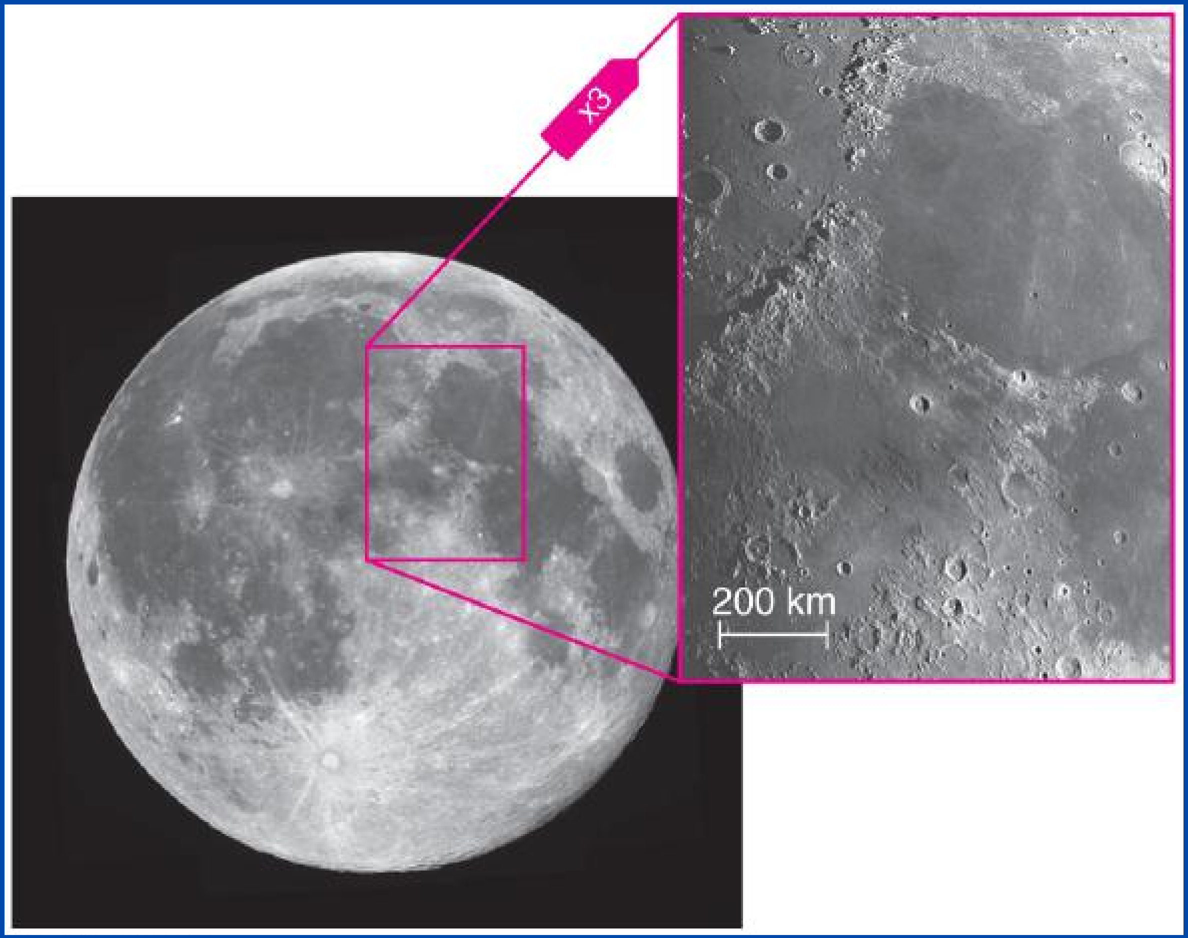


a The eruption of Mount St. Helens, May 18, 1980.

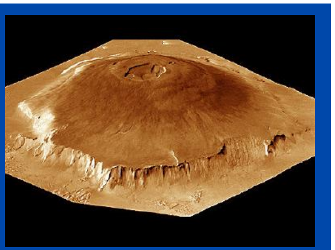
b More gradual outgassing from a volcanic vent in Volcanoes National Park, Hawaii.

Lunar Maria filled in by runny lava





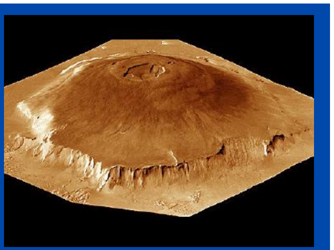
- Smooth, dark lunar maria are less heavily cratered than lunar highlands.
- Maria were made by floods of runny lava.

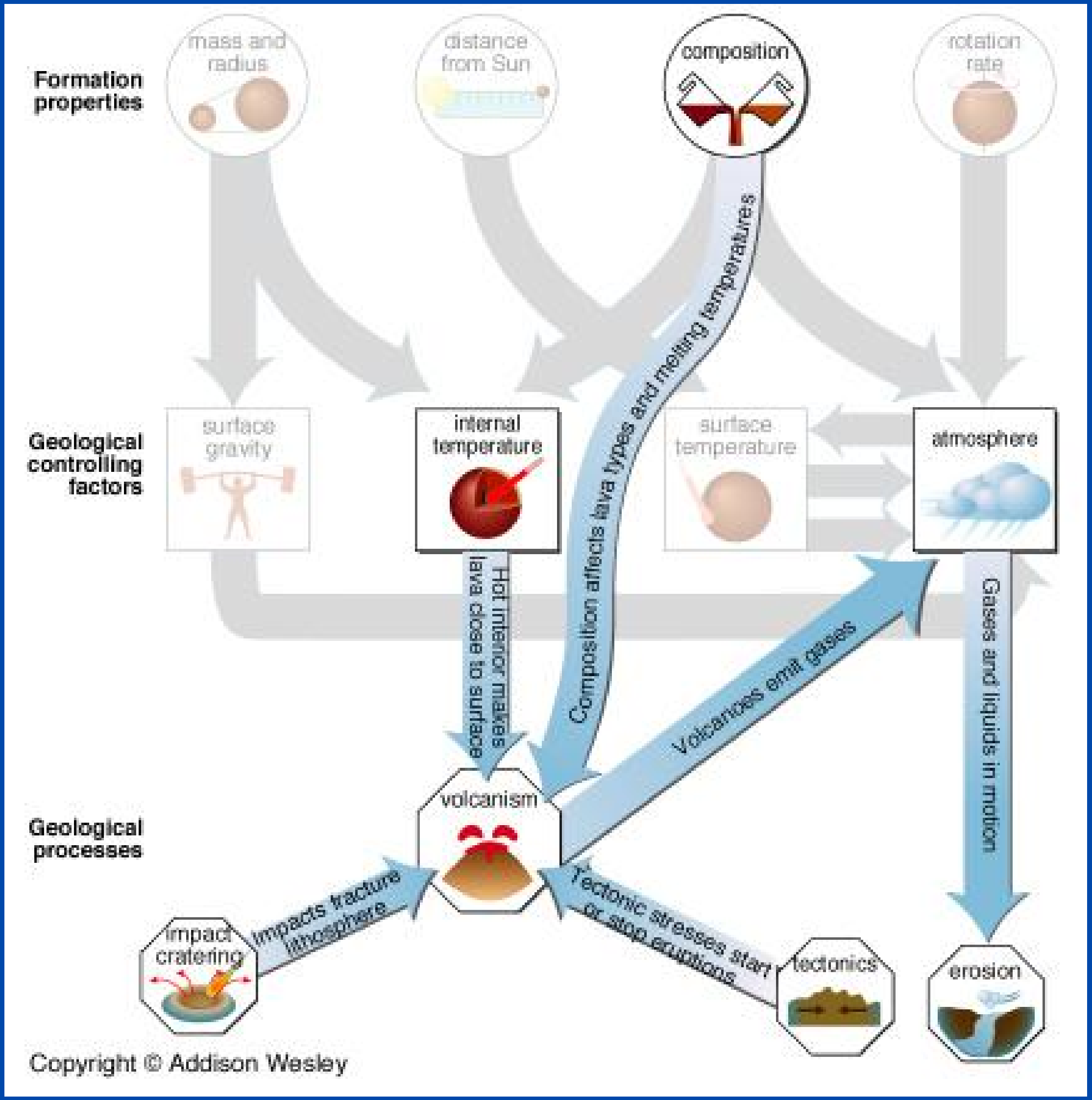


Formation of Lunar Maria

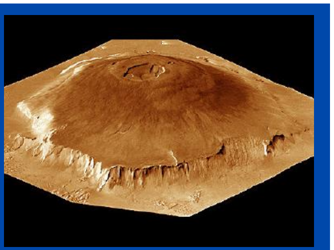
Early surface is covered with craters.	Large impact crater weakens crust.	Heat build-up allows lava to well up to surface.	Cooled lava is smoother and darker than surroundings.

Volcanism flow chart



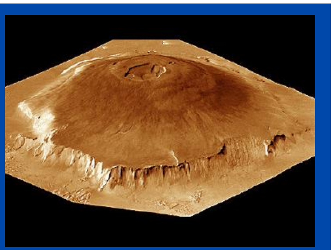


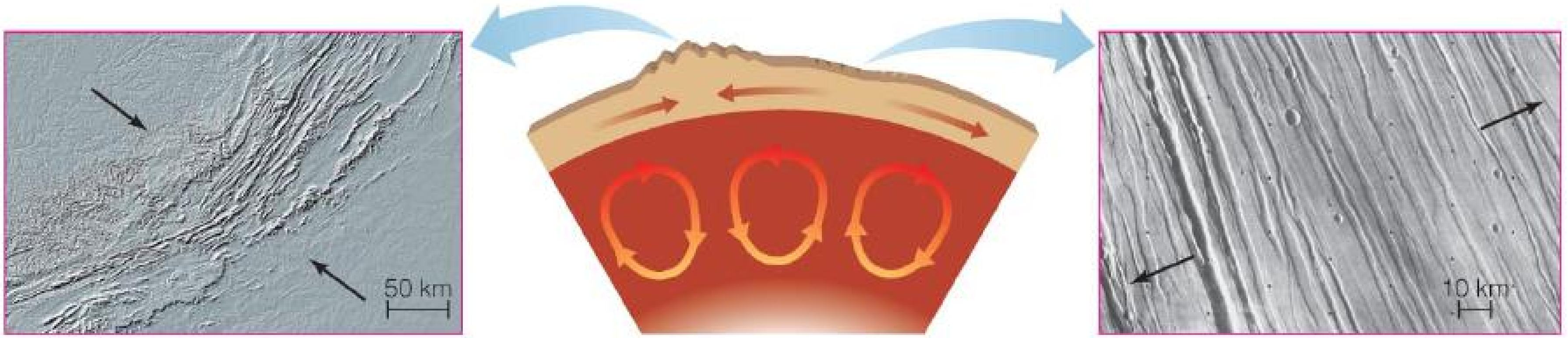
Four processes that shape planetary surfaces



- Impact cratering
- Volcanism
- Tectonics
- Erosion

What is Tectonics?



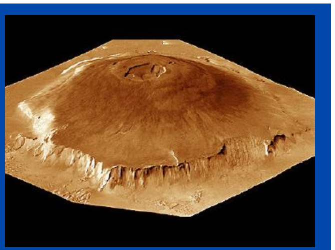


Appalachian Mountains in eastern United States

Ceraunius Valleys on Mars

- Convection of the mantle creates stresses in the crust called tectonic forces.
- Compression of crust creates mountain ranges.
- Valley can form where crust is pulled apart.

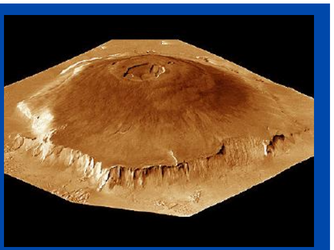
Tectonics: motions of crustal material driven by mantle convection

