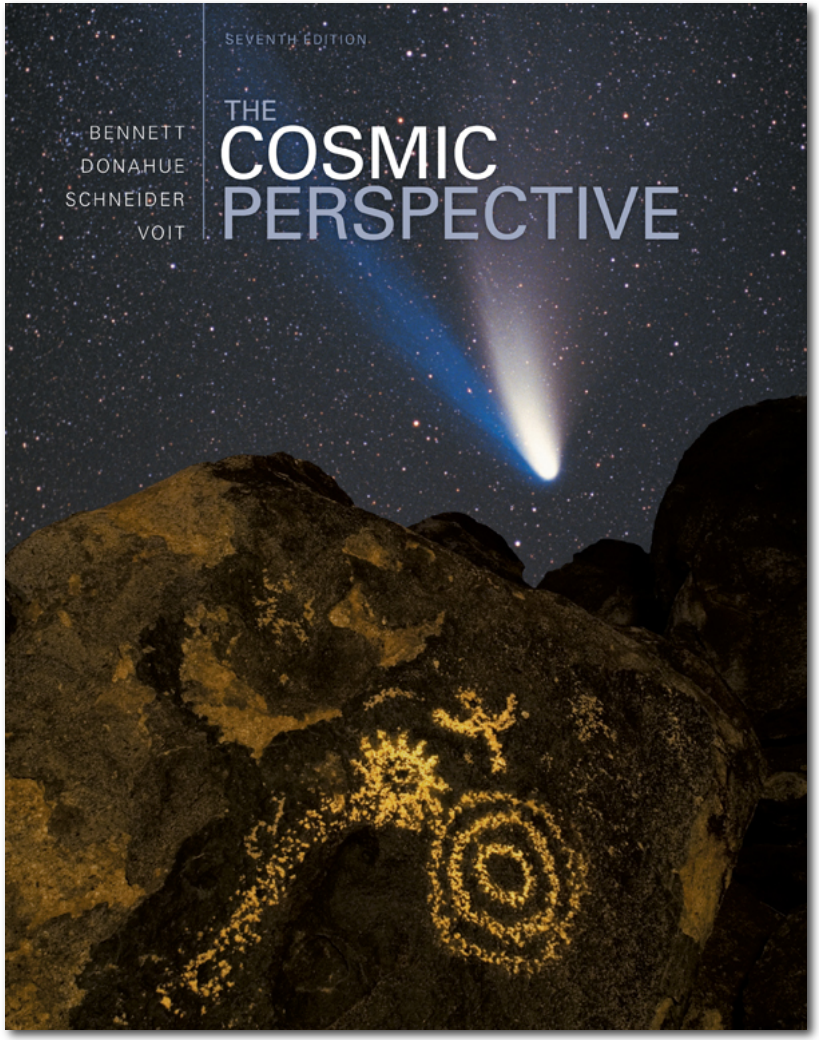
Chapter 9 Lecture

The Cosmic Perspective

Seventh Edition



Planetary Geology: Earth and the Other Terrestrial Worlds

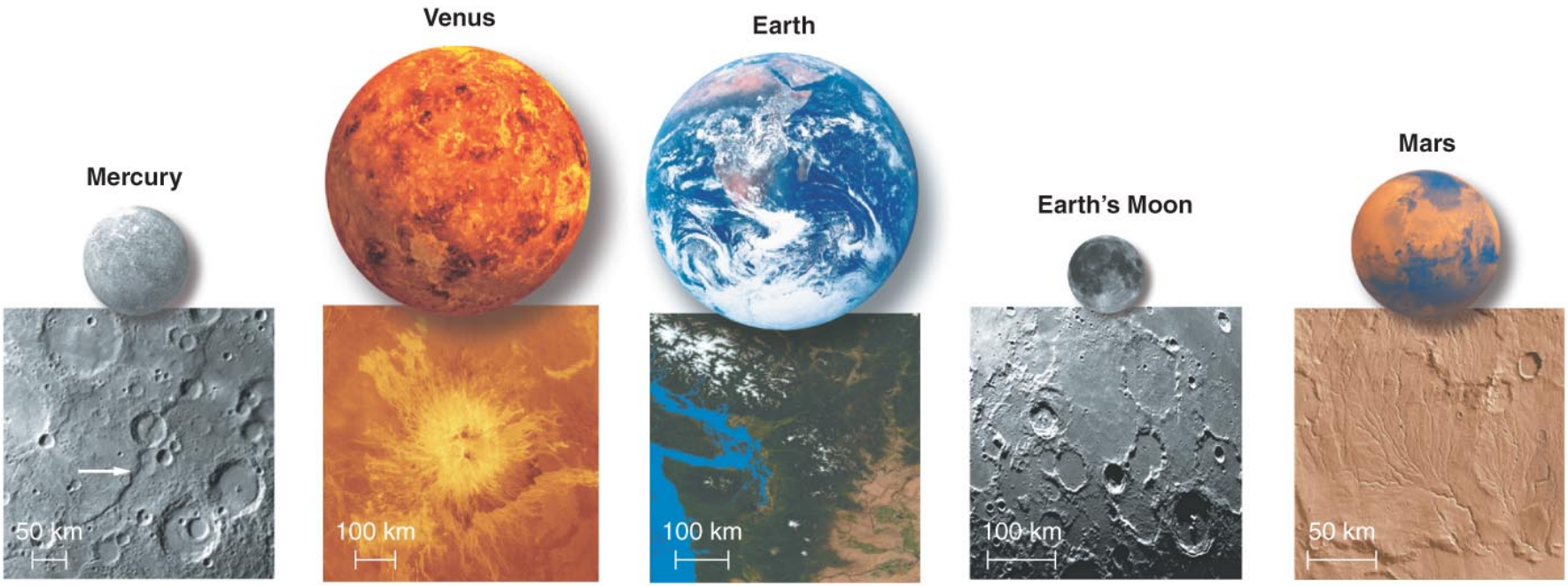
Planetary Geology: Earth and the Other Terrestrial Worlds

9.1 Connecting Planetary Interiors and Surfaces

- Our goals for learning:
  - **How did the surface differences of the planets come to be?**
  - **What causes geological activity?**
  - **Why do some planetary interiors create magnetic fields?**

How did the surface differences of the planets come to be?

Many of the geological features are shaped by geological processes that take place in the interior.



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.

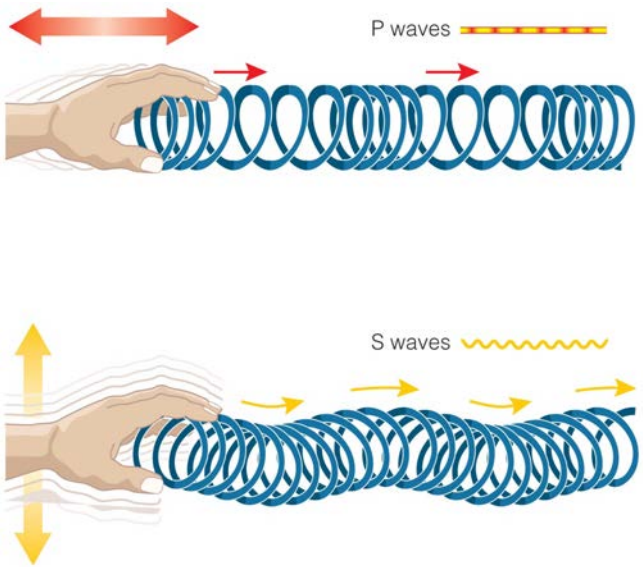
Mars has features that look like dry riverbeds; note the impact craters.

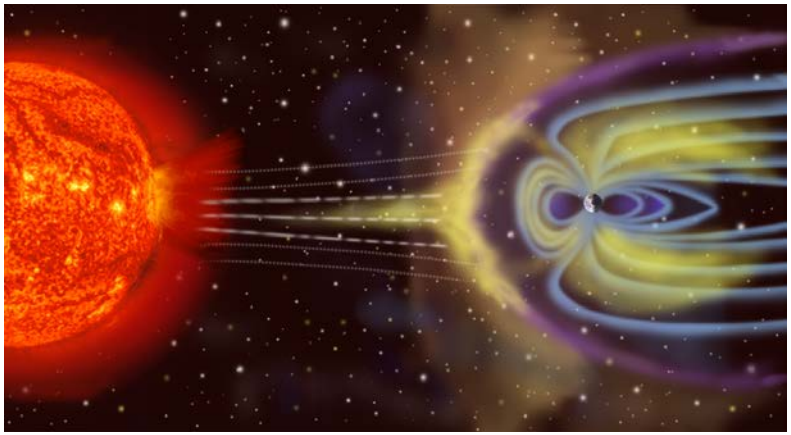
Information about the Interior

1. Seismic Waves. Vibrations that travel through Earth's interior tell us what Earth is like on the inside.

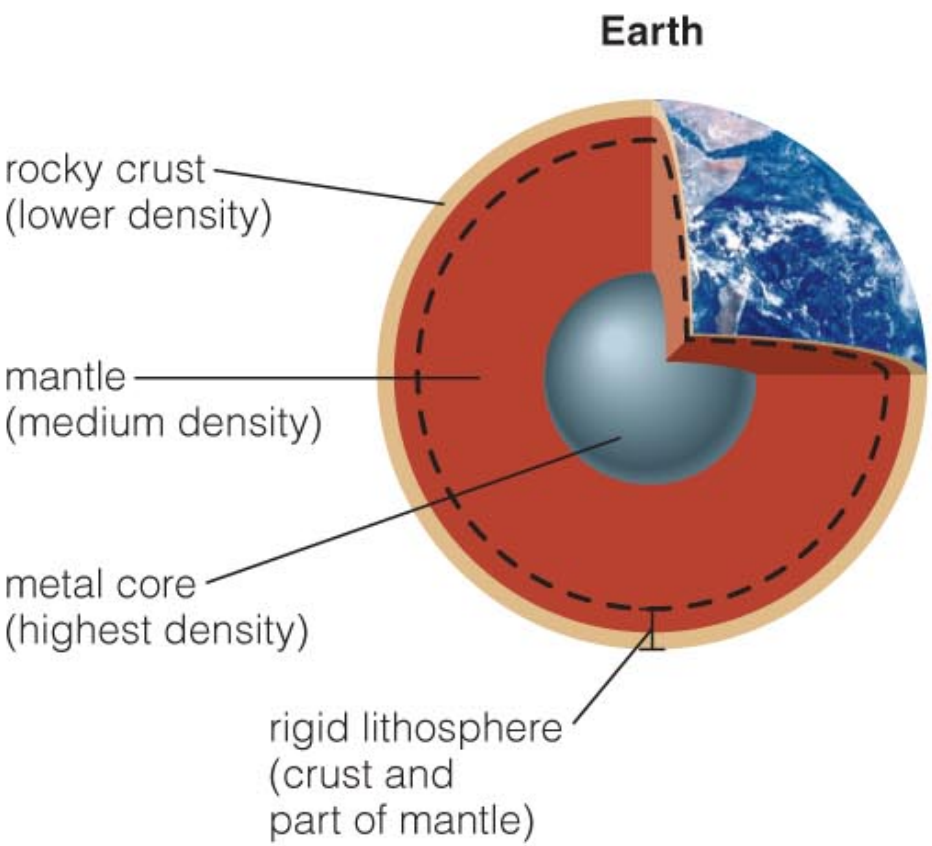
2. Comparing surface density of rocks with the average density of planet.

3. The strength of a planets magnetic field can tell us about its interior



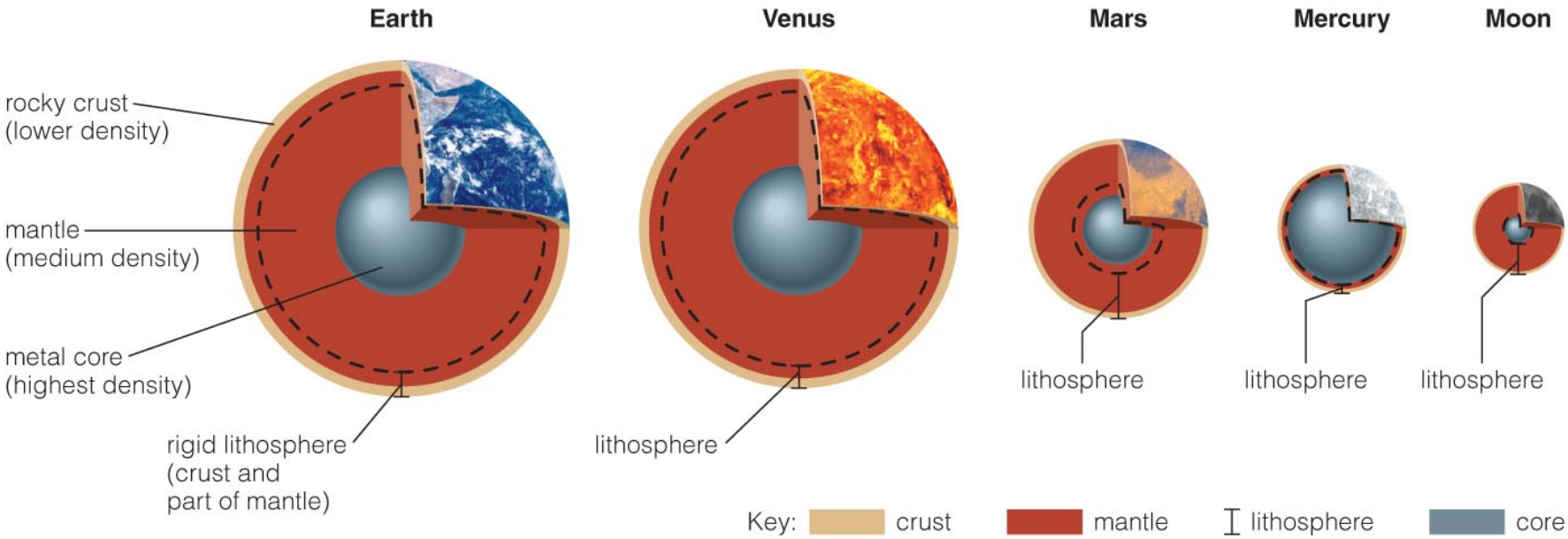


Earth's Interior



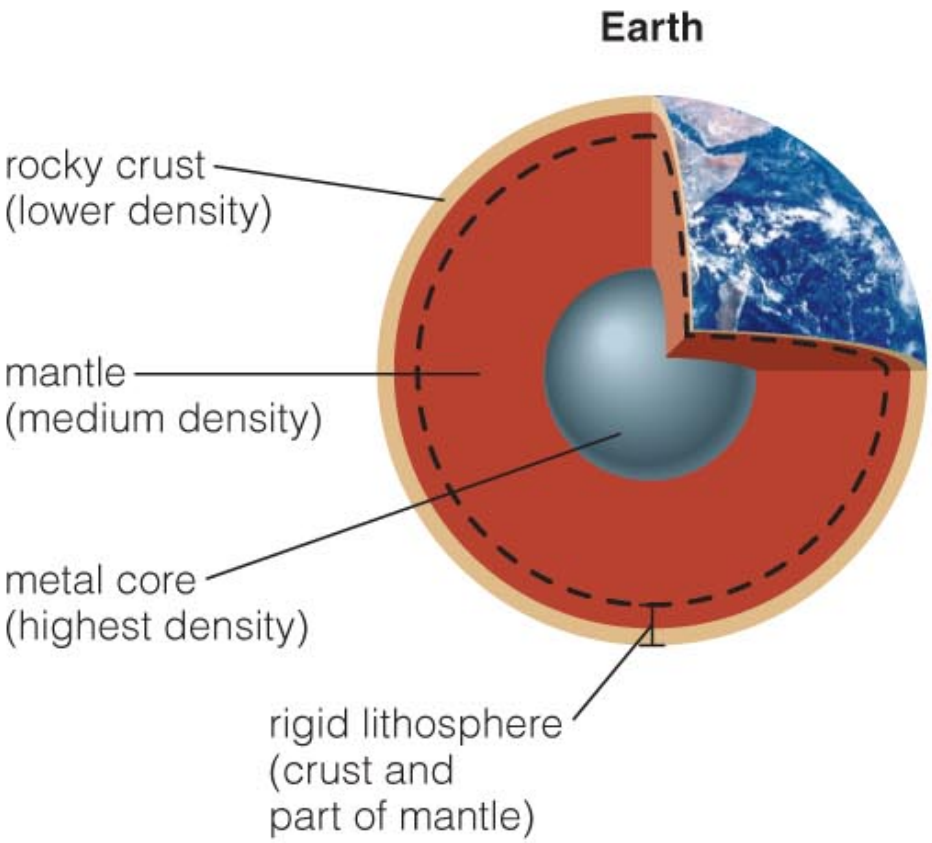
- **Core:** highest density; nickel and iron
- **Mantle:** moderate density; silicon, oxygen, etc.
- **Crust:** lowest density; granite, basalt, etc.

Terrestrial Planet Interiors



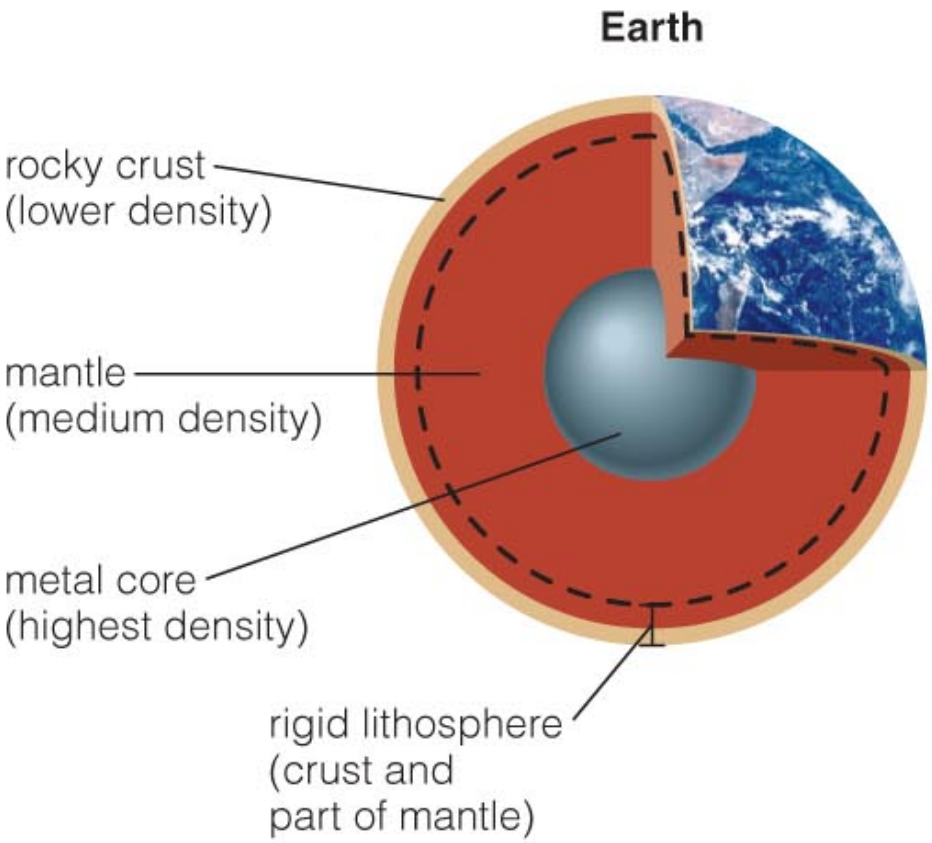
- Applying what we have learned about Earth's interior to other planets tells us what their interiors are probably like.

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.

Why Big Worlds Are Round

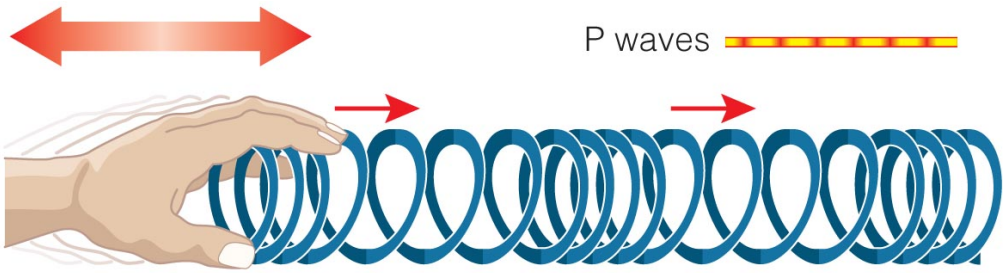
- The weak gravity of a small object is unable to overcome the rigidity of its rocky material

- For a large object gravity can overcome the strength of a solid rock, slowly deforming and molding it into a spherical shape.

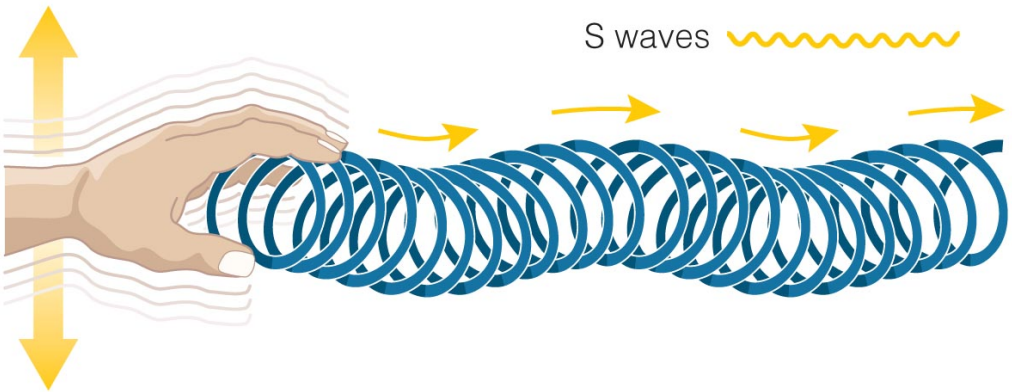
- Gravity will make a rocky object bigger than ~ 500 km in diameter into a sphere within 1 billion years.

Special Topic:

How do we know what's inside Earth?



- P waves push matter back and forth.

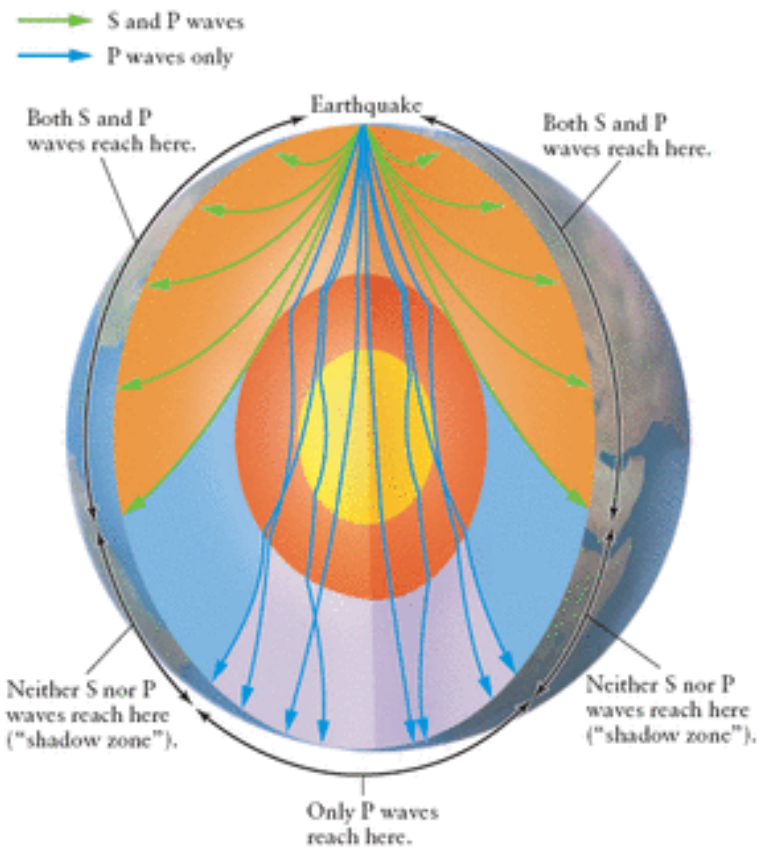


- S waves shake matter side to side

Earth's Interior Structure From Seismic Waves

When an earthquake goes off seismographs located close to the epicenter record both S and P waves. **Seismographs,** however, on the opposite side of the planet do not record any S waves.

Geologist Richard Oldham first realized that this is explained because transverse oscillations like **S waves cannot travel through liquid** and therefore the Earth must contain a **liquid core**.

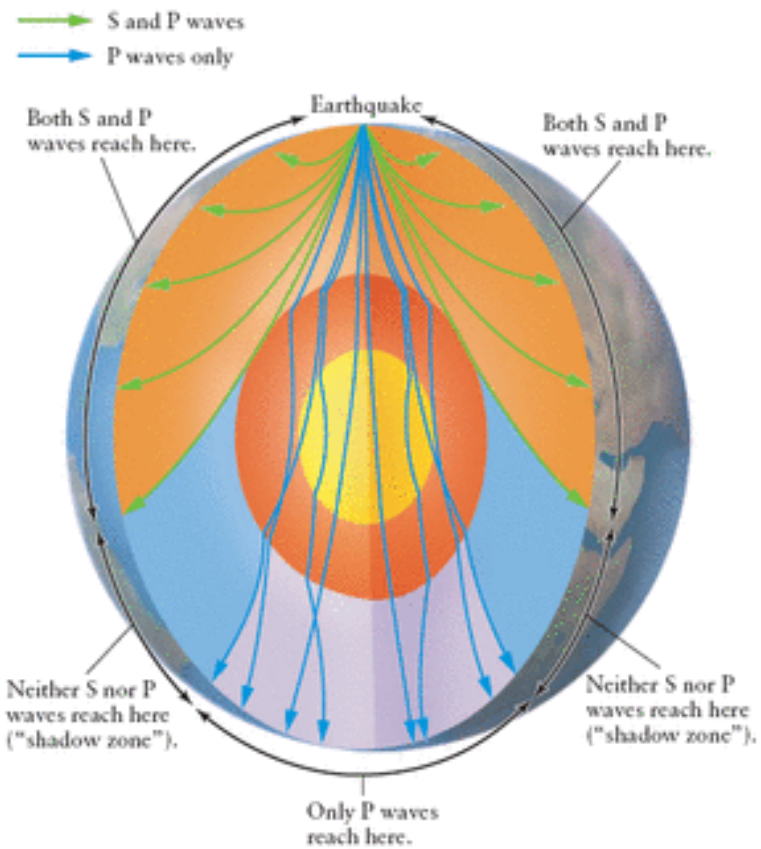


Earth’s Interior Structure From Seismic Waves

For a given earthquake there is a region on the Earth's surface called the “**shadow zone**” where neither S or P waves are recorded.

The “shadow zone” is caused by the **refraction** of P waves (their directions change) at the boundary between the solid mantle and the liquid iron core.

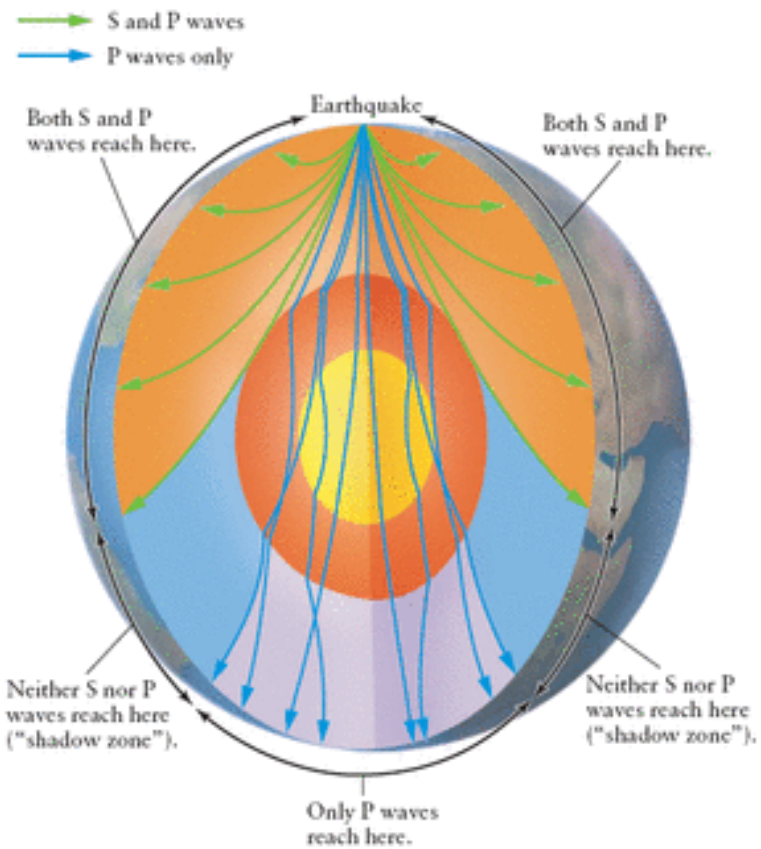
Liquid Core Radius ~ 3500 km



Earth's Interior Structure From Seismic Waves

Later on the Danish geologist Inge Lehmann explained that the detection of very faint P waves in the "shadow zone" is caused by the **deflection of P waves off a solid iron core in the center**.

