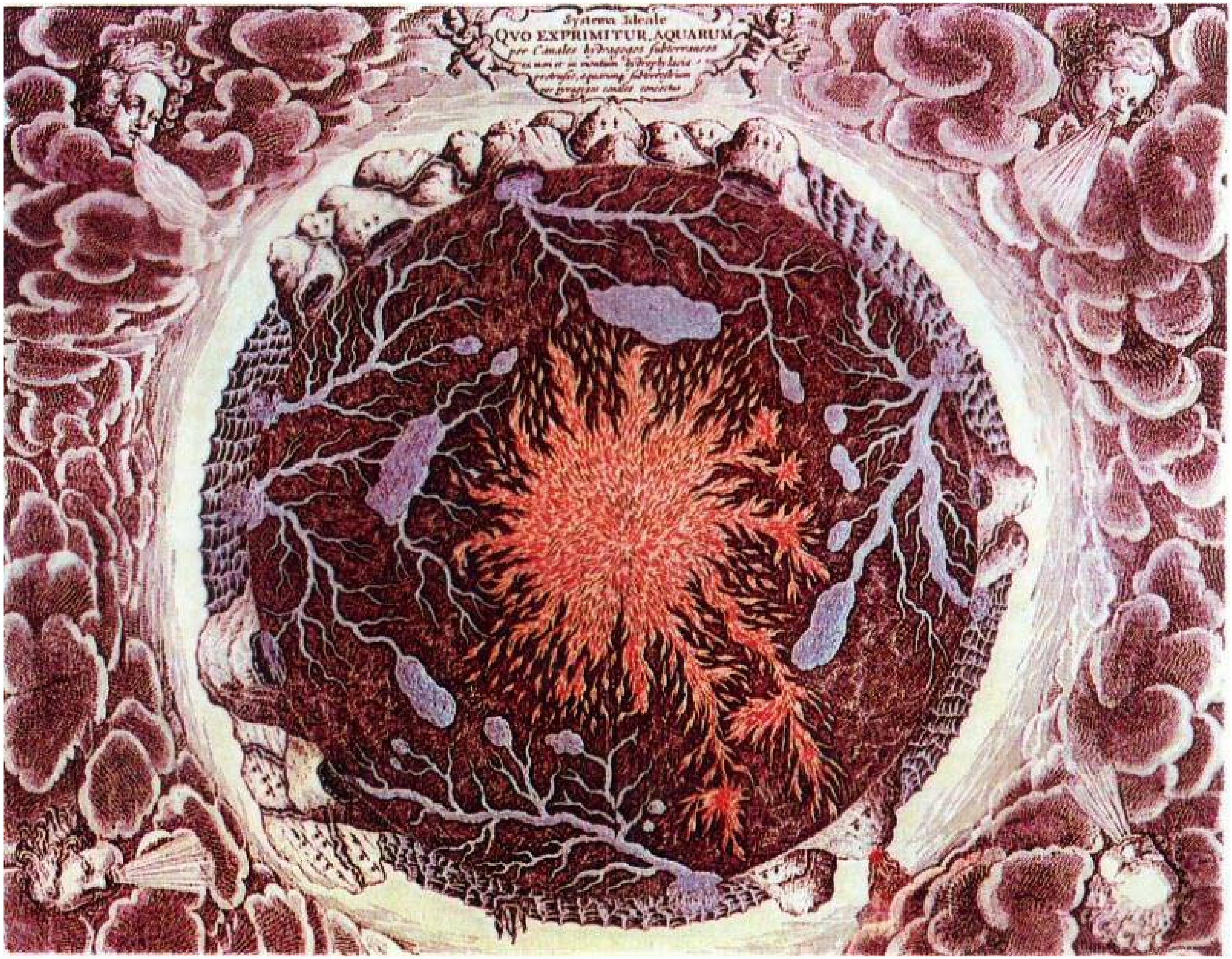
Internal heat and planetary volcanism



Heat sources

Where does the internal heat of a planet come from ?

Heat of accretion – for a homogeneous sphere the gravitational potential energy released on accretion is $E_{pot} = -3/5\ GM^2/a$. Equivalent temperature rise:
Earth: 38,000 K Mars: 8,000 K Moon: 1,600 K Ceres: 120 K.

Heat of core formation – for Earth equivalent to additional +2,000 K

Heat of radioactive decay – at present: ^{238}U, ^{235}U, ^{232}Th, ^{40}K relevant parent isotopes. Produce in Earth ~ 2×10^{13} W compared to 4.2×10^{13} W geothermal heat flow. Roughly half of Earth's internal flow is due to radioactivity and half is due to stored accretional heat (cooling rate order 100 K / Gyr)

Short-lived radioactive isotopes (^{26}Al, ^{60}Fe) have probably heated the first large planetesimals (e.g. Vesta) up to melting temperature within one Myr

Heat of tidal friction – proportional to $kGm^2a^5\Delta\omega/(QR^6)$. For present Earth ~ 3×10^{12} W, but mostly dissipated in shallow sea.

