

An aerial photograph of a planetary surface, likely Mars, showing a large, circular crater. The crater floor is covered in a dense field of smaller craters and ridges. A prominent, bright, circular feature is visible in the center of the crater. The surrounding terrain is rugged and heavily cratered. The overall color palette is a mix of reddish-brown and dark brown, with the central bright spot providing a stark contrast.

Brimstone Volatiles and Hermean Hollows

MICHAEL PHILLIPS

Planetary scientists study the planets and other “planetary bodies”.

The Not-Planets

Many large round worlds are not currently classified as planets: the solar system's major moons, the largest asteroids, and large Kuiper belt objects. These are the ones spacecraft have visited.

Images from Galileo (Jupiter's moons), Cassini (Saturn's moons), Voyager 2 (Uranus and Neptune's moons), New Horizons (Pluto), Dawn (asteroids). Data from NASA/JPL/JHU/APL/SwRI/UC/LAMPS/DLR/IDA processed by Ted Stryk, Gordan Ugarkovic, Emily Lakdawalla, and Jason Perry. Earth's Moon photo by Gari Arrillaga. Montage by Emily Lakdawalla, The Planetary Society, blog@planetary.org.

Earth's Moon:



The Moon

Saturn satellites:



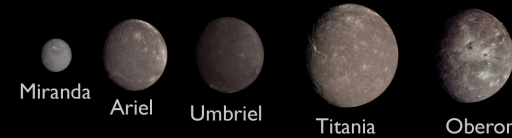
Mimas Enceladus

Tethys

Dione

Rhea

Uranus satellites:



Miranda

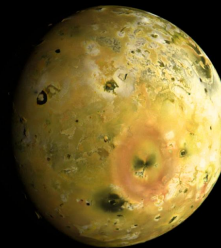
Ariel

Umbriel

Titania

Oberon

Jupiter satellites:



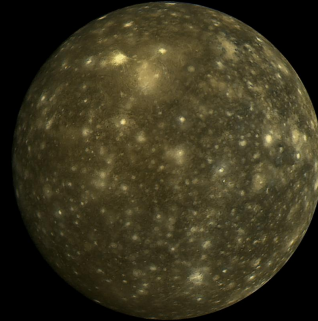
Io



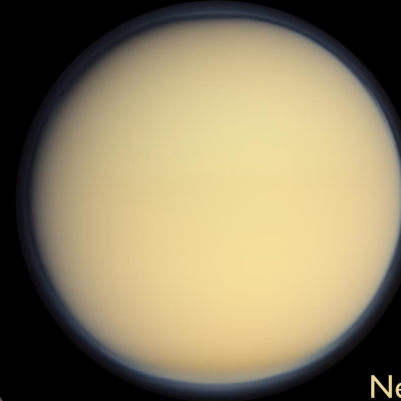
Europa



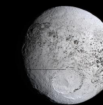
Ganymede



Callisto



Titan



Iapetus

Neptune satellites:



Triton

Pluto system:



Pluto



Charon

Asteroids:



Vesta

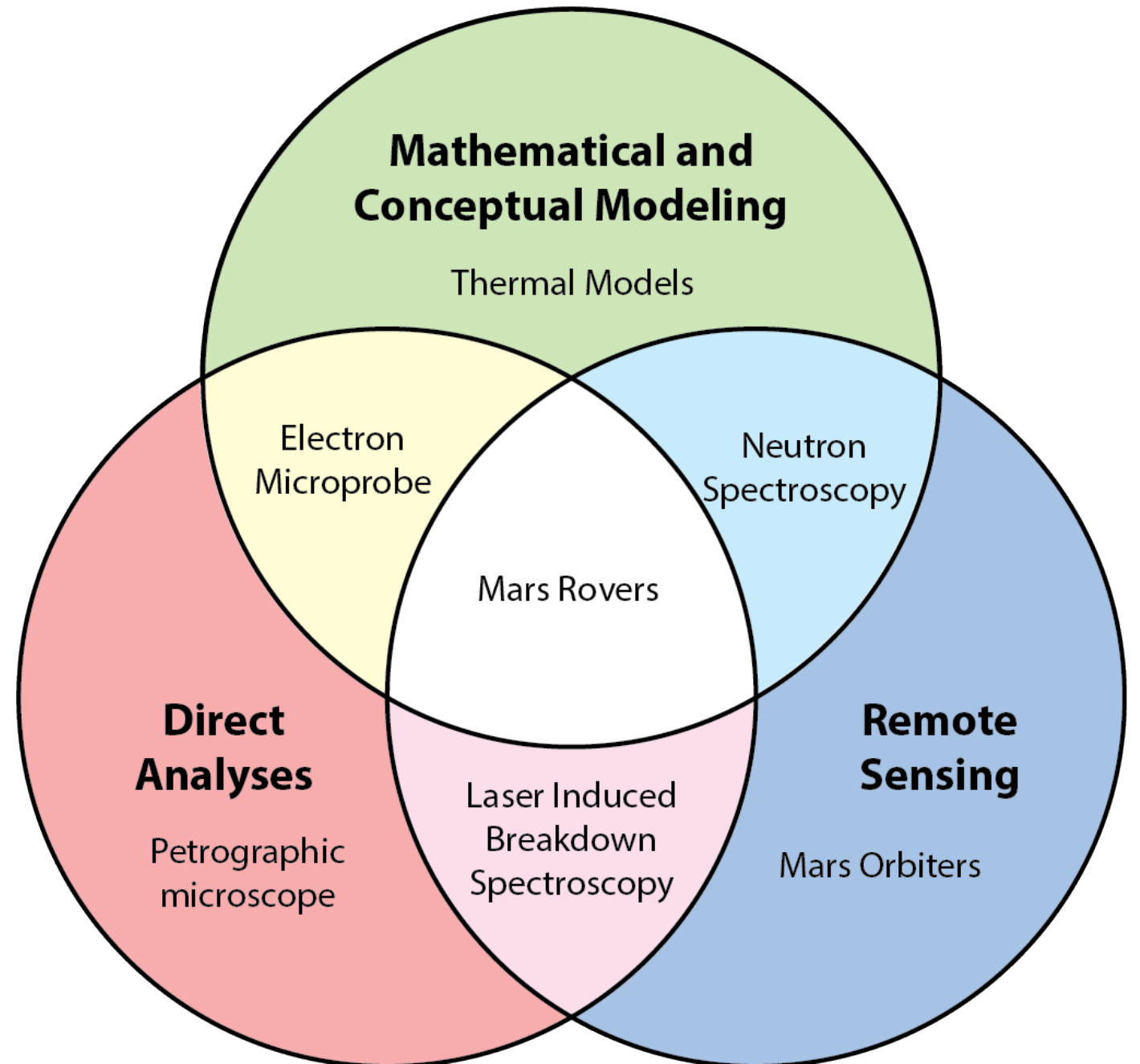
Ceres

Proteus

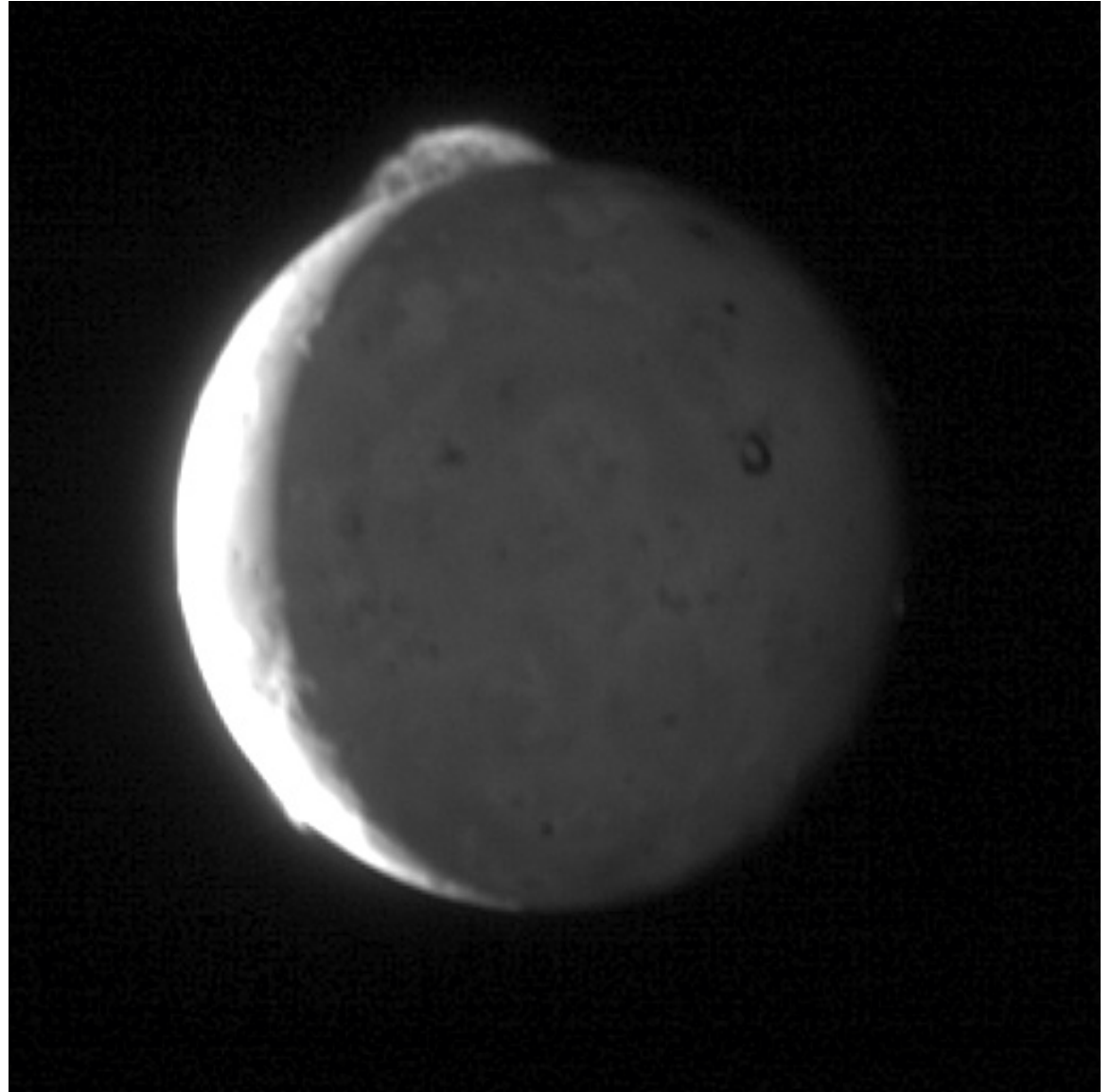


You can categorize the myriad ways to study planetary bodies into three modalities: direct analysis, remote analysis, and mathematical and conceptual modeling.

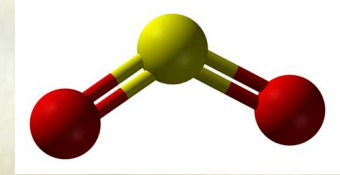
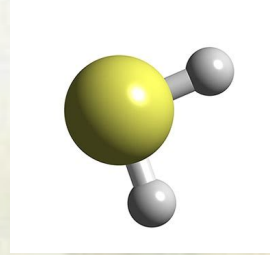
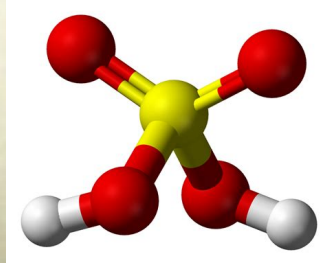
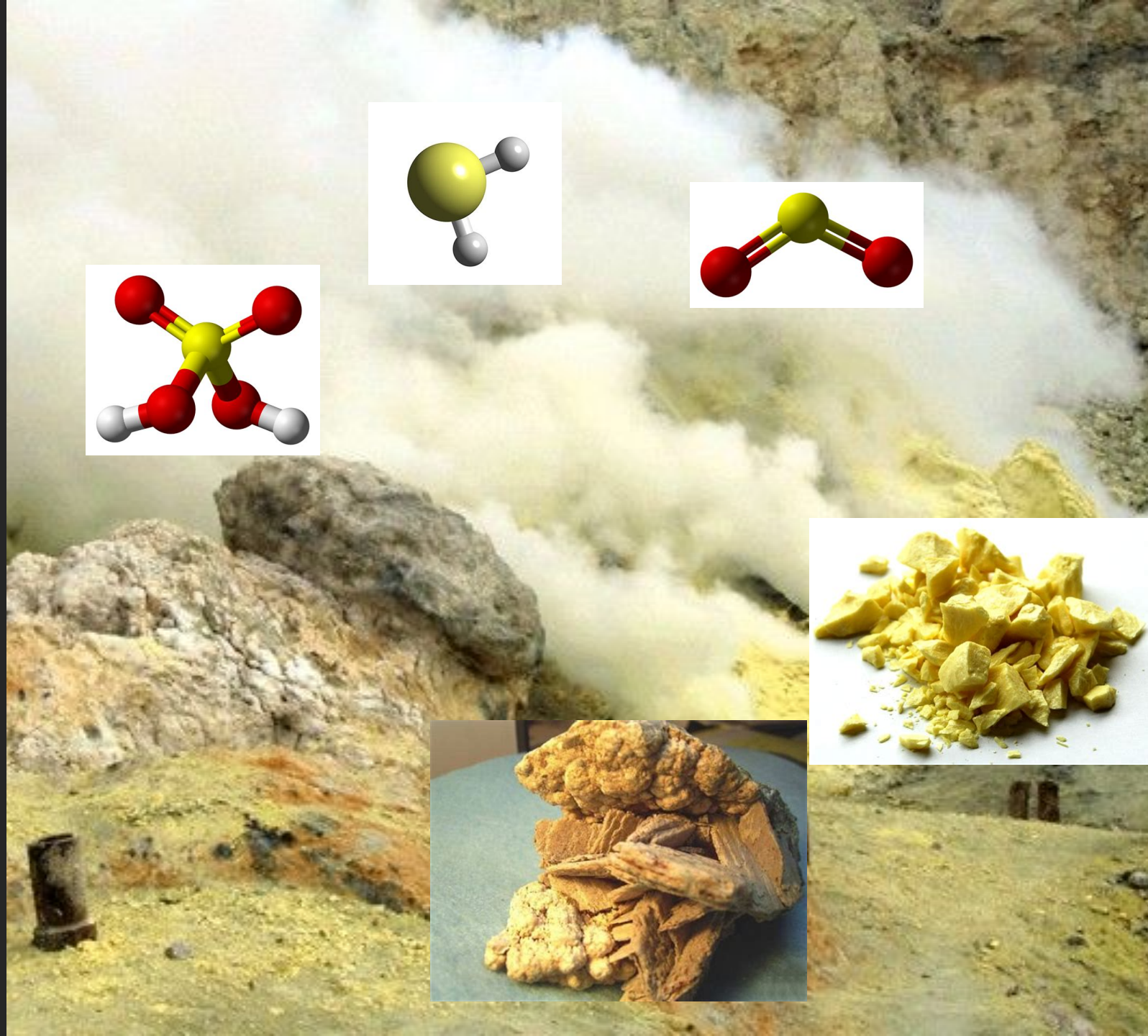
Modes of Analysis



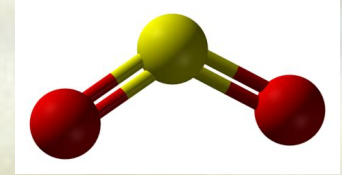
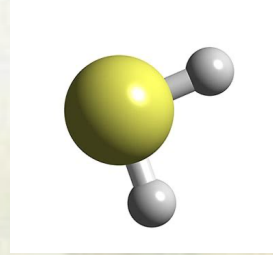
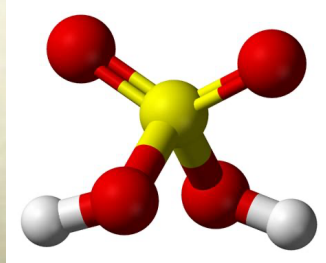
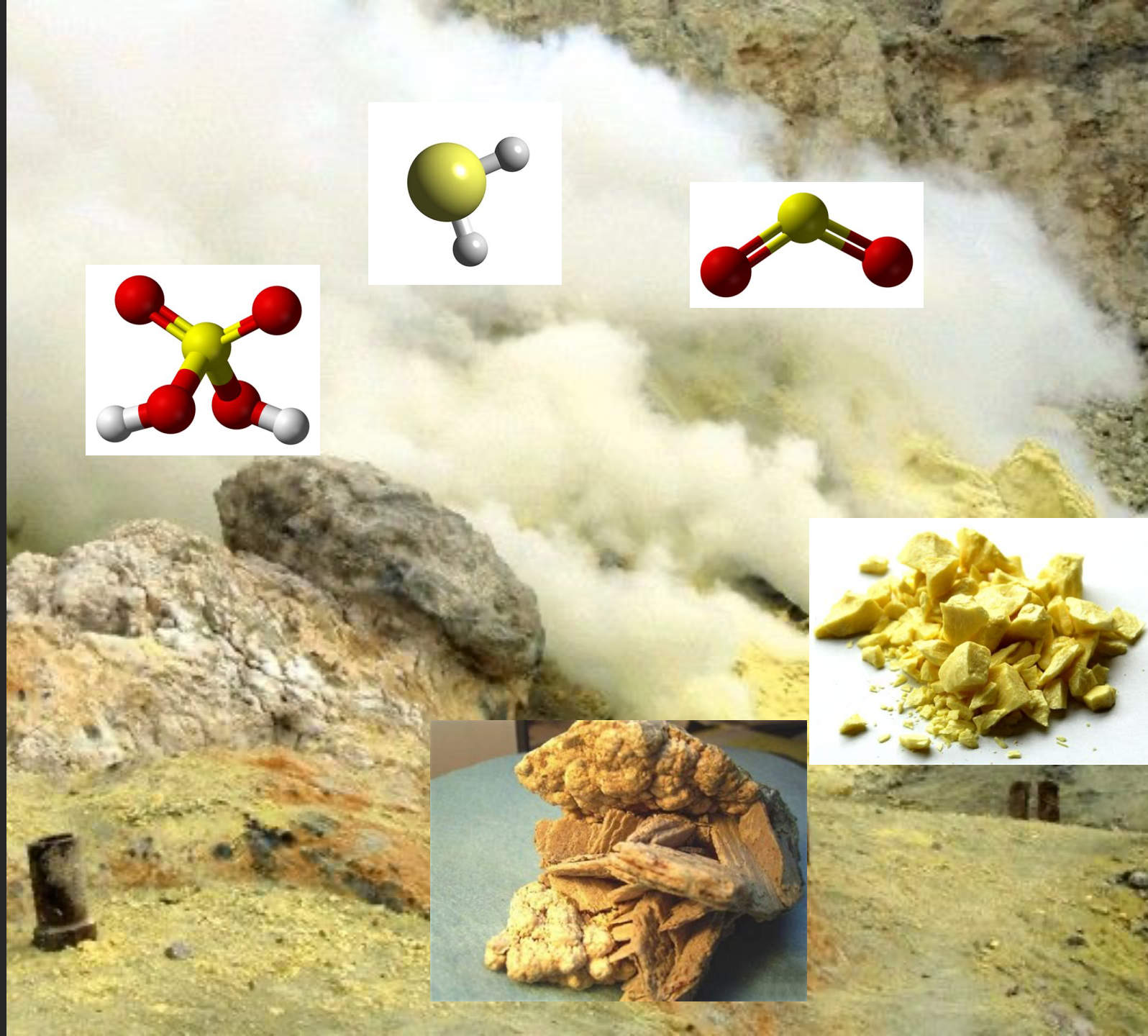
Days before the Voyager spacecrafts arrived at the Jovian system, Stan Peale and others predicted widespread and recurrent volcanism on Io mathematical models.



