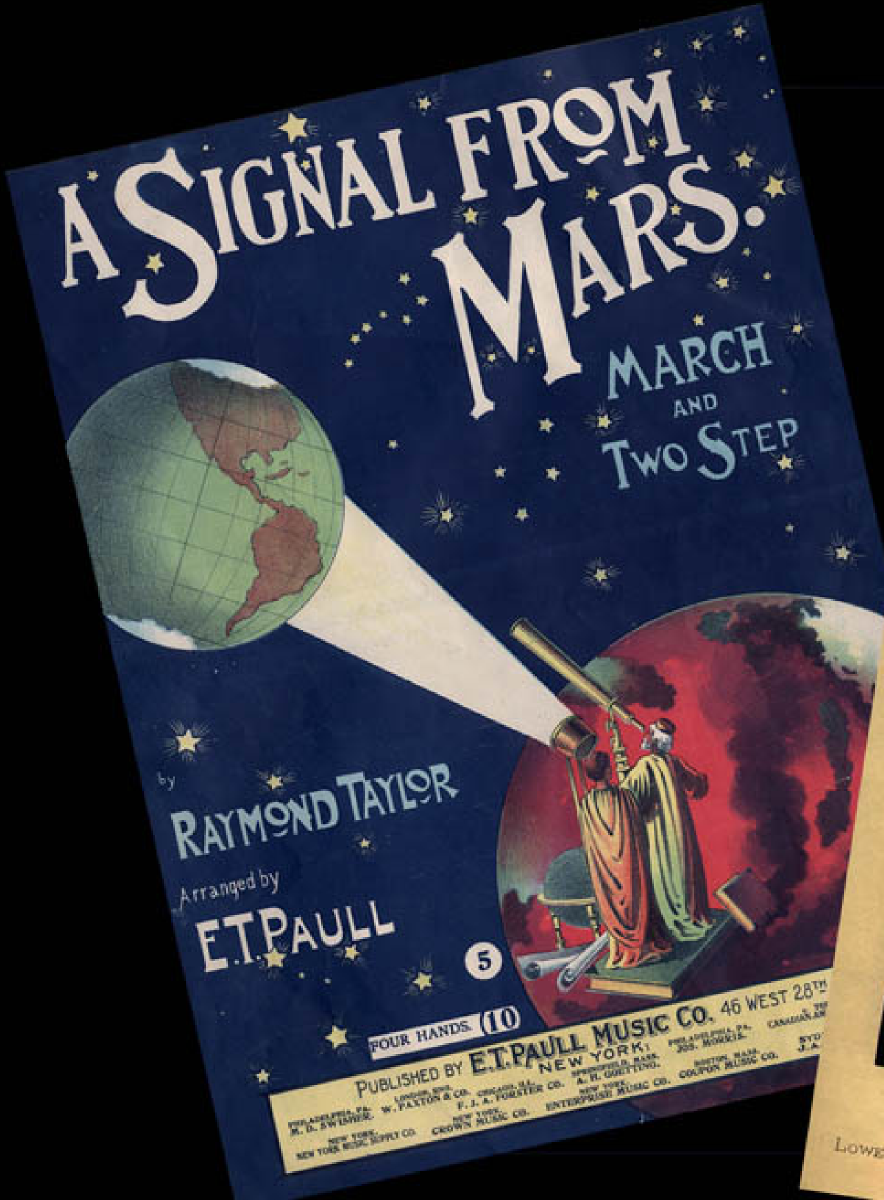
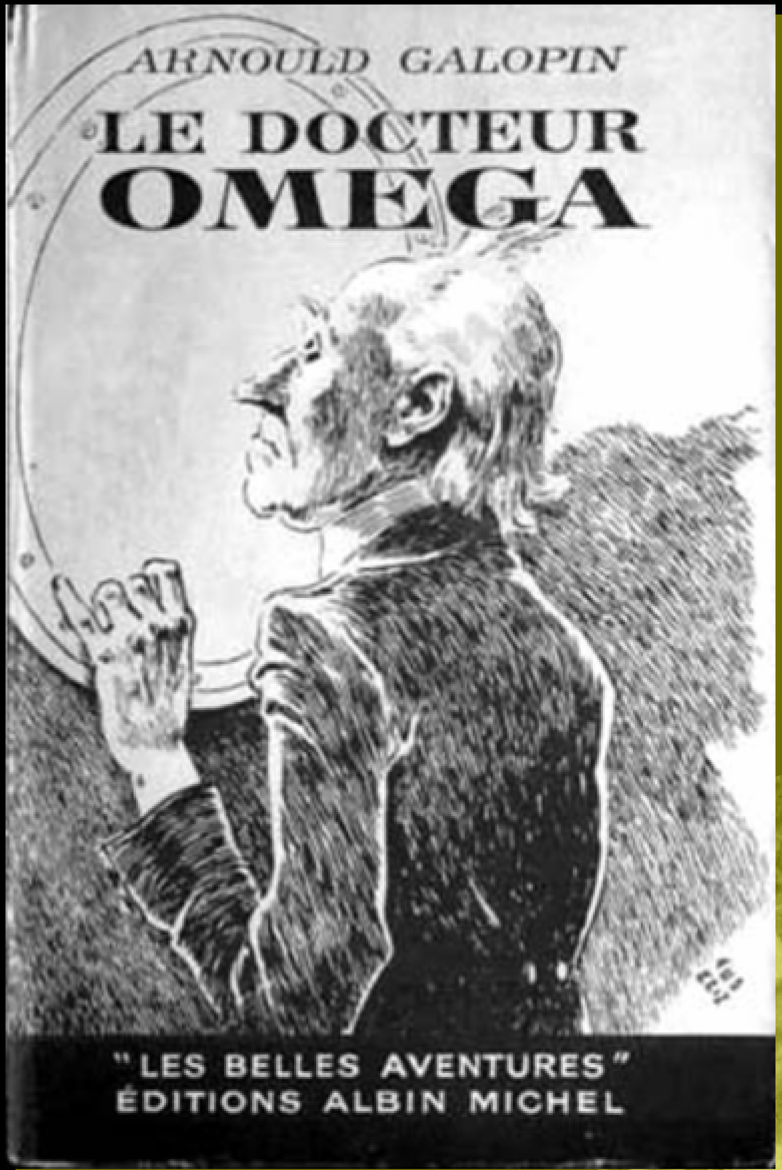
Mars:
Current State of Knowledge and Outstanding Questions

Jack Mustard, *Brown University*

Presentation to the Mars 3


A SIGNAL FROM MARS.
MARCH AND TWO STEP
by
RAYMOND TAYLOR
Arranged by
E.T. PAULL
5
FOUR HANDS. (10)
E.T. PAULL MUSIC CO. 46 WEST 28TH
NEW YORK.
PUBLISHED BY


