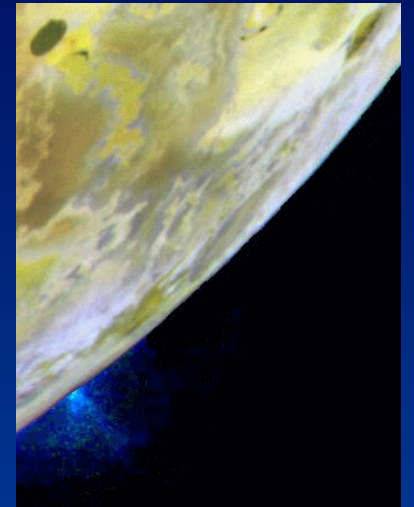
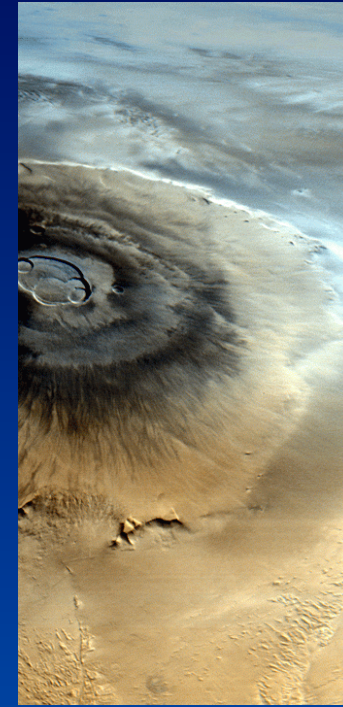
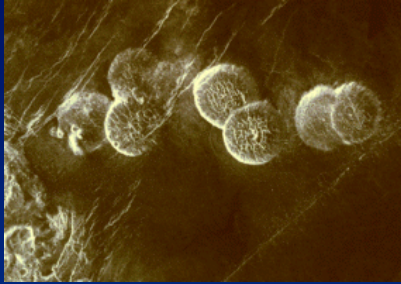
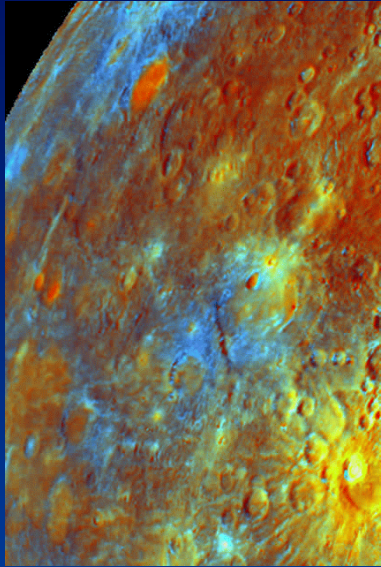
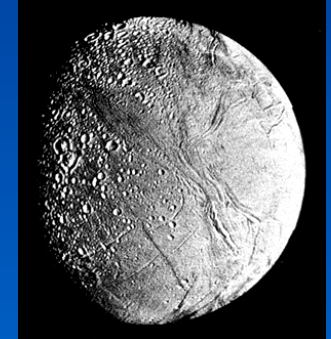
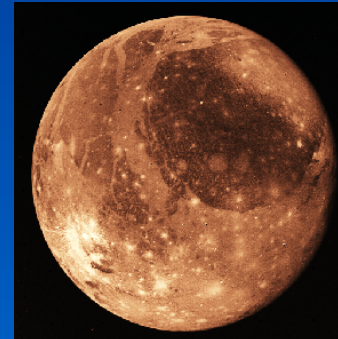
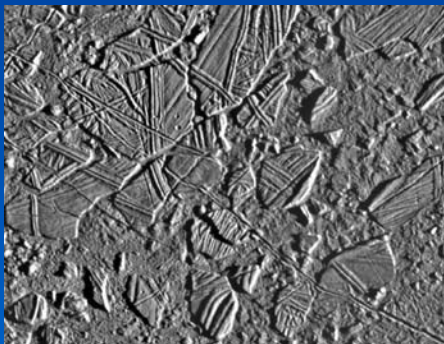


Planetary Volcanism

“Standard cases”



Cryovolcanism



Outline

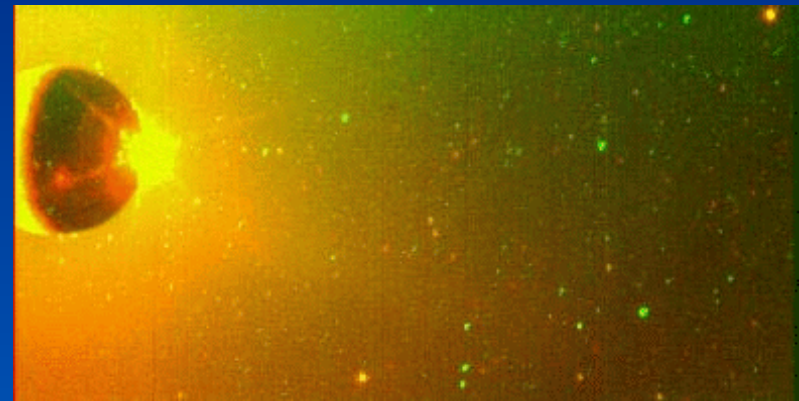
- ▶ Terrestrial volcanoes

- How do they work
 - Eruption dynamics
 - Volcanic landforms
 - Eruption products
 - Eruption types



- ▶ Other solar system bodies with “standard” volcanism

- Mercury
- Venus
- Moon
- Mars
- Io



- ▶ Cryovolcanism

- Europa, Ganymede, Enceladus, Triton

A few generalities

- Volcanism is a major process by which a planet transfers heat produced in its interior outwards to the surface
 - ▶ What produces the interior heat?
- Volcanic activity has produced at least 75% of the surface rocks on Earth and Venus as well as large parts of the surfaces of Mars, Moon, Io, and probably Mercury
- Understanding types of volcanic activities and hence the erupted magma gives indirect clues of the composition of the interior
- Volcanic activity has major impact on atmosphere and climate

Where does the heat come from?

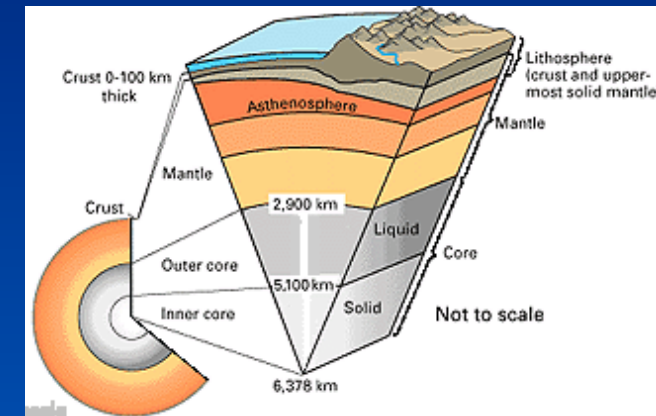
■ Accretional heat

- ▶ Compression of the forming body under its own weight: cumulated with energy of the impacts
- ▶ Earth's temperature was about 1000°C at the early formation stage



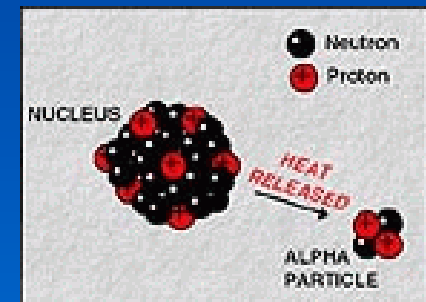
■ Iron catastrophe

- ▶ Partially molten iron and other heavy components sink downwards to form the core
- ▶ The released potential energy heats the lower mantle to temperatures $> 4000^{\circ}\text{C}$
- ▶ This happened on Earth about 500 Ma into its existence



■ Radiogenic heating (now about 80%)

■ Tidal dissipation

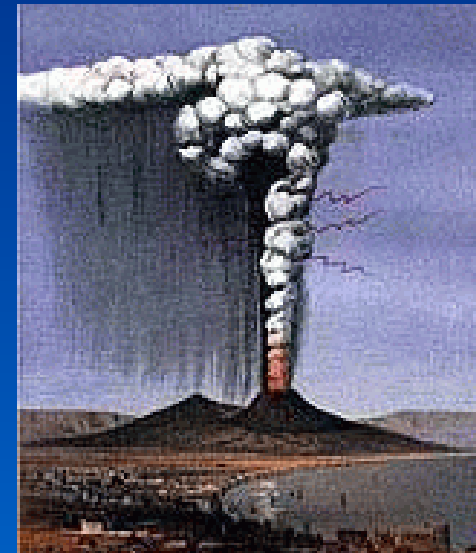


Radiogenic heating

- From radioactive decay of isotopes such as ^{238}U , ^{235}U , ^{232}Th and ^{40}K
- For present Earth this is $3\text{--}4 \times 10^{13} \text{ W}$
 - ▶ i.e. remove the Sun and Earth will still have an effective temperature of $\sim 34 \text{ K}$
- During formation and early stages
 - ▶ Concentrations of the radioactive isotopes were much higher
 - ▶ Shorter lived isotopes like ^{26}Al with its much higher energy flux were probably present
- When the solar system was young, even small bodies like the Moon or asteroids like Ceres and Vesta had enough radiogenic heating to drive some sort of volcanism

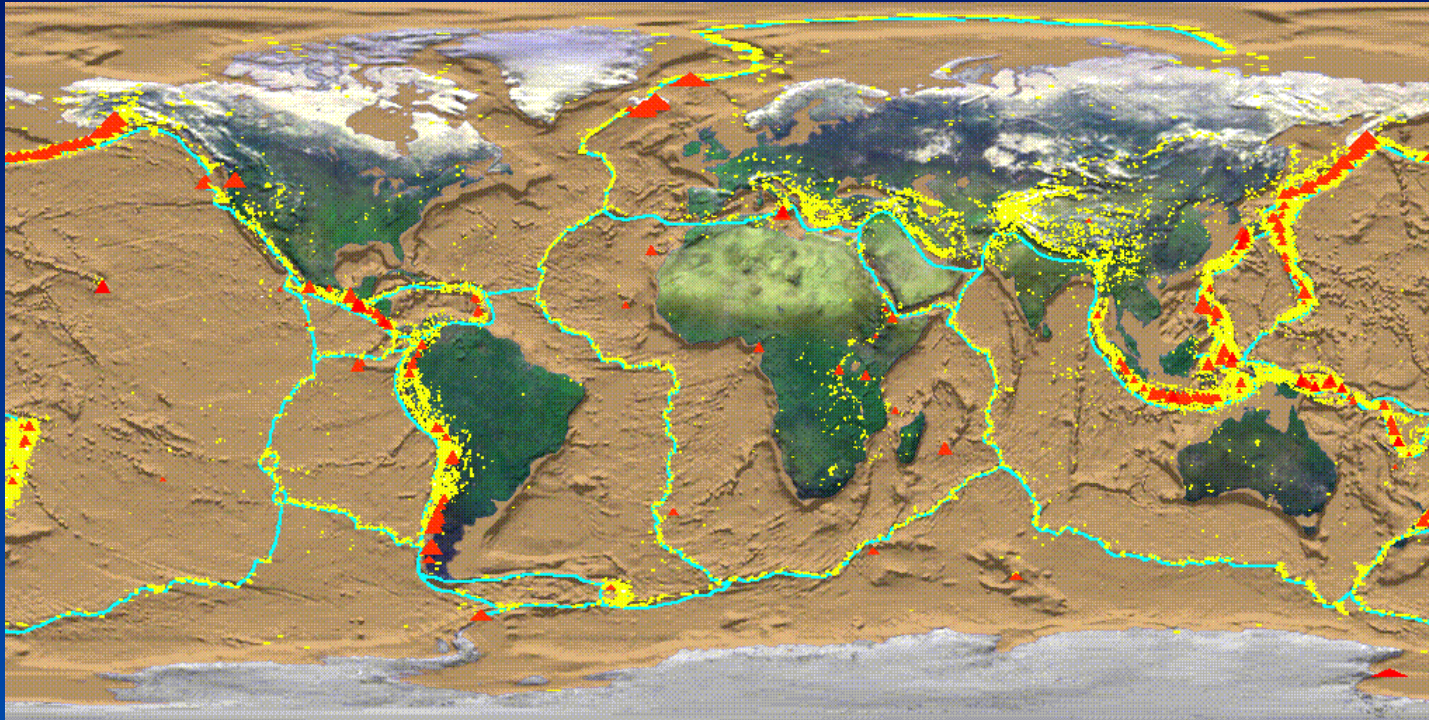
Getting rid of heat

- Amount of radiogenic heat is proportional to the volume
- The heat escape by diffusion and radiation is proportional to the surface area
- The larger the (rocky) planet the larger the volume to surface ratio
 - ▶ Heat can not escape
 - ▶ Volcanism is possible



Volcanic - tectonic environments

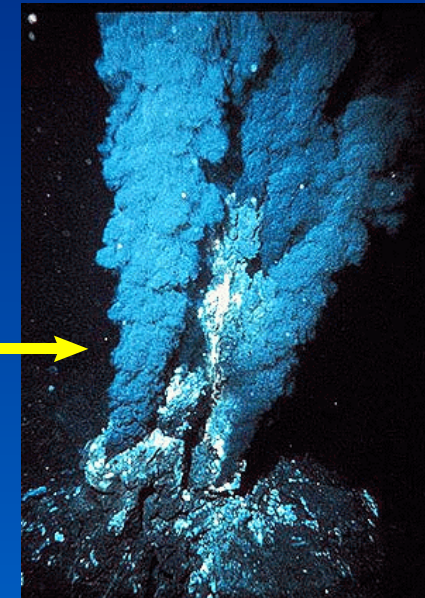
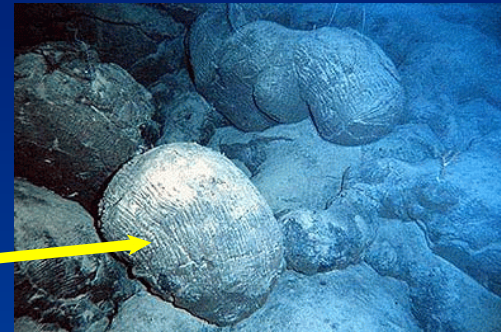
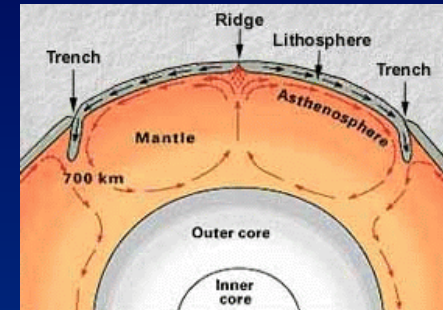
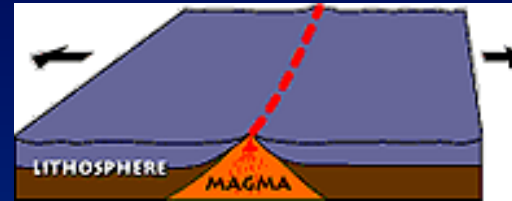
Most of the active volcanoes (~550) on earth are located along the margins of adjacent tectonic plates



- ▶ Plate boundaries - blue lines
- ▶ Recent earthquakes - yellow dots
- ▶ Active volcanoes - red triangles

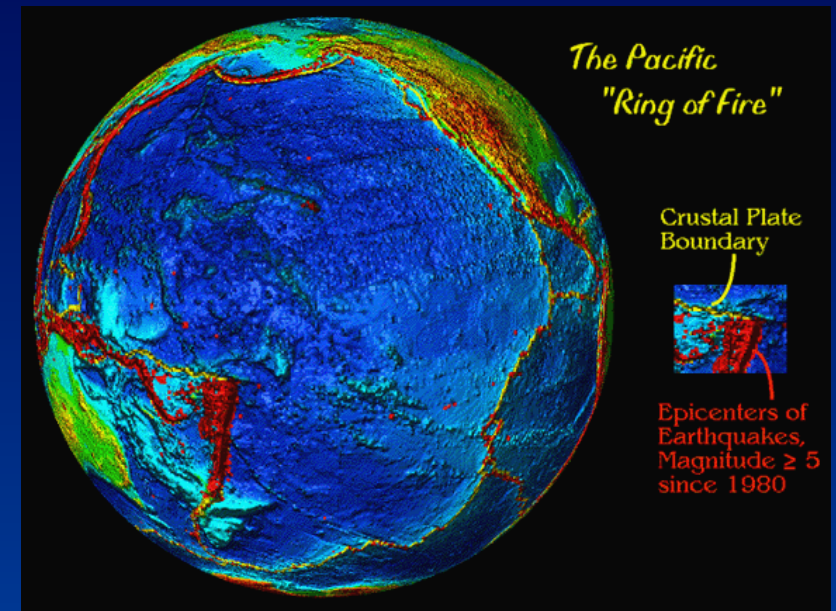
Environments - spreading center volcanism

- ▶ SCV occurs at the site of mid-oceanic ridges, where two plates diverge from each other
- ▶ As the plates are pulled apart, hot asthenosphere rises upward to fill voids of the extended lithosphere
- ▶ The asthenosphere decompresses and melts to produce basalt magmas
- ▶ The high heat content of mid-ocean ridges is evident from the occurrence of numerous hydrothermal vents
 - The hot springs created at the surface are called black smokers because they are readily identified by billowing dark clouds composed of metal-rich fluids



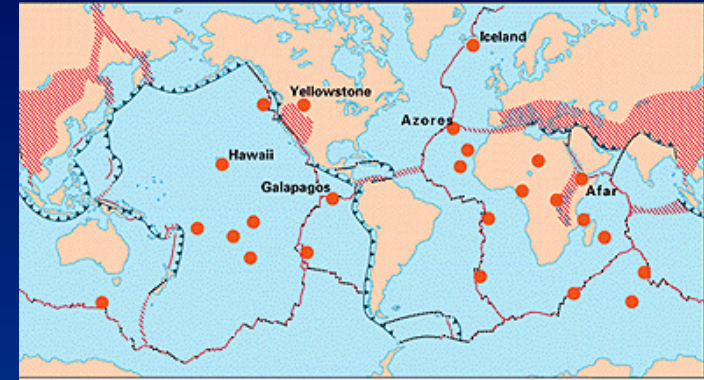
Environments - subduction zone volcanism

- ▶ The most volcanically active belt on Earth is known as the Ring of Fire, a region of subduction zone volcanism surrounding the Pacific Ocean
- ▶ Subduction zone volcanism occurs where two plates are converging on one another thus consuming the oceanic lithosphere into the earth's mantle
- ▶ As the descending plate bends downward at the surface, it creates a large linear depression called an oceanic trench
- ▶ These trenches are the deepest topographic features on the earth's surface (up to 11 km)
- ▶ When oceanic trench is involved the resultant chain is called an island arc (e.g. Aleutian Island chain)
- ▶ When continental lithosphere is involved the belt is then called a volcanic arc (Andes volcanic arc)



Environments - intraplate volcanism

- ▶ Although most volcanic rocks are generated at plate boundaries, there are a few exceptionally active sites of volcanism within the plate interiors (24)
- ▶ These intraplate regions of voluminous volcanism are called hotspots
- ▶ Most hotspots are thought to be underlain by a large plume of anomalously hot mantle
- ▶ These plumes appear to be generated in the lower mantle and rise slowly by convection.