Brimstone

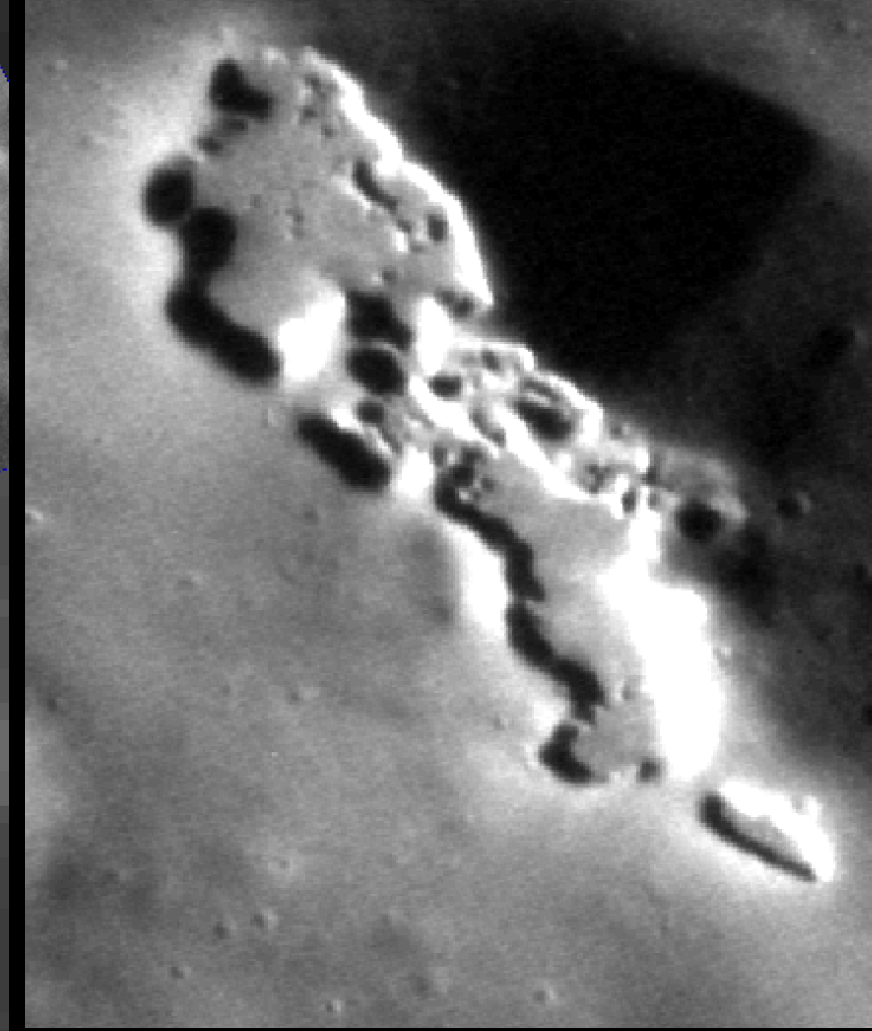
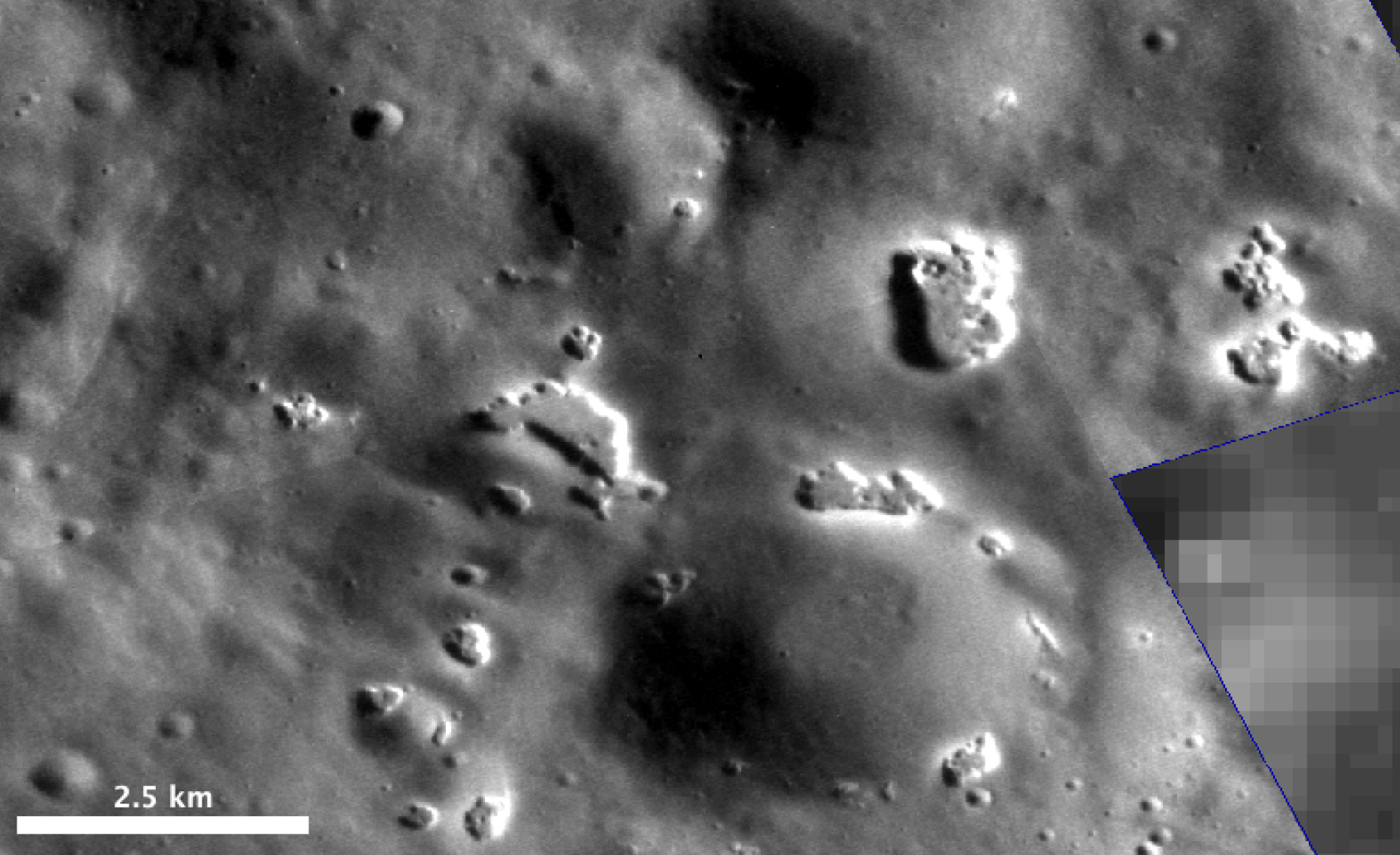


Volatiles



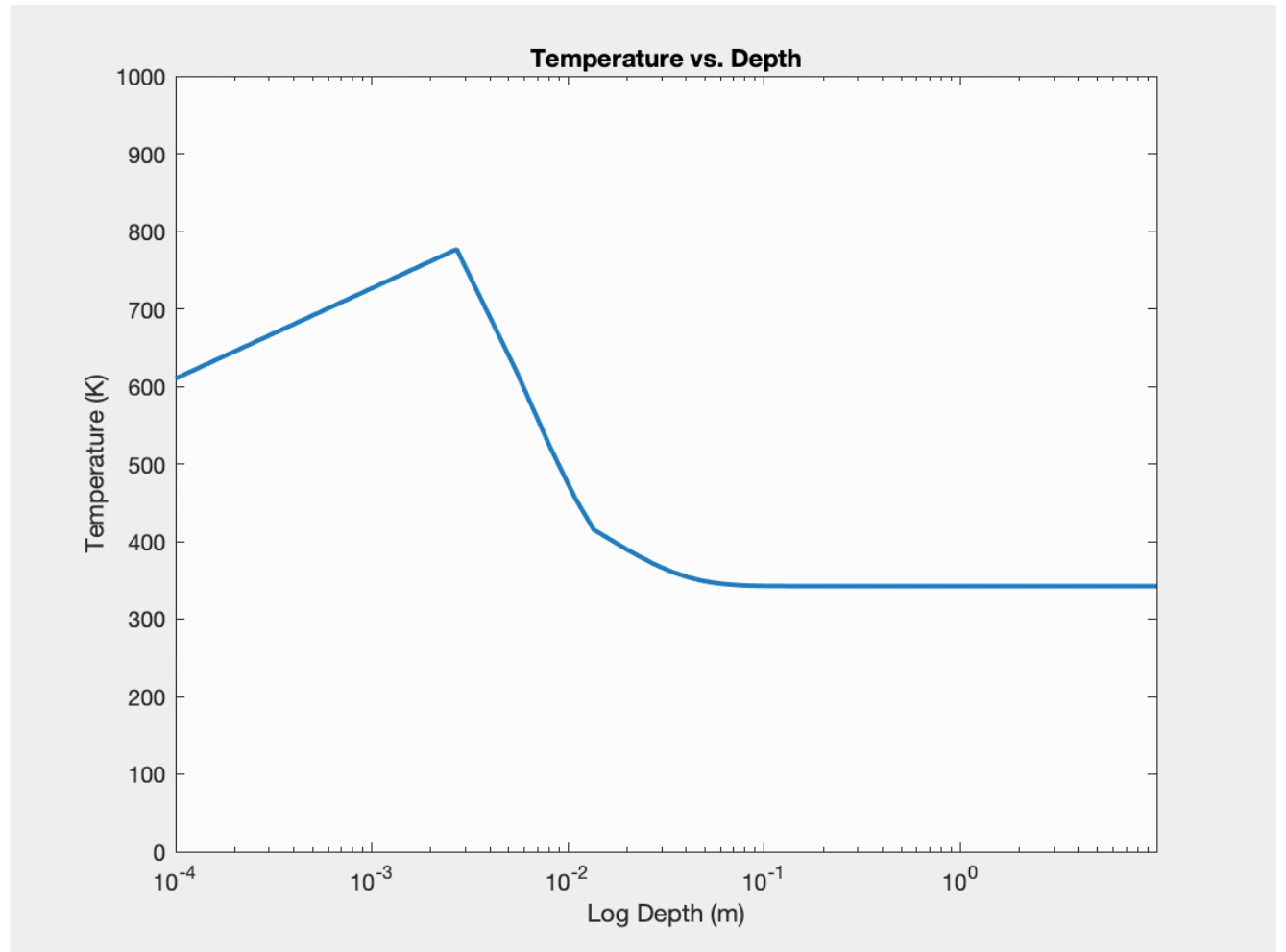


Hermean



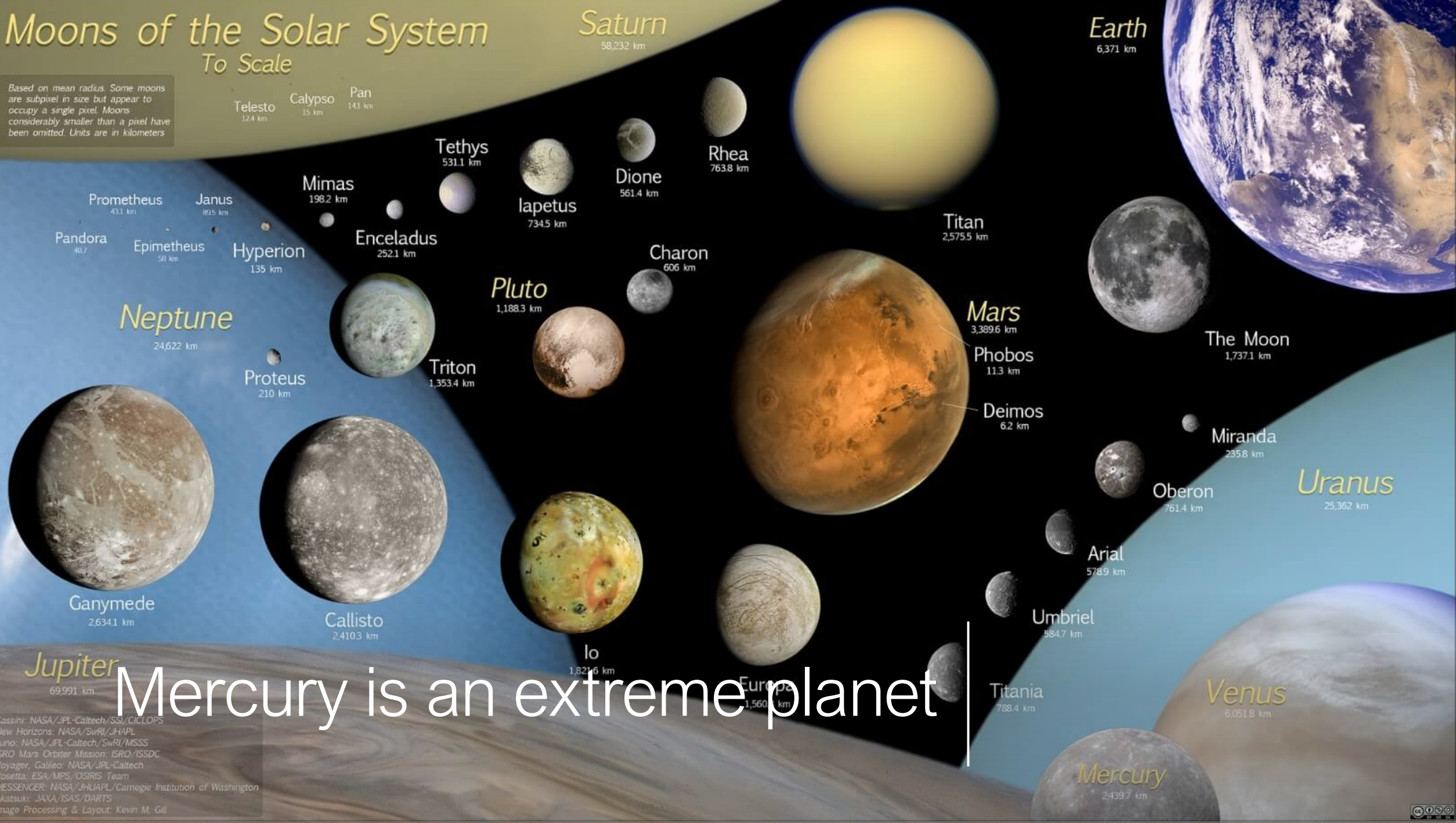
Hollows

Using temperature and diffusion calculations to test the prevailing hollow formation model.