Radius of iron solid core = 1300 km



Earth's Interior Structure From Seismic Waves

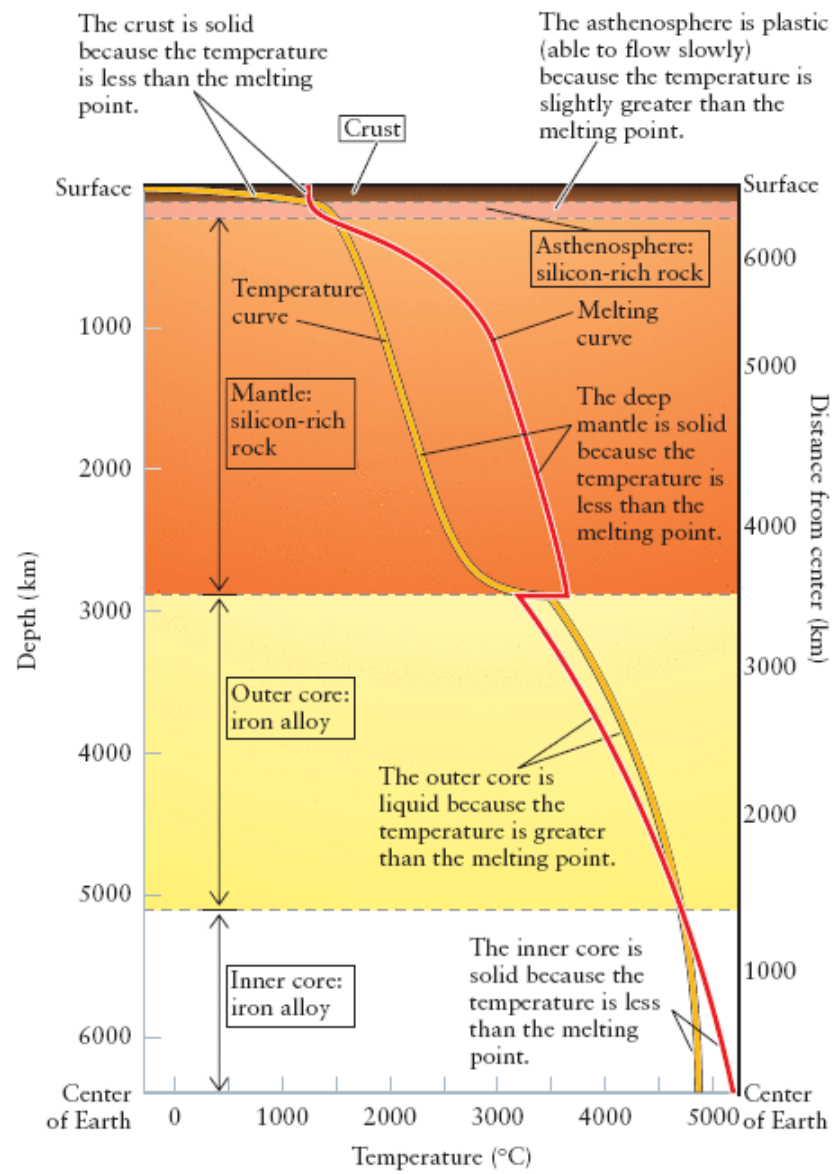
Crust: 0 – 35 km, rocks

Asthenosphere: silicon-rich
$T_{asthenosphere} \geq T_{melt}$ **(plastic)**

Mantle : 35 – 2900 km
Silicon-rich
$T_{Mantle} < T_{melt}$ **(solid)**

Outer Core: 2900 km – 5100 km
Iron-rich with some nickel
$T_{Outer\_core} > T_{melt}$ **(liquid)**

Inner Core: 5100 km – 6400 km
Iron-rich with some nickel
$T_{inner\_core} < T_{melt}$ **(solid)**



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

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

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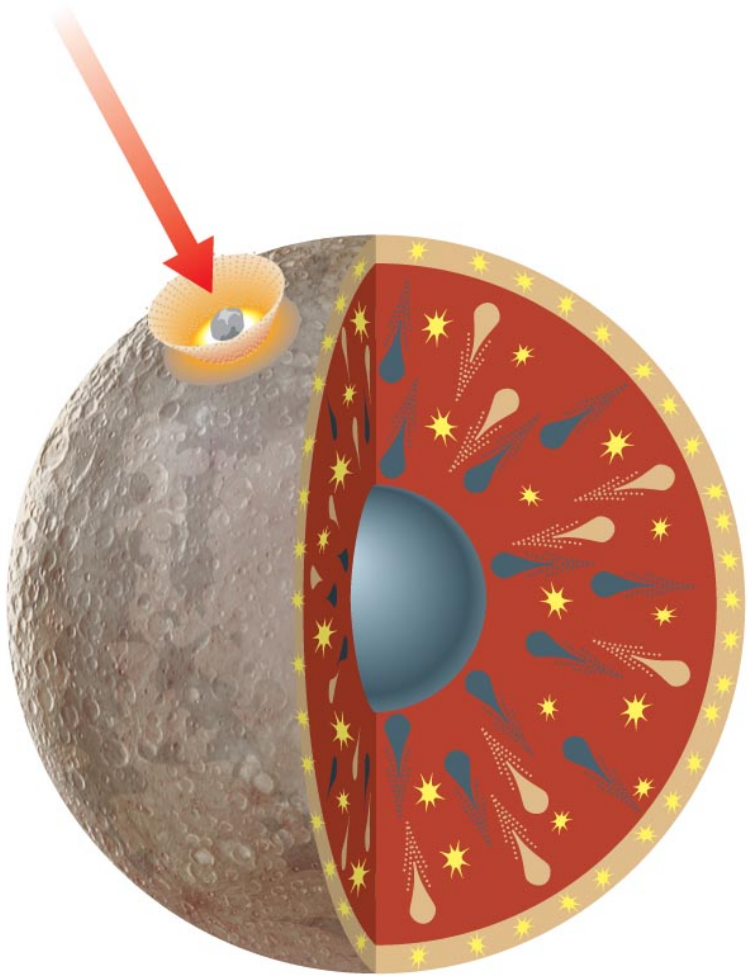
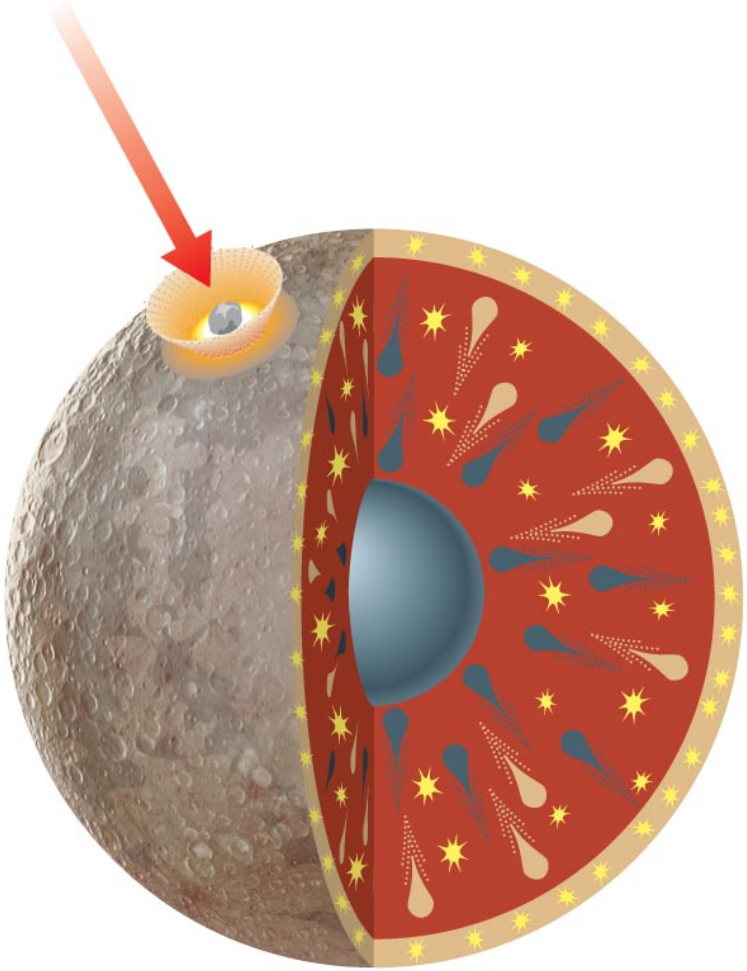
What is the source of energy that drives geological activity?

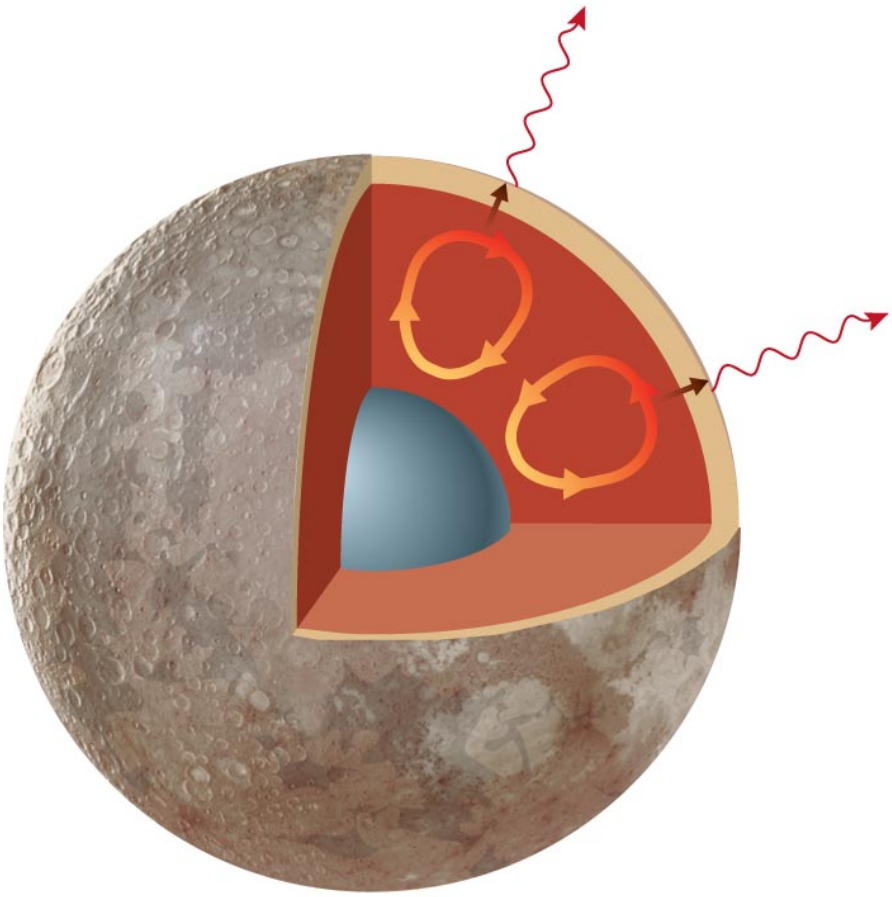


Heating of Planetary Interiors Drives Geological Activity



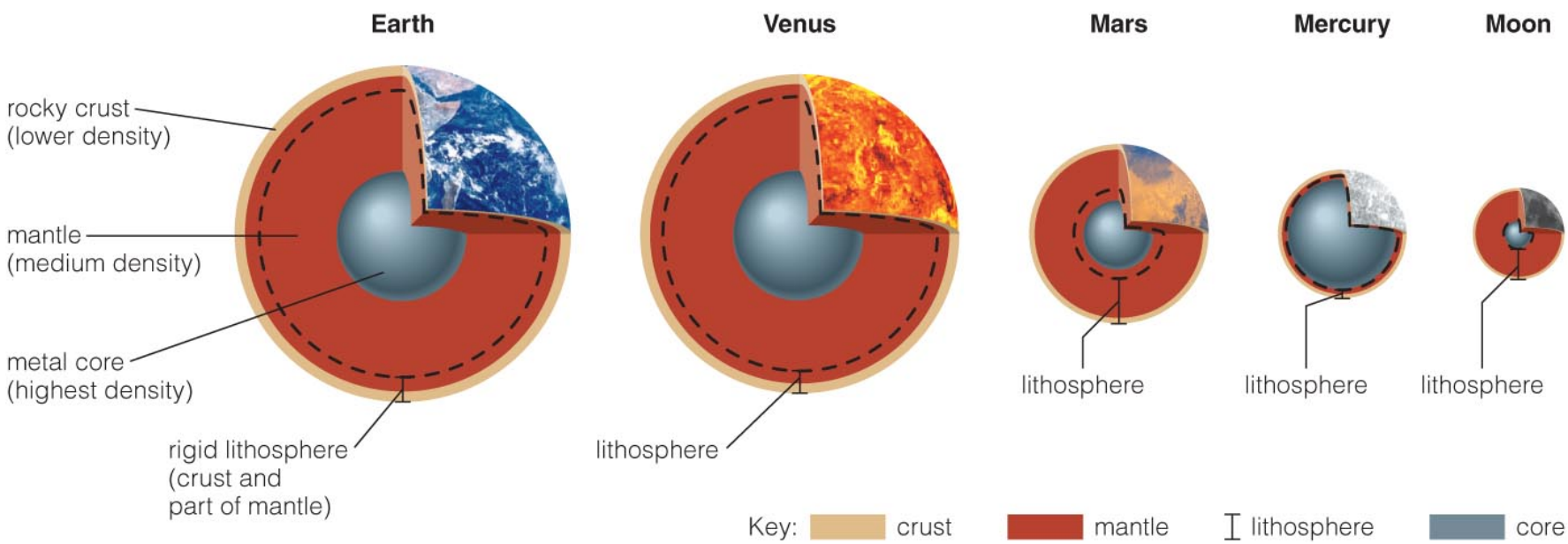
- Accretion and differentiation when planets were young
- Radioactive decay is the most important heat source today.

How Do Planetary Interiors Cool



- **Convection** transports heat as hot material rises and cool material falls.
- **Conduction** transfers heat from hot material to cool material.
- **Radiation** sends energy into space.

Role of Size on Cooling Time

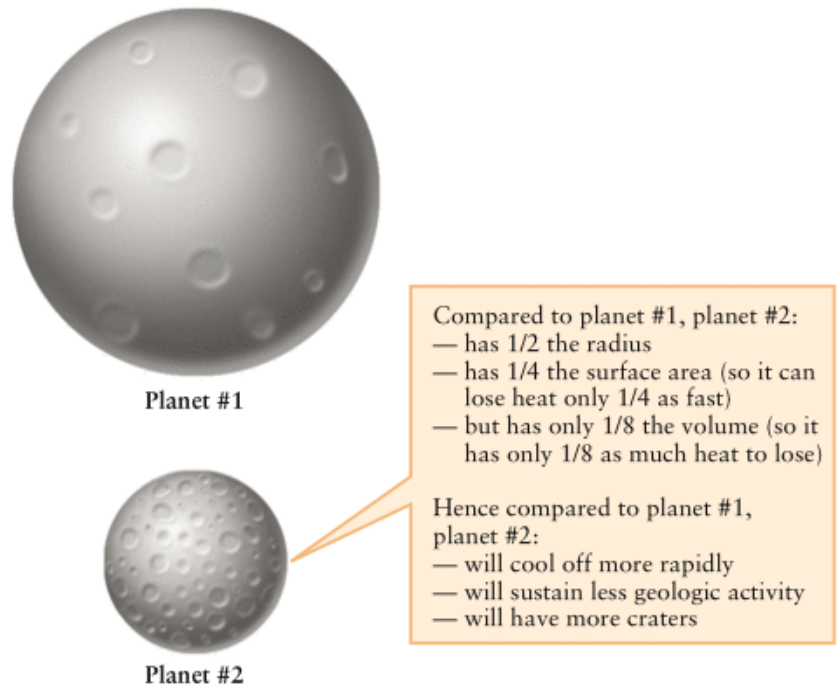


- Smaller worlds cool off faster and harden earlier.
- The Moon and Mercury are now geologically "dead."

How long does it take for a planet to cool

When a planet cools down it becomes geologically inactive

$$t_{cool} \approx \frac{E_{Total}}{\Delta E / \Delta t} \propto \frac{Volume}{Area} \propto Radius$$

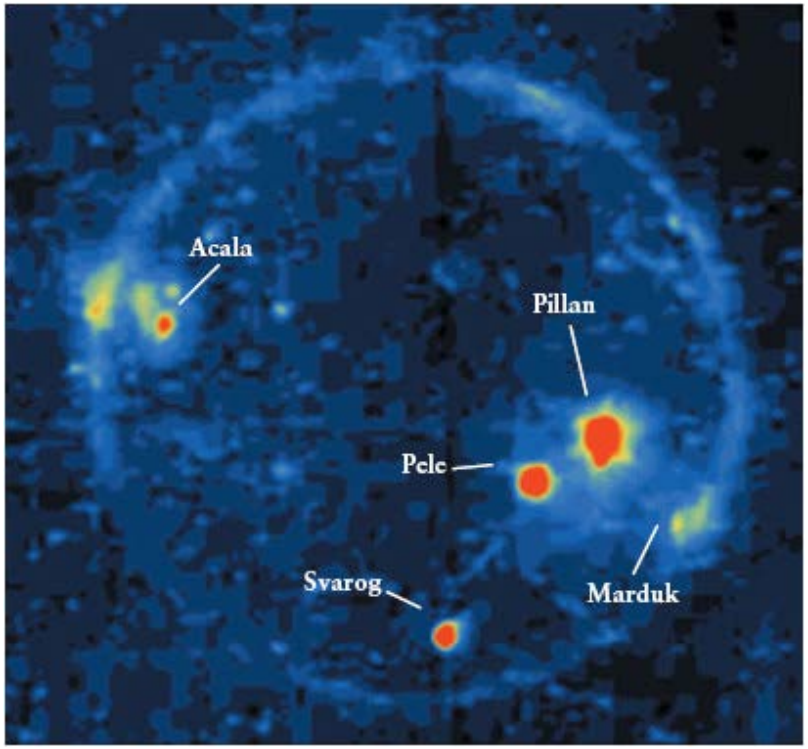


where $\Delta E/\Delta t$ is the rate of energy loss.
Since R_{moon} ~1738 km and R_{earth} ~6378 km the cooling time for Earth is longer.

How long does it take for a planet to cool

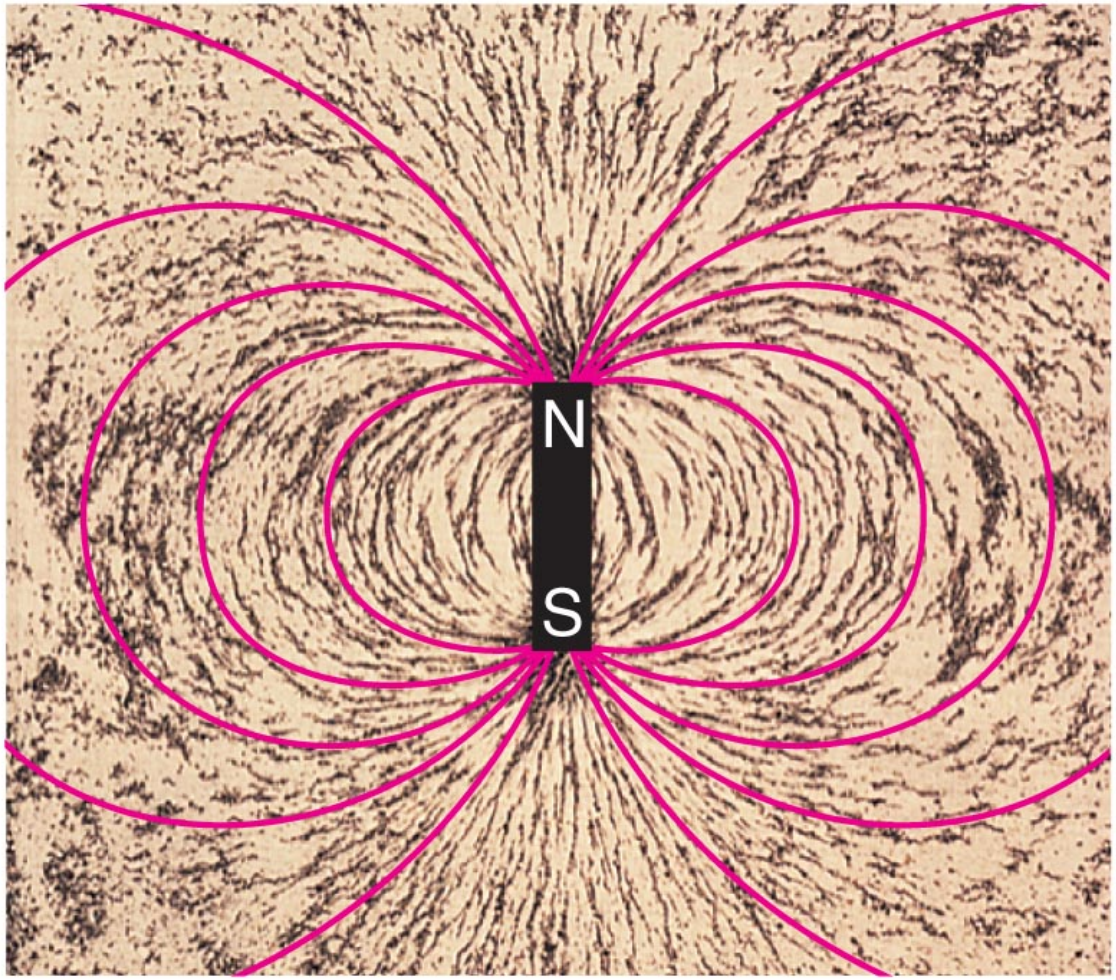
When a planet cools down it becomes geologically inactive

There are exceptions to the $t_{cool} \sim R$ rule. The cooling time will depend on the chemical composition of the planet, the initial temperature, and the presence of any external sources of energy.

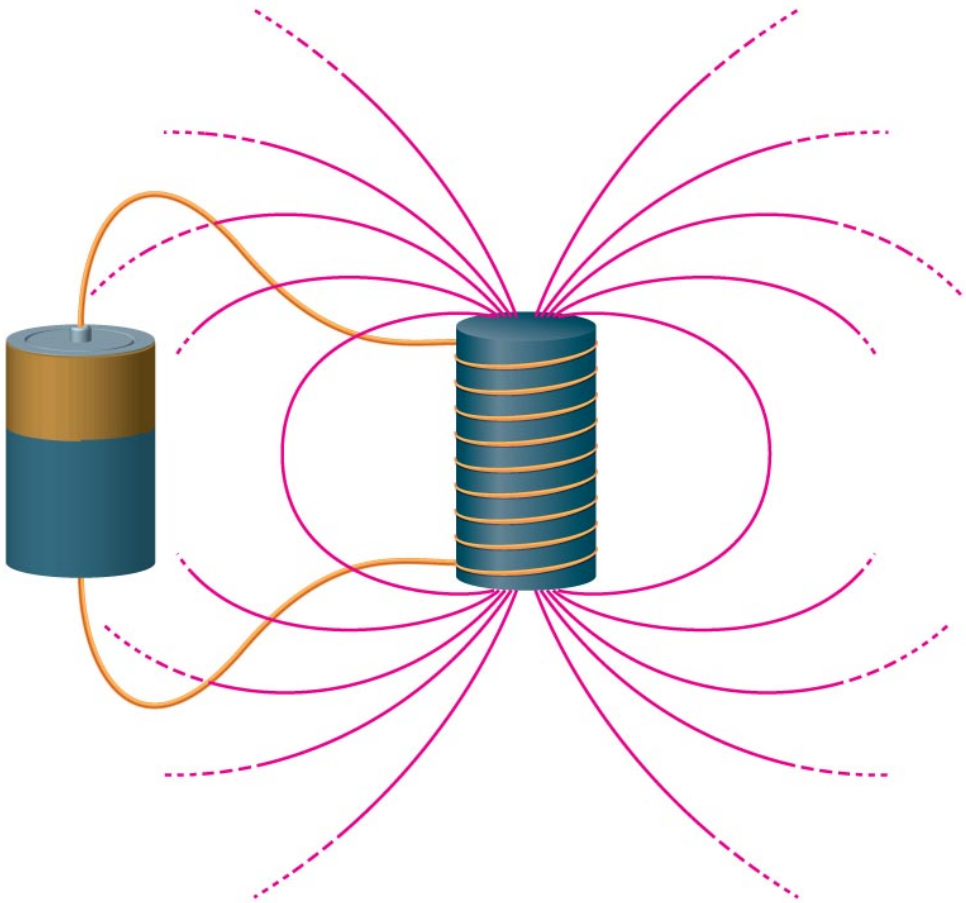


Jupiter's moon Io with a radius of only 1821 km is very geologically active. The reason for this is that Jupiter exerts strong tidal forces on Io resulting in the heating of its interior.

Why do some planetary interiors create magnetic fields?

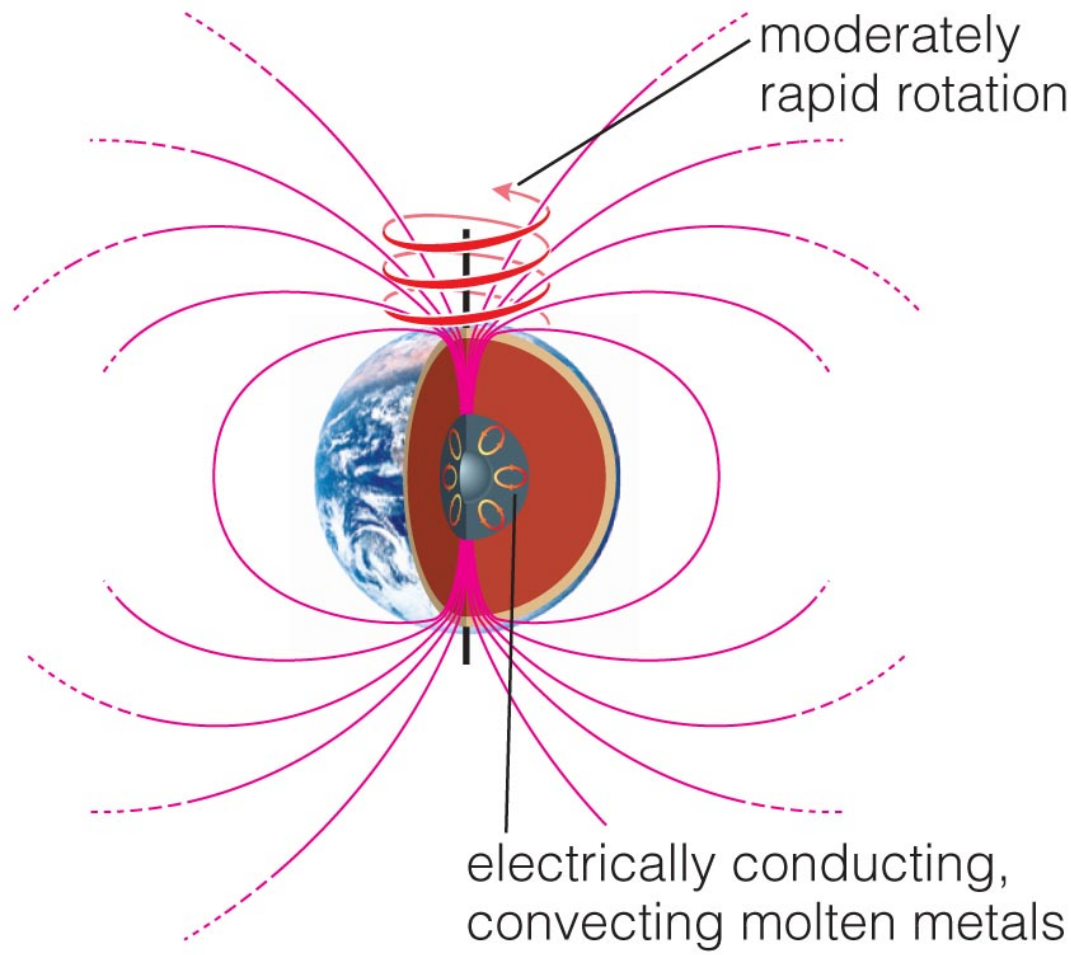


Sources of Magnetic Fields



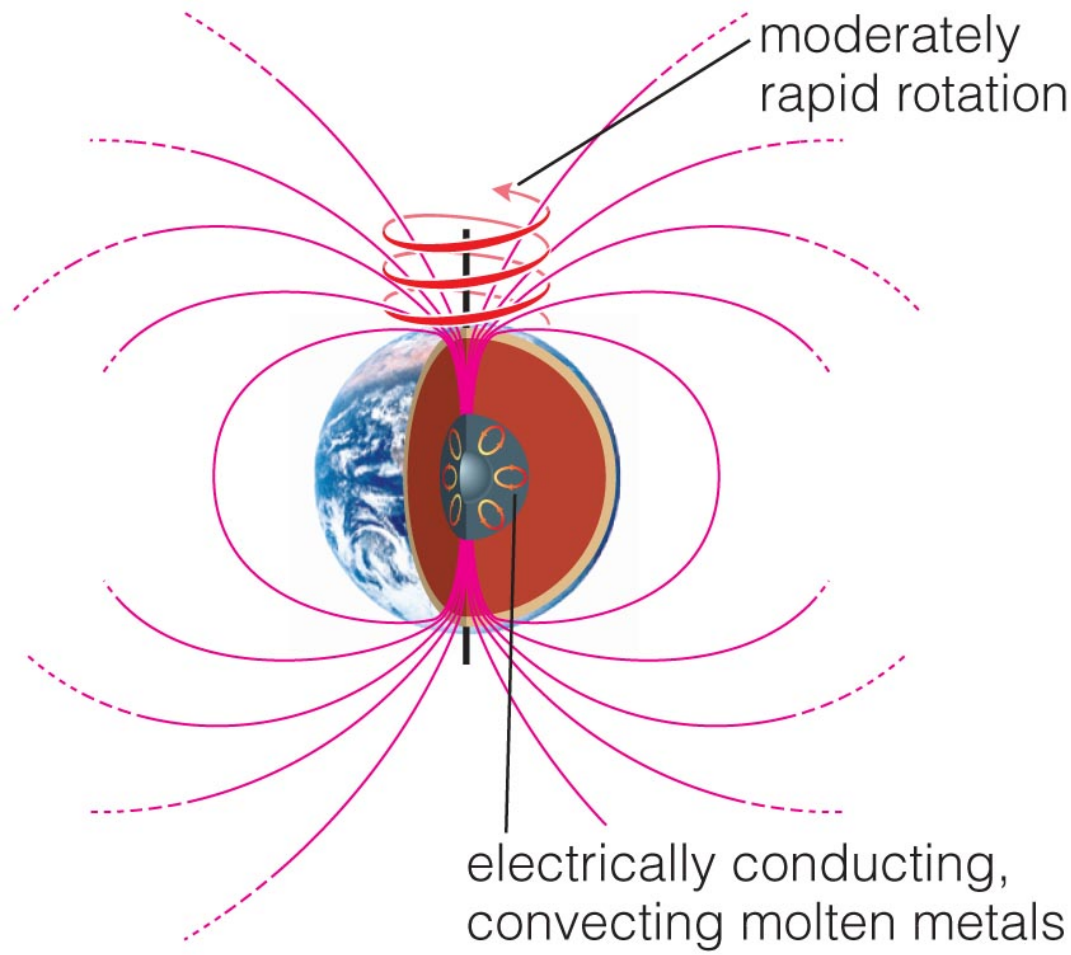
- Motions of charged particles are what create magnetic fields.

Sources of Magnetic Fields



- A planet can have a magnetic field if charged particles are moving inside.
- Three requirements:
  - Molten, electrically conducting interior
  - Convection
  - Moderately rapid rotation

Sources of Magnetic Fields



- The **Earth's** magnetic field is produced by electric currents in the liquid portion of our planet's interior.
- **Mercury** has a weak magnetic field 1% of that of Earths.
- **Venus** has almost no magnetic field even though it is geologically active (hint: rotational period = 243 days).

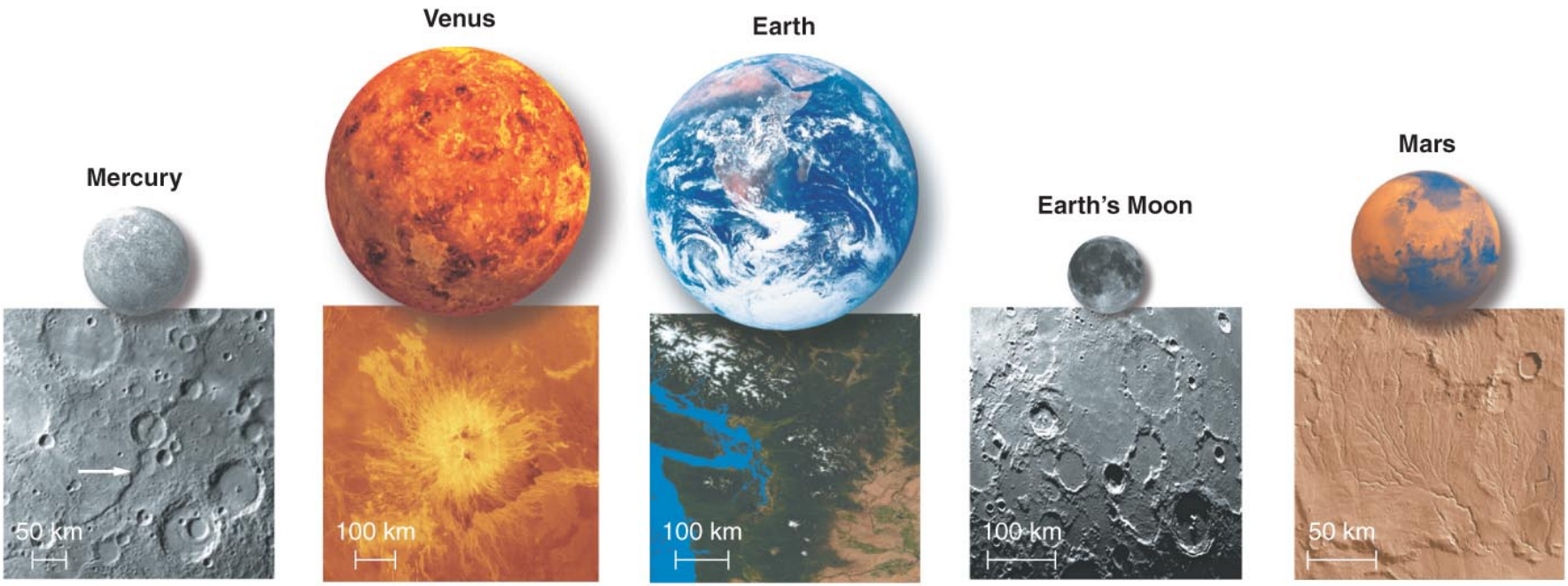
What have we learned?