Can me much larger in principle for satellites of the big gas planets.

G: constant of gravity, M: planetary mass, a: planetary radius, m: mass of tide-raising body, R – distance to tide-raising body, Q – quality factor, Δω - difference spin frequency / orbital frequency, k – tidal Love number (0.1 – 1 for large planet)

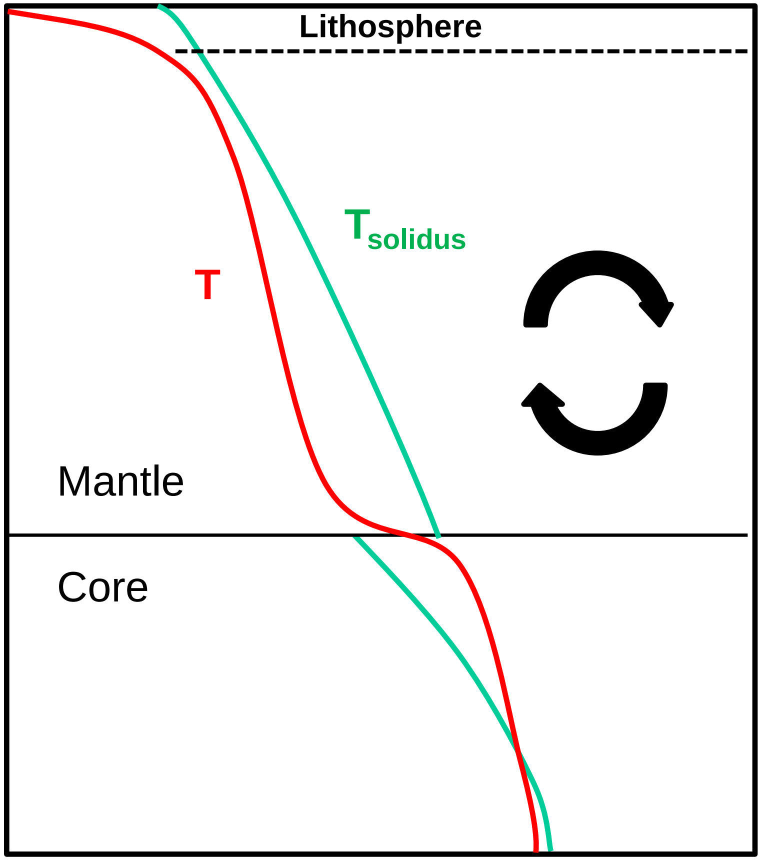
Properties of magmas

The viscosity of a magma depends on its composition, mainly its SiO_2 content.

The eruption style depends on viscosity and content of dissolved H_2O and other volatiles.

Type	Source	SiO_2	Viscosity	Eruption style
Basalt	Partial melting of mantle rock	50%	$10 - 10^3$ Pa s	Effusive, long lava flows
Andesite	Partial melting of mantle rock in presence of H_2O-rich liquid	60%	$10^5 - 10^6$ Pa s	Short lava flows, partly explosive
Rhyolite (Granite)	Partial remelting of basaltic/andesitic rock	70%	10^{10} Pa s	Magma domes, explosive

Temperature structure and melting in a terrestrial planet

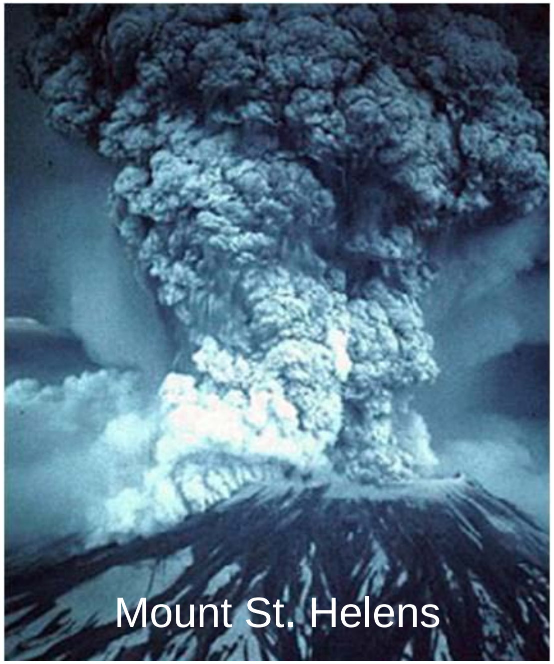


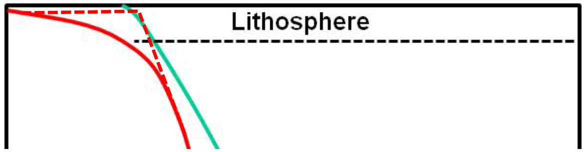
Lithosphere: low temperature, steep temperature gradient, stiff / brittle