Physicochemical controls on eruption style



Eruption of effusive basalt from the Pu'u O'o volcano on the east rift zone of the larger Kilauea volcano, Hawaii.

- ▶ Many eruptions are quiescent or effusive and are characterized by the calm extrusion of lava flows
- ▶ Other eruptions are highly explosive and are characterized by the violent ejection of fragmented volcanic debris, called tephra
- ▶ This depends on the composition of the magma (molten rock)
- ▶ The controlling factors on explosivity are
 - viscosity
 - temperature, and
 - the amount of dissolved gases in the magma



Eruption of a voluminous plume of tephra is typical of explosive (Plinian) eruptions, as demonstrated here in the 1980 eruption of Mt. St. Helens. These eruptive tephra plumes can travel tens of kilometers into the stratosphere.

Magma composition and rock types

- ▶ Only ten major elements in most magmas: O, Si, Al, Fe, Mg, Ti, Ca, Na, K and P
- ▶ O and Si are most abundant and classification is in terms of the SiO_2 content
- ▶ Mafic magma will crystallize to produce basalt
- ▶ Felsic magma will produce dacite and rhyolite (granite)

| SiO_2 content | Magma type | Volcanic rock |
|------------------------|------------------|---------------|
| ~50% | Mafic | Basalt |
| ~60% | Intermediate | Andesite |
| ~65% | Felsic (low Si) | Dacite |
| ~70% | Felsic (high Si) | Rhyolite |

Controls on explosivity

- ▶ The amount of dissolved gas in the magma provides the driving force for the explosive eruptions
- ▶ Low viscosity magma allows the gases to migrate
- ▶ Highly viscous magma impedes mobility of gas bubbles
- ▶ Basaltic magmas are nonexplosive
- ▶ Rhyolitic magmas are explosive

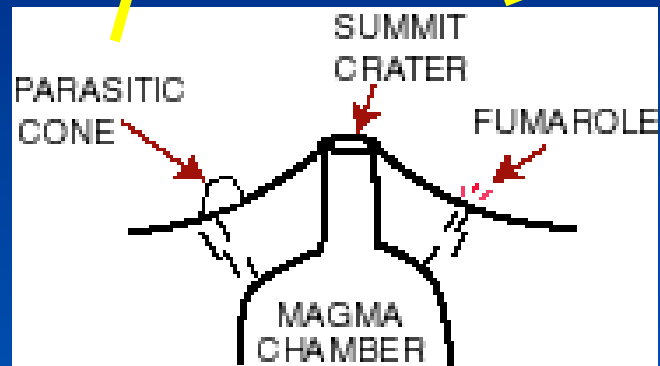
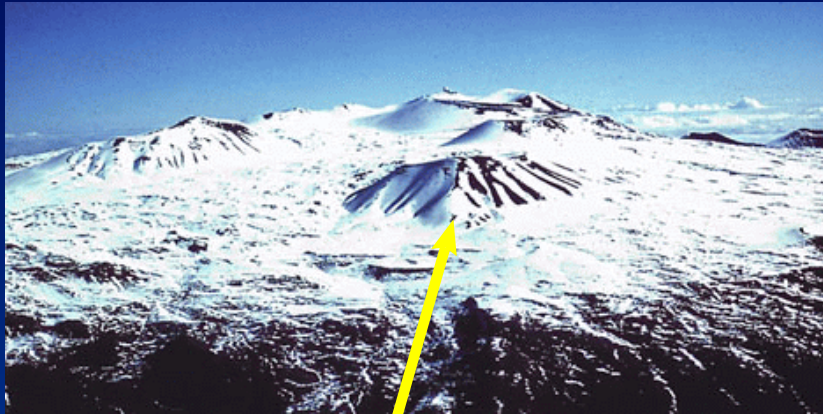
| SiO ₂ | Magma type | T [°C] | Viscosity | Gas content | Eruption style |
|------------------|--------------|--------|--------------|--------------|----------------|
| ~ 50% | mafic | ~ 1100 | low | low | nonexplosive |
| ~ 60% | intermediate | ~ 1000 | intermediate | intermediate | intermediate |
| ~ 70% | felsic | ~ 600 | high | high | explosive |

Vesiculation



- ▶ As dissolved gases are released from the magma, bubbles form
- ▶ In some basalt flows, escaping gases form vesicle cylinders
- ▶ Most lava flows contain vesicle-rich tops generated by gas release and rise of bubbles

Volcano types - generic features



Main volcano types

- ▶ Scoria cone
 - Straight sides with steep slopes
 - Large summit crater
 - Basalt tephra occasionally andesitic
- ▶ Shield volcano
 - Very gentle slopes
 - Convex upward
 - Basalt lava flows
- ▶ Stratovolcano
 - Gentle lower slopes, but steep upper slopes
 - Concave upward
 - Small summit crater
 - Highly variable composition

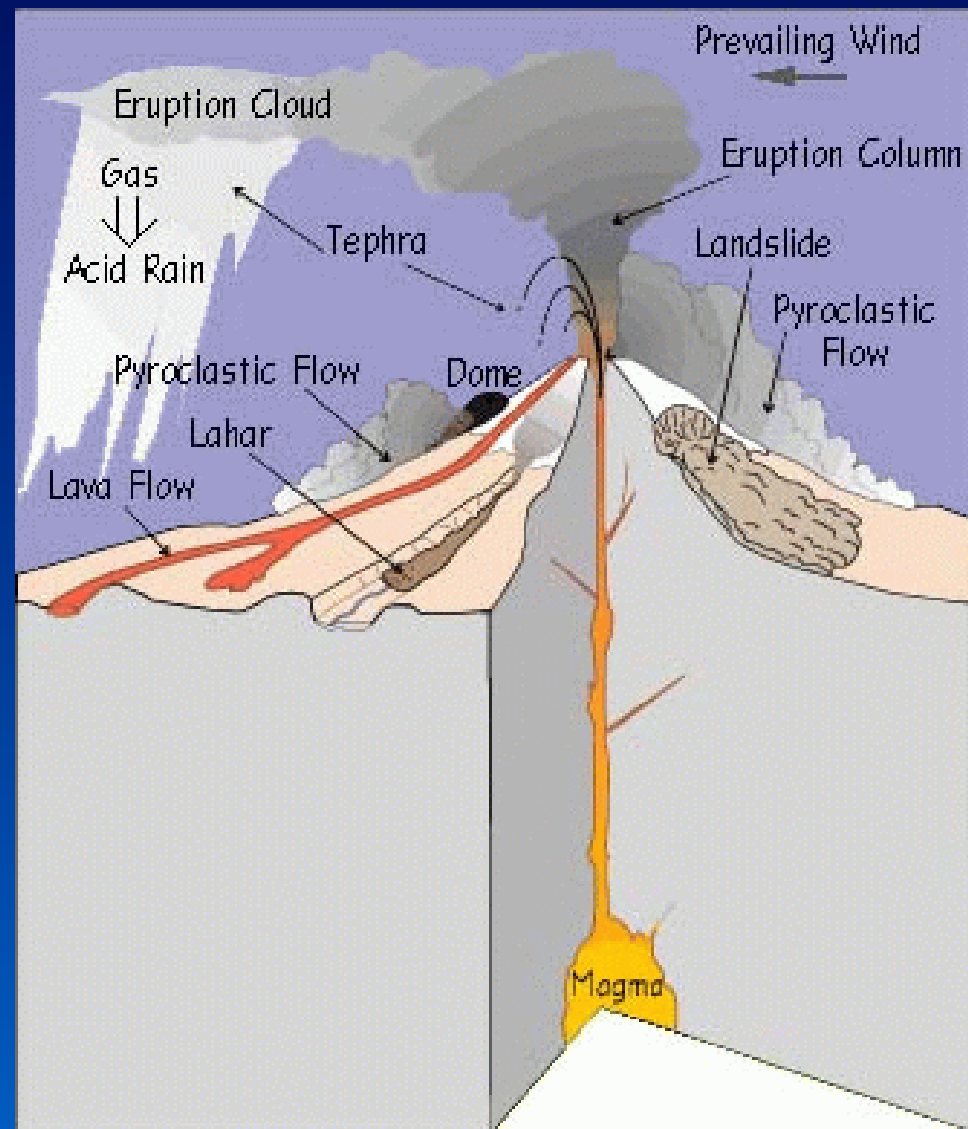


Calderas

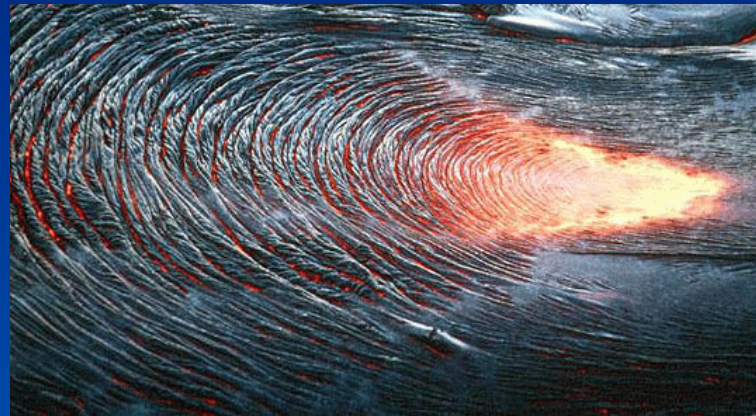


- ▶ The edifice of the volcano may collapse into the voided reservoir, thus forming a steep, bowl-shaped depression called a caldera - not a summit crater
- ▶ Crater-Lake type calderas associated with the collapse of stratovolcanoes
- ▶ Basaltic calderas associated with the summit collapse of shield volcanoes

Eruption products



Lava flow types - basaltic lava



- ▶ Volumetrically most lava is basaltic
 - No gas pressure build up
 - Relatively calm, non explosive eruptions

Lava flow types - andesitic to rhyolitic lava



- ▶ Andesite generally produces blocky lava
 - The surface contains smooth-sided, angular fragments
 - High thickness/area aspect ratio of $>1/100$
 - Usually erupts from stratovolcanoes
 - Flow advances only short distance down the flanks of a volcano

Lava channels



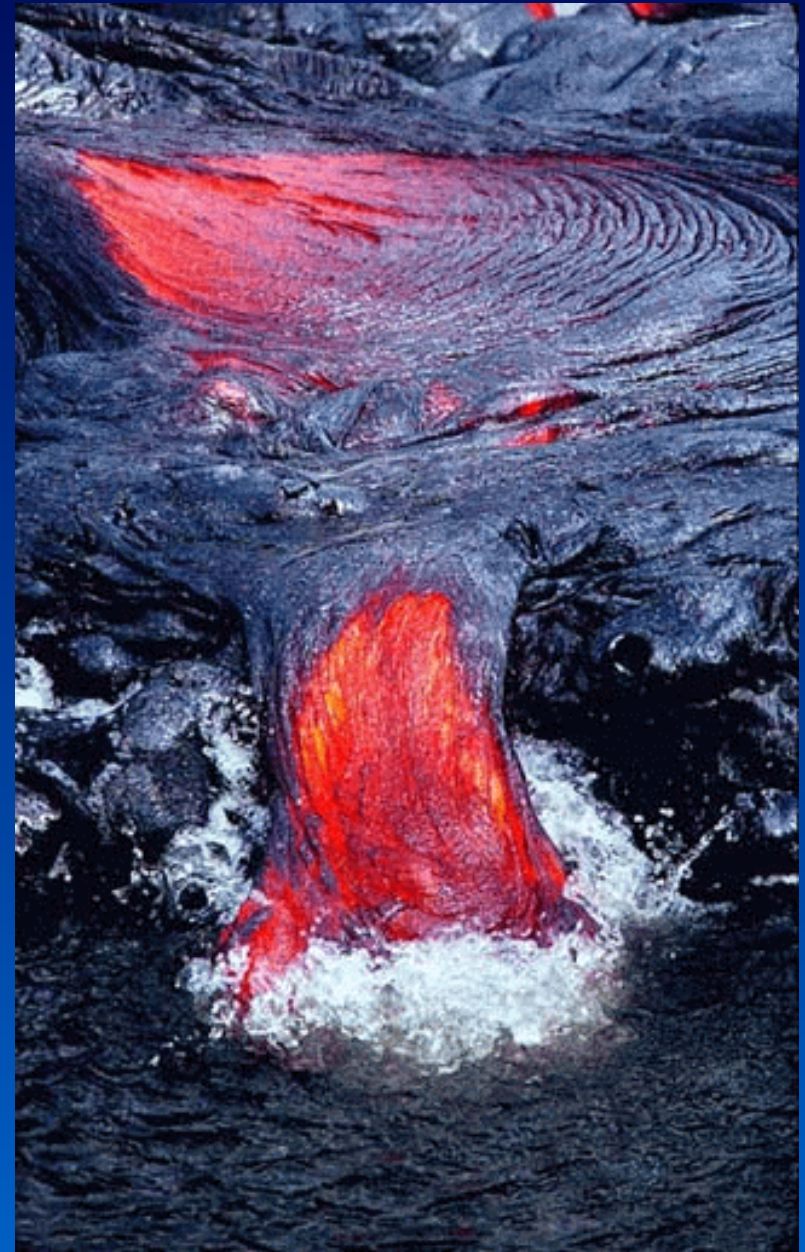
Fluid basalt will commonly move down slope by creating its own channel ways above gently sloping terrains, or by flowing down in pre-existing stream channels.



Lava and water



The injection of basaltic lava into surface water can be quiescent or highly explosive.