June 16 & 19
June 1
Oct. 14, 16, 17 & 19
Nov. 5
Oct. 21
Nov. 18, 19 & 20
LOWELL OBSERVATORY.
1894.
SEASONAL CHANGES.
P.L.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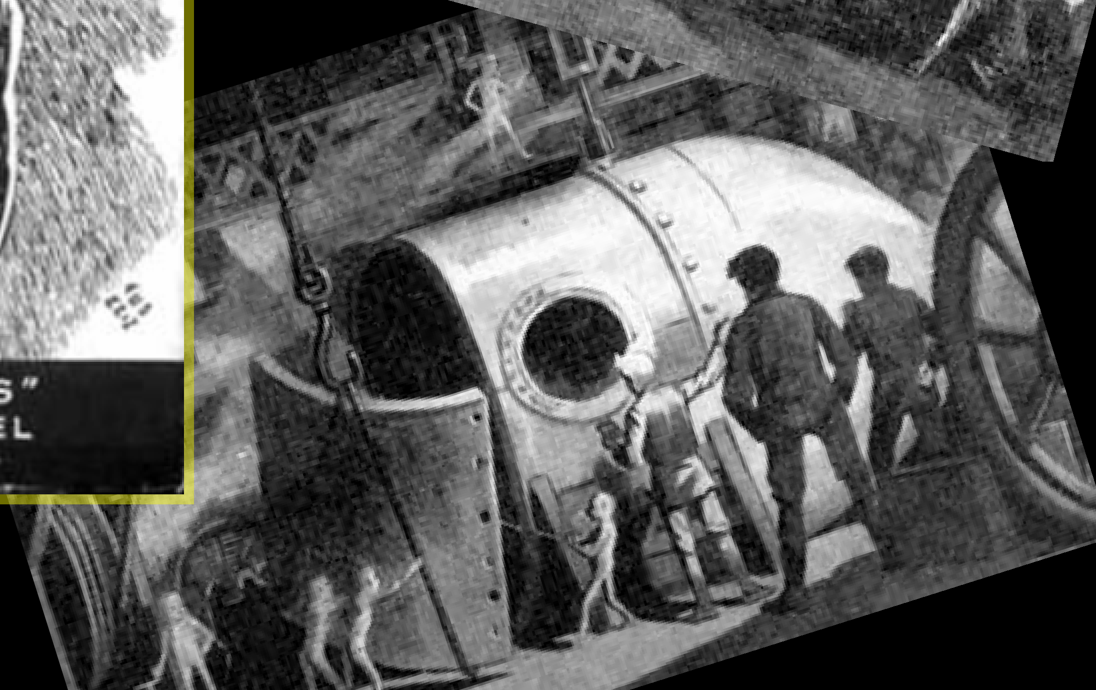
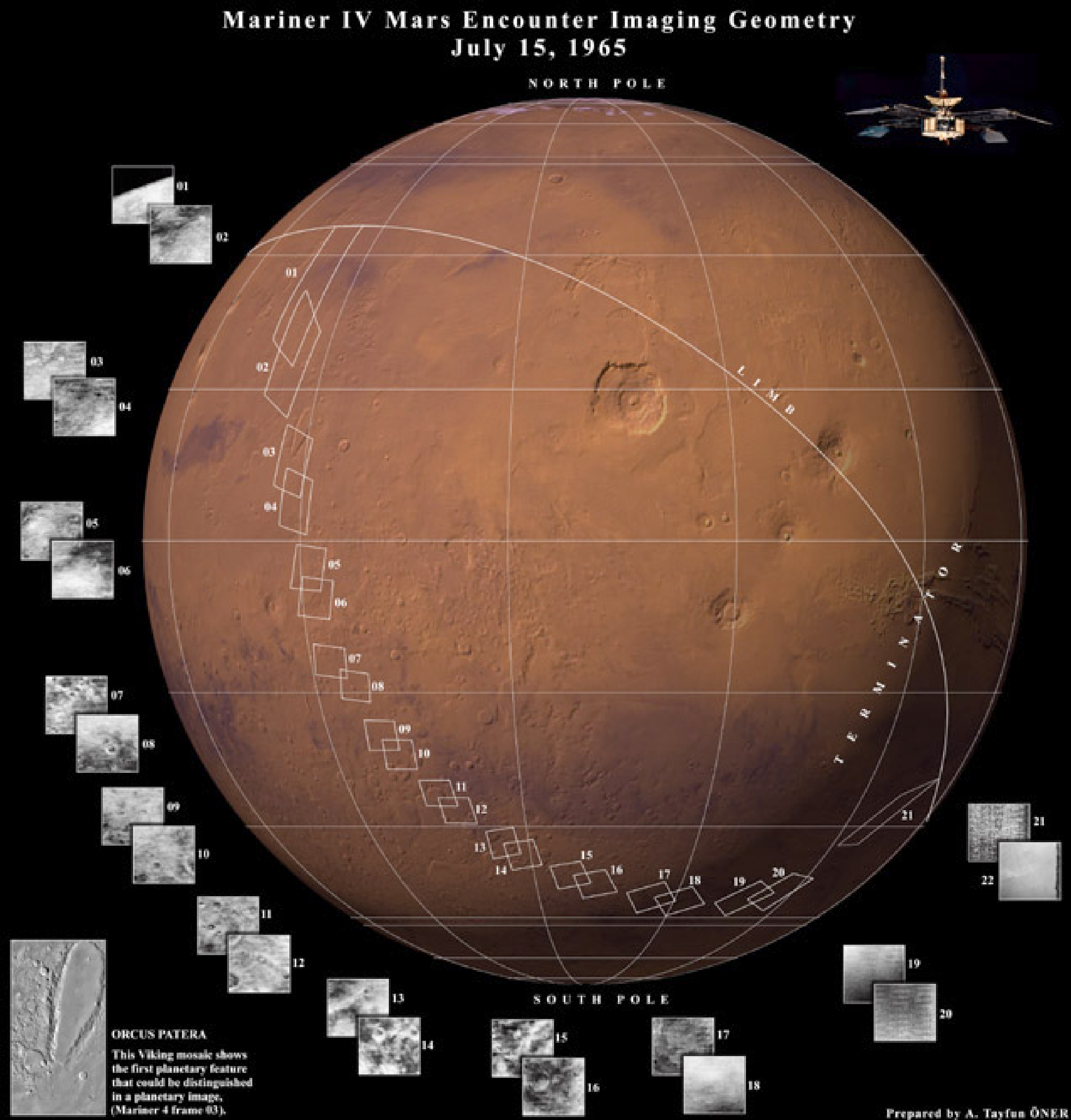
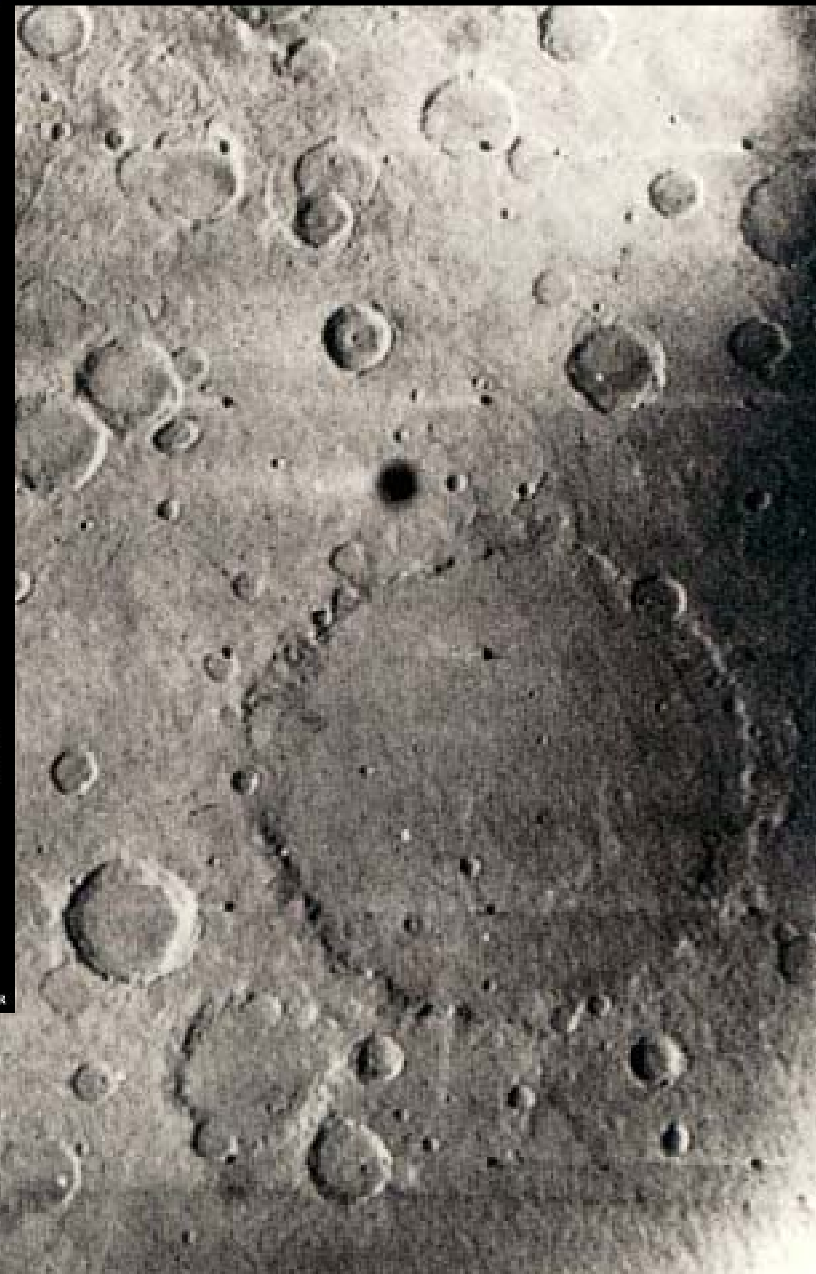
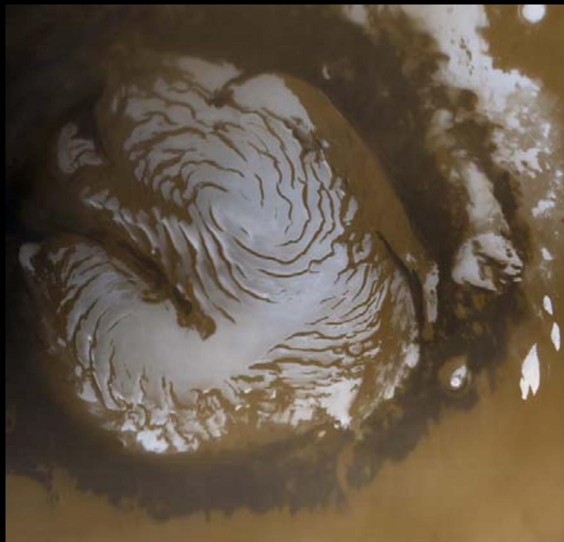
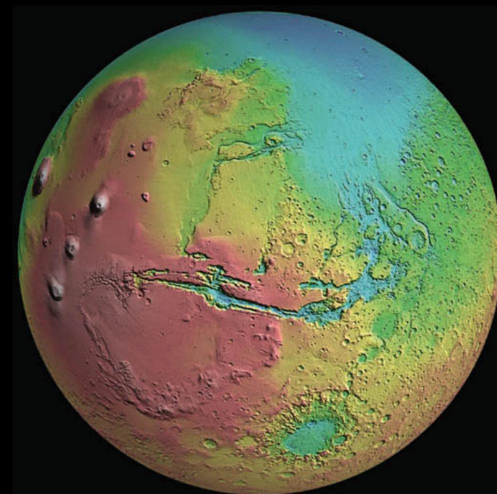