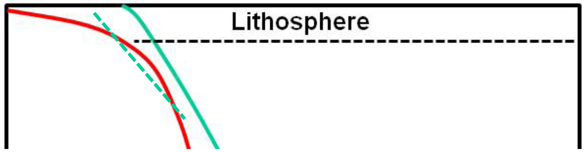
Warm mantle (asthenosphere): close to, but generally below melting temperature, small (adiabatic) temperature gradient, viscous, slow convection

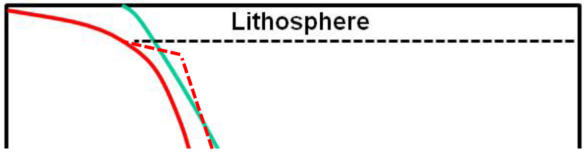
Melting of mantle rock typically occurs near the bottom of the lithosphere, because the gradient of the solidus temperature of mantle rock is steeper than the adiabatic temperature gradient

Three main types of volcanism on Earth









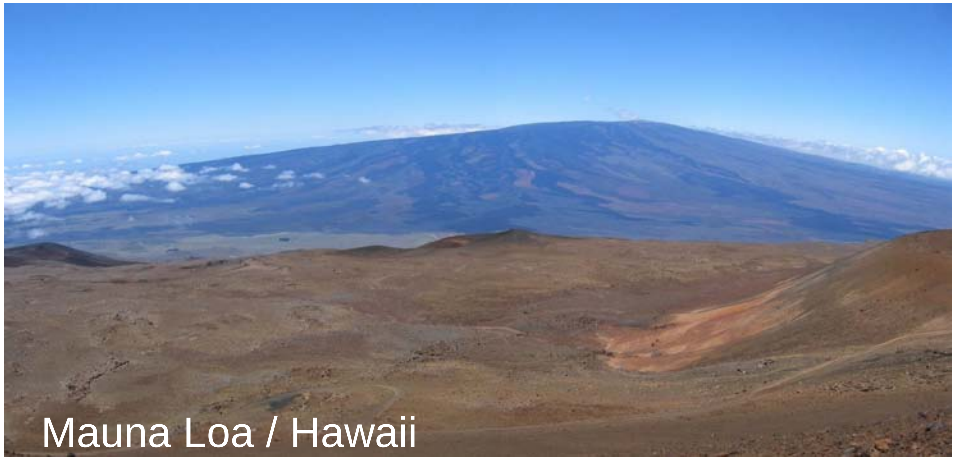
Pressure-release melting
Below mid-oceanic ridges
Basaltic magmas, effusive flow

Hydrous melting: adding water reduces melting point
Water transported into mantle at subduction zones
Andesitic magmas, explosive

Rise of hotter-than-normal mantle to bottom of lithosphere in mantle plume
Basaltic magma, effusive

Some volcanic structures

Volcanic structures depend on the kind of eruption (quiet effusion of magma, vs. explosive eruption depositing ashes) and on the viscosity of the magma


Mauna Loa / Hawaii

Shield volcano. Very gentle slopes. Formed by many flows of low-viscosity (basaltic) magma.


Mt. Fuji. Japan

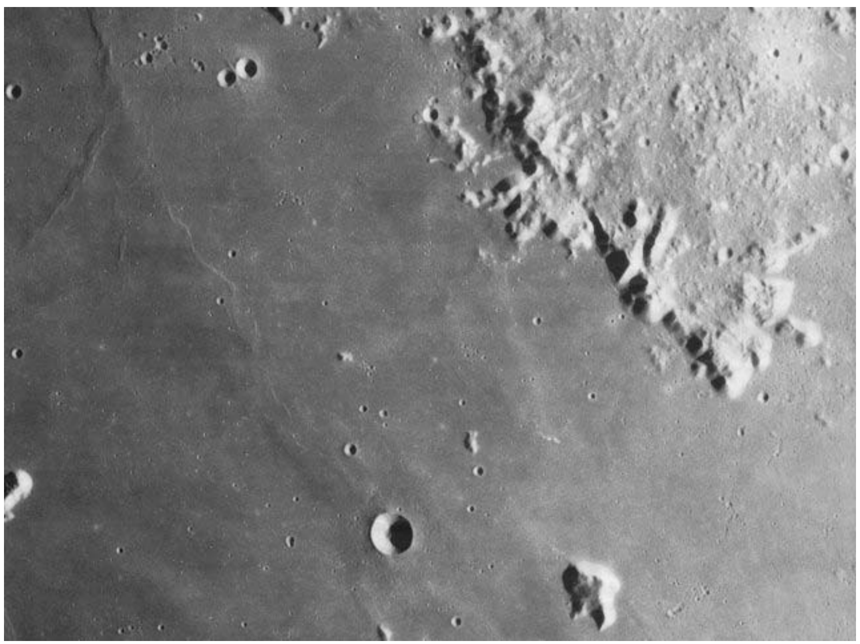
Stratovolcano. Steep slopes, steepening towards sumit. Superposition of high-viscosity (andesitic) magma flows and ash deposits.