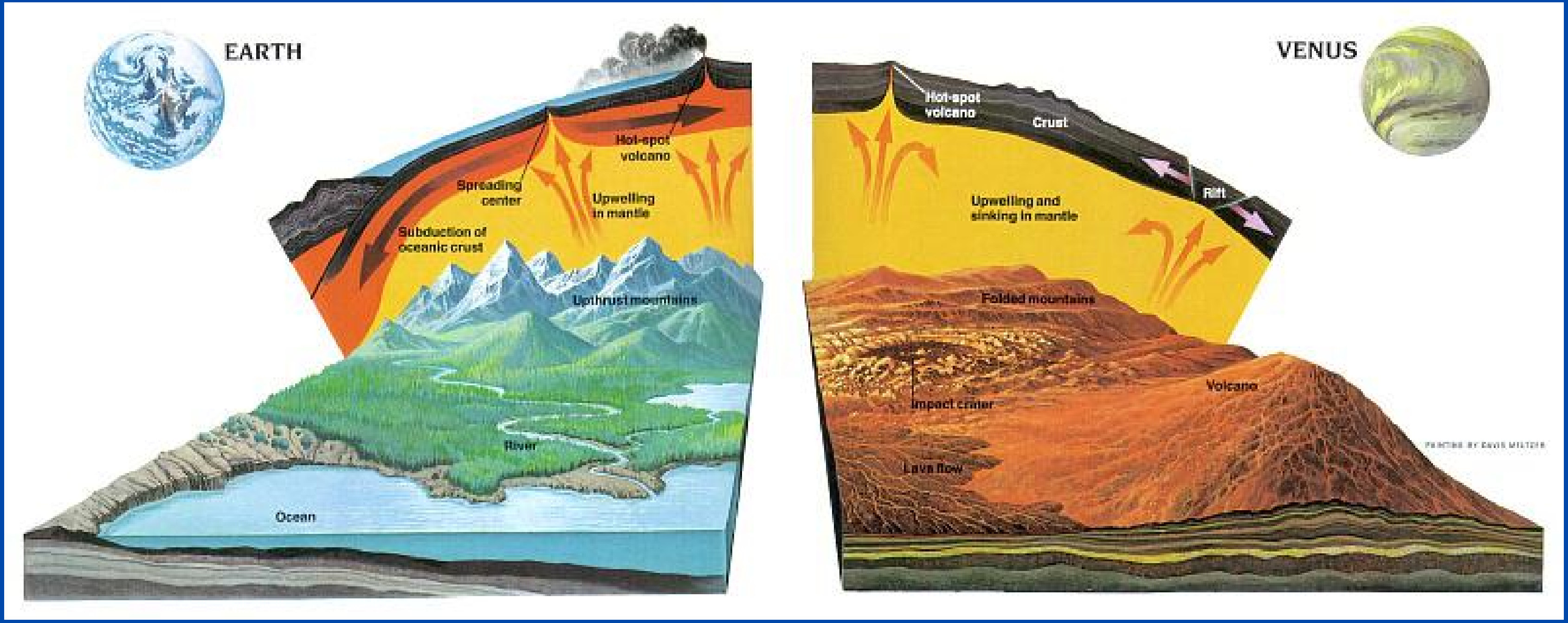


Computer simulation of mantle convection

Credit: Arizona State Univ. School of Earth and Space Exploration

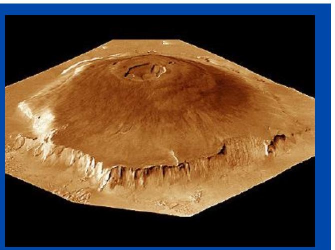
Earth, Venus tectonics contrasted

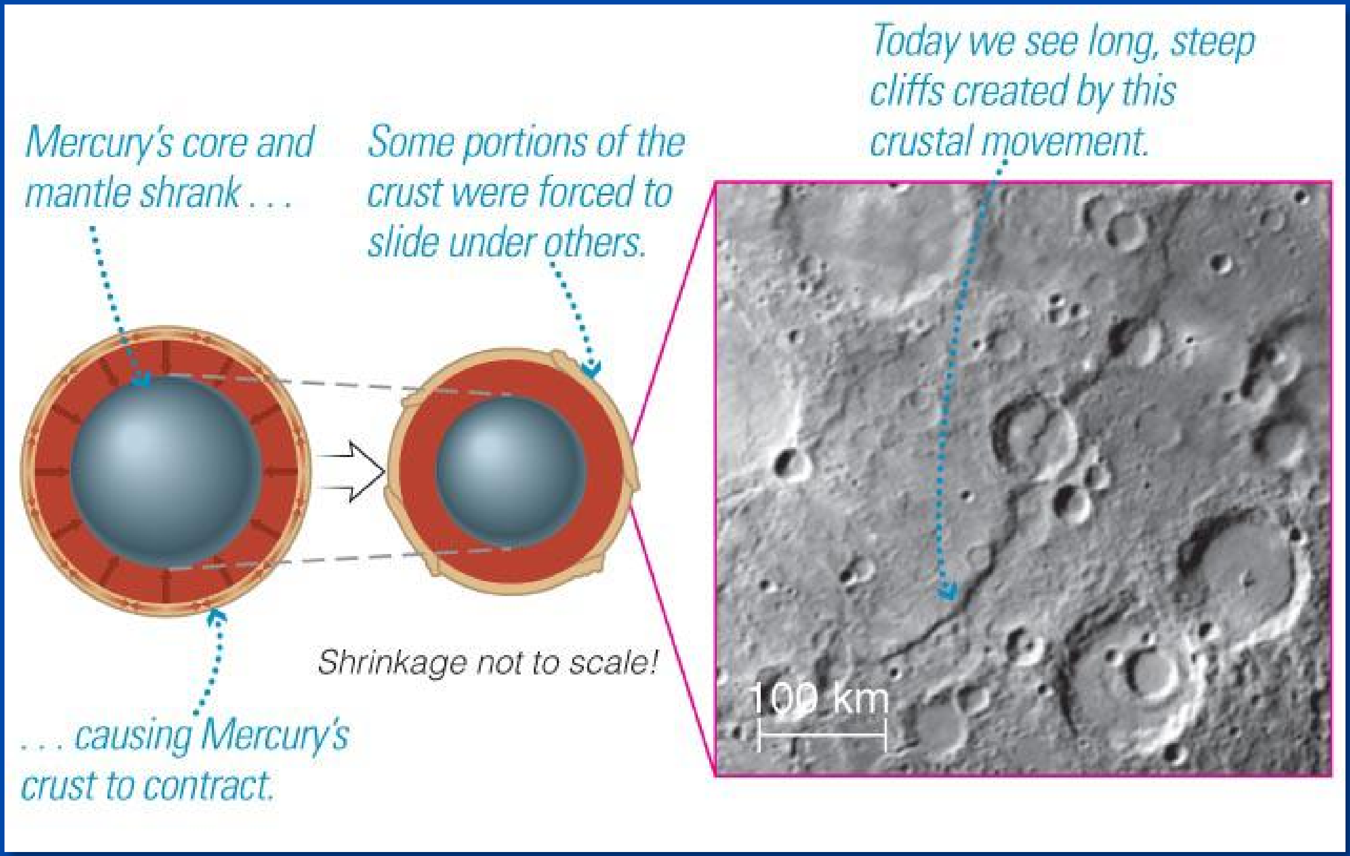




- **Venus has mantle convection but no tectonics**
- **Venus's crust: basaltic, dry, higher viscosity**
- **Most of differences bet. Earth and Venus processes can be explained by absence of water: Venus atmosphere so hot that water “baked out” of crust**

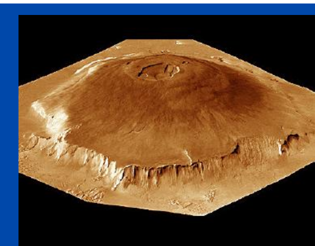
Evidence that Mercury shrank!



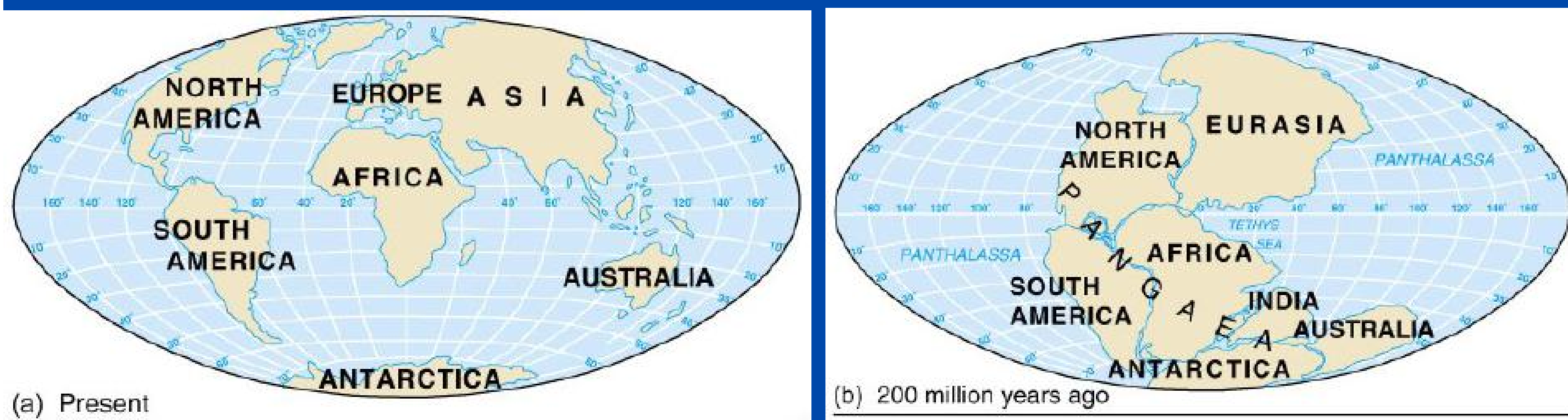


- **Long cliffs indicate that Mercury shrank early in its history.**

Earth is only planet in our Solar System that has active plate tectonics today

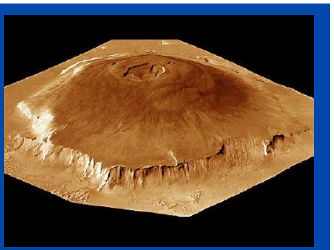


- **Crust broken up into "plates" that move due to mantle convection**
- **Evidence:**
  - **Matching coastlines on different continents**
  - **Continent motions can be measured with GPS!**