- **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

9.2 Shaping Planetary Surfaces

- Our goals for learning:
  - **What processes shape planetary surfaces?**
  - **How do impact craters reveal a surface's geological age?**
  - **Why do the terrestrial planets have different geological histories?**

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.

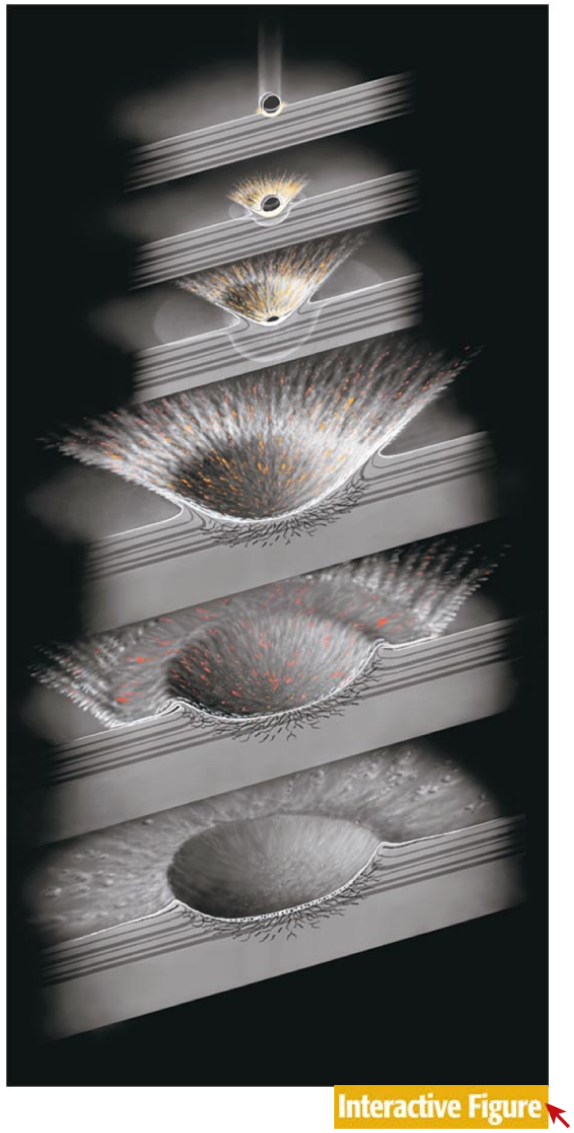
The Moon's surface is heavily cratered in most places.

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

Processes That Shape Surfaces

- Impact cratering
  - Impacts by asteroids or comets
- Volcanism
  - Eruption of molten rock onto surface
- Tectonics
  - Disruption of a planet's surface by internal stresses
- Erosion
  - Surface changes made by wind, water, or ice

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 Craters

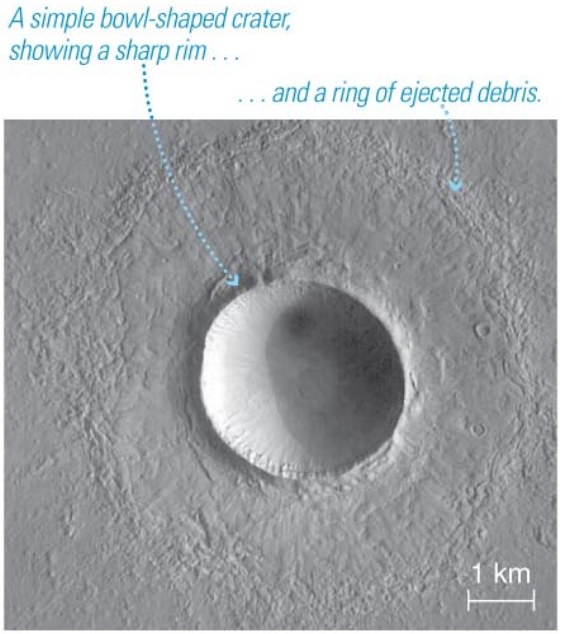
a Meteor Crater in Arizona is more than a kilometer across and almost 200 meters deep. It was created around 50,000 years ago by the impact of a metallic asteroid about 50 meters across.

b This photo shows a crater, named Tycho, on the Moon. Note the classic shape and central peak.

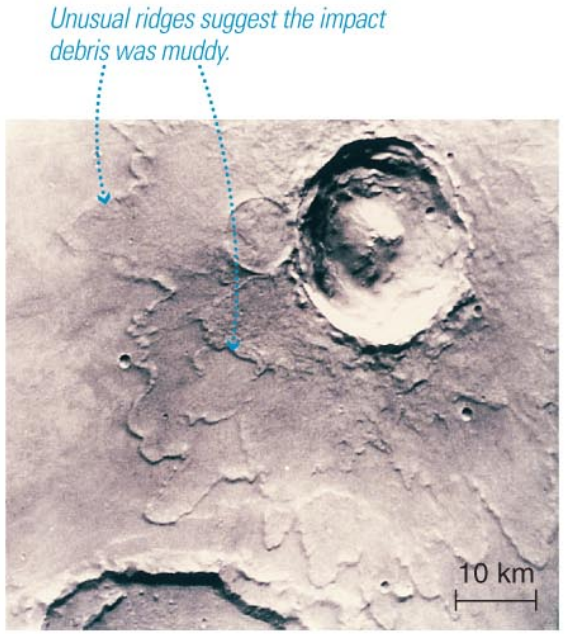
Meteor Crater (Arizona)

Tycho Crater (Moon)

Impact Craters on Mars



a A crater with a typical bowl shape.



b This crater was probably made by an impact into icy ground.

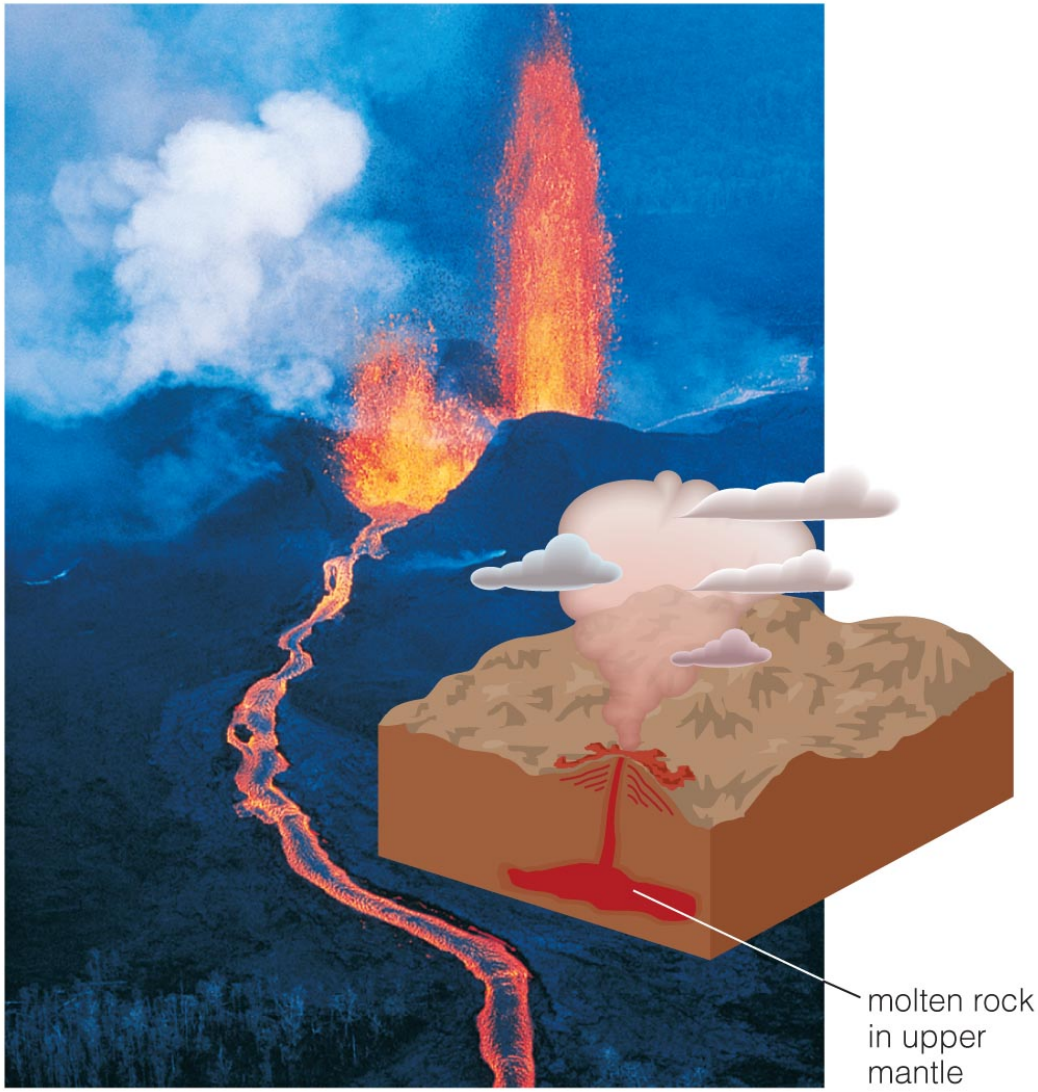
c This crater shows evidence of erosion.

"Standard" crater

Impact into icy ground

Eroded crater

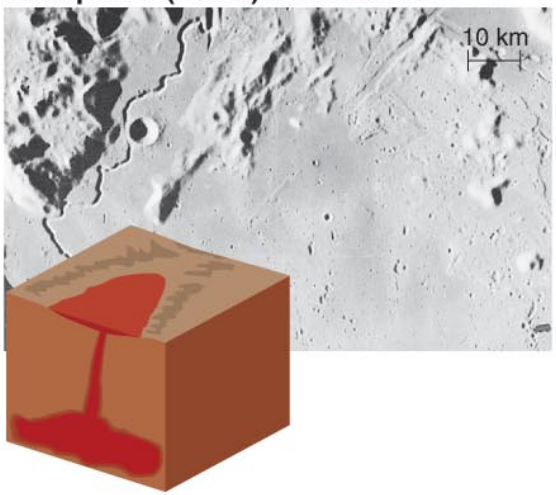
Volcanism



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

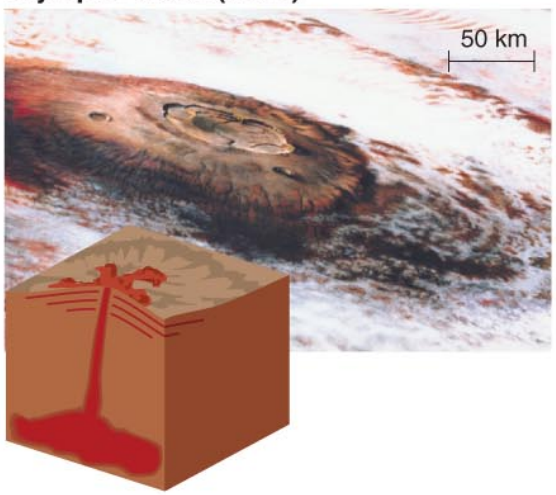
Lava and Volcanoes

Lava plains (maria) on the Moon



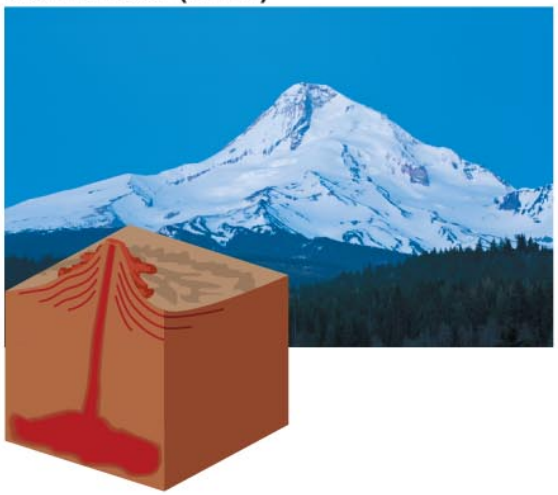
a Very runny lava makes flat lava plains like these on the Moon. The long, winding channel near the upper left was made by a river of molten lava.

Olympus Mons (Mars)



b Slightly thicker lava makes shallow-sloped shield volcanoes, such as Olympus Mons on Mars.

Mount Hood (Earth)



c The thickest lavas make steep-sloped stratovolcanoes like Oregon's Mount Hood.

Runny lava makes flat lava plains.

Slightly thicker lava makes broad *shield volcanoes*.

Thickest lava makes steep *stratovolcanoes*.

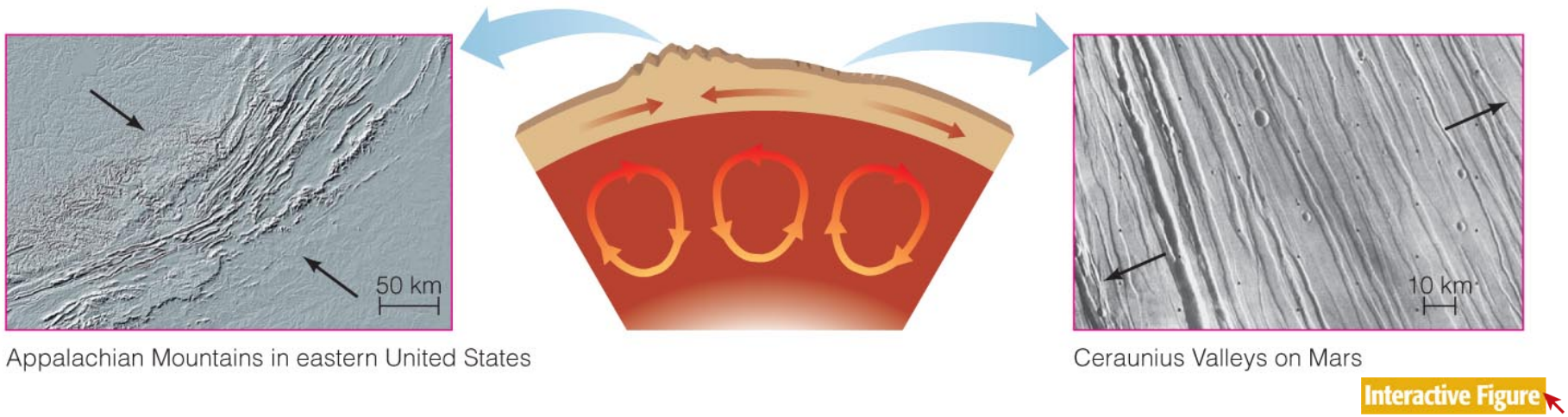
Outgassing

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

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

- Volcanism also releases gases from Earth's interior into the atmosphere.

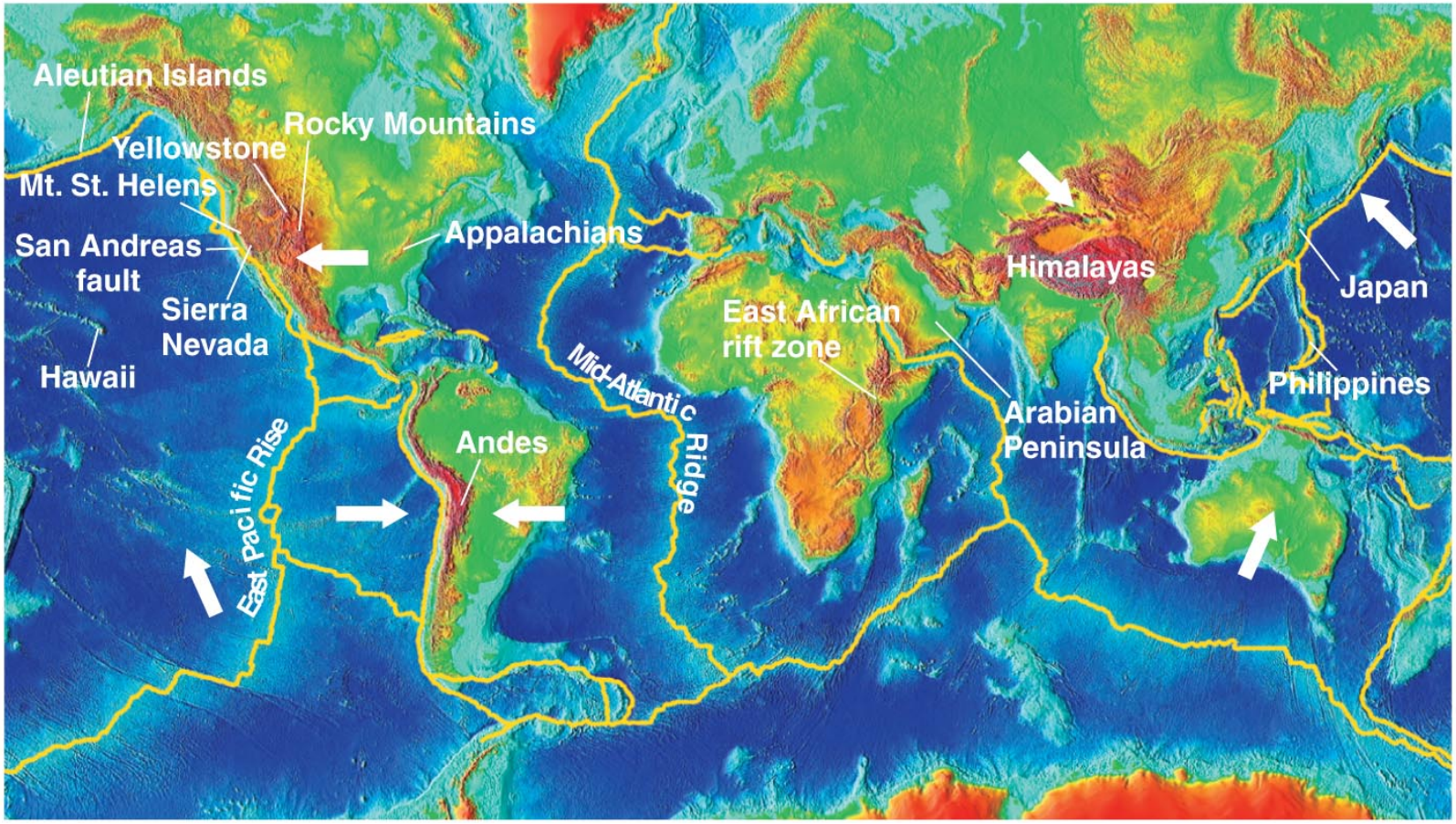
Tectonics



- 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.

Plate Tectonics on Earth

- Earth's continents slide around on separate plates of crust. Earthquakes and volcanoes tend to occur at the boundaries of the Earth's crustal plates, where the plates are colliding, separating, or rubbing against each other.



Erosion

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

Erosion by Water

- The Colorado River continues to carve Grand Canyon.

Erosion by Ice

- Glaciers carved the Yosemite Valley.

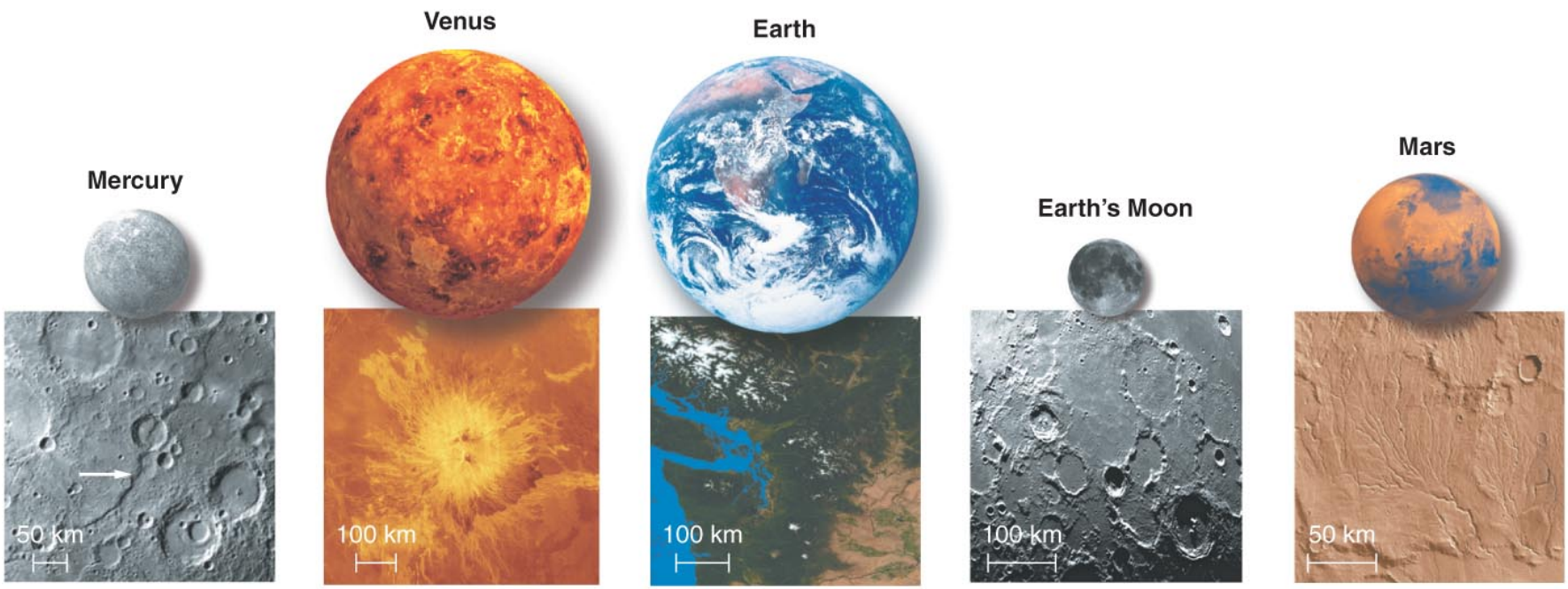
Erosion by Wind

- Wind wears away rock and builds up sand dunes.

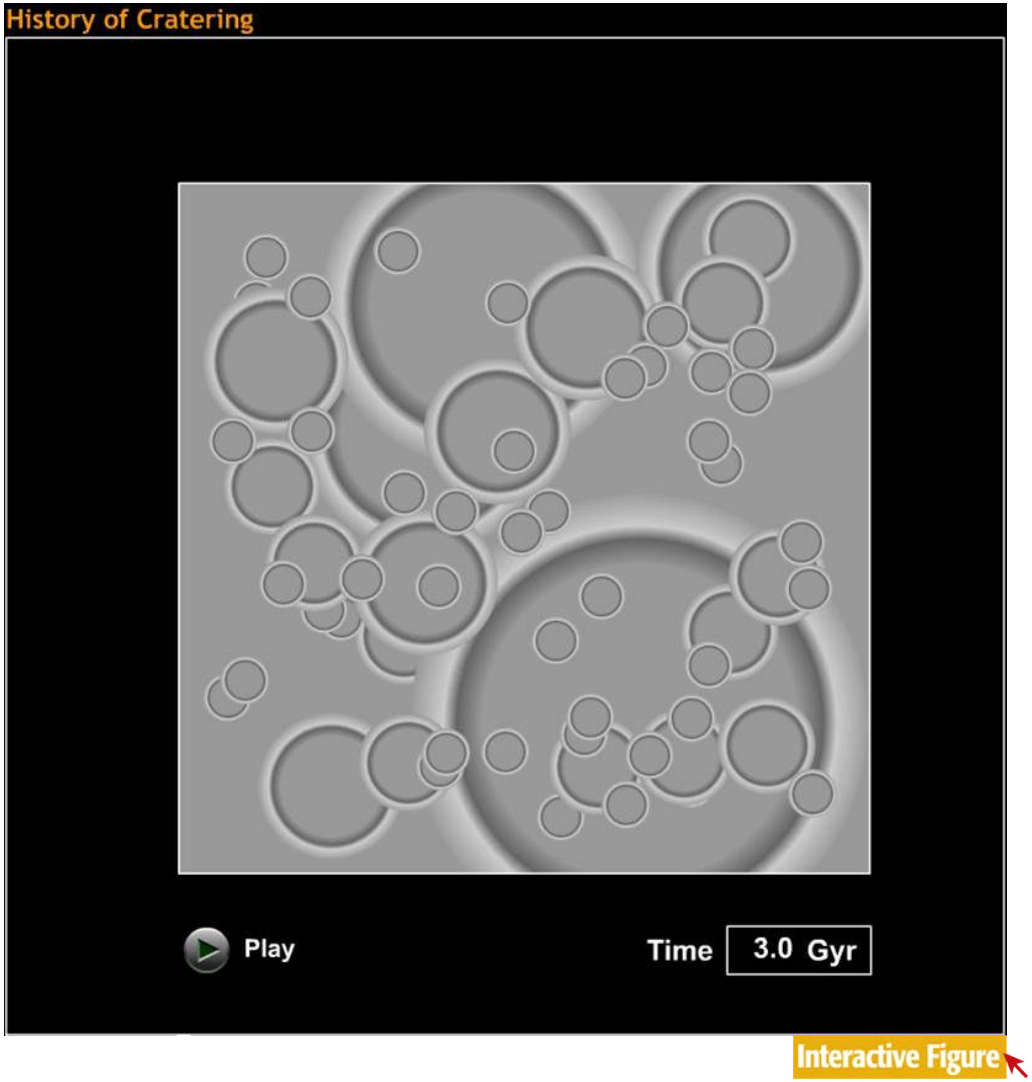
Erosional Debris

- Erosion can create new features such as deltas by depositing debris.

How do impact craters reveal a surface's geological age?

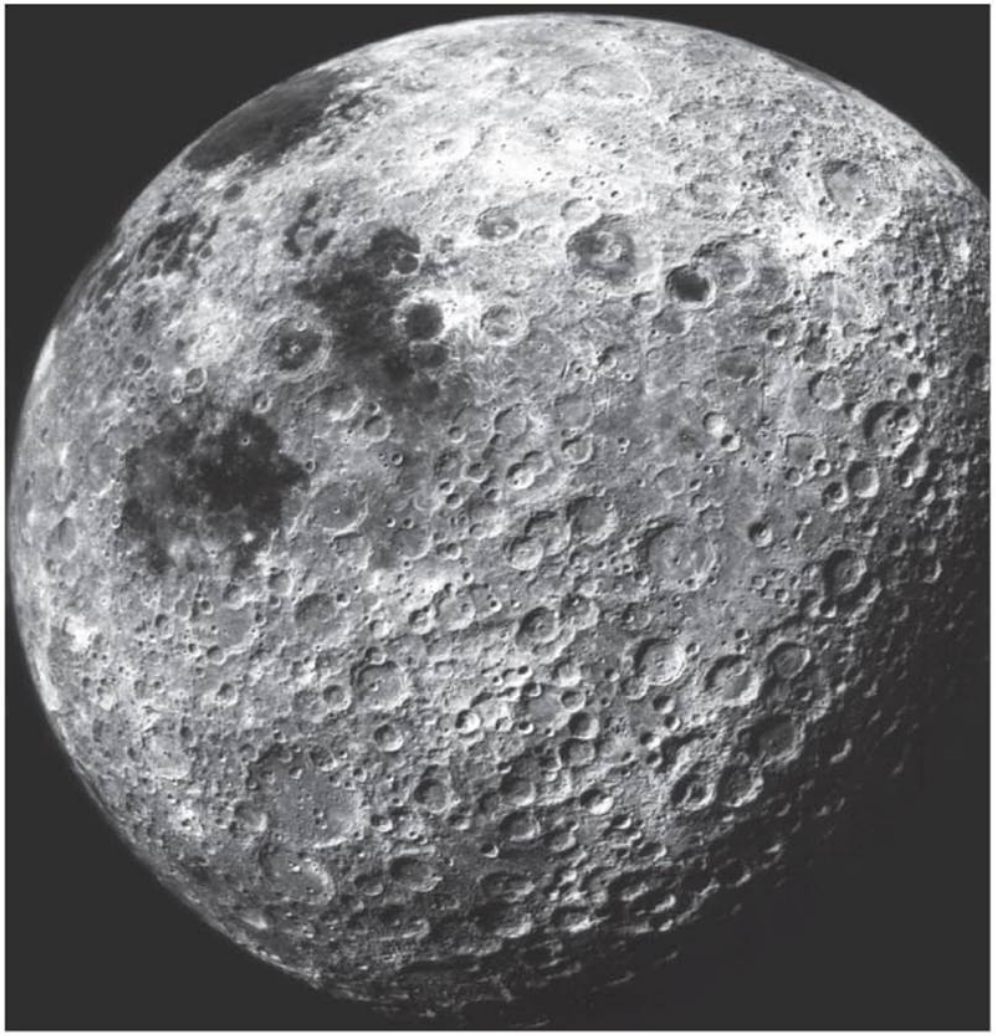


History of Cratering



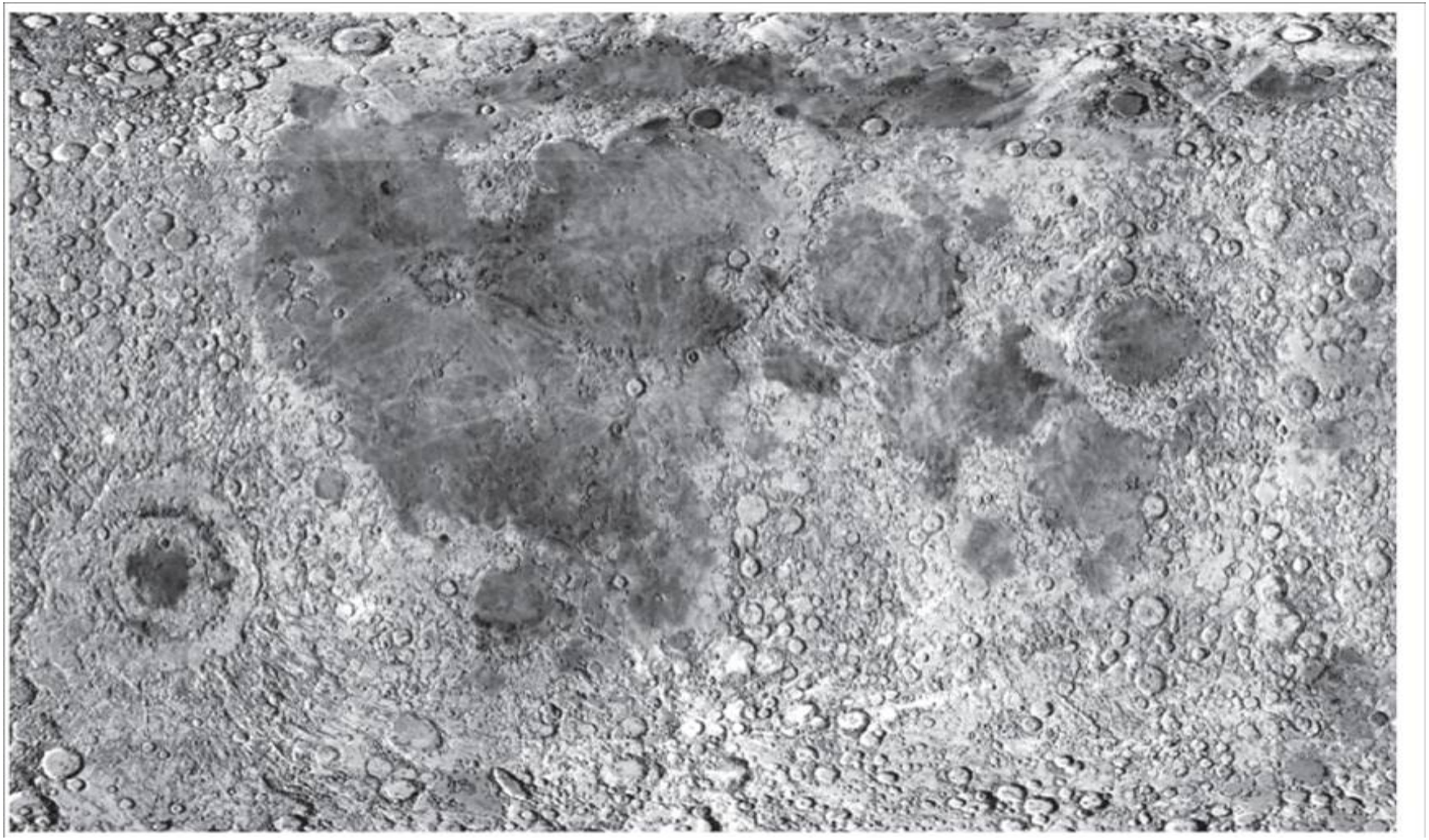
- Most cratering happened in the first billion years.
- A surface with many craters has not changed much in 3 billion years.