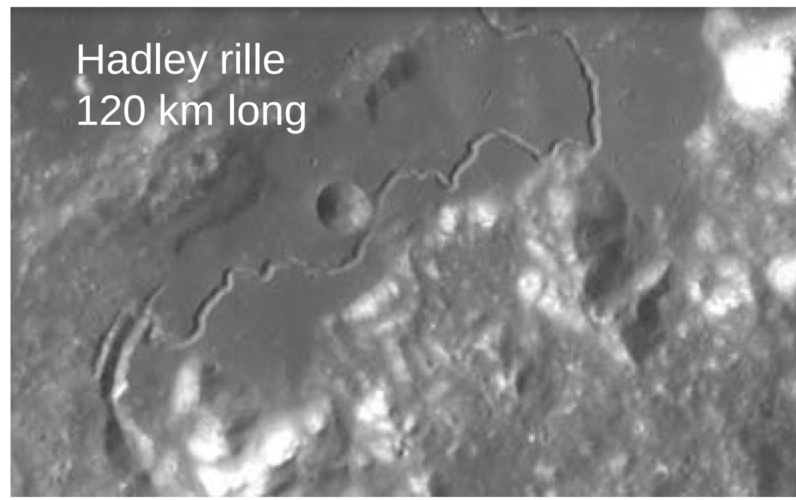
Caldera. Bowl-shaped depression formed by collapse of magma chamber below the volcano after it has been emptied. Found at both shield and stratovolcanoes.

Moon

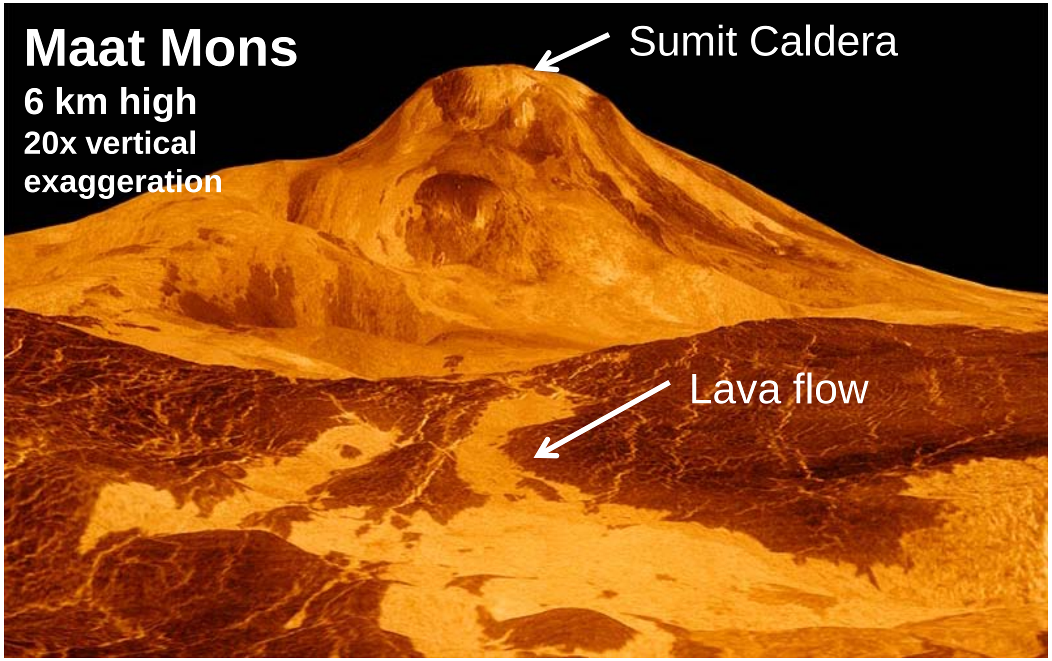
No unambiguous identification of a “classical” volcano.
Mare filling is basaltic – large scale flooding of depressions by magma (age 3 – 4 Gyr).
Viscosity of lunar basaltic magma 3-10 times less than of typical terrestrial basalts – spreads more easily over large distances.

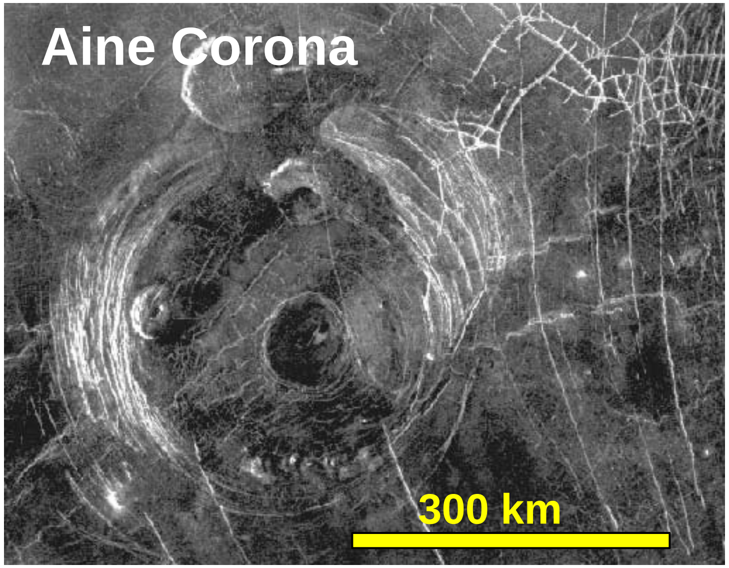
Some sinuous channels (“rilles”) similar to channels generated by basaltic lava flow on Earth, but much longer and wider. Difference probably due to difference in viscosity, gravity and flux of erupted magma.





