Ascent and Eruption of Magma on the Terrestrial Planets: A Planetary Perspective on the Moon

SSERVI SOLAR SYSTEM EXPLORATION RESEARCH VIRTUAL INSTITUTE

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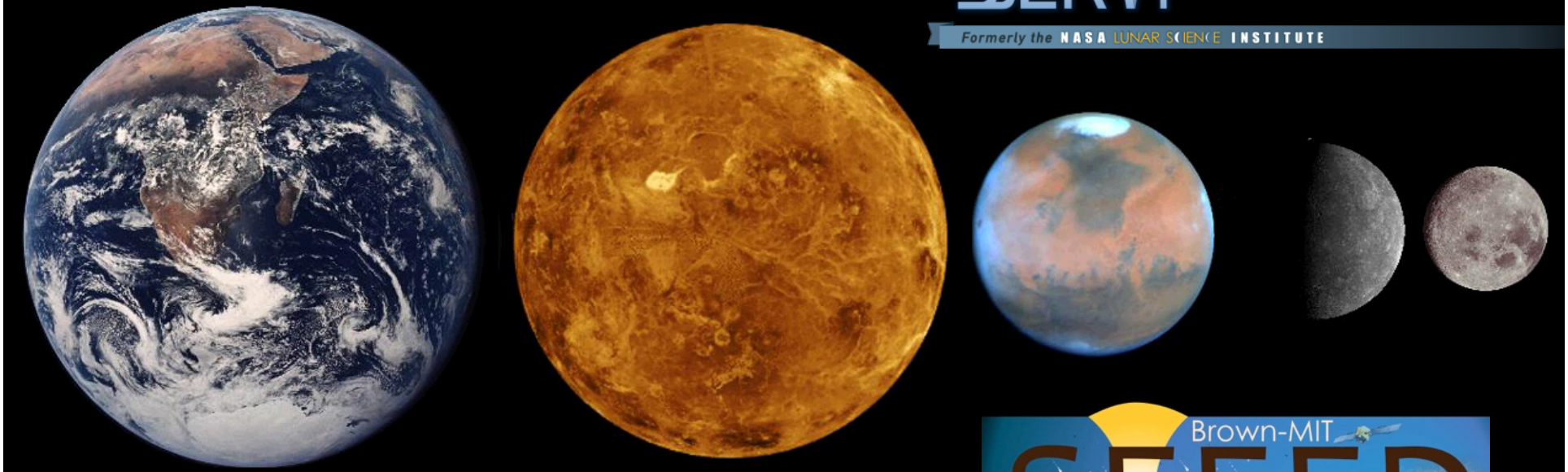
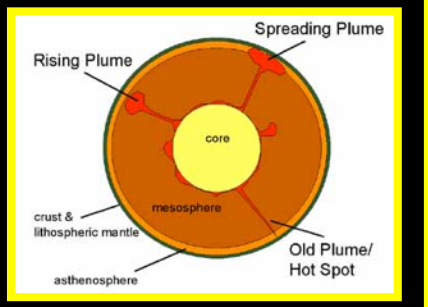
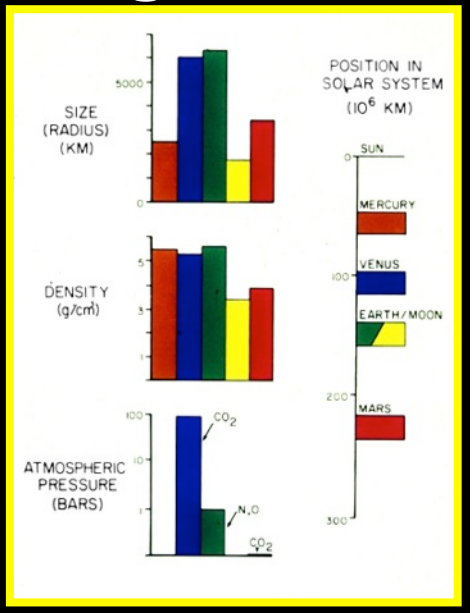


Brown-MIT SEED

James W. Head[1] and Lionel Wilson[2].
[1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA,
[2]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, U.K.

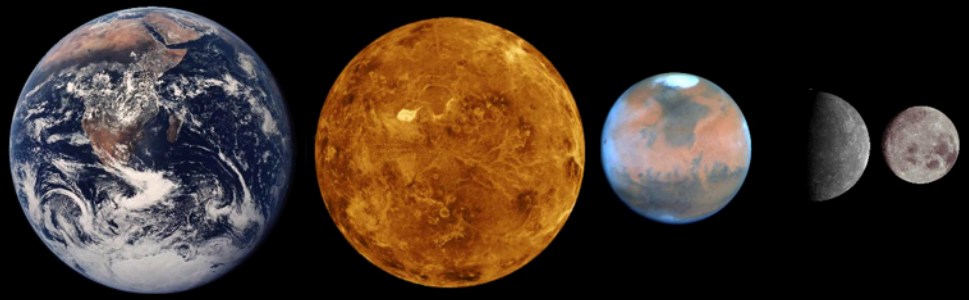
Generation, Ascent, and Eruption of Magma:





- Analysis on Earth and Terrestrial Planets:
  - Provides substantial information about the geological history/thermal evolution of each body.
- Synthesis of Array of Extrusive Features & Landforms:
  - Provides insight into eruption styles, lithospheric stress states, and mantle convection: A Grand Experiment!
- Surface of Terrestrial Planet Elemental Compositions:
  - Consistent with a range of mantle compositions, but all are likely to produce mafic to ultramafic melts.

Main Controls on the Types of Surface Volcanic Features and Accumulations



Differences in:

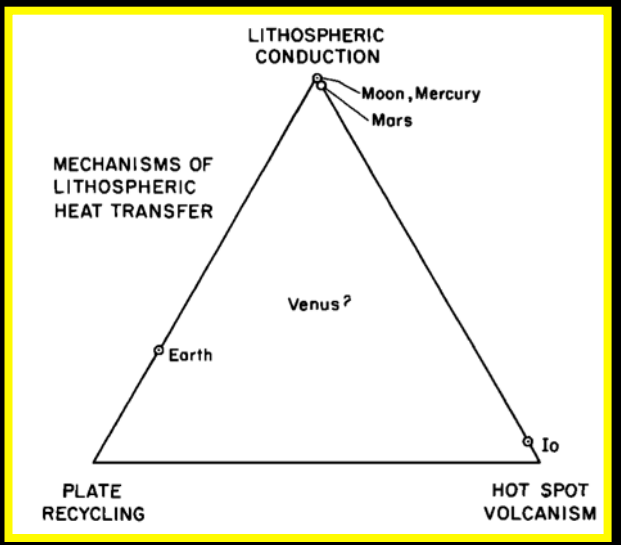
- 1) Magma composition/volatile content.
- 2) Lithosphere continuity and thickness.
- 3) Tectonic regimes.
- 4) Crustal origins and stability.
- 4) Crustal thicknesses and densities.
- 5) Mantle thickness.
- 6) Mantle convective style.

  -Preferred locations for magma reservoirs:

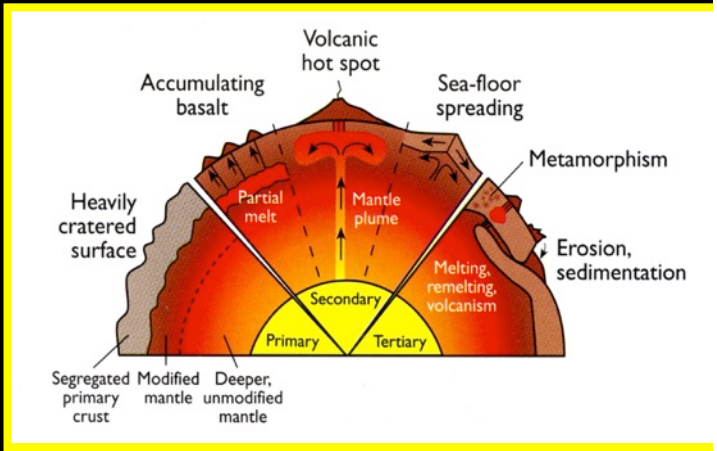
  1) at depth within a planetary interior or

  2) relatively shallow within a volcanic edifice.