Moons of the Solar System To Scale

Based on mean radius. Some moons are subpixel in size but appear to occupy a single pixel. Moons considerably smaller than a pixel have been omitted. Units are in kilometers

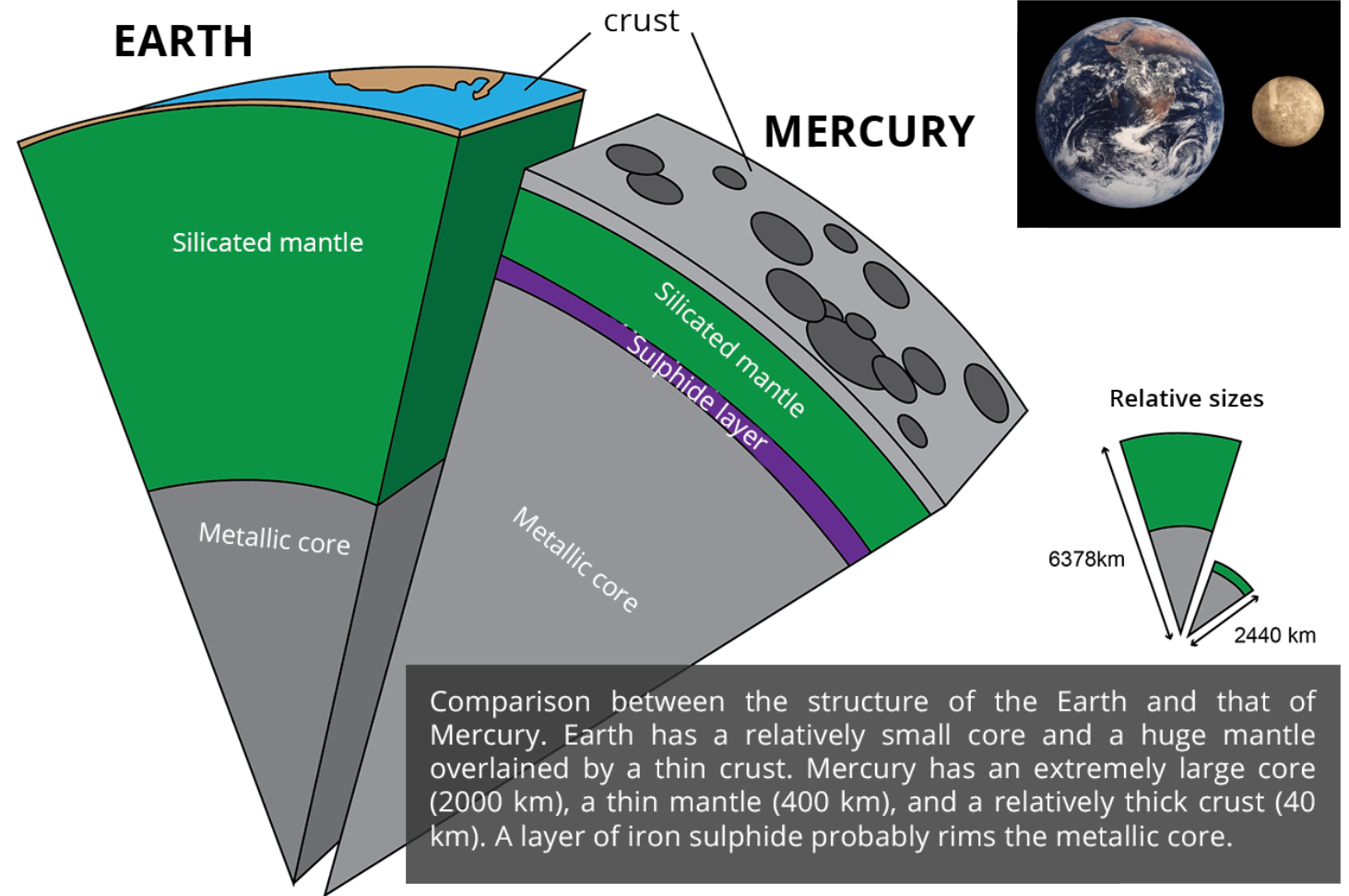


Mercury is an extreme planet

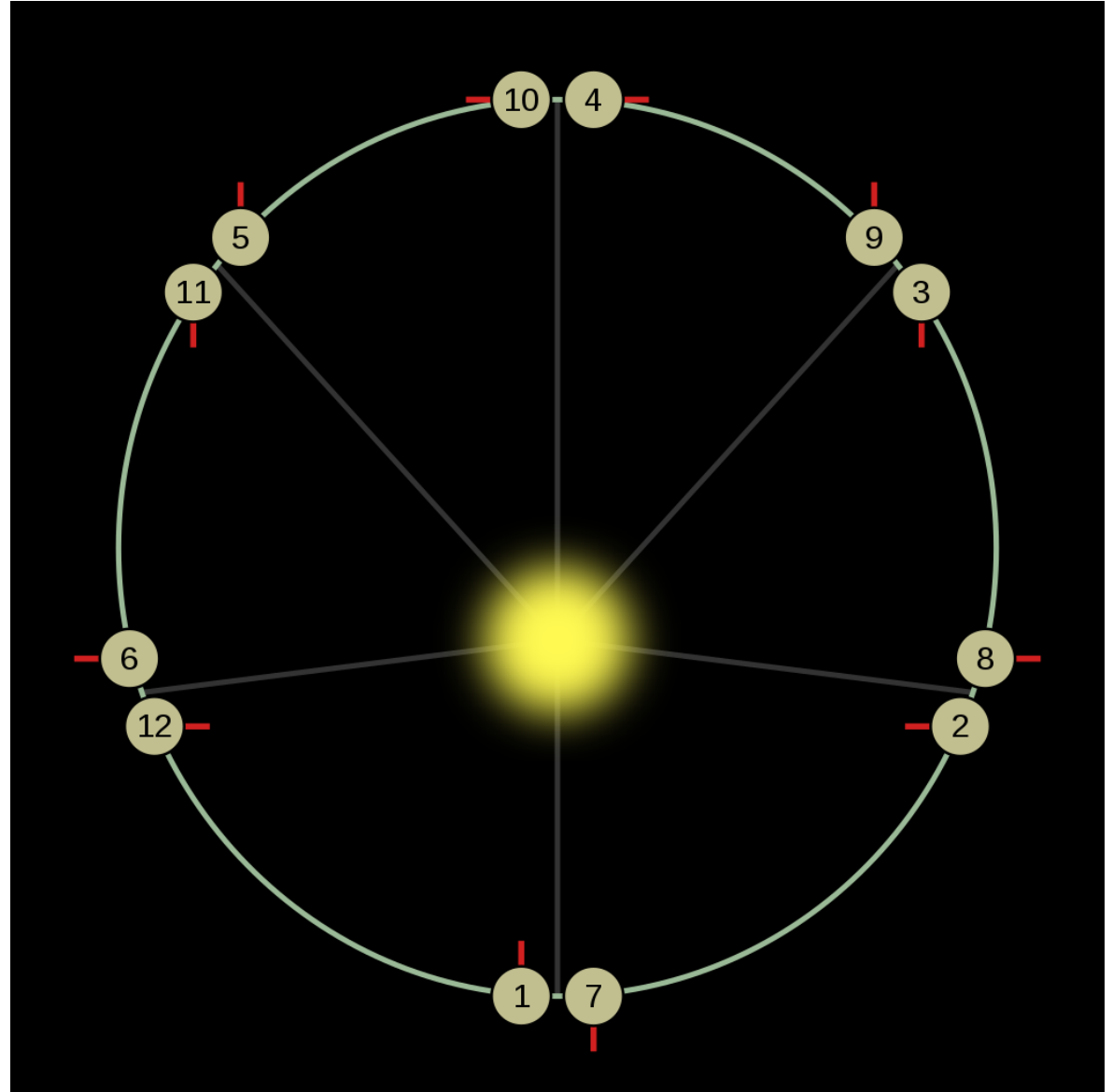
Cassini: NASA/JPL-Caltech/SSI/CICLOPS
New Horizons: NASA/SwRI/JHAPL
Juno: NASA/JPL-Caltech/SwRI/MSSS
ISRO Mars Orbiter Mission: ISRO/ISDC
Voyager, Galileo: NASA/JPL-Caltech
Rosetta: ESA/MPS/OSIRIS Team
MESSENGER: NASA/JHUAPL/Carnegie Institution of Washington
Akatsuki: JAXA/ISAS/DARTS
Image Processing & Layout: Kevin M. Gill



Mercury is almost all core.



Mercury has a 3:2 spin:orbit resonance. It spins 3 times on its axis for every 2 orbits.



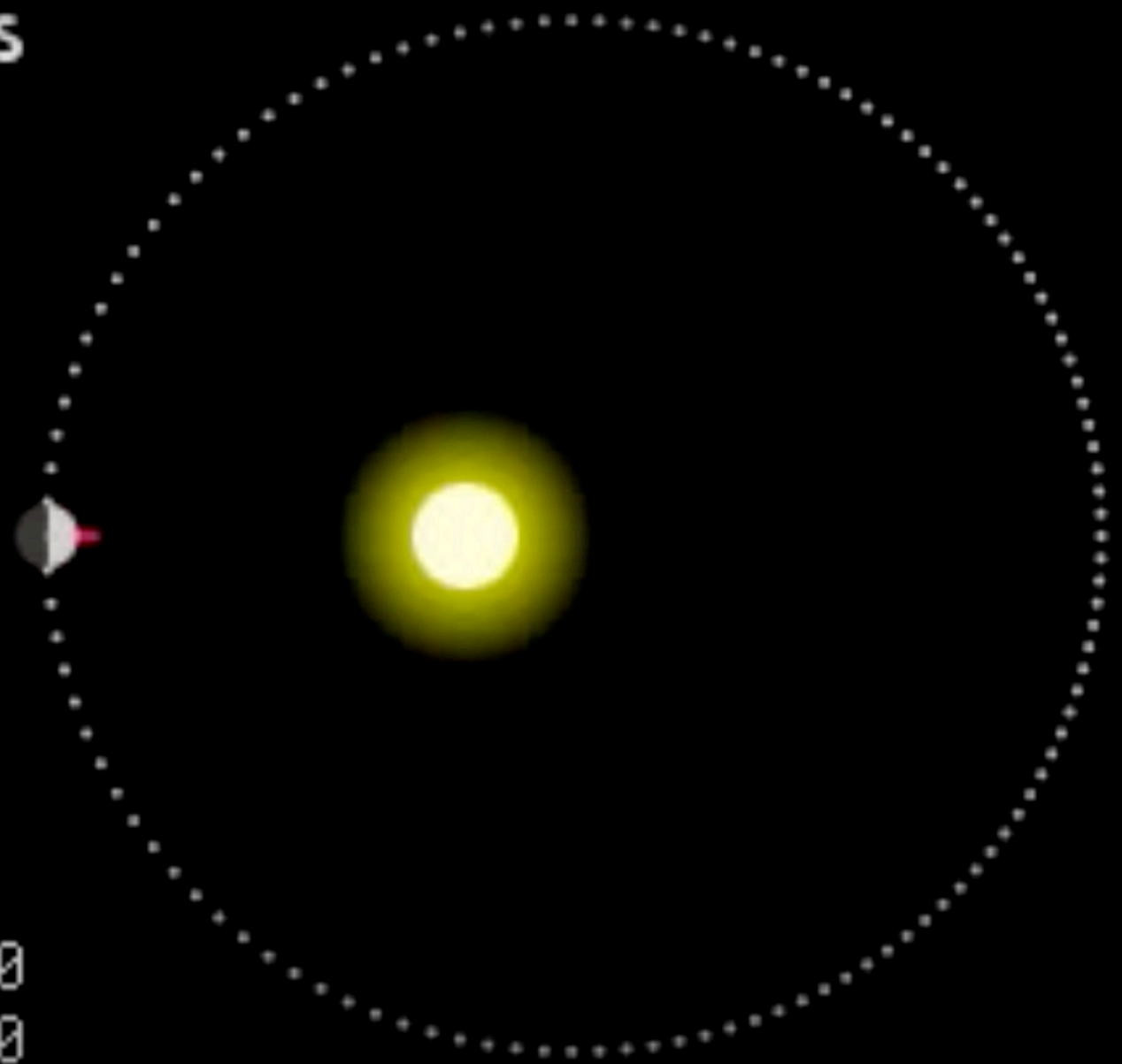


Mercury's Orbit

Mercury's Orbit



Copy link



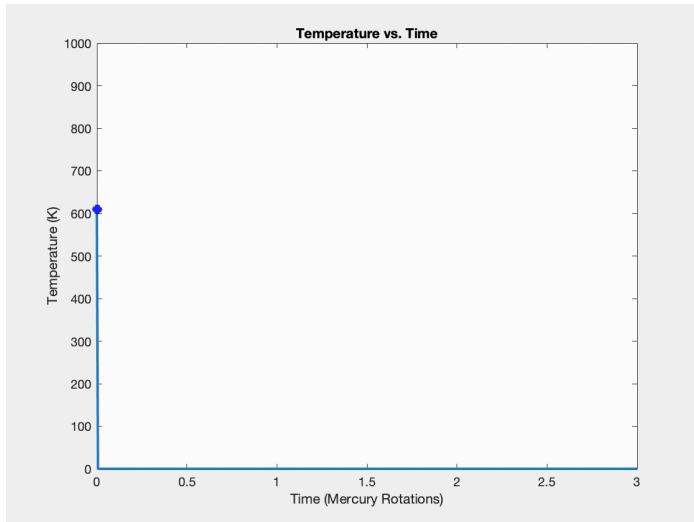
Time = 0.000
SidT = 0.000
SolT = 0.000



0:00 / 0:32



The effect of this orbit on the surface temperature of Mercury is... weird.