Venus

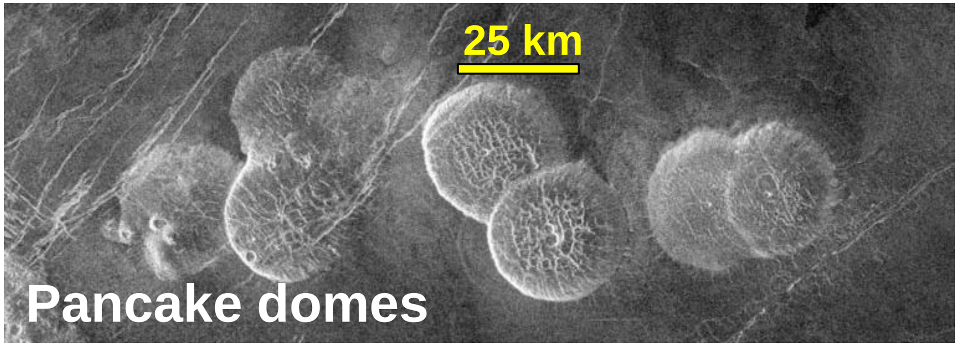




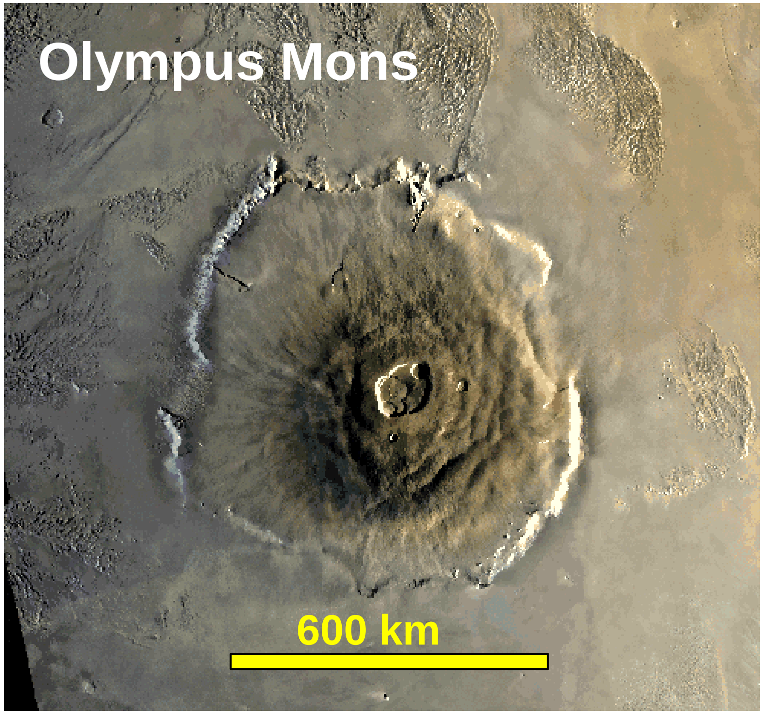
Shield volcanoes (low-viscosity magma)

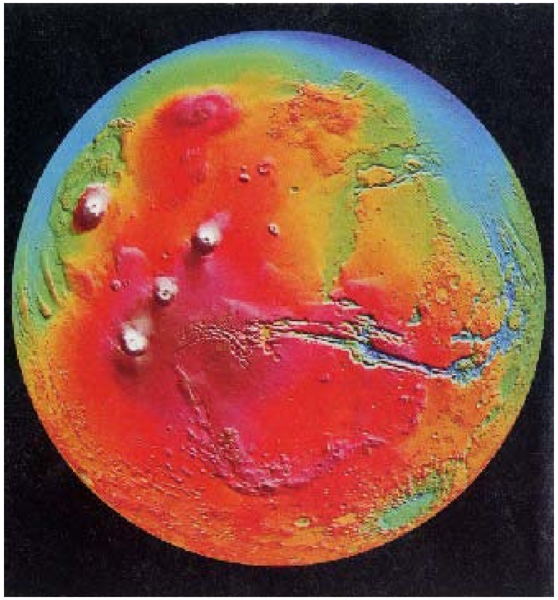
Coronae (wide oval elevations) – uplift caused by small mantle plumes ?