Pyroclastic flows



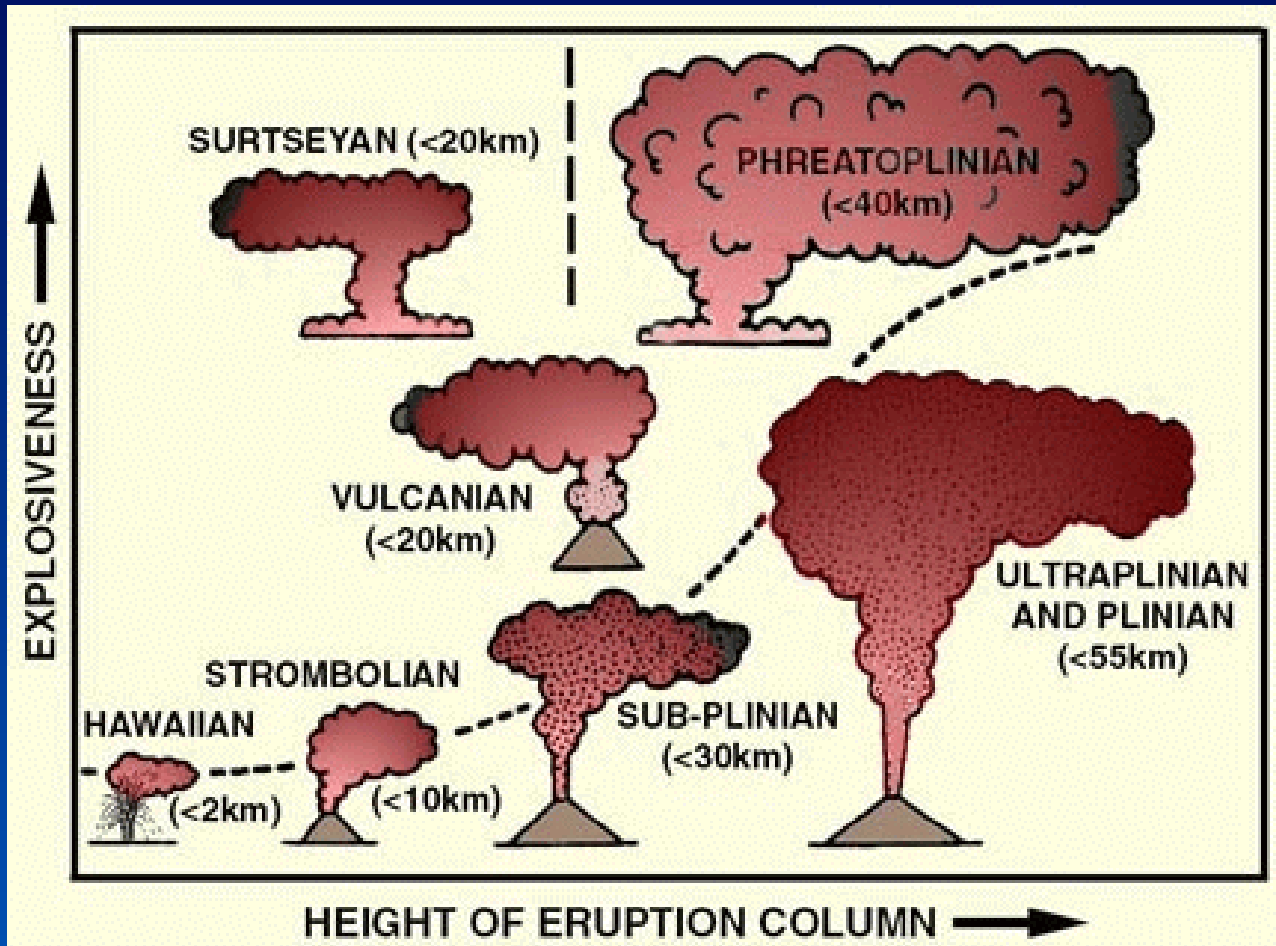
- ▶ A pyroclastic flow is a fluidized mixture of solid to semi-solid fragments and hot, expanding gases that flows down the flank of a volcanic edifice
- ▶ Heavier-than-air emulsions that move much like a snow avalanche, except that they are fiercely hot, contain toxic gases, and hurricane-force speeds, often over 100 km/hour
- ▶ They are the most deadly of all volcanic phenomena.

Volcanic gases

- ▶ Main gases
 - H_2O (70-90%)
 - CO_2
 - SO_2
- ▶ Trace gases
 - N, H, S, F, Ar, CO, Cl
 - These can combine with hydrogen to produce toxic compounds such as
 - HCl, HF, H_2SO_4 , H_2S



Eruption types



Hydrovolcanic eruptions are generated by the interaction of magma with either groundwater or surface water. They are highly explosive but have relatively low eruption columns

Westam Island - Scotland 2011











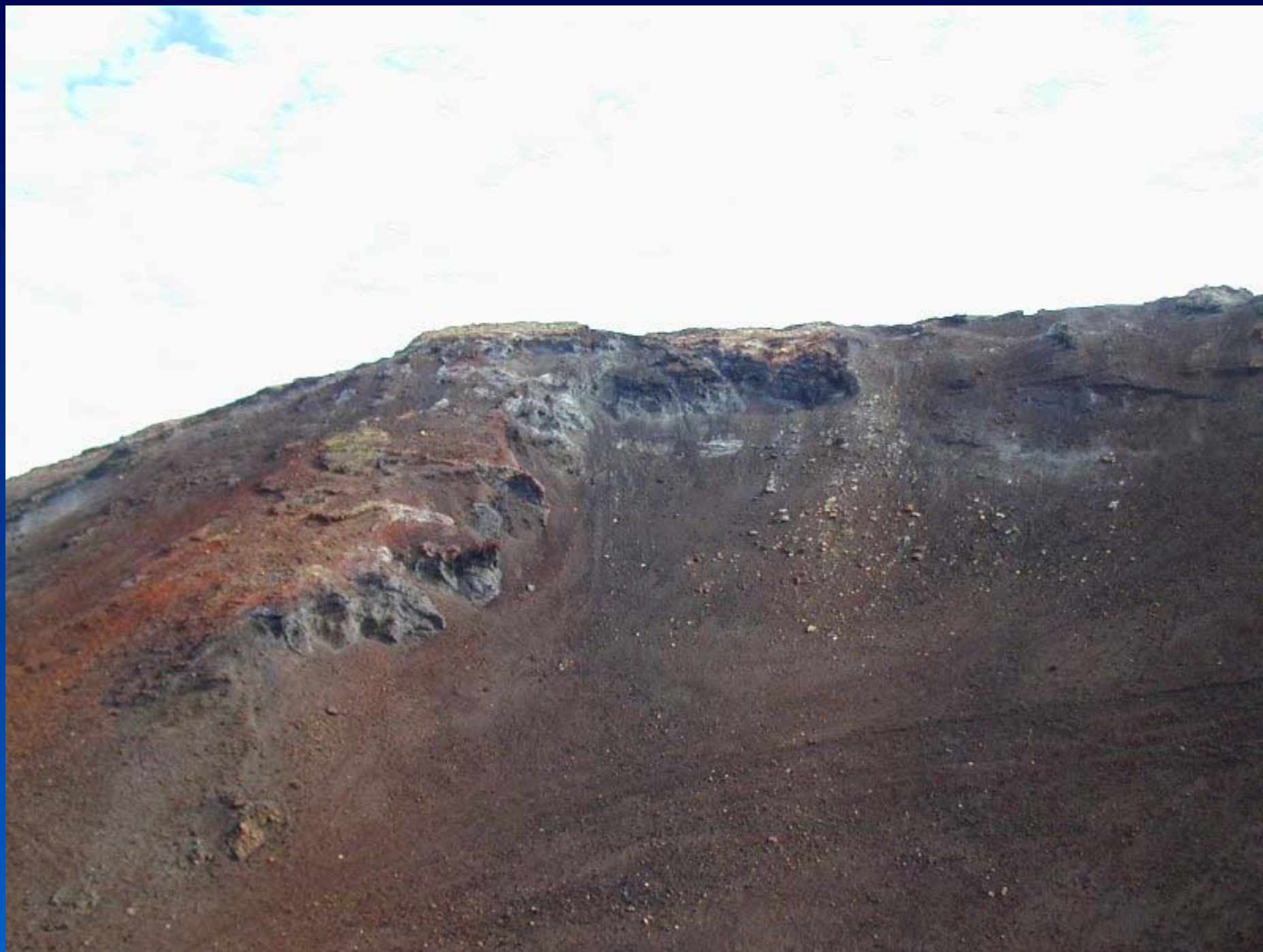




















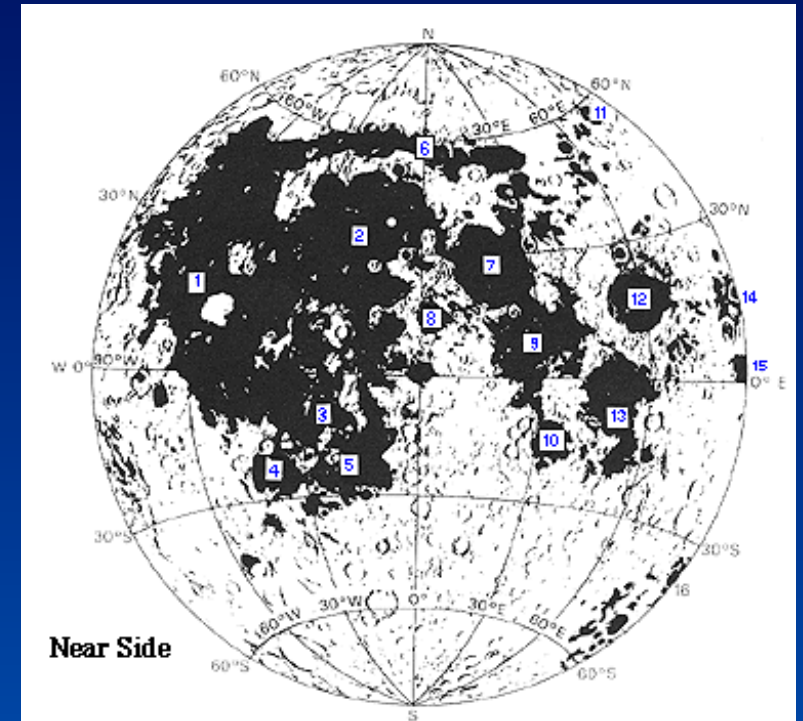


Other planets



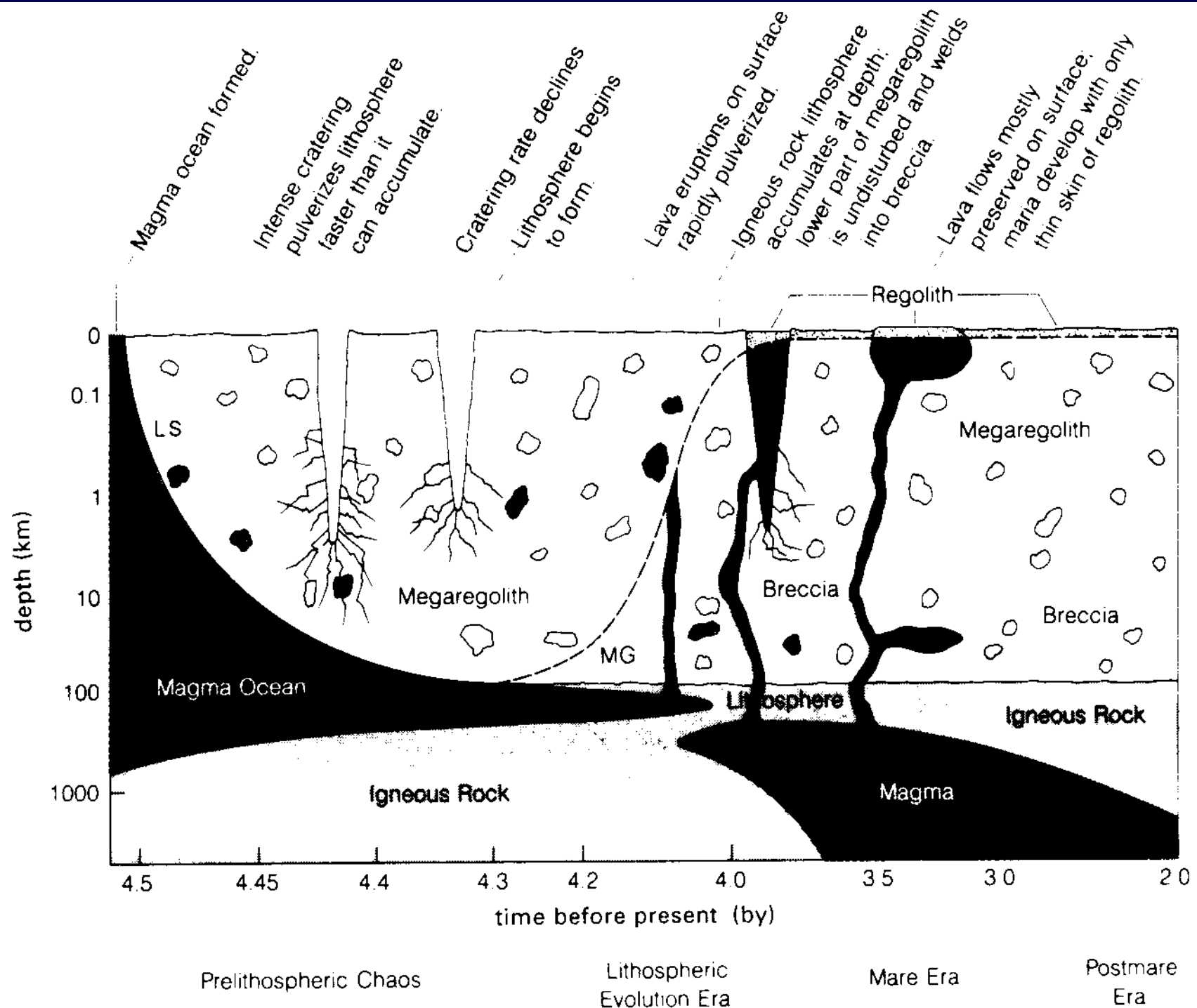
Volcanism on Moon

- ▶ It appears that on Moon volcanic rocks were produced in only one way: that of partial mantle melting
- ▶ Recycling of lunar crust did not occur or it was very rare
- ▶ The melts produced on the Moon are basalts
- ▶ Melting happened at depths of 150 to 400 km, the depth of origin increasing with time



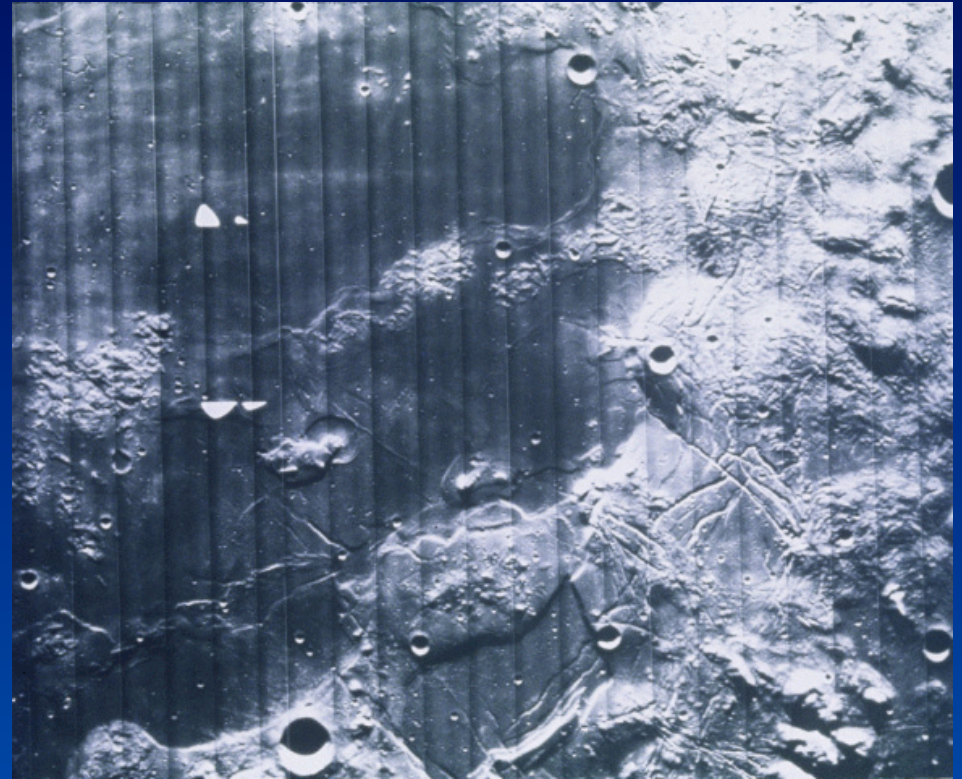
Black - Basaltic lava - Mare

White - heavily cratered
highlands



Moon - mare - extended flow

- ▶ This image of the lunar maria shows the difference between the highlands, which are heavily cratered, and the dark maria which are relatively smooth with few craters
- ▶ The absence of craters indicates that the maria are a younger age than the highlands
- ▶ The maria were created with an outpouring of lava which flooded the lower regions
- ▶ These lavas had very low viscosity, 3 to 10 times less than for the typical basalts on Earth
 - and thus had a tendency to flow back, and fill, their vents at the end of eruptions