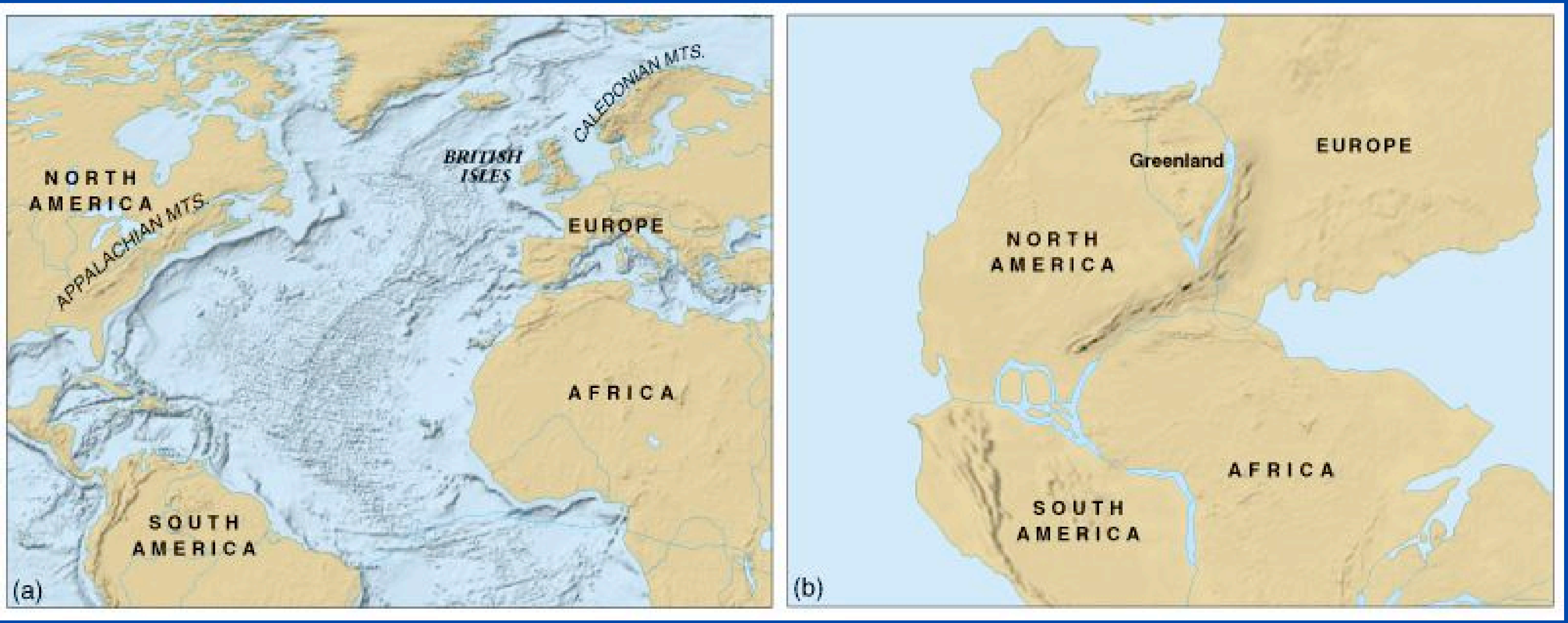


(a) Present (b) 200 million years ago

More evidence for continental drift

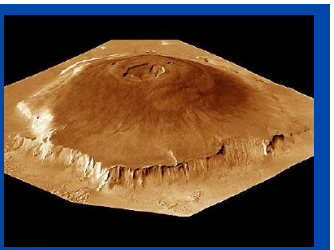


- **Matching mountain ranges across oceans**

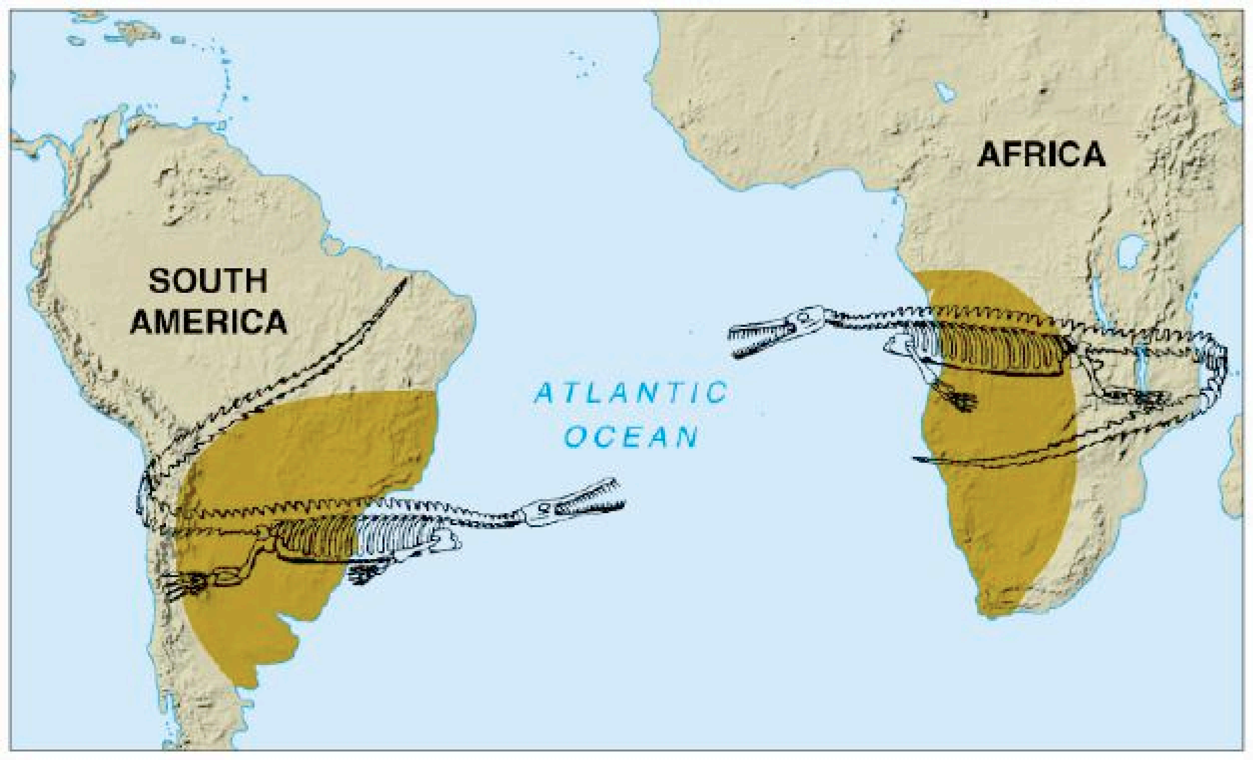


Today | **300 million years ago**

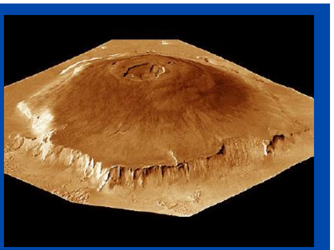
More evidence for continental drift

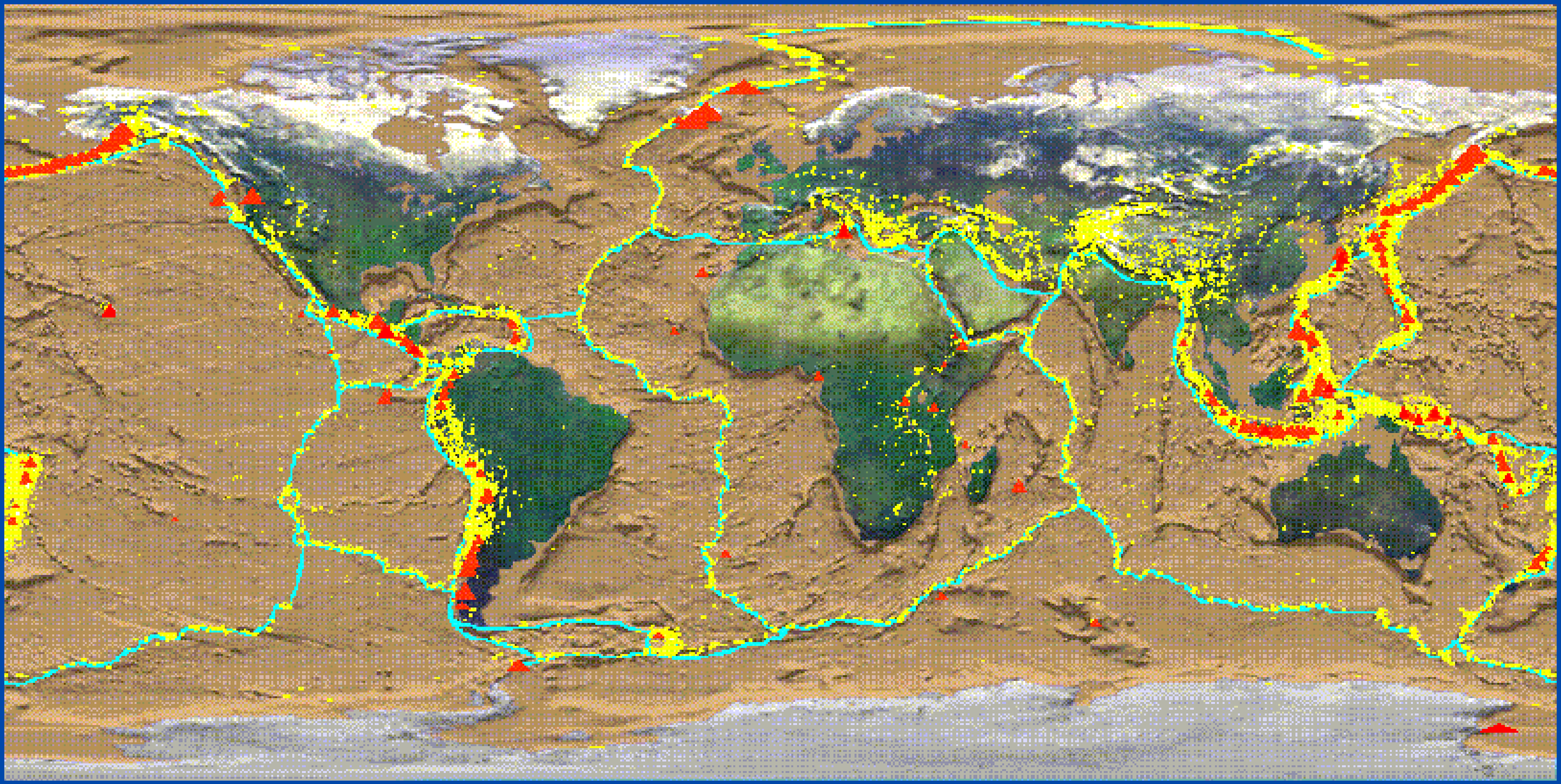


- **Distribution of fossils such as *Mesosaurus***

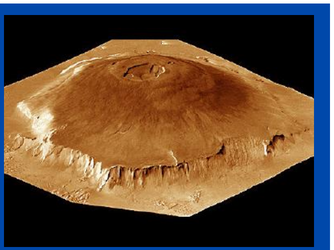


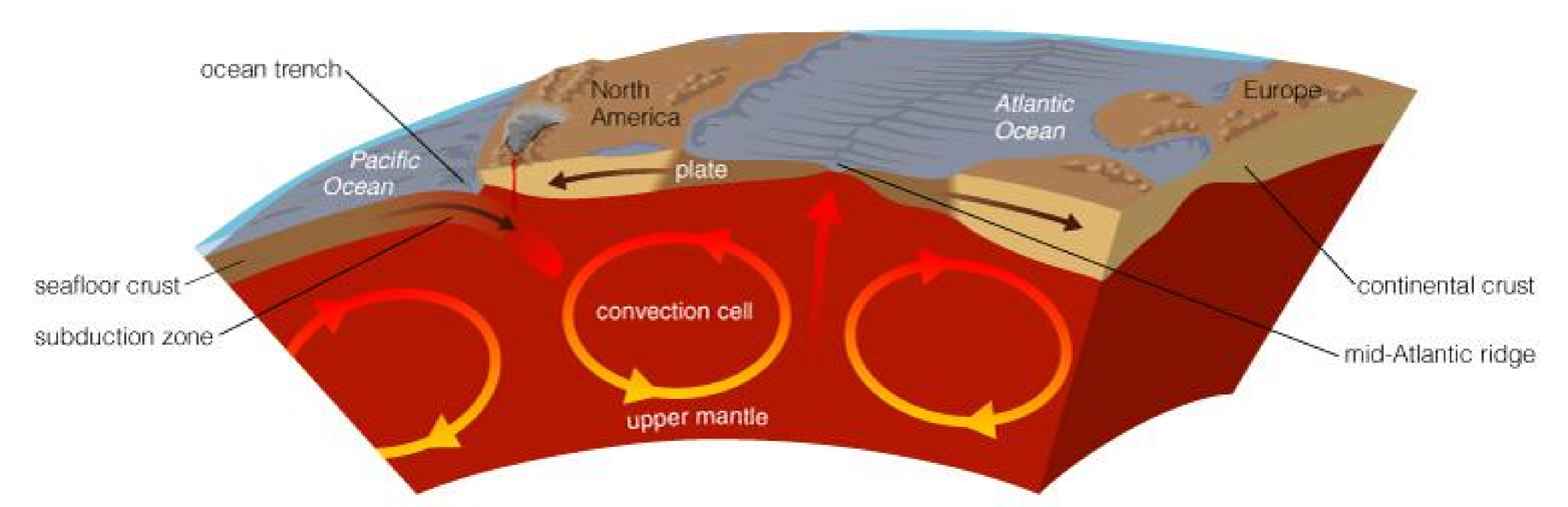
On Earth, earthquake zones and volcanoes mark plate boundaries

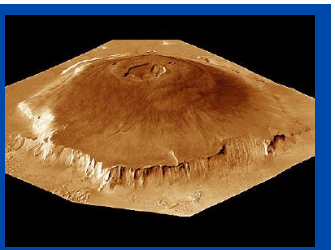




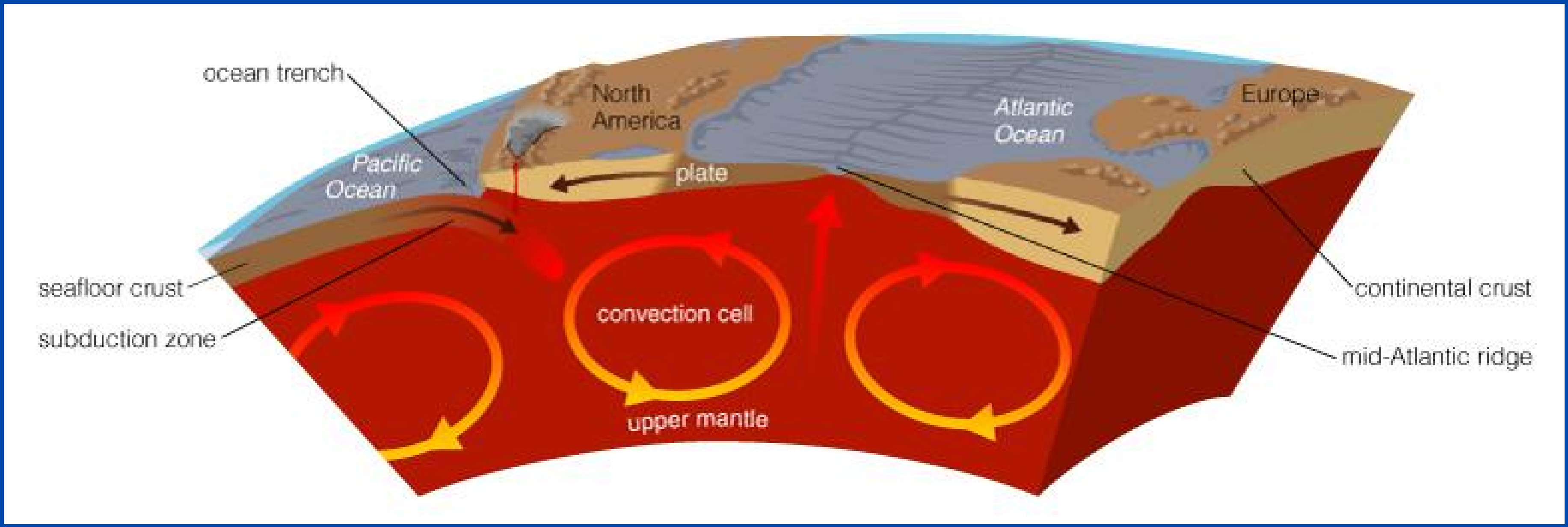
How is Earth's surface shaped by plate tectonics?





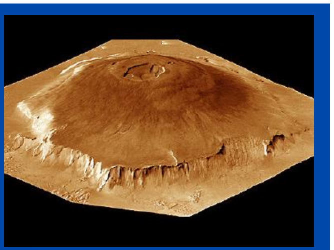


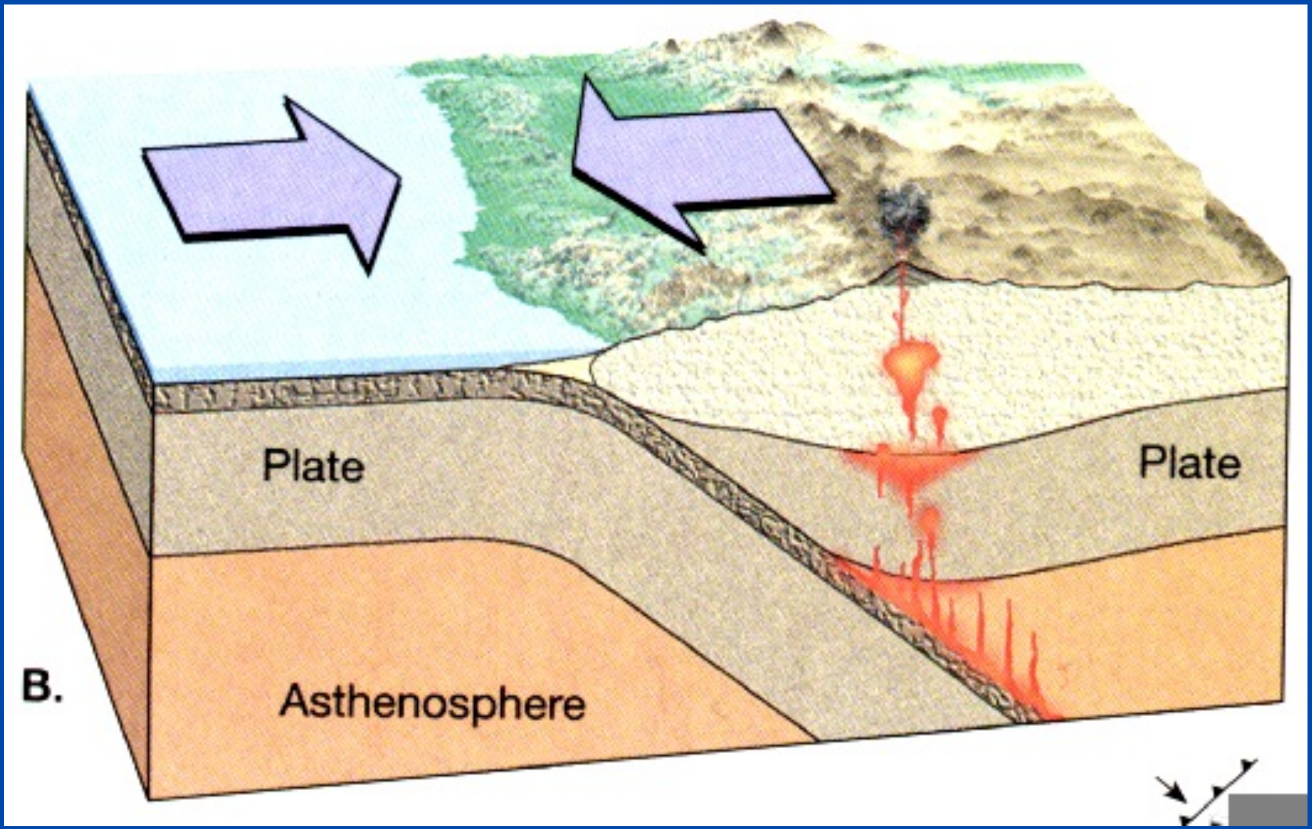
Seafloor Recycling



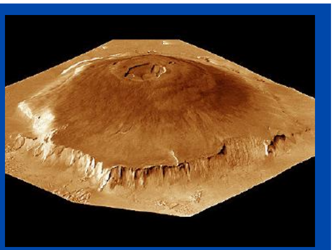
- **Seafloor is recycled through a process known as subduction**