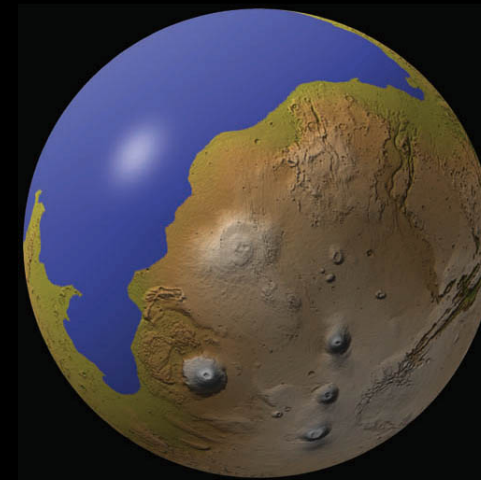
Mariner 4, 6, 7

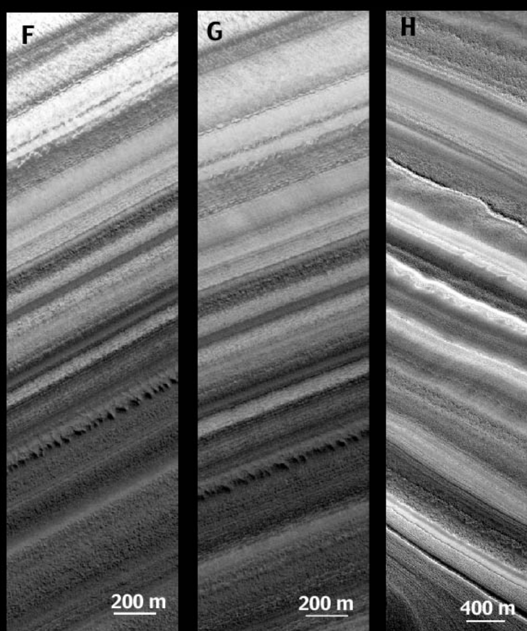

Mariner IV Mars Encounter Imaging Geometry
July 15, 1965
NORTH POLE
LIMB
TERMINATOR
SOUTH POLE
ORCUS PATERA
This Viking mosaic shows the first planetary feature that could be distinguished in a planetary image. (Mariner 4 frame 03).
Prepared by A. Tayfun ÖNER