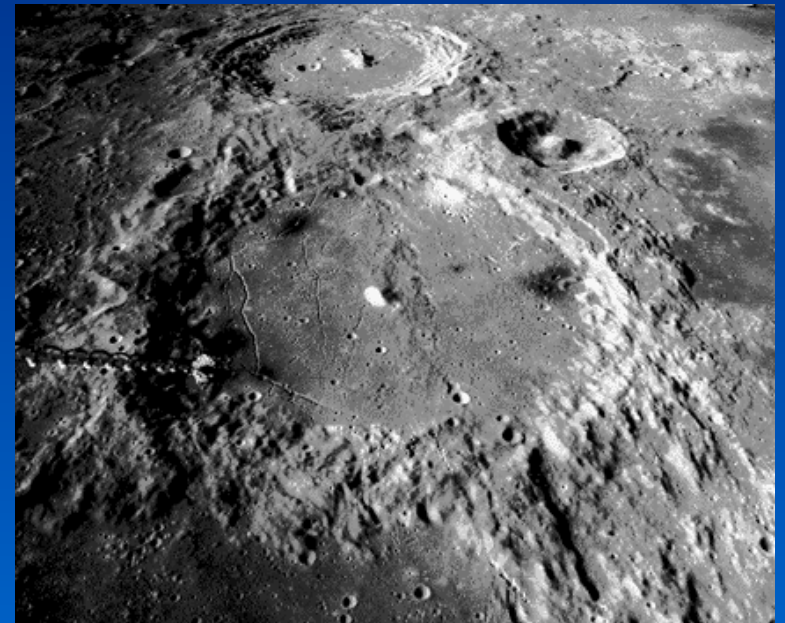
Moon - sinuous rilles



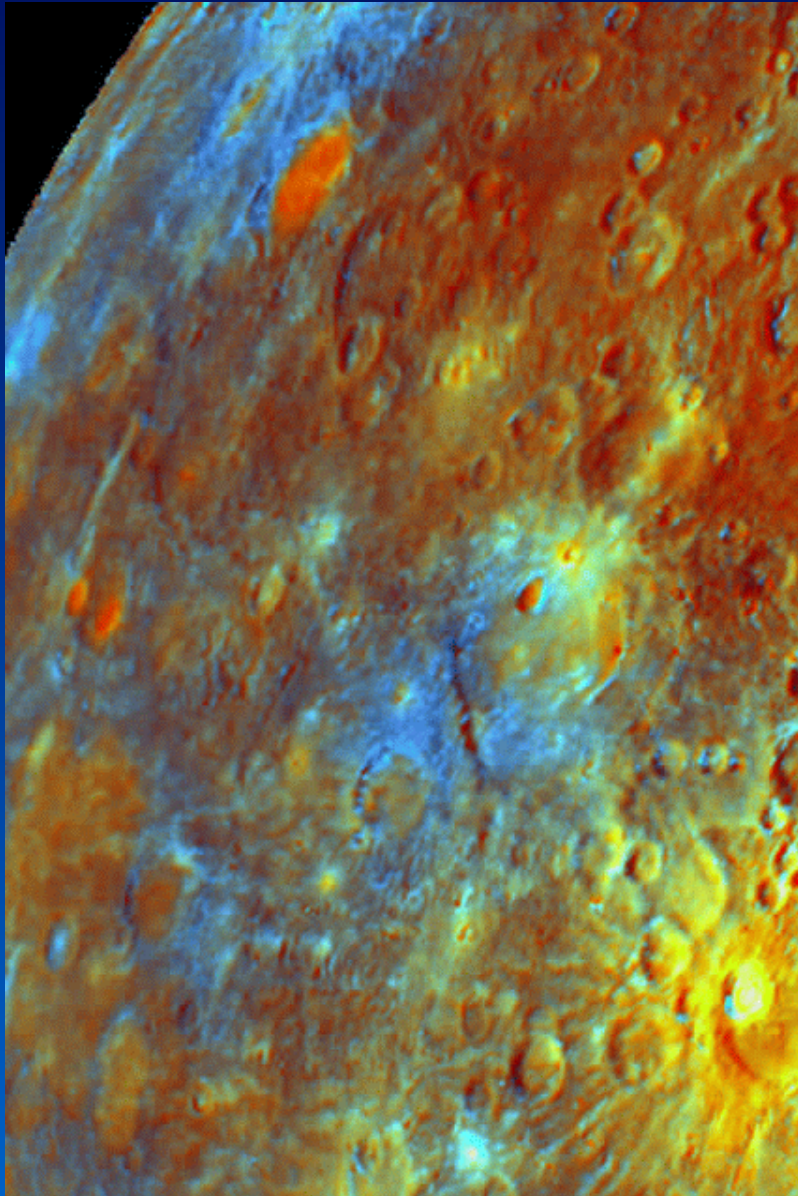
- ▶ Three views of the Hadley rille
- ▶ The rille is over 120 km long. It is up to 1.5 km across and is over 300 m deep in places
- ▶ In contrast, lava channels on Hawaii are usually under 10 km long and are only 50-100 m wide.
 - differences in the volume of erupted lava
 - the difference in gravity.

Moon - dark mantling deposits

- ▶ Although the mare formed from large effusive lava flows, there is some evidence for explosive volcanism on the Moon
- ▶ In places, the lunar surface is covered by dark layers of material
- ▶ They seem to mark areas where a thin layer has been draped over an older surface
- ▶ Apollo 17 brought back samples from one such unit
- ▶ They contain many small spheres of orange and black glass
- ▶ These spheres probably formed from small drops of lava that cooled very quickly
- ▶ Such droplets are thrown out of an eruption when bubbles of gas burst near the surface.



Mercury



- Deciding whether the smooth planes of Mercury are volcanic in origin or made up of impact ejecta can be difficult
- Colour images can be interpreted in terms of mineralogy and help - but are not always conclusive
- Nevertheless it is now thought that at least some of the surface of Mercury was produced by volcanic activity

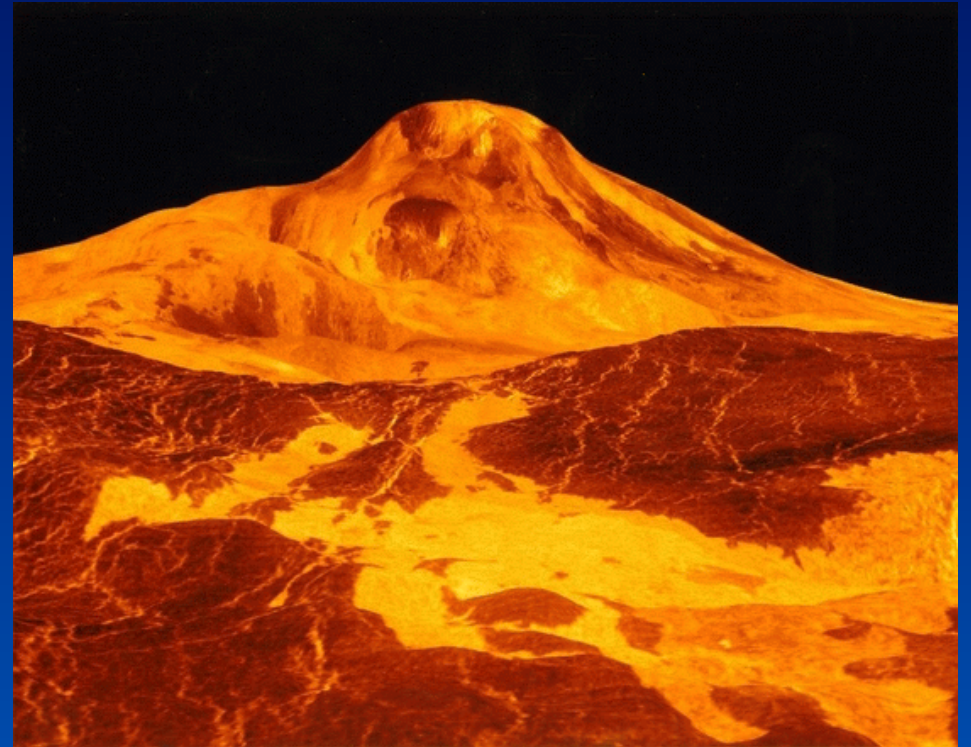
Mercury volcanism(?)

- ▶ The smooth areas inside the larger craters in this photo of Mercury may be volcanic plains
- ▶ Somewhat like the maria on the Moon
- ▶ There are many such smooth plains on Mercury.



Venus

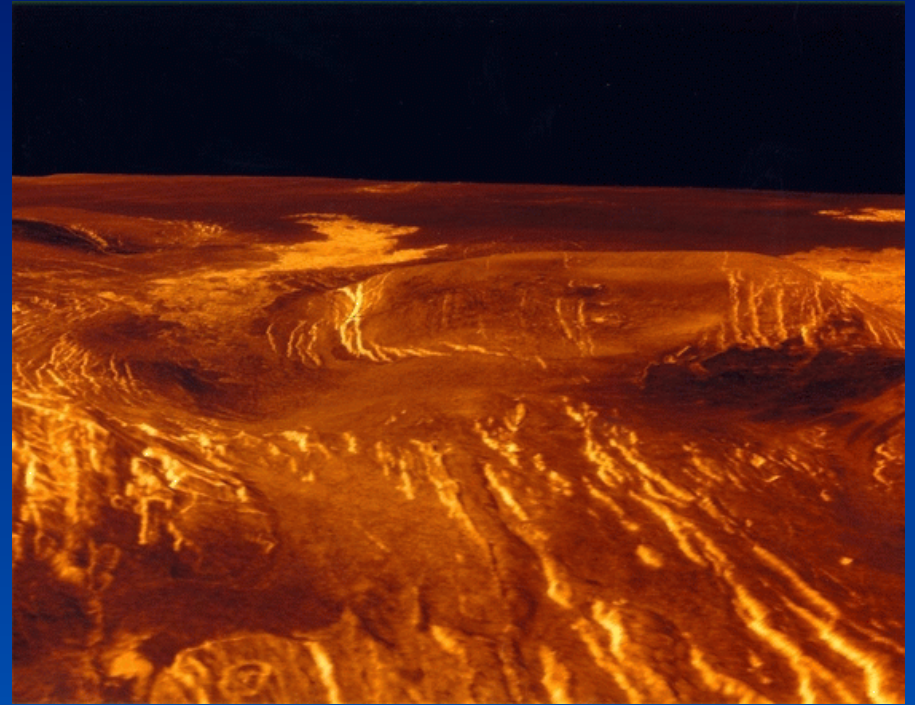
- ▶ Much of the volcanic activity on Venus occurs as basaltic eruptions that flood large areas
- ▶ Venus has several large shield volcanoes, some of which are thought to be currently active
- ▶ Recently announced findings indicate that Venus is still volcanically active, but only in a few hot spots
- ▶ Generally, it has been geologically quiet for the past few hundred million years.



Maat Mons, the highest volcano on Venus is 8 km high.

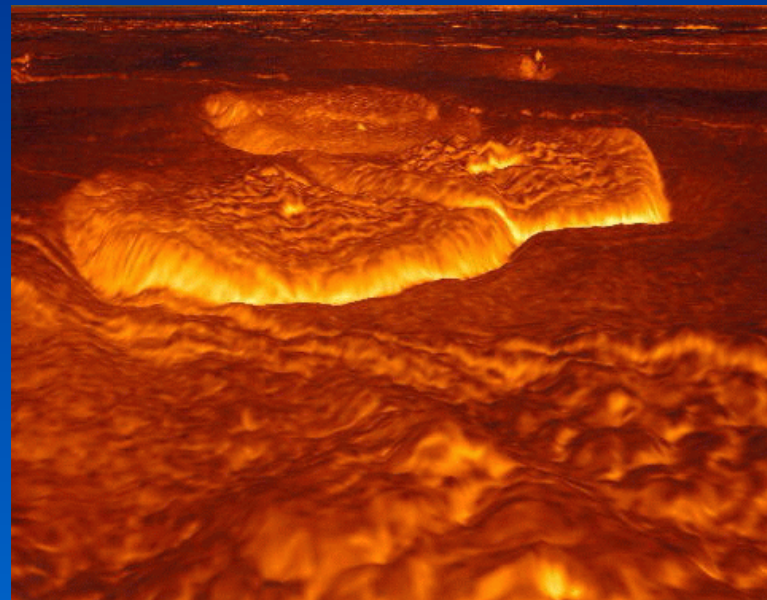
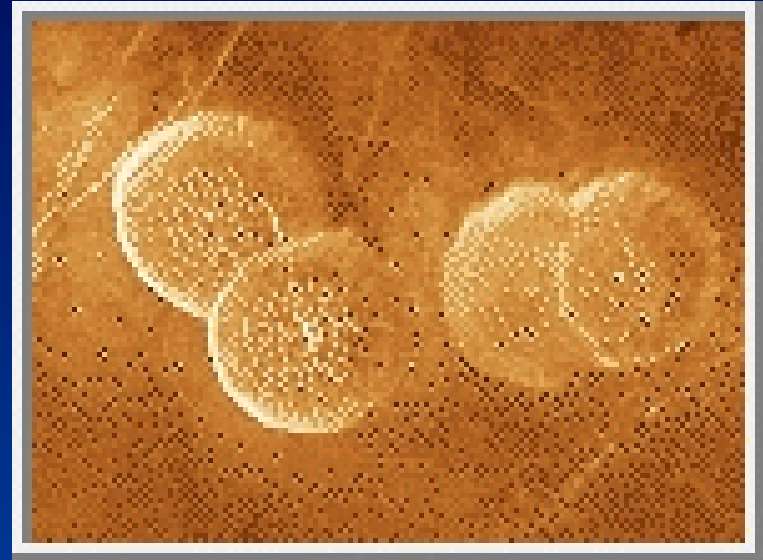
Venus

- ▶ The most distinctive volcanic features on Venus are coronae, large circular structures with a slightly raised interior surrounded by a low circular ridge and a trough
- ▶ They are typically 200 to 500 km in diameter, although the largest (Artemis) has a diameter of 2000 km
- ▶ Coronae are thought to be hot spots formed over mantle plumes that became inactive before they could form a true shield volcano.



Venus

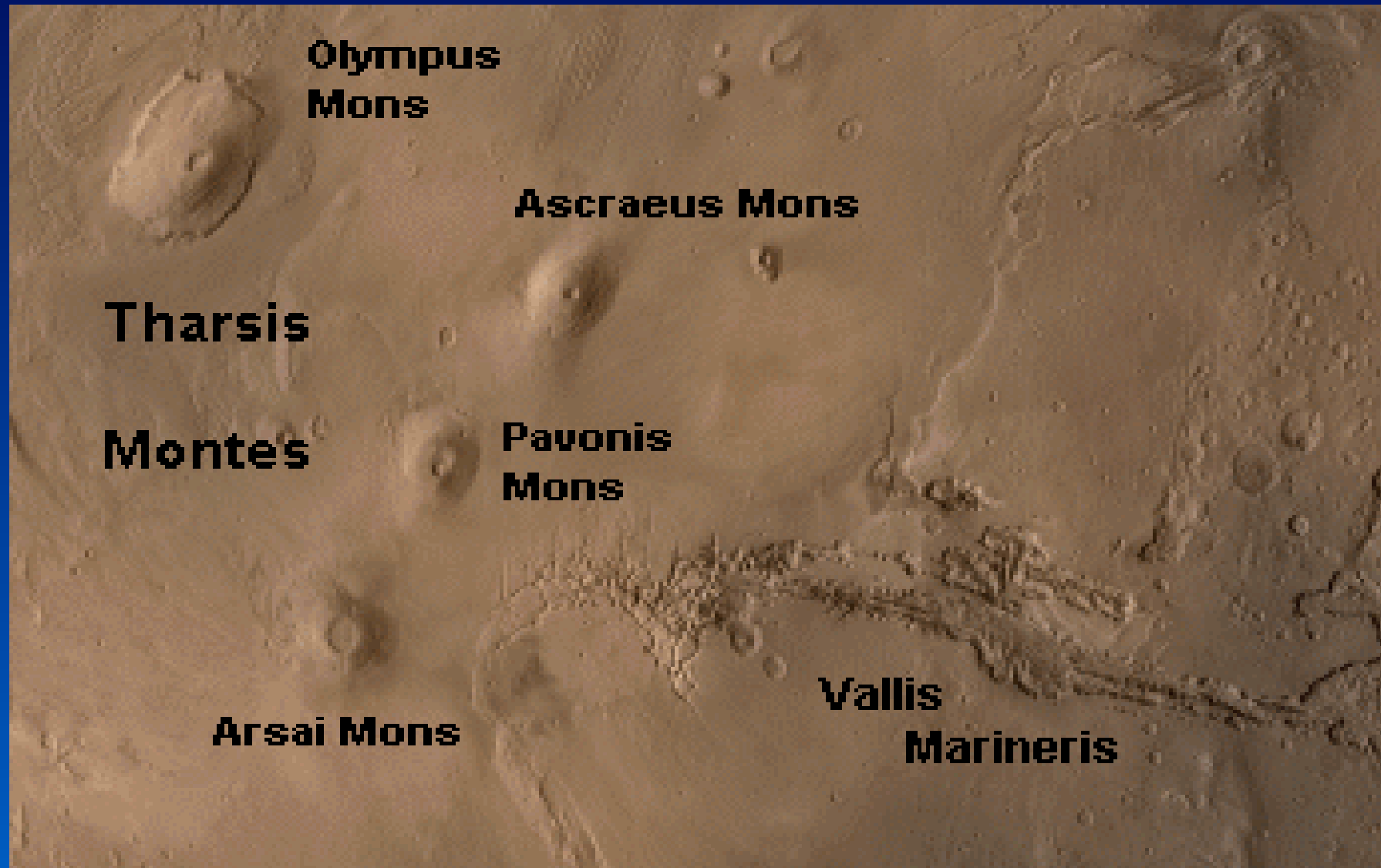
- ▶ Venus also displays unique forms of volcanism
- ▶ One such form is pancake domes, which are almost perfectly circular, flat domes with steep sides
- ▶ The domes appear to be made of highly viscous lava erupted suddenly from a single vent
- ▶ There are also rivers of extremely fluid lava, some of them hundreds or even thousands of kilometers long.