Subduction at plate boundary

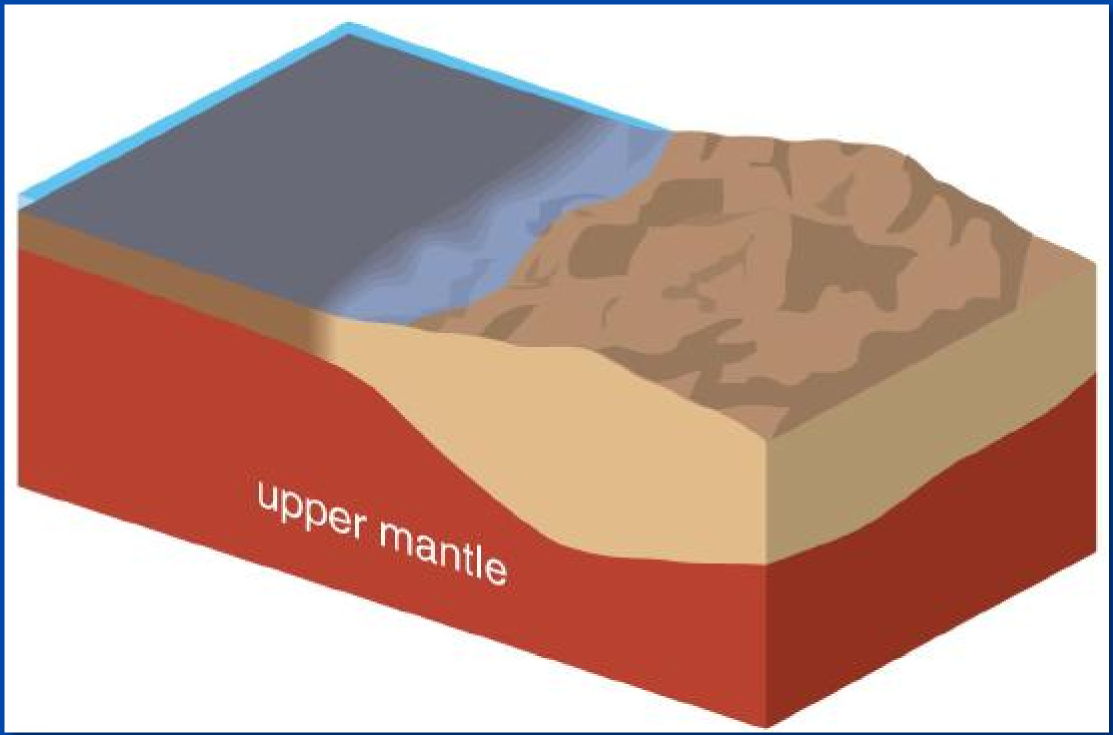




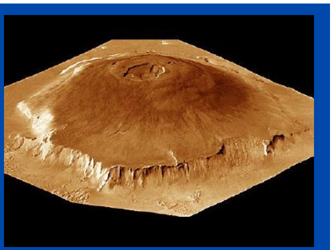
- Earthquakes more common at plate boundaries
- San Andreas fault: boundary between Pacific Plate and North American Plate



Seafloor Crust



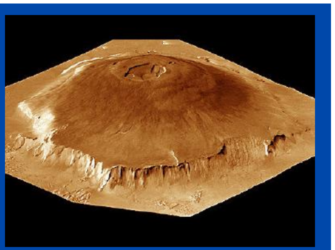
- **Thin seafloor crust differs from thick continental crust.**
- **Dating of the seafloor shows that it is usually quite young.**

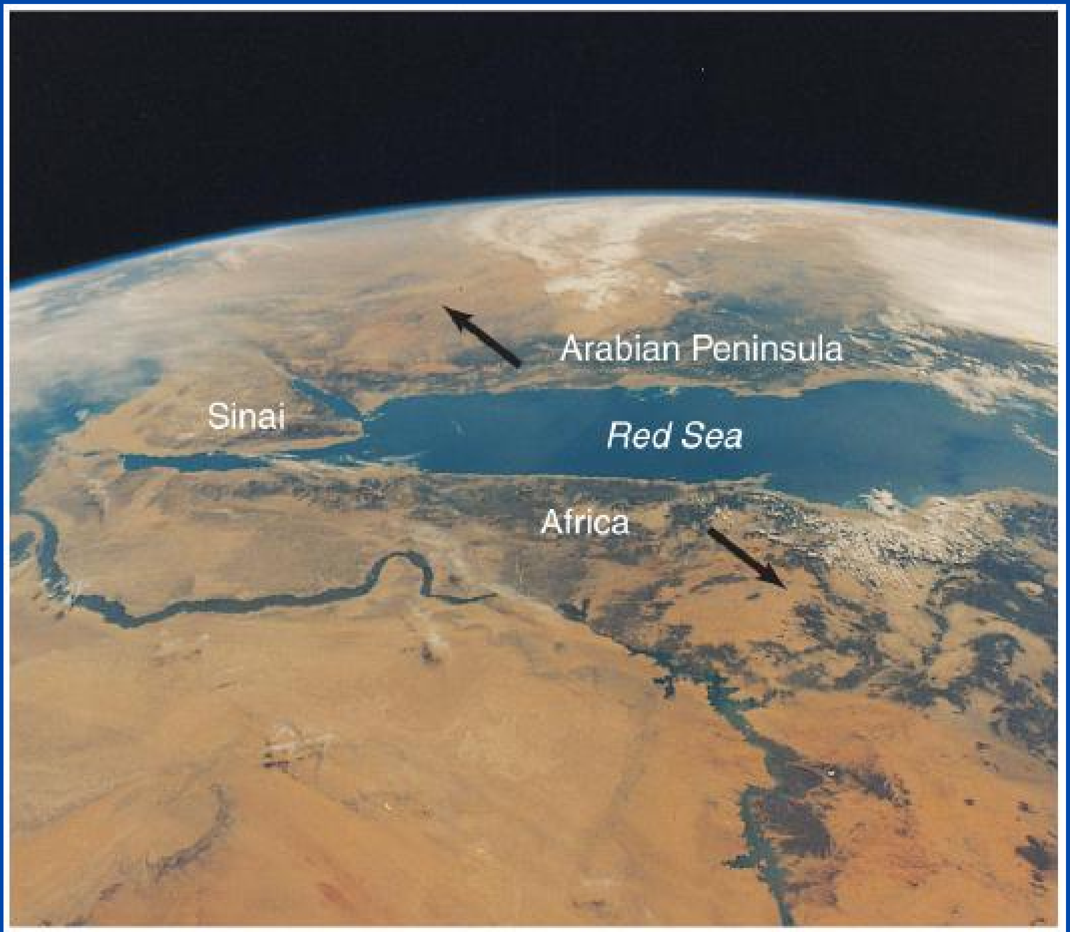


Surface Features

- **The Himalayas formed from a collision between the Indian and Asian plates.**

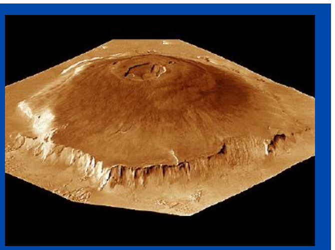
Surface Features

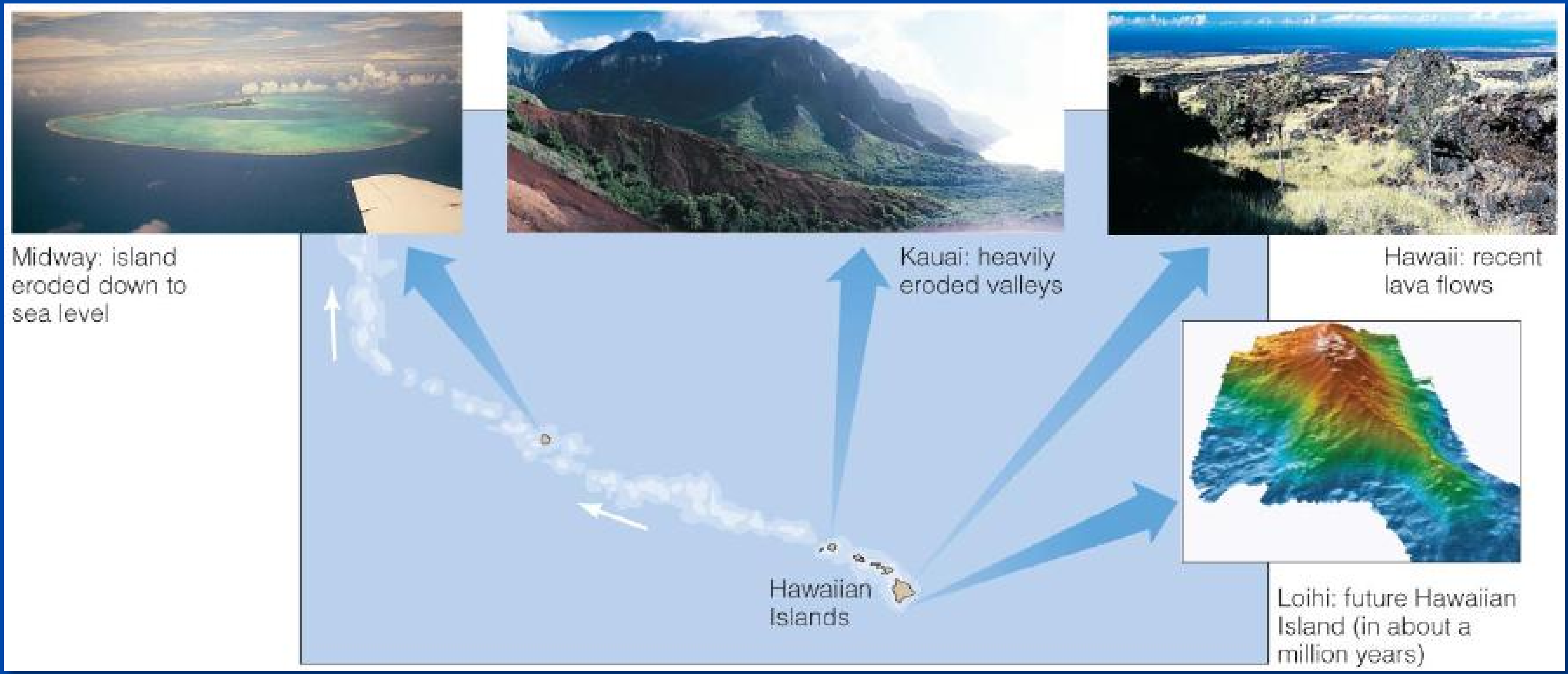




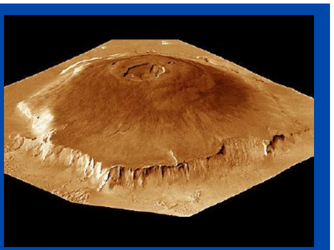
- **The Red Sea is forming where plates are pulling apart.**

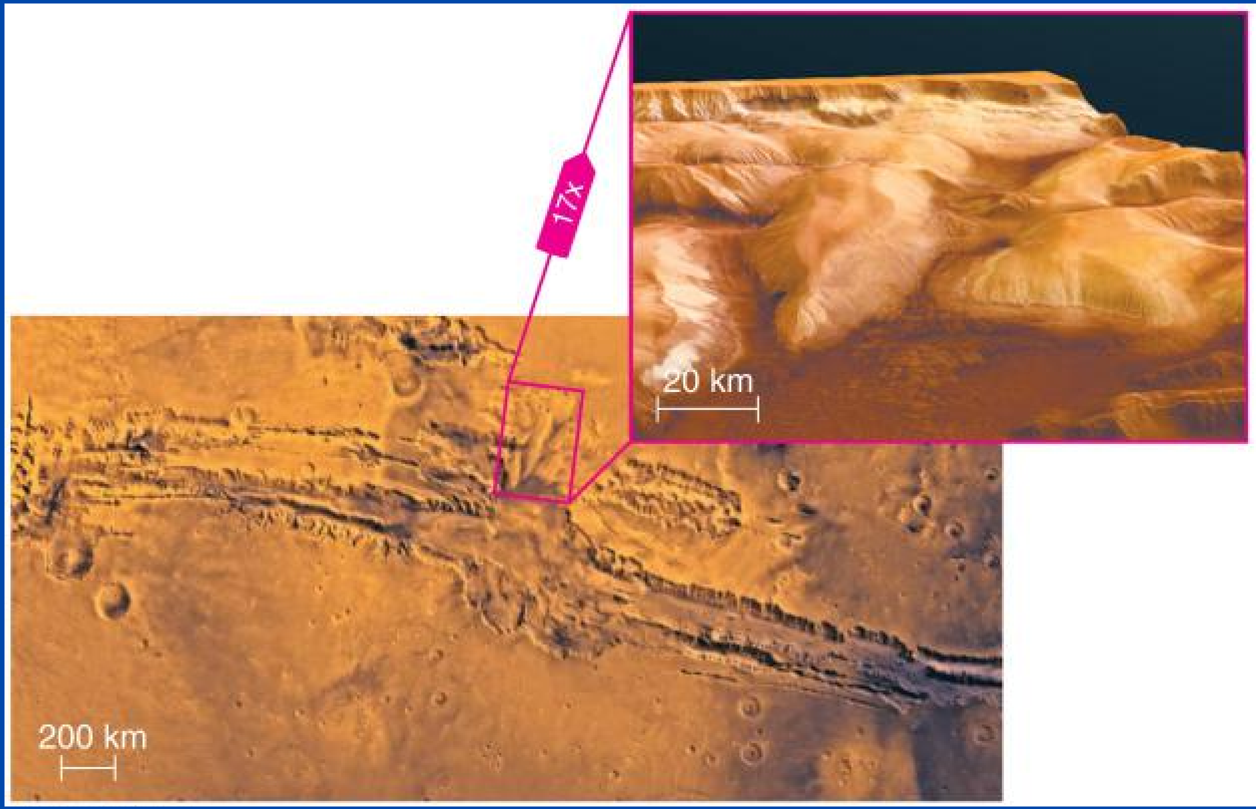
Hawaiian islands formed where plate is moving over a volcanic hot spot