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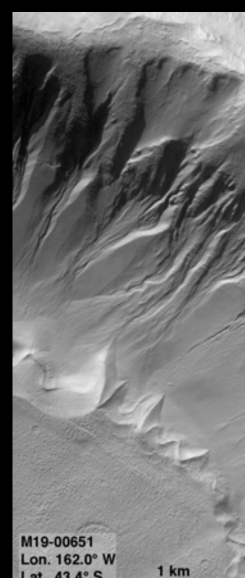
M19-00651
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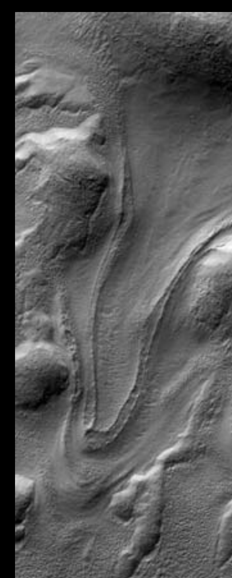
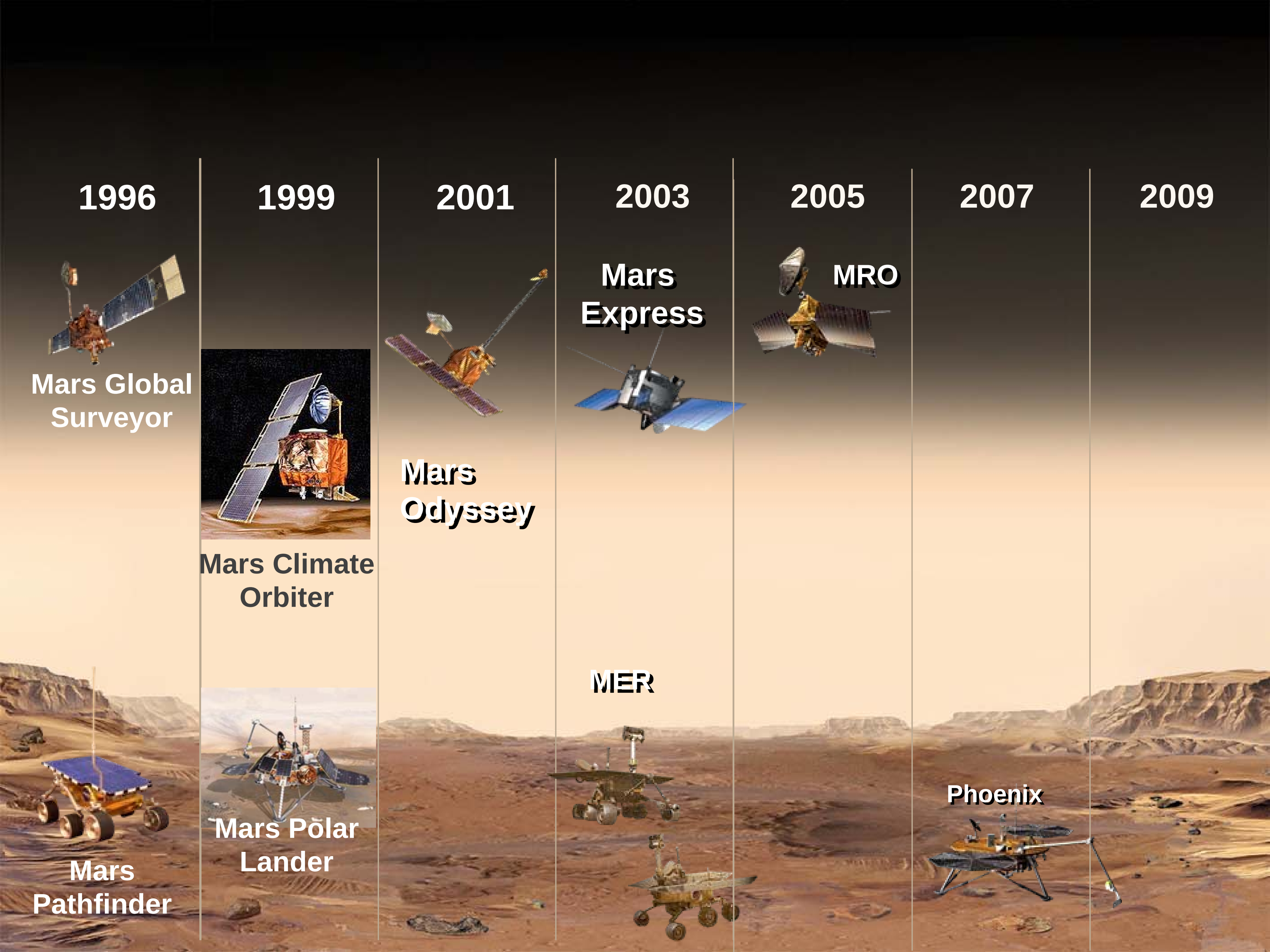
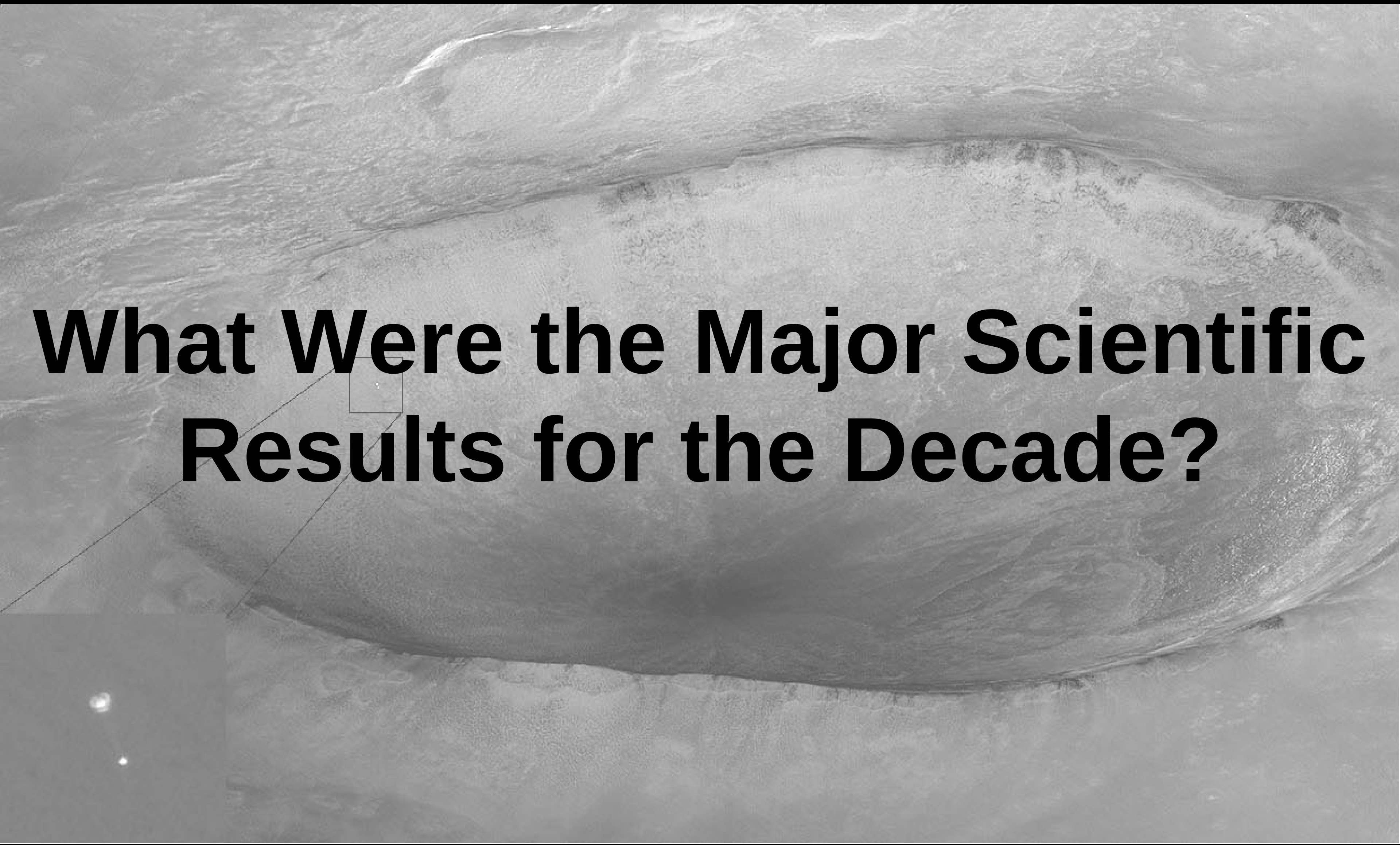


McKay, D. S.; et al. (1996). "Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH84001". Science 273 (5277): 924–930.