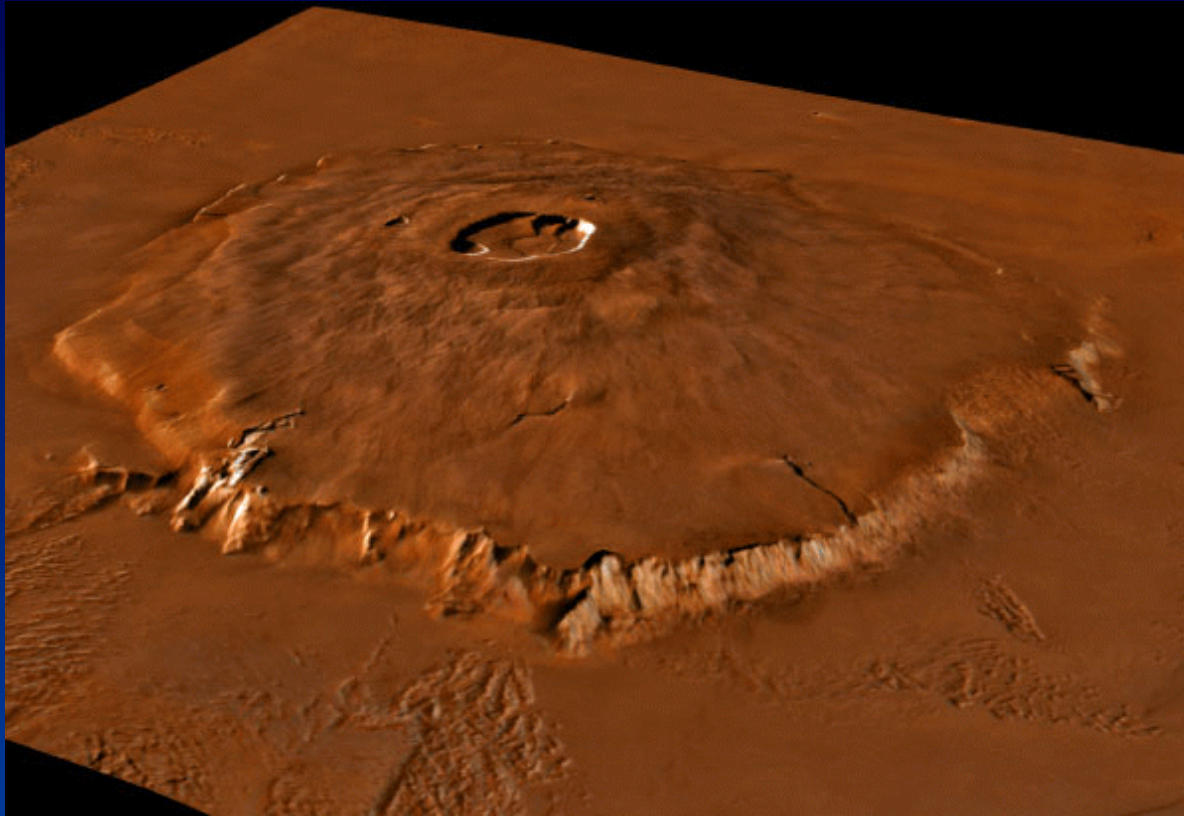


Volcanism on Mars

- ▶ Mars is only about one-half the size of Earth and yet has several volcanoes that surpass the scale of the largest terrestrial volcanoes
- ▶ The most massive volcanoes are located on huge uplifts or domes in the Tharsis and Elysium regions of Mars
- ▶ The Tharsis dome is 4,000 km across and rises to 10 km in height
- ▶ Located on its northwest flank are three large shield volcanoes: Ascraeus Mons, Pavonis Mons and Arsia Mons
- ▶ Beyond the dome's northwest edge is Olympus Mons, the largest of the Tharsis volcanoes.

Mars - Tharsis





- ▶ Olympus Mons is classified as a shield volcano. It is 24 km high, 550 km in diameter and is rimmed by a 6 km high scarp
- ▶ It is one of the largest volcanoes in the Solar System
- ▶ By comparison the largest volcano on Earth is Mauna Loa which is 9 km high and 120 km across.

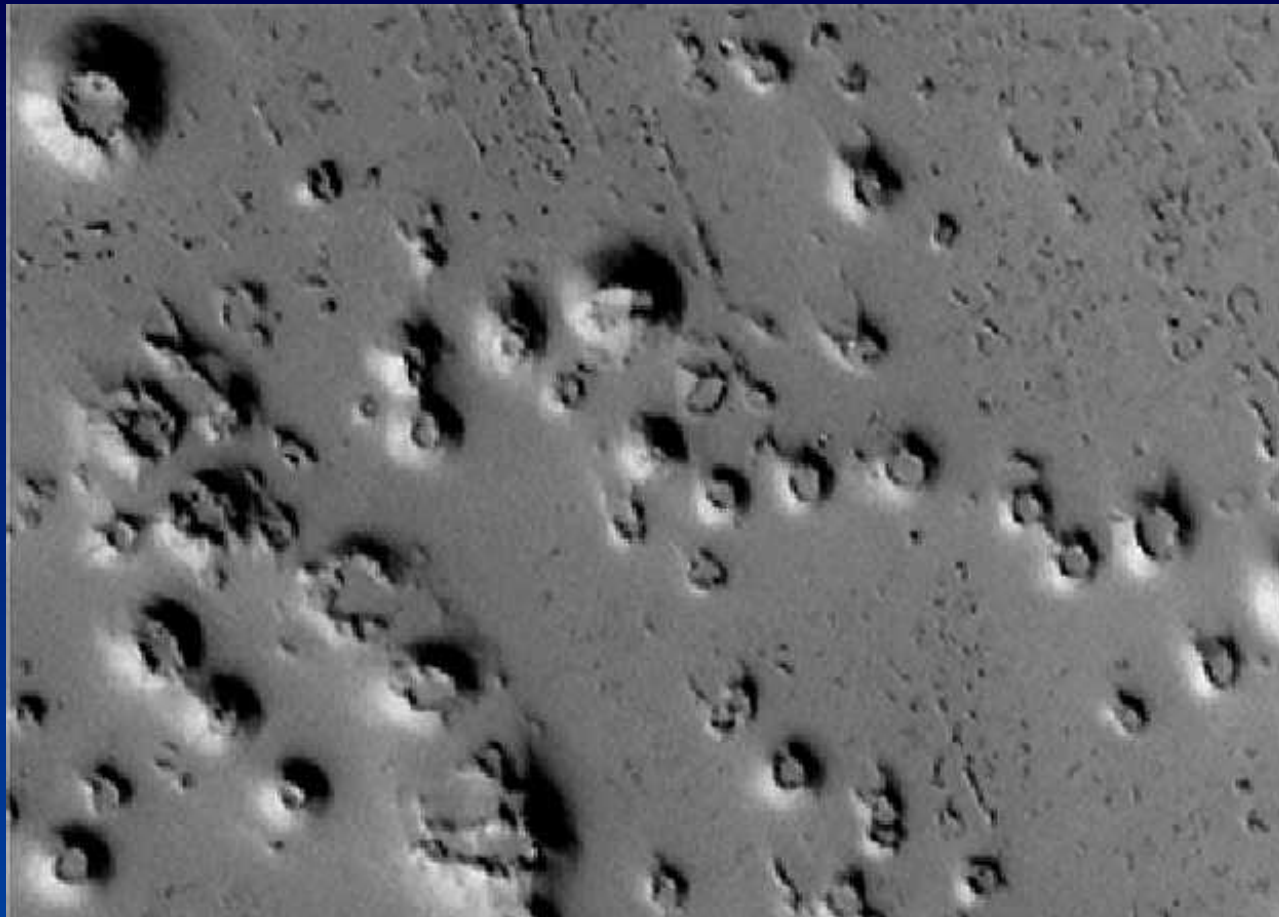


- ▶ A computer simulation of mantle convection in the interior of Mars that could have produced the Tharsis region
- ▶ The color differences are variations in temperature
 - the difference between the hot and cold regions being as much as 1000 K
- ▶ This type of mantle flow produces plate tectonics on Earth.

Volcanoes on Mars contd.

- ▶ The huge volcanoes in Tharsis and especially Olympus Mons are famous
- ▶ But there are many more, e.g., those in Elysium
- ▶ Some of the lesser known are comparable in surface to the big and famous ones (e.g., Alba Patera)
- ▶ Martian volcanoes are very old and, except for those in Tharsis, almost all of them eroded so much that they are hardly visible
- ▶ Volcanism was widespread on Mars, but that was long ago $>\sim 4\text{Gyr}$





- ▶ These unusual cone-shaped features on Mars spanning an average of only 100 m at the base
- ▶ the cones were probably formed by lava heating ice lying just below the Martian surface
- ▶ Lava heated ice would vaporize and expand, punching holes in the cooling lava flow as it escaped.

Landslides in Vallis Marineris tell about erosion rates

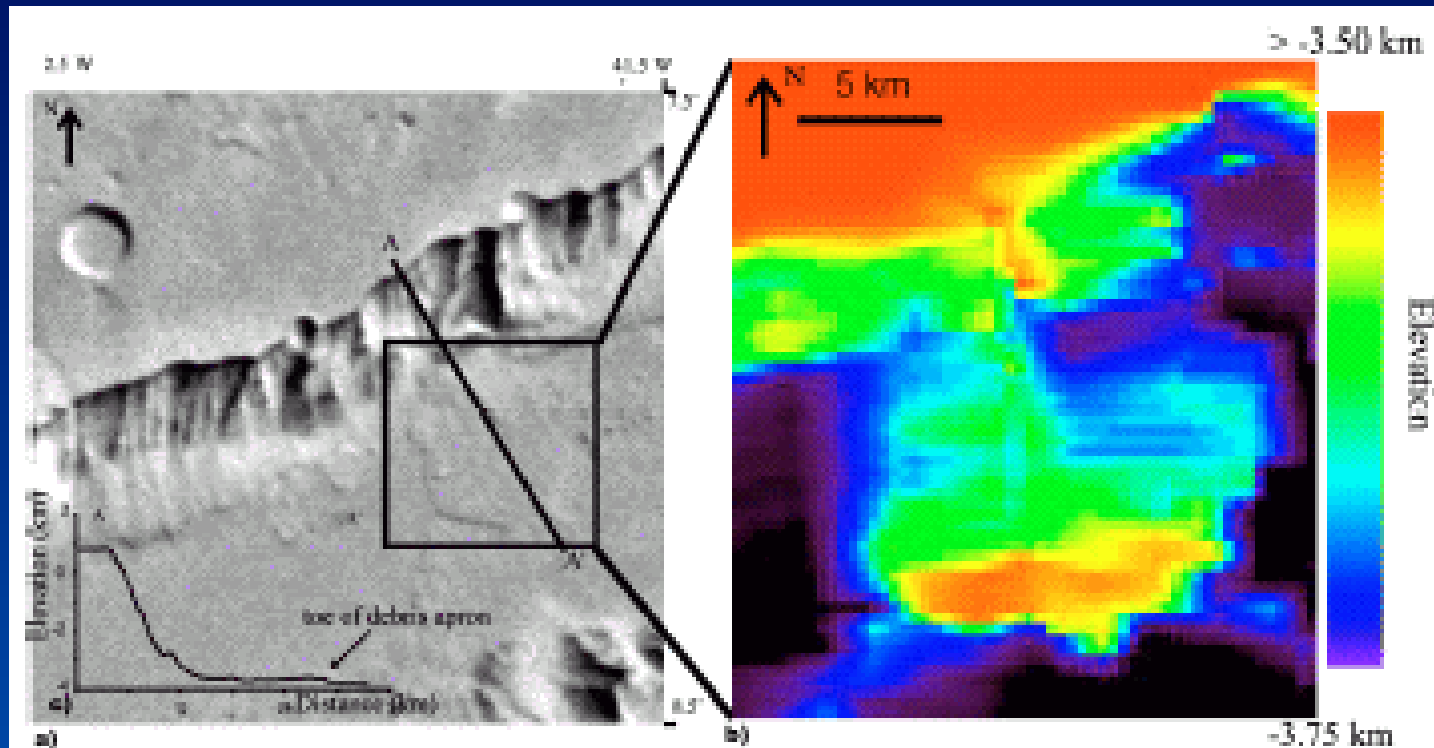


Fig.4.: Debris aprons topography a) Viking context, b) Digital Elevation Model (MOLA), c) Topographic profile.

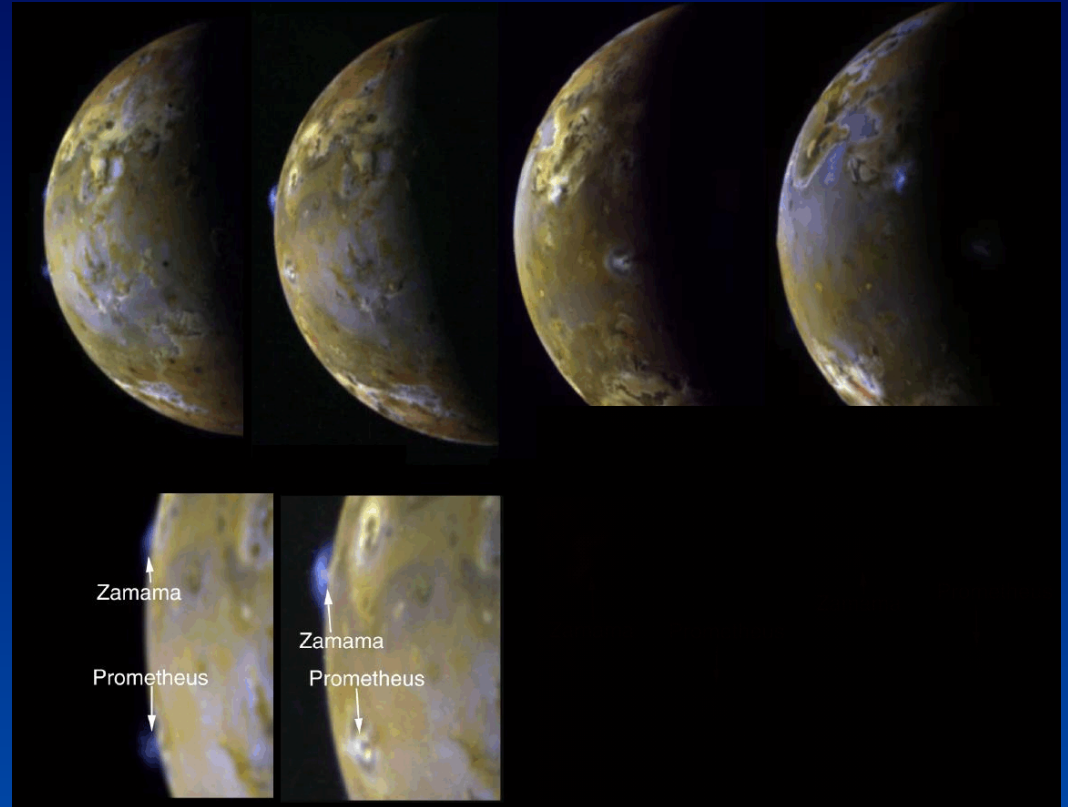
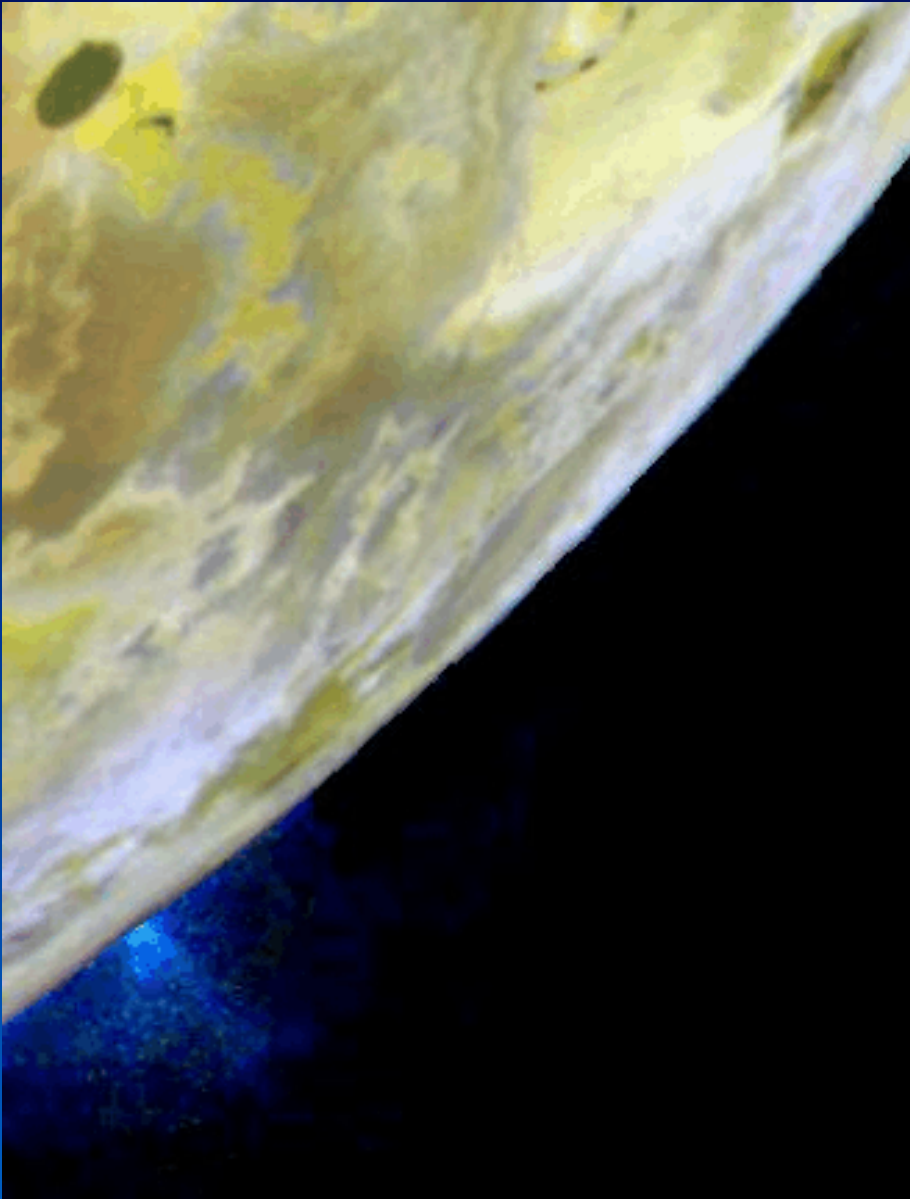
Landslides in Vallis Marineris tell about erosion rates