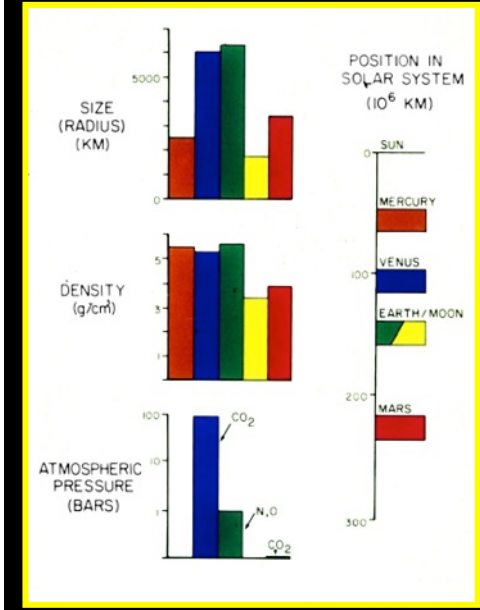
Modes of Planetary Heat Loss



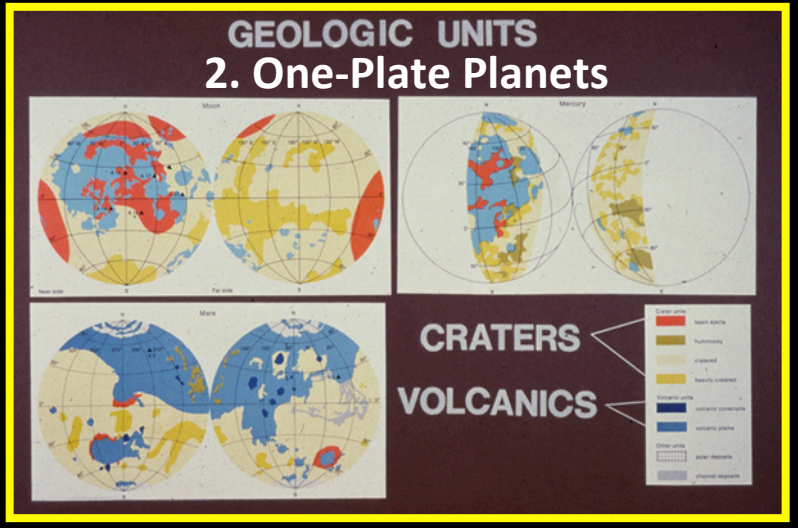
Modes of Crustal Formation

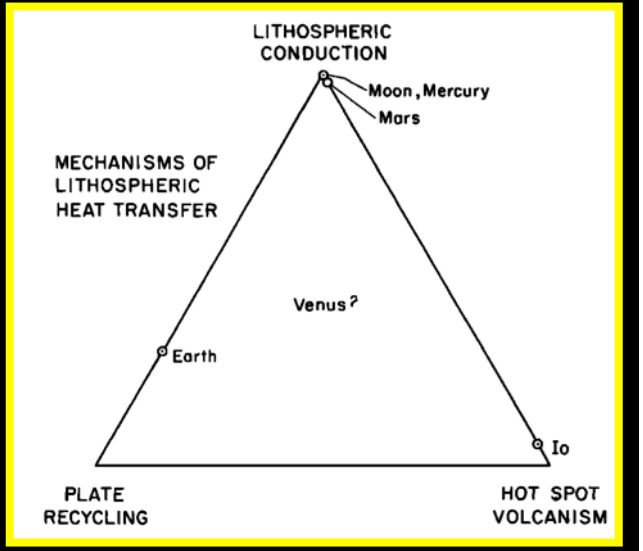


Planetary Heat Loss Mechanisms: Thermal Evolution

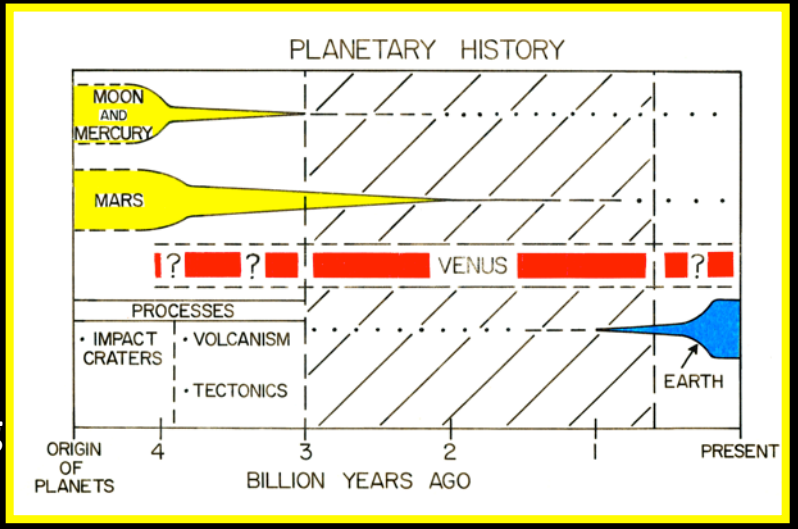


1. Planetary Size





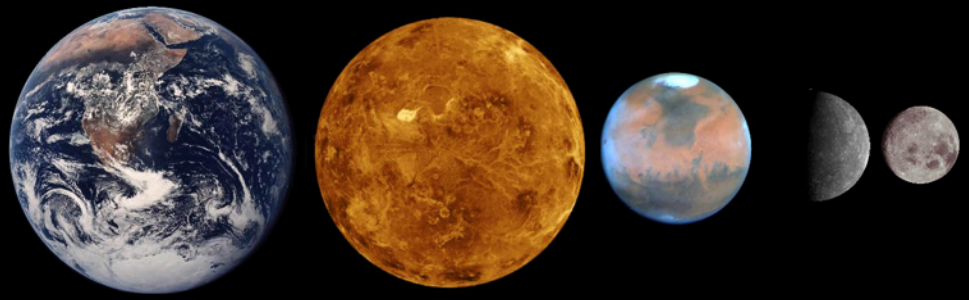
3. Heat Loss Mechanisms



4. Planetary Resurfacing

- Global stress regimes characterized by net horizontal extension favor upward propagation of dikes, whereas horizontal compression inhibits dike propagation.

Main Controls on the Types of Surface Volcanic Features and Accumulations



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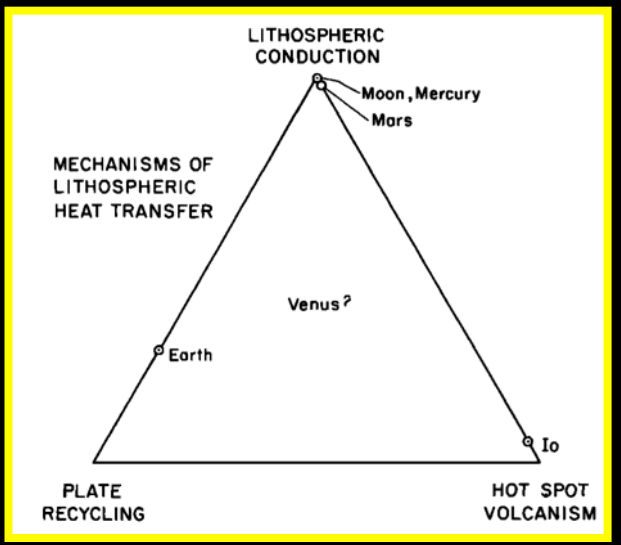

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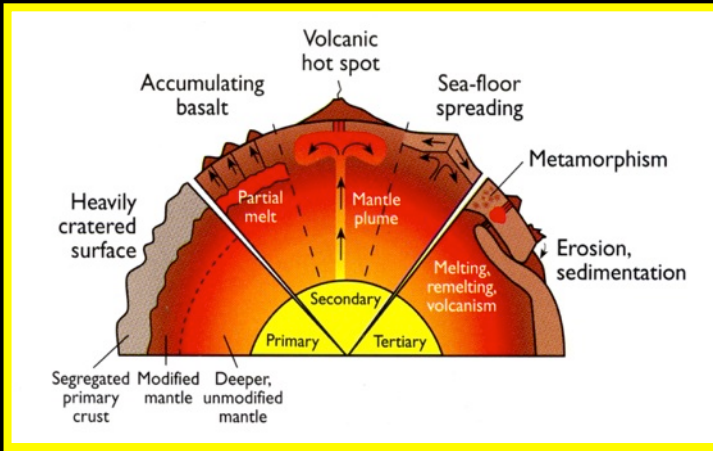

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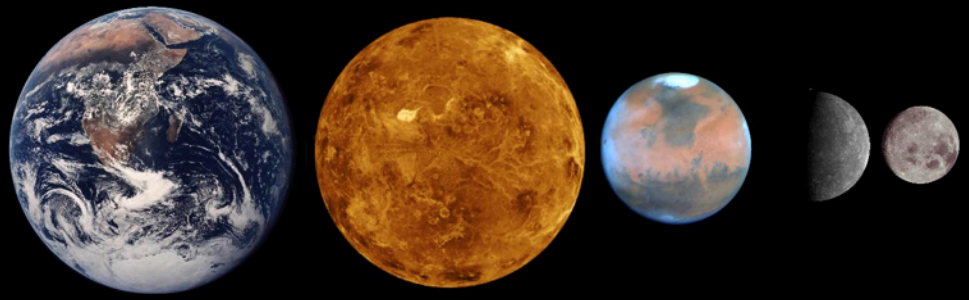

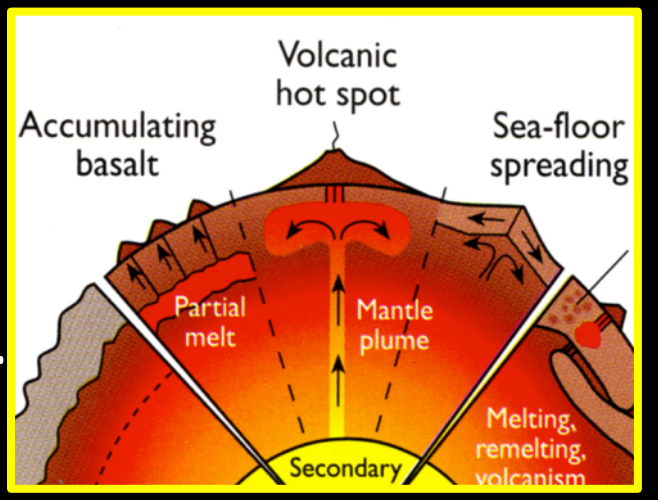

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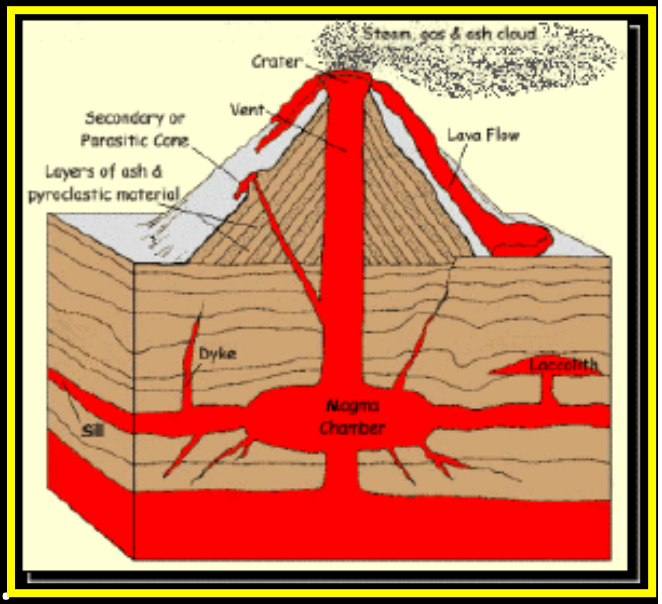
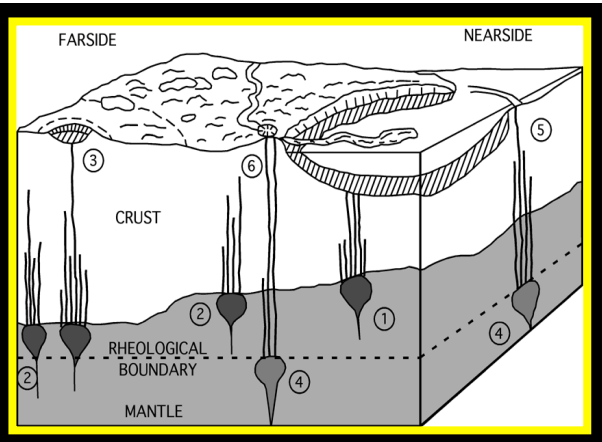
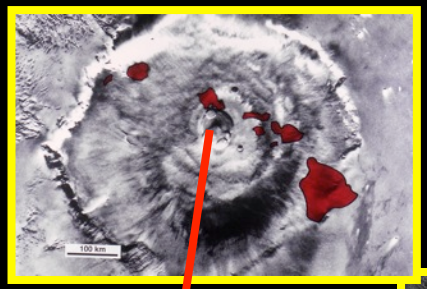
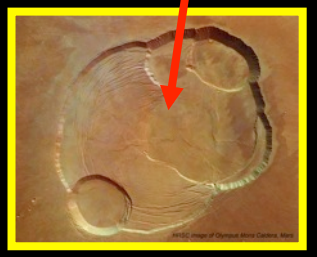


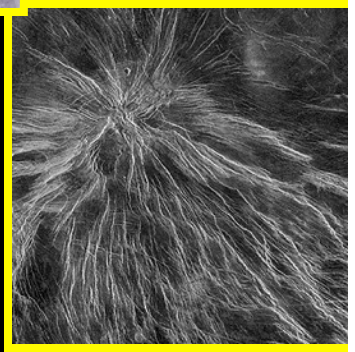
Magma Reservoir Formation

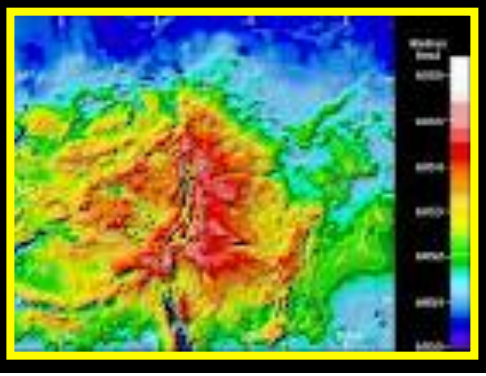
- *Deeper reservoirs*:
  - Can form near the *rheological change* at base of the lithosphere.
  - At upwellings, due to *pressure-release melting*, or
  - At vertical *discontinuities in density* such as at the base of the crust.
- Evidence for reservoirs in edifices is seen in *calderas*.
- *Floor-fractured craters* represent the surface manifestation of shallow reservoirs on the Moon.
- Evidence for *deeper magma bodies* is seen in giant dike swarms.
- The position of *ascending mantle flow* is marked by broad rises formed from thermal uplift, enhanced crustal construction, and individual edifices built by surface eruptions.