What Were the Big Questions a Decade Ago?

I. What are the major reservoirs of water?
II. Does liquid water exist on/near the surface or at depth?
III. What are the processes and history of climate?
IV. What is the composition of the major geologic units (elemental/mineralogic)?
V. What was the evolution of the surface and interior? What is the internal structure?
VI. Did/does Life exist?


1996
1999
2001
2003
2005
2007
2009
Mars Global Surveyor
Mars Climate Orbiter
Mars Odyssey
Mars Express
MRO
Mars Pathfinder
Mars Polar Lander
MER
Phoenix



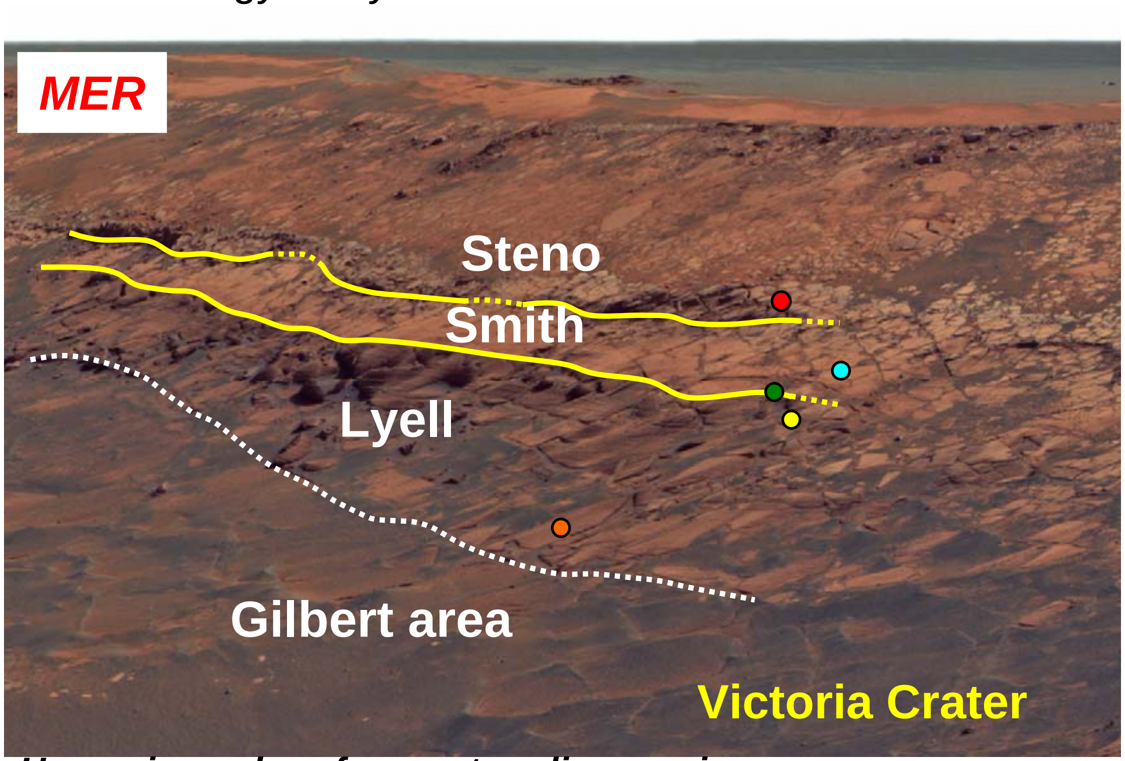
What Were the Major Scientific Results for the Decade?

Last Decade Discoveries: Diverse Planet with Complex History

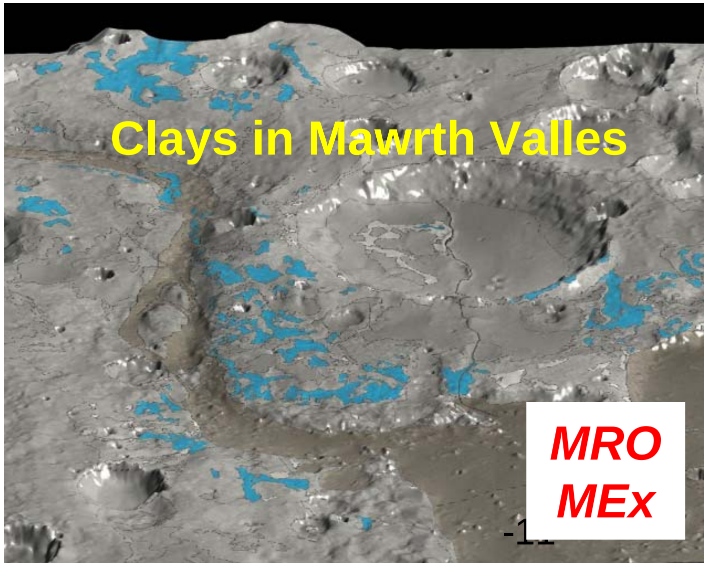
- We have made significant advances in understanding the processes and history of climate, as well as understanding the evolution of the surface.
  - Mars has areas with diverse mineralogy, including alteration by water, with a change in mineralogy over time [MGS, ODY, MER, MEX, MRO]
  - In situ confirmation of Wet (Warm?) Climate in the past [MER]
  - Pervasive water ice in globally distributed, near-surface reservoirs [ODY, MRO, MEX, PHX]
  - Sources, phase changes, and transport of volatiles (H_2O, CO_2) are known & some are quantified [MGS, MEX, MRO, PHX]
  - Increasing evidence for geologically recent climate change: stratified layers in ice and in rock [MGS, ODY, MEX, MRO]
  - Dynamic change occurring even today: landslides, new gullies, new impact craters, changing CO_2 ice cover [MGS, ODY, MEX, MRO]
  - Presence of methane indicative of active chemical processes either biogenic or abiotic [MEX and ground-based]
- Based on much of the above, the perception of *Potential for past Life* has increased, and *Modern Life* may still be possible.