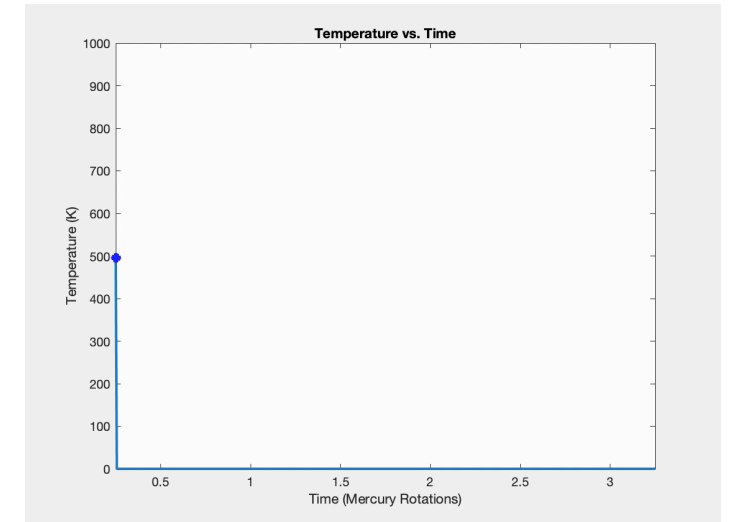


Mercury's Orbit
Mercury's Orbit

Time = 0.000
SidT = 0.000
0:00 0:32 T = 0.000

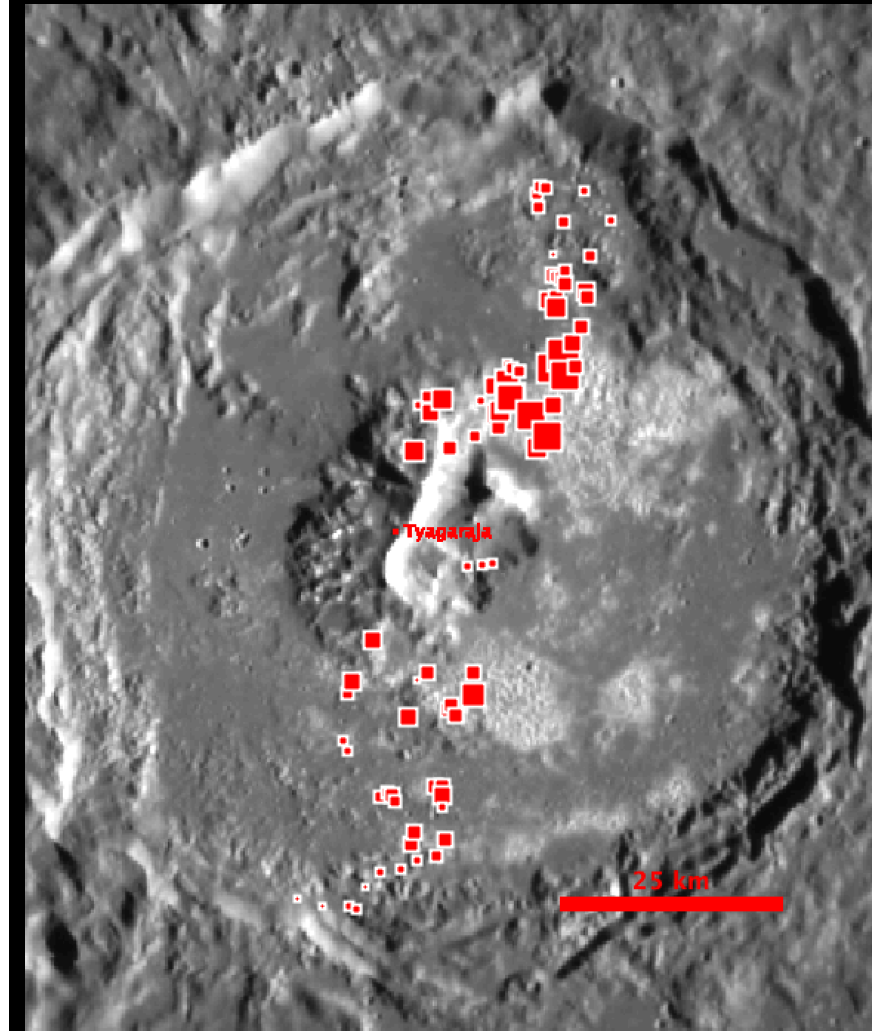
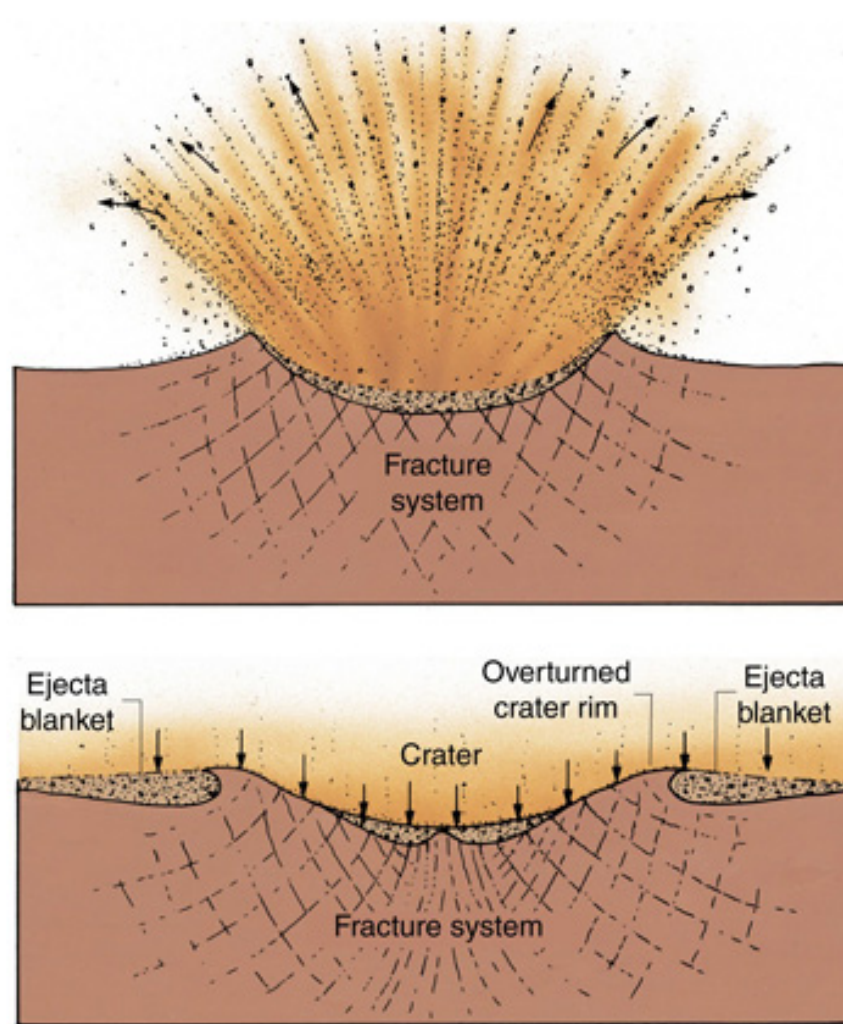
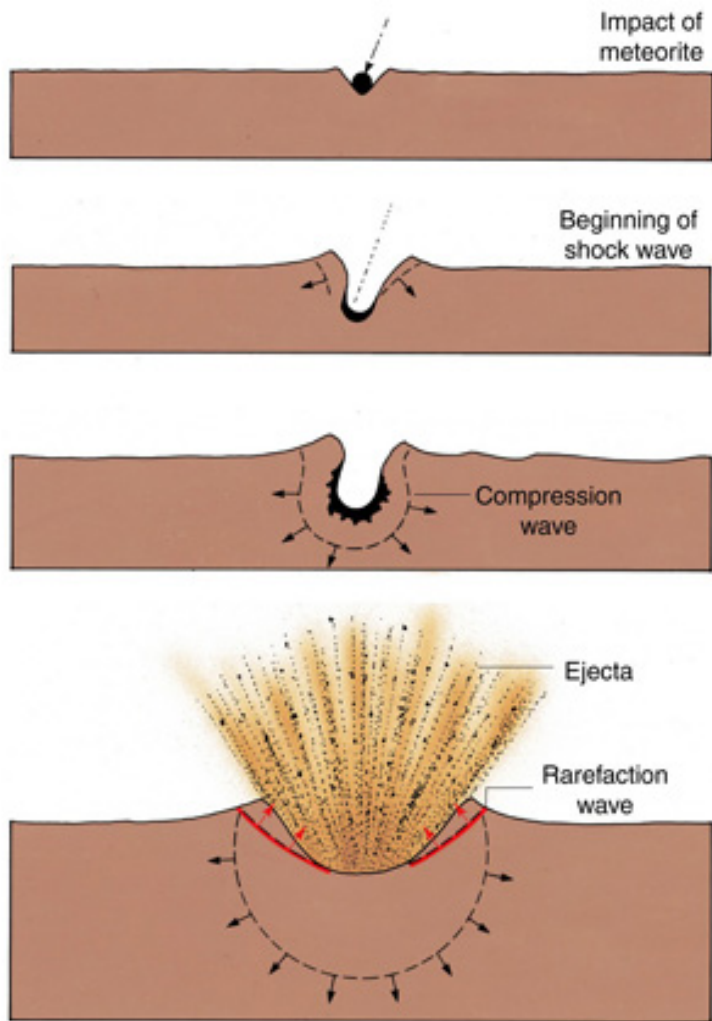
Mercury's Orbit
Copy link

The simulation interface shows a central yellow sun, a dotted circular orbit, and a small Mercury planet at the top. The text "Mercury's Orbit" is displayed vertically on both sides. A control panel on the left shows "Time = 0.000", "SidT = 0.000", and "0:00 0:32 T = 0.000". A "Copy link" button is at the bottom right.



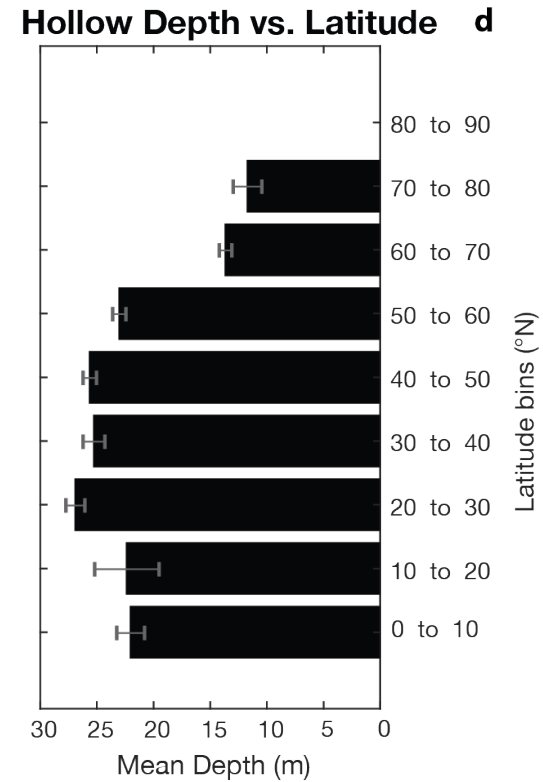
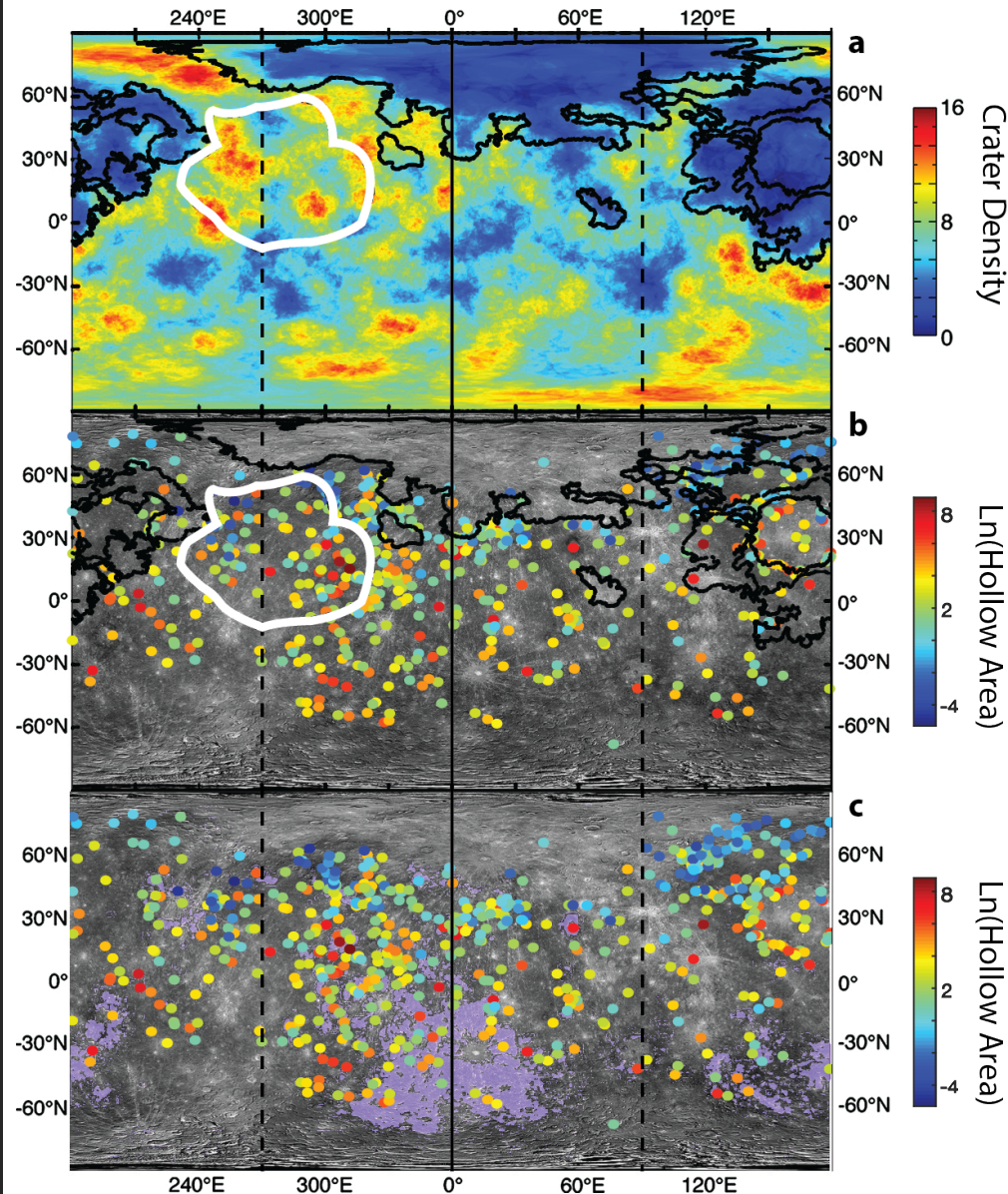


Hollows occur primarily in LRM, |
a major color unit of Mercury.

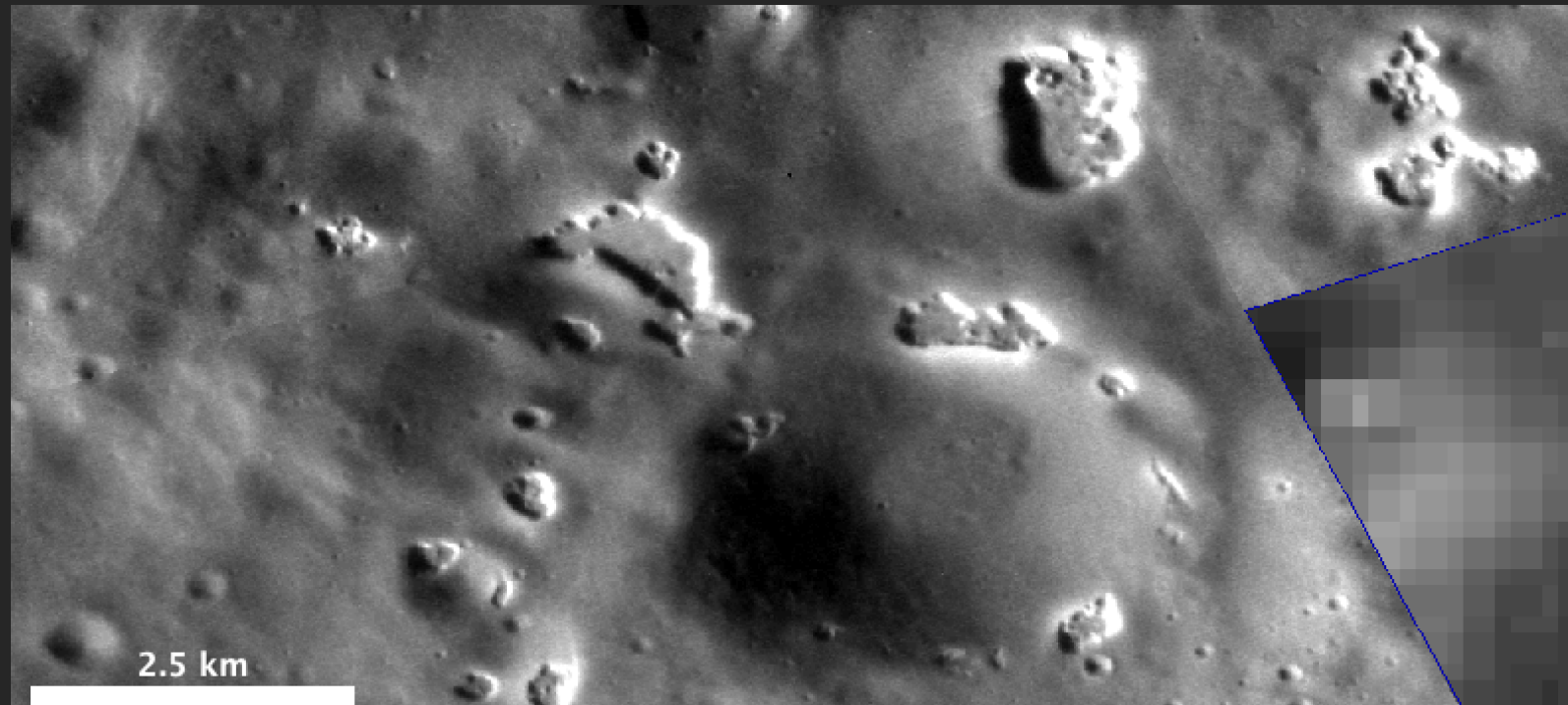


Hollows occur primarily in impact craters and related material.

Hollows are deeper and cover more area at low latitudes than at high latitudes.



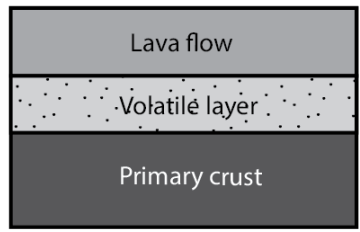
Hollow morphology suggests formation via sublimation.



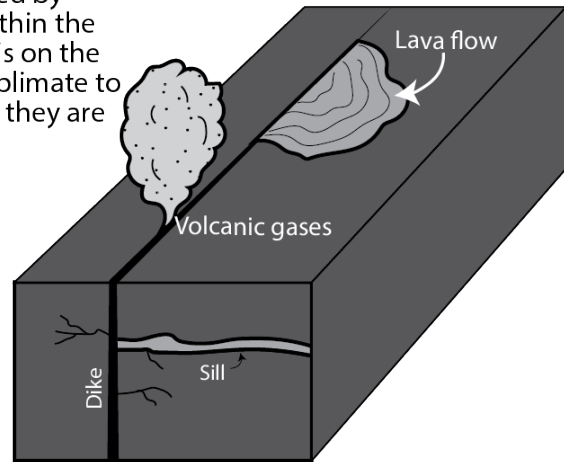
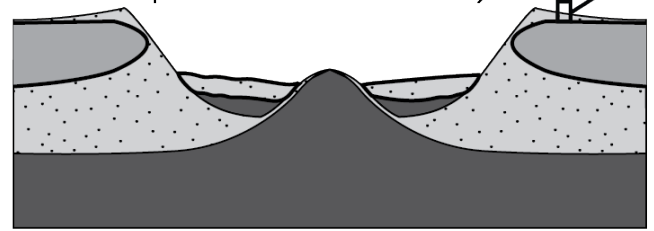
A.

① Volatiles are produced by eruptions on and within the surface. If eruption is on the dayside, volatiles sublimate to the nightside where they are deposited.

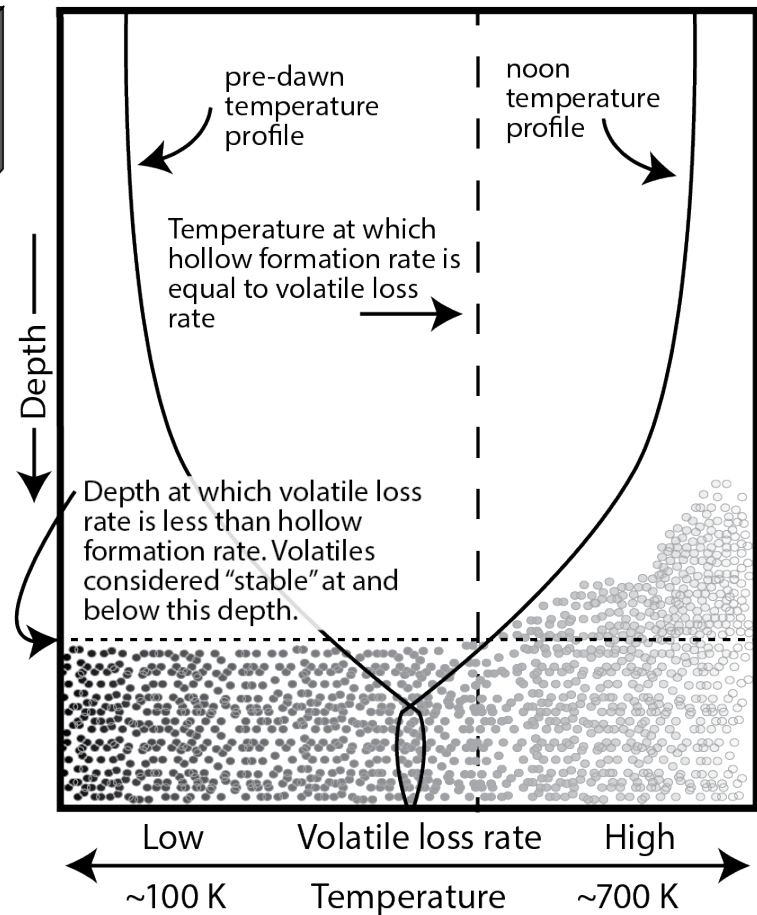
② Lava flows bury and sequesters volatile-rich layer beneath a lava "cap rock".