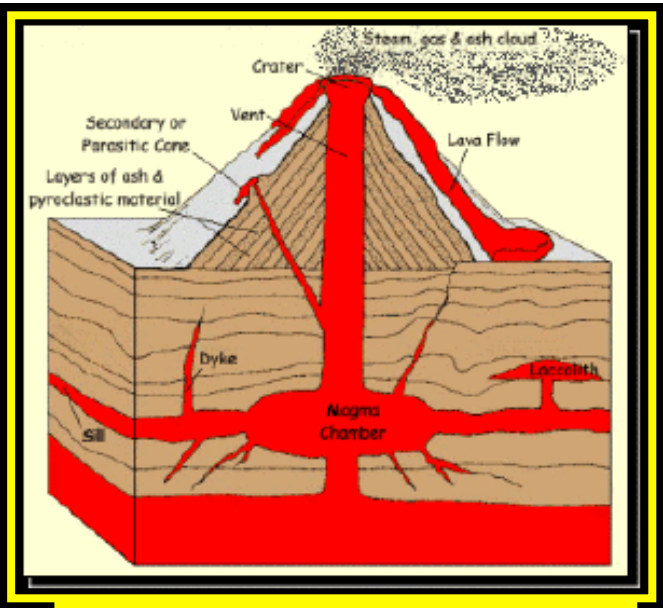


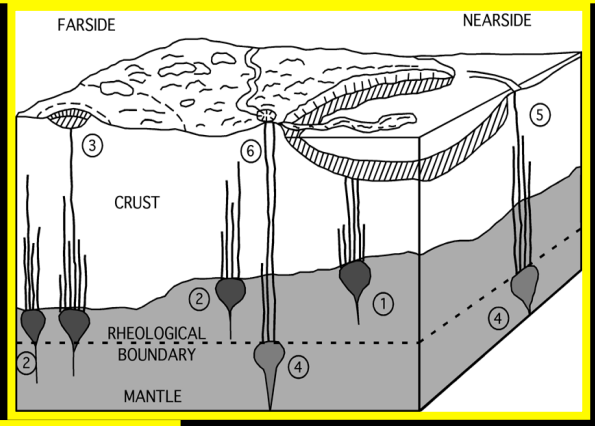




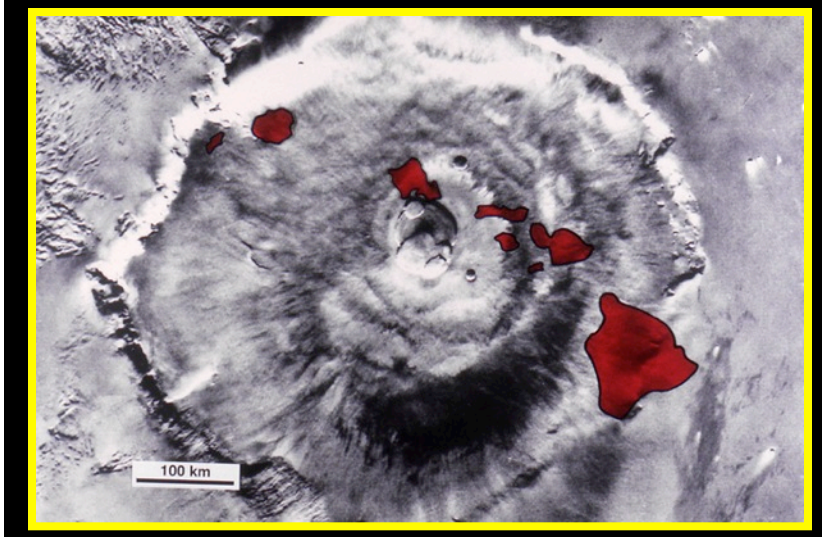
Shallow Magma Reservoirs

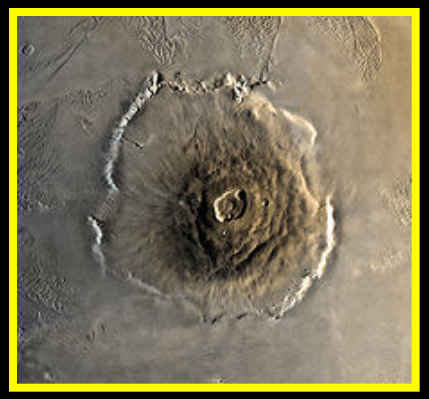
- Commonly formed within volcanic edifices on Earth, Mars, and Venus.
- Building a volcanic edifice and reservoir requires:
  - Multiple pulses of magma to rise frequently within a spatially restricted region over extended period of time.
- On the Moon, in contrast,
  - Low eruption frequencies and great flow lengths ensure that typical large edifices will not form.
- Shallow reservoirs form within edifices at levels of neutral buoyancy.
  - Repeated, relatively small-volume eruptions from the shallow reservoirs progressively build shield volcanoes of a range of sizes and aspect ratios on Earth, Mars, and Venus.
- Calderas: Large shield volcanoes commonly host summit collapse calderas, produced when substantial volumes of magma are erupted on the volcano flanks.



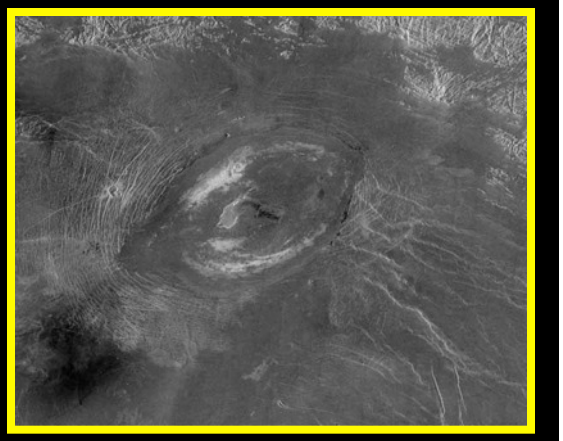


Typical Volcanic Features on the Terrestrial Planets

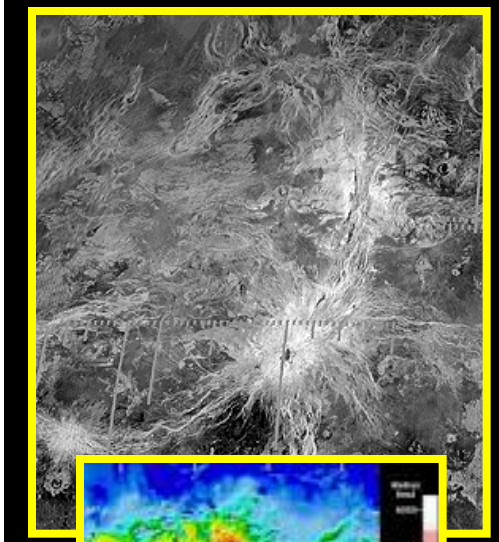


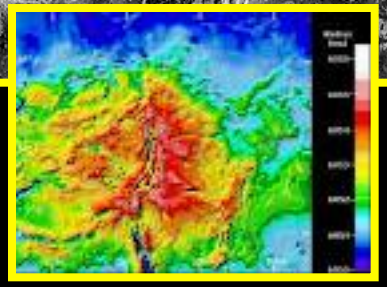


Major Shield Volcanoes.

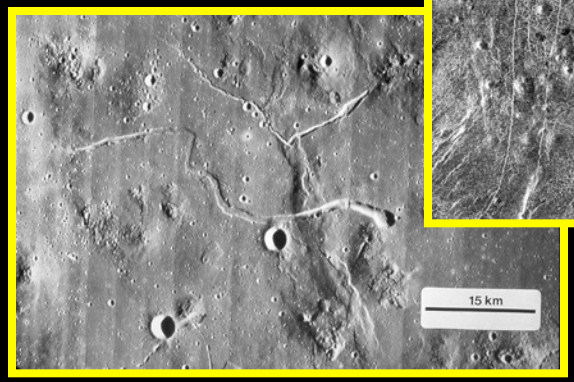


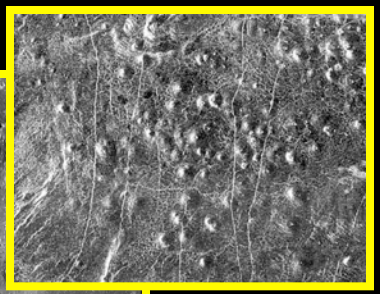
Calderas.





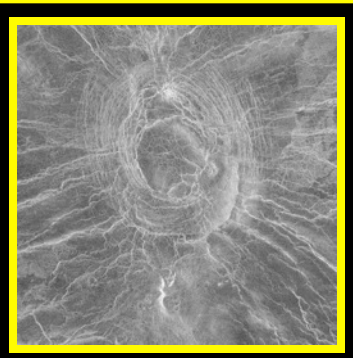
Rifted Rises.



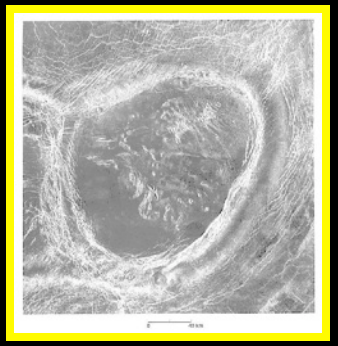


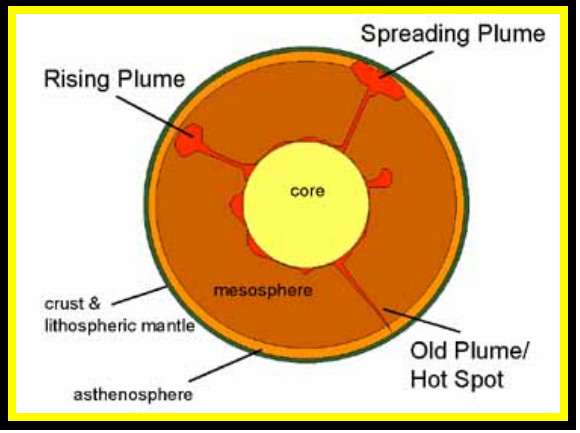
Shield Fields

Novae.

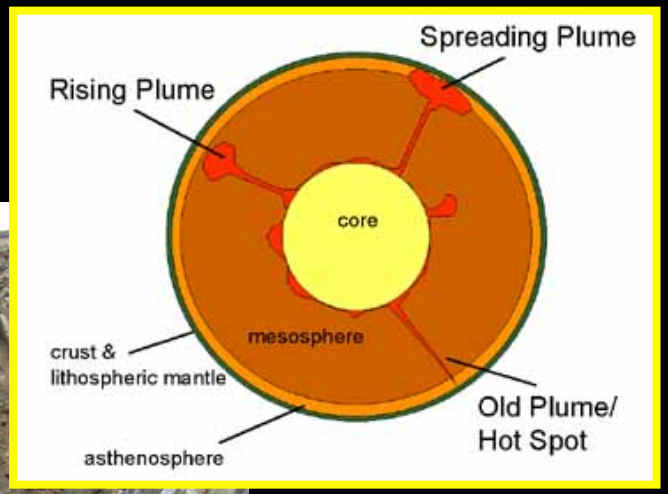


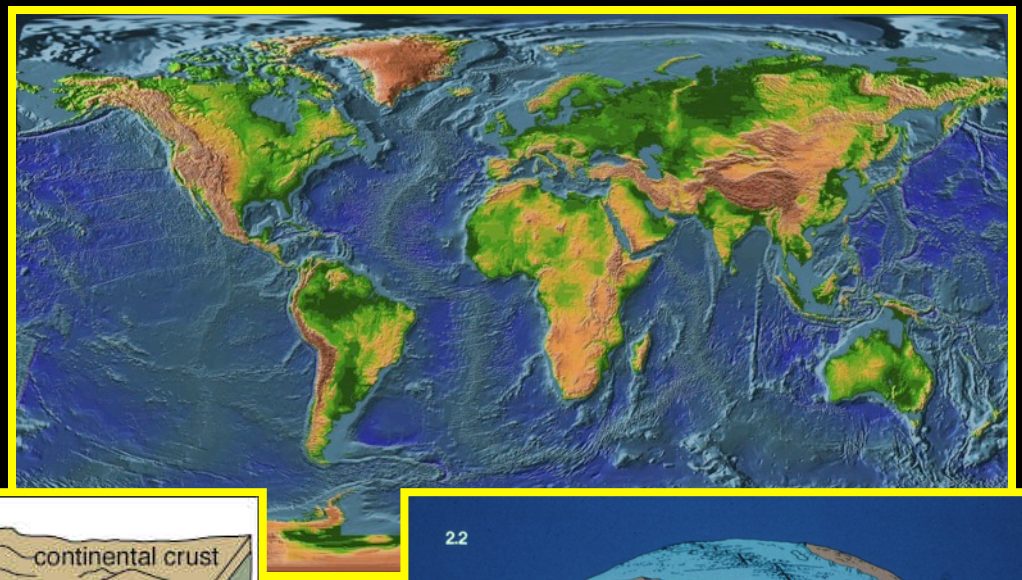
Coronae.