- ▶ Crater counts - age of landslides
 - Ages: 0.05 Gyr - 3.5 Gyr; age of the Vallis itself ~3.5 Gyr
- ▶ Even oldest landslides are well preserved and no significant difference between oldest and youngest ones
 - no heavy erosion over the last 3.5 Gyr.
- ▶ The Tharsis volcanoes are still huge and impressive because there was only slow erosion after they formed
- ▶ Older volcanoes, but not older by more than 10-20%, did experience heavy erosion
 - About 3.5 - 4 Gyr ago something changed dramatically

Mars -what happened between 3.5-4 Gyr BC

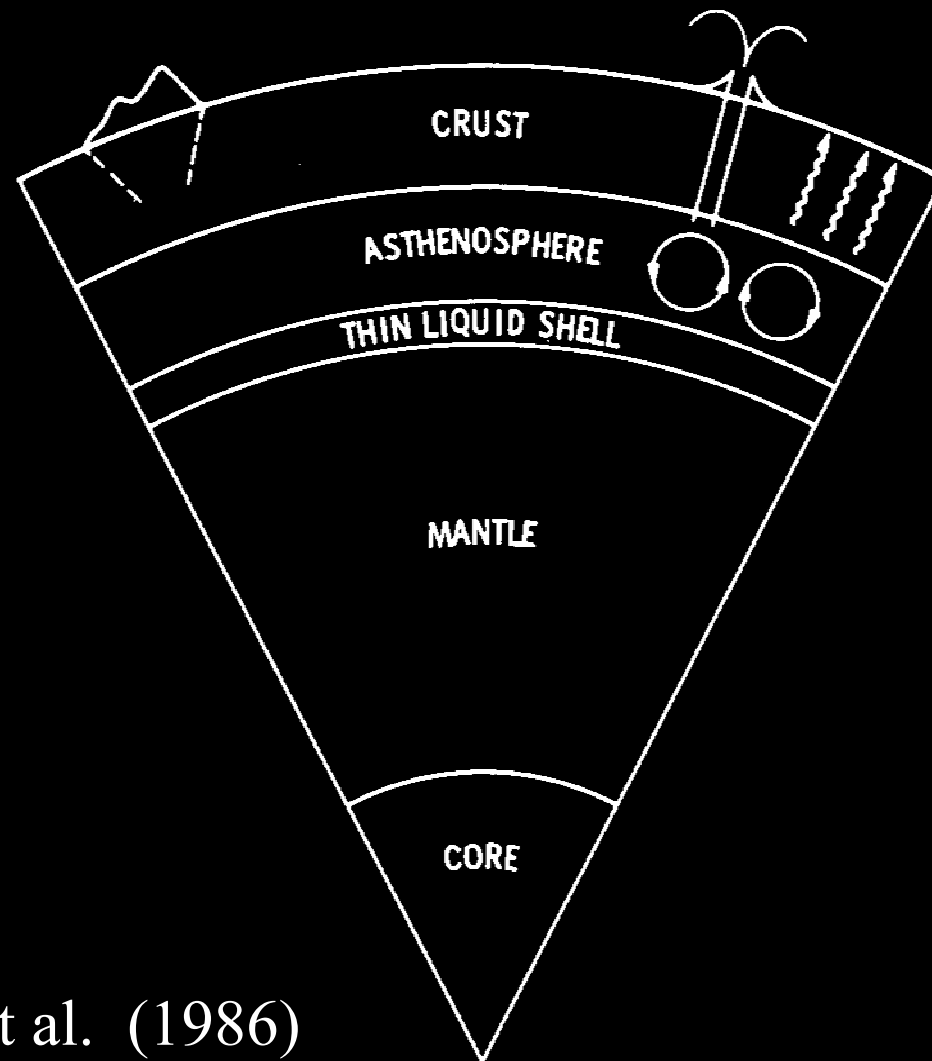
- ▶ Possibly the early wild days were caused by big impacts
 - Once the big impacts stopped Mars may have become a very quiet place
- ▶ Possibly radiogenic heating and residual heat from the formation initially invoked volcanism and a dense warm atmosphere for about 1 Gyr
 - Then Mars' crust became too thick for volcanism,
 - The dense CO₂ atmosphere got trapped in the surface almost completely
 - The greenhouse collapsed, Mars froze and became a quiet place

Volcanism on Io



- Io is the most volcanically active object in our Solar System

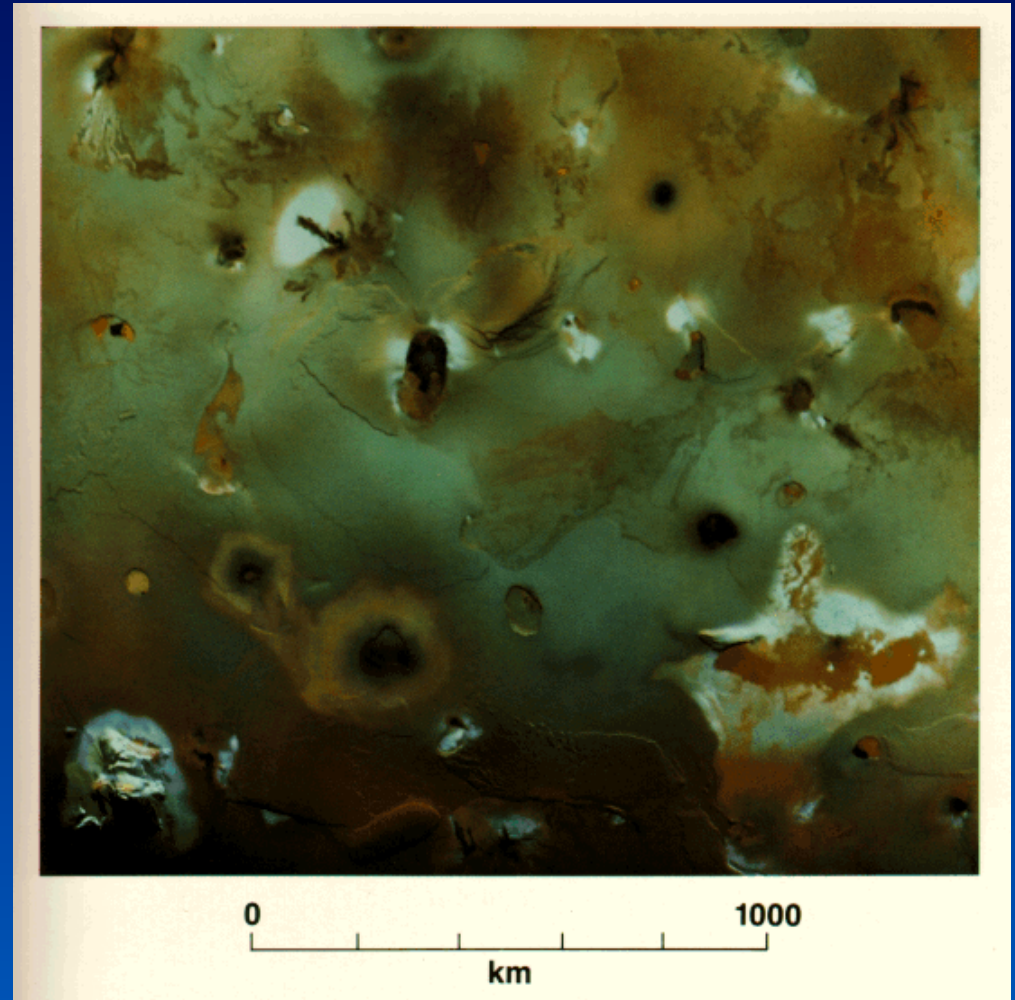
Structure of Io's interior



Nash et al. (1986)

The surface of Io

- ▶ Sulphur allotropes dominate the colour of the surface.
- ▶ SO₂ frost observed at 4.08 μm .
- ▶ H₂S postulated as a surface frost at the poles.
- ▶ No unambiguous detection of anything other than S and O species in reflectance spectra.
- ▶ BUT, structures of volcanic vents suggest additional surface components (silicates?)
- ▶ Lack of impact craters indicates resurfacing at $>10^{-4} \text{ m y}^{-1}$.



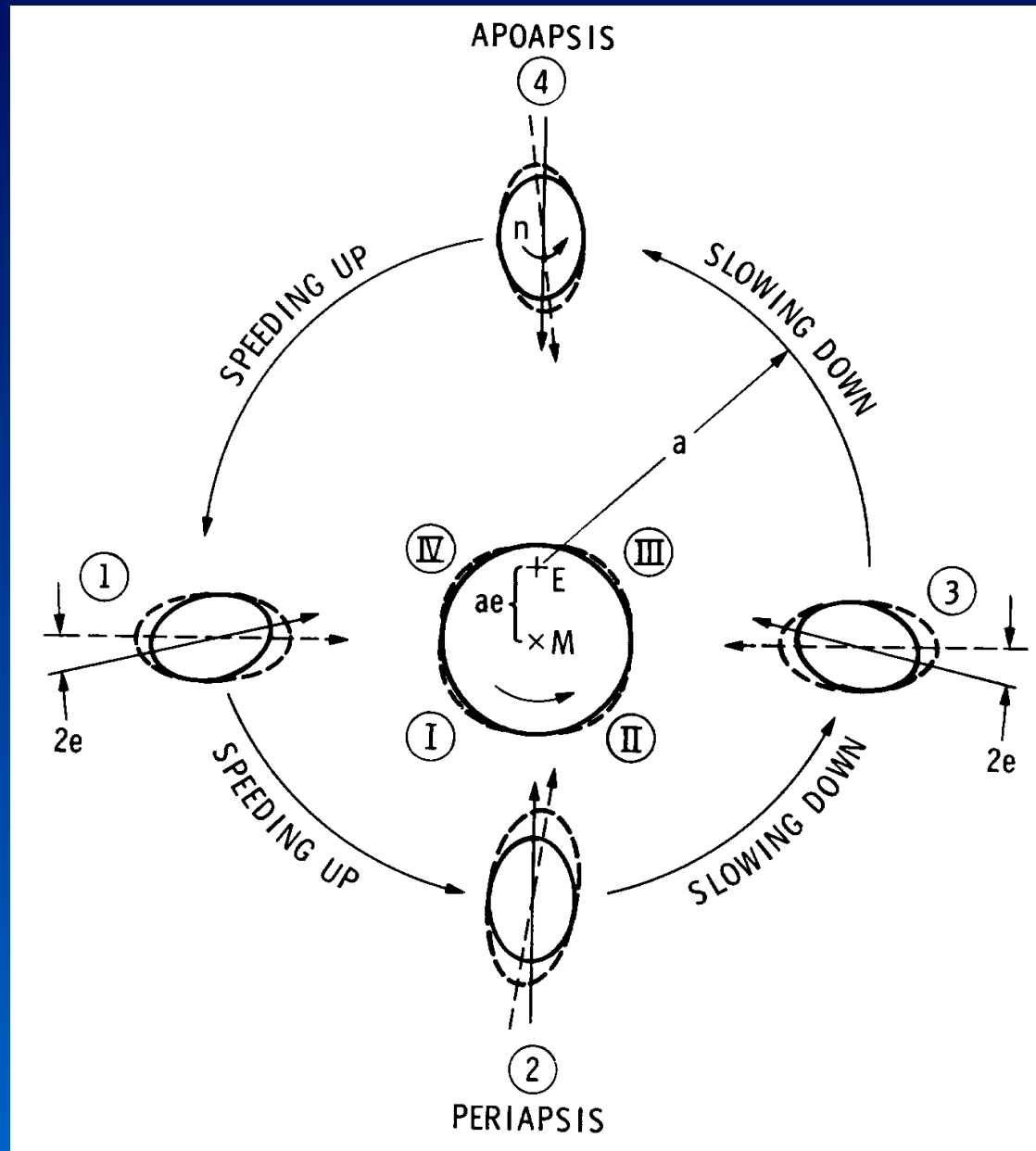
The atmosphere of Io

- ▶ Ionosphere detected by Pioneer 10 radio occultation experiment in 1973
- ▶ SO₂ discovered at 7.4 μm by Voyager 1 IRIS
- ▶ Two models
 - SO₂ in equilibrium with surface frost
 - SO₂ emitted from volcanic vents
- ▶ Detection in sub-mm in 1990 suggests later is correct
- ▶ Atmosphere covers only limited part of surface
- ▶ Line shapes indicate SO₂ has a Doppler shift!
- ▶ Surface pressures $<10^{-8}$ bar

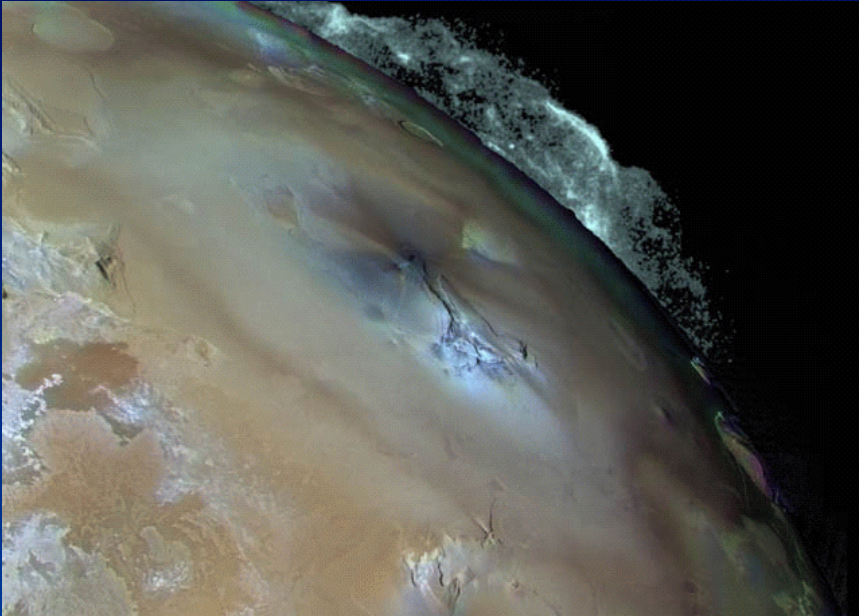
Tides on Io

- ▶ Io is in a strict resonance with Europa and Ganymede
- ▶ The resonance raises tides on Io (as much as 100m)
- ▶ The inelastic part of this deformation generates heat in the interior
- ▶ The surface heat flow is equivalent to $\approx 2 \text{ W m}^{-2}$ (cf. the Moon $\approx 0.017 \text{ W m}^{-2}$)
- ▶ Total heat flux is around $8 \cdot 10^{13} \text{ W}$! (Earth value is $4 \cdot 10^{13} \text{ W}$ but Earth has over 12 times large surface)
- ▶ This by far outweighs the radiogenic heat and is the source of heat driving Io volcanism