Pancake domes, often associated with coronae, interpreted as resulting from outpouring of very viscous (silicic) magma



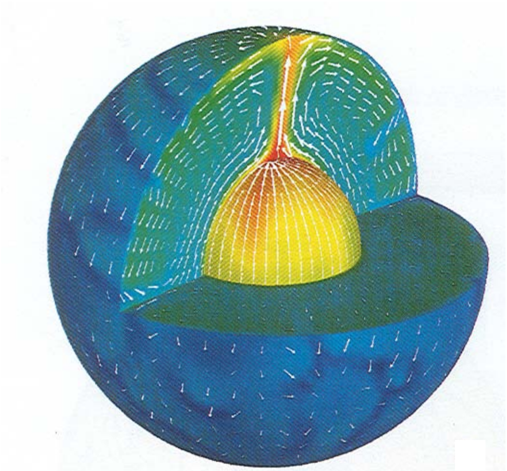
Mars





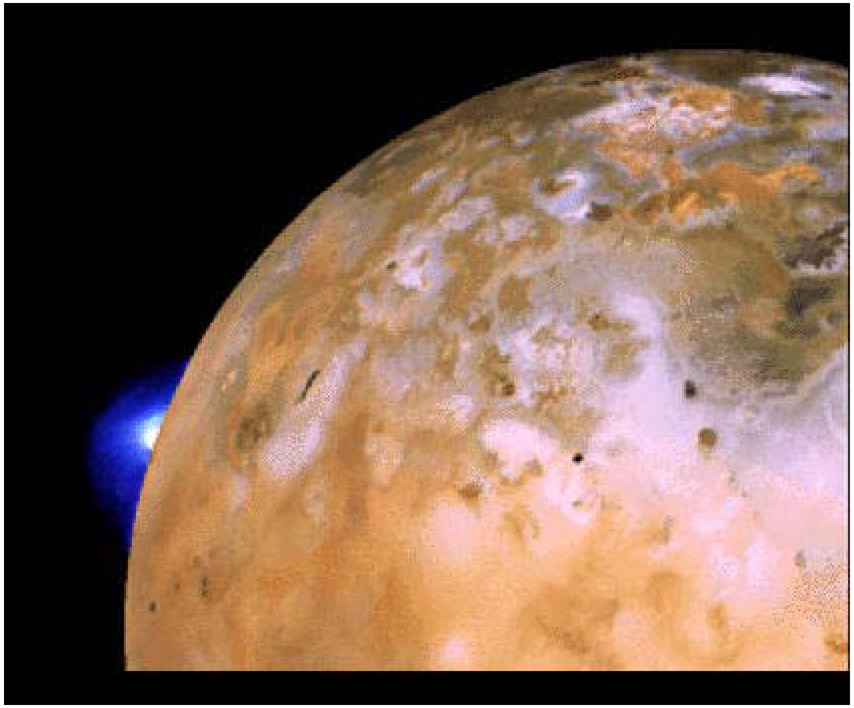
Giant shield volcanoes on the Tharsis bulge.
Olympus Mons 24 km high x 600 km wide
(Mauna Loa, Hawaii: 9 km x 120 km)
Cause for larger edifice on Mars: Lower gravity, no plate motion, longevity of plume ?

Concentration of large volcanoes on Tharsis:
Very large mantle plume below Tharsis ?