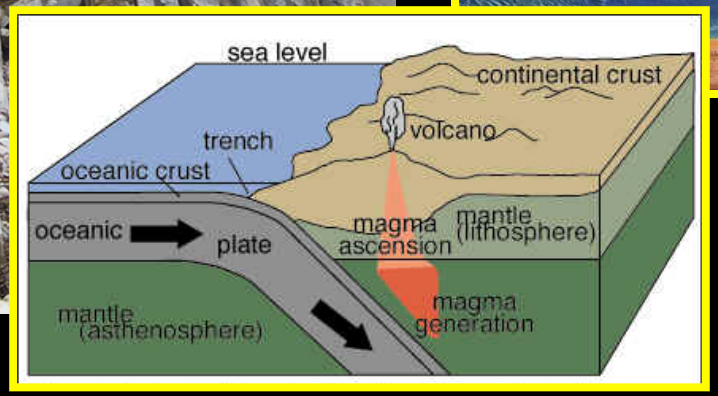


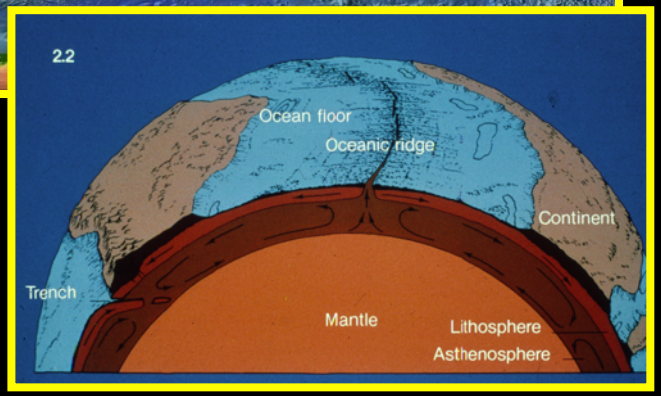


Earth

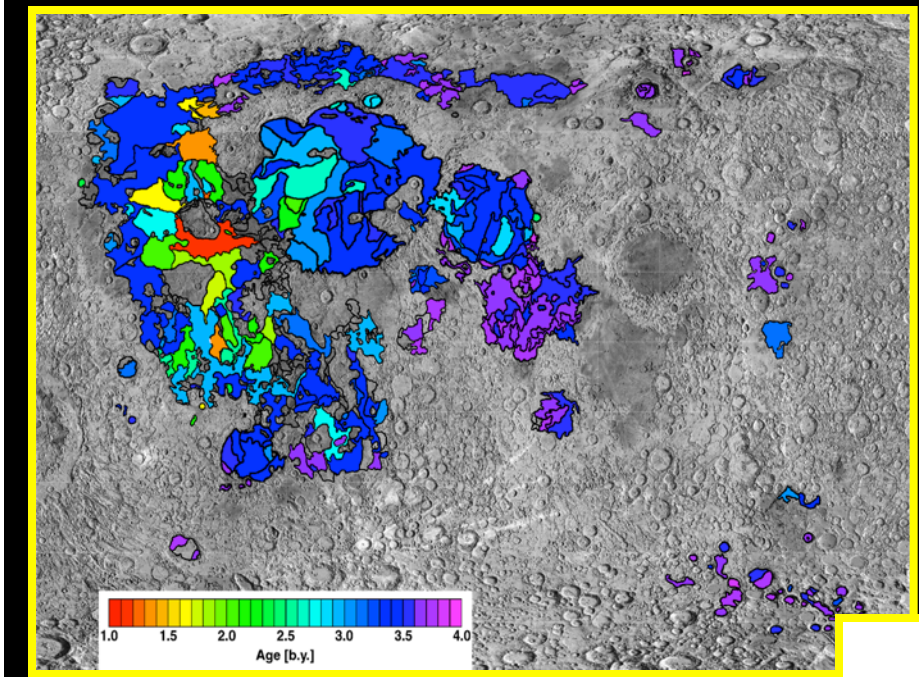

Spreading Plume
Rising Plume
core
mesosphere
crust &
lithospheric mantle
Old Plume/
Hot Spot
asthenosphere

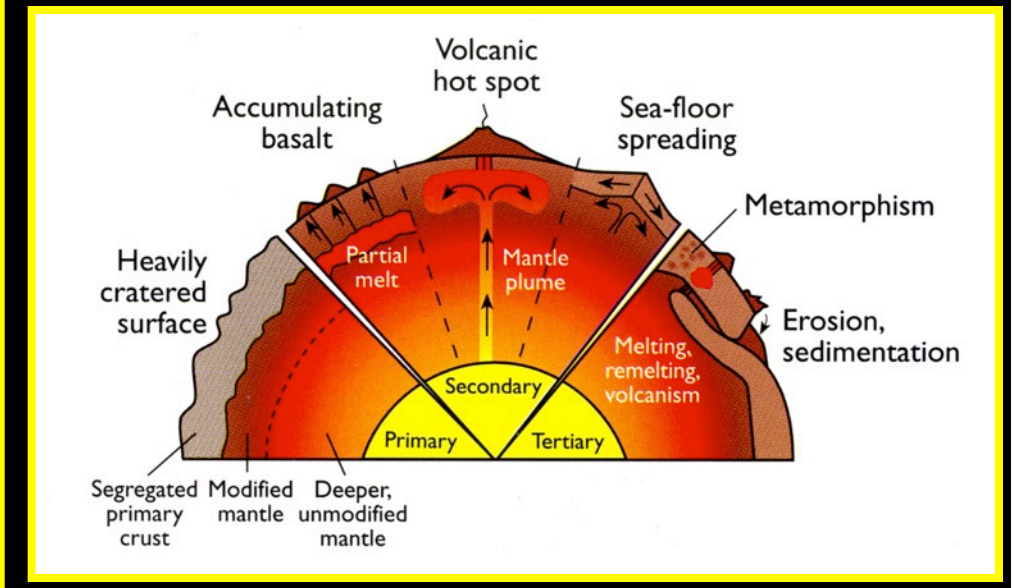



sea level
continental crust
trench
volcano
oceanic crust
oceanic
plate
magma
ascension
mantle
(lithosphere)
mantle
(asthenosphere)
magma
generation


2.2
Ocean floor
Oceanic ridge
Continent
Trench
Mantle
Lithosphere
Asthenosphere

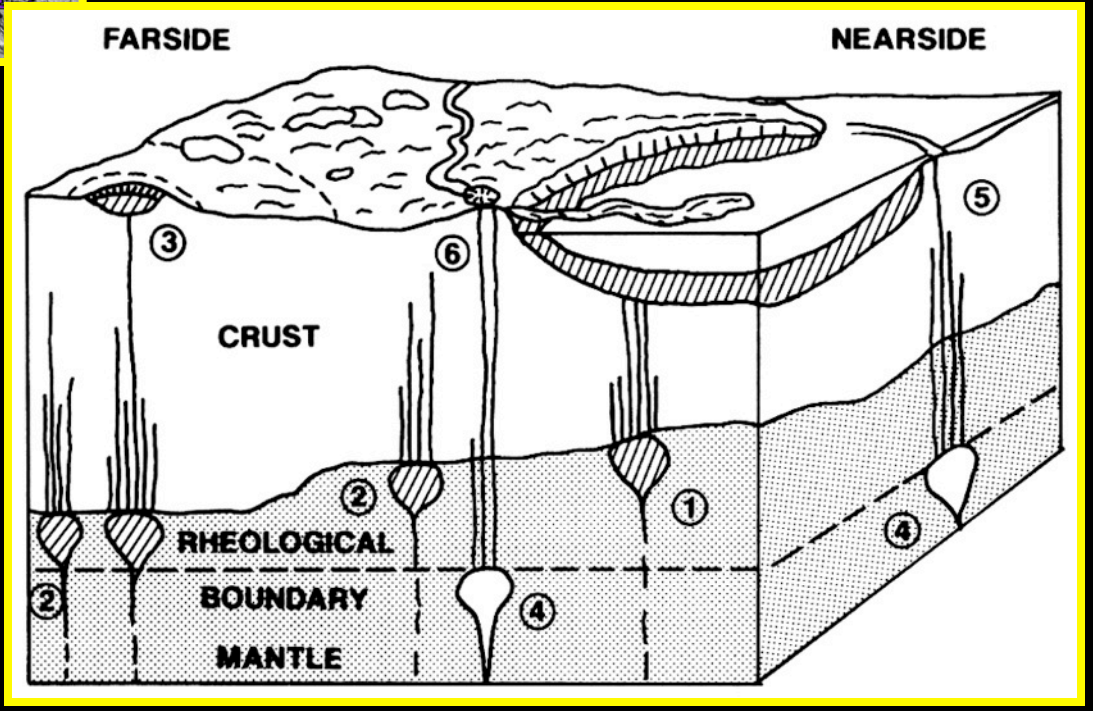
Planetary Crustal Formation and Lunar Volcanism