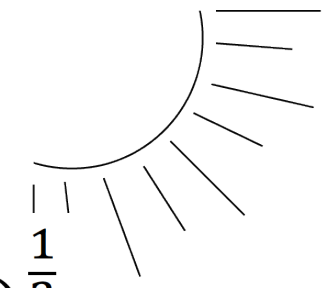
③ Impact exhumes volatile-rich layer. Hollows form as volatiles sublimate from floor, walls, peak, and ejecta. Hollow formation ceases when an insulating lag deposit shields the volatile layer.



B.

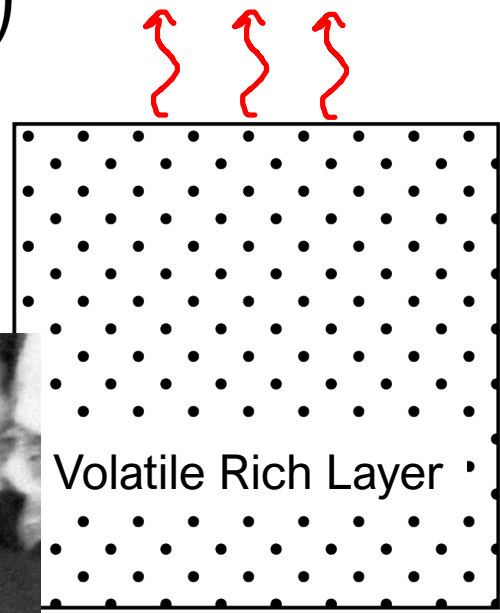
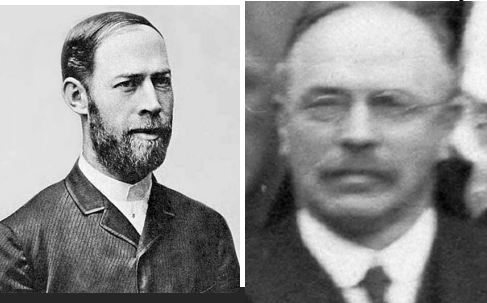


Prevailing hollow formation model involves excavation, sublimation, and sequestration of a volatile-rich layer.



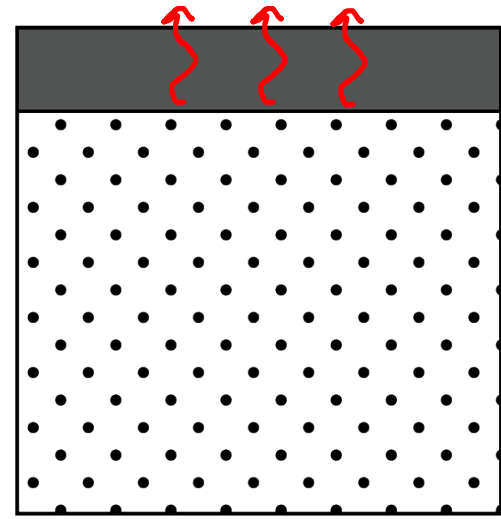
$$E_i = P_v \left(\frac{\mu_i}{2\pi RT} \right)^{\frac{1}{2}}$$

Hertz-Knudsen, give you sublimation rate from the surface



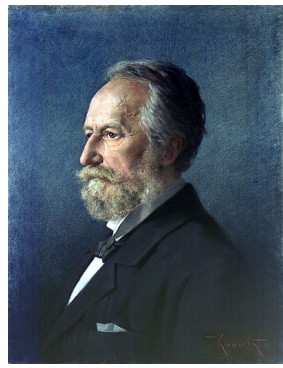
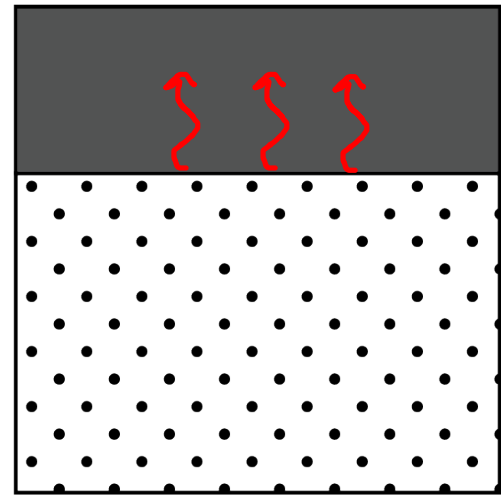
$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z}$$

Fourier 1822, gives you temperature as a function of depth and time.



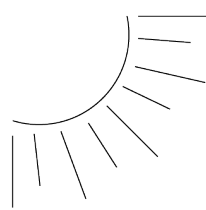
$$F_i = D_k(T) \frac{\phi}{\tau} \frac{\delta N_i(T)}{\delta z}$$

Fick 1855, gives you volatile diffusion through a porous medium.



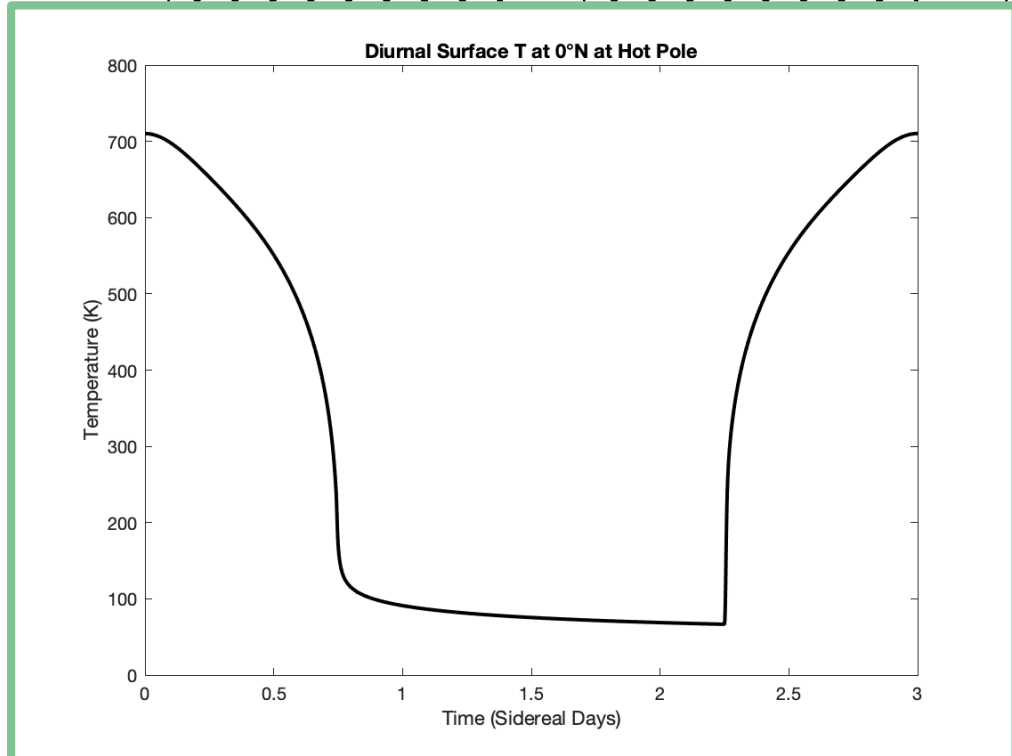
I calculated the sublimation rate of 57 candidate hollow-forming volatile phases to narrow the list of plausible phases.

Two constraints for volatile phase: 1) must be volatile enough to sublime at high latitudinal extent of hollow formation, 2) must be refractory enough to be sequestered under a lag deposit at the equator.



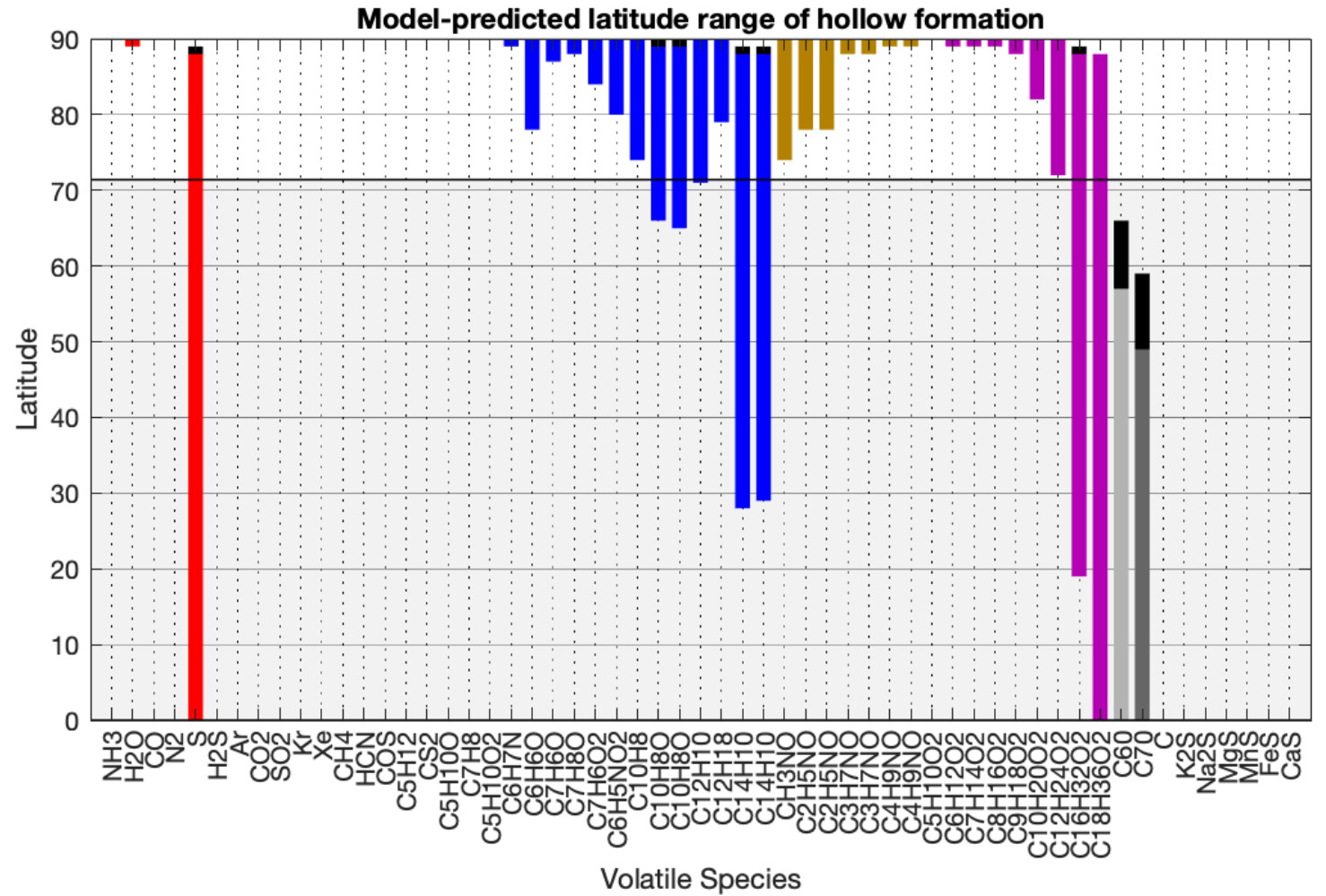
$$E_i = P_v \left(\frac{\mu_i}{2\pi RT} \right)^{\frac{1}{2}}$$

$$F_i = D_k(T) \frac{\phi}{\tau} \frac{\delta N_i(T)}{\delta z}$$

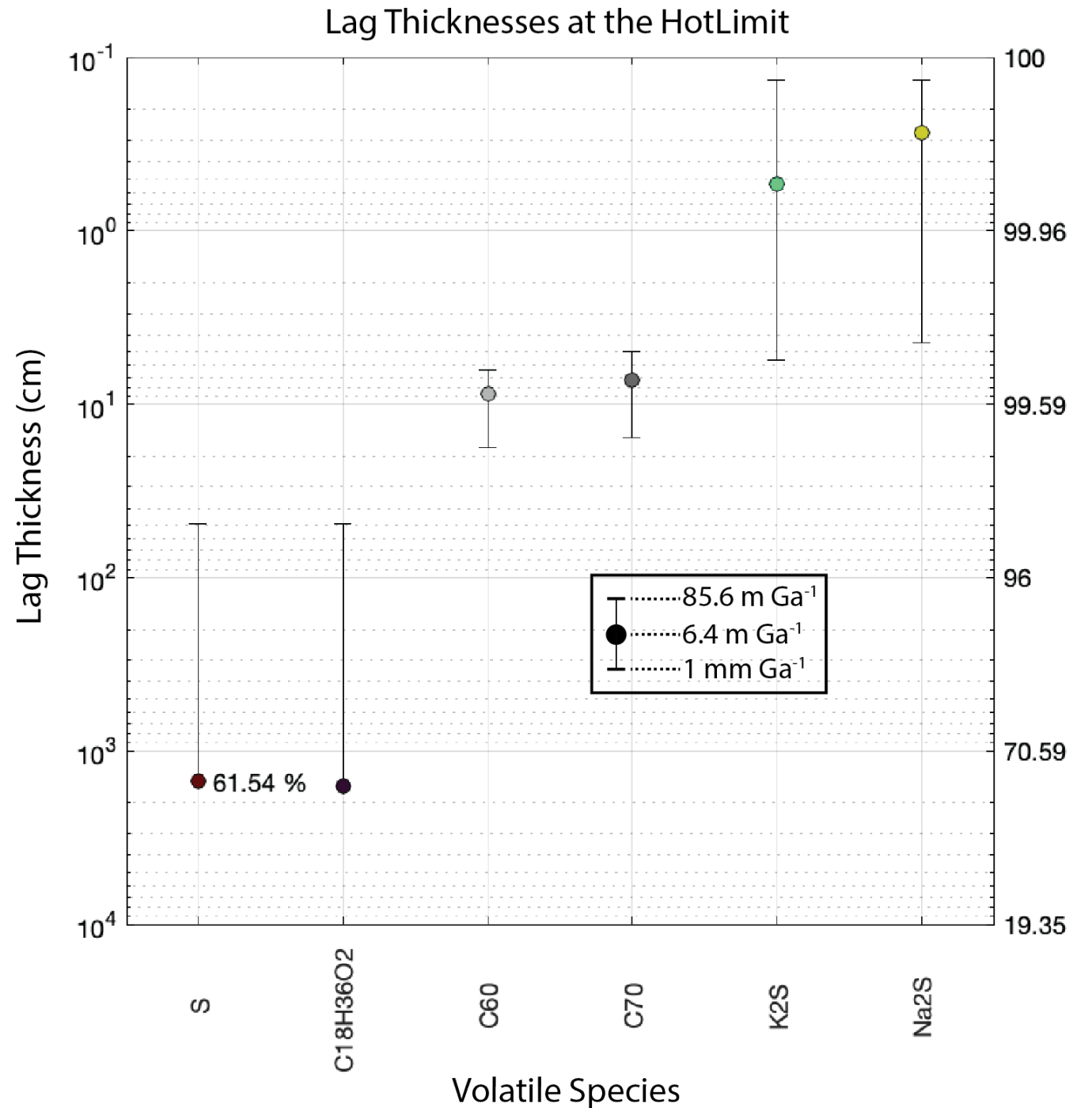


$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k \frac{\partial T}{\partial z}$$

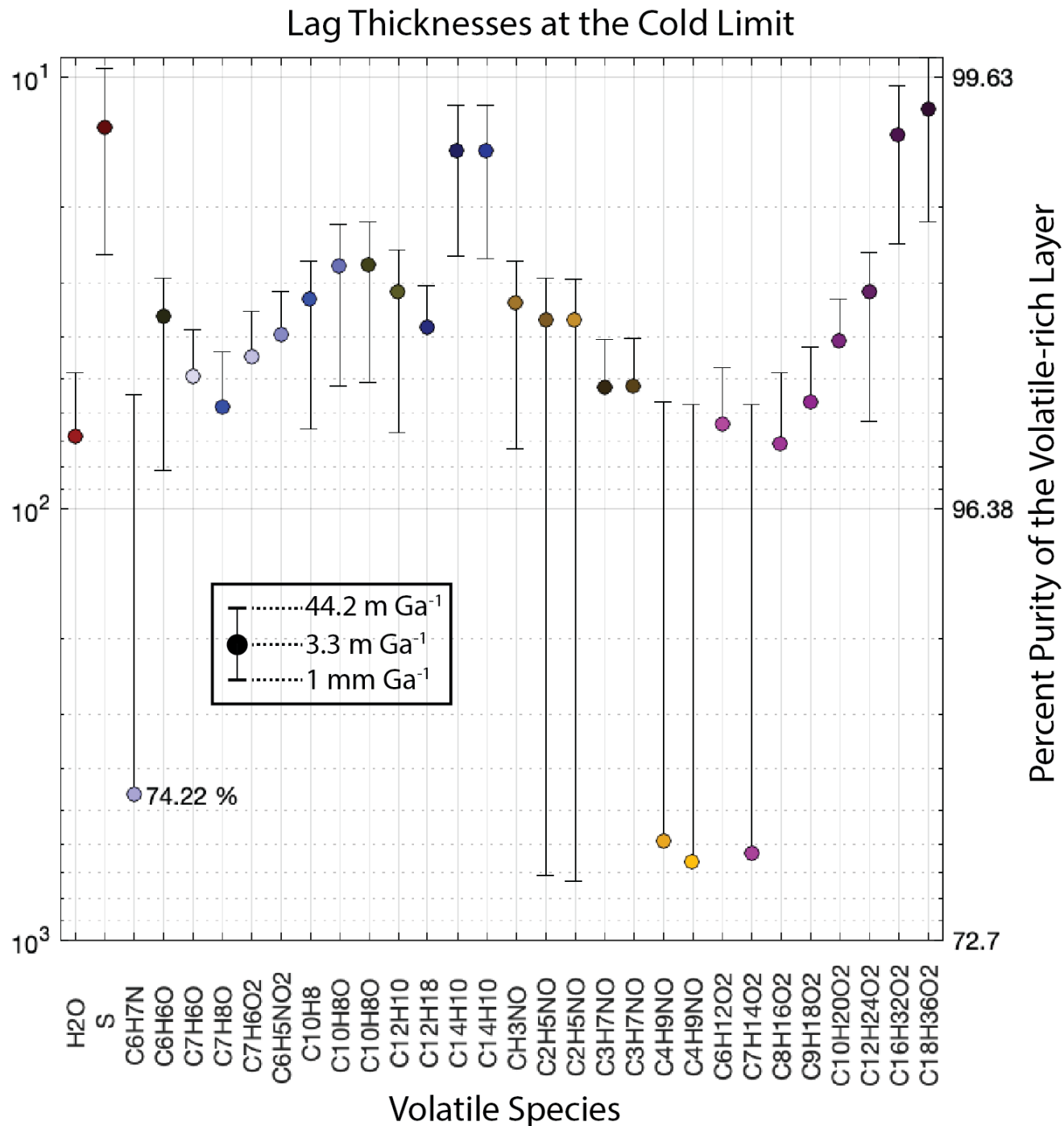
Only elemental sulfur, stearic acid, and \pm fullerenes fit the bill.