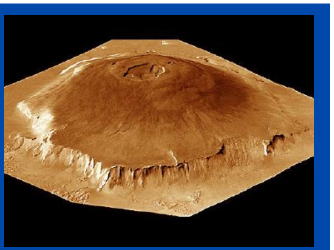
Tectonics on Mars was active in past





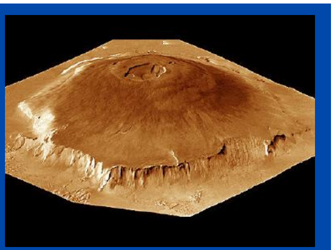
- **System of valleys known as Valles Marineris is thought to originate from tectonics.**

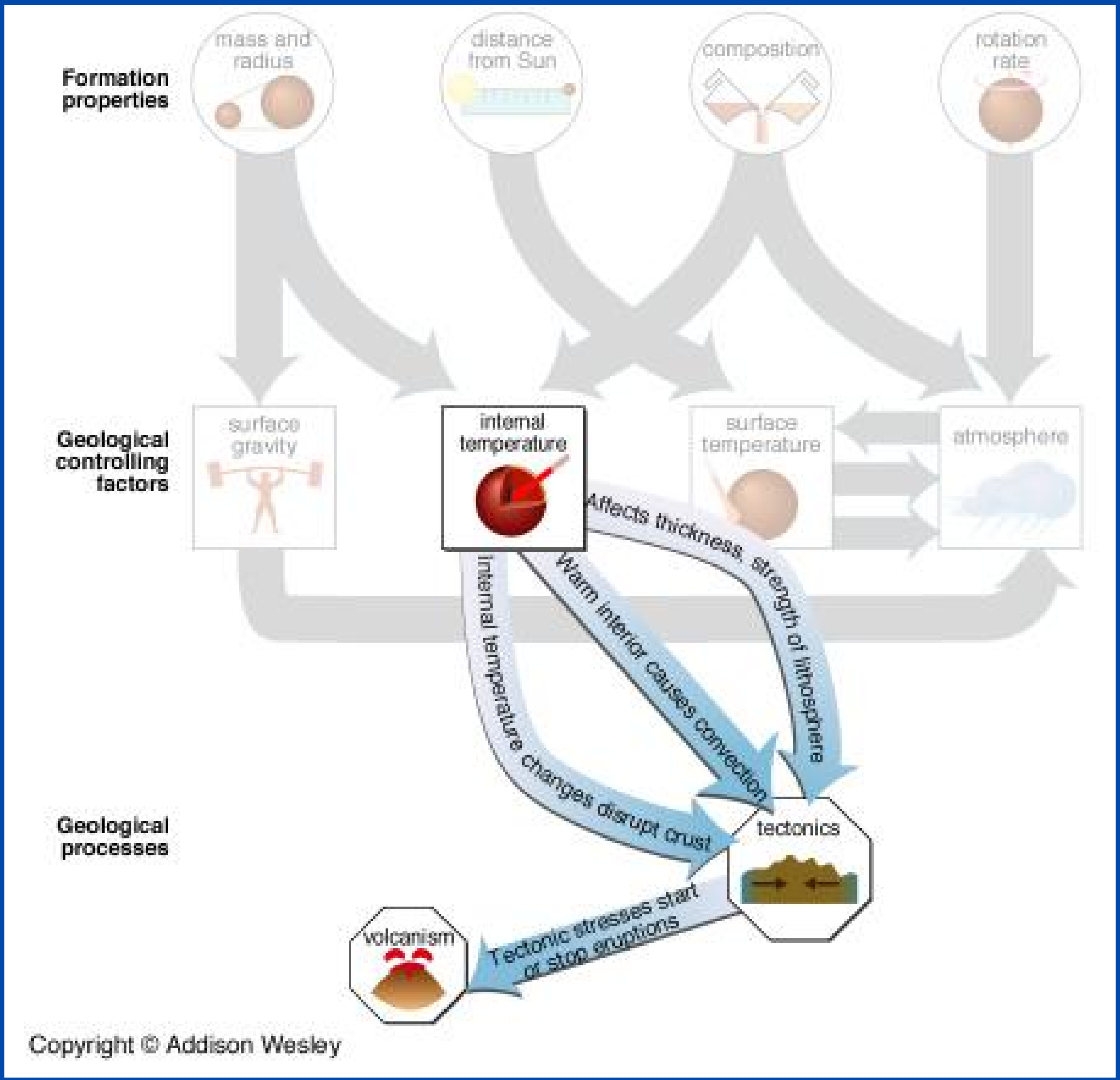
Does Venus have plate tectonics?



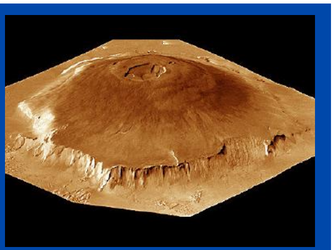
- Venus does not appear to have plate tectonics, but entire surface seems to have been "repaved" 750 million years ago.
  - » Weaker convection?
  - » Thicker or more rigid lithosphere?

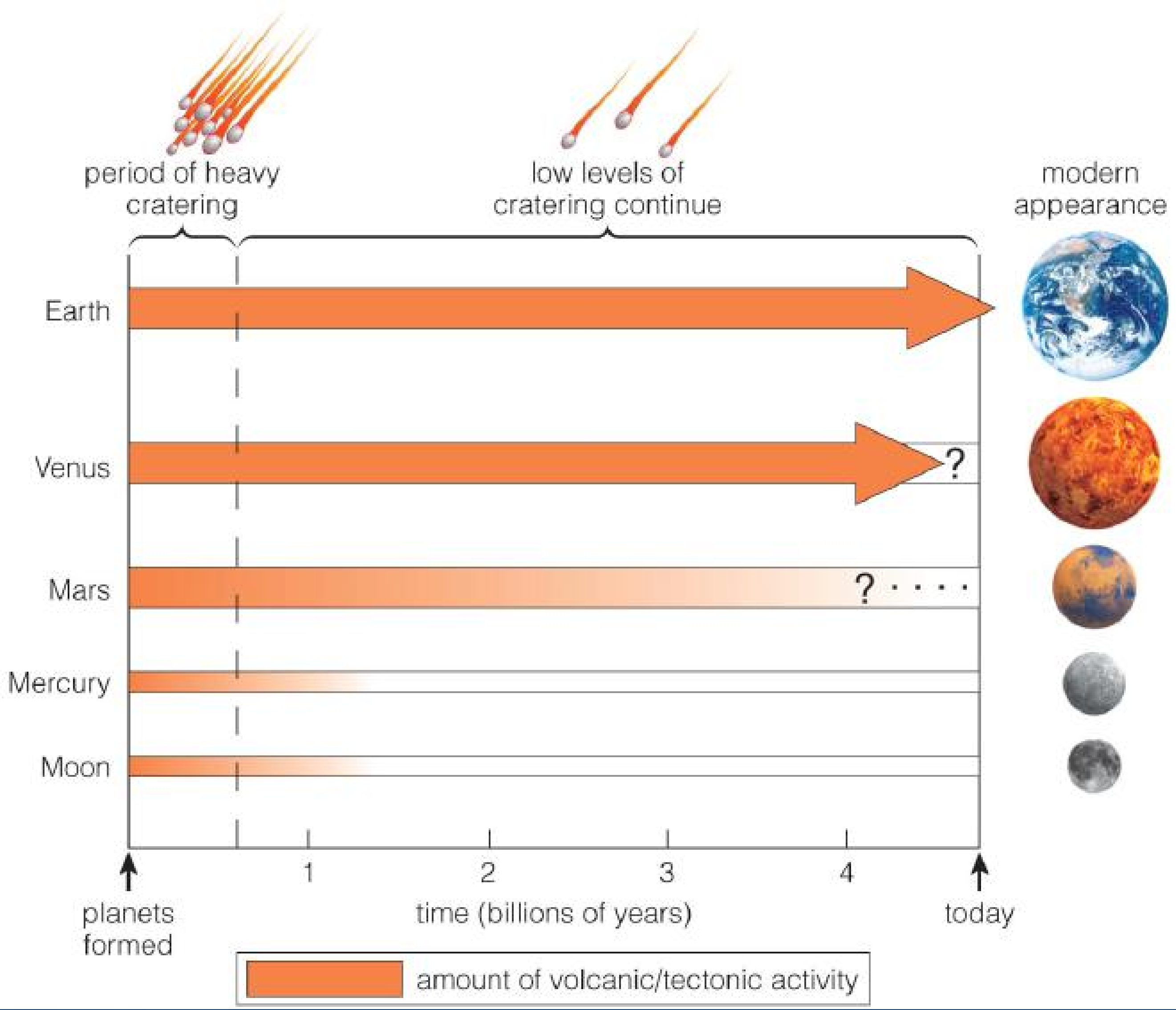
Tectonics flow chart



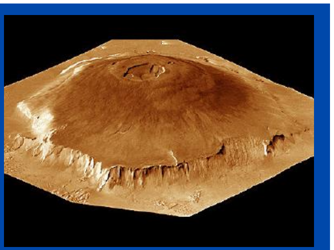


Was Earth's geology destined from birth?



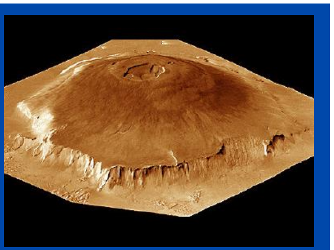


Four processes that shape planetary surfaces



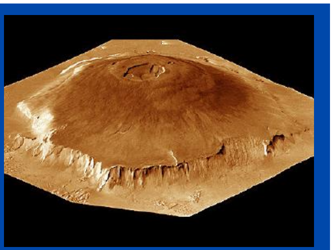
- Impact cratering
- Volcanism
- Tectonics
- Erosion

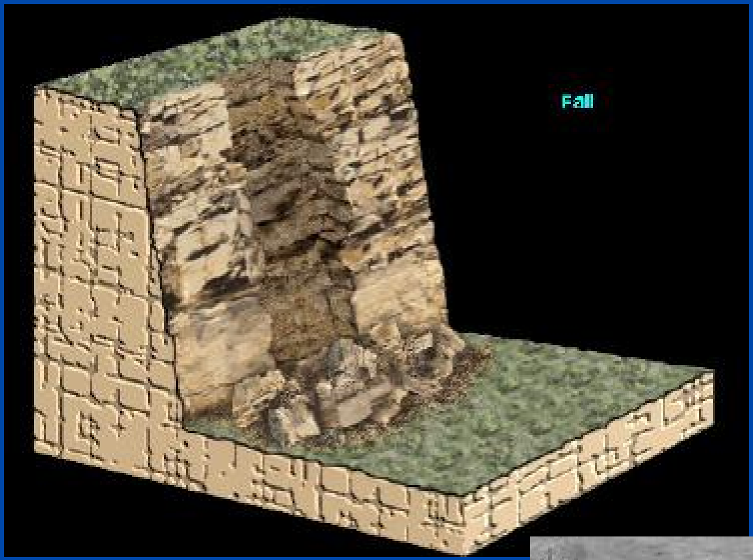
Erosion



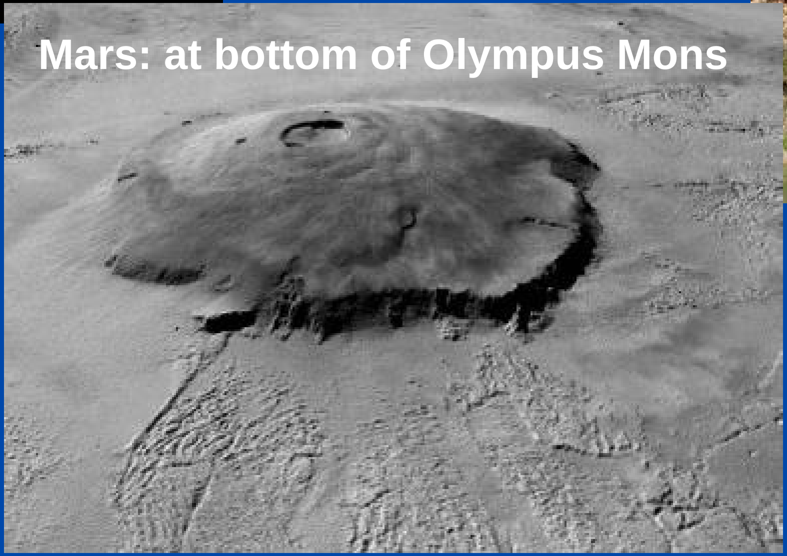
- Erosion is a blanket term for weather-driven processes that break down or transport rock and soil.
- Processes that cause erosion include:
  - glaciers
  - water
  - wind