Tidal flexing on Io



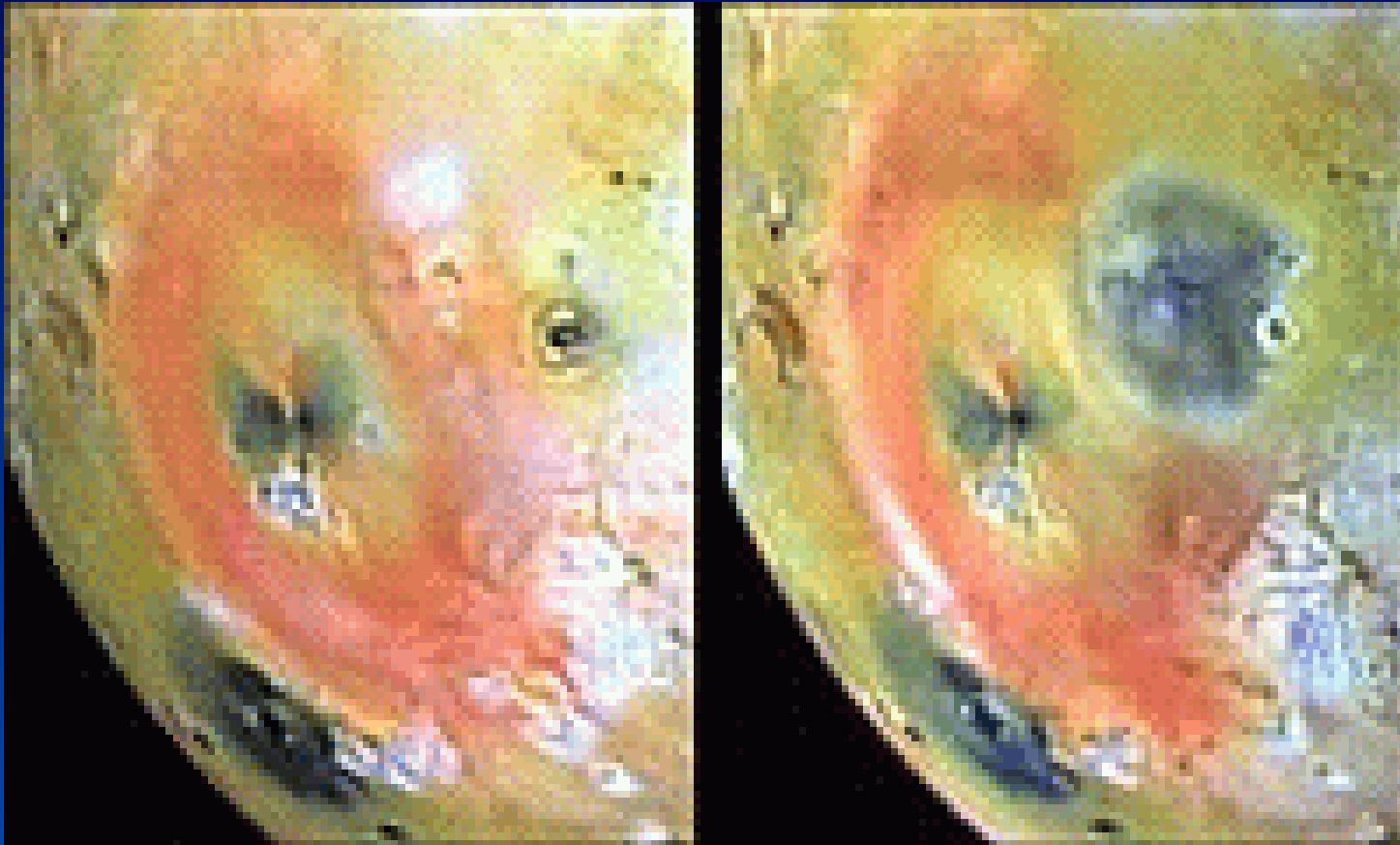
Io's volcanoes at work



An eruption of Pele. The volcanic plume rises 300 kilometers. The plume fallout covers an area the size of Alaska. The vent is a dark spot just north of the triangular-shaped plateau (right center).

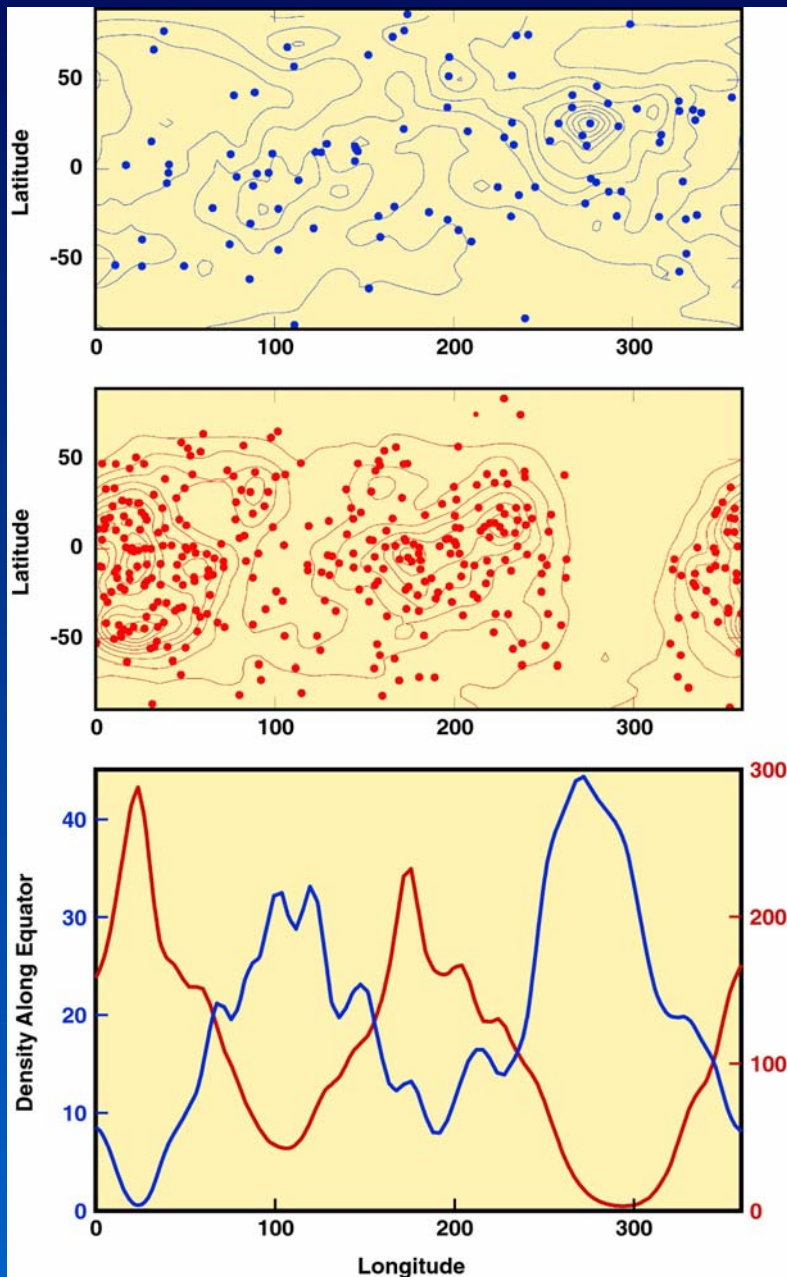
- ▶ Io's plumes are driven by S and SO_2
- ▶ Io's volcanoes are the hottest spots in the solar system with temperatures sometimes exceeding 1800 K
- ▶ The plumes can rise as much as 500 kilometers into space
- ▶ The various colors arise from various forms of sulphur
- ▶ White is SO_2 frost

Io's volcanoes at work



Pillan Patera: in the \sim four months between two Galileo flybys in 1997 a new dark region with a diameter of \sim 400 km formed.

Io's volcanoes and mountains

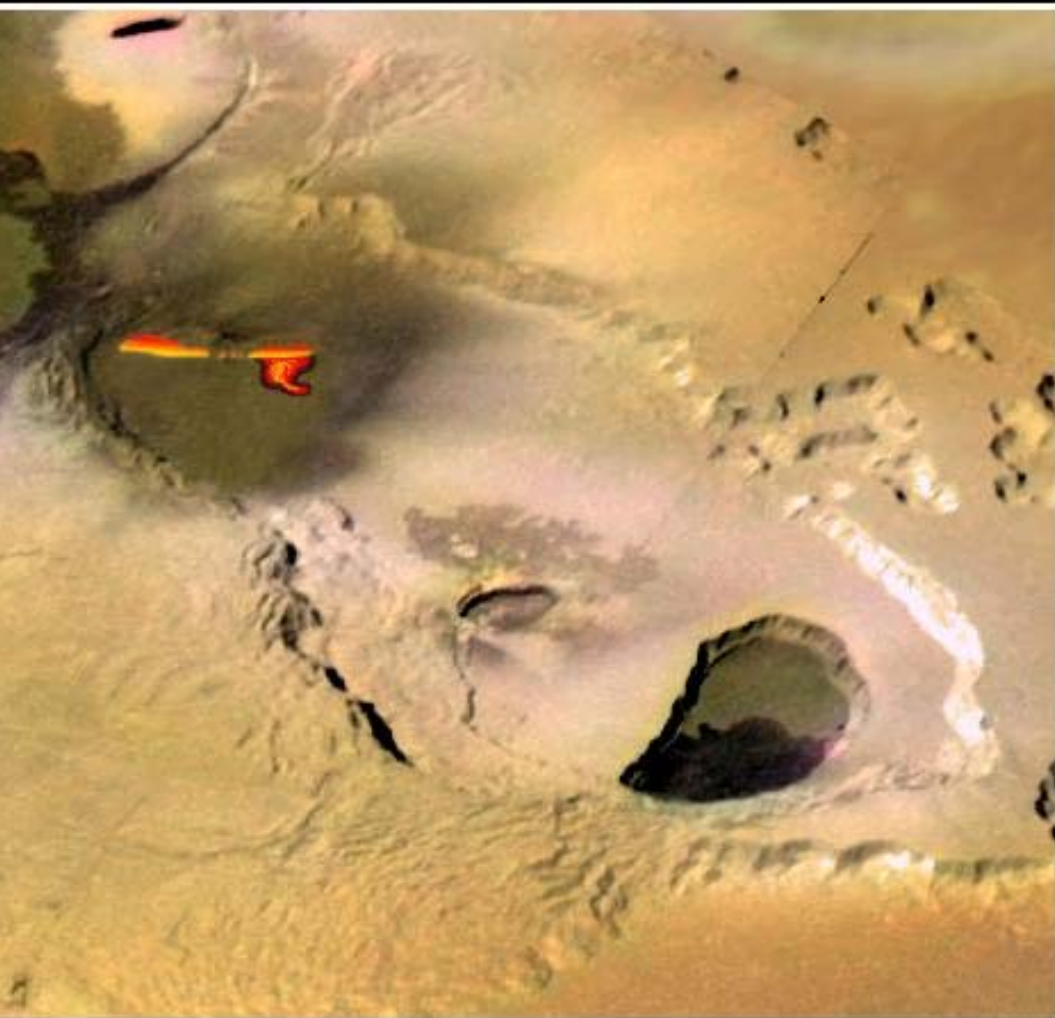


- ▶ **Red:** volcanoes
- ▶ **Blue:** mountains
- ▶ Volcanoes are concentrated on sub- and anti-Jovian points
 - Tidal deformation is largest here
- ▶ Mountains prefer regions with few volcanoes
 - Crust is stronger there

Active lava flow on Io

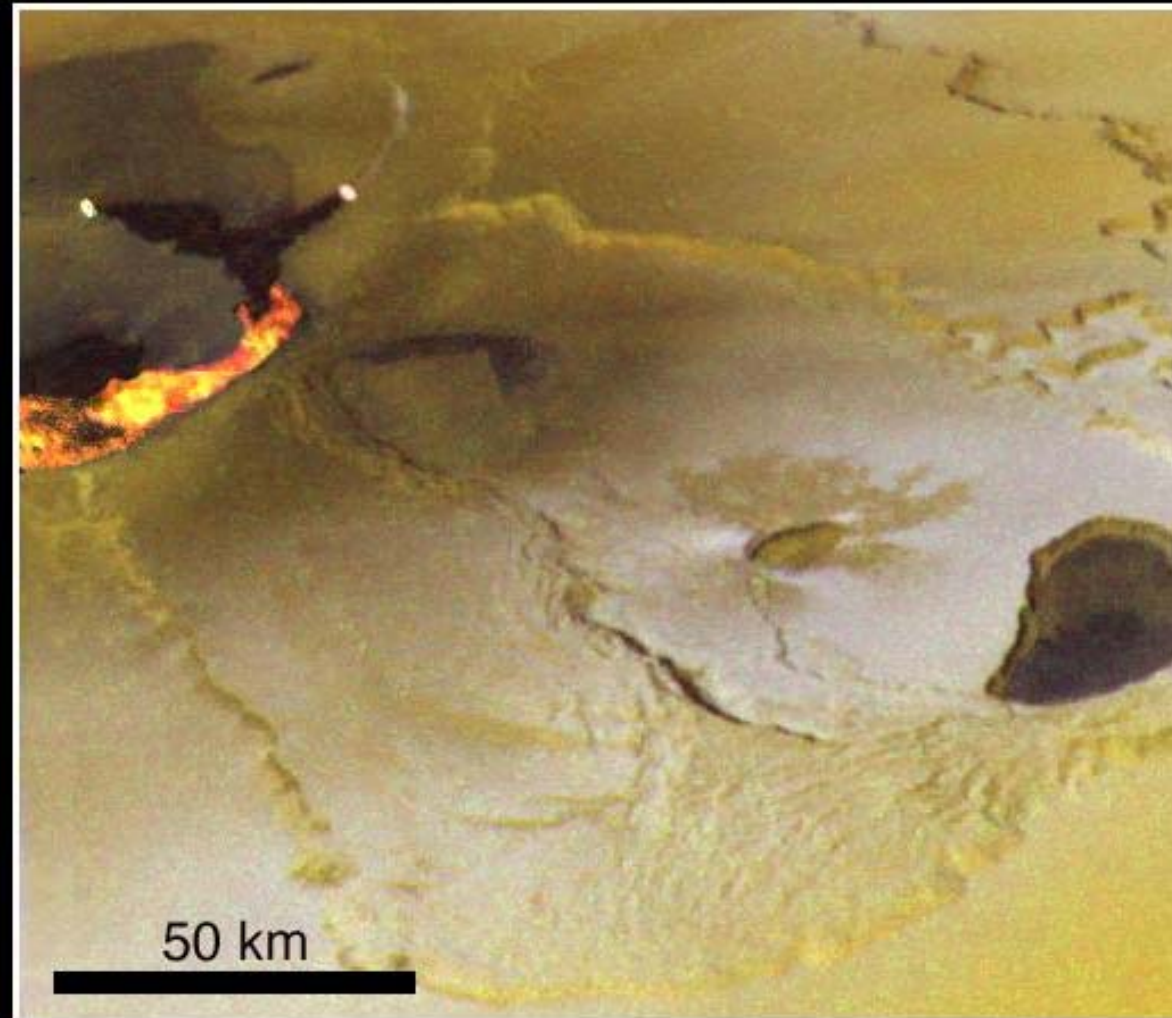
I25 (26 Nov 1999)

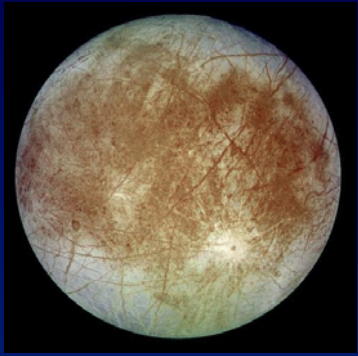
+ C21 low-resolution color
+ fire fountain sketch