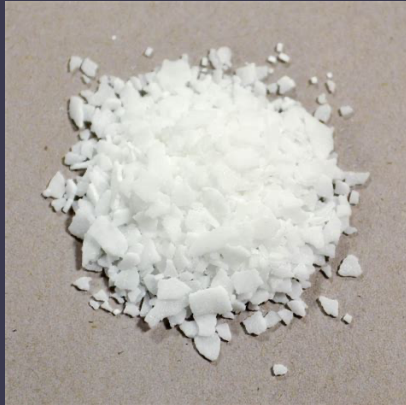
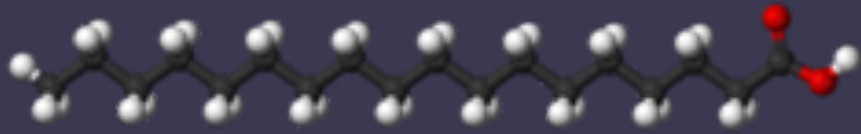


These volatiles would have to occur in relatively pure layers.



These volatiles would have to occur in relatively pure layers. Especially at high latitudes.





Could stearic acid exist on Mercury in enough volume to account for hollows?

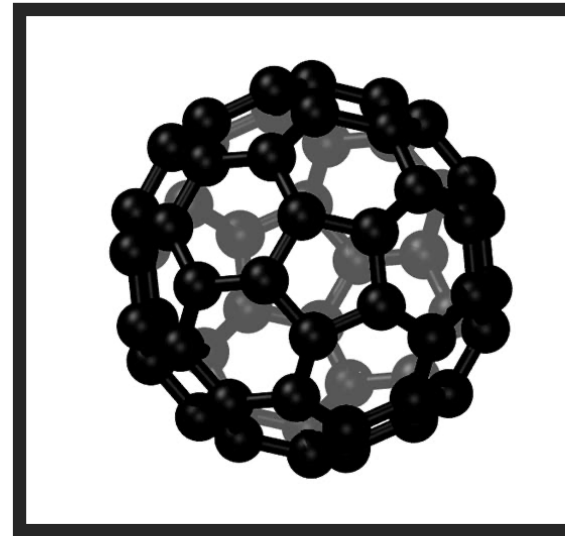
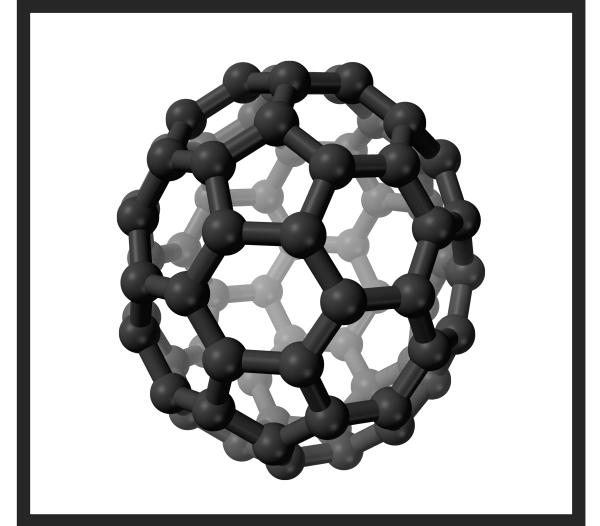
No.



Could fullerenes exist in enough abundance to account for hollows?

Fullerene Facts:

1. Named after Buckminster Fuller, the creator of the geodesic dome.
2. Condense spontaneously from carbon vapors.
3. Are found in the interstellar medium, and in association with lightning strikes and impact craters on Earth.



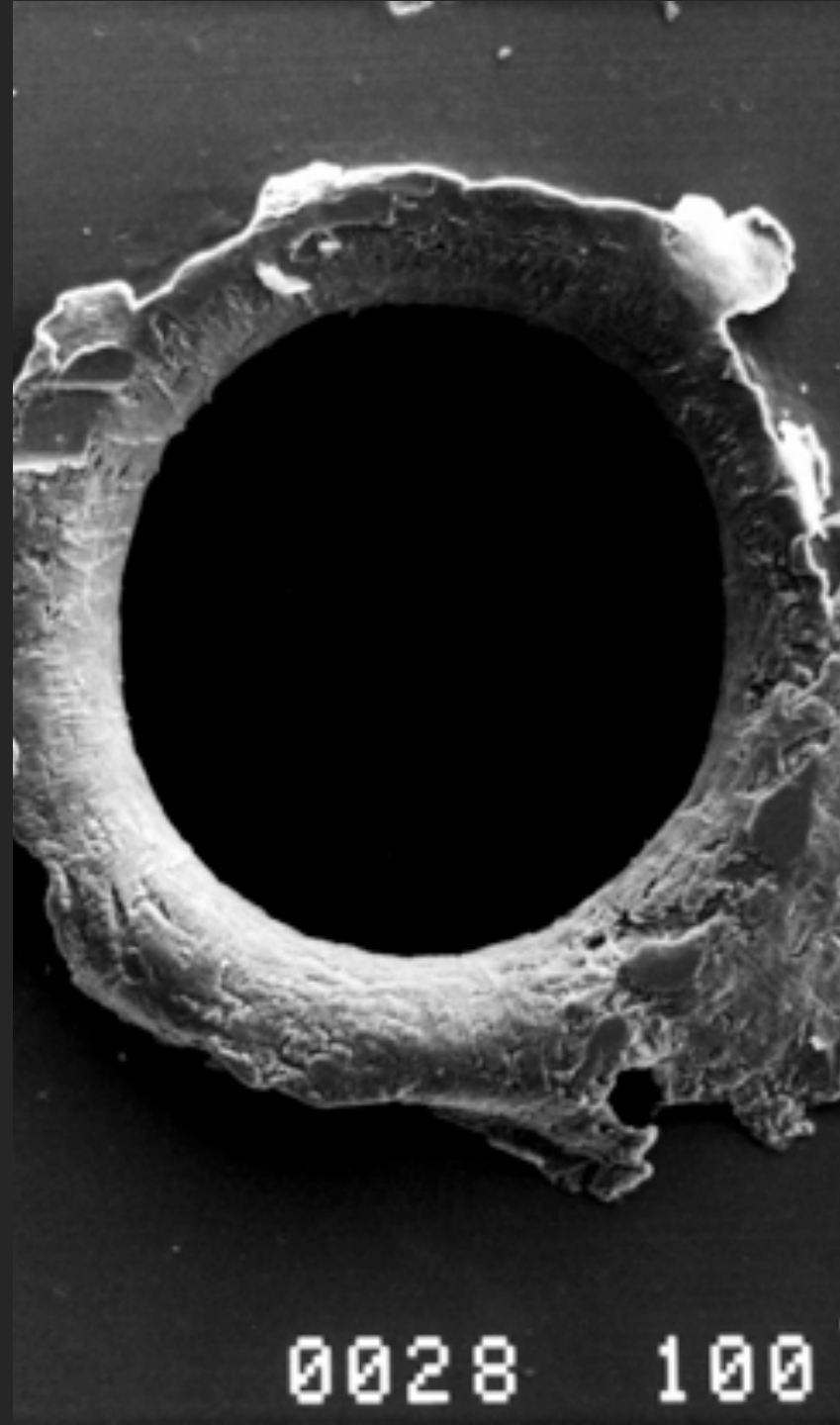
Could space weathering of Mercury's primary graphite crust have produced fullerenes?

Hollow volume expressed as a global layer:

- 1.87 to 3.61 cm-thick

Estimate for fullerene production on Mercury:

- 0.6 to 48 μm -thick.

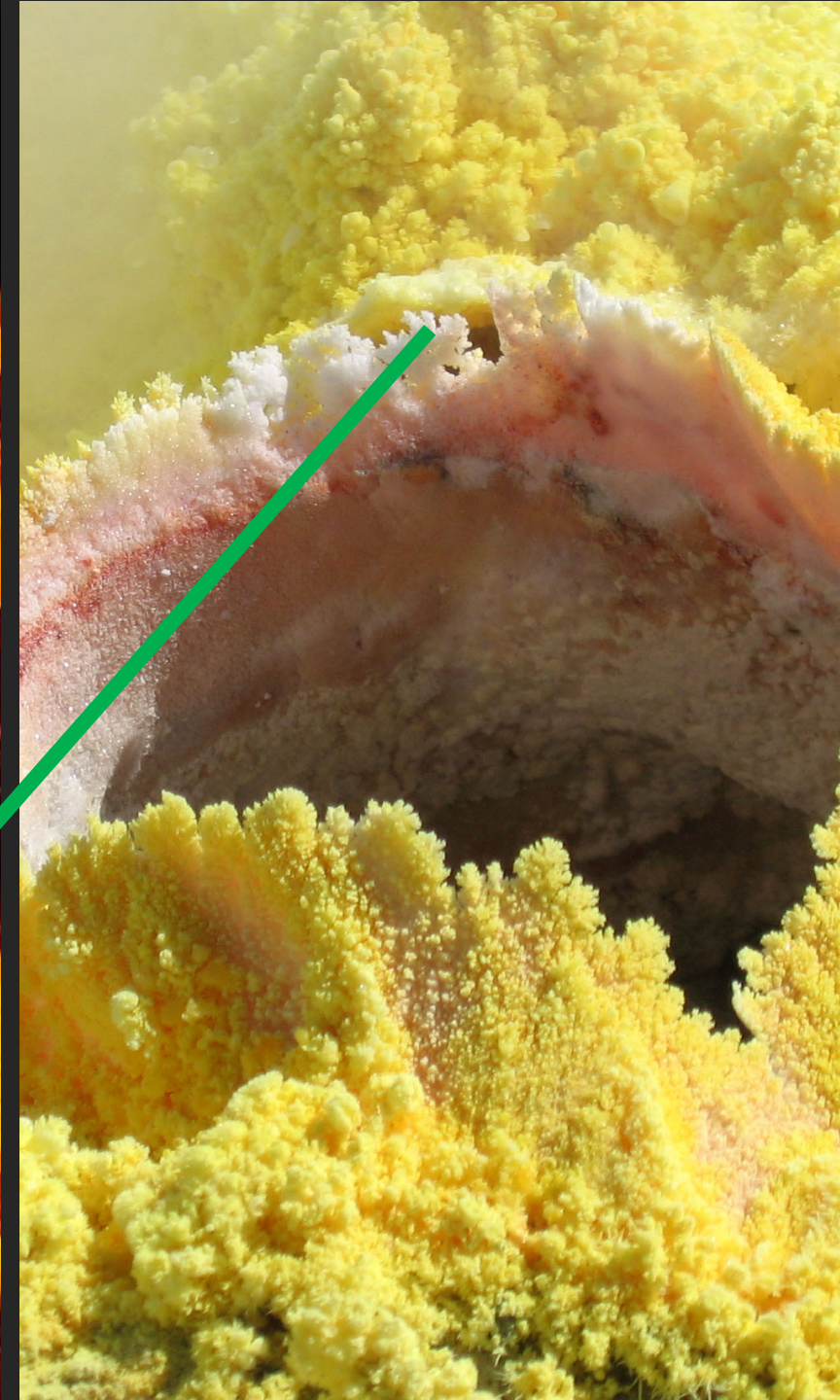
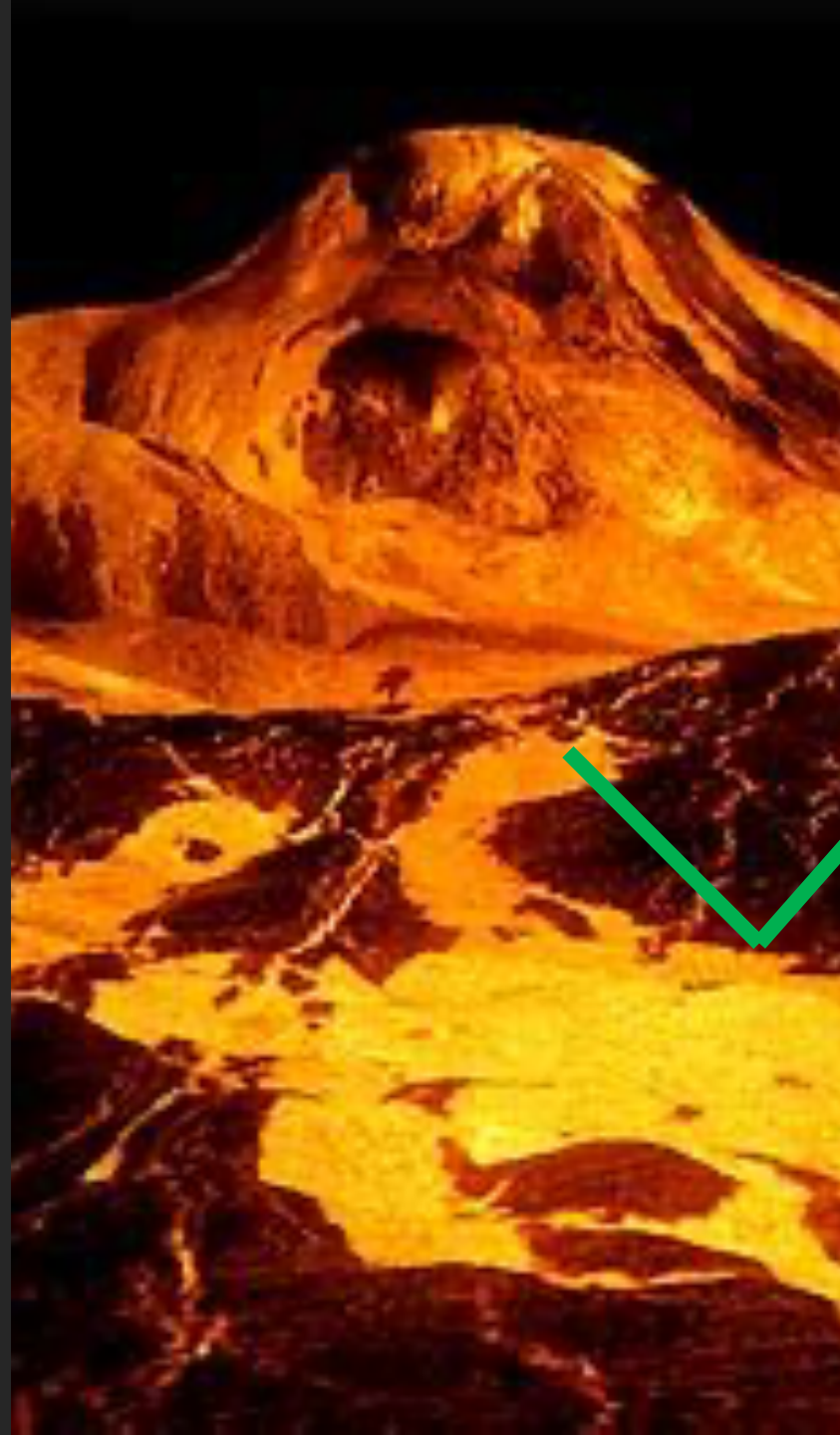


Could extensive volcanism on Mercury have produced enough Sulfur?