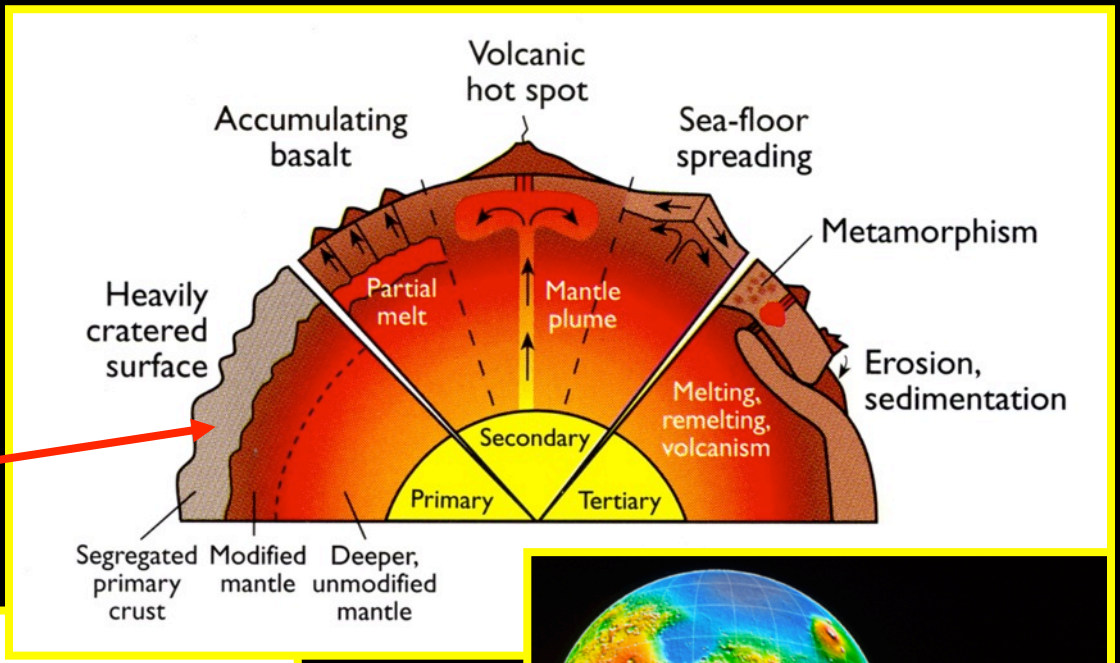


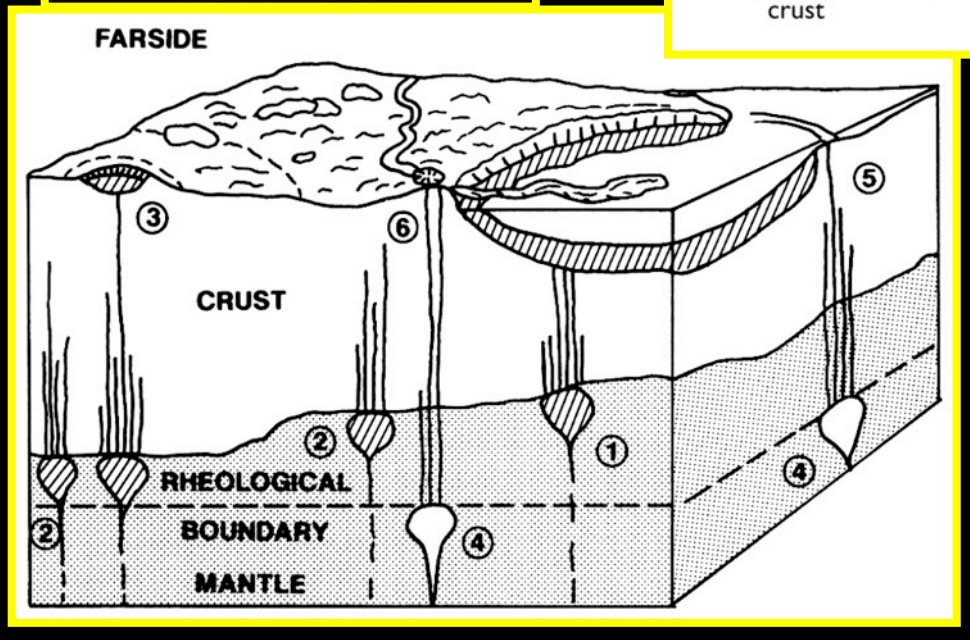
<u>Some Basic Points</u>:

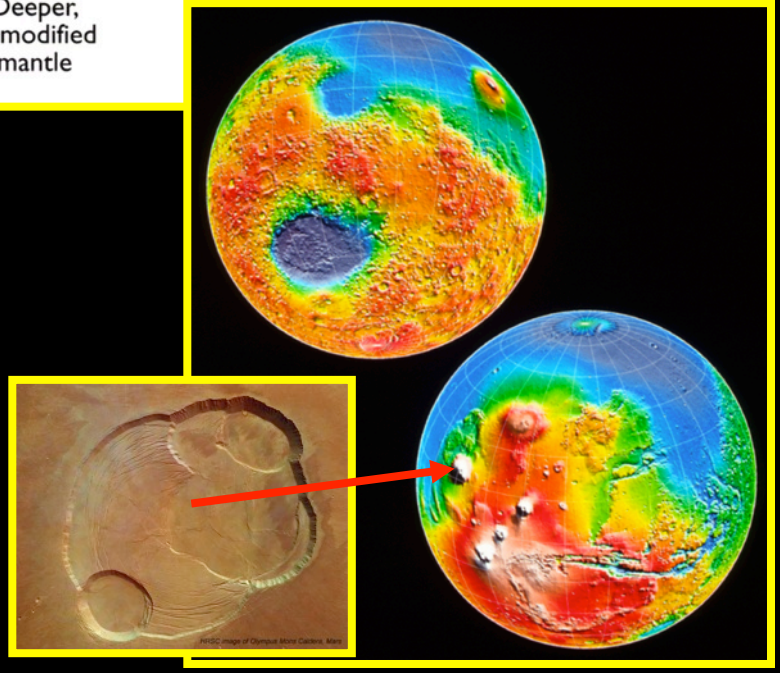
1. Primary crustal formation.
2. Secondary Crustal Formation- Mare Volcanism.
3. Neutral buoyancy zones.
4. Cooling, shrinkage and inhibition to eruption.
5. Very high effusion rates/ volumes.
6. Nearside-farside difference.



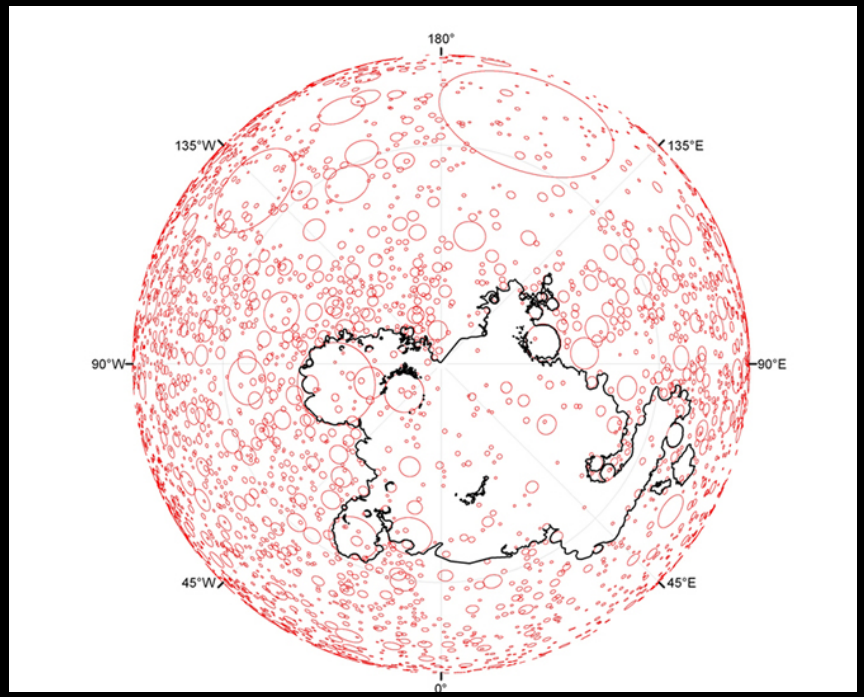
The Moon: Primary Anorthositic Crust, One Plate Planet, Cools Rapidly, Deep Magma Sources