I27 (22 Feb 2000)

visible wavelength data
+ IR data of active lava flow

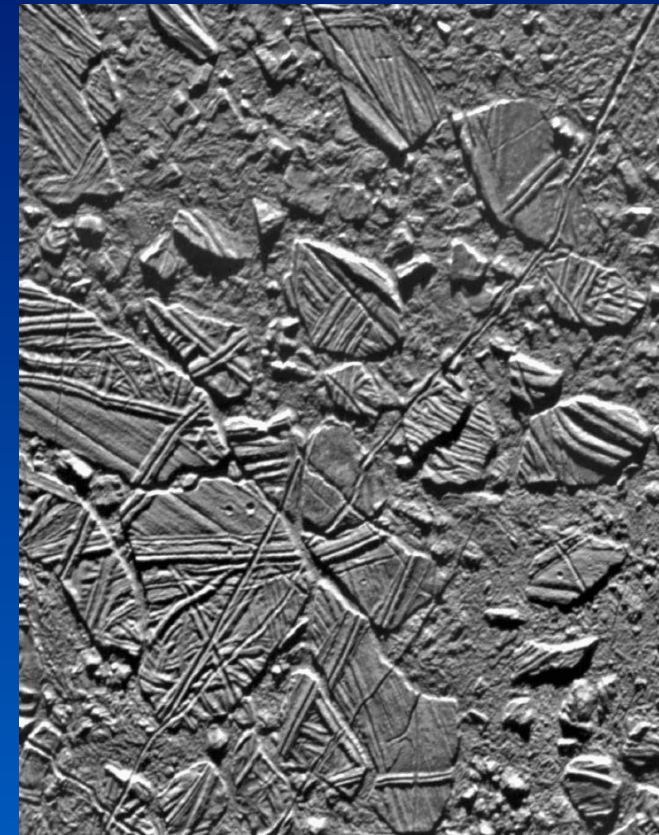




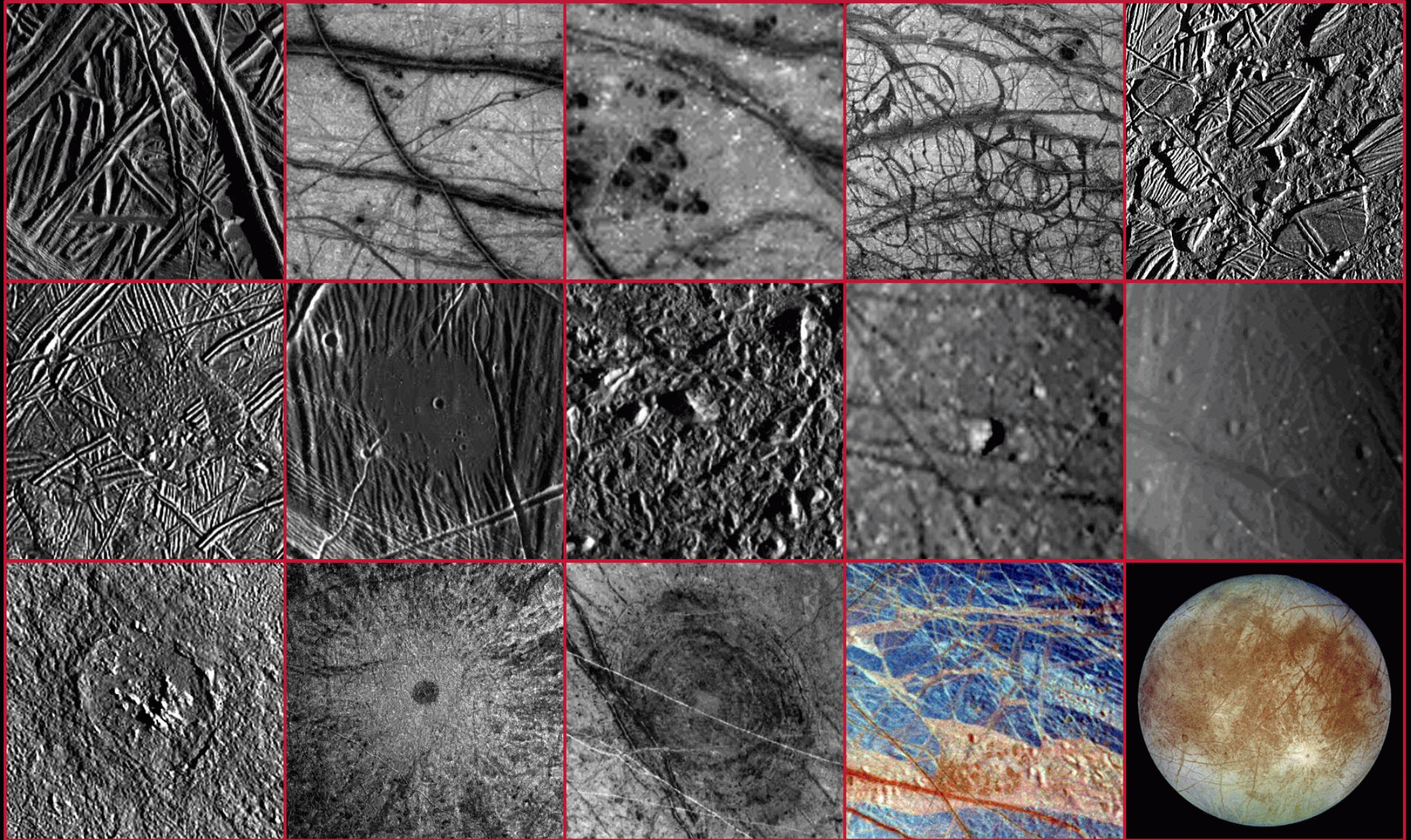
Europe and Ganymede



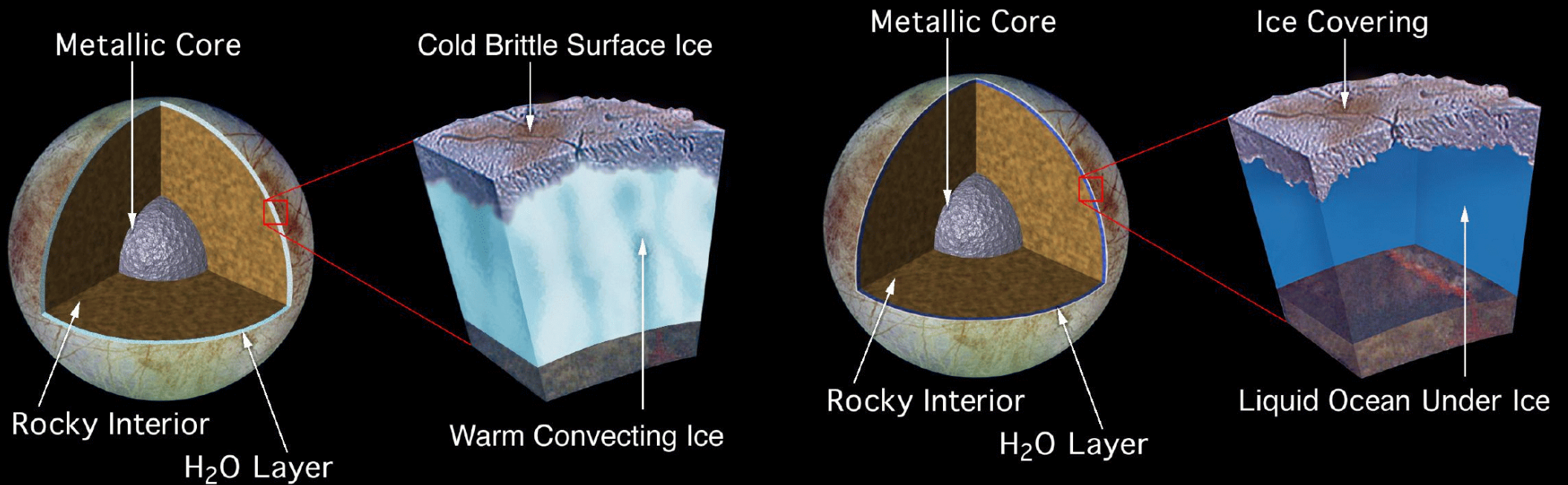
- ▶ Tidal forces also heat Europe, but nowadays probably about 100 times less than Io
- ▶ The tidal heating of Ganymede is much smaller than its radiogenic heating
- ▶ Computer simulations show that orbital eccentricities of the Jovian moons vary with time
 - The heating of Europe may sometimes be 10 times larger than it is now
 - Ganymede may sometimes heat up enough to become 'Europe like'



EUROPA — Surface-feature examples



Europa is covered with a frozen ocean over 100 km thick



Cryo-volcanism (what is it)

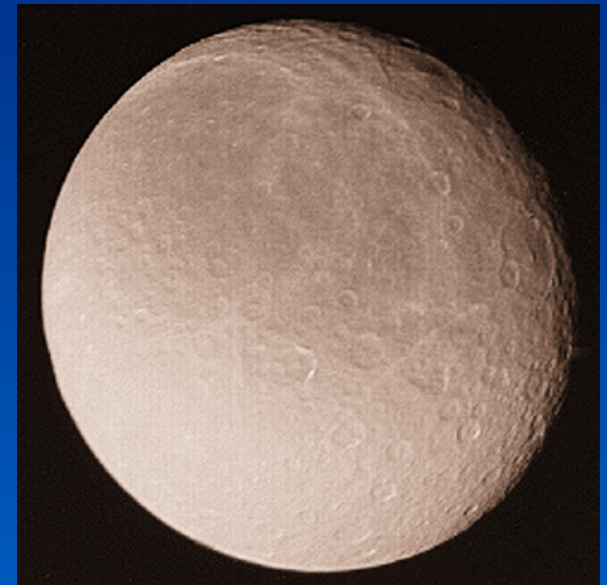
- ▶ In the outer solar system water and various other volatiles are quite solid and rocky, but
 - low temperature volcanic activity can make those icy rocks flow like lavas
 - ▶ On Earth the energy that drives venting from geysers and pyroclastic explosions comes mainly from boiling water and CO₂, but
 - on Triton it comes from boiling nitrogen
 - ▶ Such low temperature variants of volcanism are named ‘cryo-volcanism’
- (Background: volcanic plains on Triton)

Cryo-volcanism (where is it)

- ▶ Observed on Triton
 - Nitrogen geysers
- ▶ Probably active on Pluto, compare Triton
- ▶ Possibly active on Charon and larger KBOs
- ▶ Enceladus and Rhea: internal heating, possibly caused by orbital resonances, may once upon a time have melted enough water to resurface parts of these icy moons
- ▶ Iapetus, the large moons of Uranus?
- ▶ Very cold objects in the ISM ($T < 25\text{K}$)
 - explosively evaporating Neon may cause
 - disruption of smaller objects

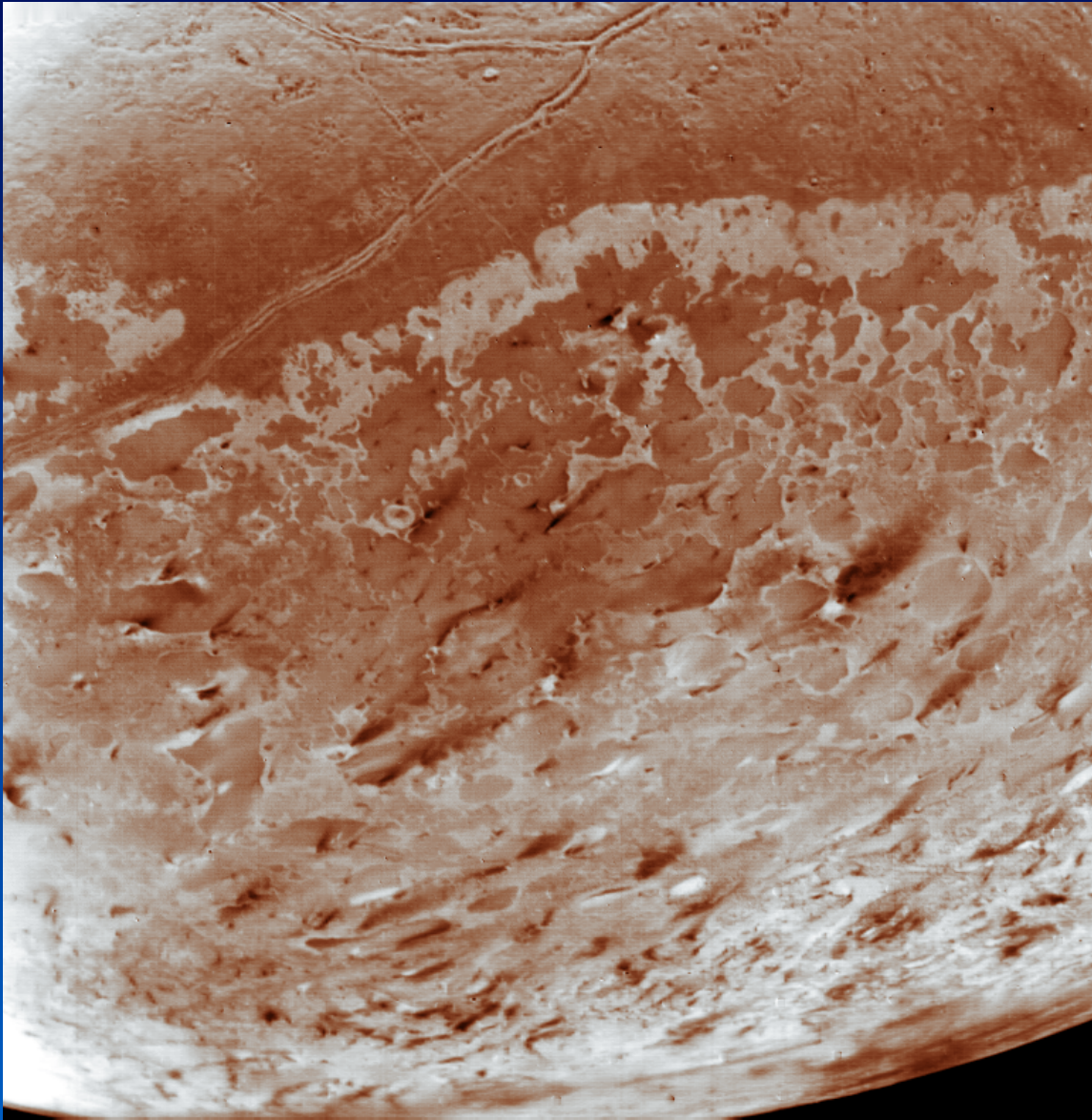


Enceladus



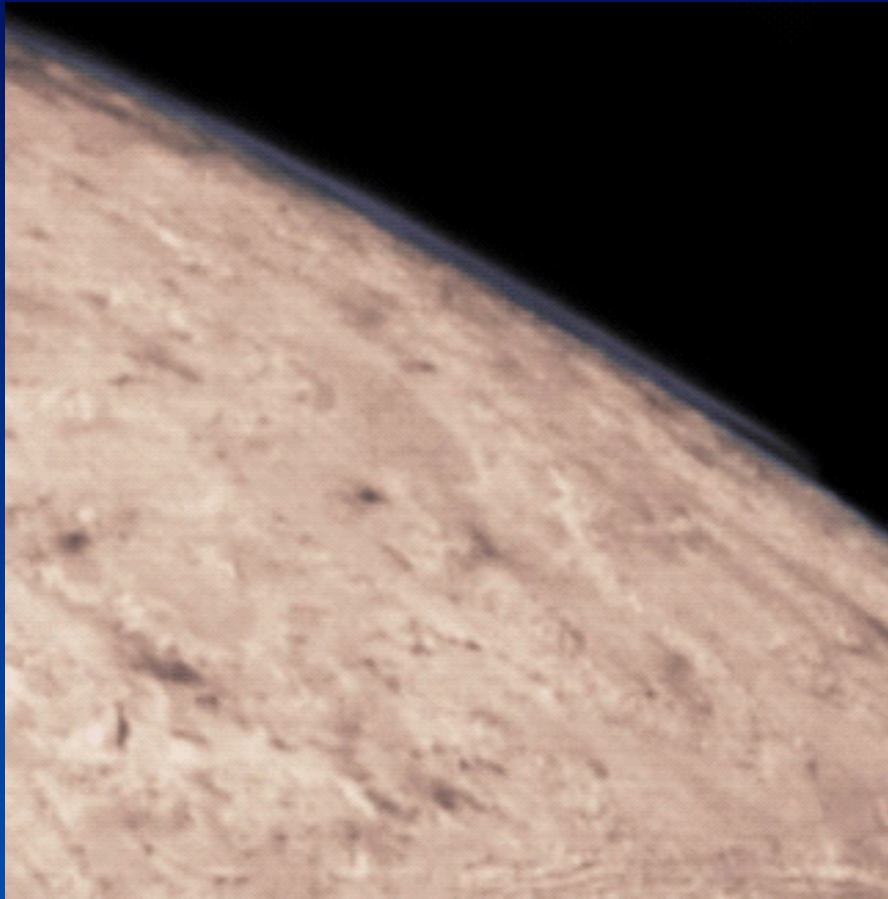
Rhea

Triton and Cryo Volcanism



- ▶ Active geysers show up as white dots
- ▶ Dark streaks form where the vented material, carried by the tenuous winds, falls down
- ▶ Voyager 2 observed lots of active geysers shooting material 8 km up

Triton and Cryo Volcanism



- ▶ A tenuous nitrogen atmosphere with ~ 1 Pa surface pressure
- ▶ Large amount of nitrogen lies frozen at the surface
- ▶ How to create active geysers
 - One way
 - Nitrogen ice is very transparent
 - Sun shines through a Nitrogen ice sheet and heats the bottom
 - so called ‘solid state greenhouse’
 - Nitrogen at the bottom evaporates and makes a geyser
 - Another way:
 - Internal heat-flow heats bottom of nitrogen ice sheets