An estimate of sulfur produced during volcanism expressed as a global layer:

- 7.5 to 550 m-thick

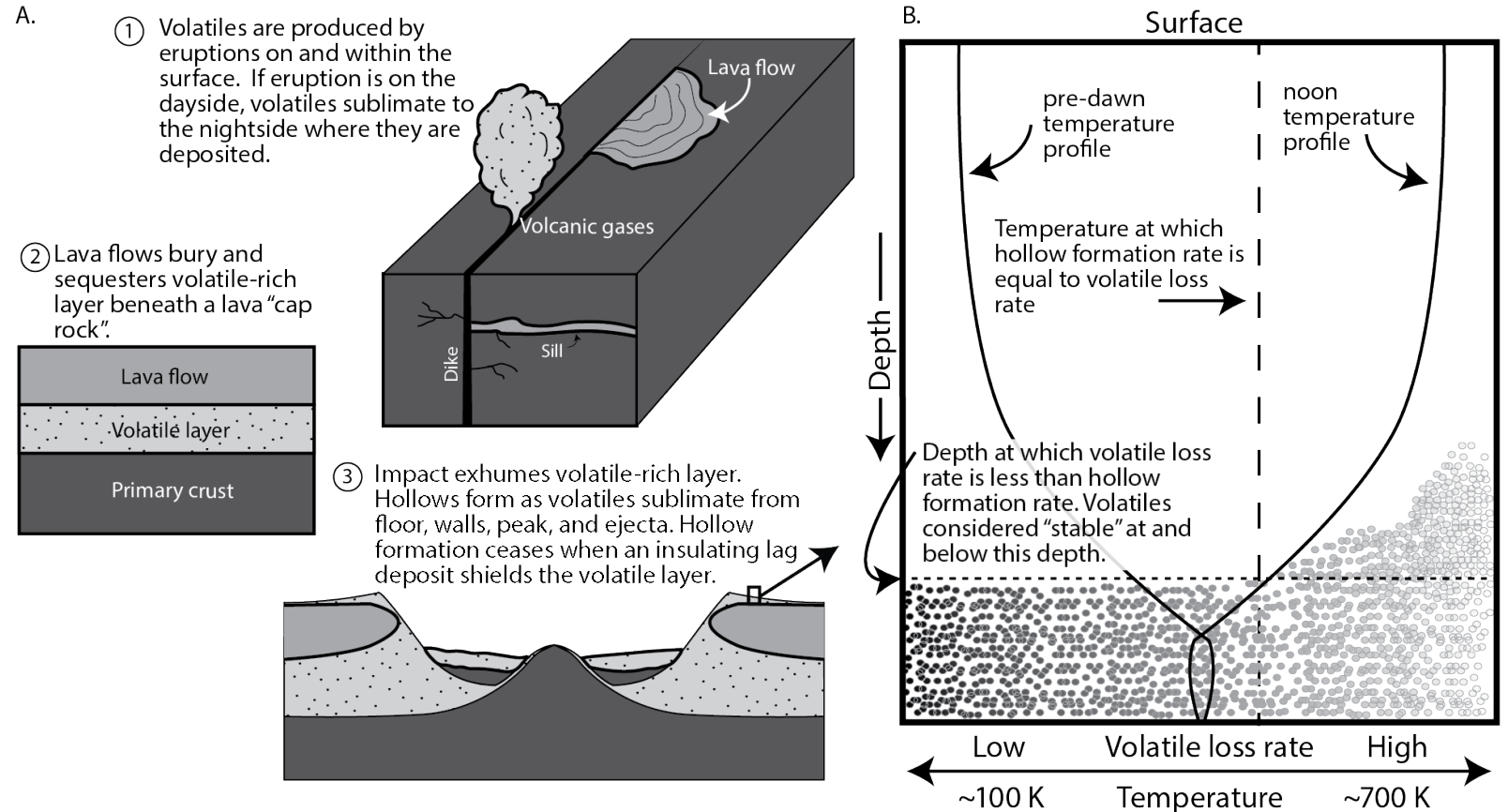
Even if <1% of this volcanic sulfur was elemental S, it would be sufficient to account for hollows.



Does the prevailing hollow formation model work with elemental S as the volatile?

Requirements:

- Concentration
- Burial/sequestration
- Exhumation by impacts



Concentration could occur through global volatile transport.

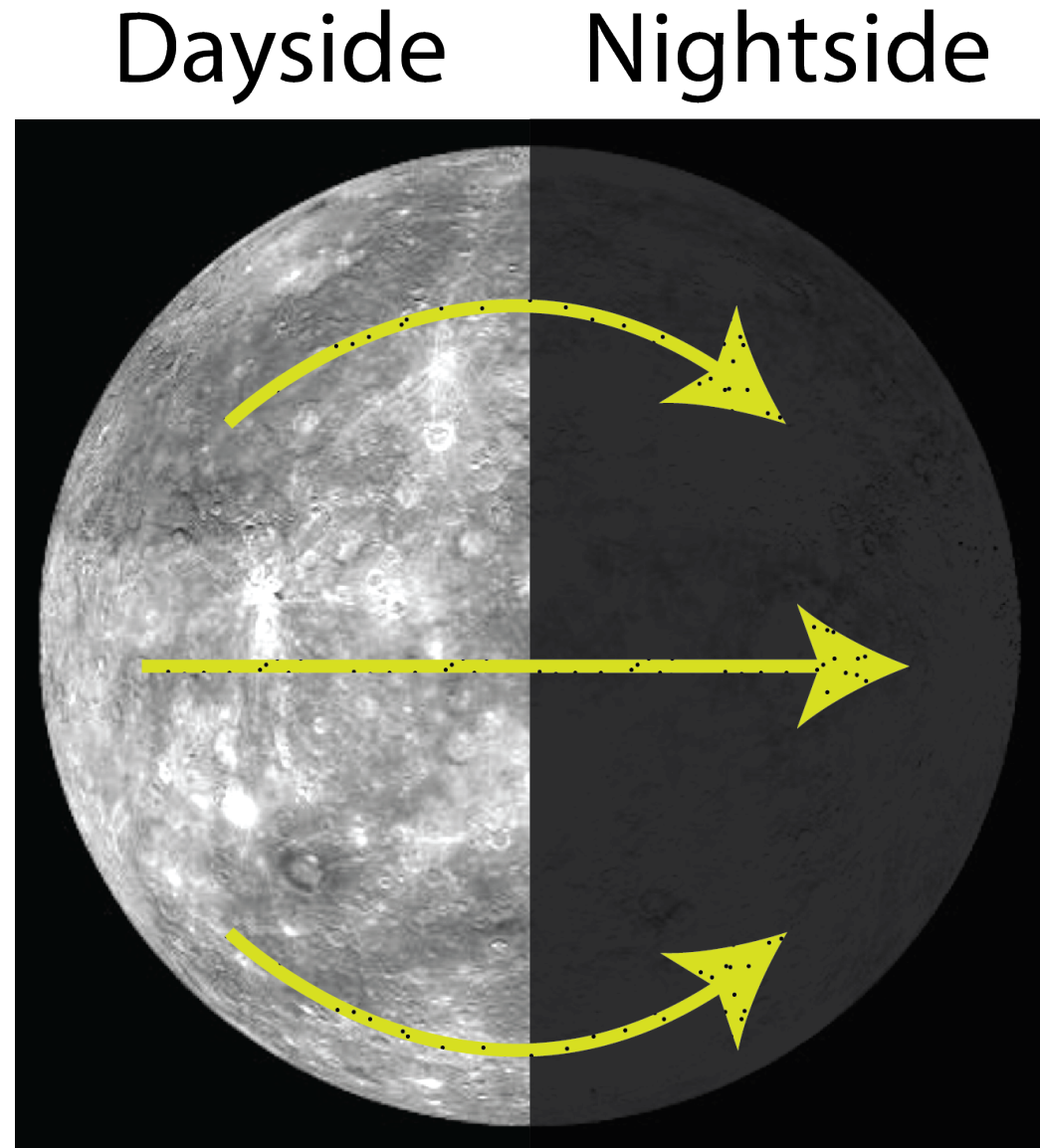
Especially if Mercury's ancestral orbital resonance was 2:1.

Sublimation rate on dayside:

- 4 m/yr to 120 m/yr

On nightside:

- Basically 0 m/yr



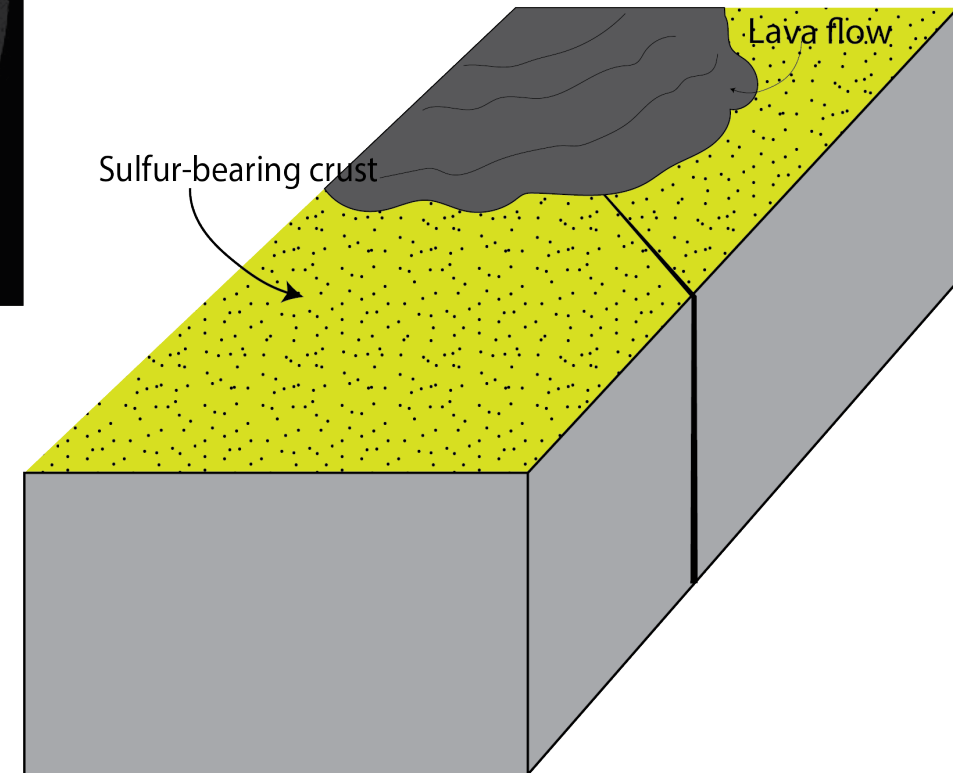
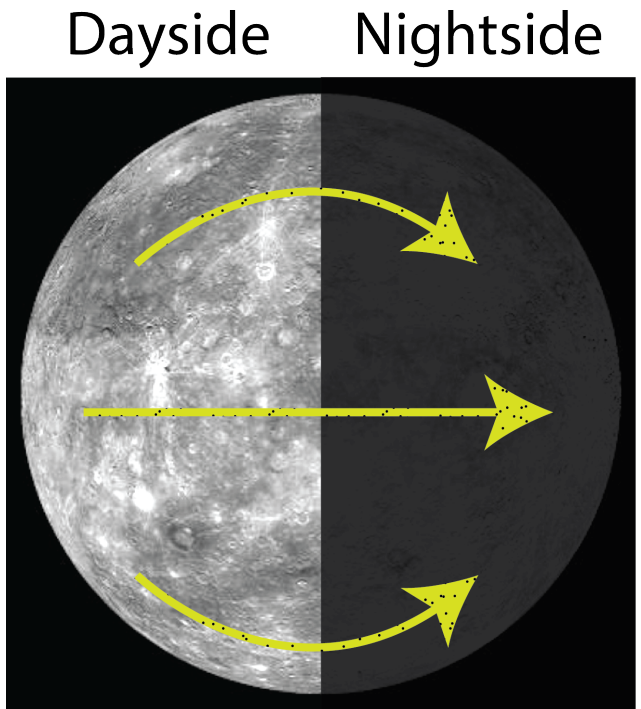


Burial
could
occur via
volcanism.

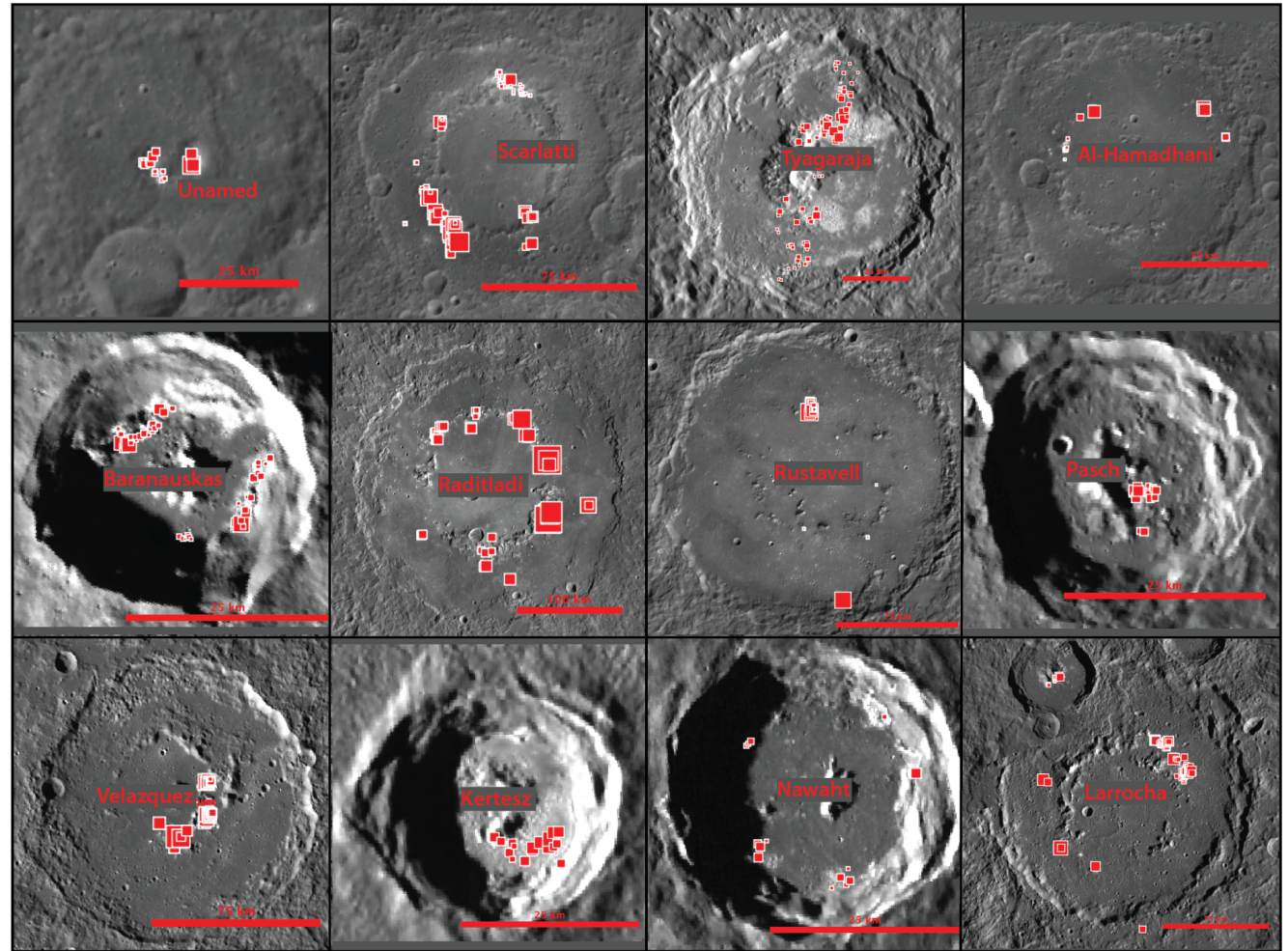
Does the prevailing hollow formation model work with elemental S as the volatile?