Cratering of Moon



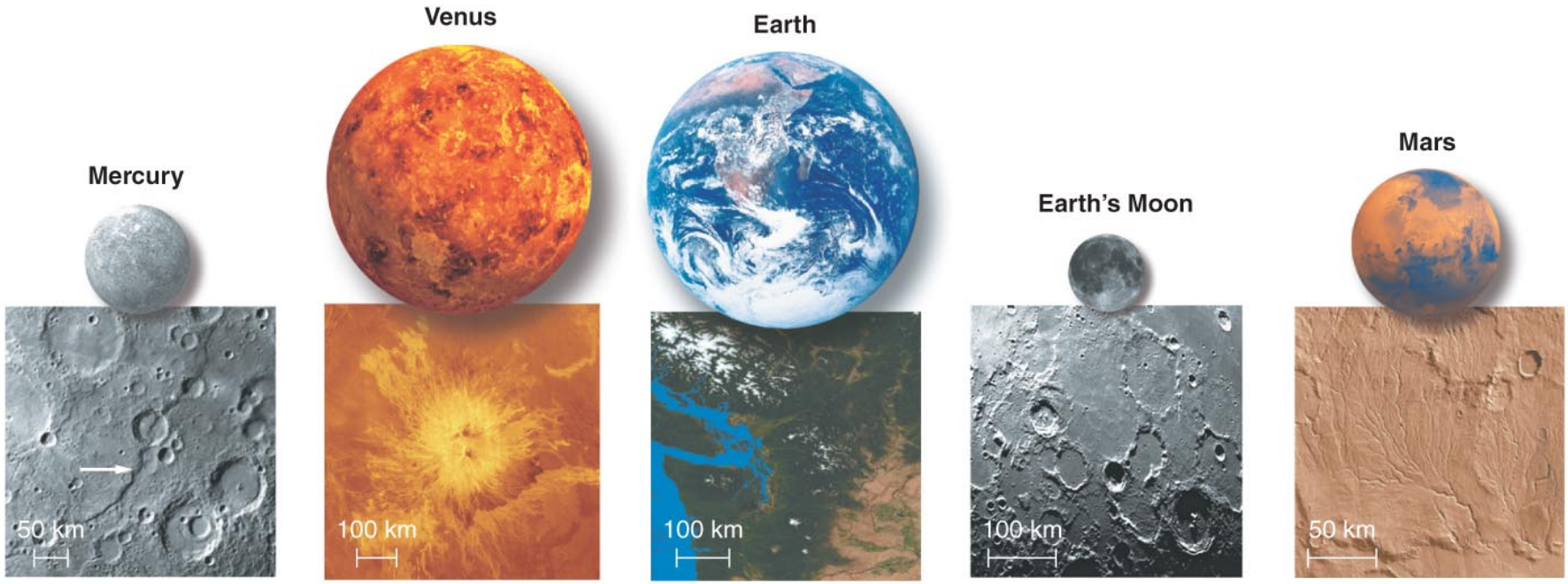
- Some areas of Moon are more heavily cratered than others.
- Younger regions were flooded by lava after most cratering.

Cratering of Moon



Cratering map of the Moon's entire surface

Why do the terrestrial planets have different geological histories?



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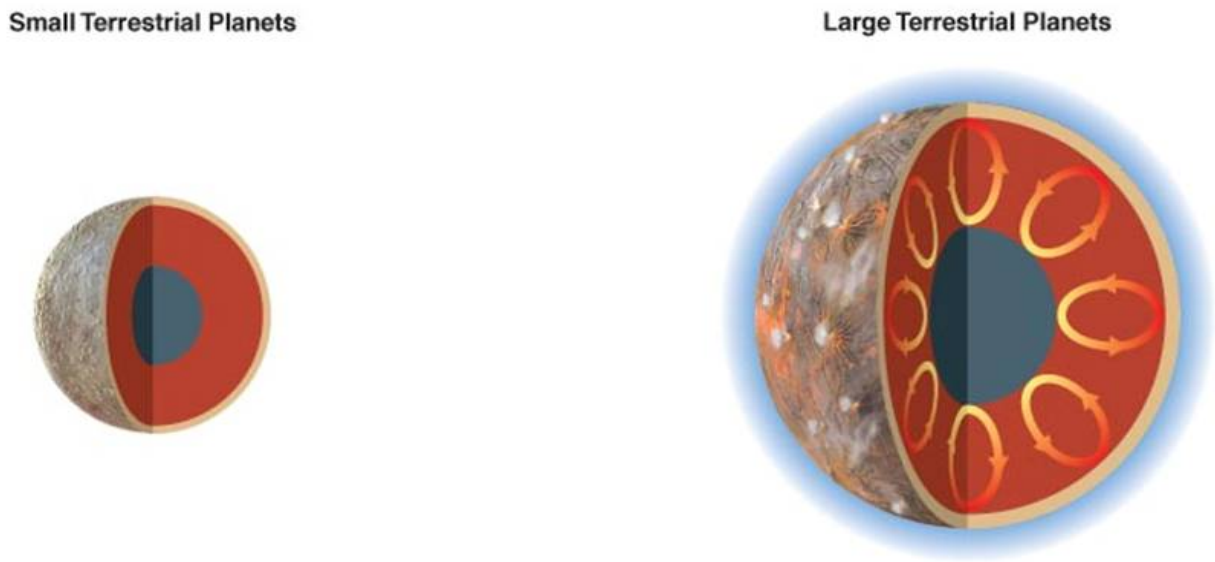
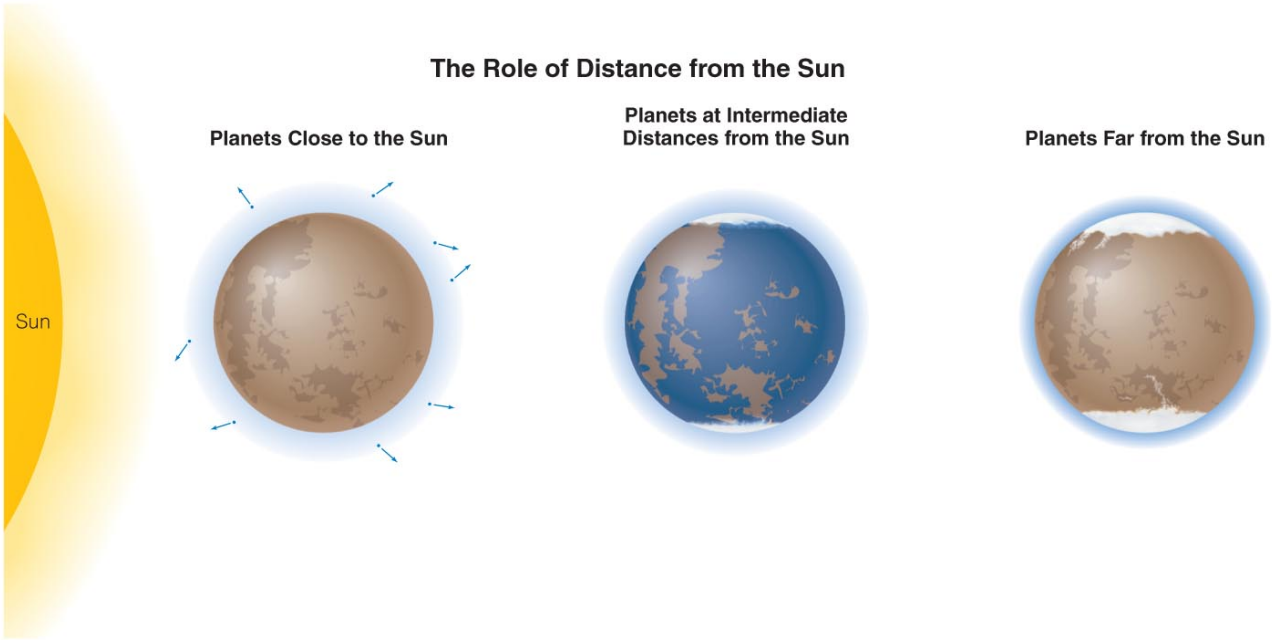
Role of Planetary Size



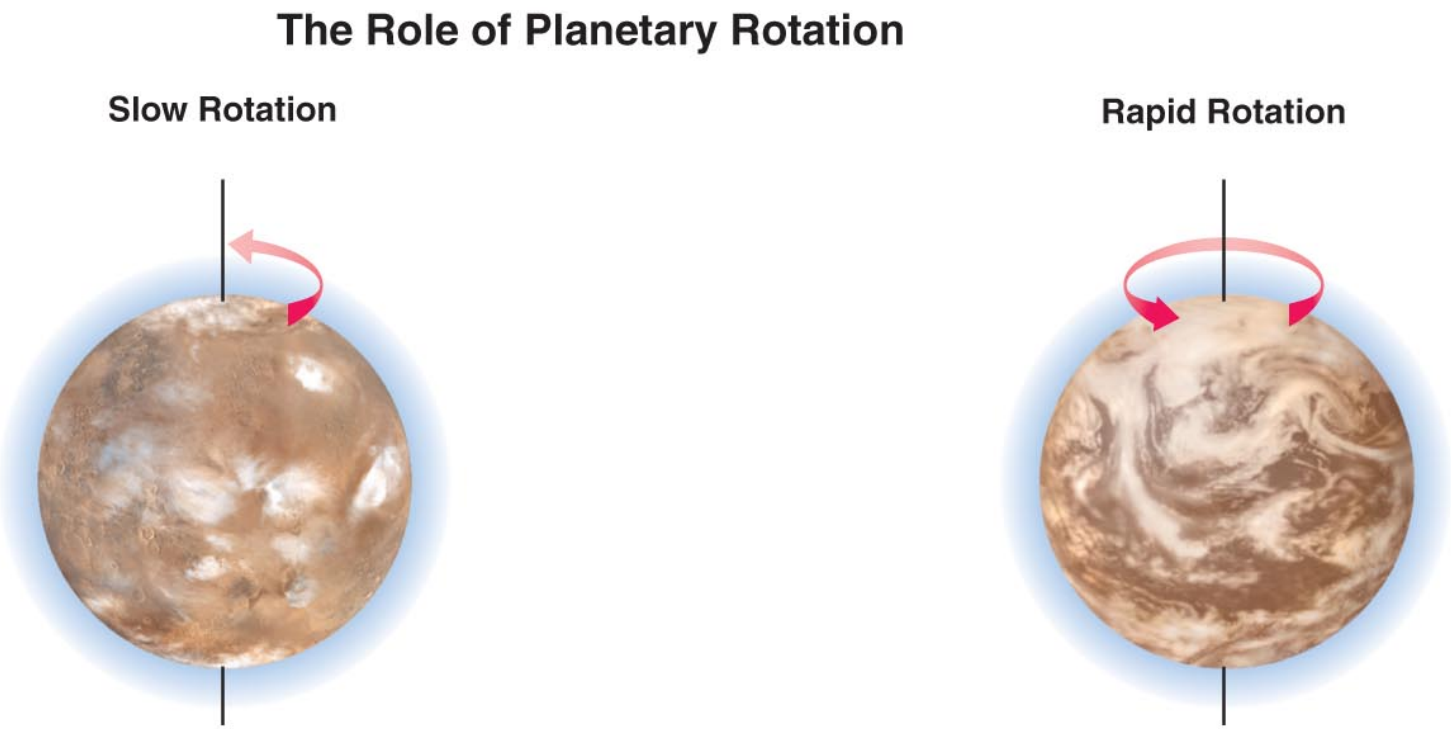
- Smaller worlds cool off faster and harden earlier.
- Larger worlds remain warm inside, promoting volcanism and tectonics.
- Larger worlds also have more erosion because their gravity retains an atmosphere.

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.

Thought Question

How does the cooling of planets and potatoes vary with size?

a) Larger size makes it harder for heat from inside to escape.
b) Larger size means a bigger ratio of volume to surface area.
c) Larger size takes longer to cool.
d) all of the above

Thought Question

How does the cooling of planets and potatoes vary with size?

a) Larger size makes it harder for heat from inside to escape.
b) Larger size means a bigger ratio of volume to surface area.
c) Larger size takes longer to cool.
d) all of the above

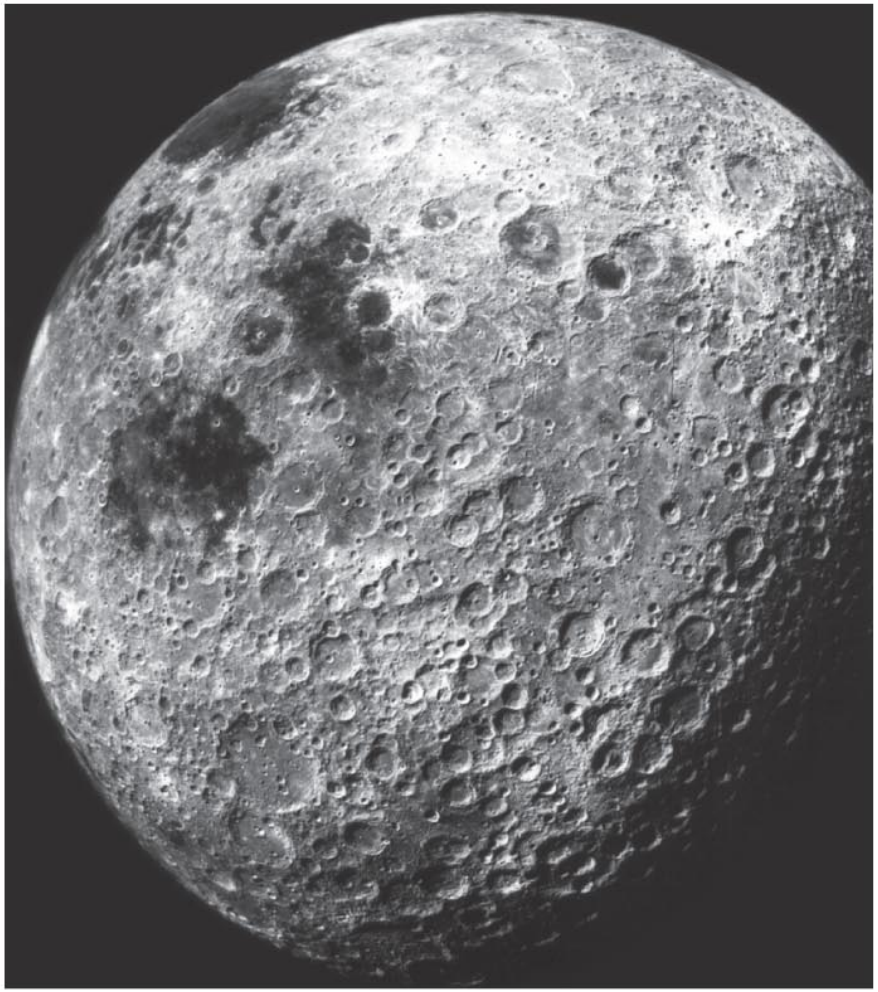
What have we learned?

- **What processes shape planetary surfaces?**
  - Cratering, volcanism, tectonics, erosion
- **How do impact craters reveal a surface's geological age?**
  - The amount of cratering tells us how long ago a surface formed.
- **Why do the terrestrial planets have different geological histories?**
  - Differences arise because of planetary size, distance from Sun, and rotation rate.

9.3 Geology of the Moon and Mercury

- Our goals for learning:
  - **What geological processes shaped our Moon?**
  - **What geological processes shaped Mercury?**

What geological processes shaped our Moon?



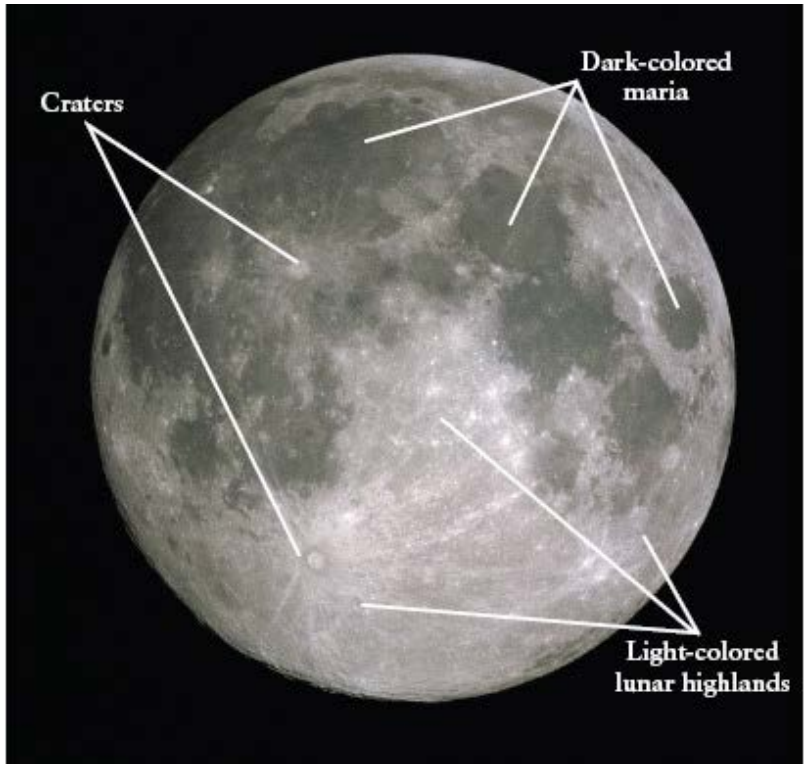
Features on the Moon

With a telescope you can make out: **craters,** the dark-colored **maria**, and the **lunar highlands.**

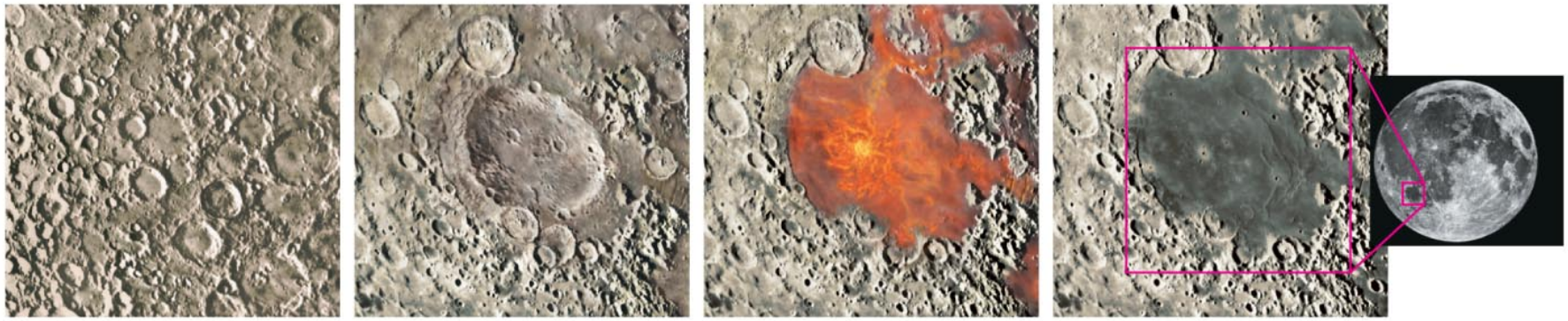
Maria are the remains of huge lava flows and get their appearance from the dark color of the solidified lava.

Maria have far fewer craters than the surrounding terrain.

Since craters are caused by meteoritic bombardment, this means that the maria have not been exposed to that bombardment for as long as the surrounding terrain.



Formation of Lunar Maria



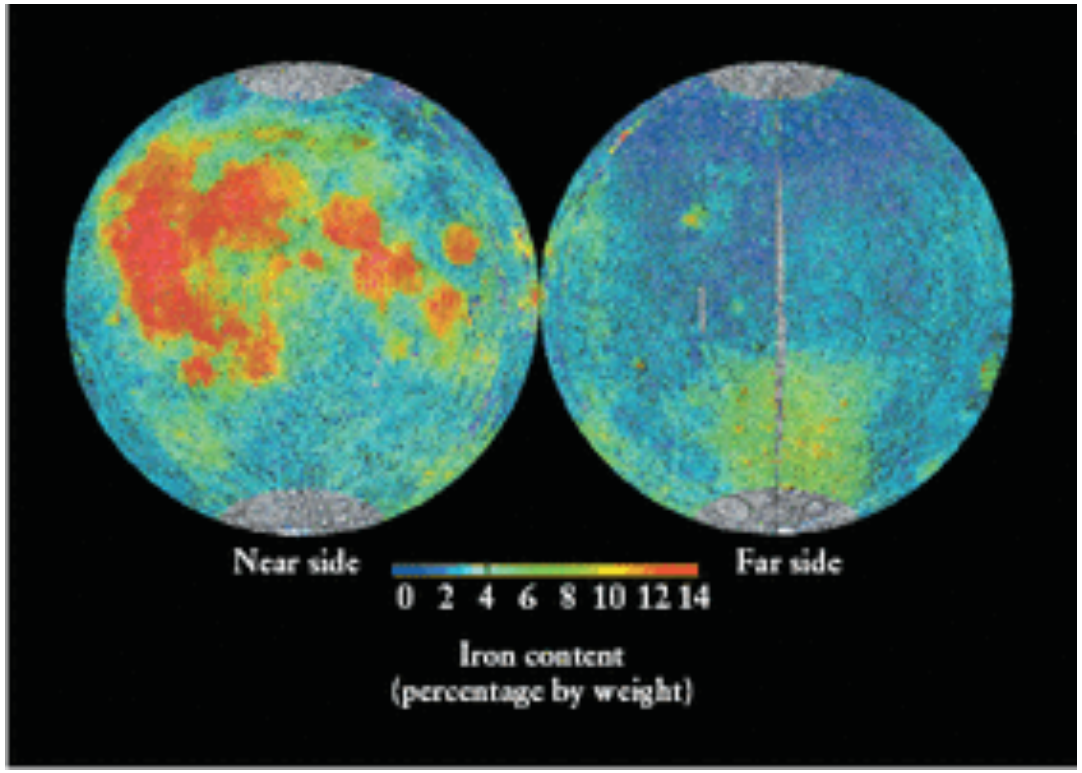
Early surface is covered with craters.

Large impact crater weakens crust.

Heat build-up allows lava to well up to surface.

Cooled lava is smoother and darker than surroundings.

Lunar Maria



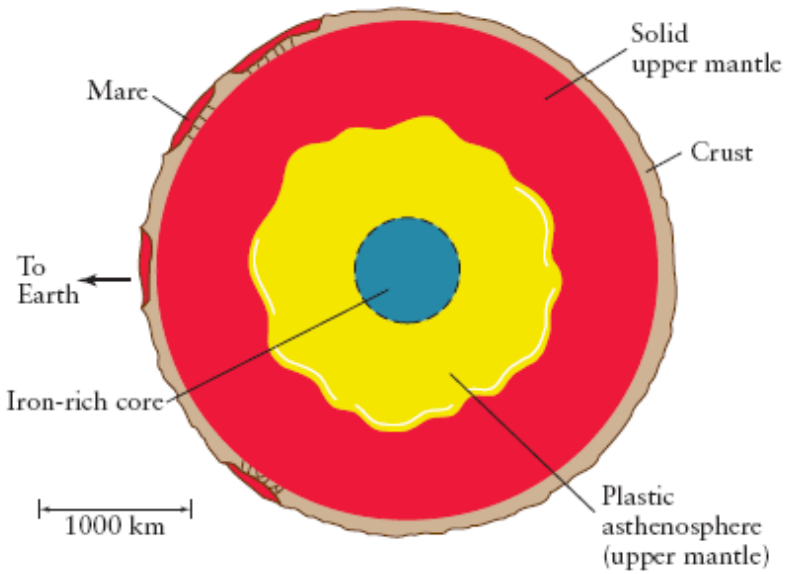
Iron concentrations on the moon mapped out with the Clementine spacecraft. **High levels of Fe near maria** and low levels near lunar highlands.

Lunar Interior

The astronauts using magnetometers found **no global magnetic field**.
But the surface rocks indicated that the Moon once had a weak magnetic field and therefore once must have had a molten iron core.

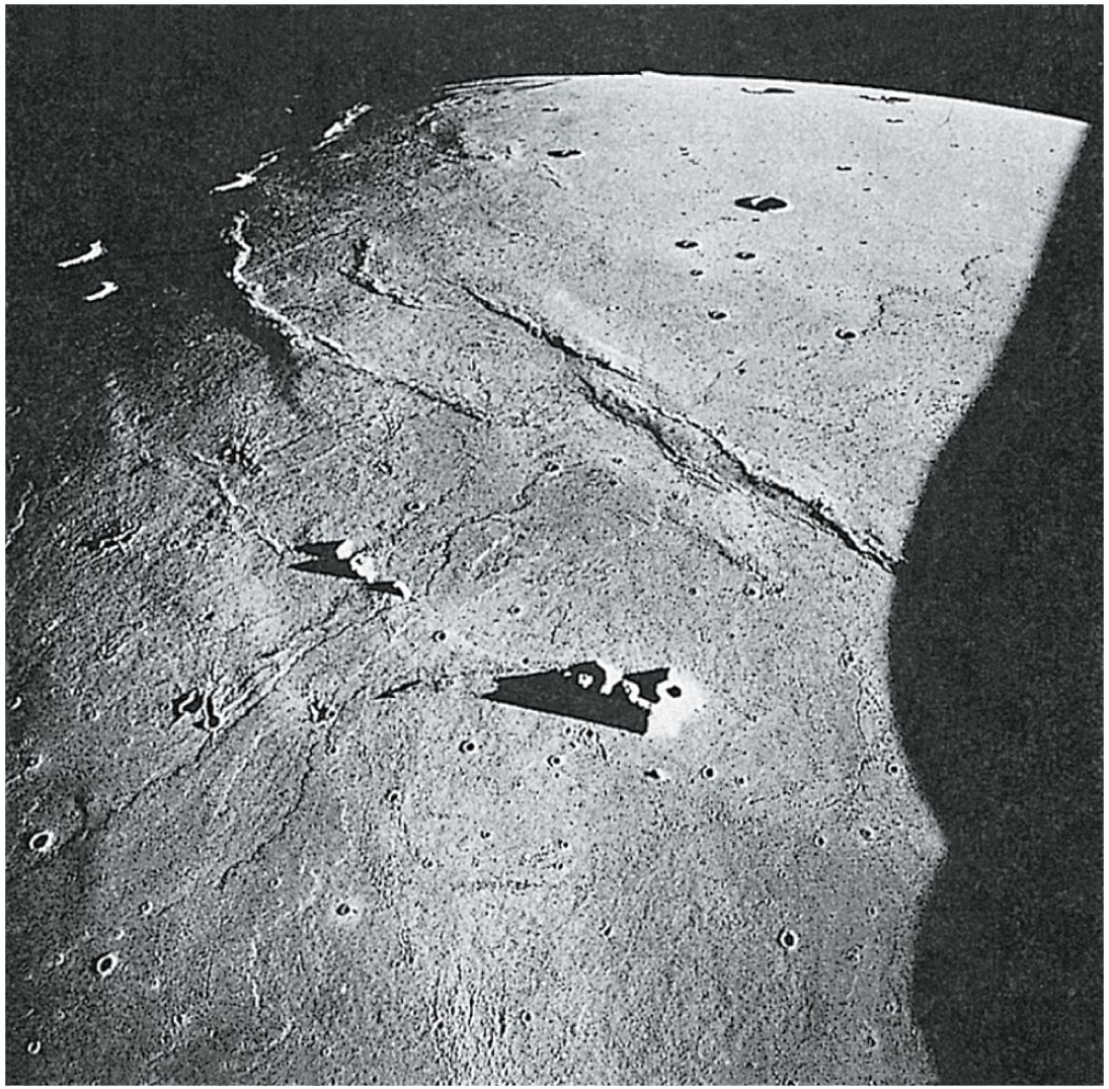
Using seismographs the astronauts measured **moonquakes**.

Moonquakes are caused by tidal forces from the Earth. These forces deform the solid body of the moon.



The lunar crust has an average thickness of about 60 km on the Earth-facing side but about 100 km on the far side. This explains why there are more Maria on the side facing the Earth

Tectonic Features



- Wrinkles arise from cooling and the contraction of a lava flood.

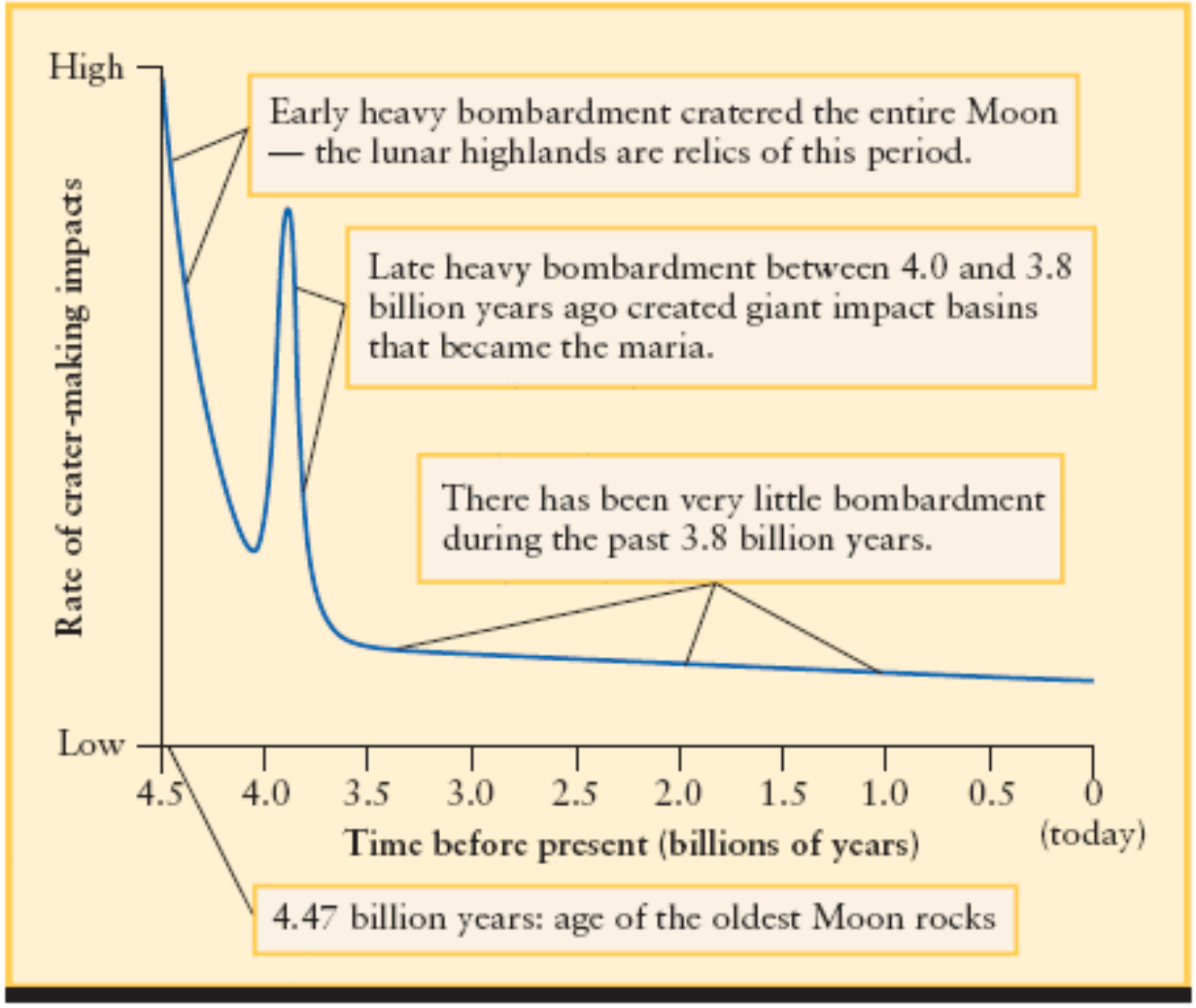
Geologically Dead

- Moon is considered geologically "dead" because geological processes have virtually stopped.