Last Decade Discoveries: Diversity of Environments

- **Chemistry and morphology indicate changing environments throughout geologic history**
  - Acidic waters at Meridiani
  - Basic waters at Phoenix landing site
  - Mineralogy: clays to sulfates to oxides

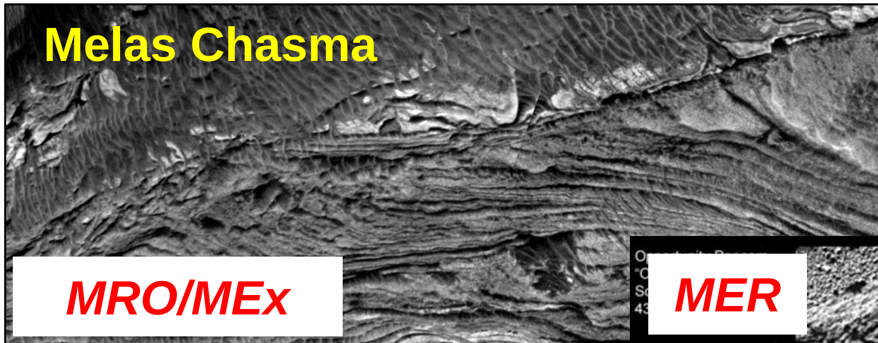


Hesperian subsurface water, diagenesis



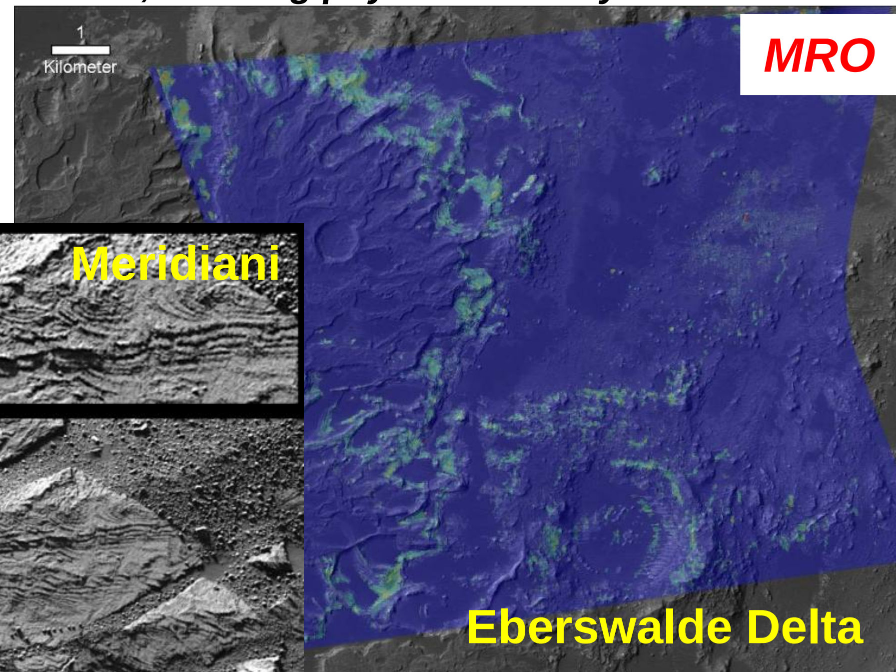
Past Decade Results:

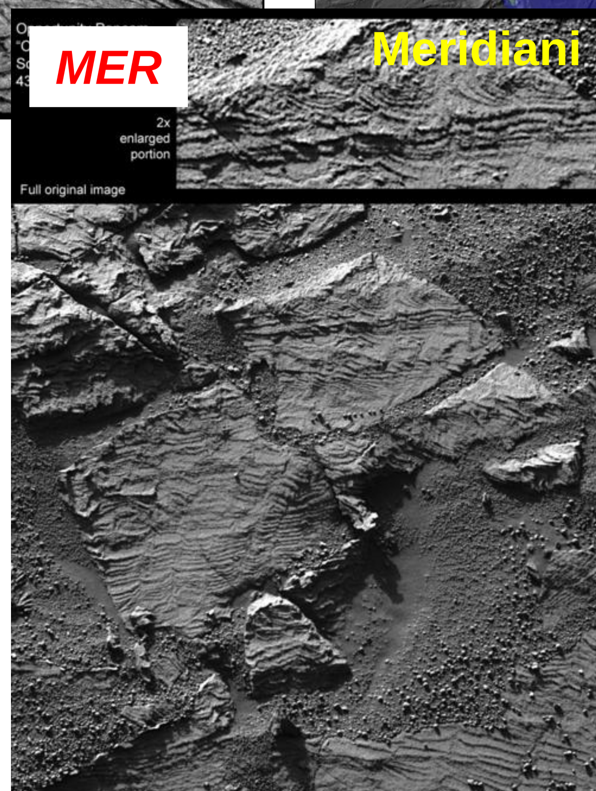
Wide variety of sedimentary deposits



Large-scale sedimentary structures

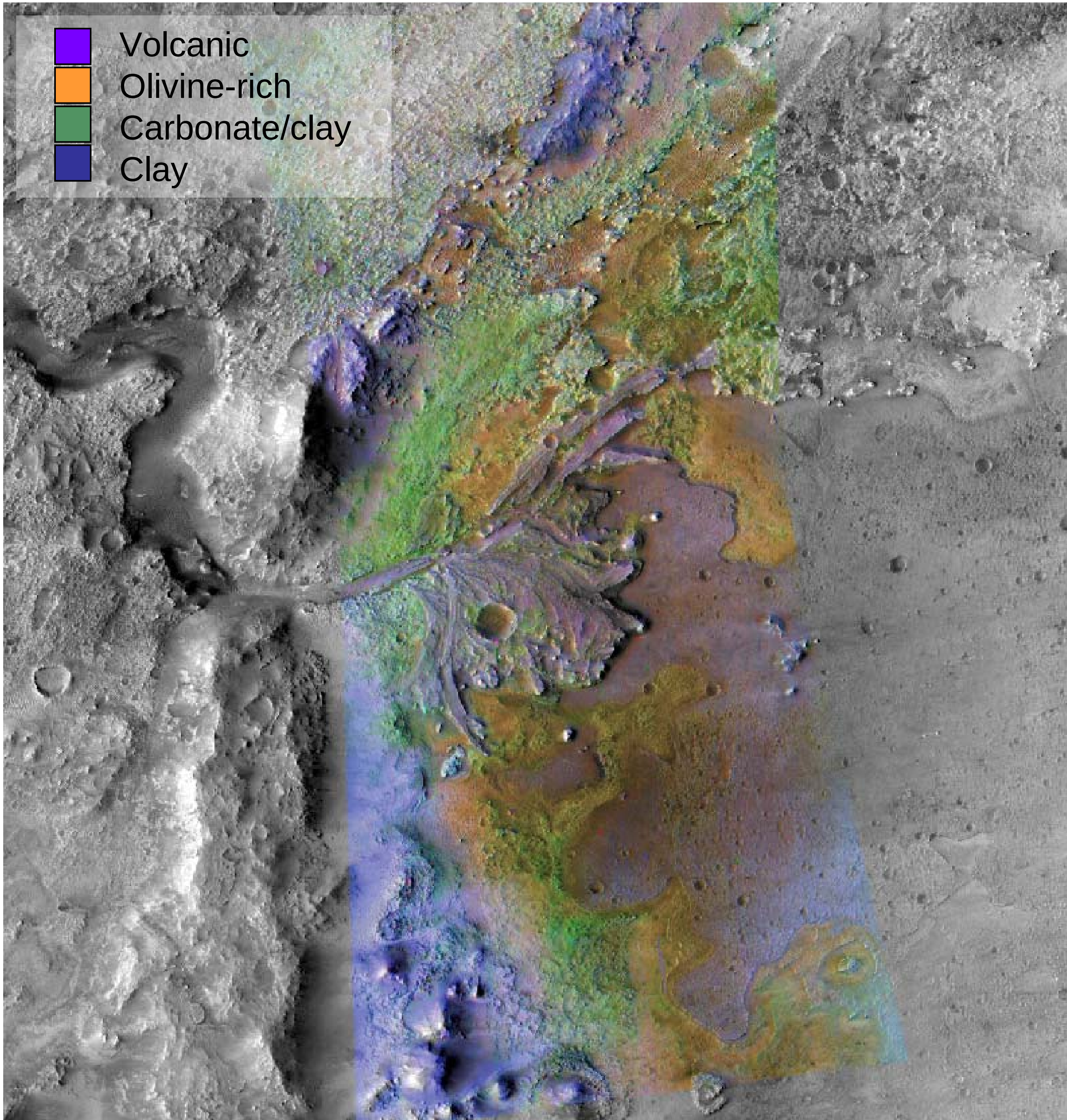
Delta, showing phyllosilicate layers



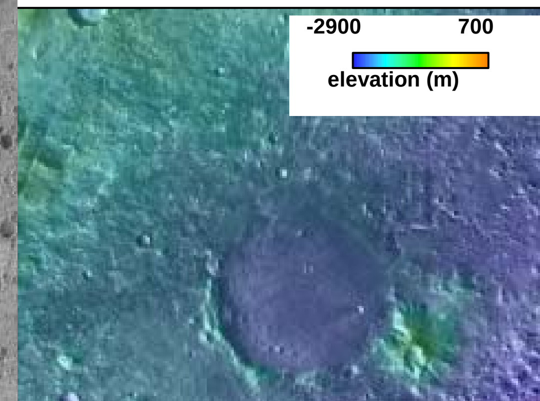


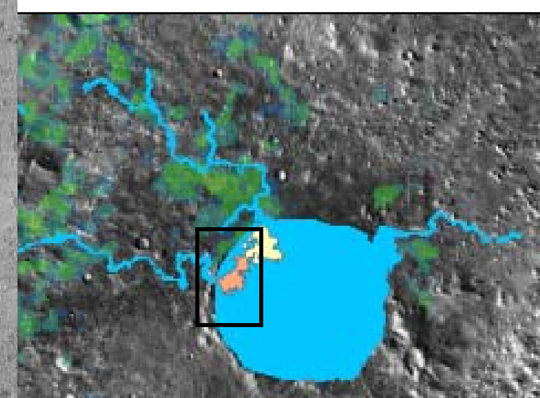
Fine-scale sedimentary structures

- **Depositional processes created a sedimentary record**
  - Developed in topographically low areas
  - Spectacular stratification at multiple scales
  - Evidence of persistent standing water, lakes
  - Sediments systematically change in character with time
  - Multiple facies recognized



Fe/Mg smectite
carbonate





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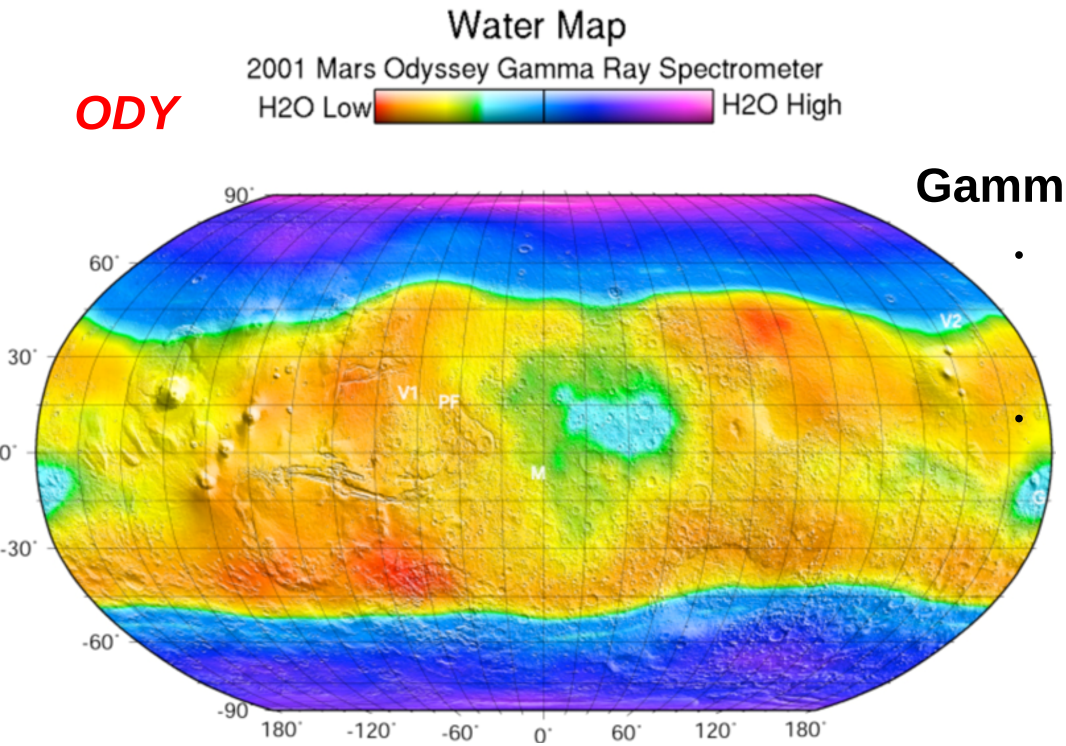
Past Decade Results:

Distribution of Modern Water

ODY



Global Near-Surface Reservoirs of Water

Gamma Ray Spectrometer

- Global hydrogen abundance and equivalent H_2O
- Ground ice to +/-60° in high abundance

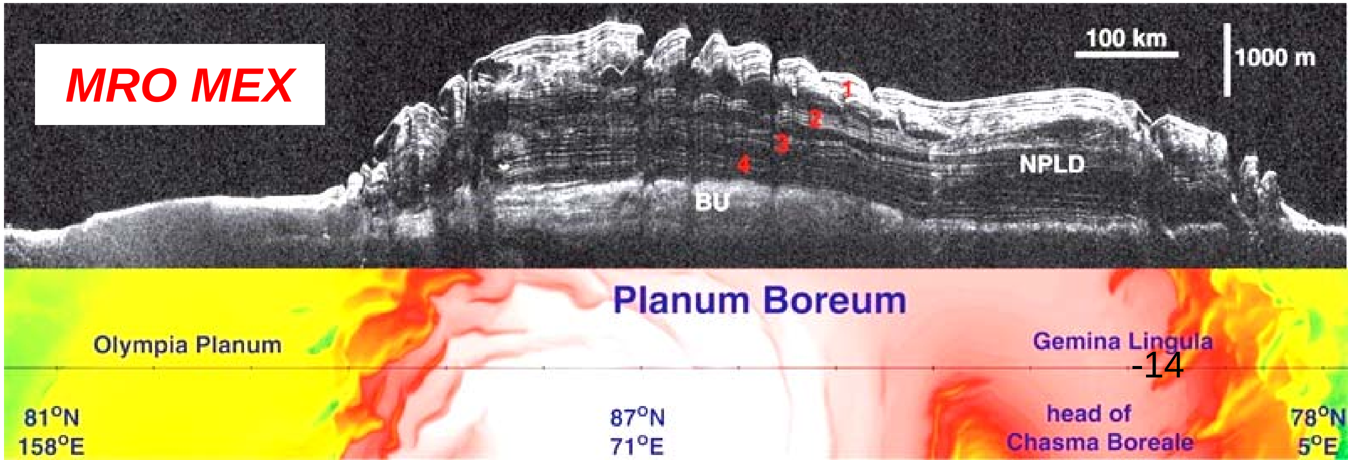
Phoenix results

PHX

SHARAD and MARSIS

- Nearly pure water ice
- Distinct layering
- No deflection of crust
- Ice-cored lobate debris aprons in mid-latitudes