Requirements:

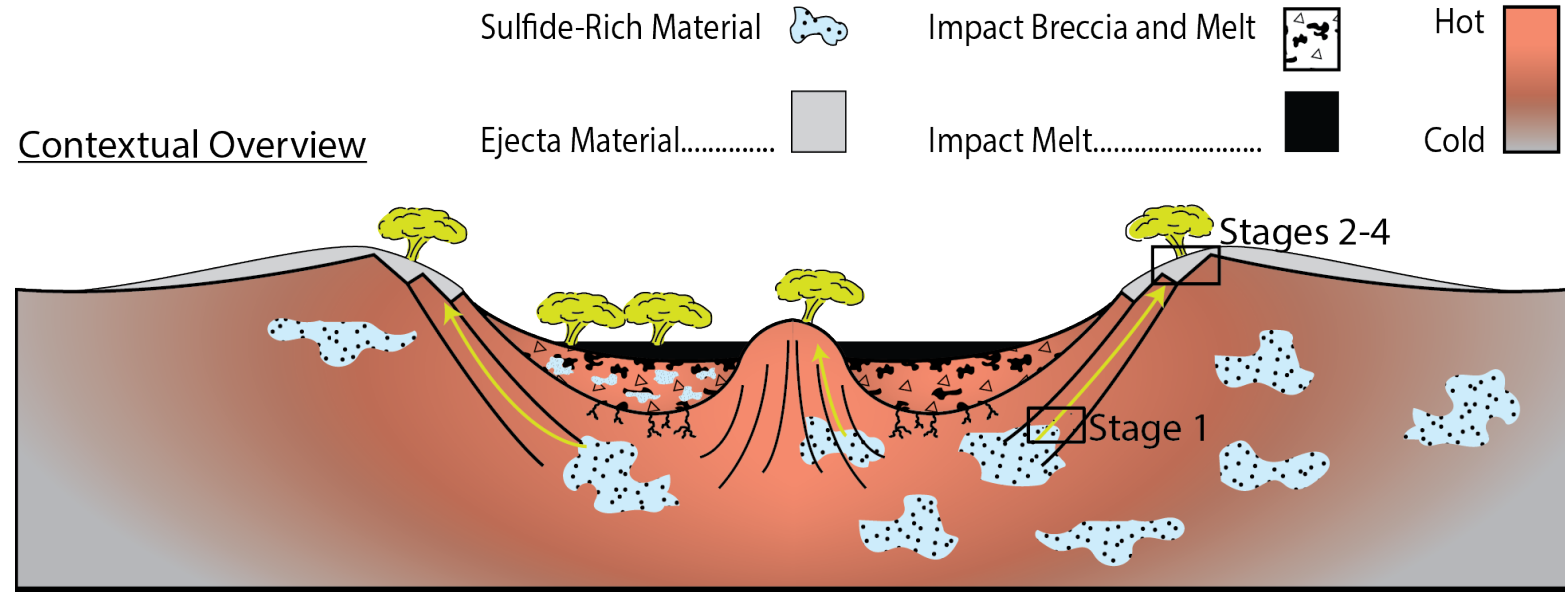
- Concentration
- Burial/sequestration



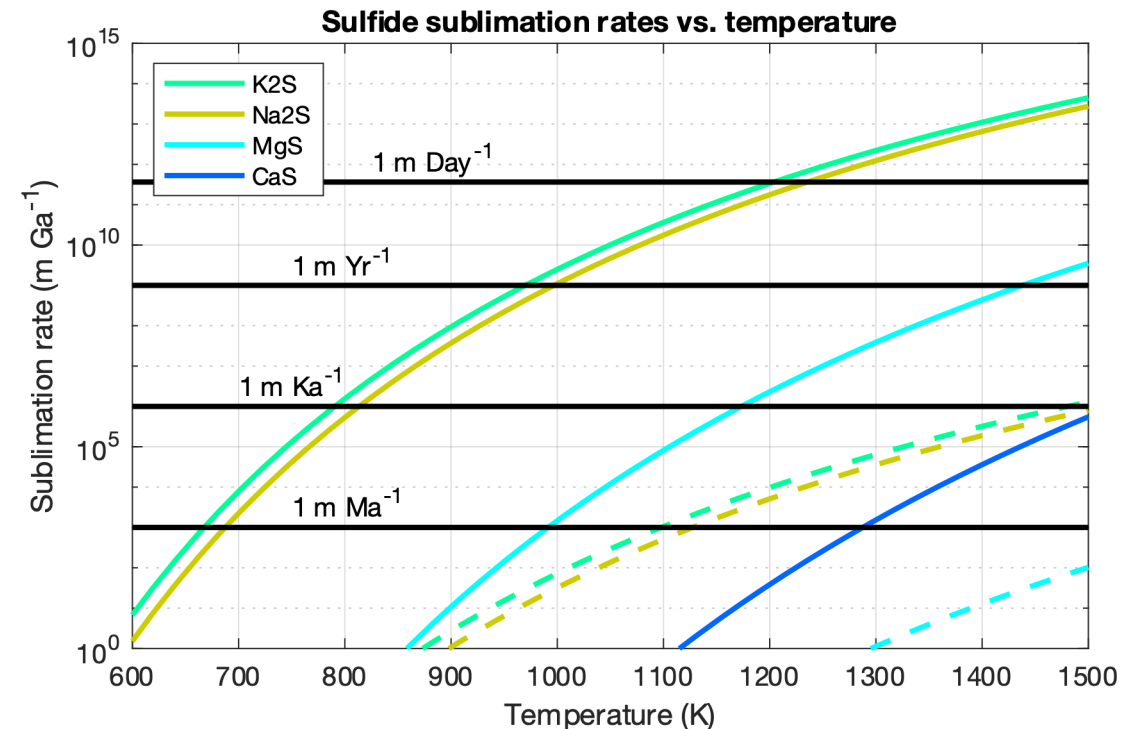
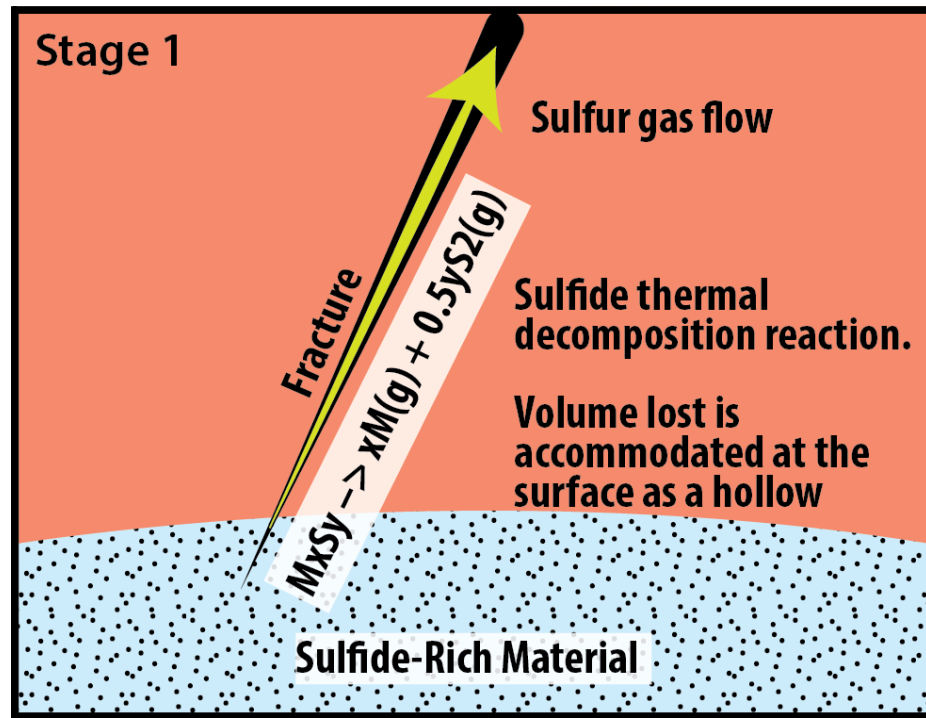
Could Sulfur survive the impact exhumation process? Do the distributions of hollows match what would be expected if impacts exhumed the material?



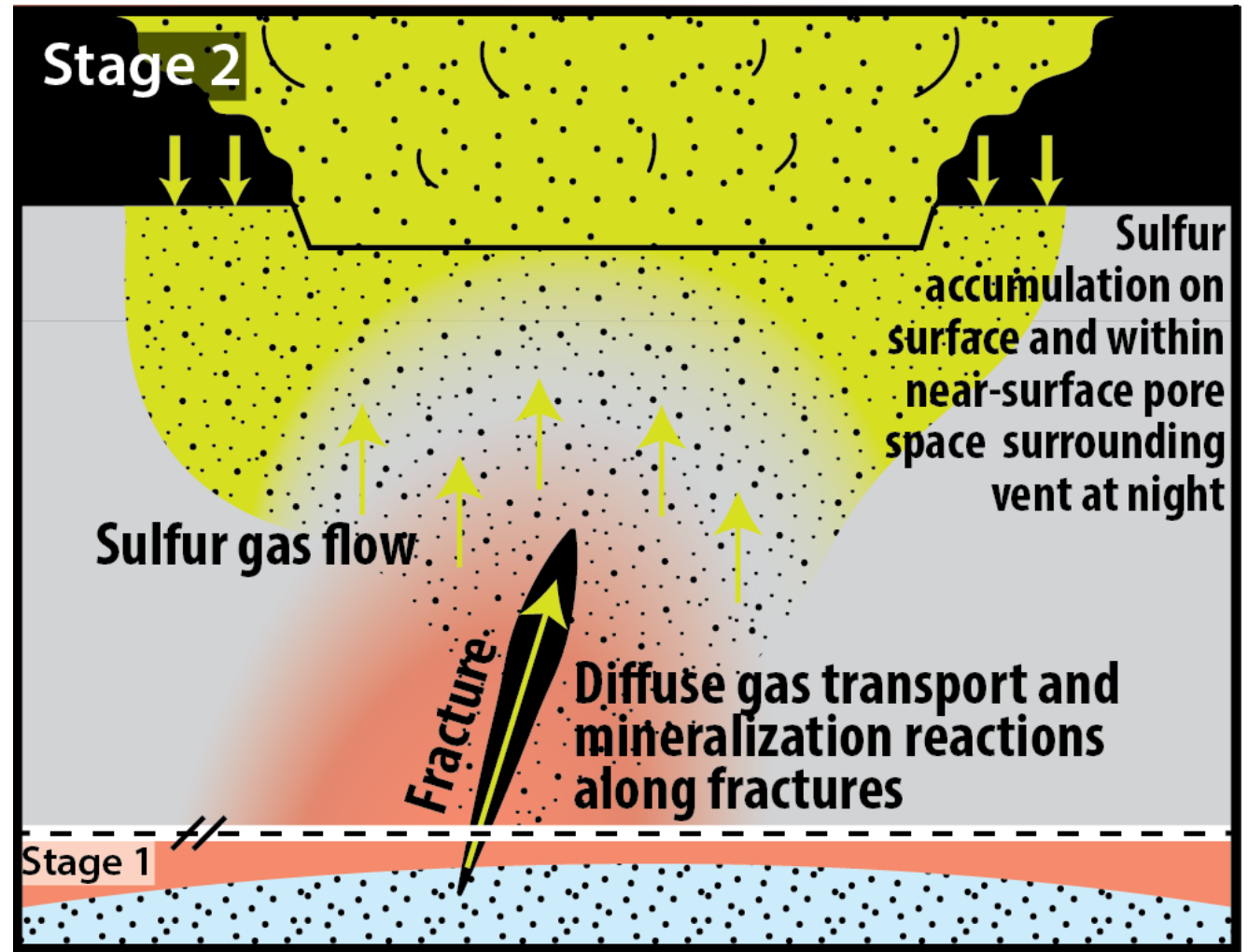
I propose a different model for hollow formation in impact-induced hermeothermal systems.



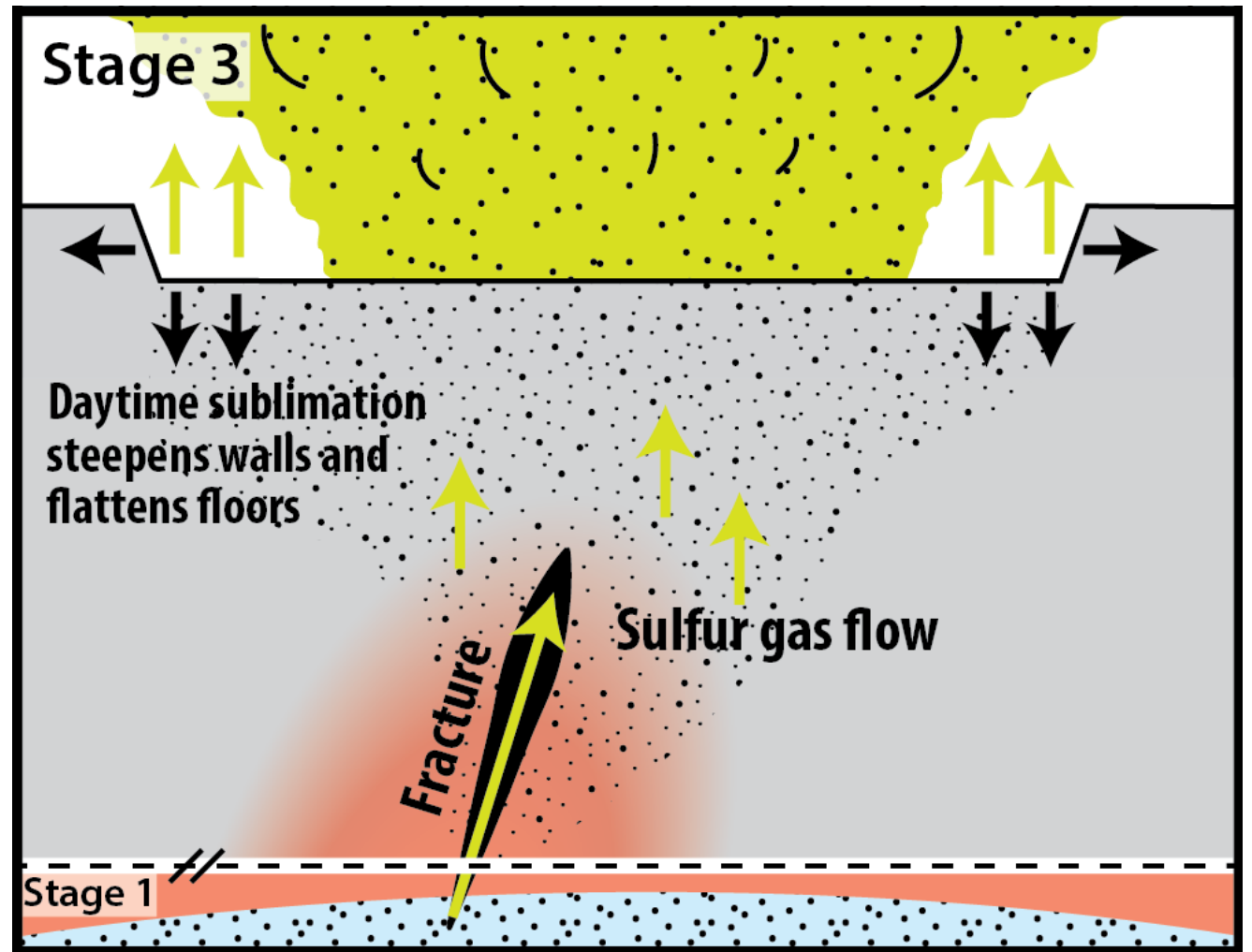
Sulfide decomposition at the temperatures achieved in the vicinity of an impact proceeds at a sufficient rate to generate hollows.



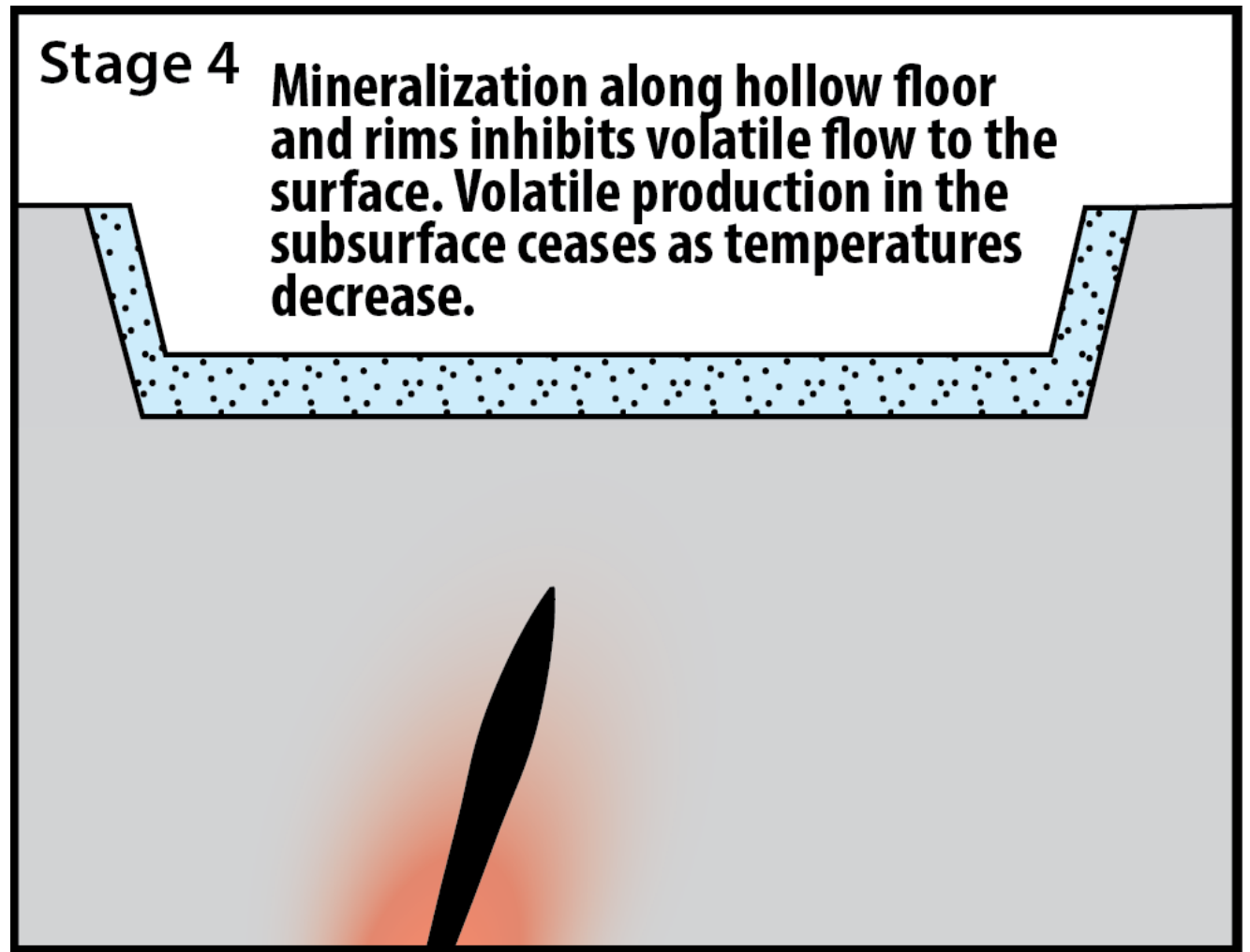
The surface of Mercury is very cold at night, allowing for deposition of sulfur and sulfur gases in the vicinity of fumarole vents at night.



During the day, the volatiles on the surface and in the near-surface surrounding vents would sublimate.



Reprecipitation of sulfides (and, likely, other minerals) and cooling of the impact site would preclude further transport of volatiles.



If hollows form in hermeothermal systems, perhaps studying them presents an opportunity for comparative planetology with Earth, Mars, and Ceres.