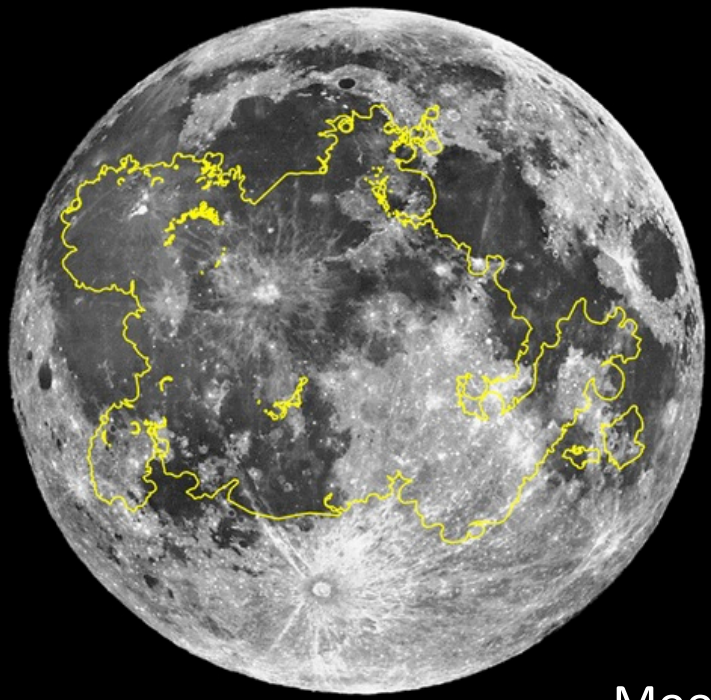




Mercury: Areal Extent of the Northern Plains - A Comparison



Mercury



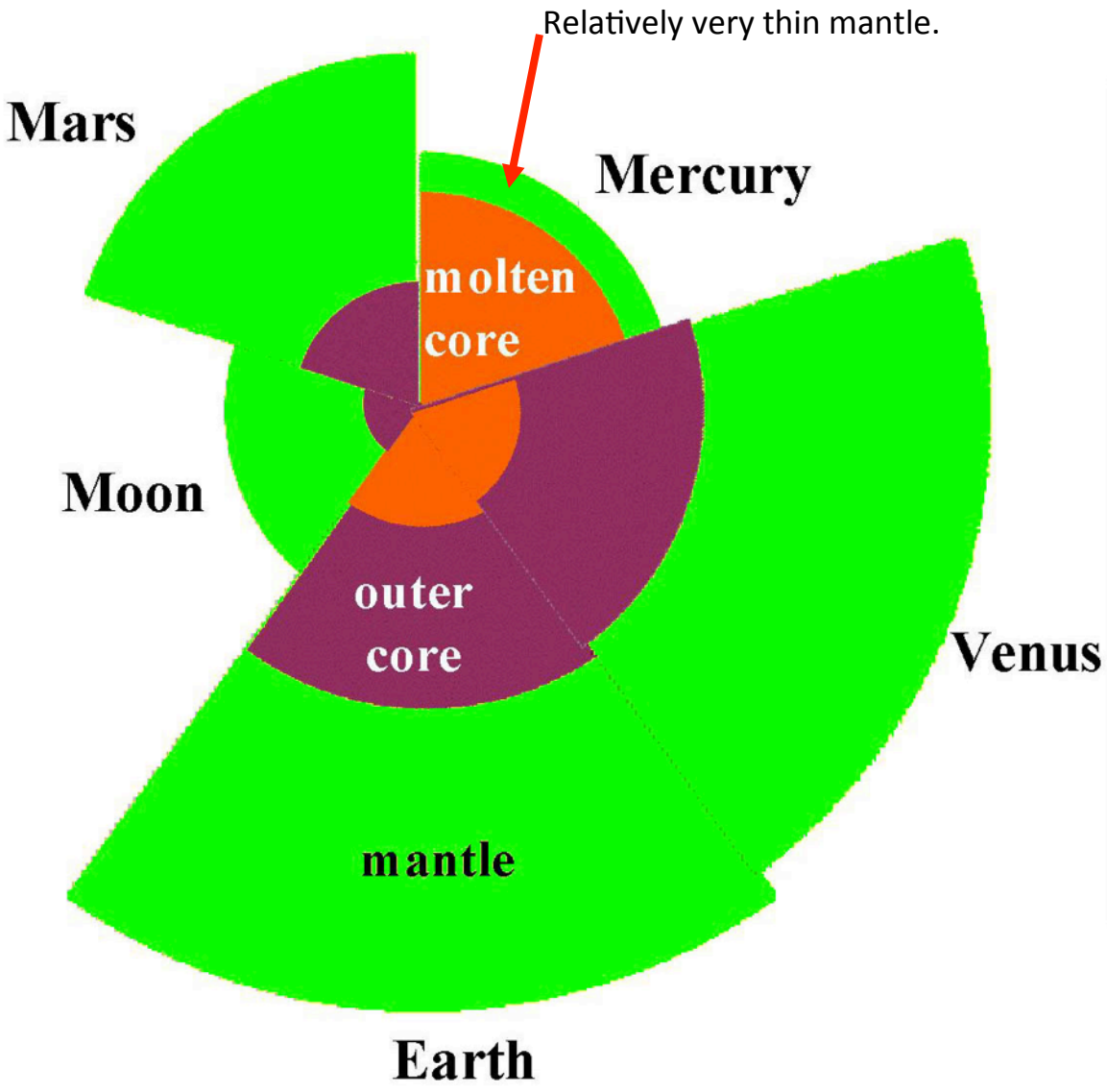
Moon

Earth

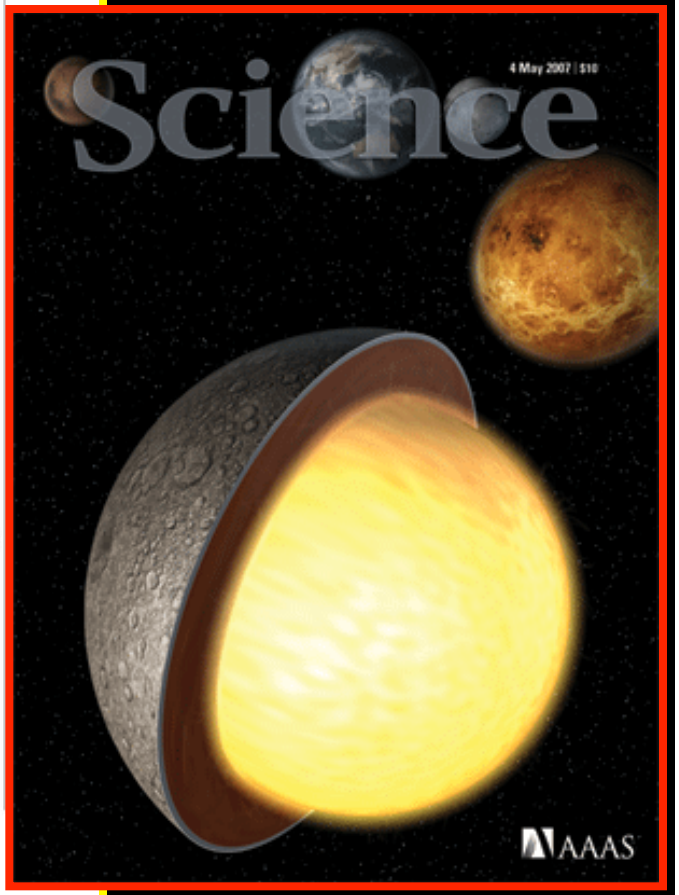
What is the nature and mode of emplacement of the northern plains?

(Head et al., 2011)

How Does the Mantle of Mercury Compare to Other Terrestrial Planets?



(G. Rieke, U. of A.)

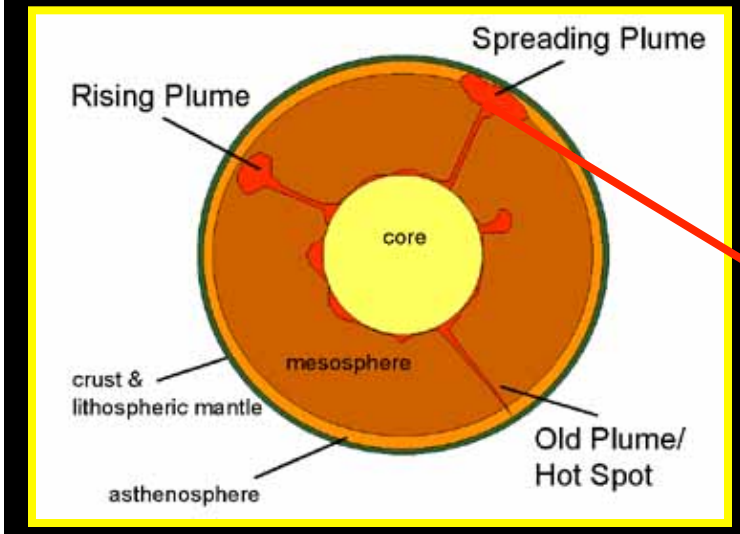


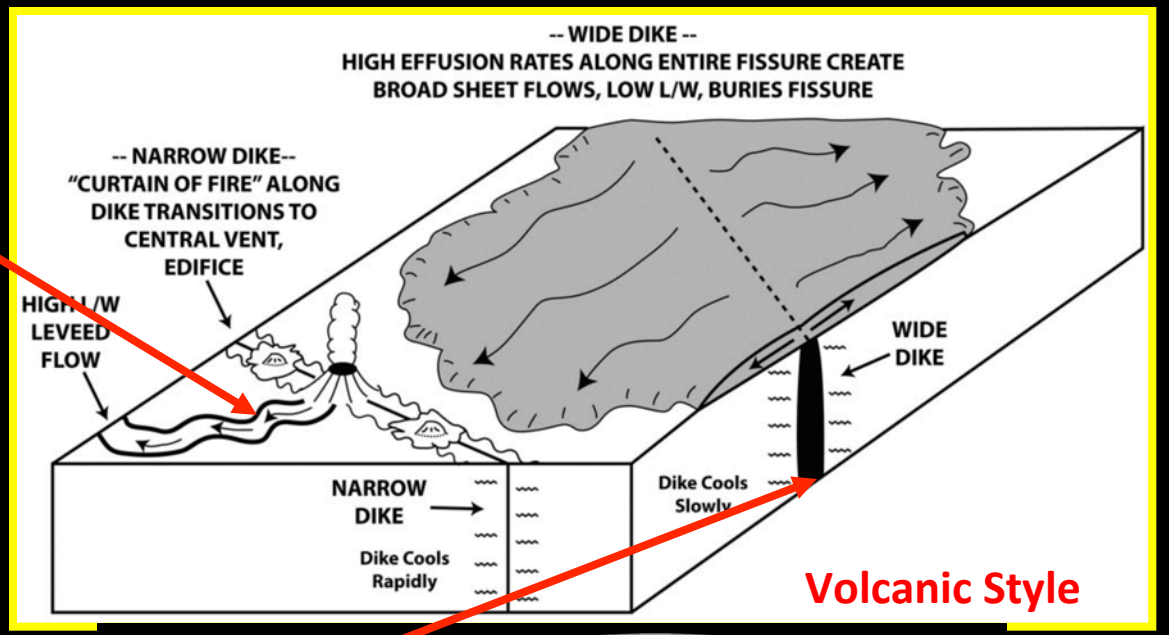
(C. Bickel, *Science*)

Style of Mantle Convection, Heat Loss, Volcanism

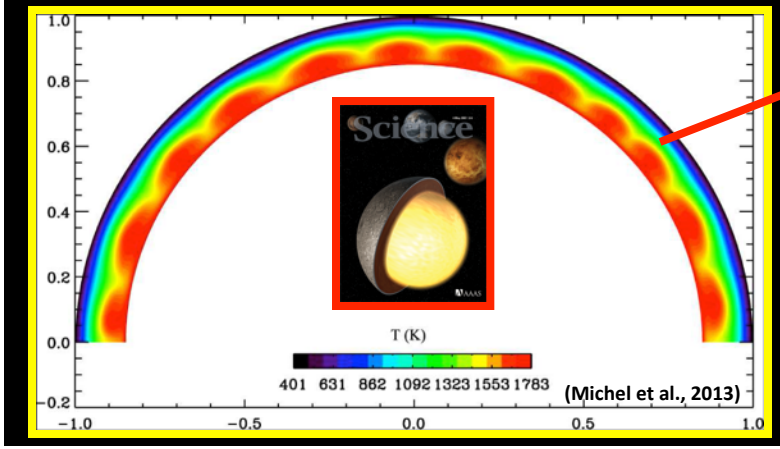
(Two End-Members)