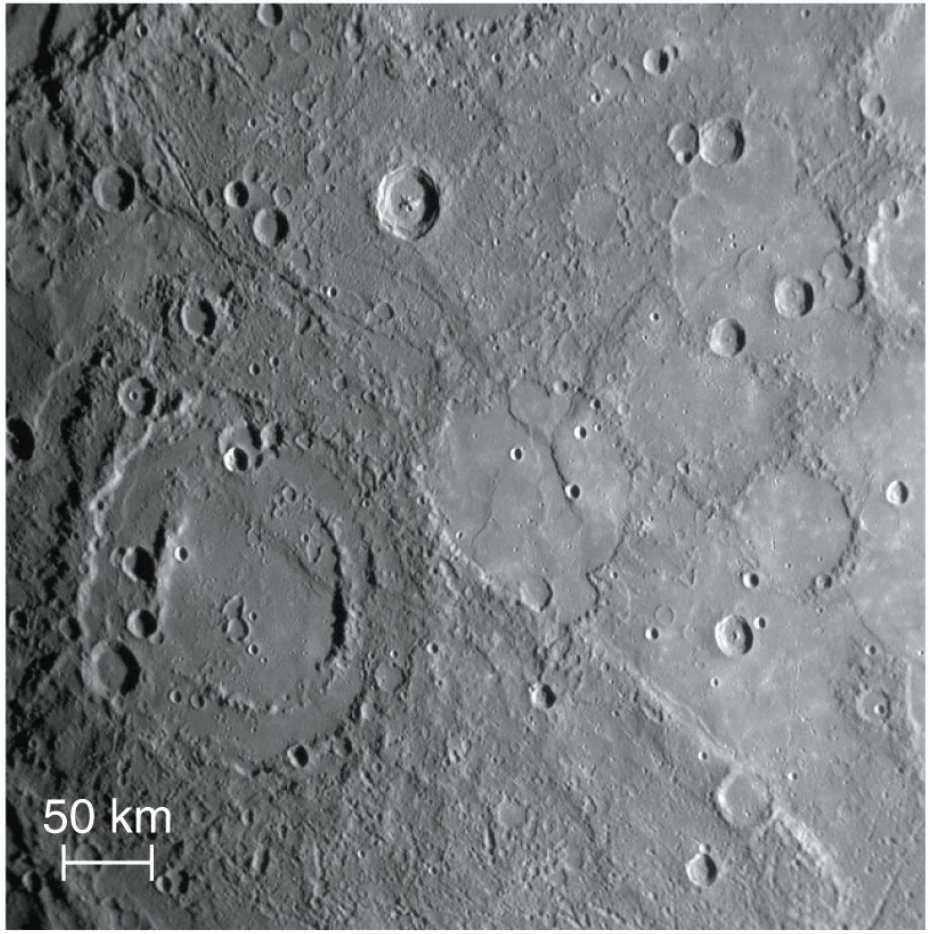
- The constant bombardment by meteorites has turned the surface rocks into fine dust and rock fragments called **regolith.**

An astronaut’s bootprint in regolith.

History of Lunar Cratering

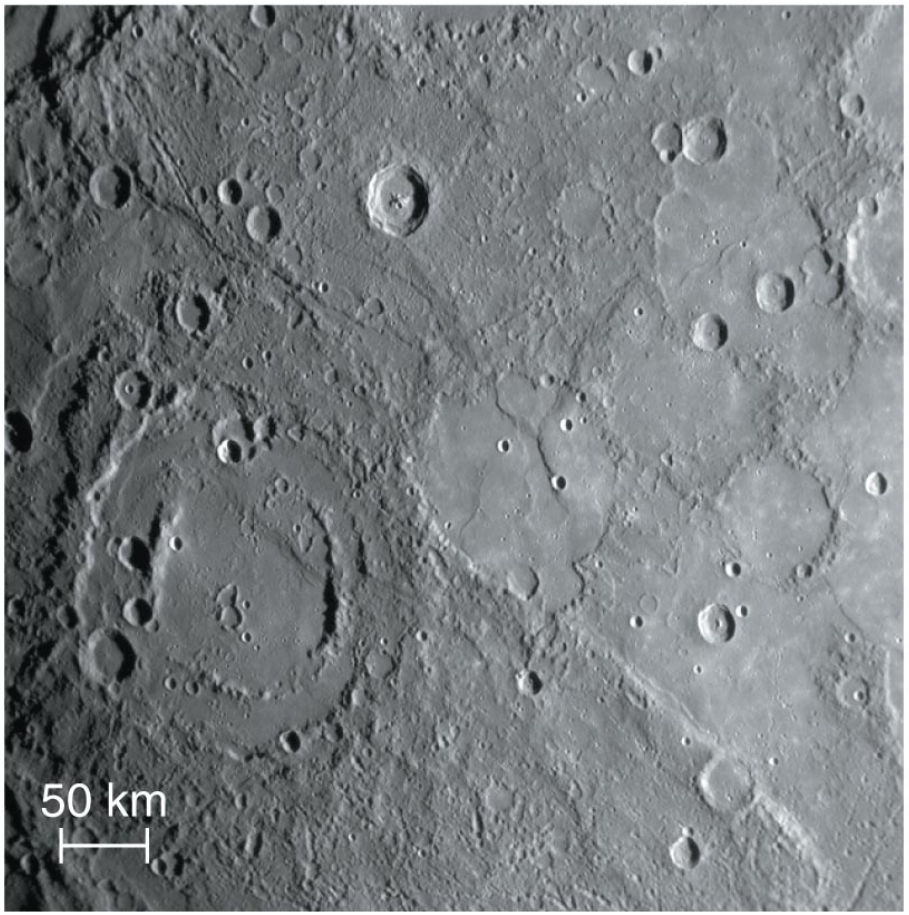


What geological processes shaped Mercury?



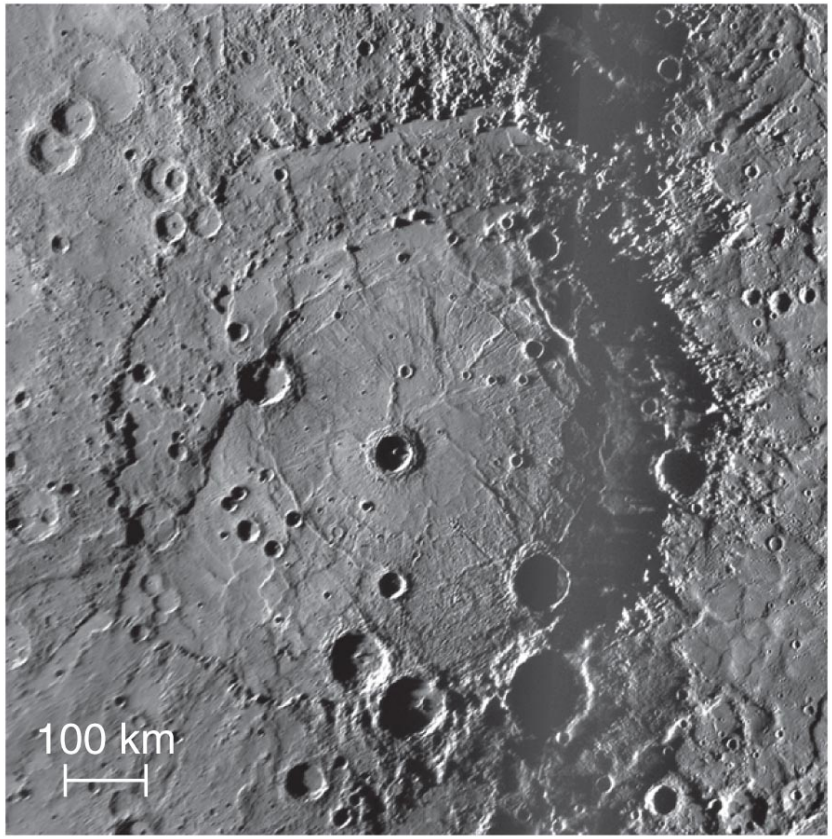
a A close-up view of Mercury's surface, showing impact craters and smooth regions where lava apparently covered up craters.

Cratering of Mercury

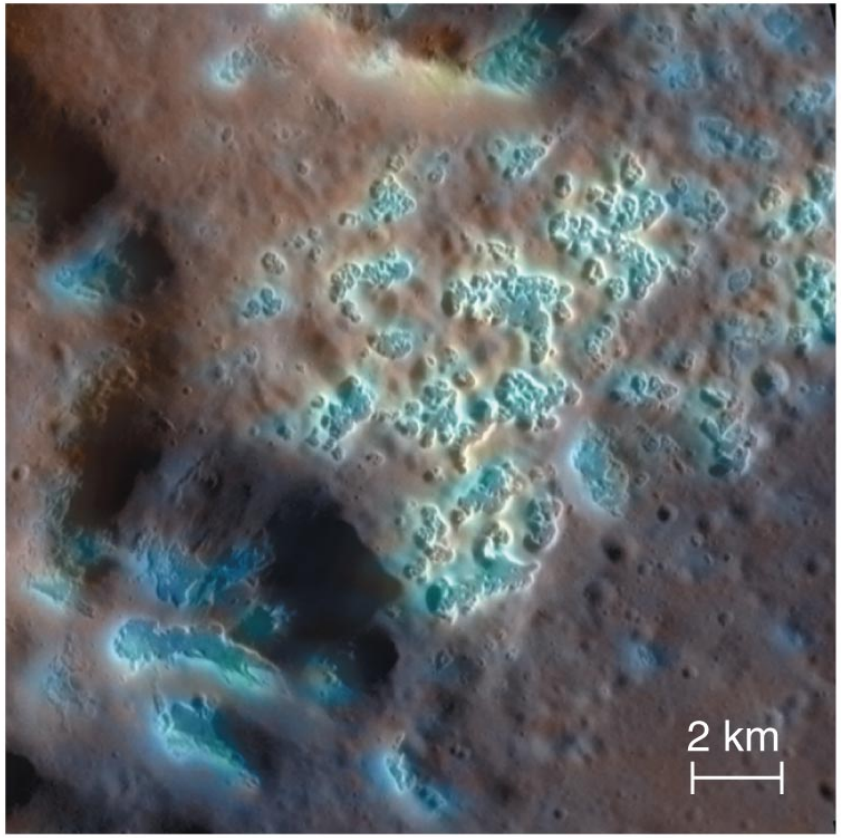


- Mercury has a mixture of heavily cratered and smooth regions like the Moon.
- Smooth regions are likely ancient lava flows.

Cratering of Mercury

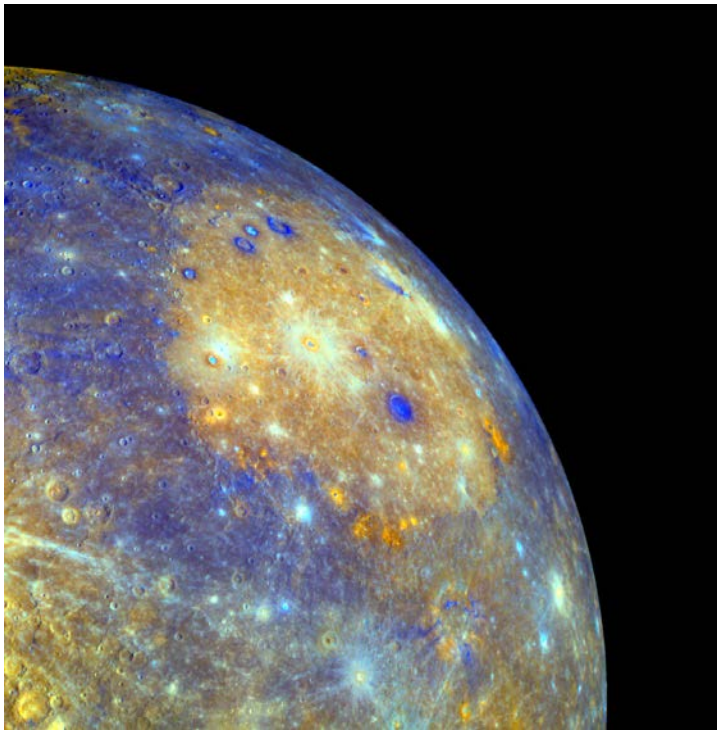


The Rembrandt Basin is a large impact crater on Mercury.

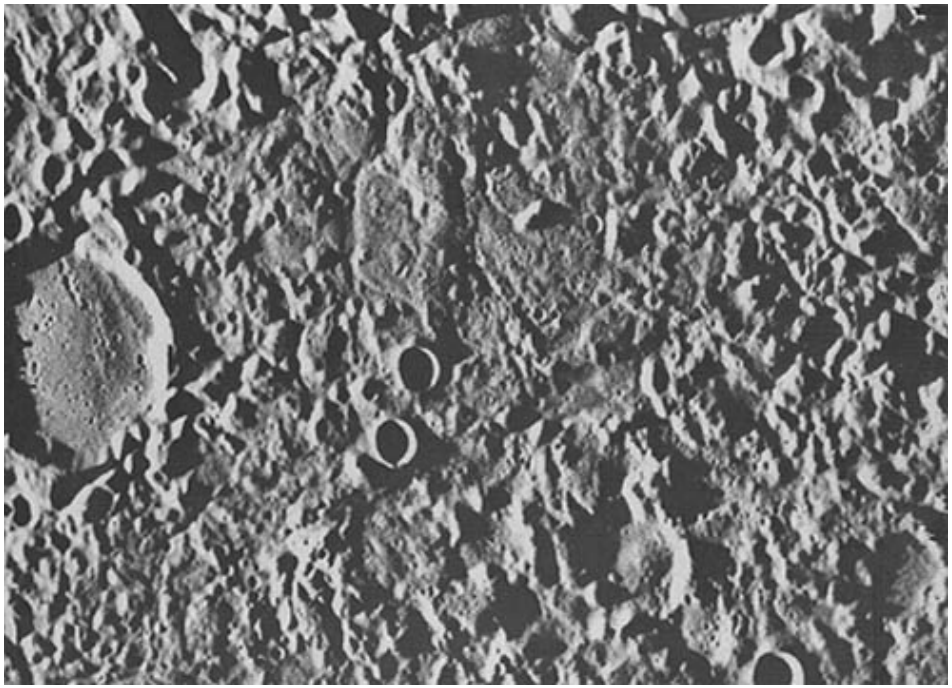


Hollows in a crater floor created by escaping gases.

Cratering of Mercury

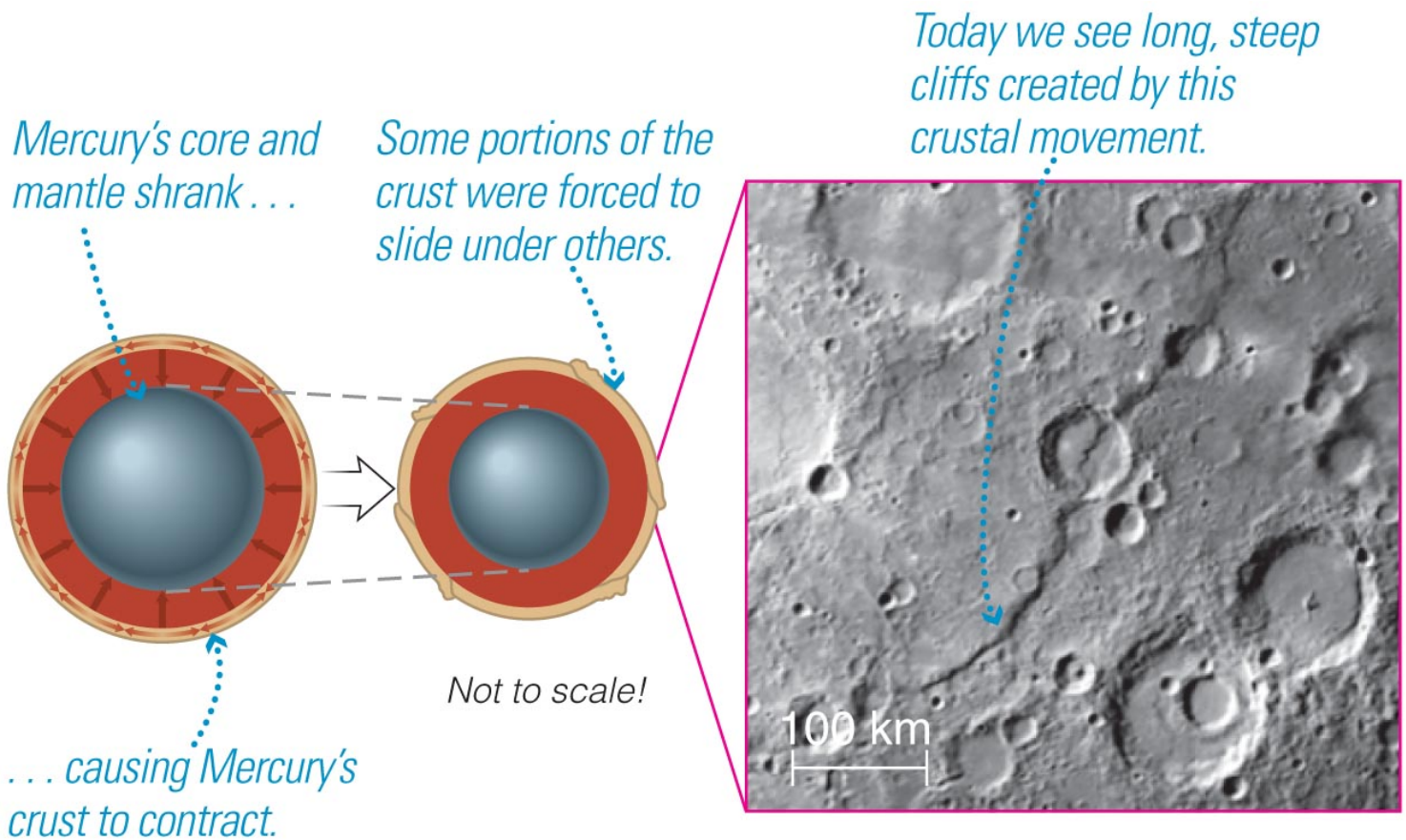


Enhanced image of Mercury's **Caloris Basin** with a diameter of 1550 km is one of the largest impact features in the Solar System (from NASA's Messenger spacecraft).



The so-called "Weird Terrain" was formed by the Caloris Basin impact at its **antipodal point**.

Tectonics on Mercury

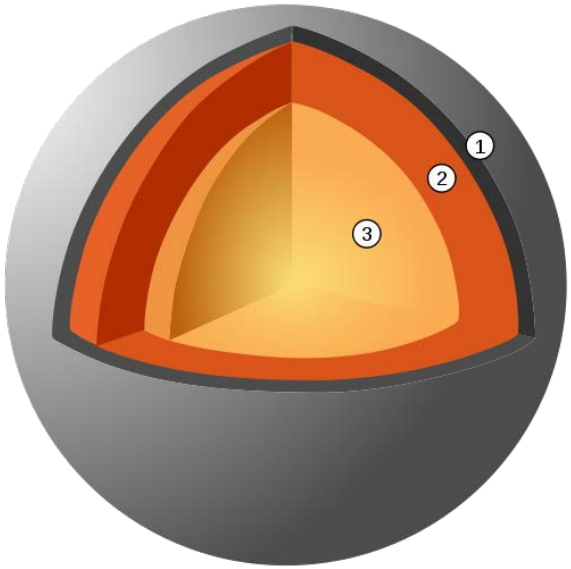


- Long cliffs indicate that Mercury shrank early in its history.

Mercury's Interior

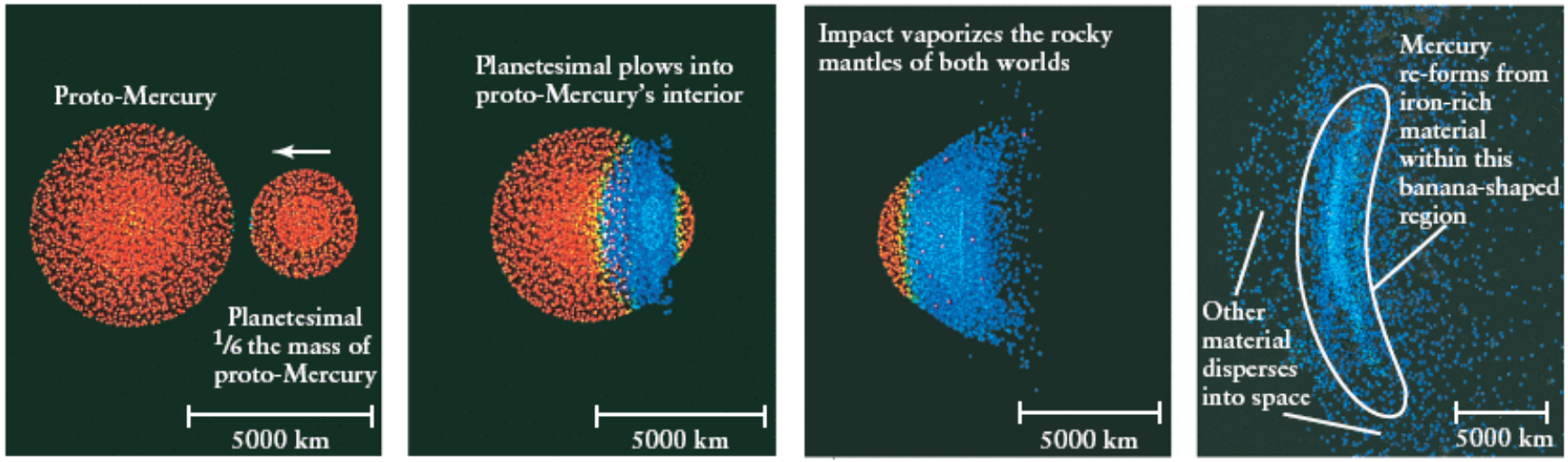
Diagram of the interior structure of the planet Mercury :

1 Crust - 100-200 km thick
2 Mantle – 600 km thick
3 Core - 1,800 km radius



A theory to explain Mercury's large iron core: During the final stages of planet formation, Mercury was struck by a large planetesimal that resulted in the ejection of much of the lighter mantle.

Mercury's Interior



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What have we learned?

- **What geological processes shaped our Moon?**
  - Early cratering is still present.
  - Maria resulted from impacts and volcanism.
- **What geological processes shaped Mercury?**
  - Had cratering and volcanism similar to Moon
  - Tectonic features indicate early shrinkage.
  - Mercury's large core can be explained by a large impact

9.4 Geology of Mars

- Our goals for learning:
  - **What geological processes have shaped Mars?**
  - **What geological evidence tells us that water once flowed on Mars?**

"Canals" on Mars

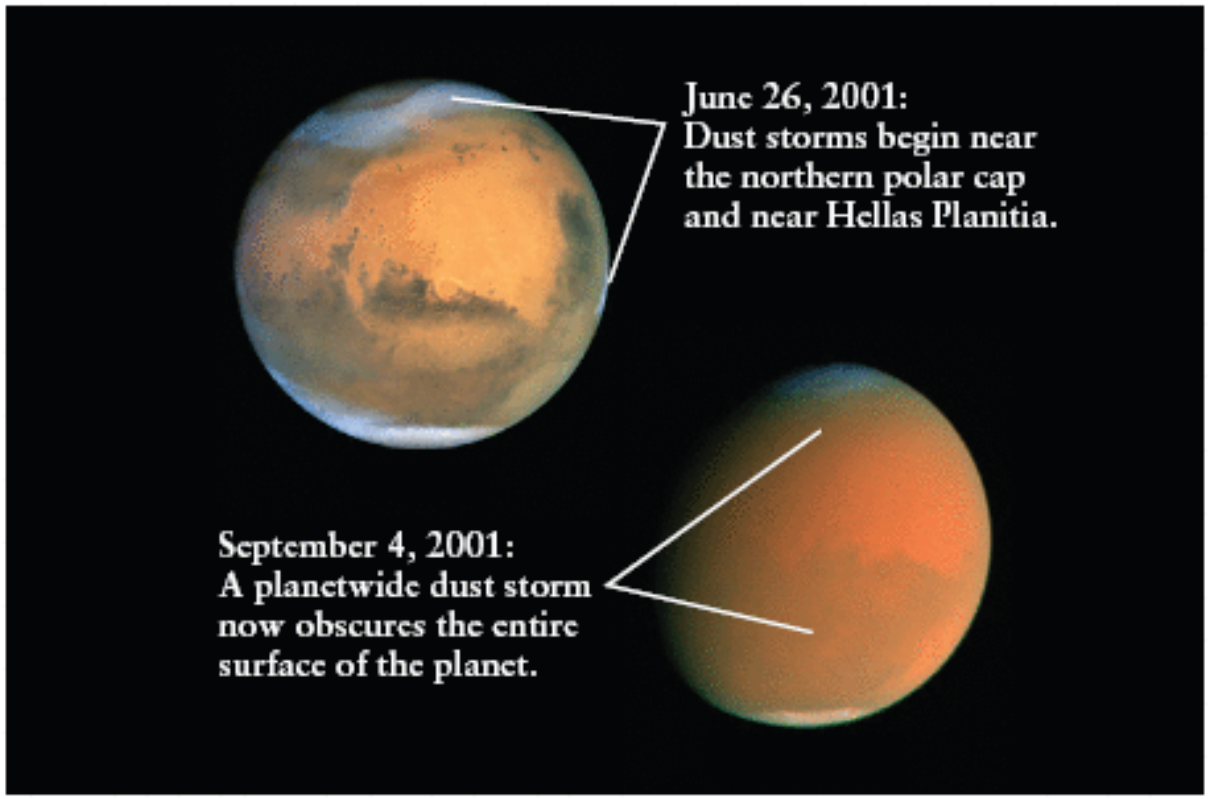
Ground based telescopes indicate **seasonal changes in** the size of the **polar caps** and the colors of various dark markings on the planet.

In 1877 the Italian astronomer **Giovannni Schiaparelli** reported seeing channels (canali in Italian)**.**

The American astronomer **Percival Lowell** with a new observatory in Flagstaff Arizona confirmed these observations and even found more canals on Mars.

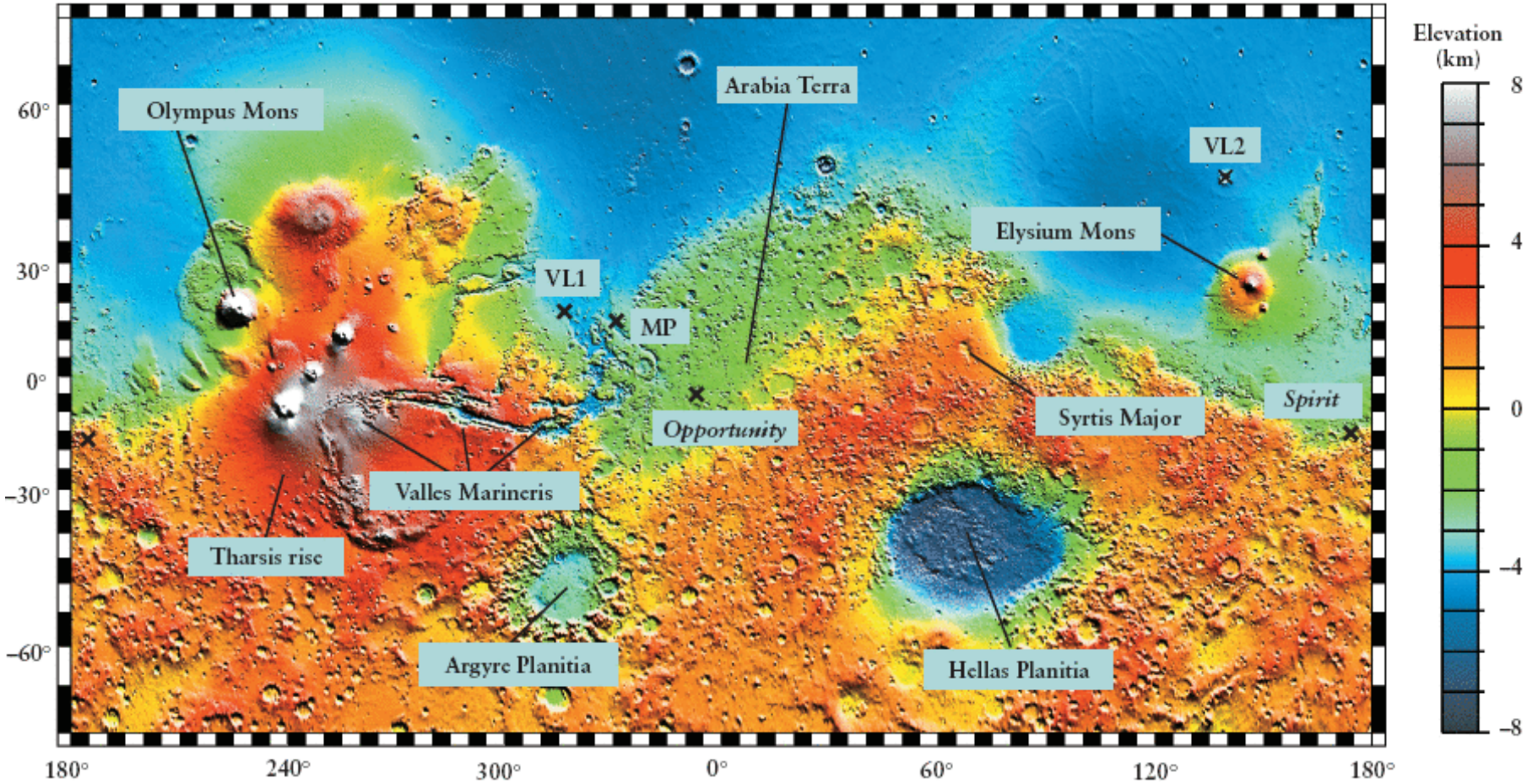
The Mirage of Martian Canals reported by Schiaparelli. Later observations with larger telescopes showed beyond doubt that these canals **were mere illusions**.