Erosion: rockfalls



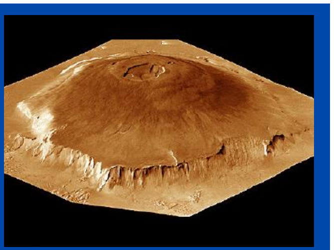


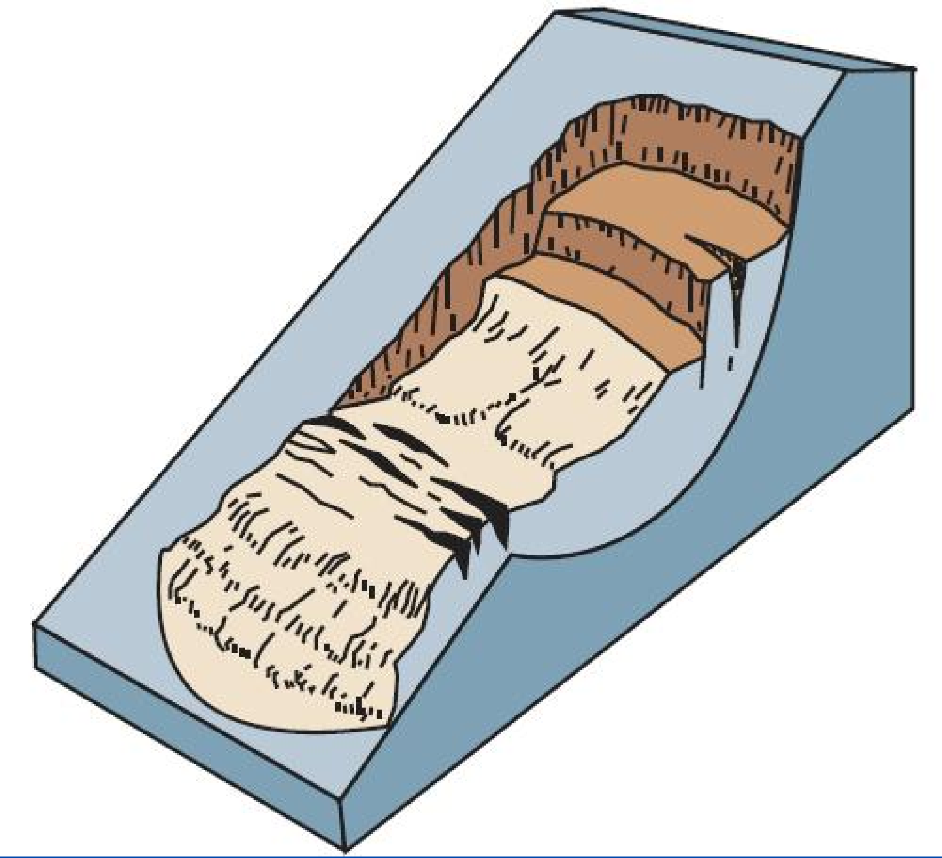
Earth: Grand Canyon



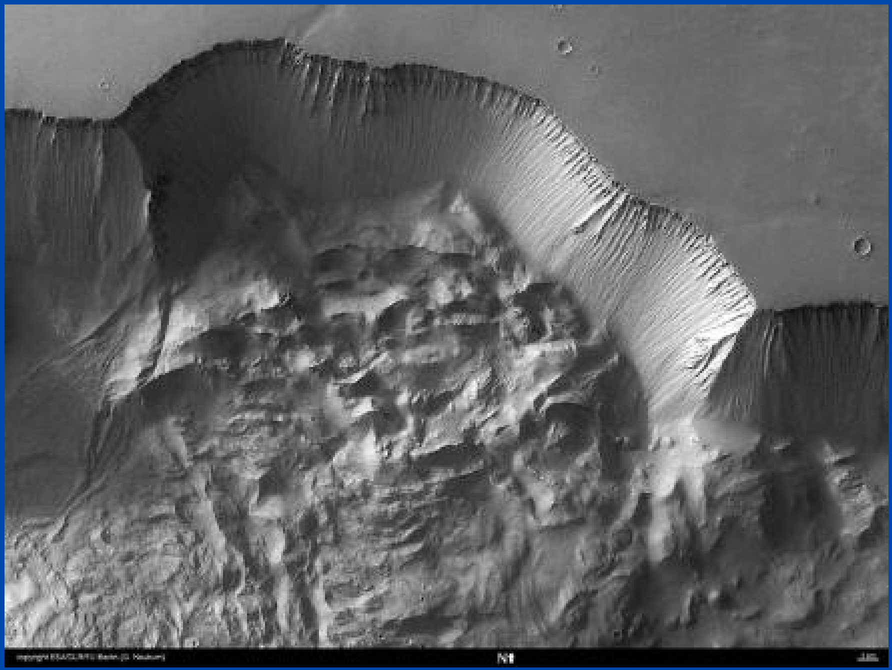
Mars: at bottom of Olympus Mons

Erosion: slumps

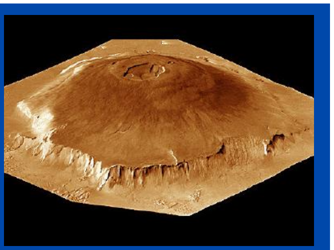




Slump on Mars

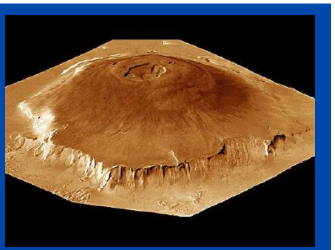


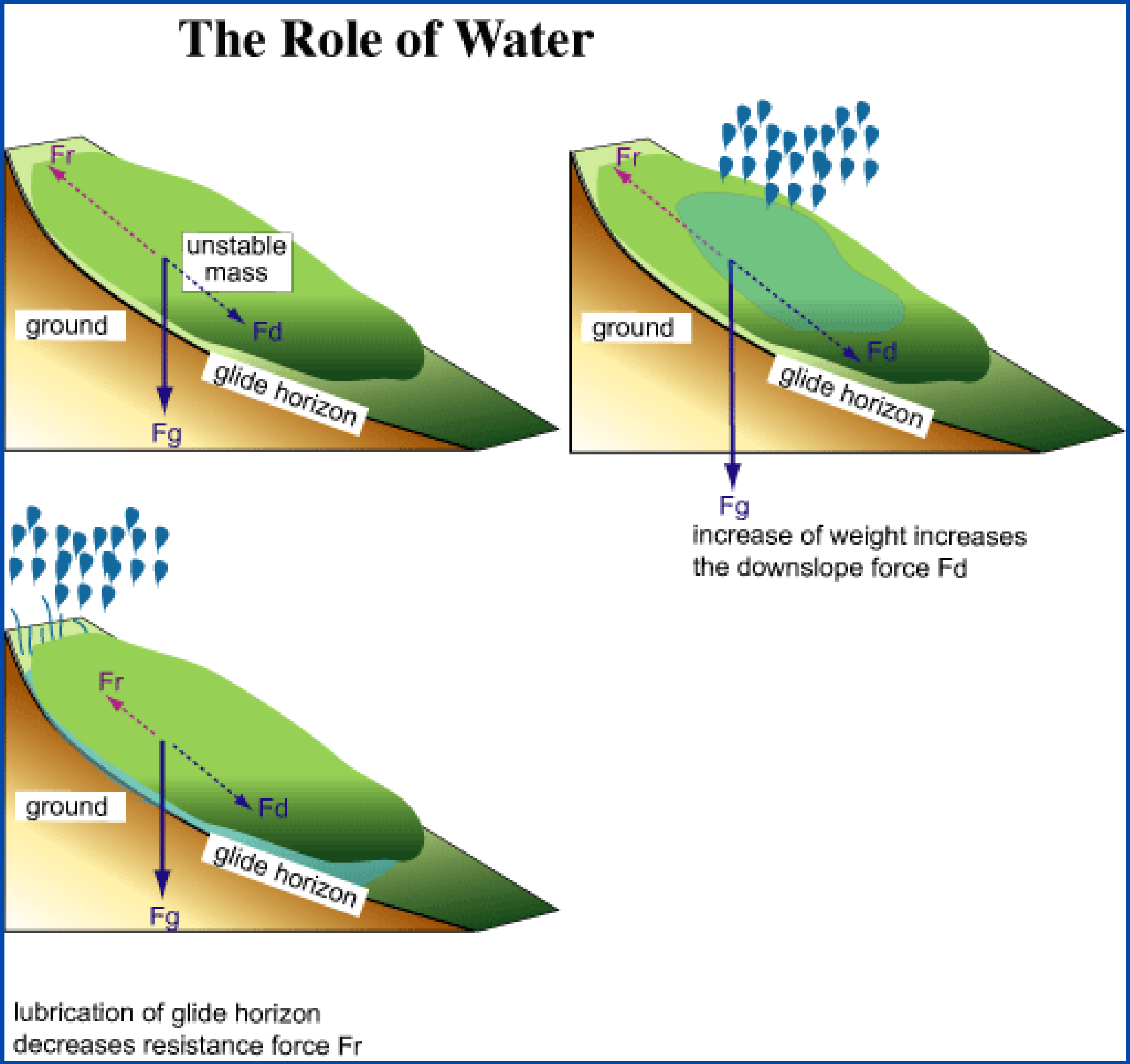
Slump in Berkeley CA



On Wildcat Canyon Road

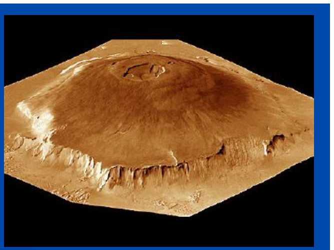
Slumps on Earth are usually due to liquid water





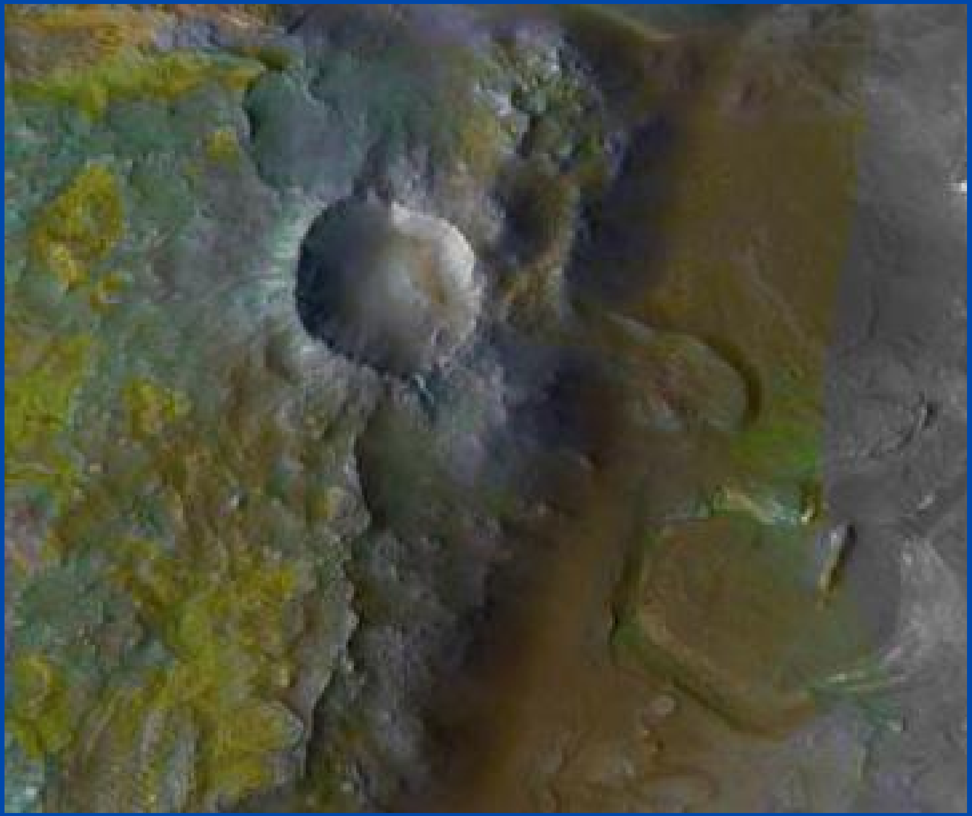
- **Is this indirect evidence for liquid water on Mars?**