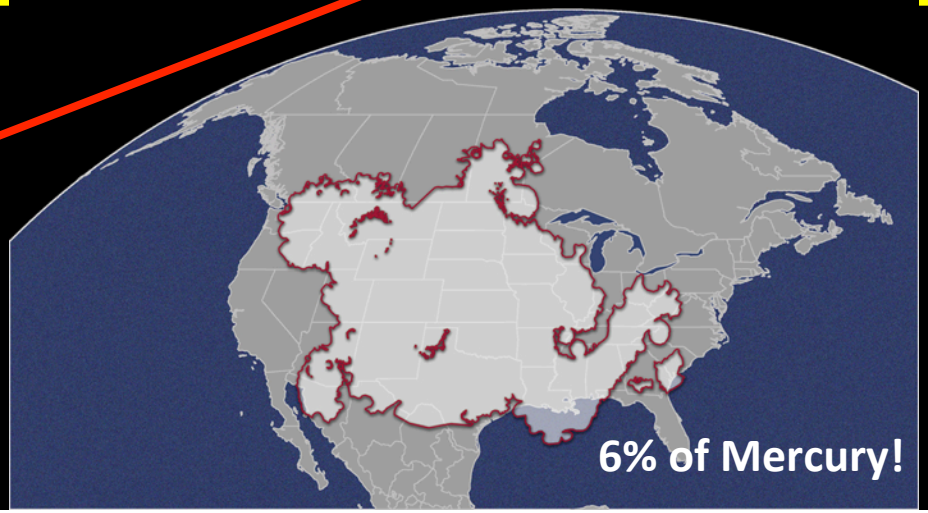
1. **Thick Mantle: Convecting Plumes.**



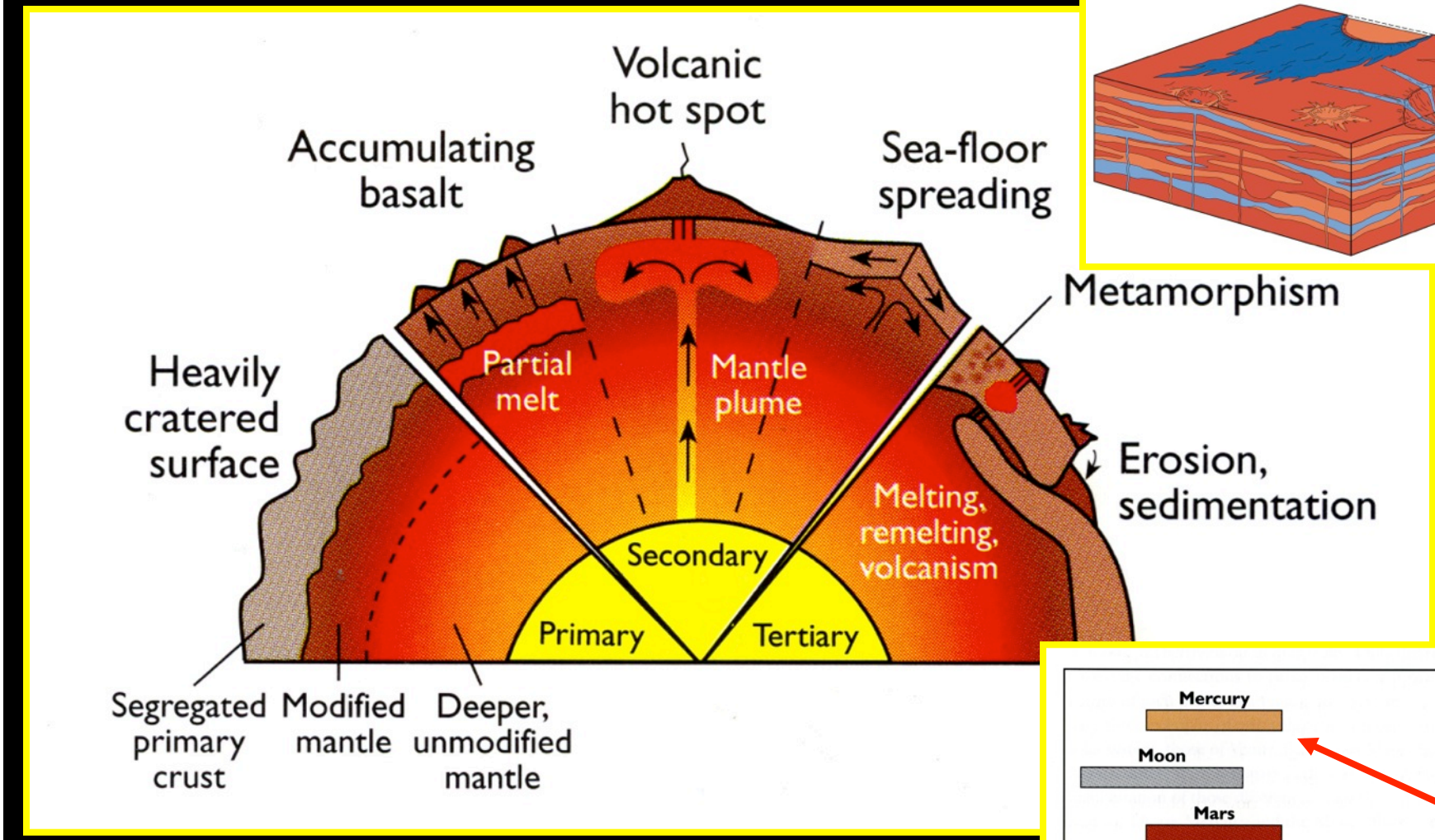


2. **Thin Mantle: Convection Inhibited.**

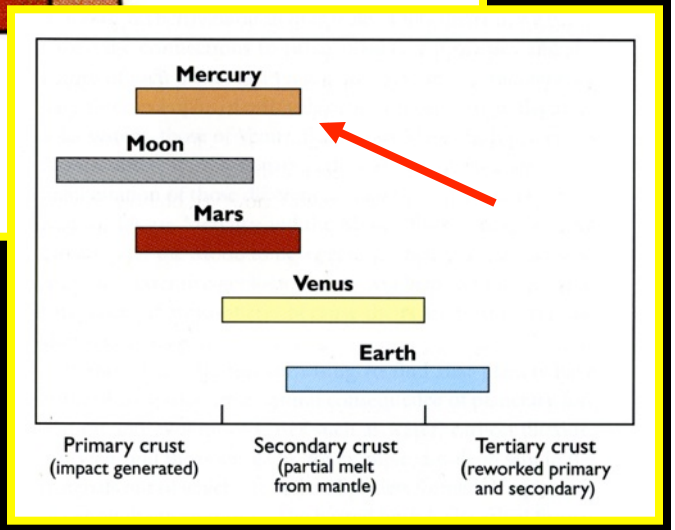




Crustal Formation and Evolution: Primary, Secondary, Tertiary

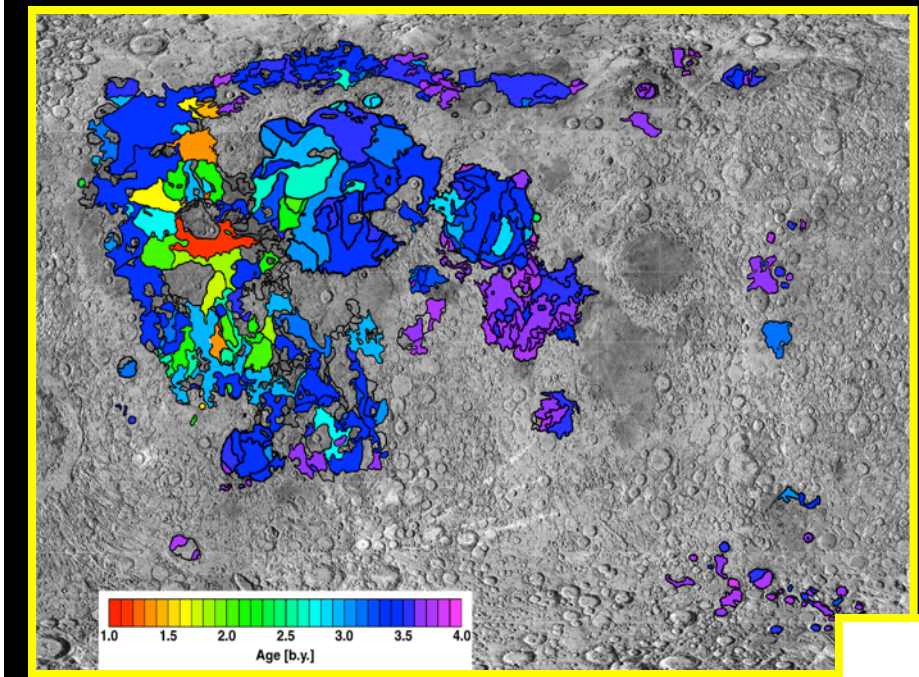


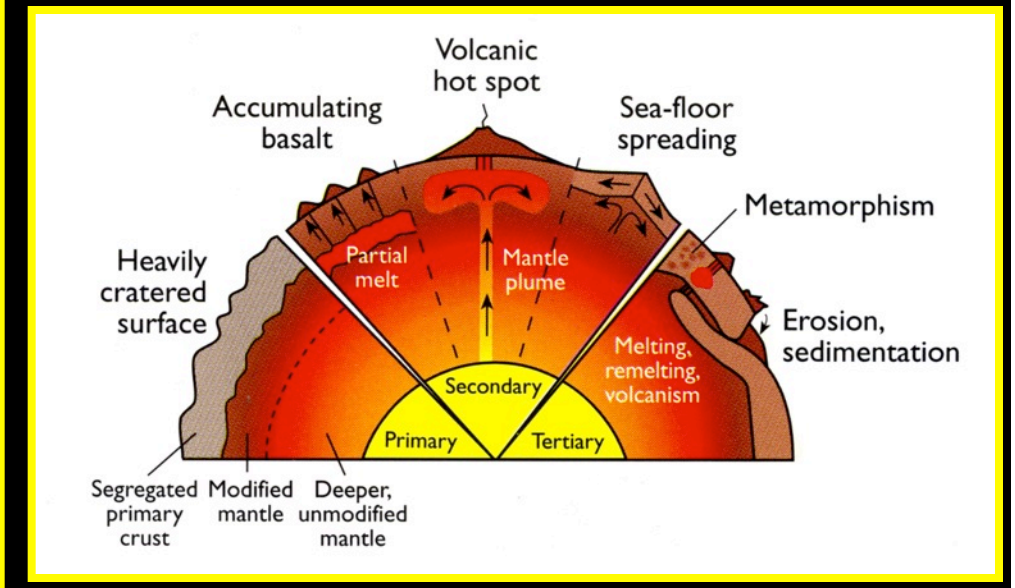
S. Ross Taylor



- No positive evidence for a Moon-like plagioclase flotation primary crust.
- Abundant evidence for global, thick volcanic deposits: Similar to secondary crust on the Moon and Mars.
- What is the nature of primary crust on planets like Mercury?

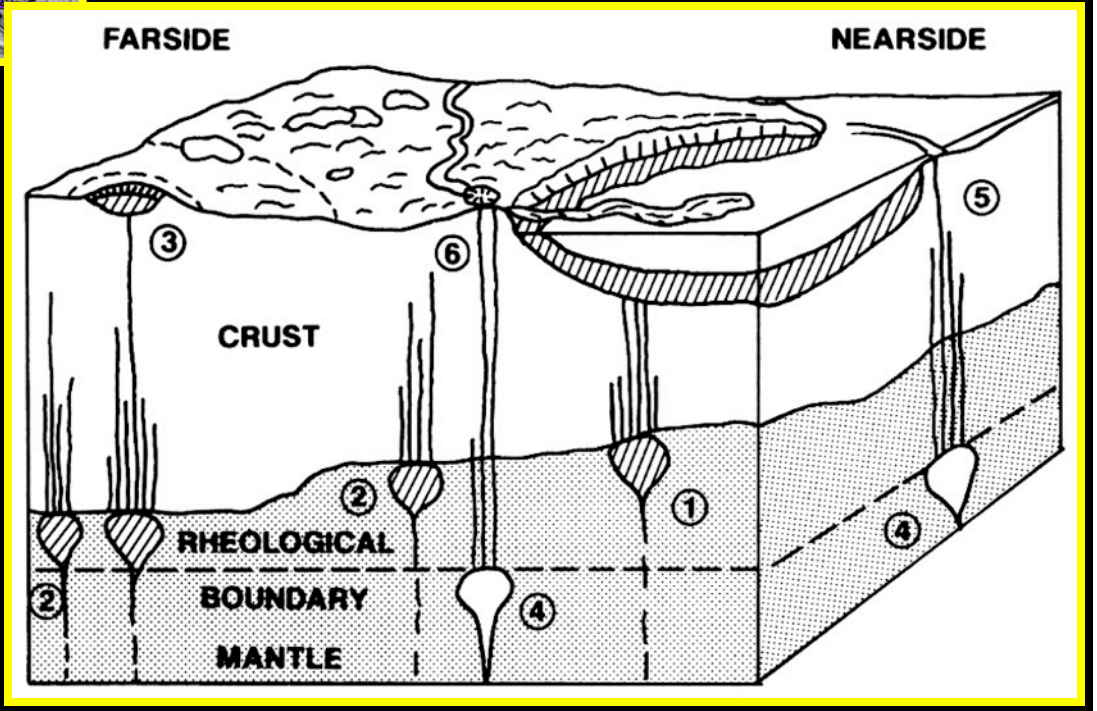
Planetary Crustal Formation and Lunar Volcanism





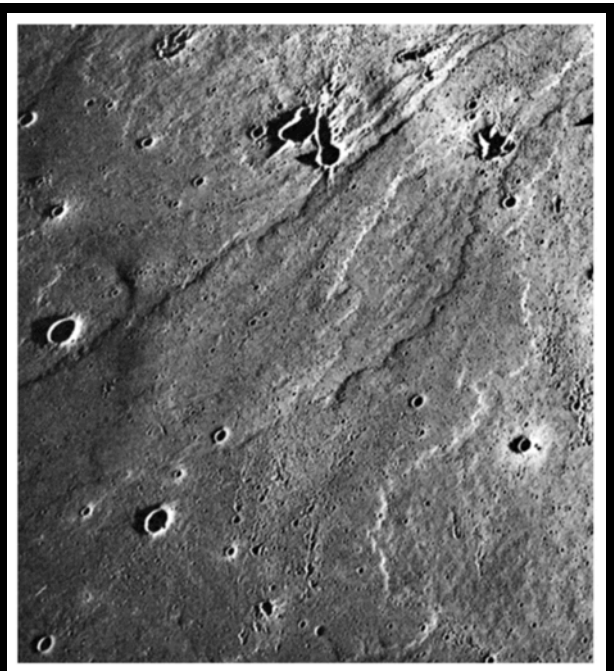
<u>Some Basic Points</u>:

1. Primary crustal formation.
2. Secondary Crustal Formation- Mare Volcanism.
3. Neutral buoyancy zones.
4. Cooling, shrinkage and inhibition to eruption.
5. Very high effusion rates/ volumes.
6. Nearside-farside difference.