Dust Storms on Mars



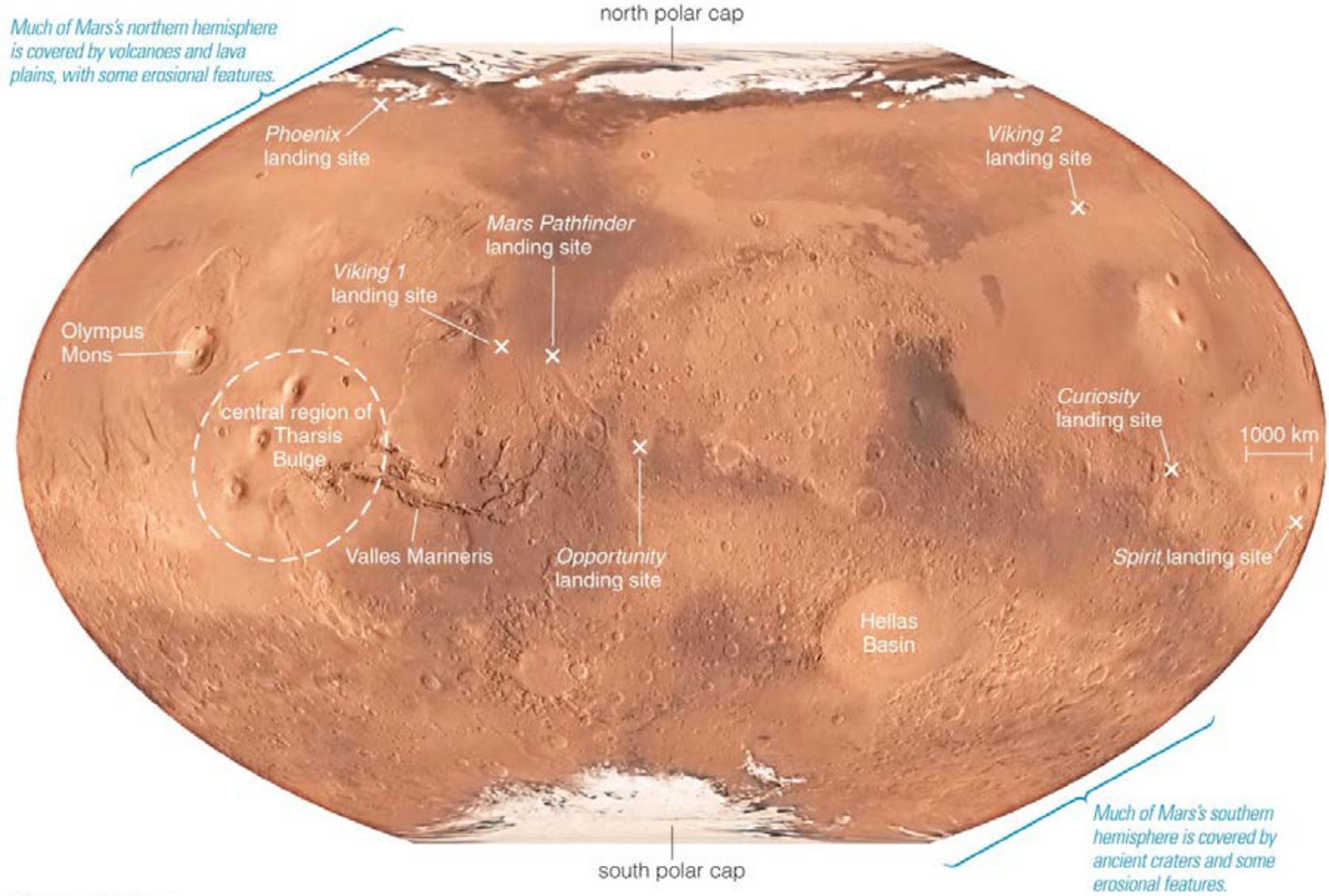
HST images of Mars show how dust storms that blow in different directions in different seasons can explain the seasonal variations of color.

Topography of Mars

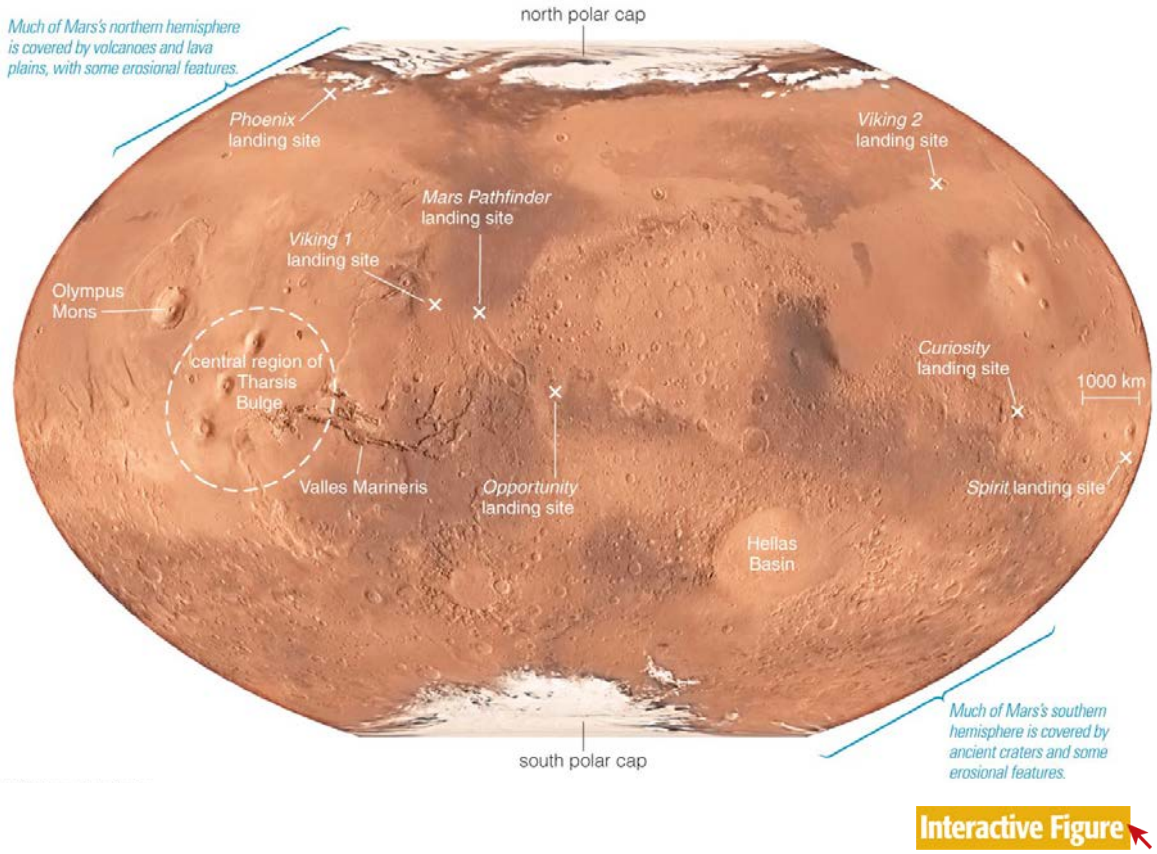


Crustal dichotomy. This map made with the laser altimeter on board the Mars Global Surveyor spacecraft. Most of the southern hemisphere lies several kilometers above the northern hemisphere

What geological processes have shaped Mars?



Geological processes shaping the surface of Mars: Cratering



- The amount of cratering differs greatly across Mars's surface.
- Many early craters have been erased.

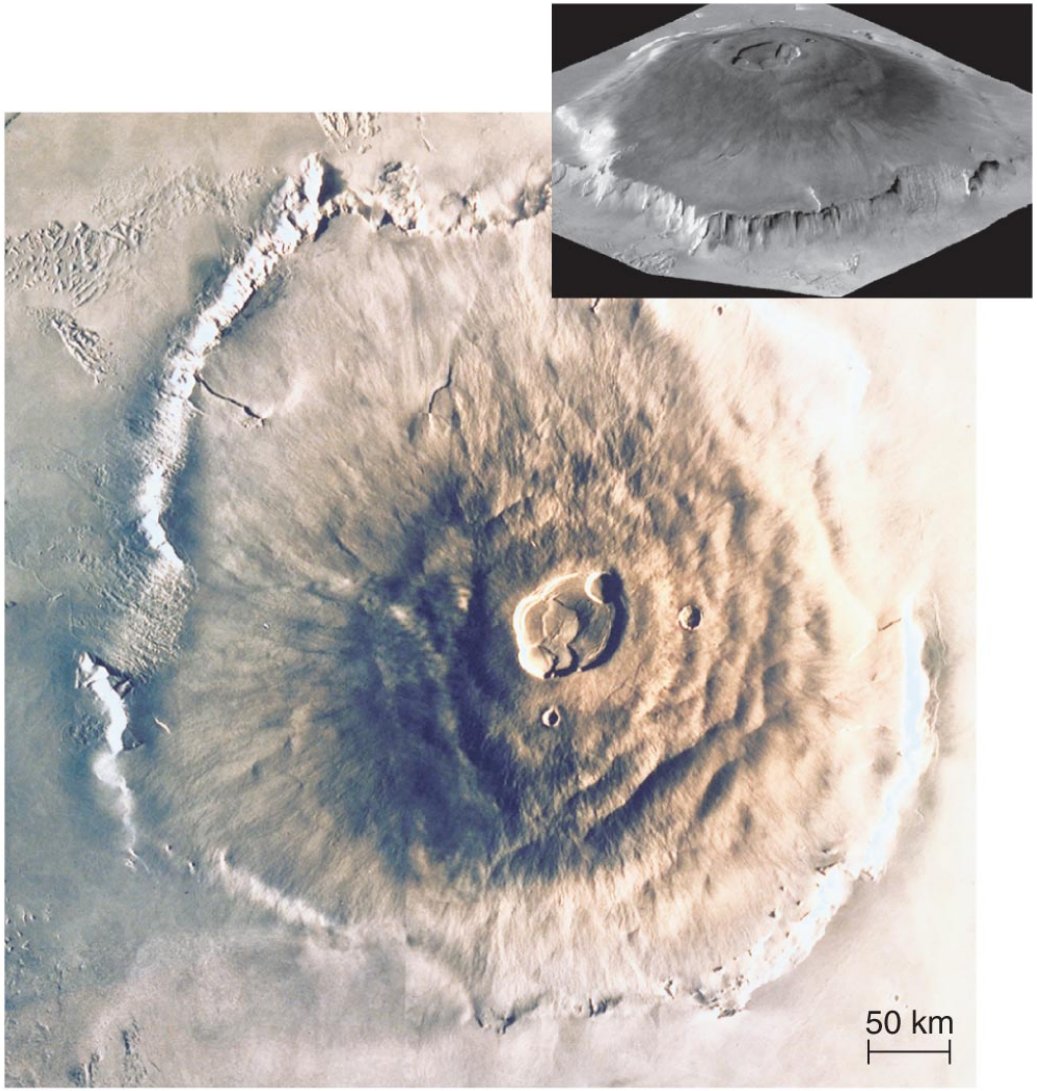
Tectonics of Mars

Images of Mar's surface do not show any ridges or signs of subduction zones. Mars can be considered to have only one plate. **Mars therefore lacks plate tectonics**.

The main reason Mars does not have plate tectonics is that its **crust is too thick**.

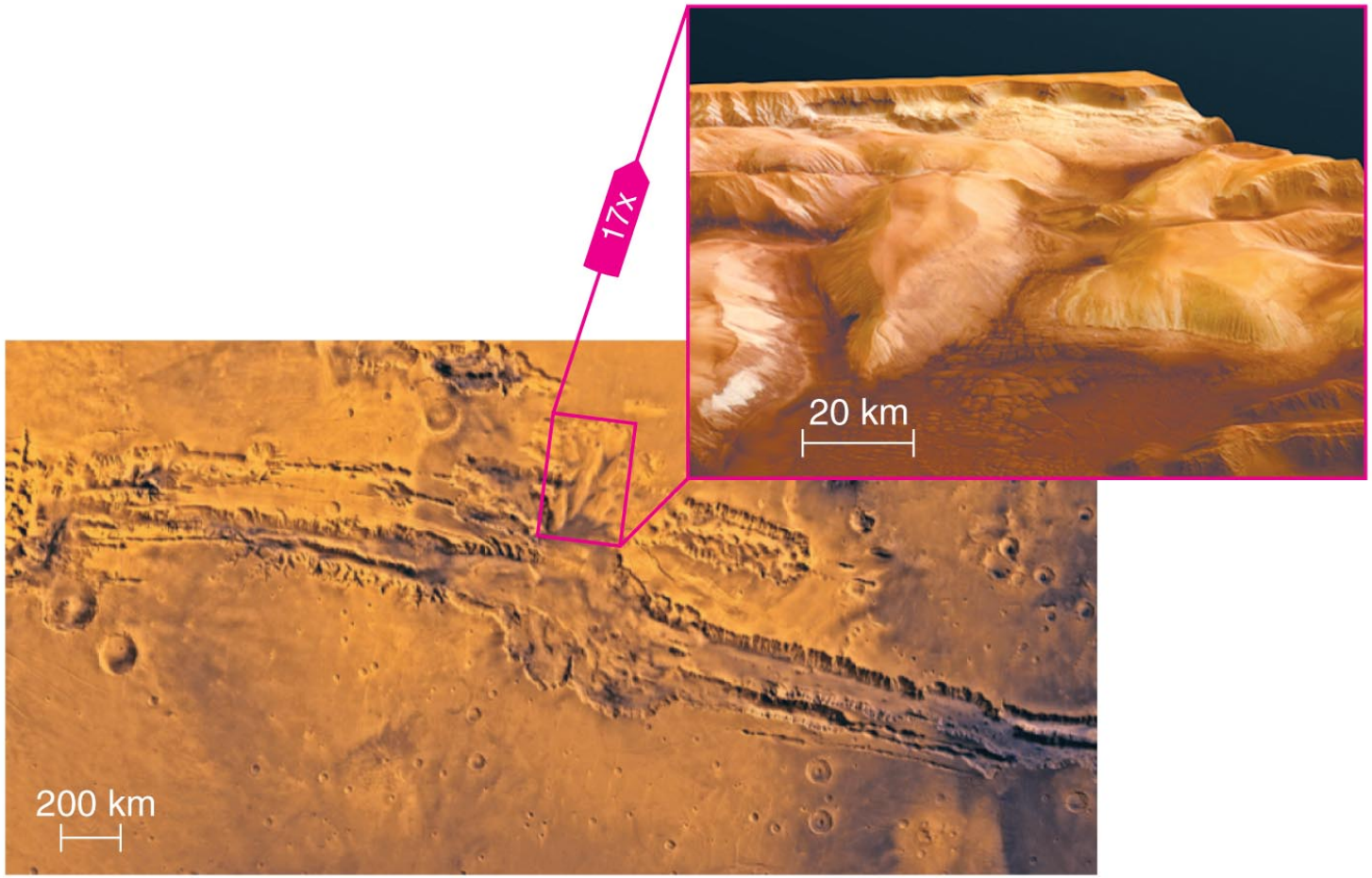
Measurements performed with the Mars Global Surveyor indicate that the average thickness of the crust in the Northern hemisphere is ~ 40 km and about 70 km in the Southern hemisphere.

Volcanism on Mars



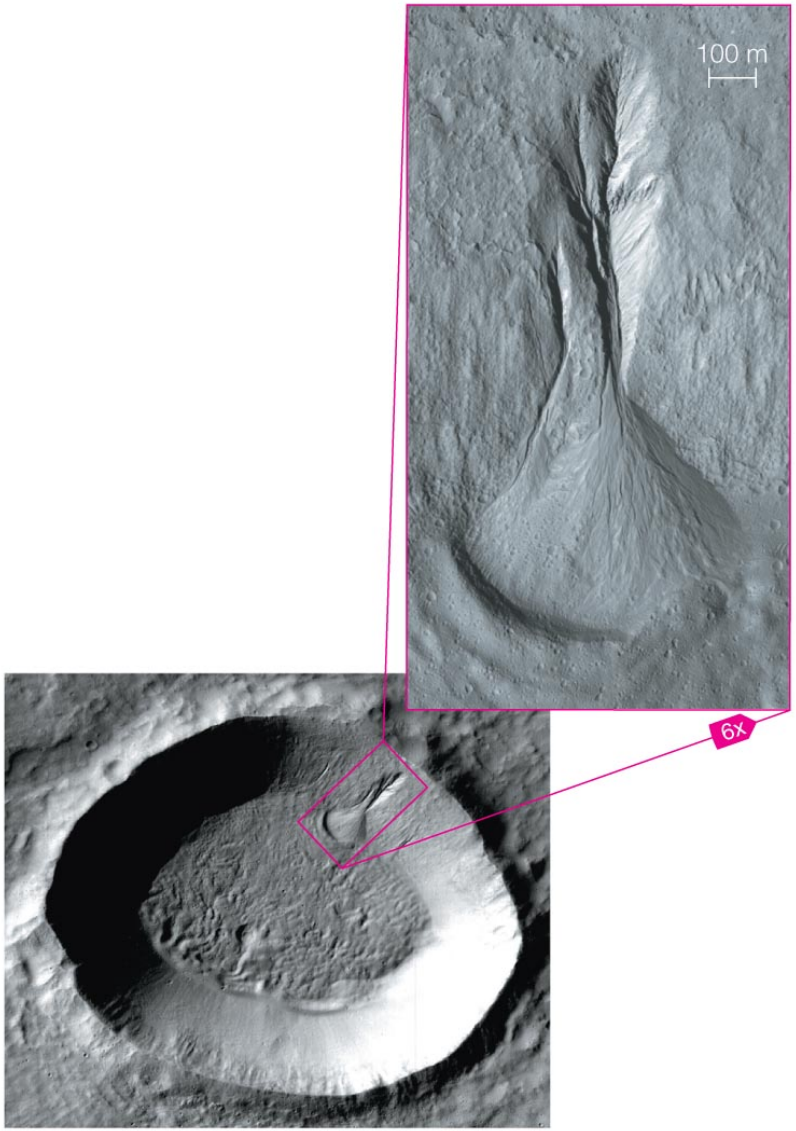
- Mars has many large shield volcanoes.
- Olympus Mons is the largest and tallest (24 km) volcano in the solar system.

Tectonics on Mars

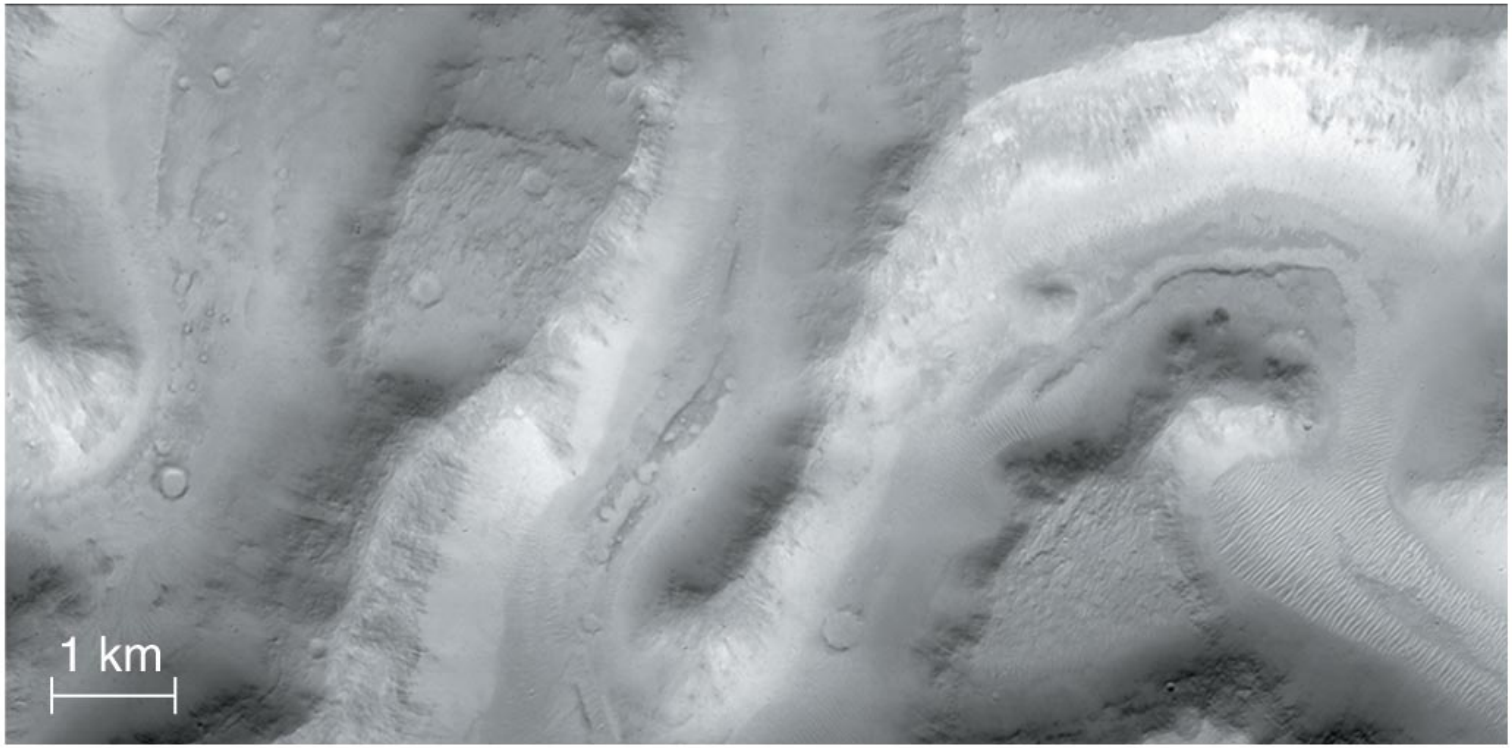


- The system of valleys known as Valles Marineris is thought to originate from tectonics.

What geological evidence tells us that water once flowed on Mars?



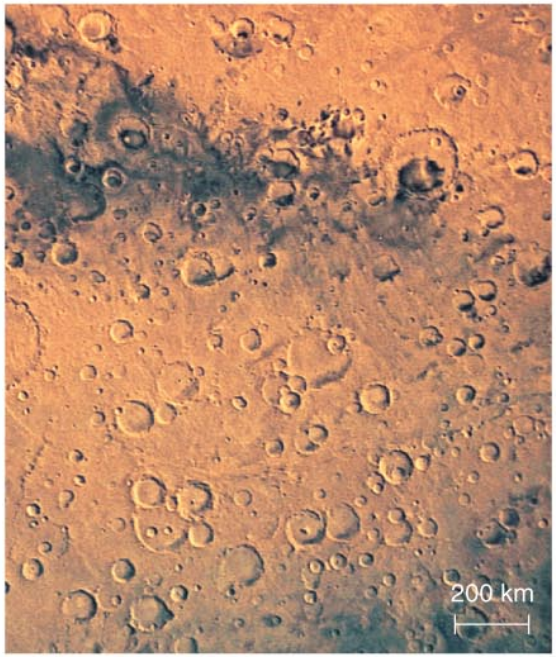
Dry Riverbeds?



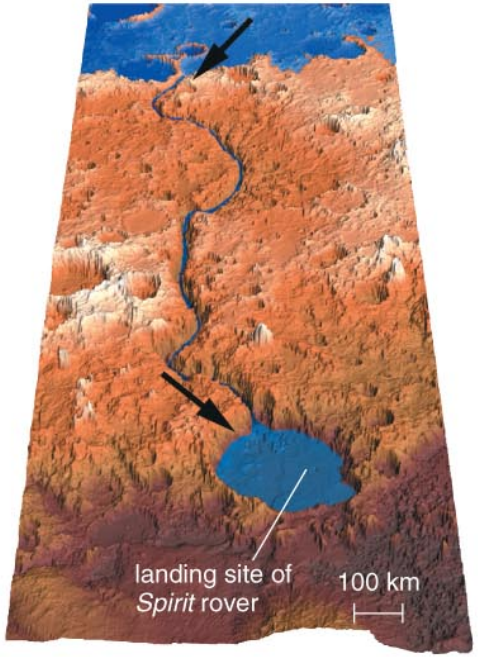
- Close-up photos of Mars show what appear to be dried-up riverbeds.

Erosion of Craters

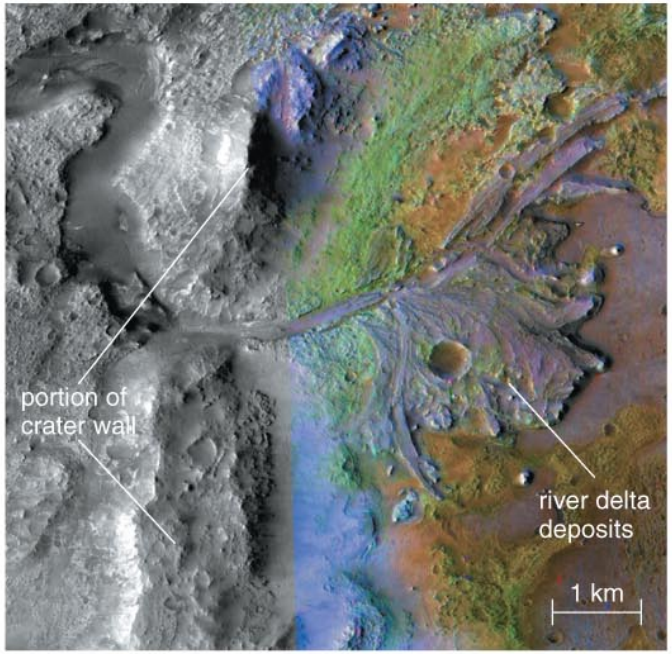
- Details of some craters suggest they were once filled with water.



a This photo shows a broad region of the southern highlands on Mars. The eroded rims of large craters and the relative lack of small craters suggest erosion by rainfall.

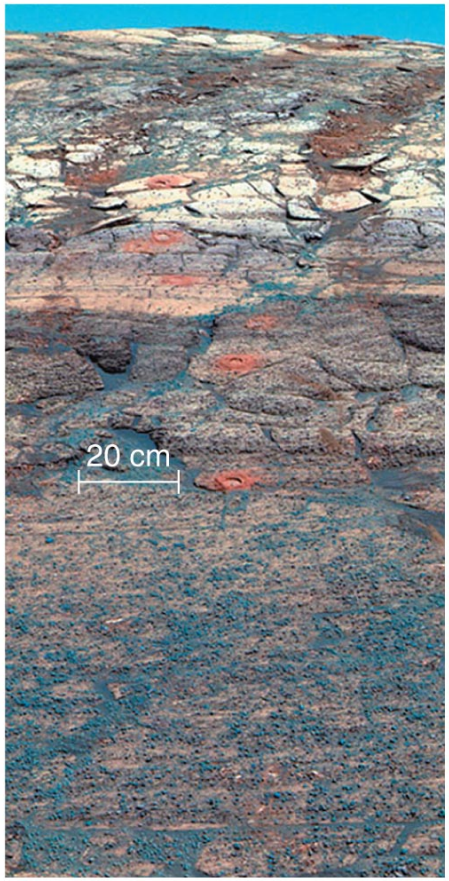


b This computer-generated perspective view shows how a Martian valley forms a natural passage between two possible ancient lakes (shaded blue). Vertical relief is exaggerated 14 times to reveal the topography.

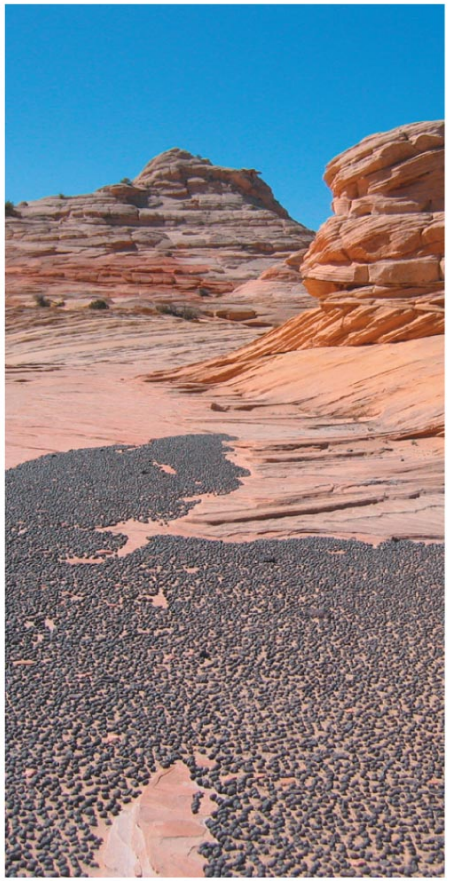


c Combined visible/infrared image of an ancient river delta that formed where water flowing down a valley emptied into a lake filling a large crater (portions of the crater wall are identified). Clay minerals are identified in green.

Martian Rocks



Mars (Endurance Crater)



Earth (Utah)

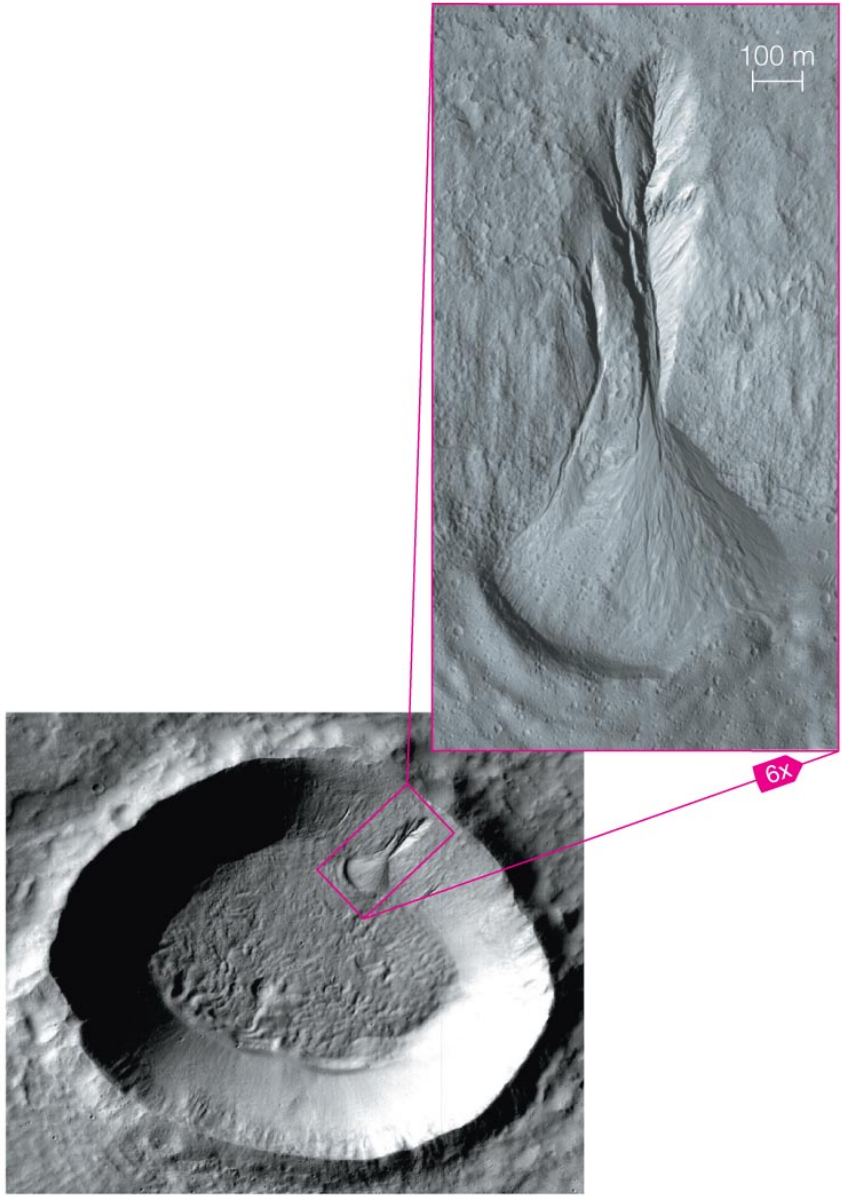
- Mars rovers have found rocks that appear to have formed in water.