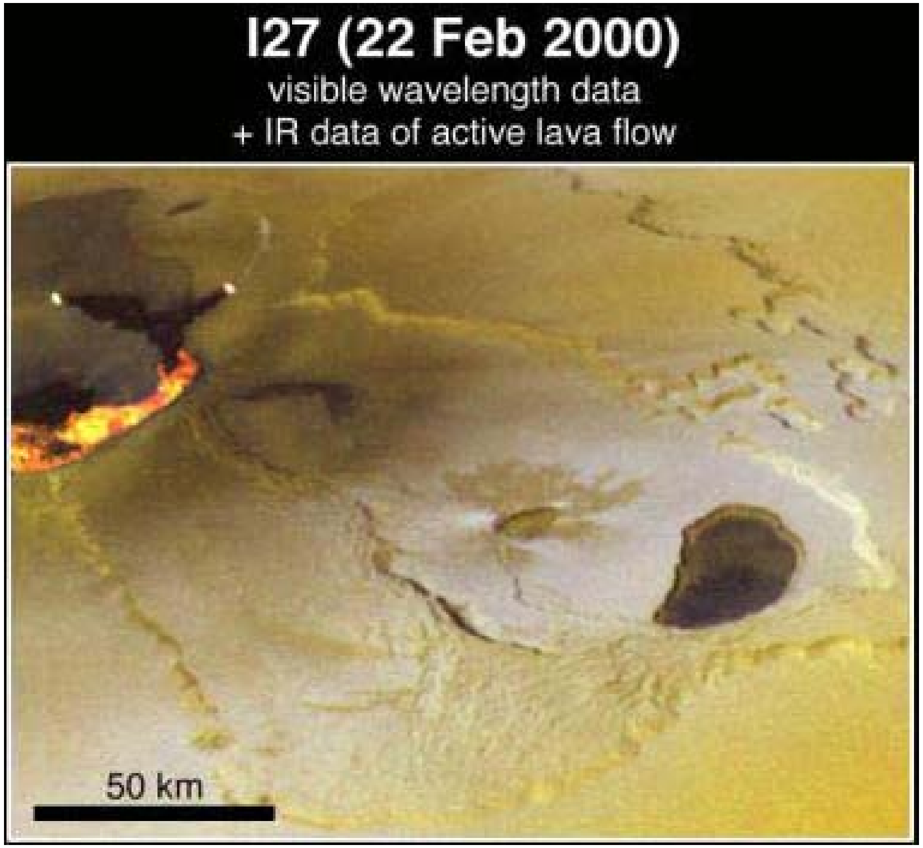


Numerical simulation of mantle convection in Mars, showing single large plume

Io

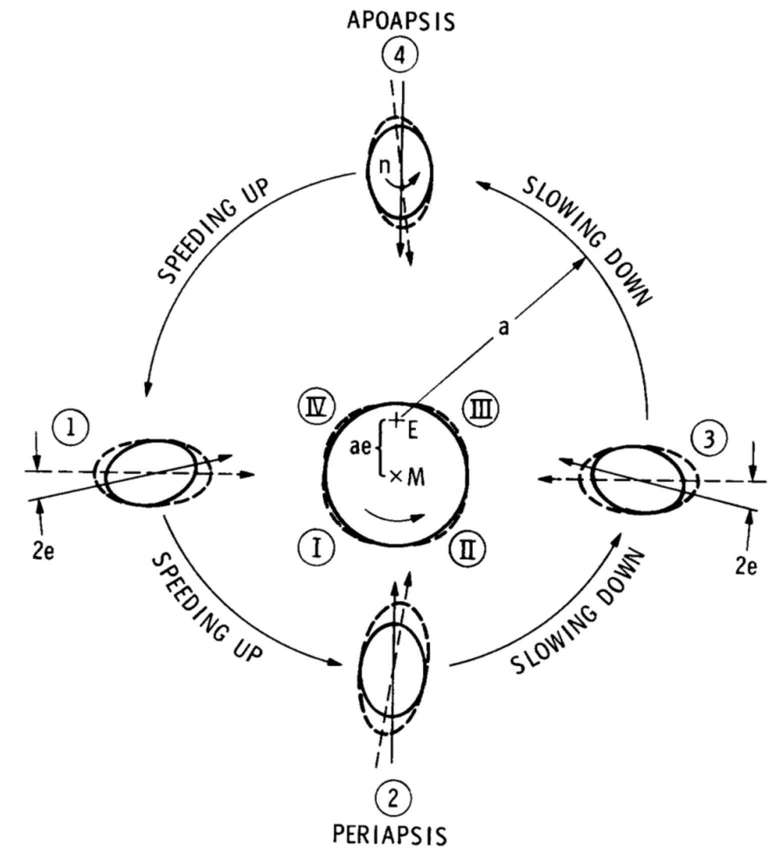


Volcanically most active body in solar system
Volcanic plumes several hundred km high, driven by SO_2 and sulphur
Colorful surface: different forms of sulphur, white = SO_2 frost
No impact craters: Resurfacing at a rate >100 m/Myr



Active lava flows, IR – observations show local temperatures as high as 1400^{o}C
$\Rightarrow$ silicate magma
Lava lakes and various volcanic landforms

What drives volcanism on Io ?



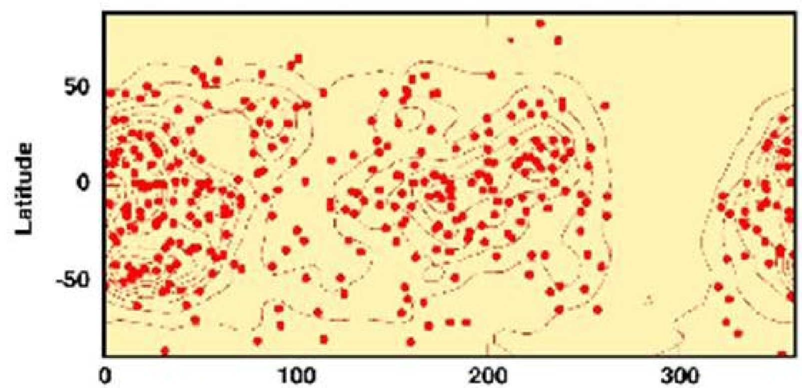
Tidal flexing: Tidal bulge is 13 km high (but basically static because of synchronous rotation)

Orbital eccentricity $\varepsilon = 0.004$ causes changes in tidal bulge on the order of 300 m

Orbital eccentricity is maintained by 4:2:1 resonance in orbital periods of Io, Europa, Ganymede