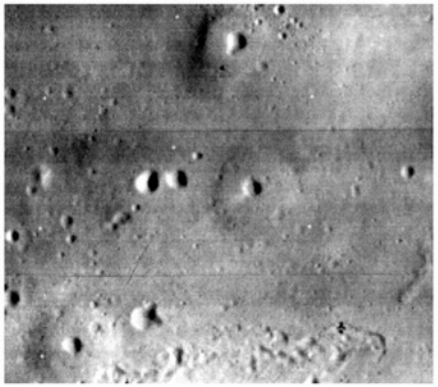
Range of Lunar Volcanic Landforms

How can this diversity be explained?



Mare Imbrium

Cones



Small Domes

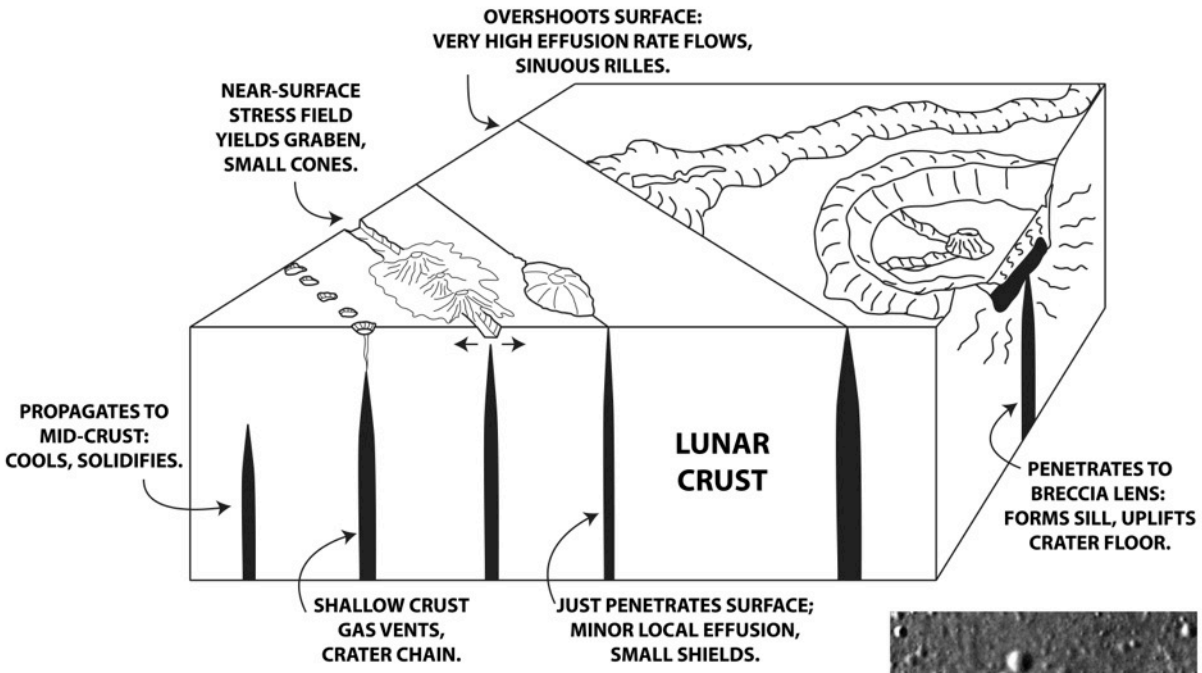
Pits

Crater Chains

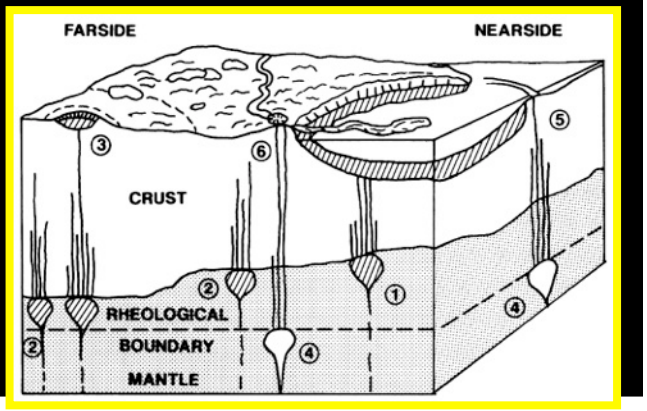
Linear Rilles

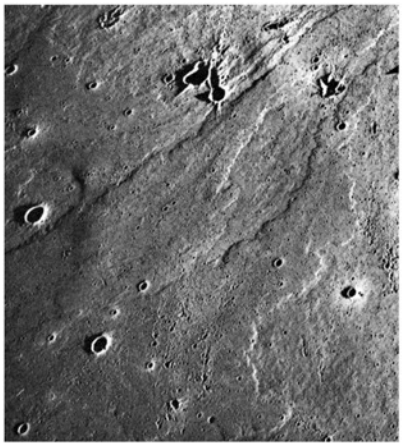
Floor-Fractured Craters

Rimae Prinz



Spectrum of Overpressurization and Dike Emplacement Events

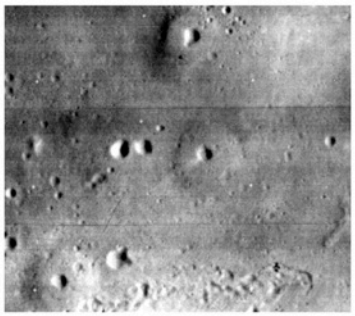




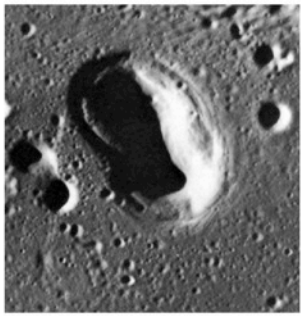
Mare Imbrium

Rimae Prinz

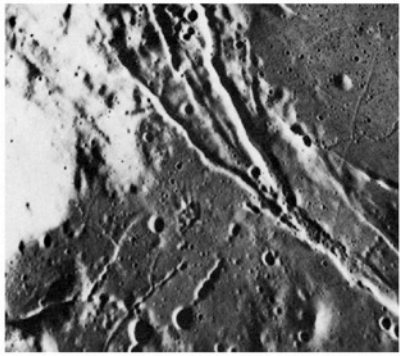
Cones



Small Domes



Pits



Crater Chains

Linear Rilles

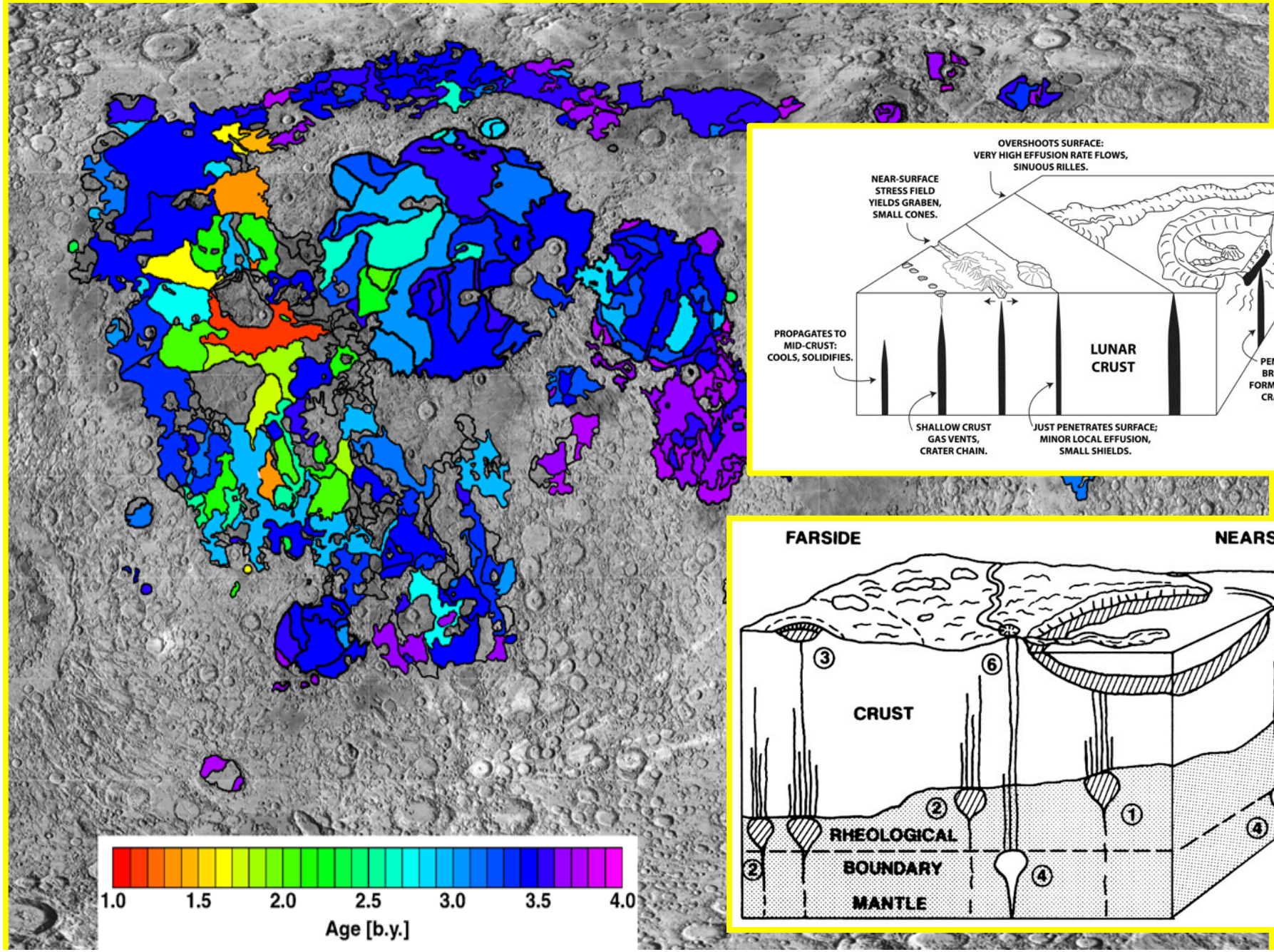
Floor-Fractured Craters

Future Human and Robotic Exploration of the Moon:

- What are the most likely locales for deep mantle xenoliths.
- What is the nature and origin of young mare basalt volcanism?
- What is the chronology of young mare basalt volcanism?
- What is the origin of Ina "caldera" and similar features.
- What is the relationship of lunar picrites, glasses and lava flows?
- Nearside/Farside mare basalt differences: Age, mineralogy, volumes and processes.
- Human Exploration:
- Geometry of dikes to test ascent and eruption models.
- Magnetic properties, diameter, density, gravity.
- Floor-fractured craters: Intrusion, alteration, hydrothermal activity.
- Marius Hills: Gravity structure and relation to solidified magma reservoirs.
- Sinuous rille source regions:
- Abundance of deep dikes in the lunar crust.
- Emplacement dynamics of lunar pyroclastics: Vent structure and 3D characteristics. Role of volatile sources and sinks.
- Dikes as recorders of the history of the magnetic field.
- Cryptomaria: Are the GRAIL anomalies actually cryptomaria?
- What is the role of impact basins in the generation, ascent, eruption and collection of magma?
- How are spinel minerals related to dike emplacement.

Treated in Detail in the Paper

Lessons for Human and Robotic Exploration of the Moon:



Future Human and Robotic Exploration of the Moon:

- Geological Exploration: Major Processes:
- Mineralogical Diversity and Origin:
- Petrological Diversity and Petrogenesis:
- Geophysics: Seismology, Gravity, Magnetics, GPR:
- Regolith Formation and Evolution:
- In Situ Resource Utilization: