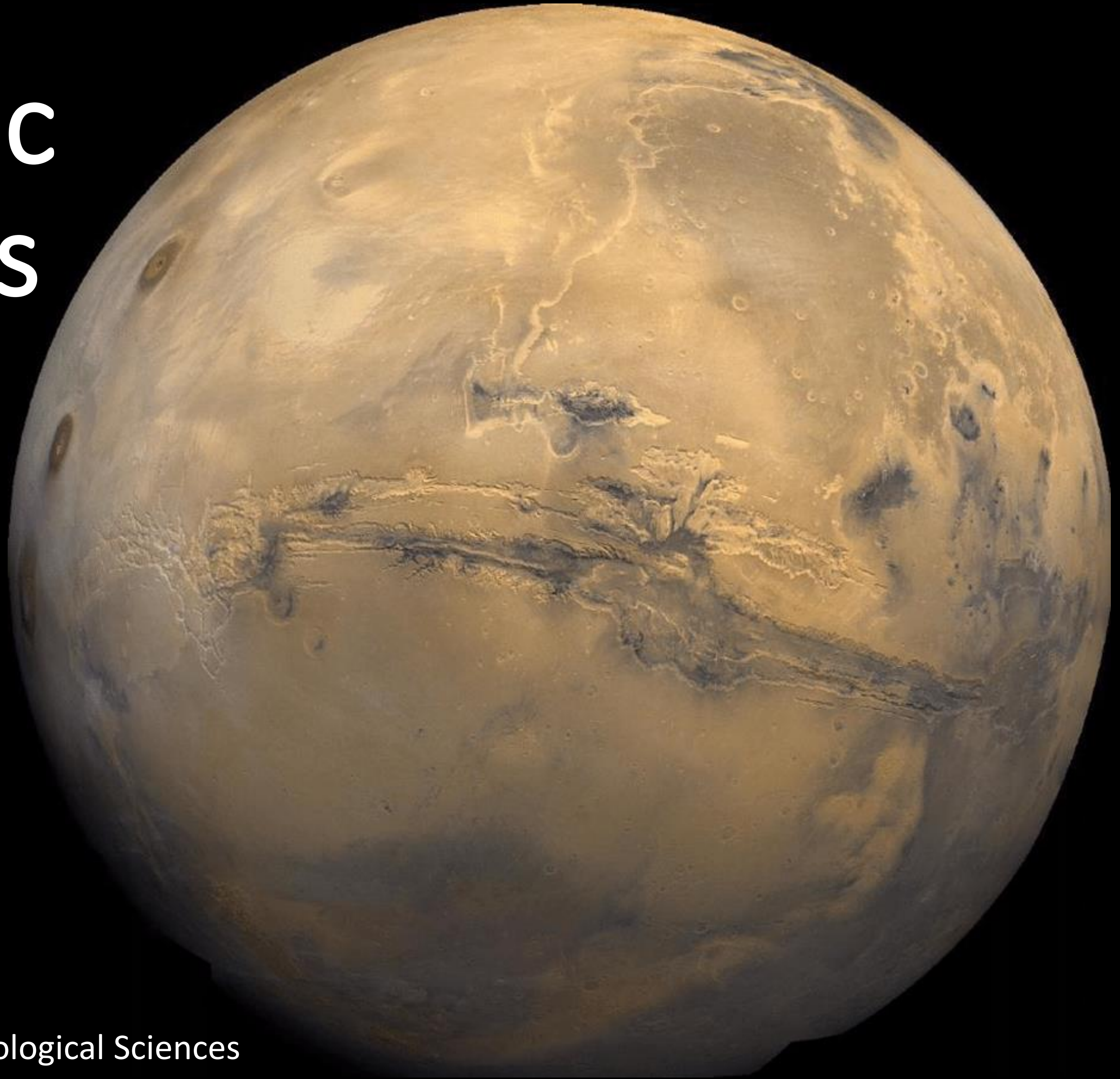
A Brief Geologic History of Mars



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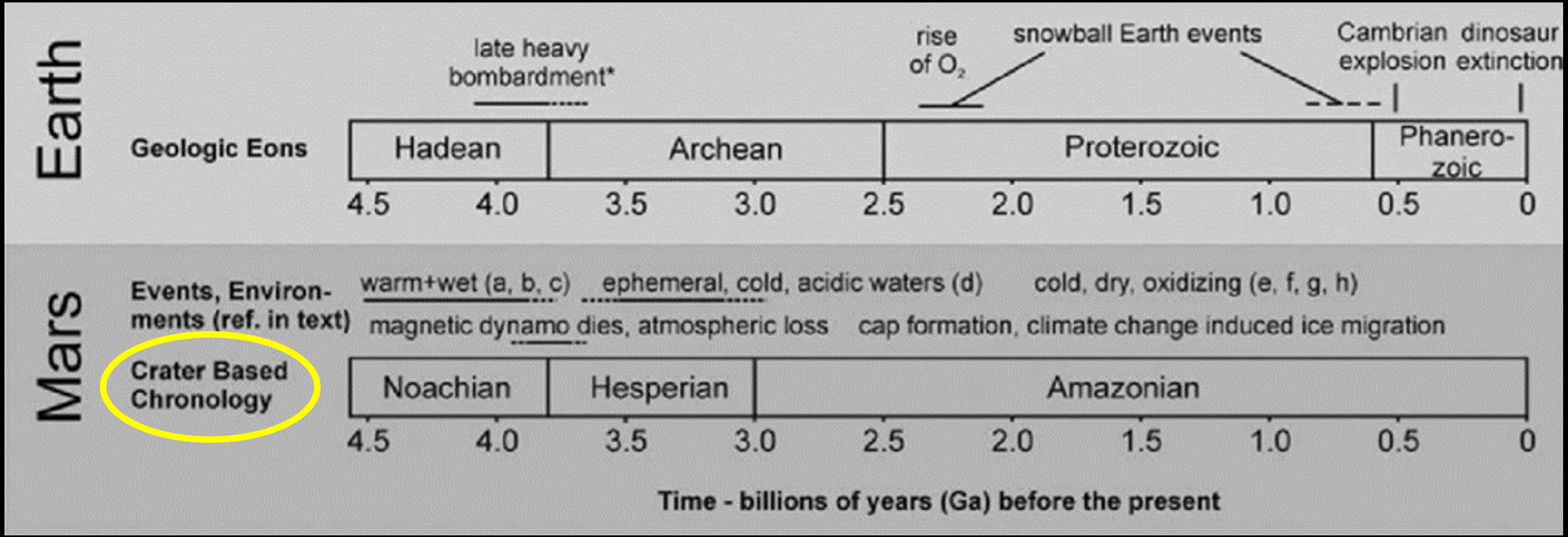
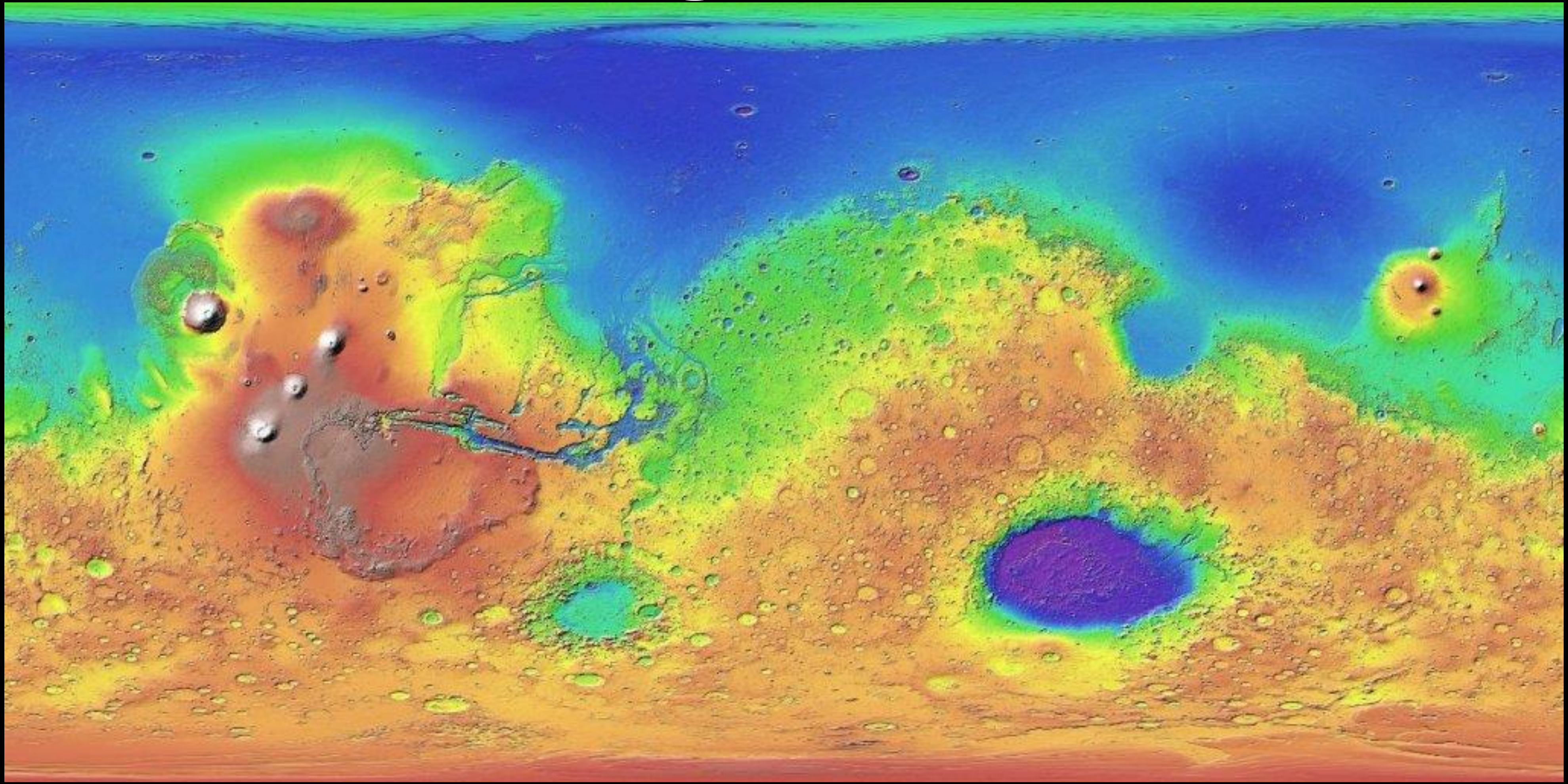
Geologic History

- On Earth, we can reconstruct geologic time based on observation of rocks, and actually dating rock and minerals to determine their age
- Martian rocks have only be analyzed in situ by robots and satellites
- We do not have (reliable) samples from the Martian surface, so age must be inferred



Abrevaya, X. C., Anderson, R., Arney, G., Atri, D., Azúa-Bustos, A., Bowman, J. S., ... & Wong, T. (2016). The Astrobiology Primer v2. 0. Astrobiology, 16(8), 561-653.

Crater Counting

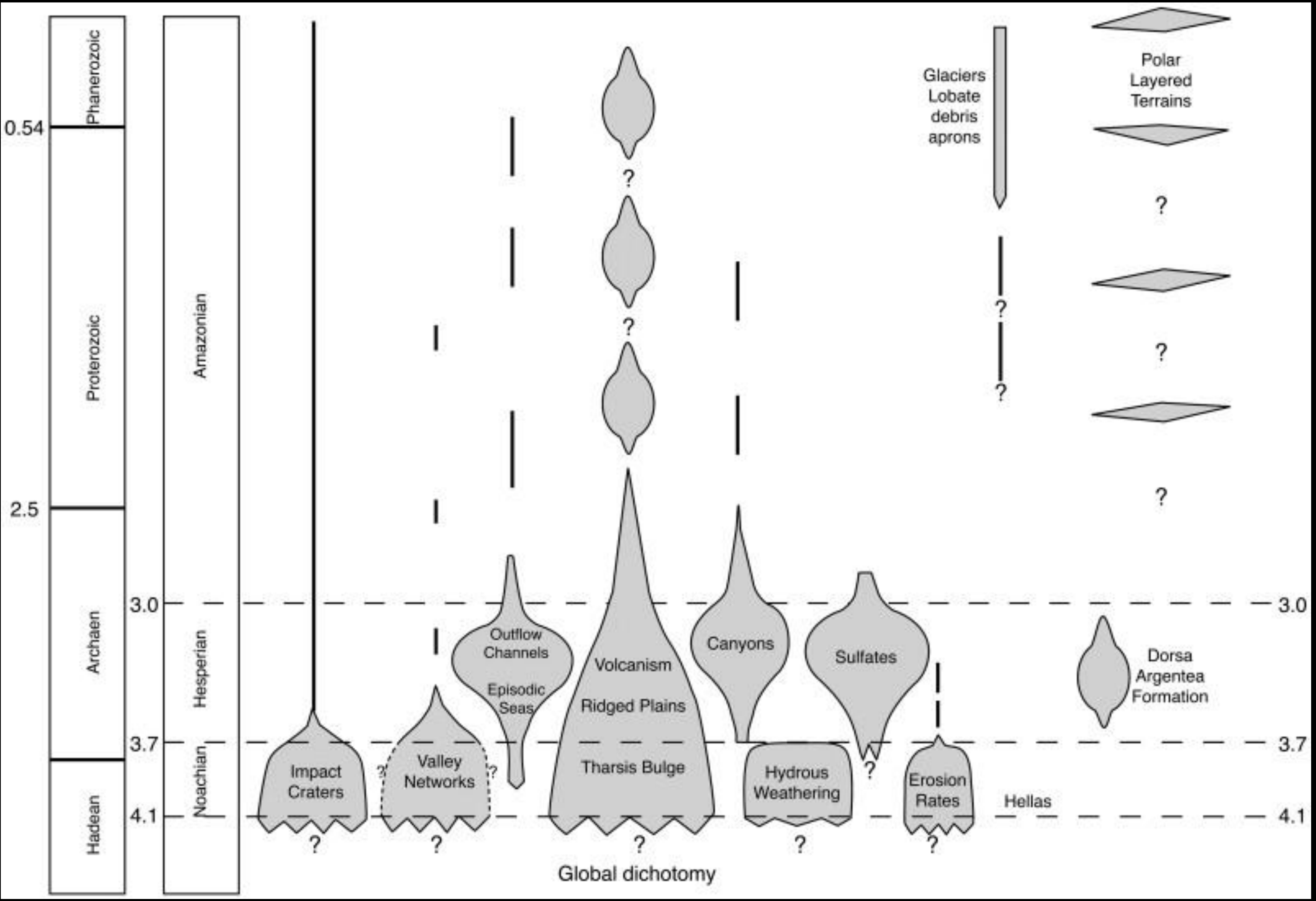


Digital Elevation Model (DEM) of Martian Surface

- Areas with **high crater density**, and size diversity are **old- Noachian**
- **Moderate crater density** and low size are medium age- **Hesperian**
- **Low crater density** are the **youngest** surfaces on Mars- **Amazonian**
- Each of these epochs is known to host specific geologic and environmental conditions at the Martian surface

Remote Sensing Helps "Complete" the Picture

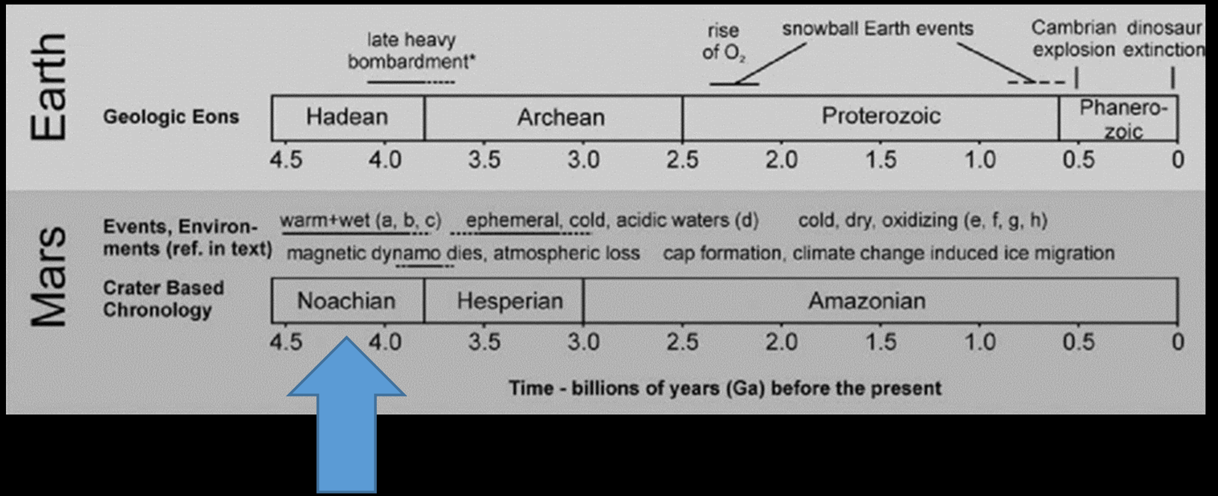
- **High-resolution photography-** fine detail in landscape and morphology
- **Radar altimetry-** identification of subtle changes in topography
- **Infrared Spectroscopy-** mineralogy and hydration
- **Gamma Ray Spectroscopy-** composition of rock and sediment
- **Magnetic/Gravitational field strength-** crustal thickness and compositional info
- Combining this information with the estimated age of the crust allows for the construction of a sequence of evolution of the planet



Geological activity as a function of time on Mars. Shown are the relative importance of different processes (impact cratering, volcanism), the time and relative rates of formation of various features and units (valley networks, Dorsa Argentea Formation), and types and rates of weathering, as a function of time.

Carr, M. H., & Head III, J. W. (2010). Geologic history of Mars. Earth and Planetary Science Letters, 294(3-4), 185-203.

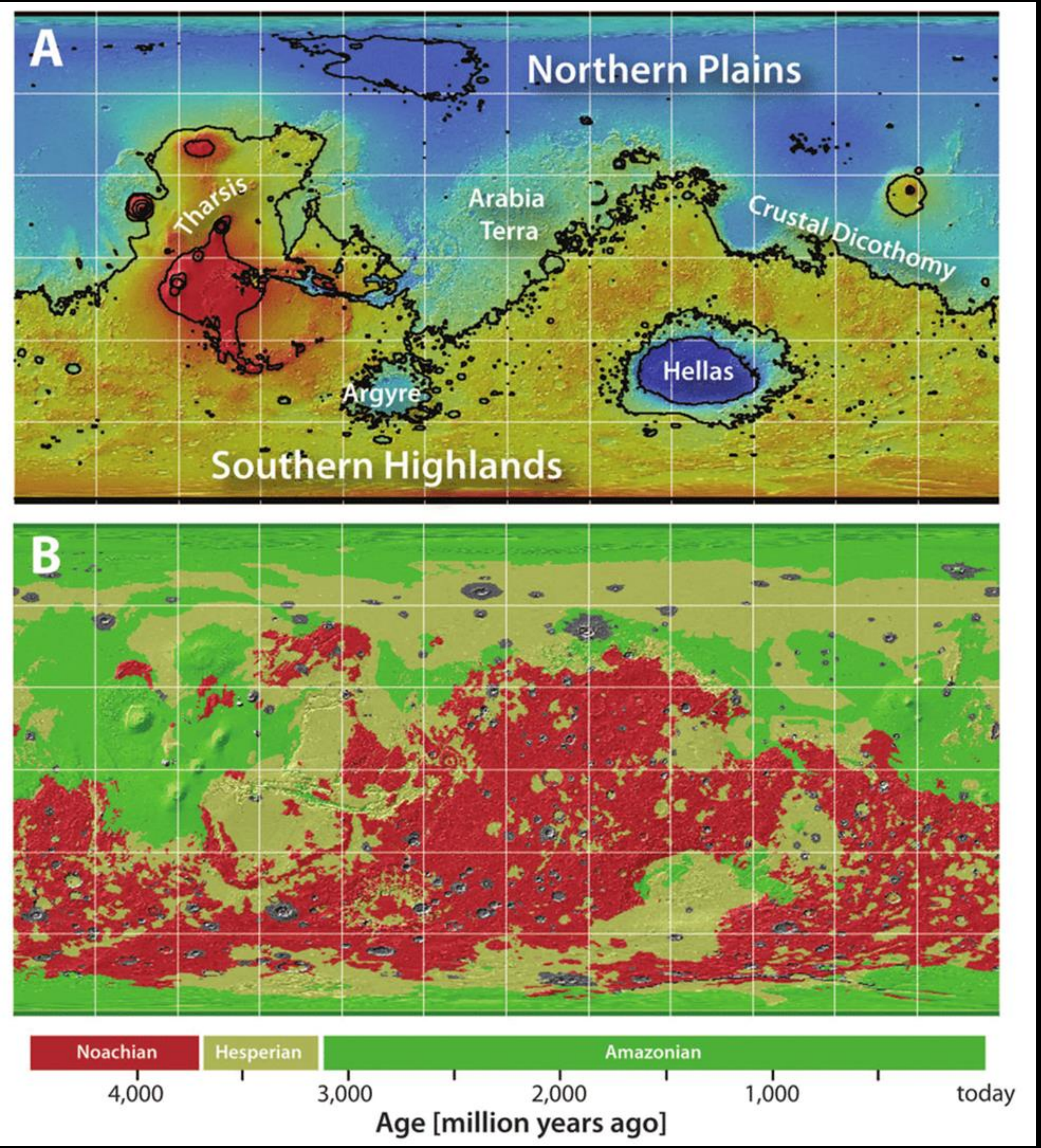
Noachian Mars



- ~4.1-3.7 Ga
- **Impact rates were high**
  - Origin of the ***Crustal Dichotomy?***
- **Volcanic eruptions common**
  - Buildup of **Tharsis**
- Development of a **planet-wide hydrological system**
  - Formation of **valleys**, and hydrated **clay minerals**

Impacts on Mars- Crustal Dichotomy

- Largest positively identified crater is **Hellas-** deepest basin on Mars
- Northern lowlands could be a huge impact crater!
- An impact like that could have partially melted the interior, jumpstarting long lived **volcanoes**



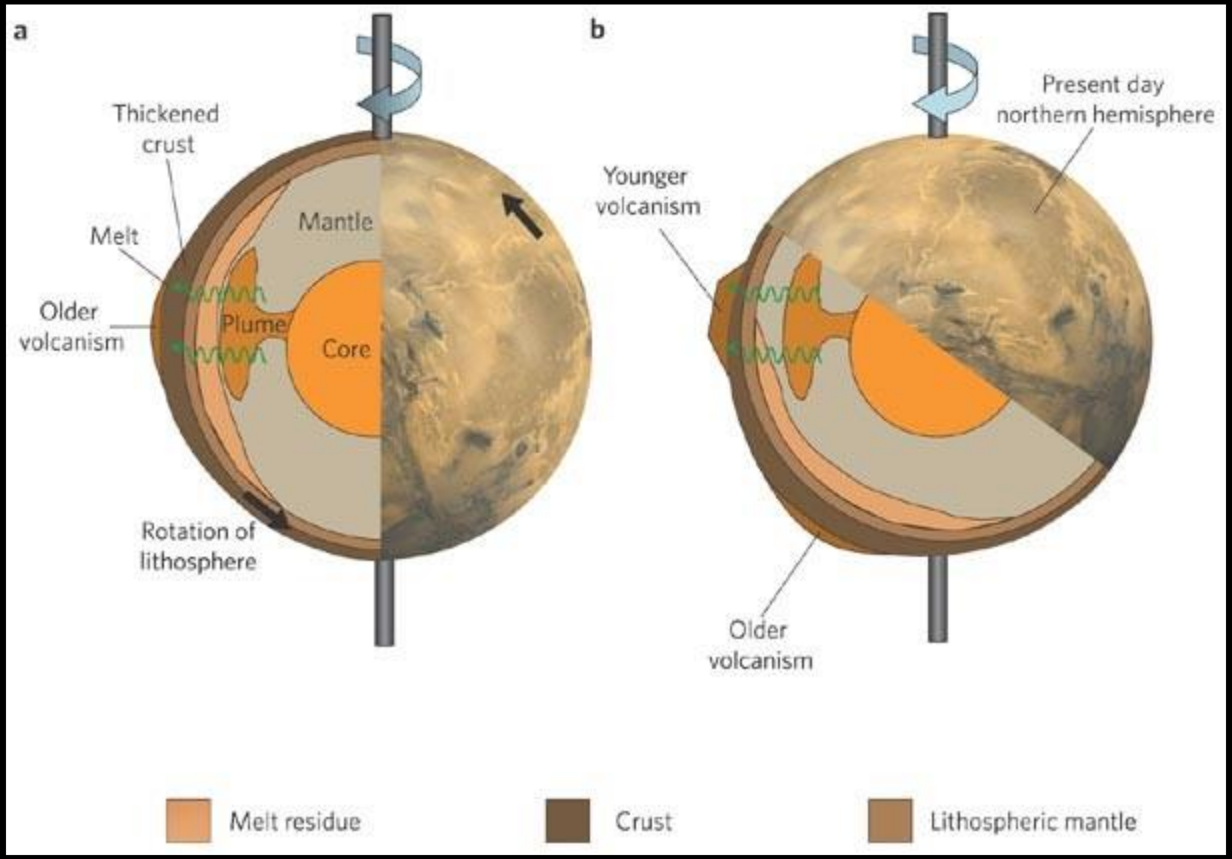
A. Color-coded (blue=low, red=high) global shaded relief. 5-km spacing topographic contours are indicated. The so-called crustal dichotomy boundary is roughly at the border between yellowish and greenish areas, where the zero datum contour is located (NASA Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) data, Smith et al. (1999)). B. Simplified global geological map, indicating the three main eras on Mars: Noachian (4.65 − 3.7 Gyr), Hesperian (3.7 − 3.0 Gyr) and Amazonian (3.0 Gyr−present)

Rossi, A. P., & Van Gasselt, S. (2010). Geology of Mars after the first 40 years of exploration. Research in Astronomy and Astrophysics, 10(7), 621.

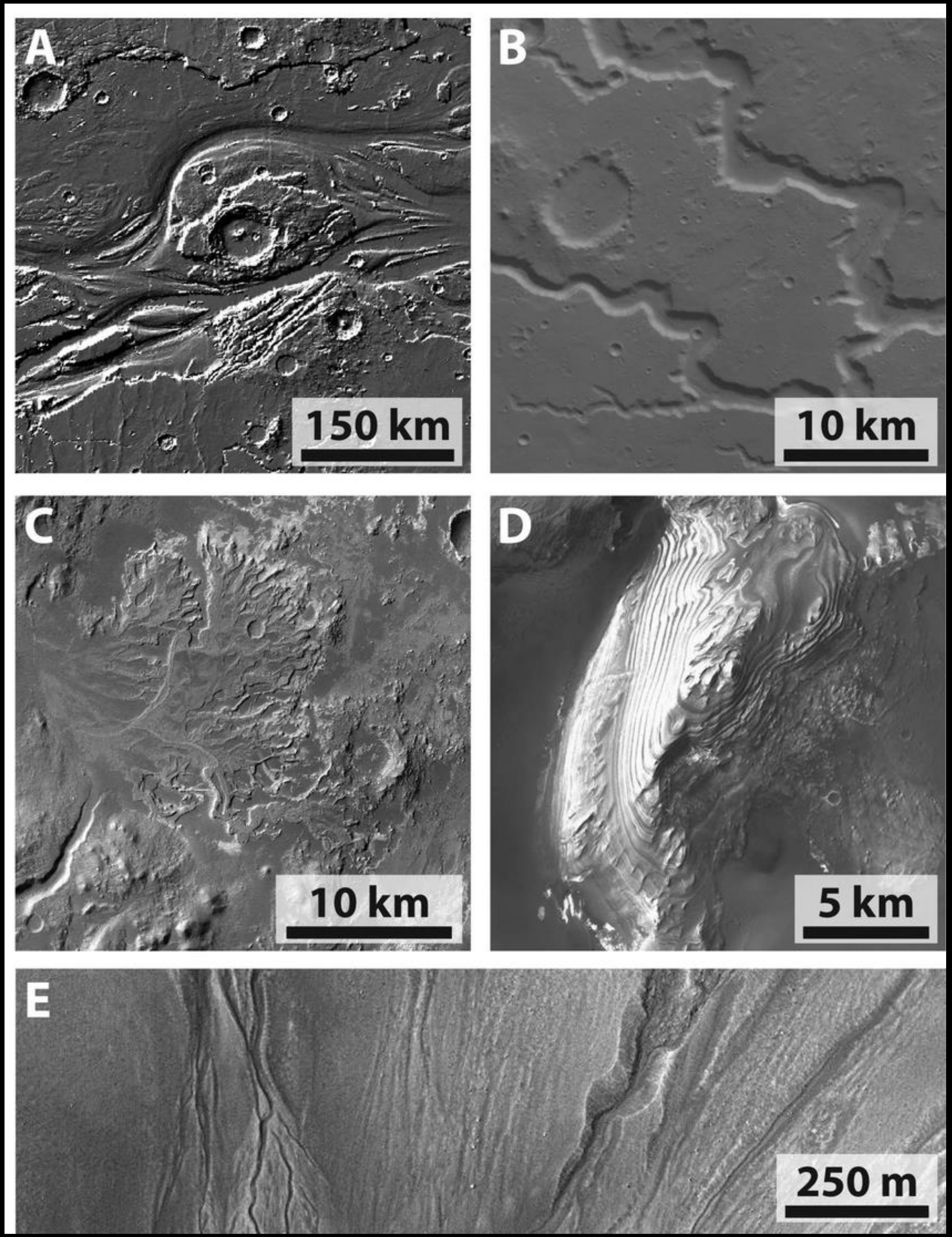
Early Mars Volcanism: Tharsis Bulge

Nimmo, F. Mars's rotating shell. Nature Geosci 2, 7–8 (2009)

- Area of uplifted crust and high volcanic activity (up to the *present*?)
- Likely fed by a ***plume*** of magma pushing against the thick crust
- More **basalt**
- Supplied **water** to the Martian atmosphere



a. A single mantle plume rises beneath lithosphere underlain by a melt residue and causes the initiation of Tharsis volcanism. Zhong proposes that stresses induced by the plume trigger rotation of the lithosphere, which moves the thickened crust away from the plume through time.
b. Younger, more voluminous volcanism occurs when lithospheric rotation stops with the plume at the edge of the melt residue layer. On Mars, this occurs at the hemispheric dichotomy boundary



Evidence of Water

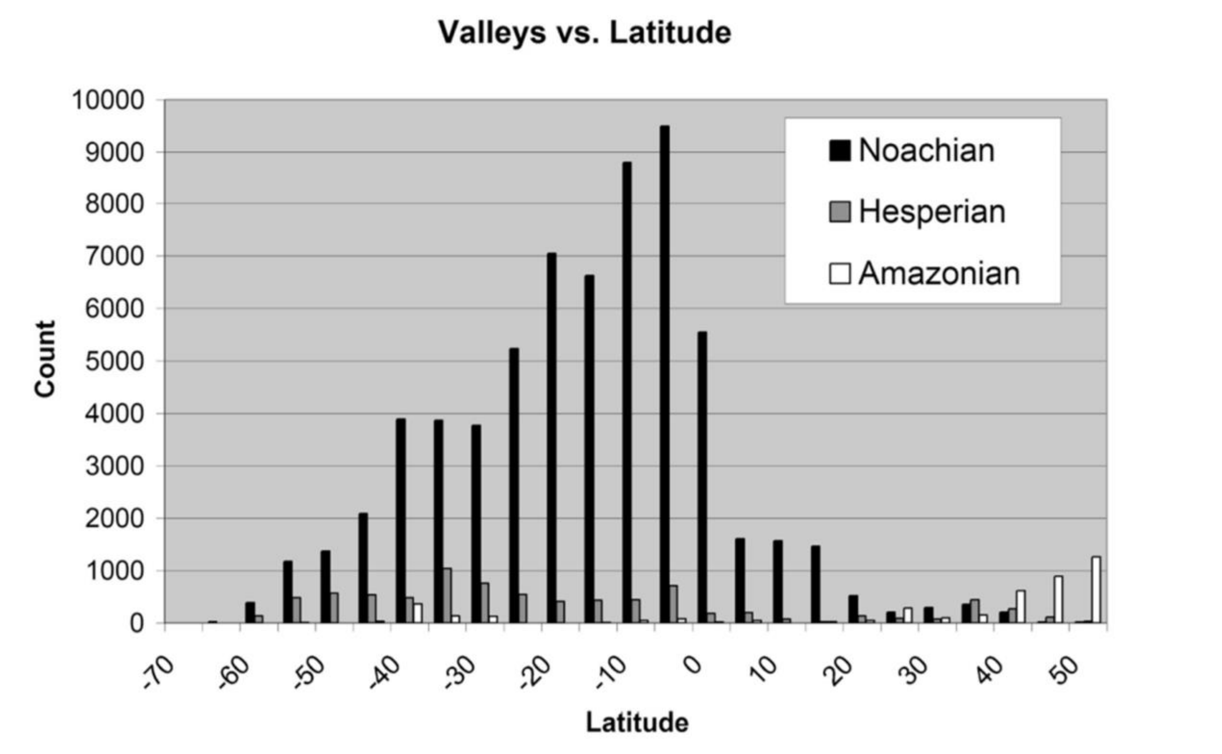
- Widespread valleys and deltas suggest a large amount of water
- Water from volcanism and impact-driven outgassing of steam
- It is unclear what conditions prevailed during valley formation:
  - Cold, glaciers, with transient melt water flow
  - Warm and wet, with continued runoff
  - Temperate and dry, with groundwater sapping

Samples of exogenic landforms and sedimentary deposits. A. Outflow channels: Kasei Vallis (shaded relief derived form MGS MOLA data) B. Valley network, possible sapping: Nanedi Vallis (MEX HRSC nadir from orbit 905) C. Deltas: Eberswalde fan delta (MRO CTX mosaic) D. Interior Layered Deposits (ILD) in Juventae Chasma (MEX HRSC nadir from orbit 243). E. Recent gullies on Mars (MGS MOC R1002078).

Rossi, A. P., & Van Gasselt, S. (2010). Geology of Mars after the first 40 years of exploration. Research in Astronomy and Astrophysics, 10(7), 621.

Location and Timing of the Martian Valley Networks

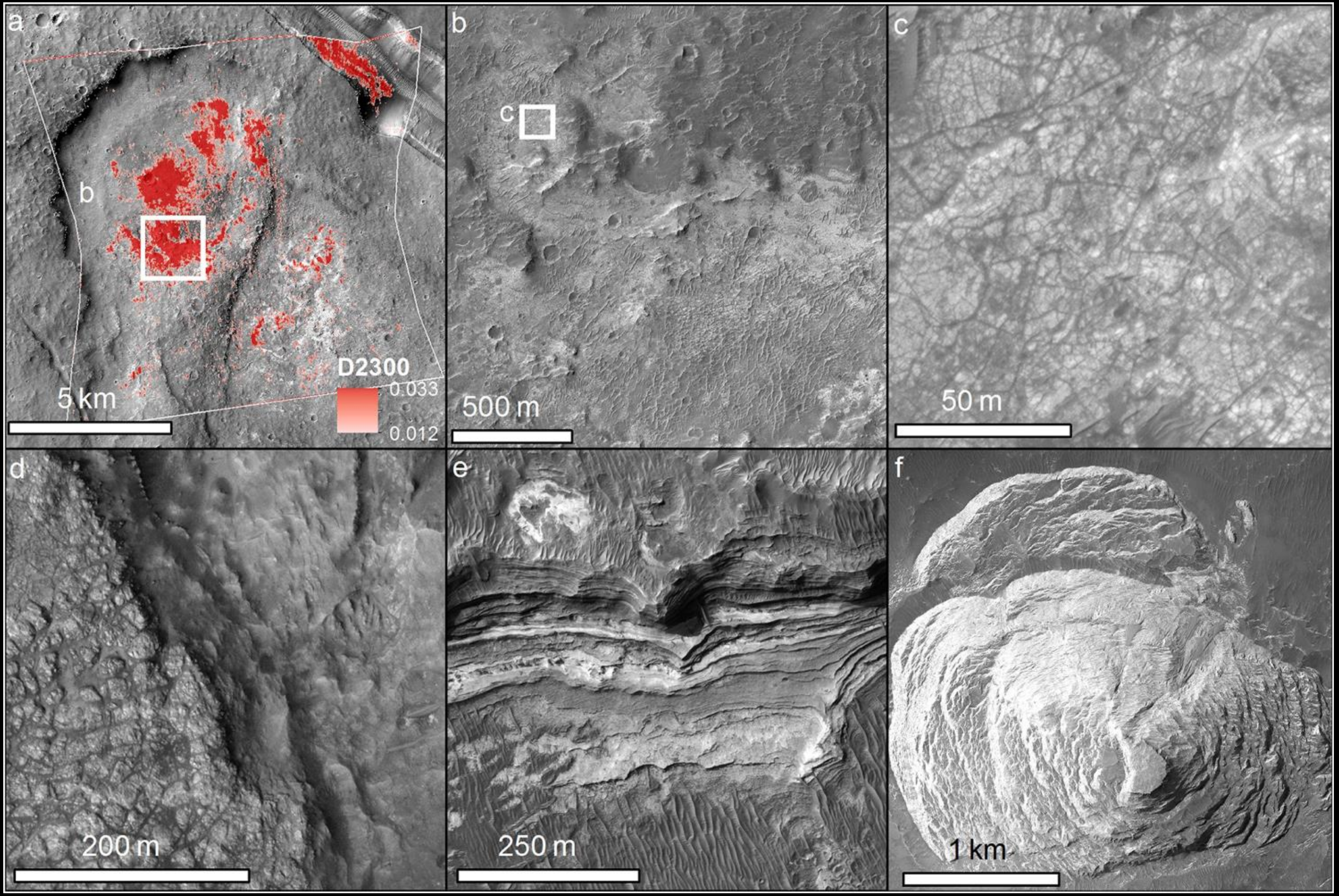
- Most valley networks appear to have formed in the mid-late Noachian, into the Hesparian
- The density of valley networks at low (tropical) latitudes suggests that they are the result of precipitation runoff, though groundwater is suggested for some younger ones



Hynek, B. M., Beach, M., & Hoke, M. R. (2010). Updated global map of Martian valley networks and implications for climate and hydrologic processes. Journal of Geophysical Research: Planets, 115(E9).

Clay Minerals

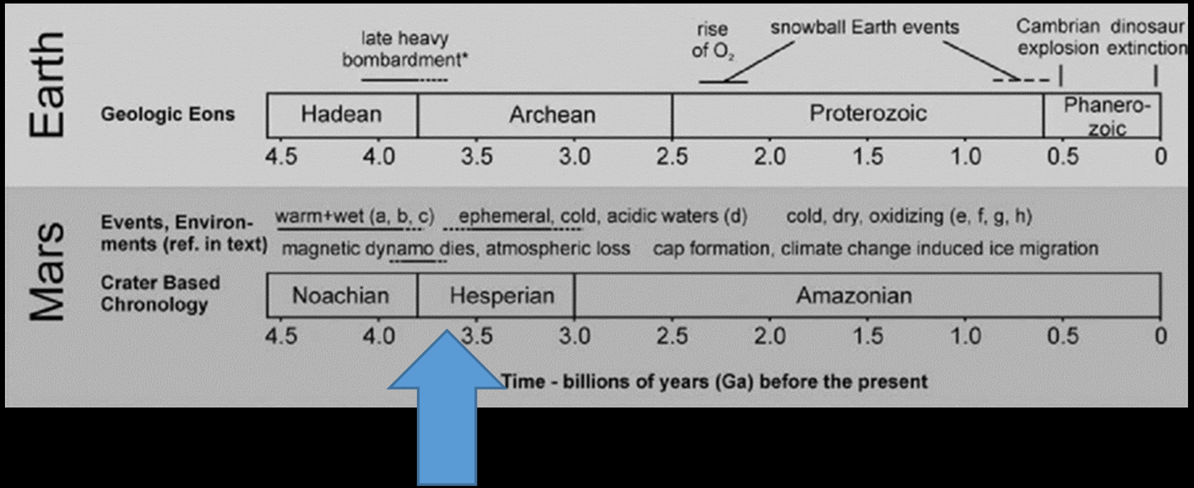
- ***Phyllosilicates***, and more specifically, ***clay minerals*** typically only form in environments with relatively neutral pH water
- Evidence of phyllosilicates in Noachian-aged rock at the Martian surface suggest that this rock was exposed to water shortly after it formed



Spectral and morphological characteristics of clay-bearing and sulfate-bearing units. The white rectangles indicate the extent of subparts. (a) Spectral parameter D2300 from FRT00018AF5 indicates that (b) Fe/Mg clays in light-toned material in close-up Figure 4b were exposed from beneath darker material (Ladon basin, −20.95°E, −2.95°N, base image CTX B21_017739_1771_XN_02S021W). (c) HiRISE ESP_017739_1770 shows this deposit to be densely fractured. (d) Indistinct, (e) distinct and light/dark, and (f) larger-scale and distinct layering in clay-bearing crater floor material at −20.5°E, −5.9°N (HiRISE ESP_012715_1740) (Figure 4d); a clay-bearing scarp in Ladon Valles (HiRISE PSP_008931_1590) (Figure 4e); and a sulfate-bearing ILD in Aurorae chaos (HiRISE PSP_007415_1730) (Figure 4f).

Thomas, R. J., Hynek, B. M., Osterloo, M. M., & Kierein-Young, K. S. (2017). Widespread exposure of Noachian phyllosilicates in the Margaritifer region of Mars: Implications for paleohydrology and astrobiological detection. Journal of Geophysical Research: Planets

Hesperian Mars



- ~3.7-3.0 Ga
- **Outflow Channels**
  - Appear to have formed rapidly, from catastrophic flooding
- **Surface water likely became scarcer and more acidic from volcanic outgassing**
  - **Sulfates** begin to form in large quantities
- **Valles Marineres forms** and begins to erode

Outflow Channels

- Many appear to form from huge amounts of groundwater erupting onto the surface (probably not lava)
- Very different from valley networks- most contain few large channels originating from “chaotic terrain”
- Many channels seem to originate around volcanic centers and empty into basins

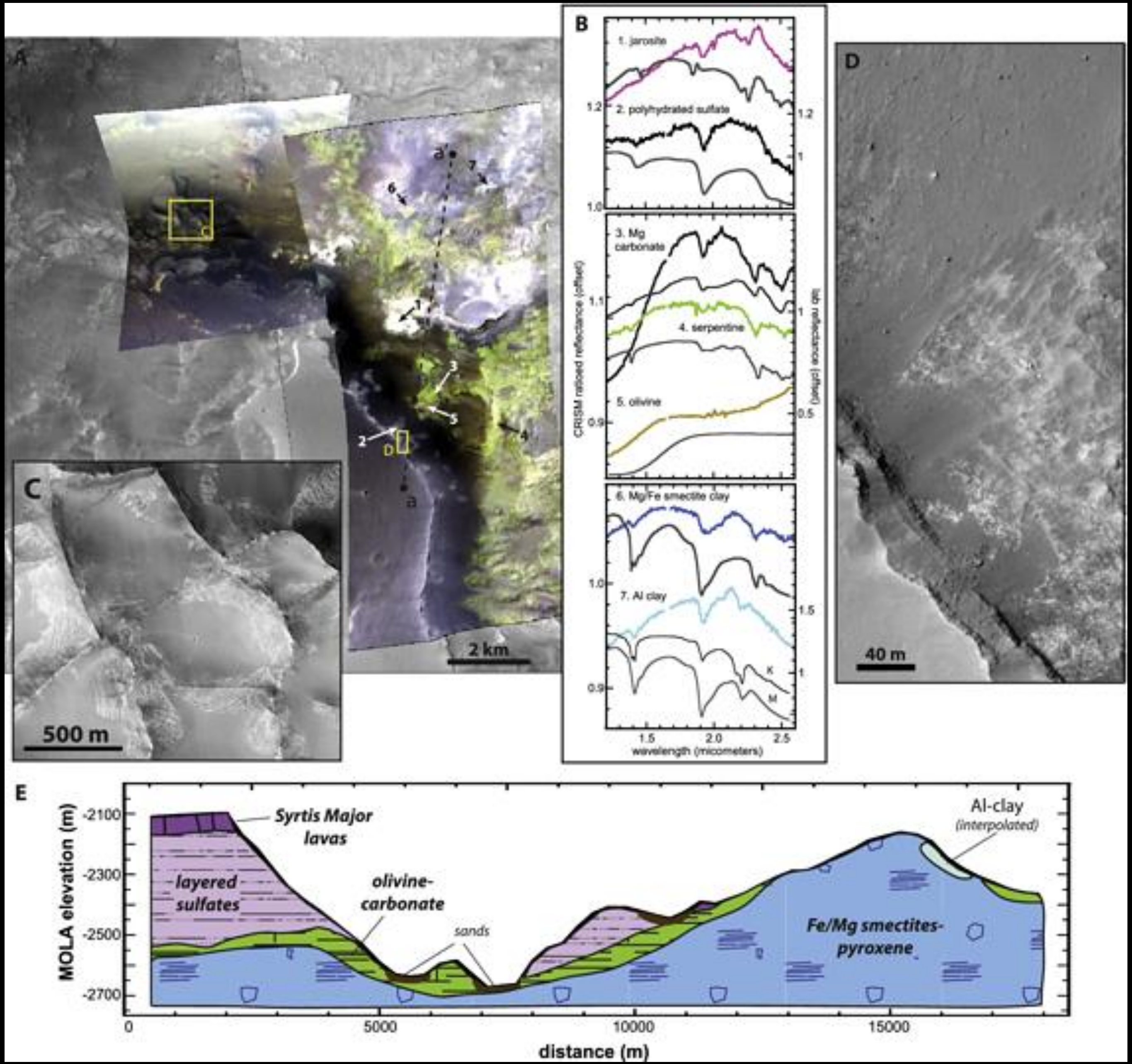
Kasei Vallis (25° N, 300° E), the largest outflow channel on the planet, emerges from a shallow north–south canyon to the west of the scene shown here. To the east, the channel extends deep into the northern plains.

Carr, M. H. (2012). The fluvial history of Mars. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences

Ravi Vallis (1° S, 316° E), like several other channels in the south Chryse region, emerges from a rubble-filled depression. The floor of the depression is 1.5 km below the outlet. The channel is thought to have formed by an eruption of groundwater.

Sulfate Formation

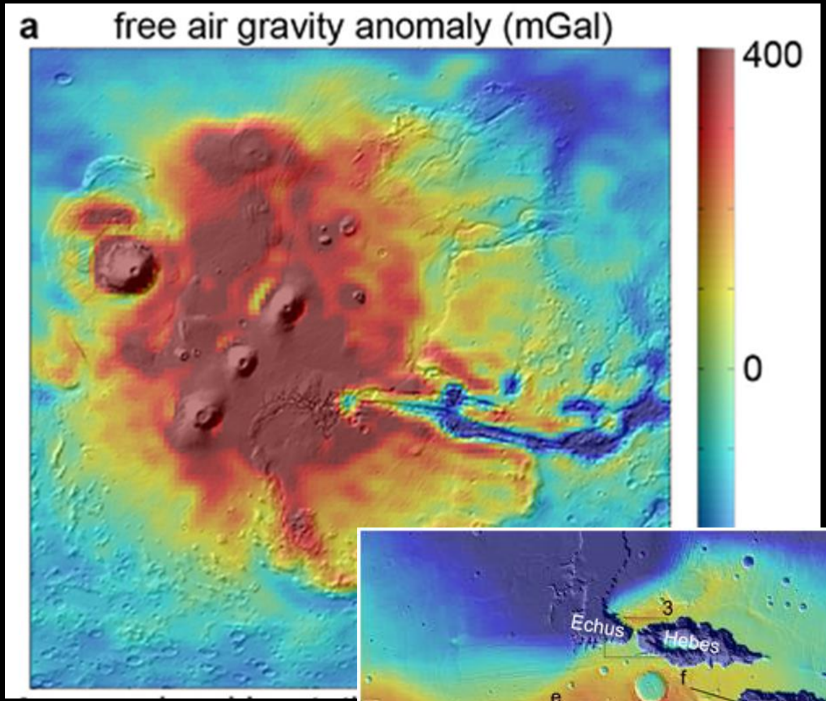
- Sulfates (jarosite, gypsum) are identified stratigraphically on top of (younger) than Noachian weathered basalts
- Highly oxidizing, acidic conditions- playa?
- Global transition to more acidic environment

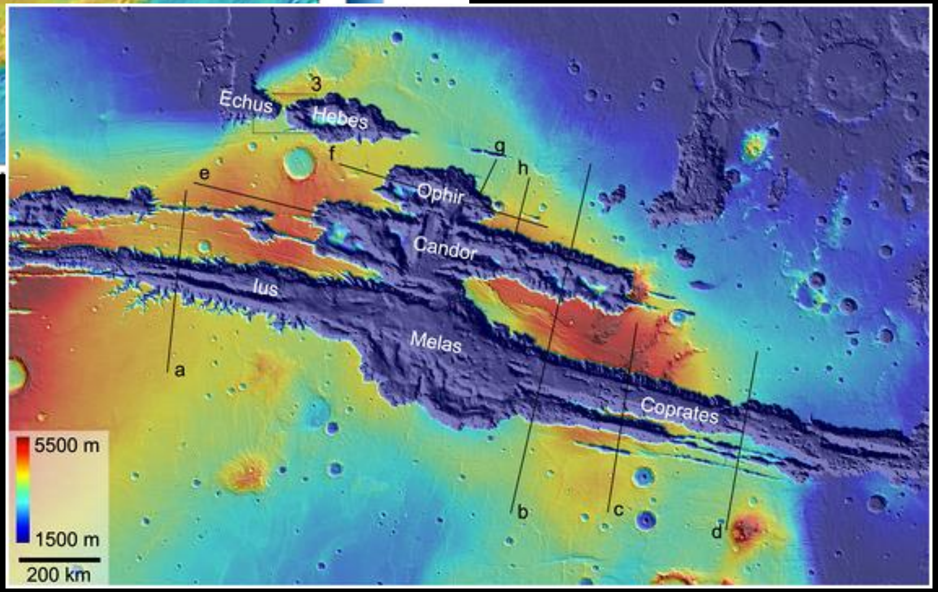


Sulfates exposed near the NE Syrtis scarp. (a) False-color CRISM images (HRL0000B8C2, FRT000128D0) at the northern extent of the Syrtis Major lava flows (purple in Figure 2a) are overlain on CTX images. (b) Sulfates (bright white in Figure 2a), including jarosite and a polyhydrated phase, are identified in B8C2 by comparison to laboratory data and overlie a Noachian olivine-rich unit (green in Figure 2a), which has been variably altered to Mg carbonate and serpentine [Ehlmann et al., 2008a, 2010]. This in turn overlies a basement unit with Mg-rich smectites and Al-clays (cyan to white in Figure 2a). (c) In some locations, sulfate-bearing materials exhibit a ridged, box-like structure upon erosion, interpreted to represent exhumed, mineralized conduits of subsurface fluids (subset of ESP_013041_1975). (d) A tens-of-meter-thick, coherent Syrtis Major lava unit that sheds boulders overlies the sulfate-bearing unit. Boulder trails are visible at upper left in this subset of HiRISE PSP_009217_1975. (e) MOLA point shot data profile a-a' shows contacts between the stratigraphic units are unconformable with superposition of later units on pre-existing topography.

An in-situ record of major environmental transitions on early Mars at Northeast Syrtis Major Geophysical Research Letters, Volume: 39, Issue: 11, First published: 06 June 2012, DOI: (10.1029/2012GL051594)

Valles Marineris- Largest Canyon in the Solar System

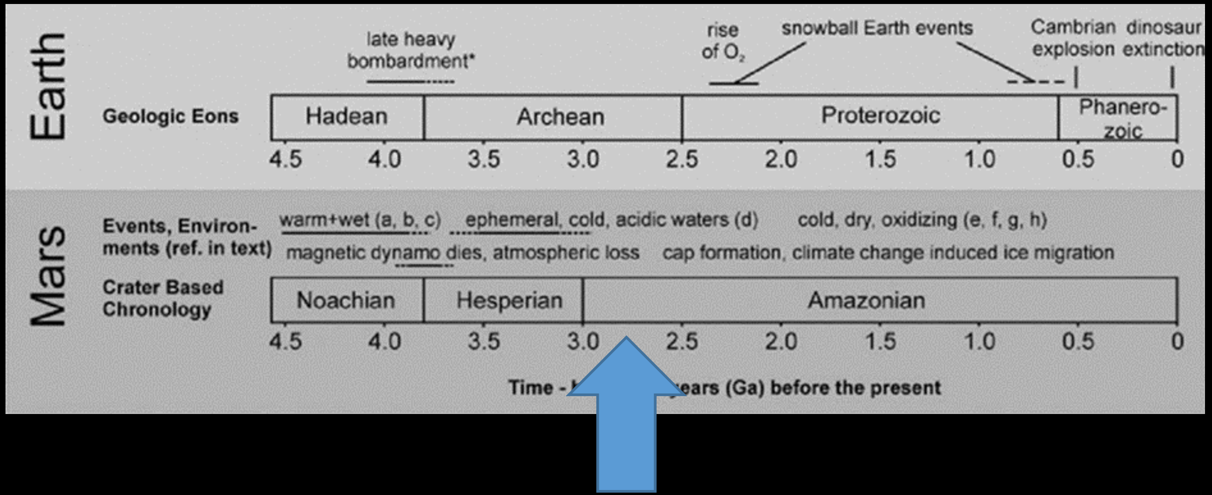




Andrews-Hanna, J. C. (2012). The formation of Valles Marineris: 1,2. Tectonic architecture and the relative roles of extension and subsidence. Journal of Geophysical Research: Planets, 117(E3).

- Opened up as the crust was stretched, as *Tharsis* rose up
- Likely formed along the *crustal dichotomy* because this was an area of weakness
- Tectonism continued into the Amazonian with ongoing volcanism

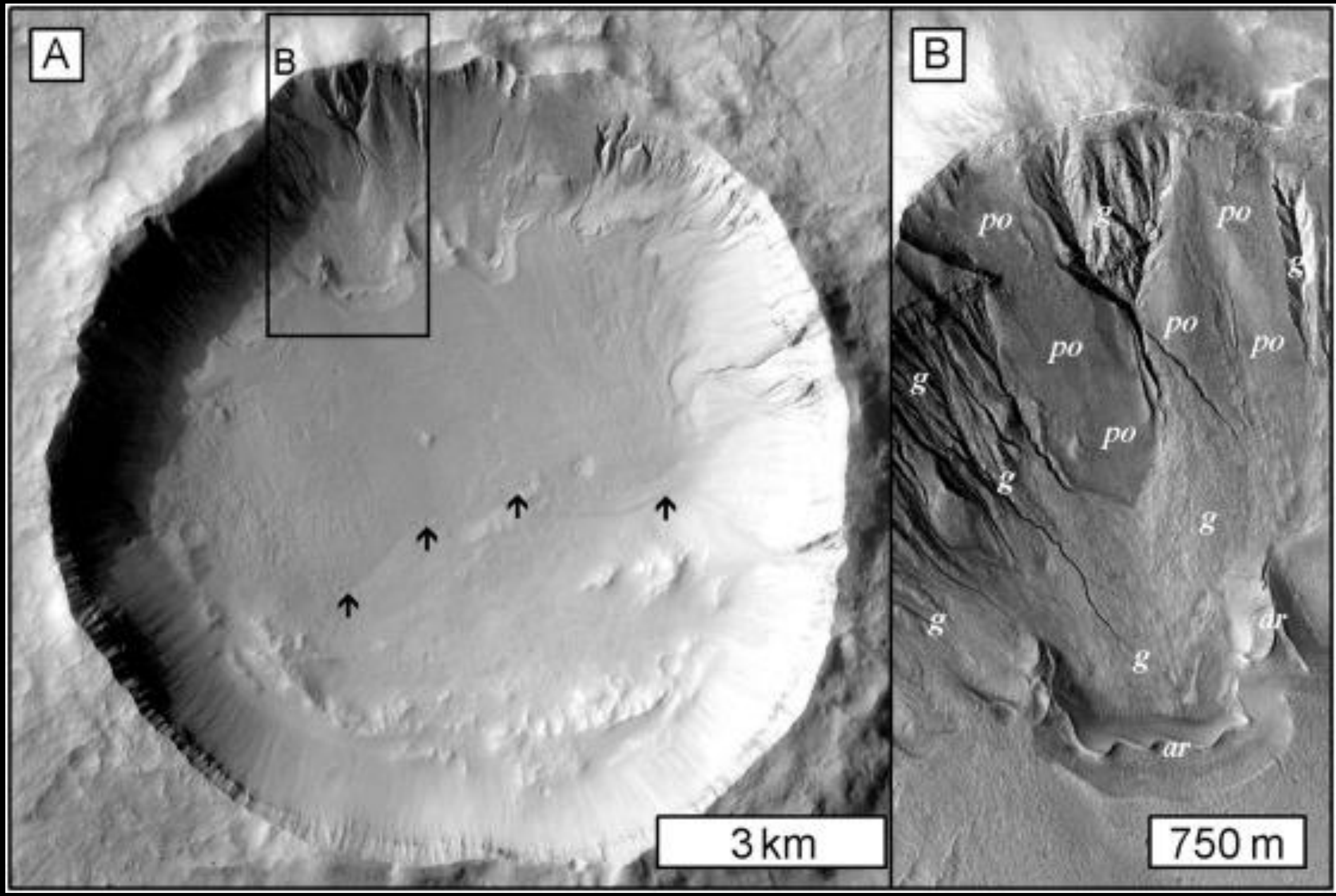
Amazonian Mars



- ~3.0 Ga- present
- Planet has become increasingly dry, arid and cold
  - Water escaped to space or soaked into the ground?
- Volcanism continues, but decreases over time
  - Tharsis and Olympus Mons continue to grow
- Gullies could be formed from small amounts of flowing water/brine
- Glaciers and ice are the dominant drivers of resurfacing

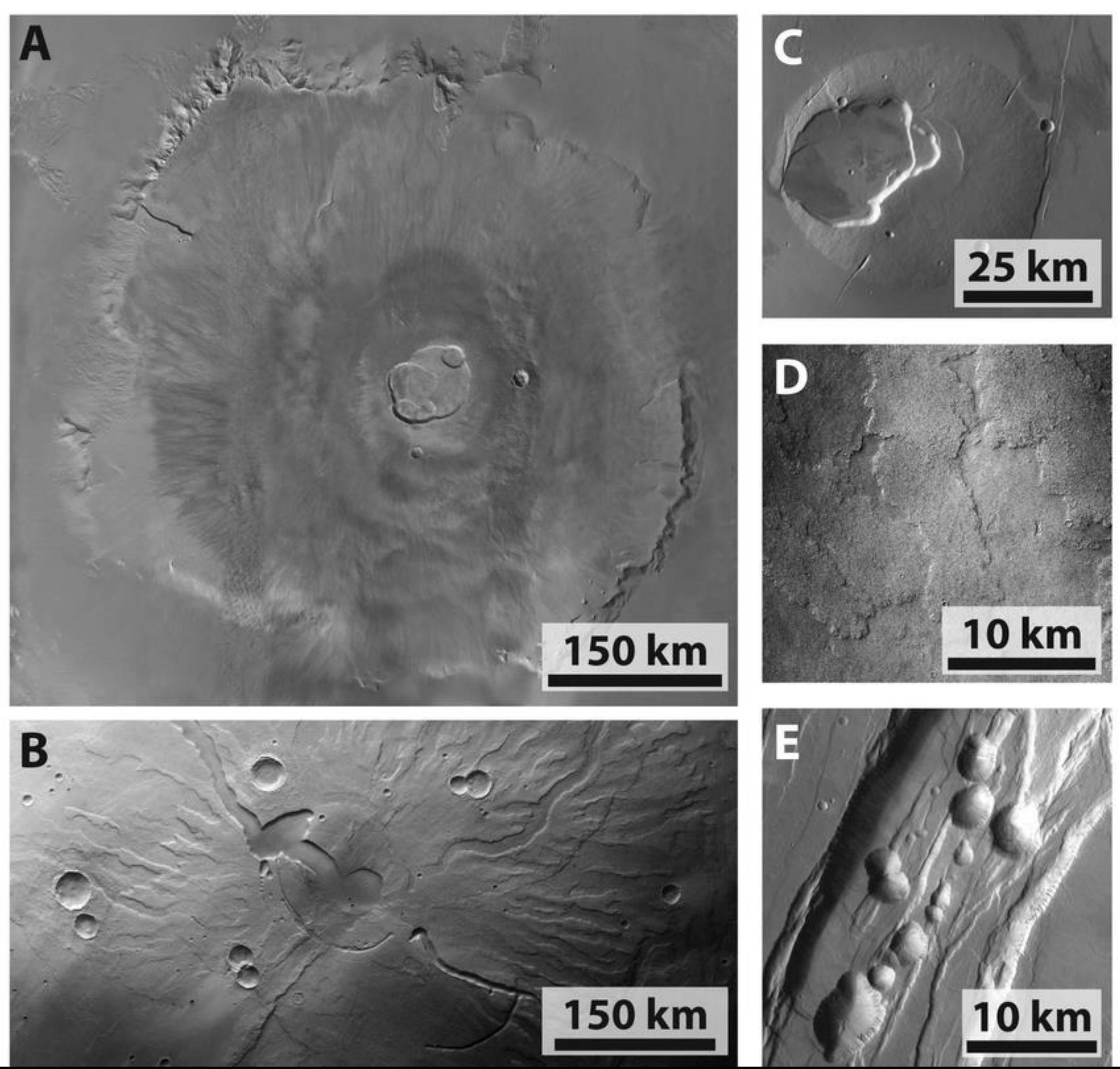
Martian Glaciers

- A lot of surface-ice interaction occurred on Mars in the last few hundred Ma
- Sediment morphology and debris flows appear to support recent glacial activity and mass movement at the surface
- Erosion of crater walls and bedrock is associated with sediment deposits resembling glacial till and other landforms



Niquero Crater on Mars, an example with a crater interior ice deposit, arcuate ridges, pasted-on terrain and gullies.

Conway, S. J., Butcher, F. E., de Haas, T., Deijns, A. A., Grindrod, P. M., & Davis, J. M. (2018). Glacial and gully erosion on Mars: A terrestrial perspective. Geomorphology, 318, 26-57.



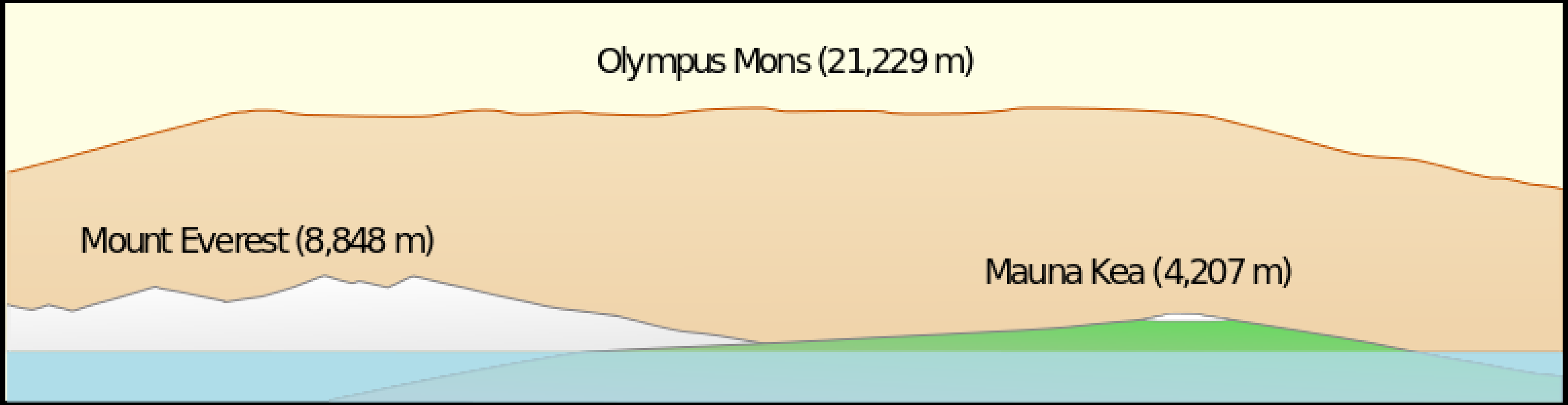
Young Volcanics

- The last evidence of volcanism on Mars is inconclusive, but it is likely that volcanoes have erupted very late in the Amazonian
- Fumaroles (volcanic gas and steam vents) may still be operating on the surface- perhaps the best chance for life!

Samples of volcanic landforms, deposits and terrains on Mars. A. Volcanic shields: Olympus Mons (MEX HRSC nadir mosaic, courtesy A. Dumke) B. Highland Pateras: Tyrrhena Patera, nearby Hellas Basin (MEX HRSC nadir from orbit 1920) C. Examples of Tholus on Mars (MEX HRSC nadir from orbit 2983) D. Lava flow on the flanks of Arsia Mons (MRO CTX P17 007484 1657 XN 14S117W) E. Pit chains over extensional grabens (MRO CTX P17 007813 2132 XN 33N106W).

Rossi, A. P., & Van Gasselt, S. (2010). Geology of Mars after the first 40 years of exploration. Research in Astronomy and Astrophysics, 10(7), 621.

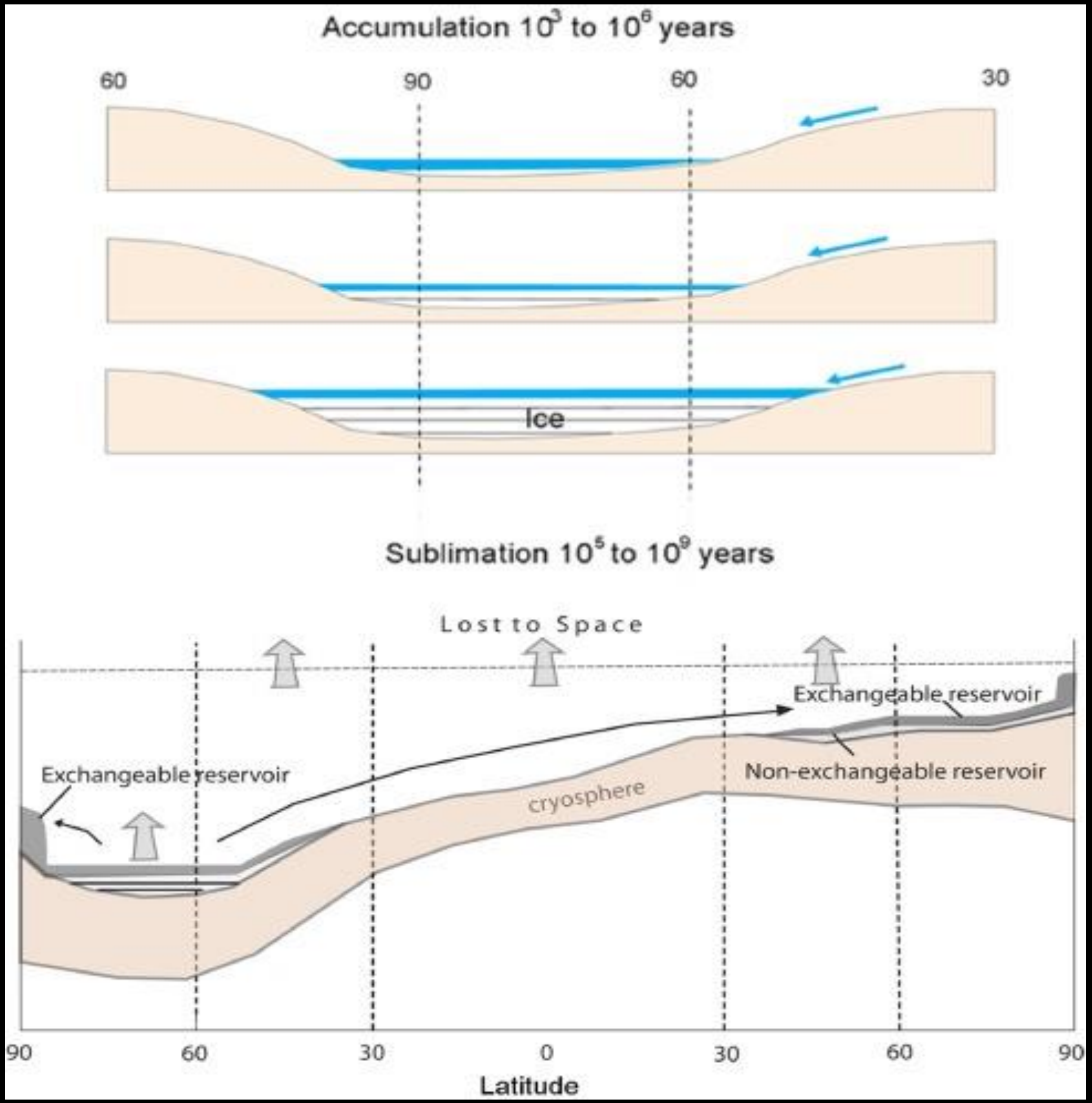
Olympus Mons



- Largest volcano in the Solar System- likely still active (somewhat)
- Started forming earlier, but continued to build and erupt into the Amazonian

Carr, M., & Head, J. (2019). Mars: Formation and fate of a frozen Hesperian ocean. Icarus, 319, 433-443.

Mars Water Today



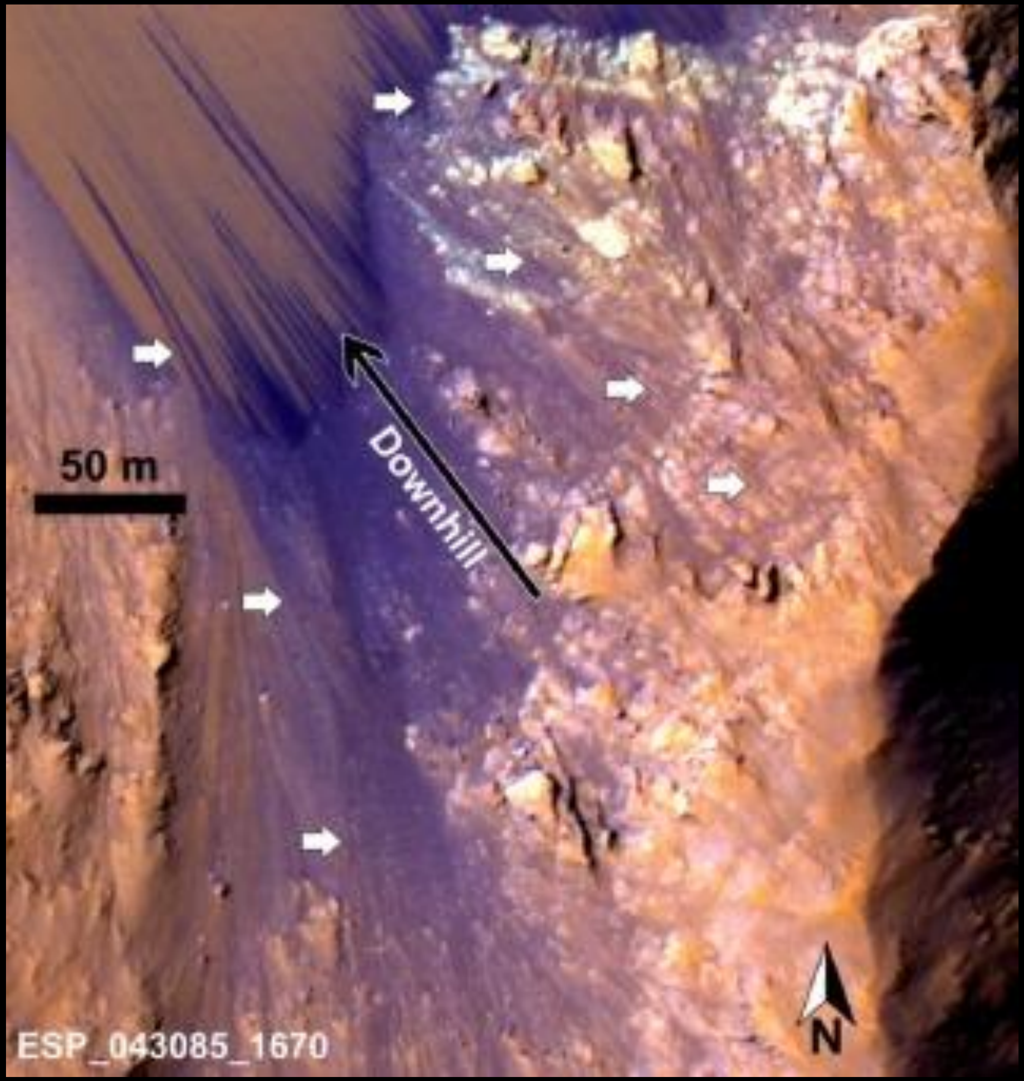
Top: Floods that cut the large outflow channels enter the northern basin and form temporary lakes that rapidly freeze. Successive floods build a sequence of ice layers up to the −3650 contour which marks the edge of the last large flood. Bottom: After the flooding era the ice slowly sublimates, some being lost to space and some being redistributed to form the polar layered deposits and other near-surface ice deposits.

- *Liquid* water is **not stable** at the surface
- Water evaporates, and is concentrated at the **poles**
  - Some water is lost to space- ***sputtering***
- Data suggest that large stores of H_2O may be in the shallow subsurface

Gullies and Recurring Slope Lineae (RSL)

Stillman, D. E., Michaels, T. I., & Grimm, R. E. (2017). Characteristics of the numerous and widespread recurring slope lineae (RSL) in Valles Marineris, Mars. Icarus, 285

- Recurring slope lineae (RSL) narrow, (0.5–5 m) dark features that appear on steep slopes, fade in colder seasons, and *recur* annually
- Can be formed by **liquid flows** occurring in warm seasons
  - Saltwater brine- not pure water
  - Could be *dry debris flows*, not related to water

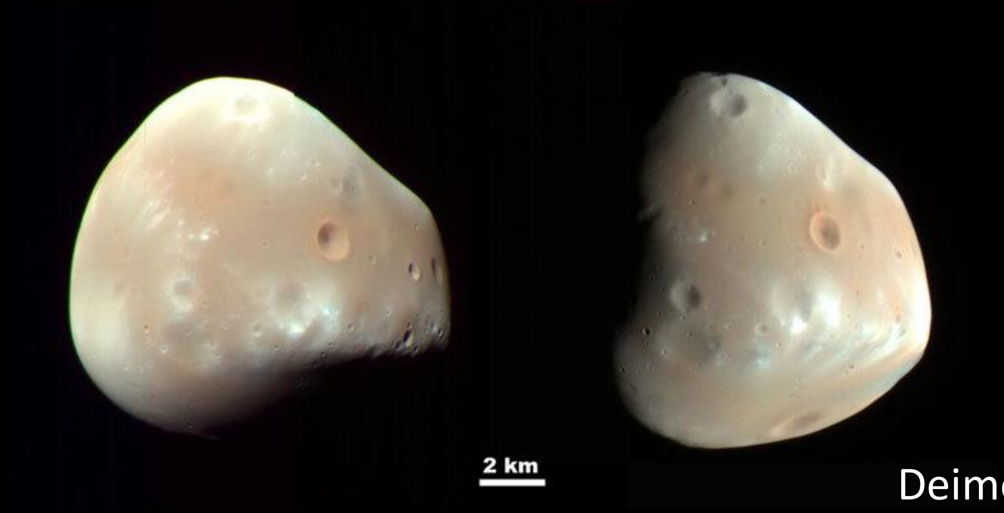


Typical spur-and-gully VM RSL. These RSL (purple in false color; white arrows point to two RSL) start just below bedrock, then tributaries merge and the flow continue into the distal sand fan.

Martian Moons

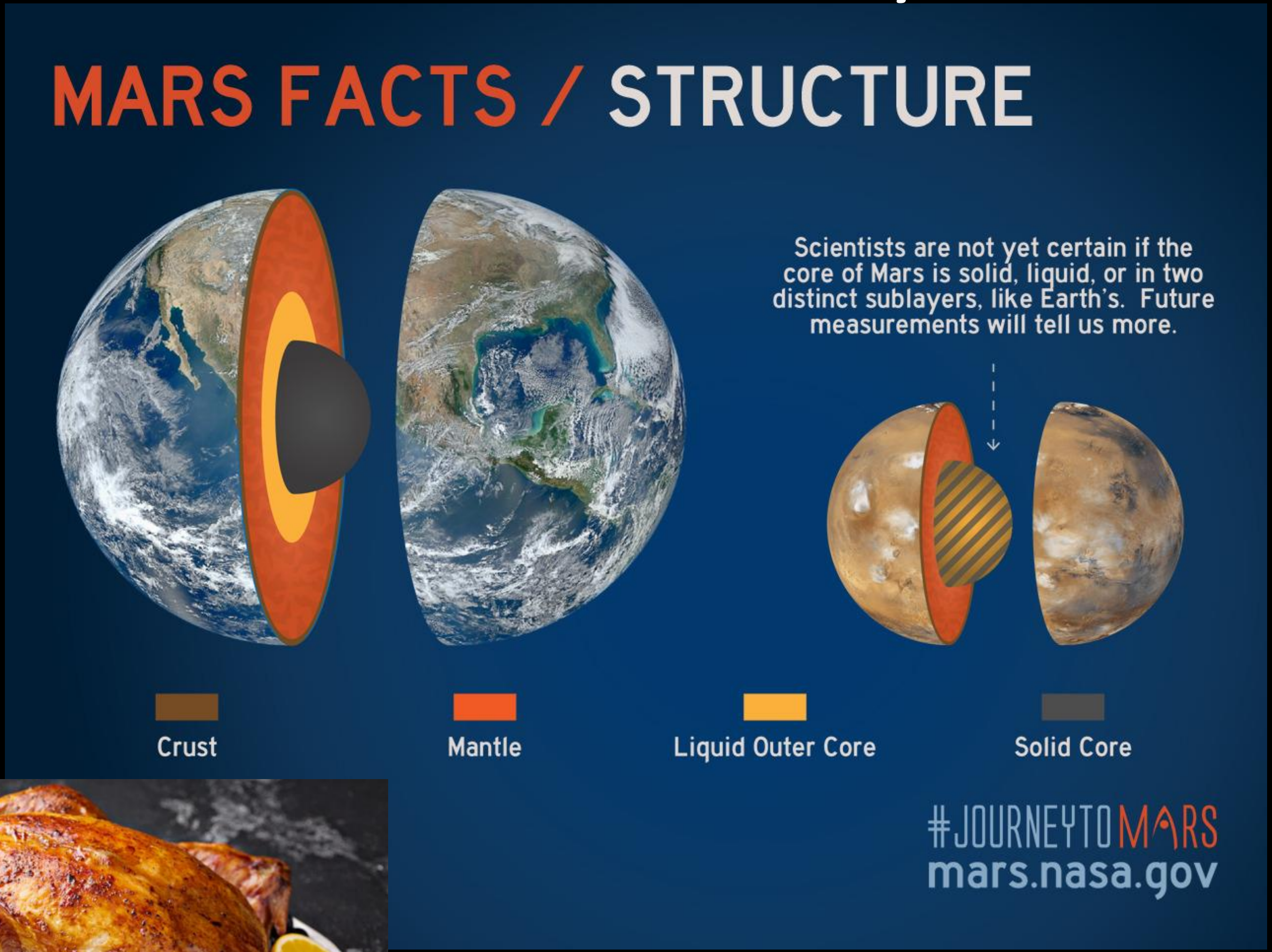
- Phobos and Deimos are the two tiny (27/15 km) moons in orbit of Mars
- Discovered in 1877, originally thought to be asteroids captured during the Amazonian
- However- very close, near-circular equatorial orbits favor an impact-genesis theory, similar to Earth's Moon

Phobos



Deimos

Mars vs. Earth- Why so Different?



- Earth and Mars formed around the same time, from the same stuff, but evolved very differently
- Mars is much **smaller** than the Earth is- therefore it took less time for it to **cool off internally**
- Earth's size also means it has a stronger **gravitational field-** and more able to retain its atmosphere and hydrosphere

Earth is like a big turkey, to Mars' Cornish hen- it will stay hotter longer after you take it out of the oven.

Thanks! Questions?