Heating by tidal friction dominates radioactive heating by far. Mean surface heat flow on Io is 2000 mW/m^2 (Earth 80 mW/m^2, Moon 17 mW/m^2)

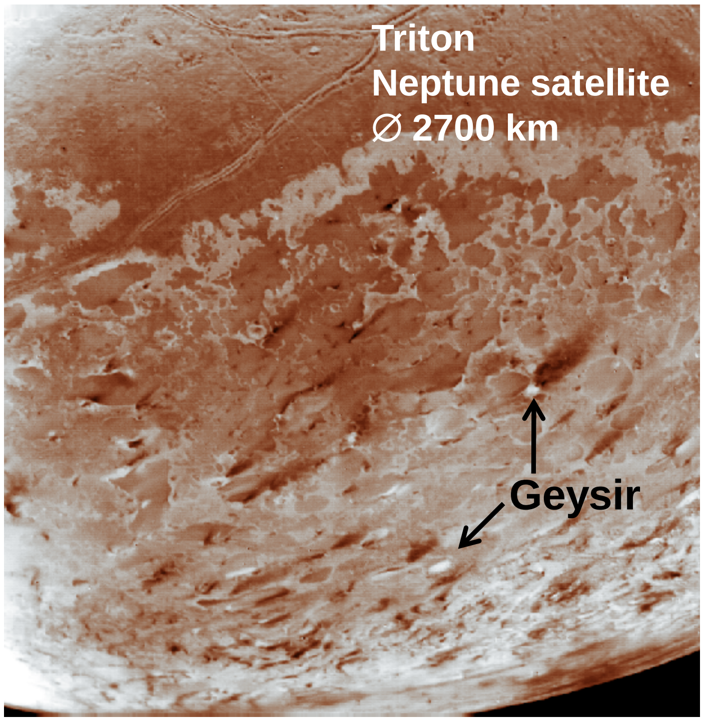
Distribution of volcanos on Io: Concentration at sub-Jovian and anti-Jovian point where tidal friction is strongest

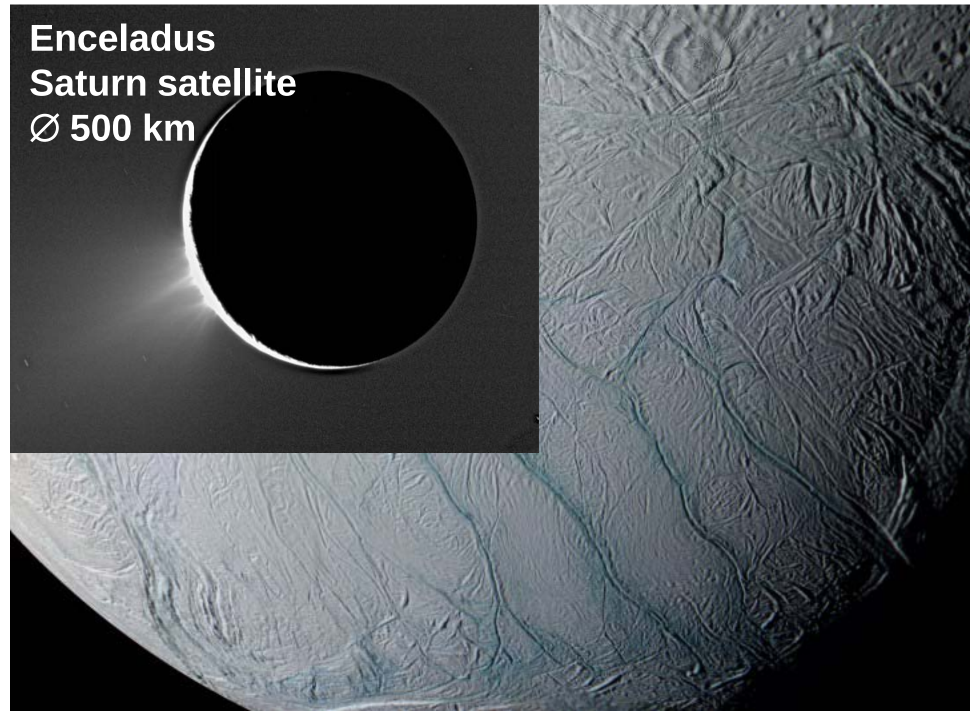


Christensen et al., Planetary Interiors and Surfaces, June 2011

Cryovolcanism

Volcanic phenomena on satellites in the outer solar system not driven by melting of silicate rock, but by melting and/or vaporization of H_2O, NH_3, CH_4, CO_2, CO or N_2. Driven by tidal heating and/or radioactive heating





Triton: surface temperature 30 K, thin (1 Pa) N_2 atmosphere, deposits of frozen N_2. Many active Geysirs of N_2 observed by Voyager 2 (1989), with plumes up to 8 km high.
Enceladus: Geysirs (mainly H_2O) erupt from vents (“tiger stripes”) near South pole and expand into space