Erosion: debris flows on Earth and Mars

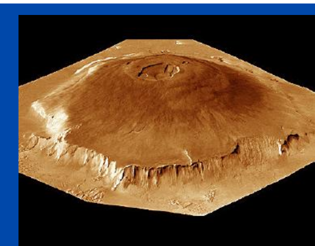


Earth: San Jacinto Mountains, CA

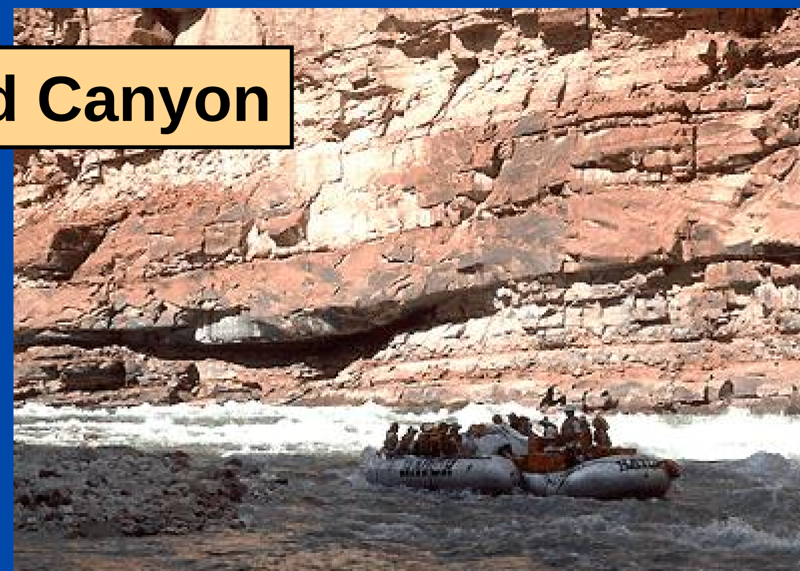
Mars: (wet?) debris flow

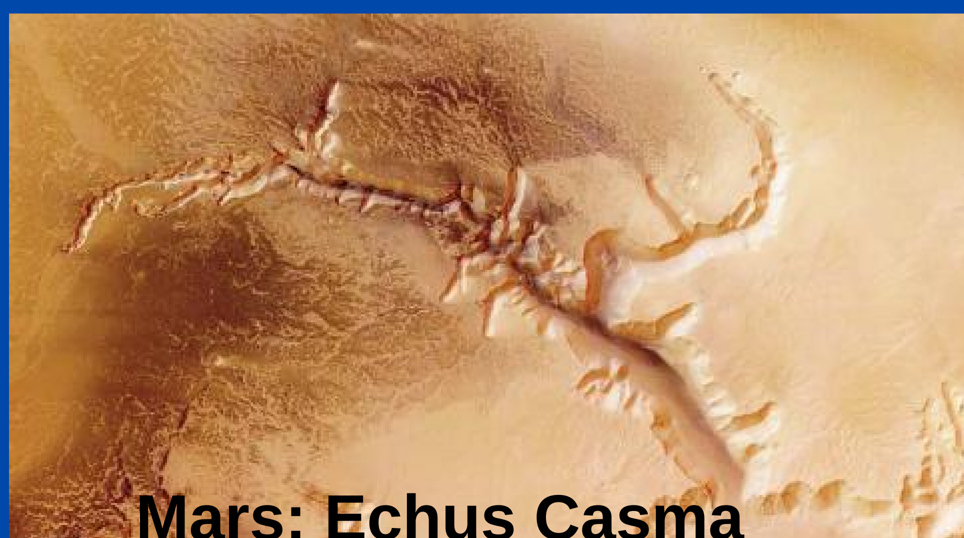


Erosion: water can carve canyons



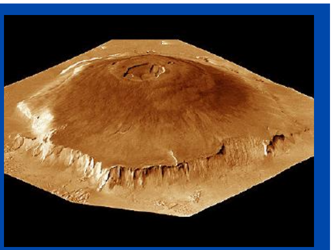
Earth: Grand Canyon



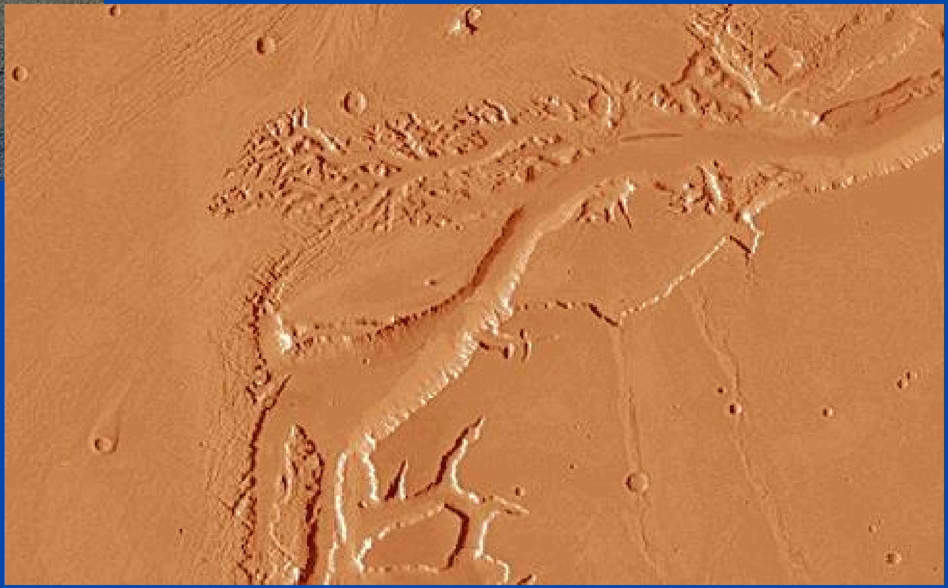


Mars: Echus Casma

Erosion: flood channels on Earth, Mars

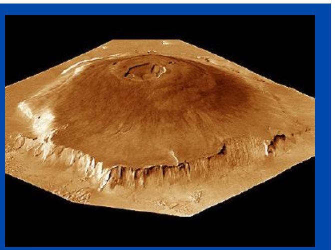


Washington State: channeled scablands Giant flood 13,000 yrs ago

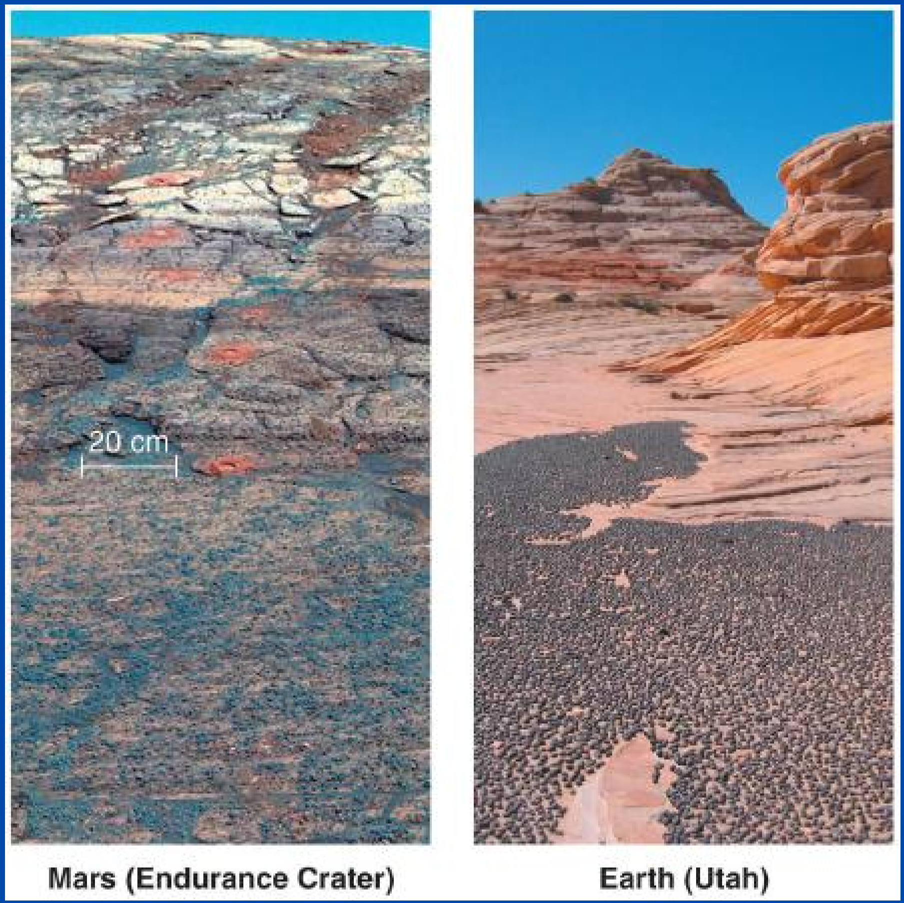


Mars: Kasei Valles flood channel

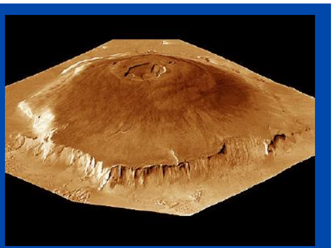
Some Martian rocks appear to have formed in water

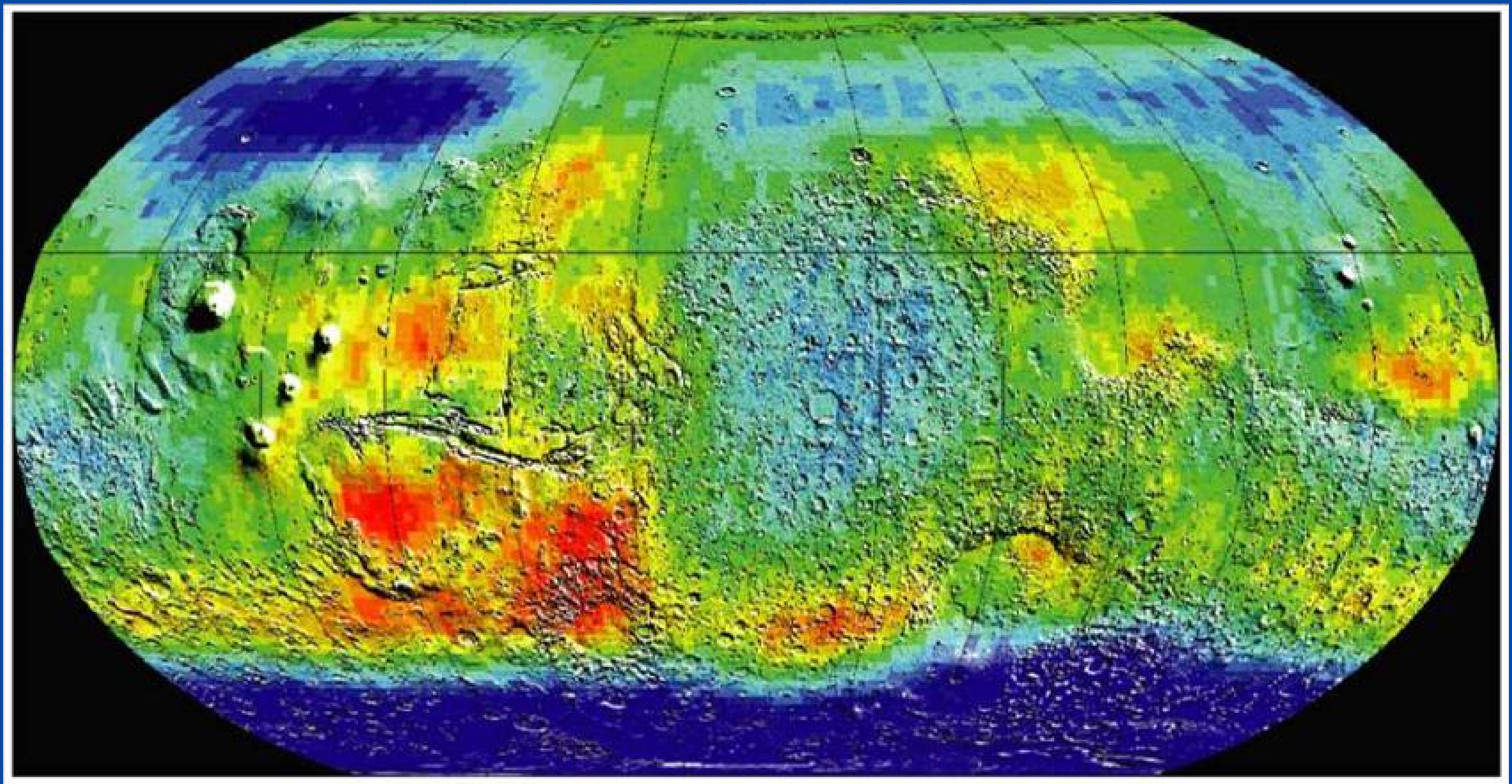


- **Mars rovers (Spirit, Opportunity)**
- **Found rocks of a type that typically forms in water, on Earth**
  – **Hermatite "blueberries"**
  – **Formed in sedimentary layers (in background)**
  – **Later eroded out and rolled downhill**



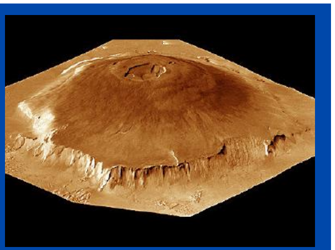
Mars' Hydrogen Content: further evidence of liquid water in the past

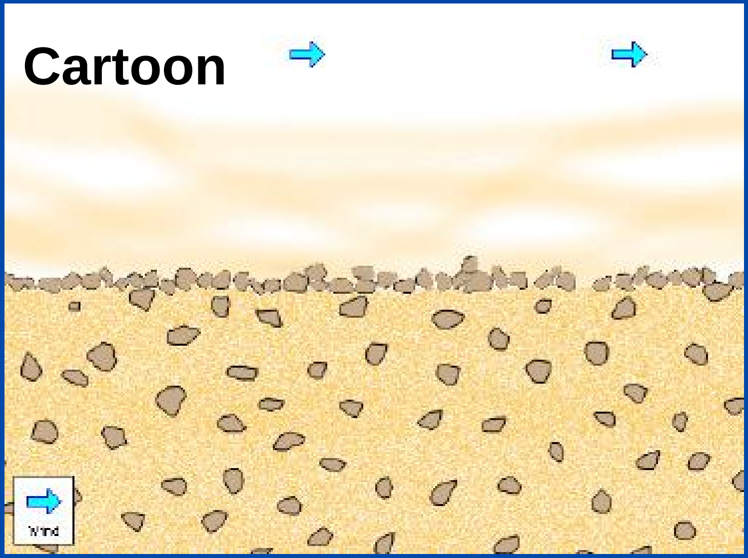


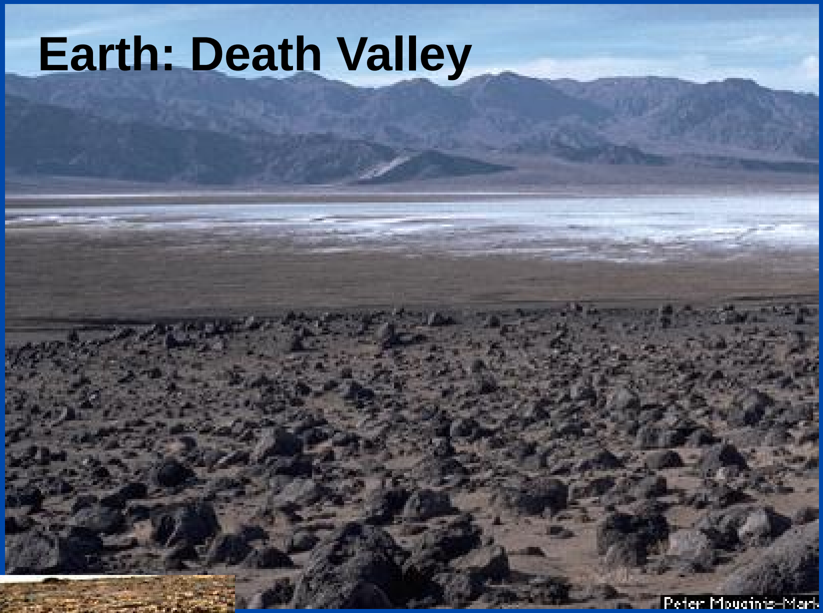


- **Map of hydrogen content (blue) shows that low-lying areas contain more water ice.**

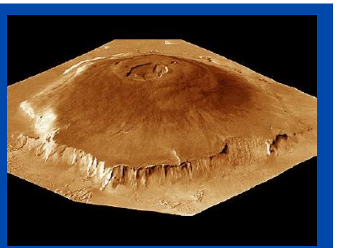
Erosion: desert pavement on Earth, Venus, Mars

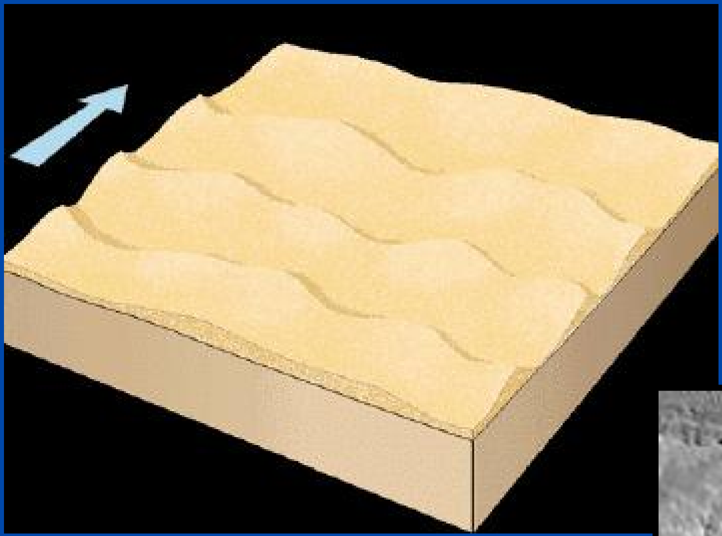


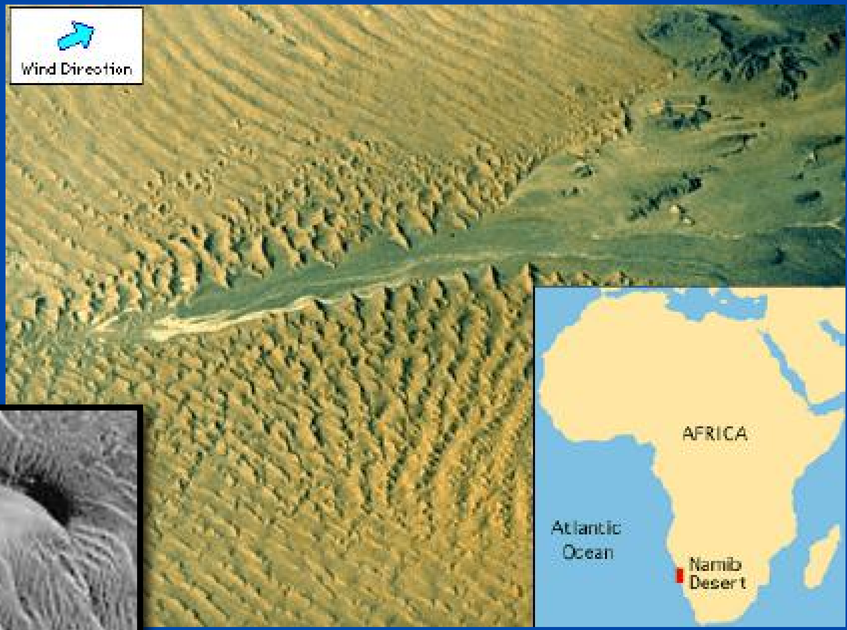




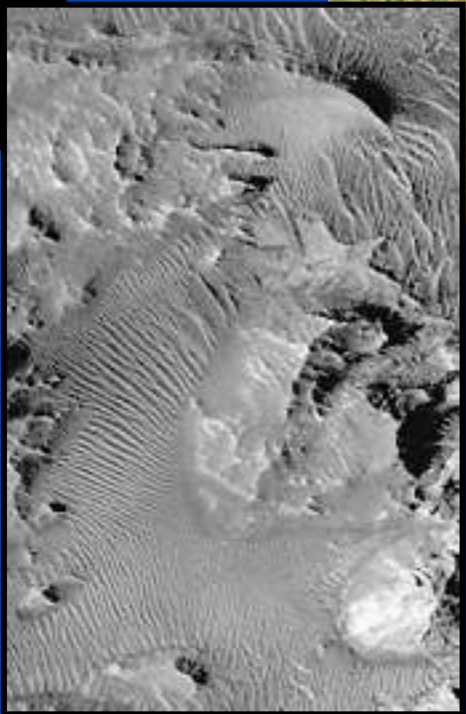
Erosion: transverse sand dunes





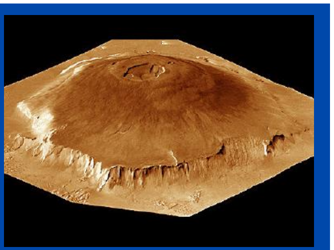


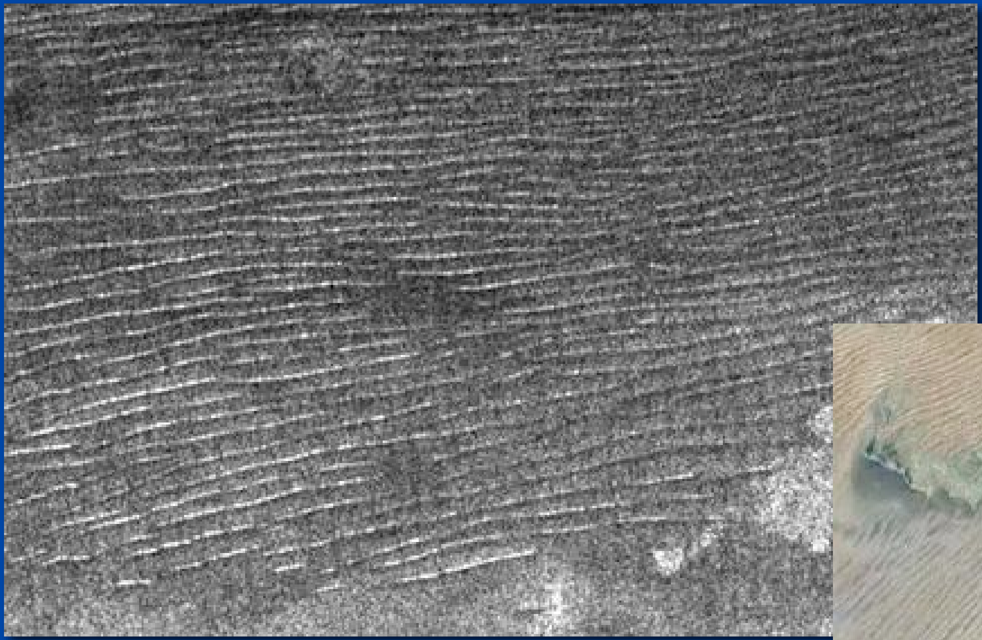
Earth: Namib desert



**Mars:
Hebes Casma dunes**

Dunes on Saturn's moon Titan

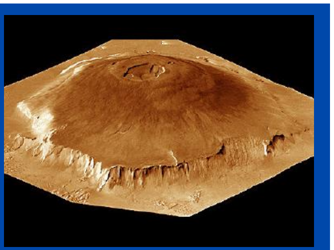


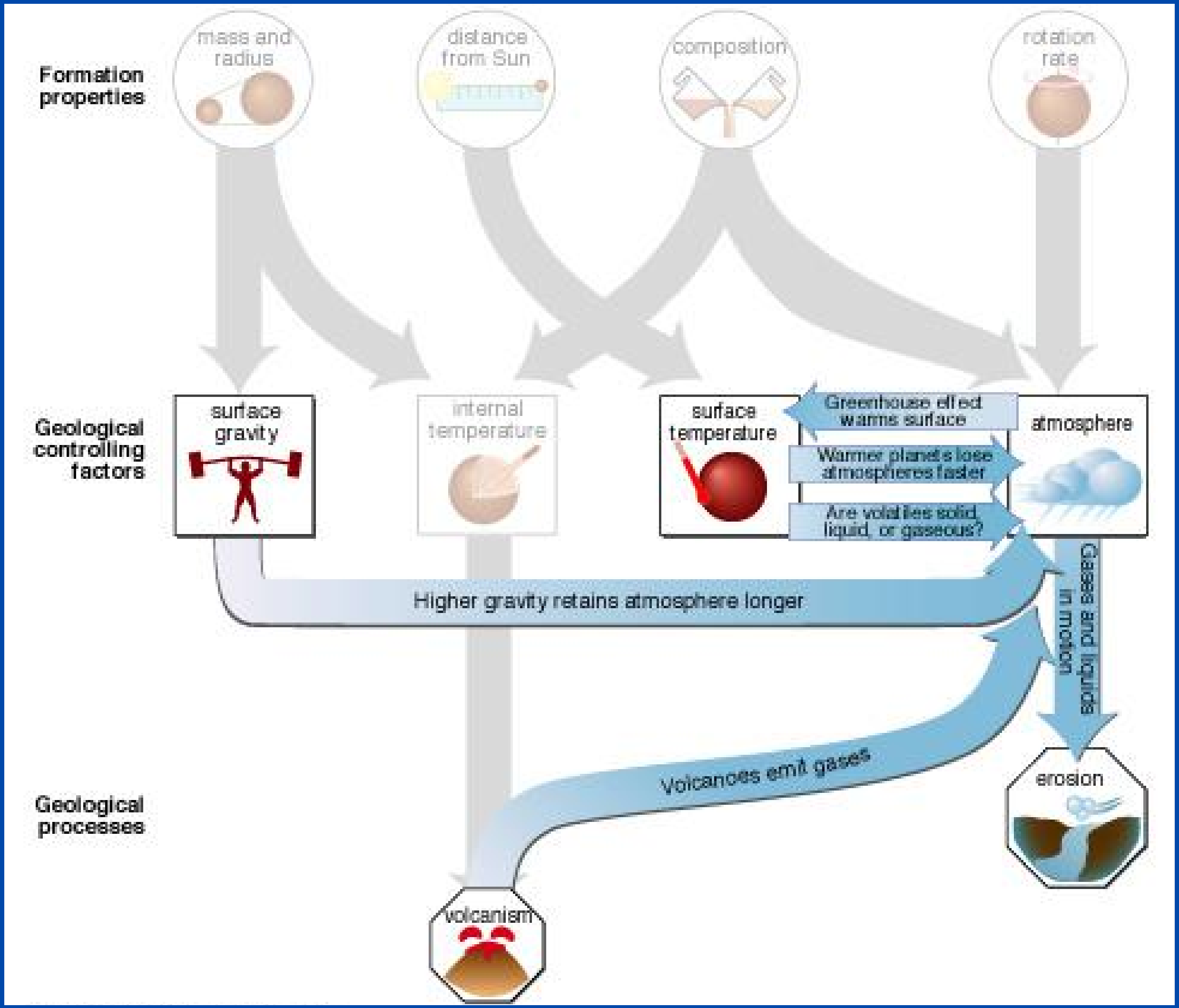


Titan dunes
(radar image)

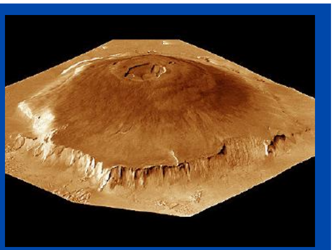
Earth dunes
in Yemen

Erosion: flow chart



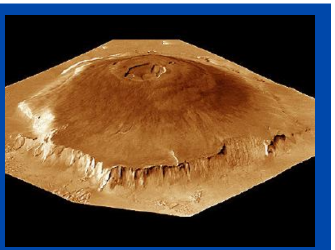


Concept Question



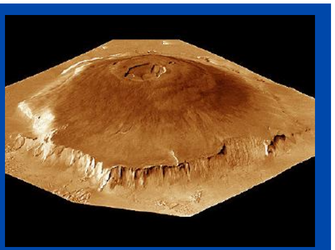
- Consider the four geological processes: cratering, volcanism, tectonics, erosion.
- Which two do you think are most closely connected with each other?
- Give several ways in which these processes are connected

What have we learned?



- **How do we know that Earth's surface is in motion?**
  - **Direct measurements of plate motion confirm idea of continental drift**
- **How is Earth's surface shaped by plate tectonics?**
  - **Plate tectonics responsible for subduction, seafloor spreading, mountains, rifts, and earthquakes**
- **Was Earth's geology destined from birth?**
  - **Many of Earth's features are determined by Earth's size, distance from Sun, and rotation rate**

The Main Points



- A few basic processes mold surfaces and interiors of terrestrial planets
- All terrestrial planets were once heavily cratered, but craters have since been erased on some
- Planet size influences volcanism, tectonics; atmosphere influences erosion
- General features should be same in other solar systems, not just our own