Martian Rocks

- Mars rovers have found rocks that appear to have formed in water.

Crater Walls

- Gullies on crater walls suggest occasional liquid water flows have happened less than a million years ago.

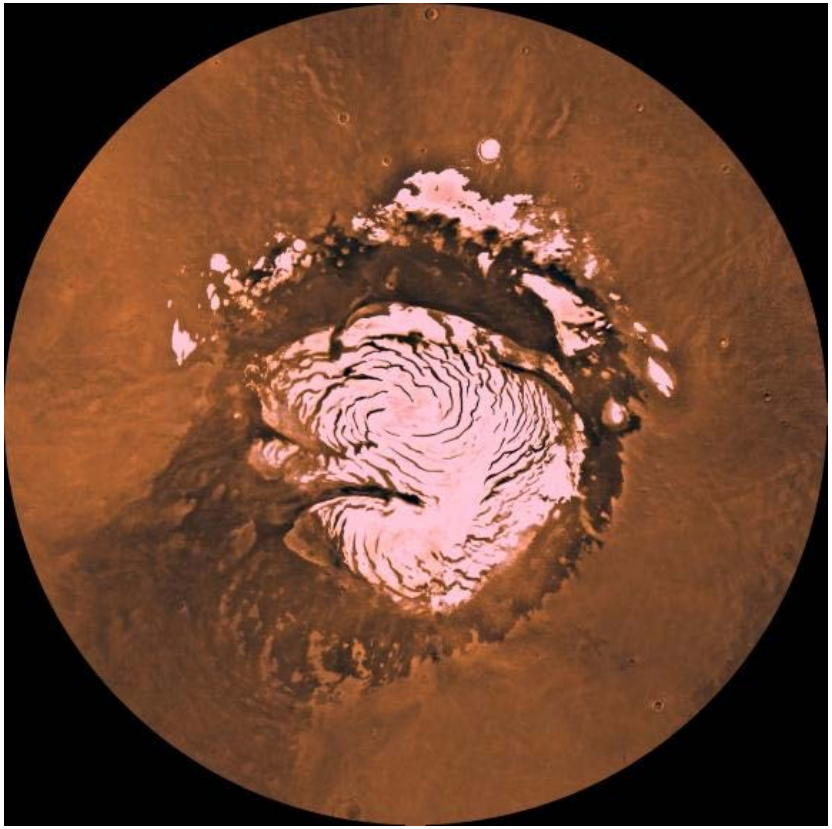


Water and CO_2 at the polar caps of Mars

The two polar ice caps are made largely of **water ice**.

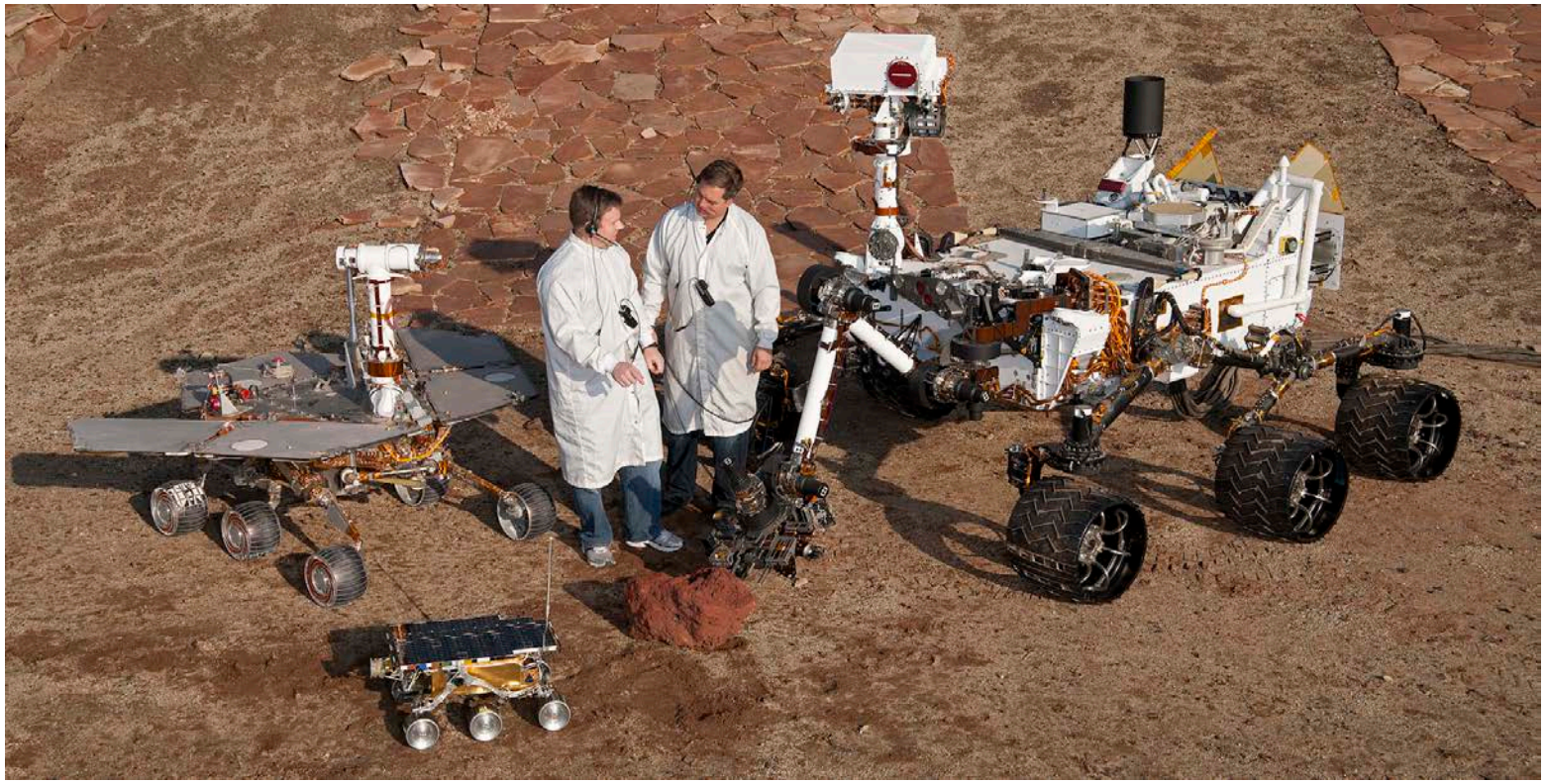
Frozen CO_2 (dry ice) accumulates as a thin layer about one meter thick on the north cap in the northern winter only, while the south cap has a permanent dry ice cover about eight meters thick.

During winter freezing CO_2 adheres to water-ice crystals and dust grains in the atmosphere,
causing them to fall to the ground and coat the surface with frost.



Mars's Northern ice cap.

Missions to Mars



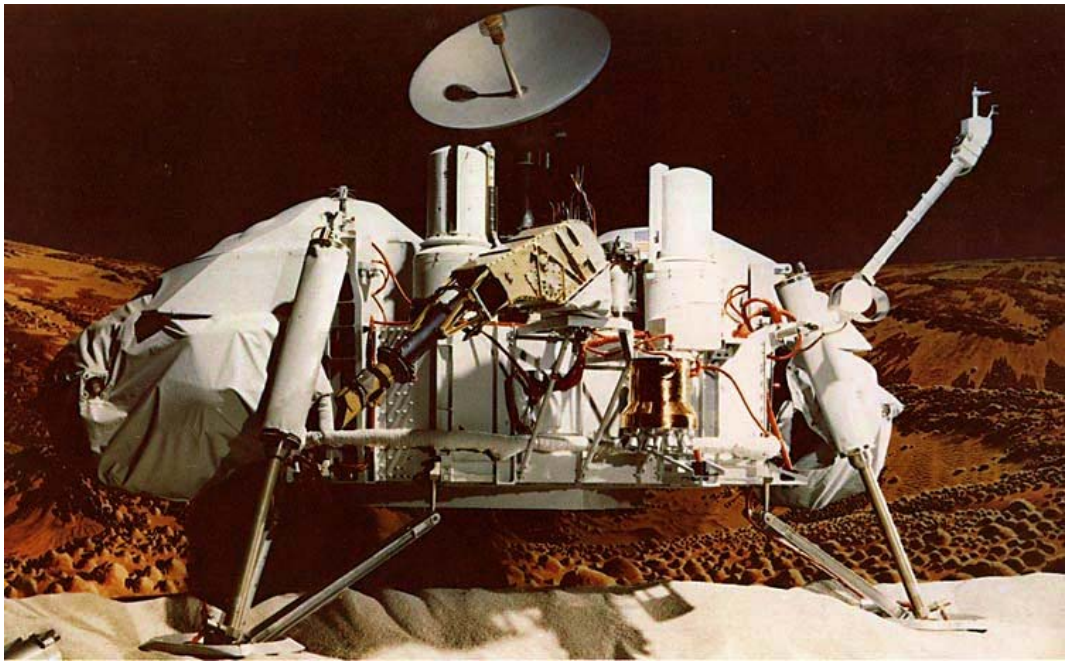
Missions to Mars

1. Viking Lander 1 and Viking Lander 2, touched down in 1976.

2. Mars Pathfinder (landed 1997)

3. Three Mars Exploration Rovers (Spirit and Opportunity) (landed 2004), Curiosity (landed 2012) were equipped with electrically driven wheels that allow travel over the surface.

Missions to Mars: VIKING LANDERS



Martian Regolith was found to be rich in **iron, silicon, and sulfur** and in unstable chemicals called **peroxides** and superoxides, which break down in the presence of water to release oxygen gas.

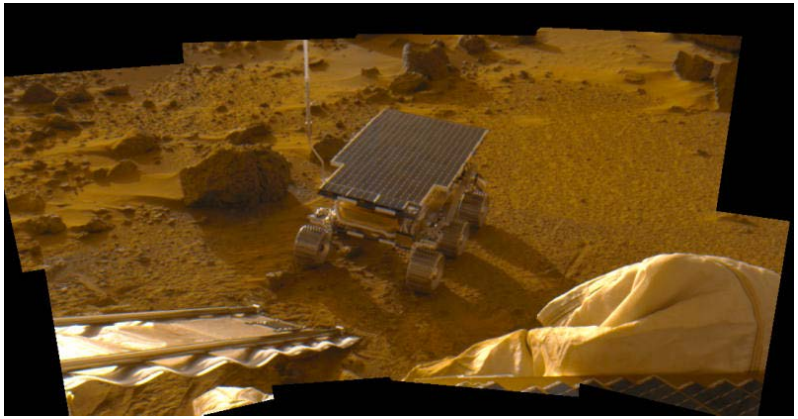
Viking Landers did not detect any biologically significant chemical reactions in samples of the Martian regolith.

Missions to Mars: Pathfinder

Pathfinder landed on northern lowlands called **Ares Vallis**, which appears to be an ancient flood plain. Found igneous, and rocks with layered structure similar to **sedimentary rocks** on Earth.

Frequent "**dust devils**" were found and these gusts are a possible mechanism for mixing dust into the atmosphere.

Pathfinder found **rounded pebbles and cobbles** on the ground that possibly formed in running water, during a warmer past in which liquid water was stable.



Missions to Mars: Rovers

The two Mars Exploration Rovers also landed (2004) in sites that were suspected to have been under water in the distant past.
Spirit touched down in **Gusev Crater**, a possible former lake in a giant impact crater.

The destination for **Opportunity** was the flat plain of Sinus Meridianii. Opportunity discovered rocks containing **hematite,** a type of iron oxide and rocks containing sulfur-rich minerals. These rocks tend to form in wet locations.

Curiosity landed in Gale Crater containing sedimentary rock layers.

What have we learned?

- **What are the major geological features of Mars?**
  - Differences in cratering across surface
  - Giant shield volcanoes
  - Evidence of tectonic activity

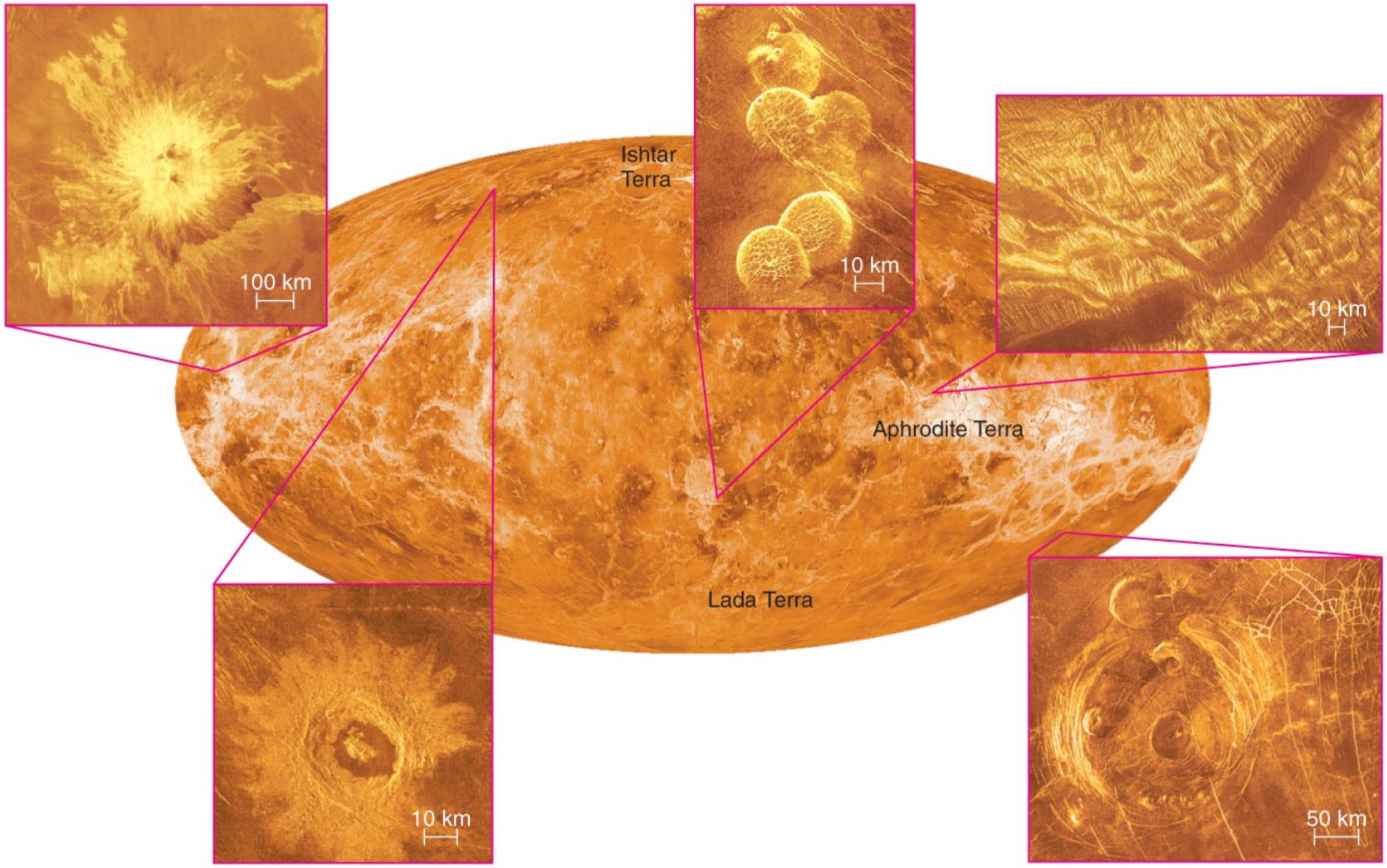
What have we learned?

- **What geological evidence tells us that water once flowed on Mars?**
  - Some surface features look like dry riverbeds.
  - Some craters appear to be eroded.
  - Rovers have found rocks that appear to have formed in water.
  - Gullies in crater walls may indicate recent water flows.

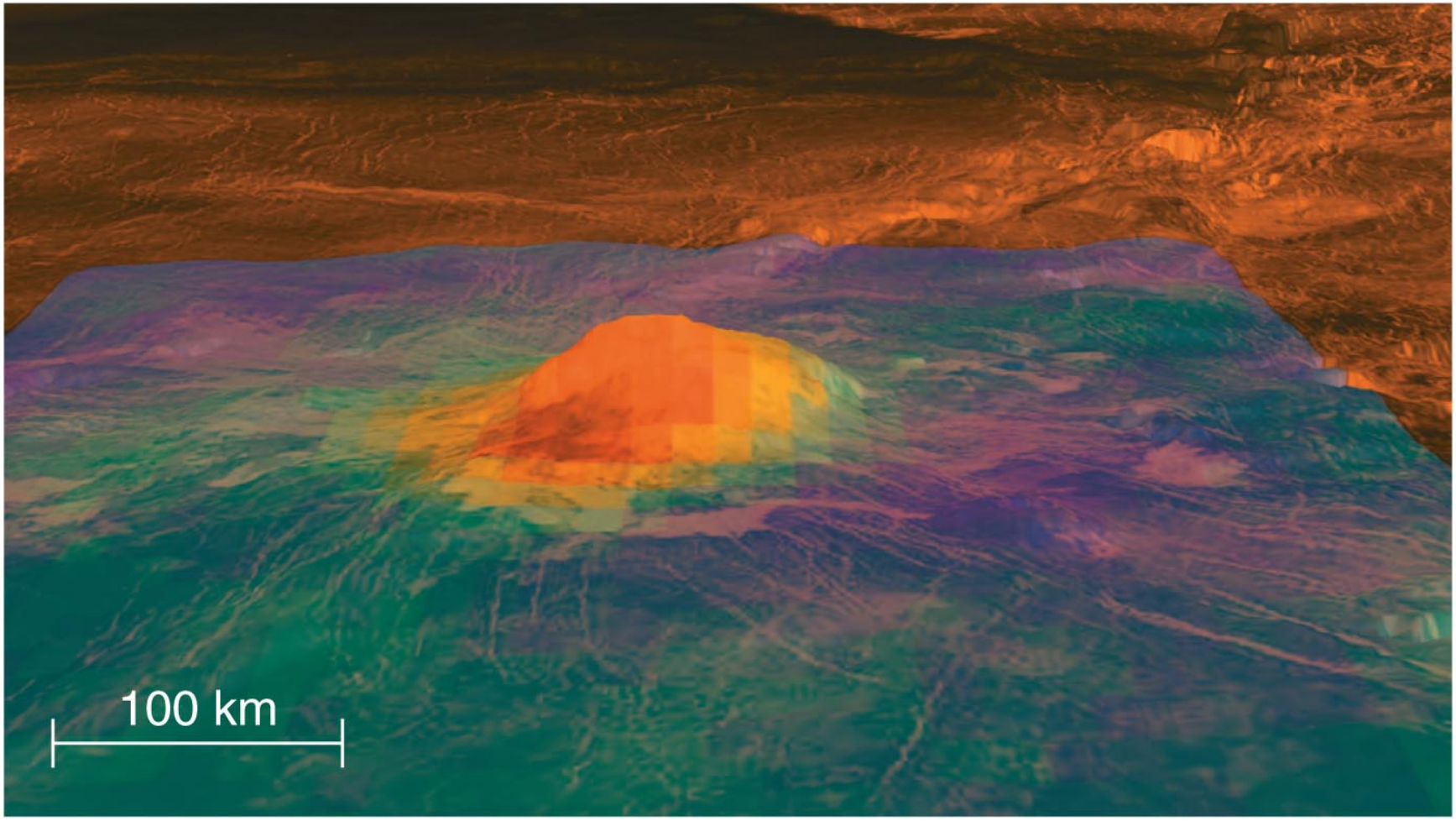
9.5 Geology of Venus

- Our goals for learning:
  - **What geological processes have shaped Venus?**
  - **Does Venus have plate tectonics?**

What geological processes have shaped Venus?

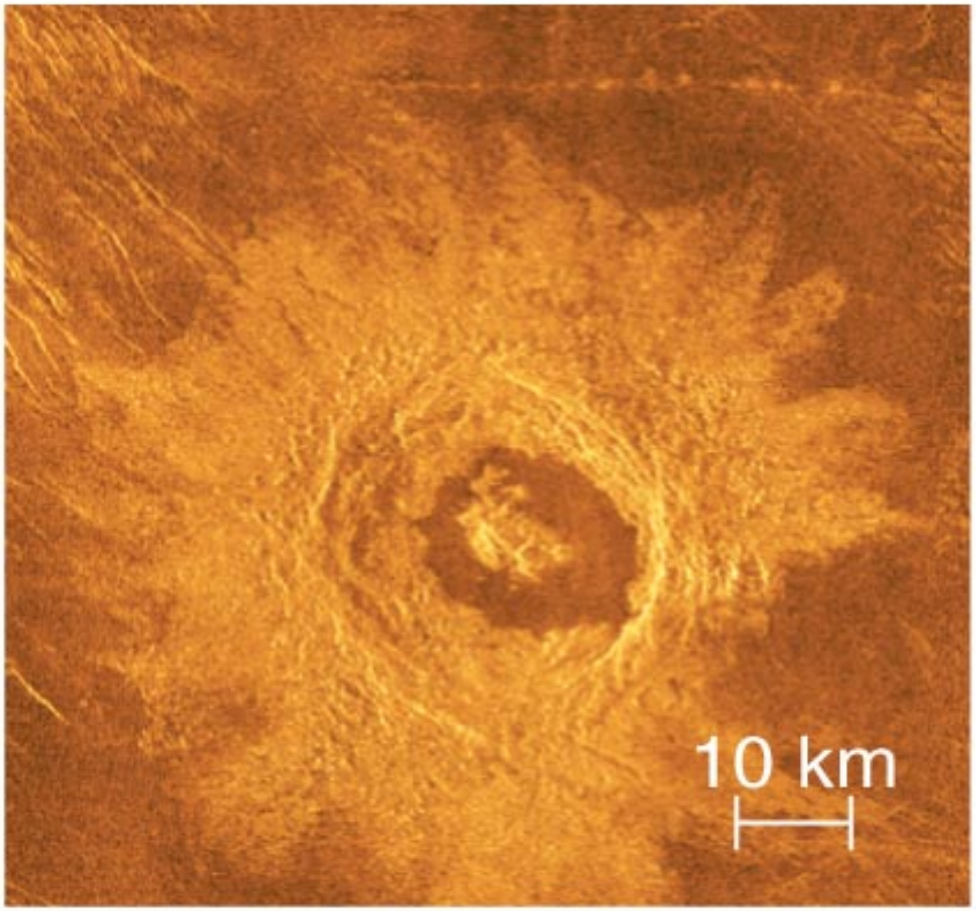


Radar Mapping



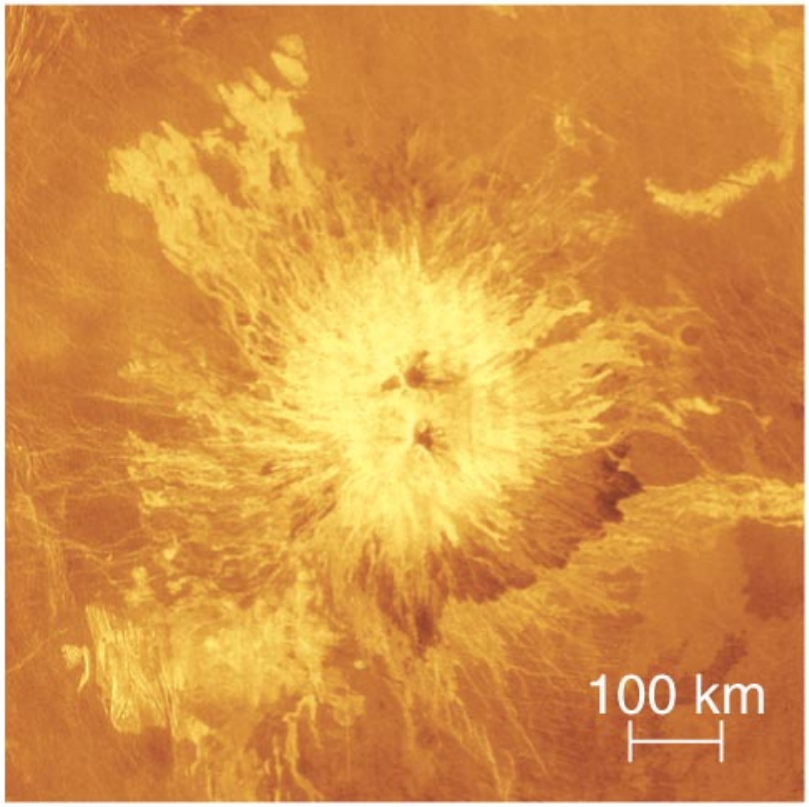
- Its thick atmosphere forces us to explore Venus's surface through radar mapping.

Cratering on Venus



- Venus has impact craters, but fewer than the Moon, Mercury, or Mars.
- Lack of small craters (small meteoroids likely did not make it through Venus's thick atmosphere)

Volcanoes on Venus

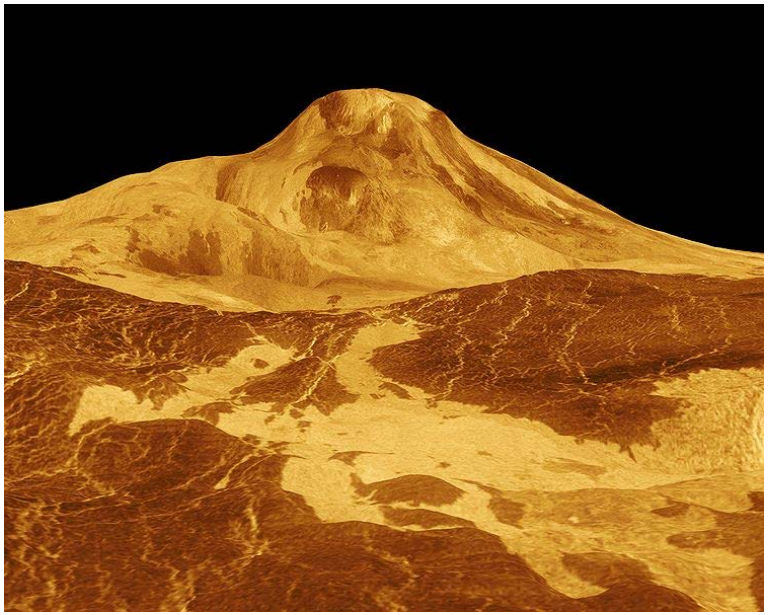


- It has many volcanoes, including both shield volcanoes and stratovolcanoes.

Volcanoes on Venus

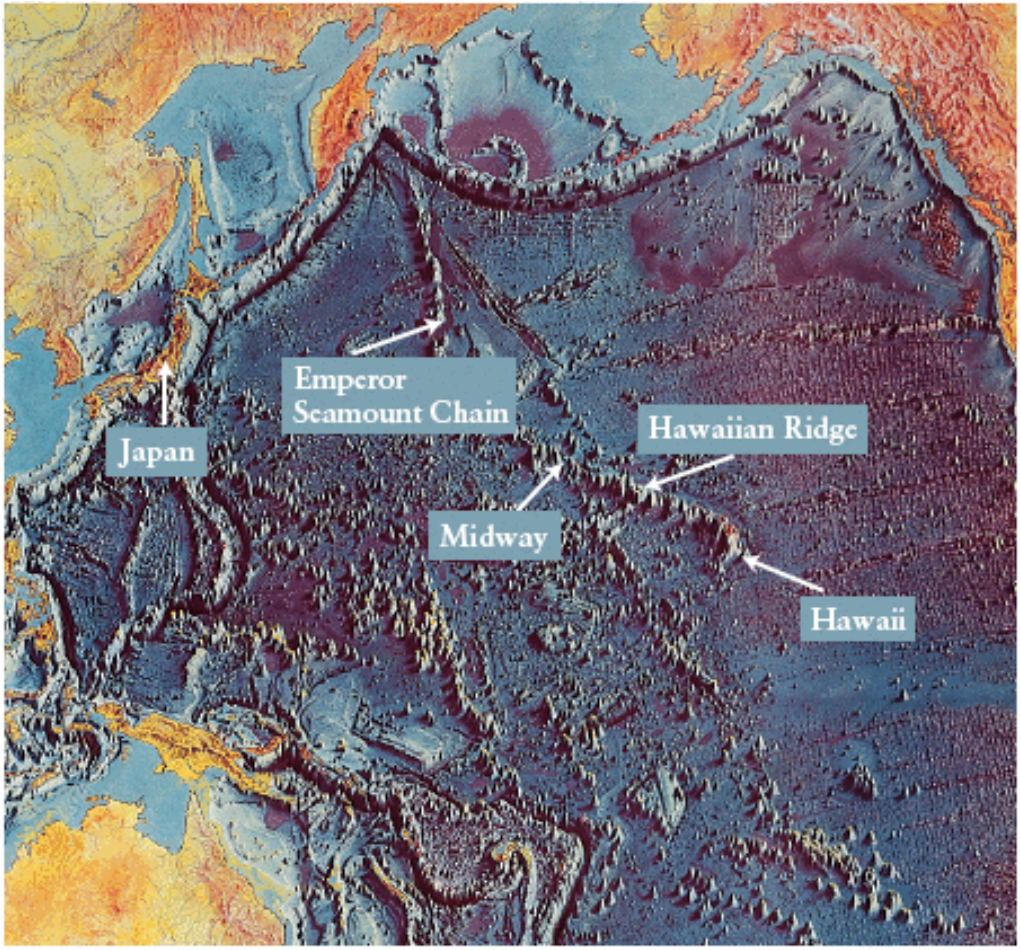
On Venus shield volcanoes are thought to be formed by **hot-spot volcanism.**

Hot-Spot volcanism is a process in which magma rises to the surface from a hot spot in the mantle elevating the overlying surface and creating a shield volcano.



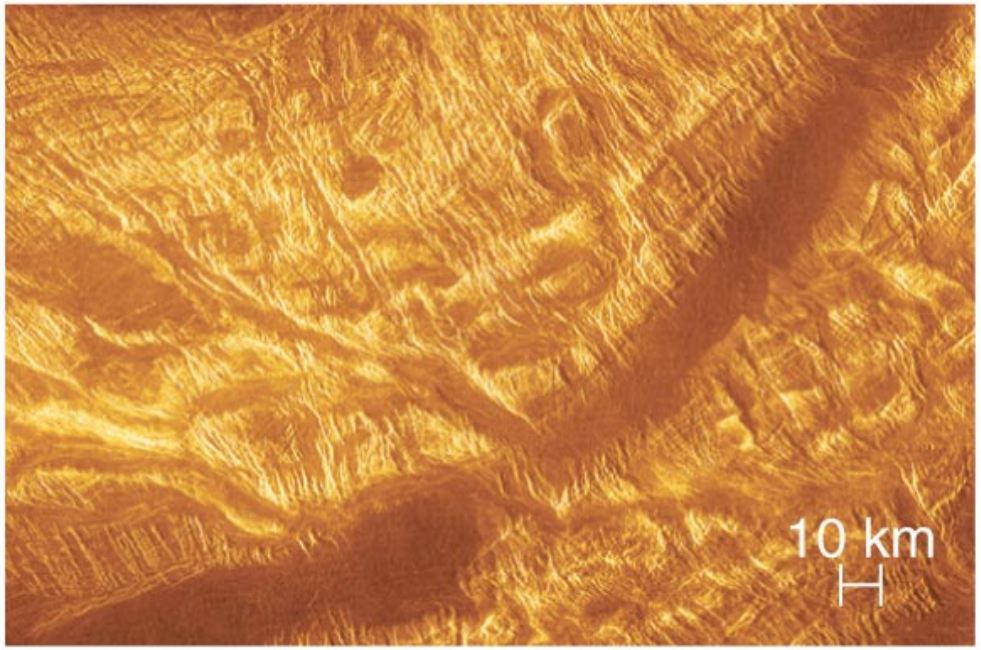
Maat Mons on Venus. The vertical scale has been stretched by a factor of 22.5

Hot-Spot Volcanism on Earth



A hot spot under the Pacific plate has produced the Hawaiian Islands and the Emperor Seamount Chain.

Tectonics on Venus



- The planet's fractured and contorted surface indicates tectonic stresses.

Erosion on Venus

- Photos of rocks taken by landers show little erosion.
- Venus does not appear to have plate tectonics, but entire surface seems to have been "repaved" 750 million years ago.

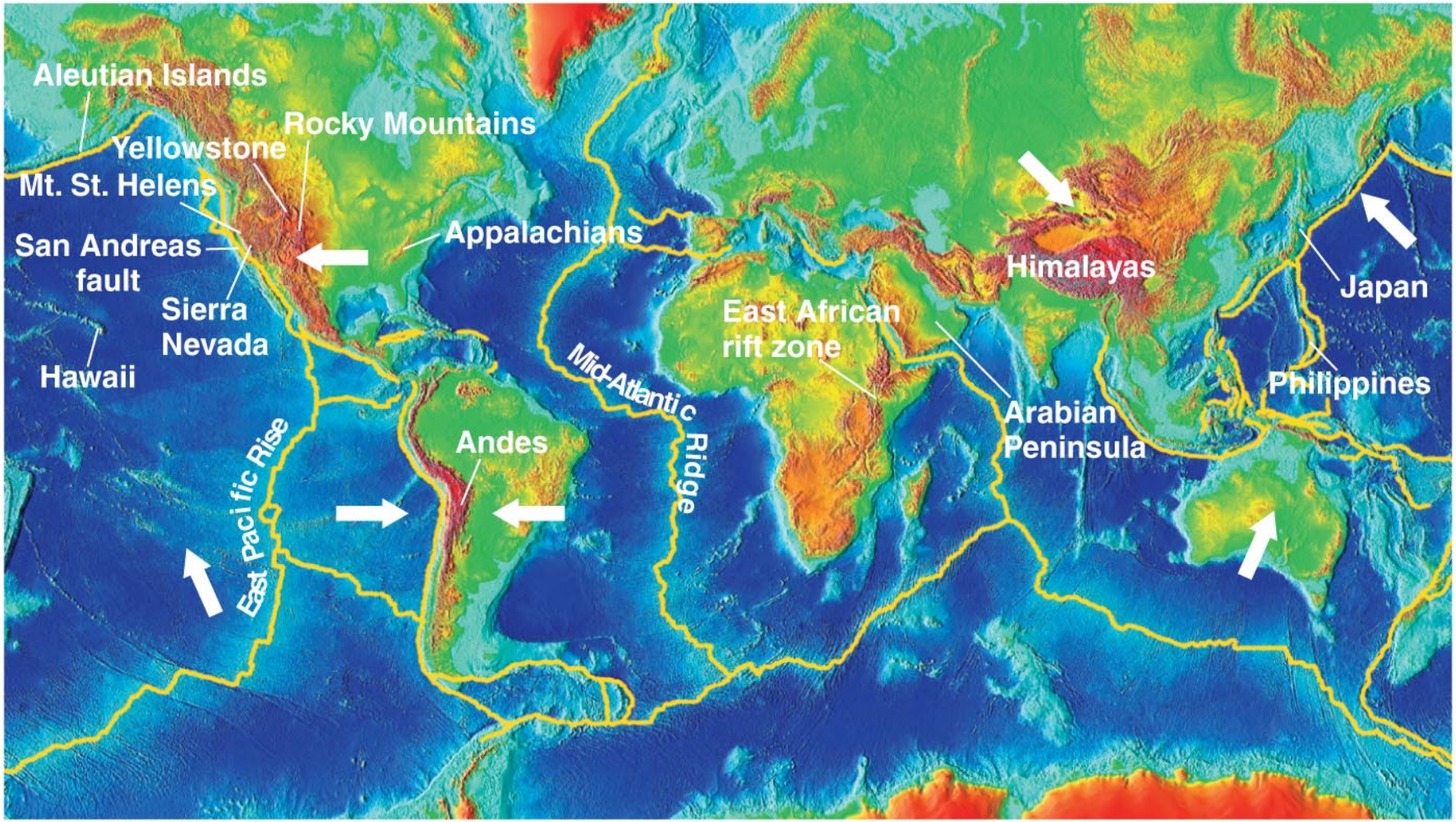
What have we learned?

- **What geological processes have shaped Venus?**
  - Venus has cratering, volcanism, and tectonics but not much erosion.
- **Does Venus have plate tectonics?**
  - The lack of plate tectonics on Venus is a mystery.

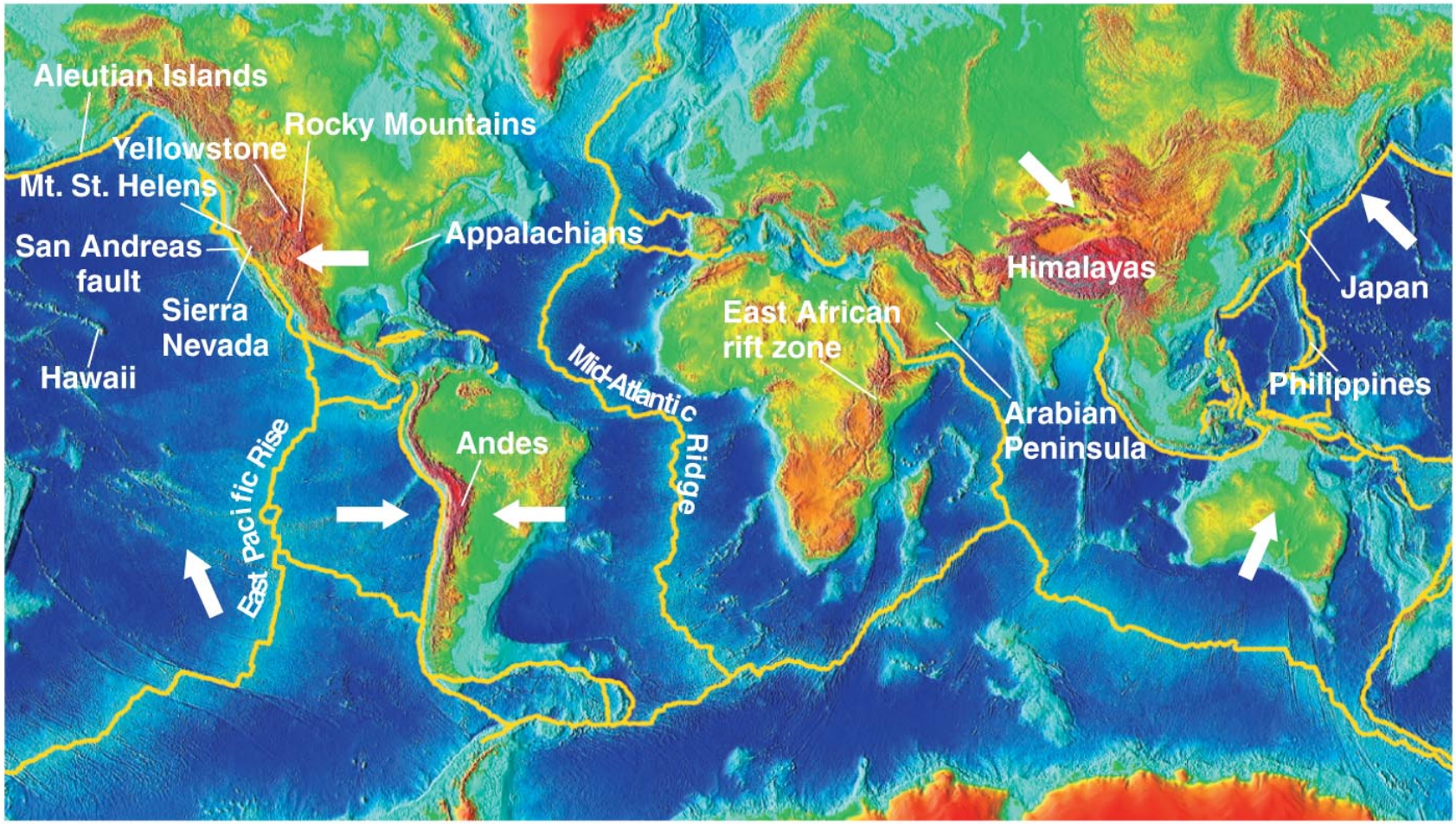
9.6 The Unique Geology of Earth

- Our goals for learning:
  - **How is Earth's surface shaped by plate tectonics?**
  - **Was Earth's geology destined from birth?**

How is Earth's surface shaped by plate tectonics?



Continental Motion



- Motion of the continents can be measured with GPS.

Continental Motion

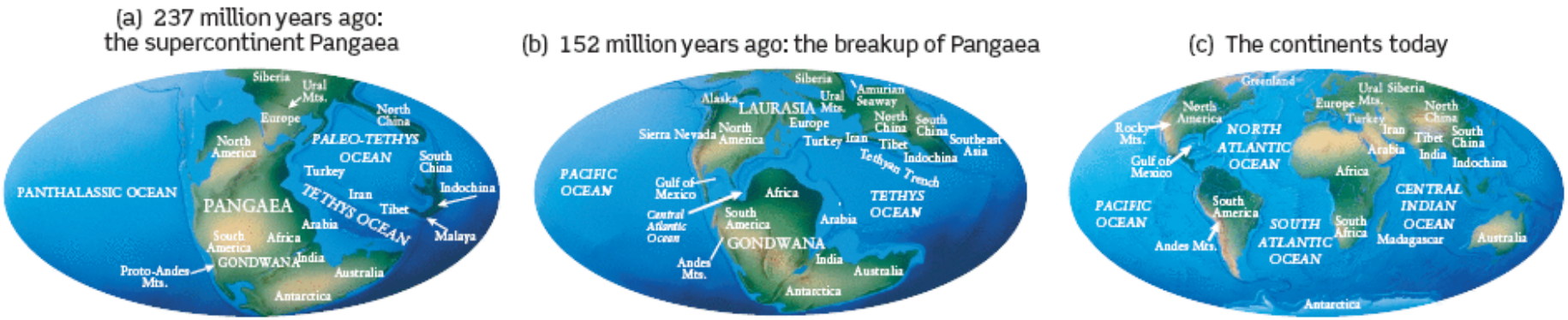
Continental Drift Theory

Alfred Wegener proposed that continents drift and that about 2 $\times 10^8$ years ago there was one "**supercontinent**" that he called **Pangaea.**

A refined theory posits that the Pangaea first split into **Gondwana** and **Laurasia** seperated by the Tethys Ocean.

Gondwana later split into Africa and South America, with Laurasia dividing to become North America and Eurasia.

Continental Motion



The breakup of the supercontinent Pagaea.
Among the evidence confirming this picture are nearly identical rock formations 200 million years in age that today are thousands of kilometers apart but would have been side by side on Pangaea.

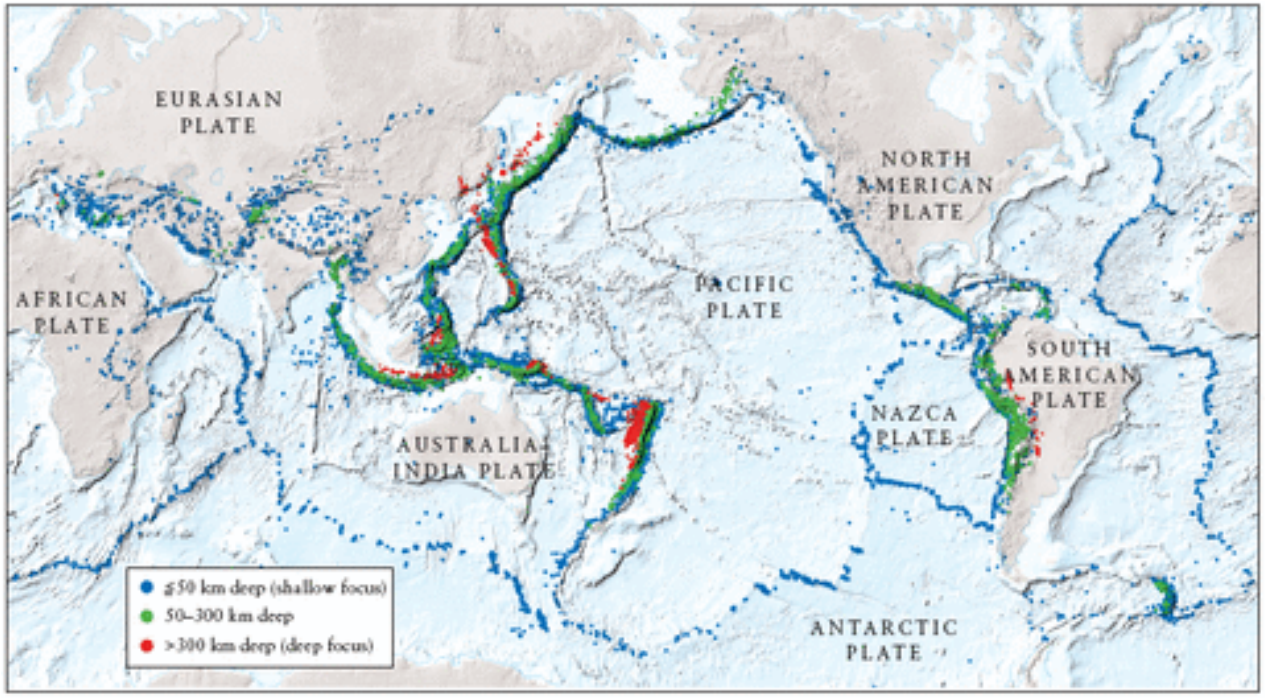
Continental Motion

In the mid 50's Bruce C. Heezen discovered long mountain ranges on the ocean floors, such as the **Mid-Atlantic Ridge**, which stretches all the way from Iceland to Antarctica.

The ridge is caused by lava seeping up from the Earth's mantle along a rift that extends from Iceland to Antarctica.

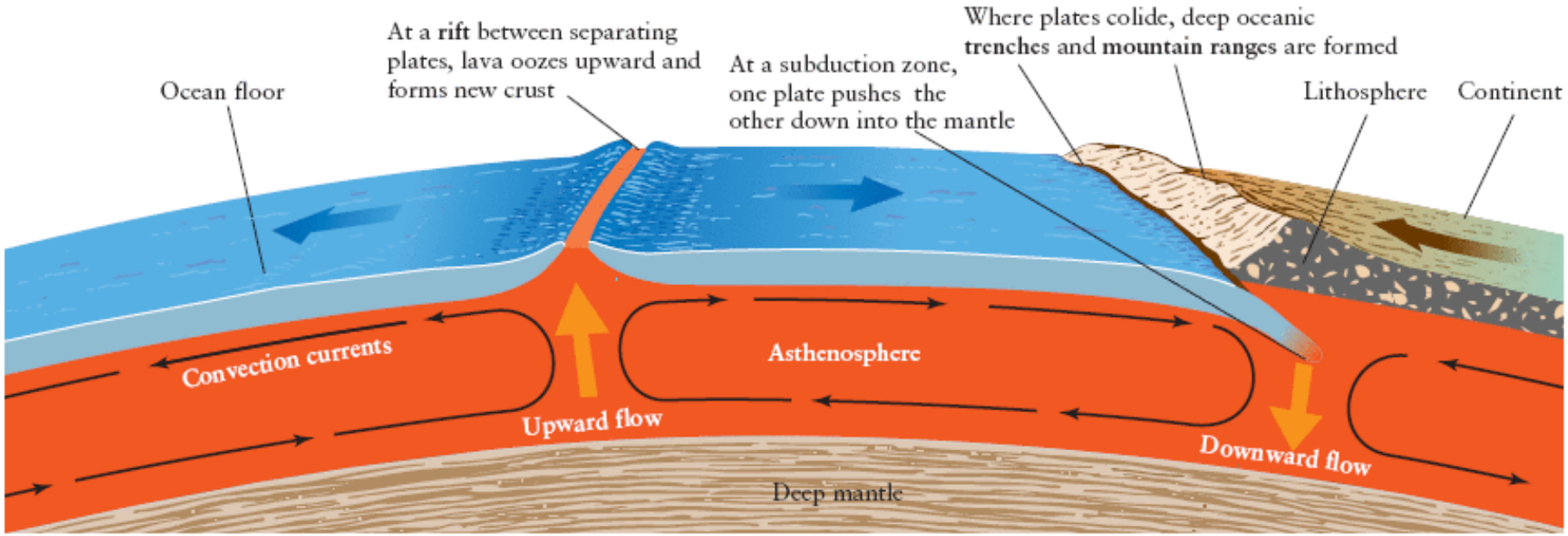
This upwelling of material along the Ridge forces the existing crusts apart, causing **seafloor spreading** at a speed of 3 cm per year.

Plate Tectonics



Earthquakes and volcanoes tend to occur at the boundaries of the Earth's crustal plates, where the plates are colliding, separating, or rubbing against each other. epicenters

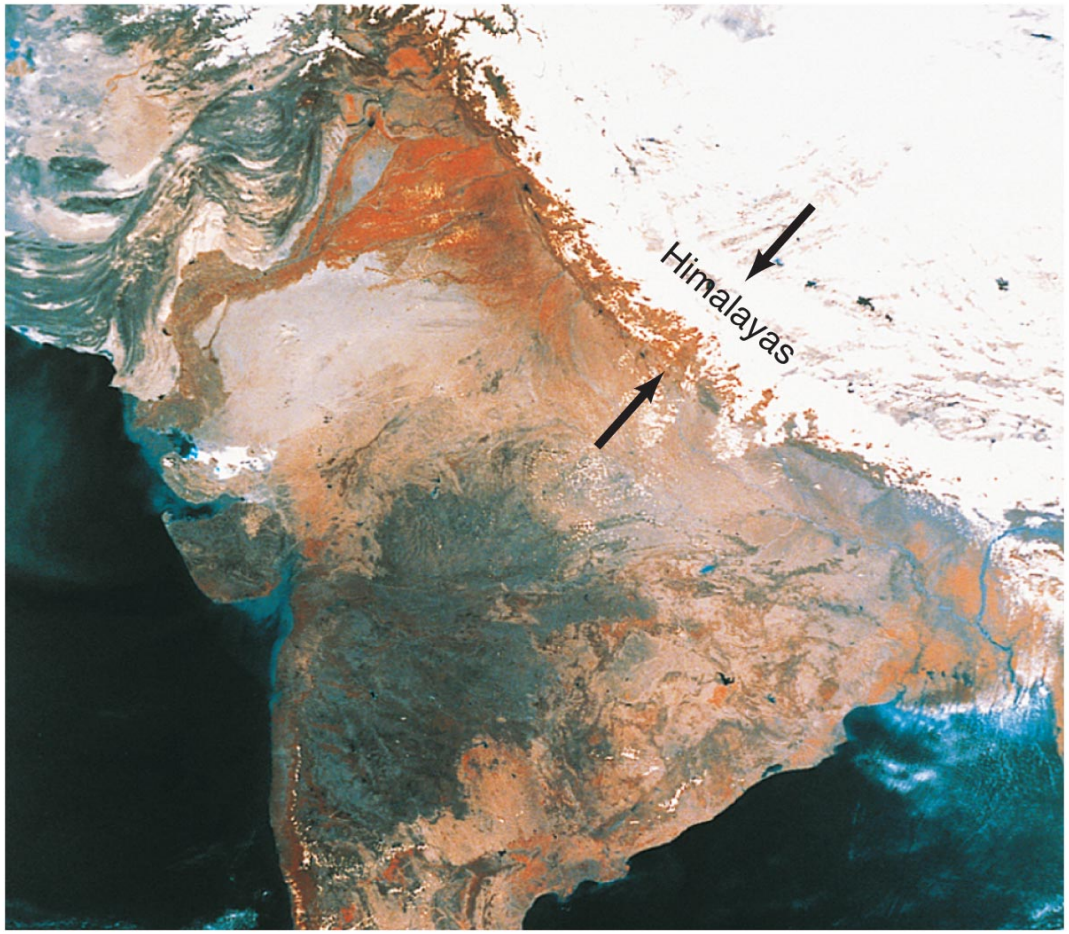
Plate Tectonics



What makes plates move:

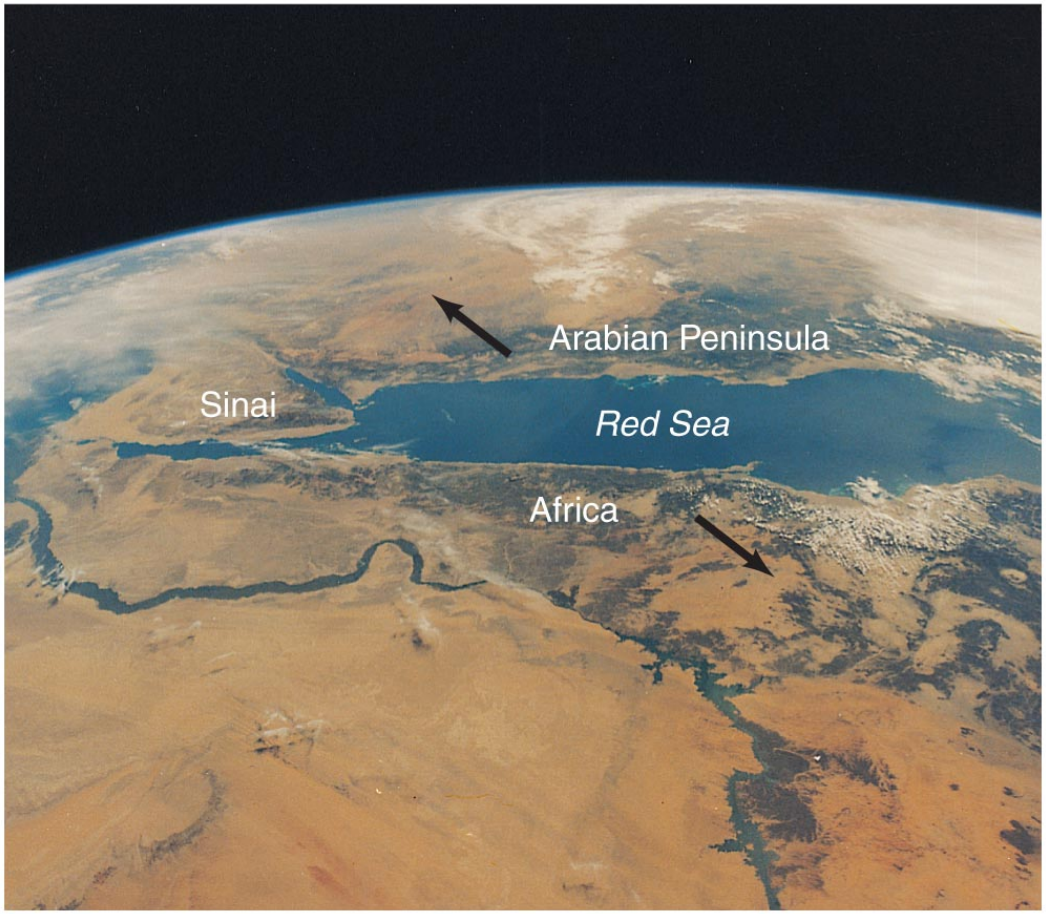
Convection currents in the asthenosphere are responsible for pushing around rigid, low-density crustal plates. New crust forms in oceanic rifts, where lava oozes upward between separating plates. Mountain ranges and deep oceanic trenches are formed where plates collide.

Surface Features



- The Himalayas formed from a collision between plates.

Surface Features



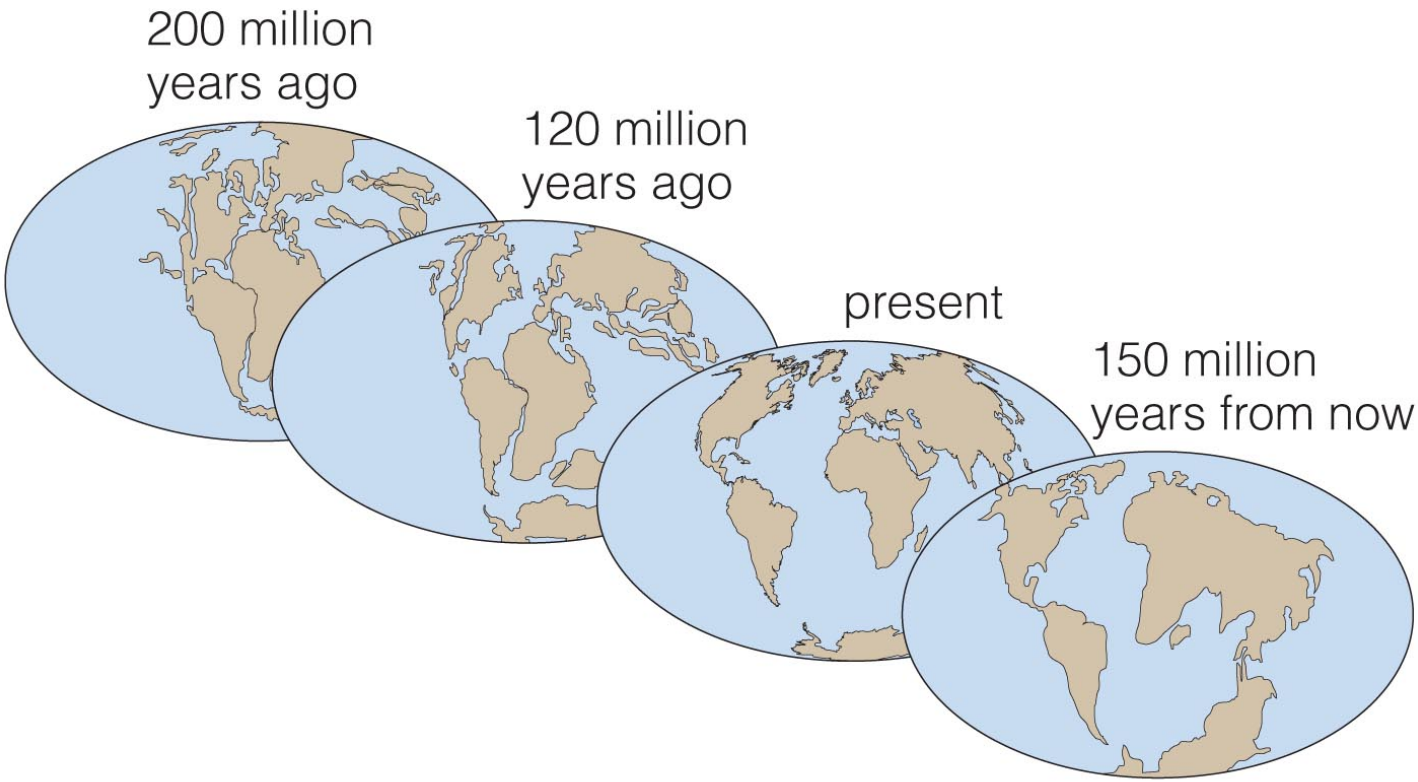
- The Red Sea is formed where plates are pulling apart.

Rifts, Faults, Earthquakes

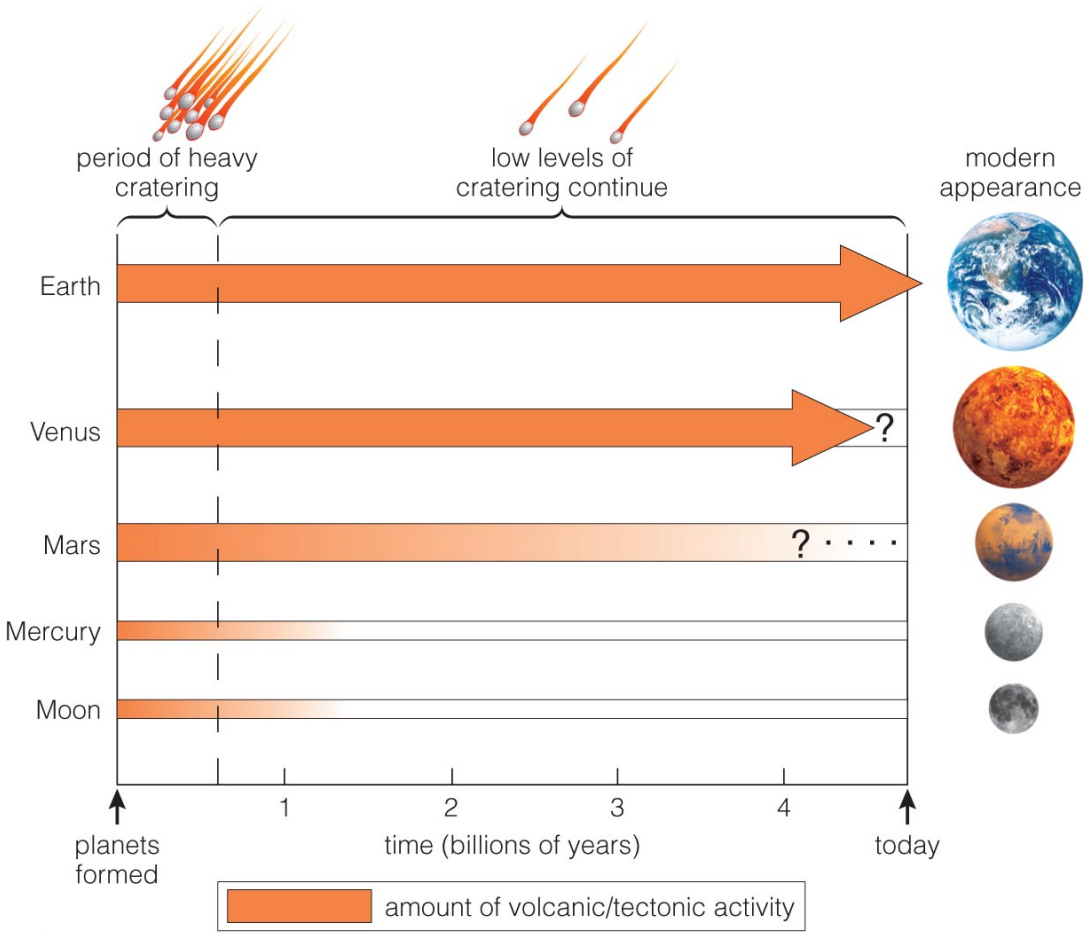
- The San Andreas fault in California is a plate boundary.
- Motion of plates can cause earthquakes.

Plate Motions

- Measurements of plate motions tell us past and future layout of the continents.



Earth's Destiny



- Many of Earth's features are determined by its size, rotation, and distance from Sun.

What have we learned?

- **How is Earth's surface shaped by plate tectonics?**
  - Measurements of plate motions confirm the idea of continental drift.
  - Plate tectonics is responsible for subduction, seafloor spreading, mountains, rifts, and earthquakes.

What have we learned?

- **Was Earth's geology destined from birth?**
  - Many of Earth's features are determined by its size, distance from Sun, and rotation rate.