MRO MEX

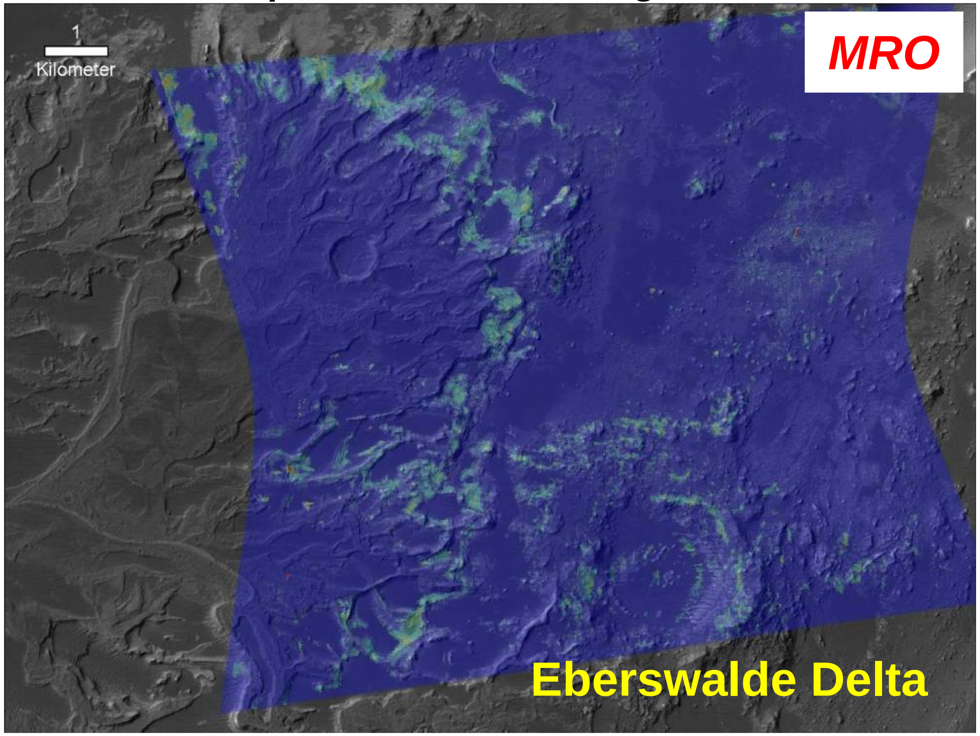


Past Decade Results:

Ancient Mars Was Wet (Episodically?)

Channels formed by rainfall runoff

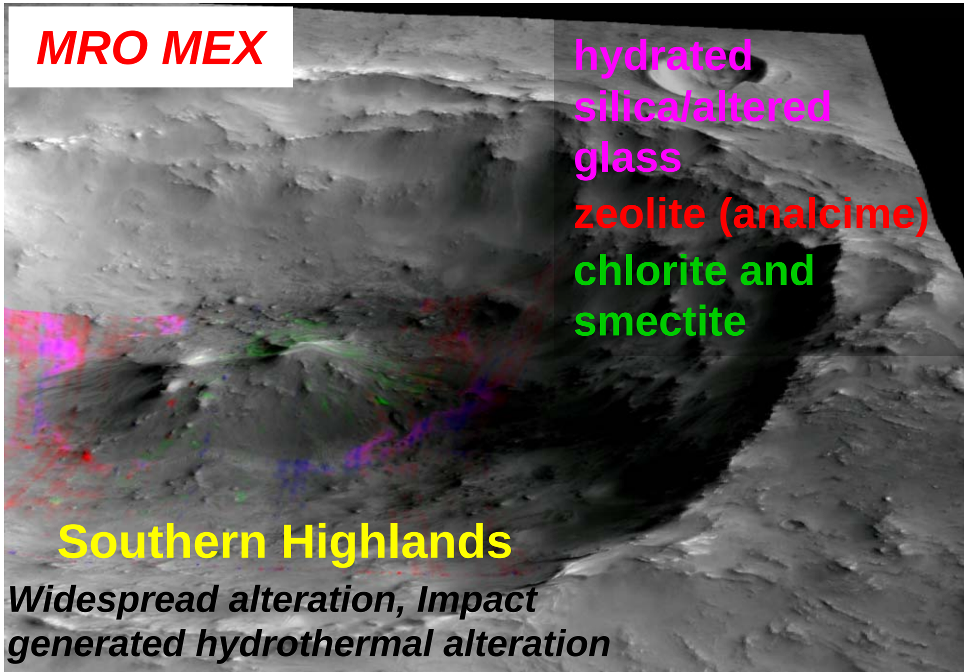
Delta, deposition into standing water

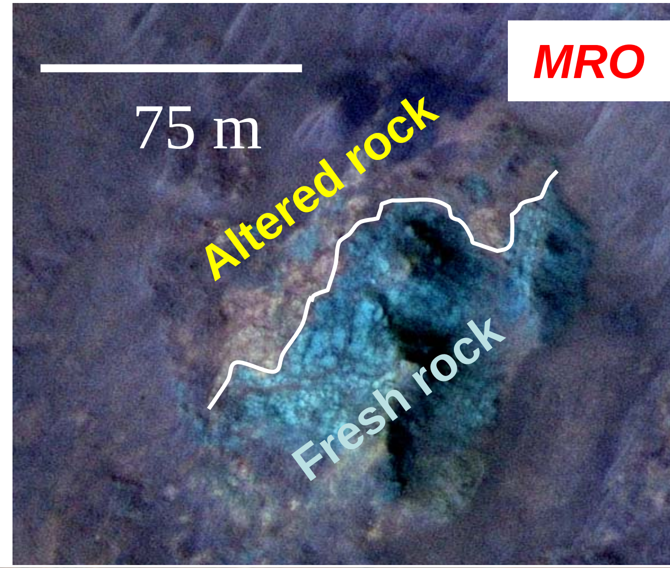


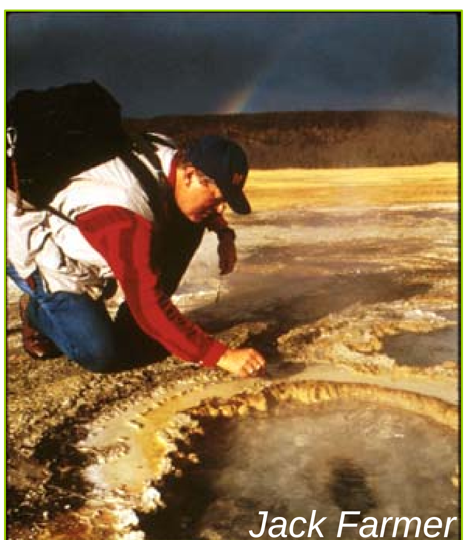
- **Ancient features indicate water present at the surface**
  - Evidence of persistent standing water, lakes
  - Evidence of rainfall, valley networks
  - Lake overflow features

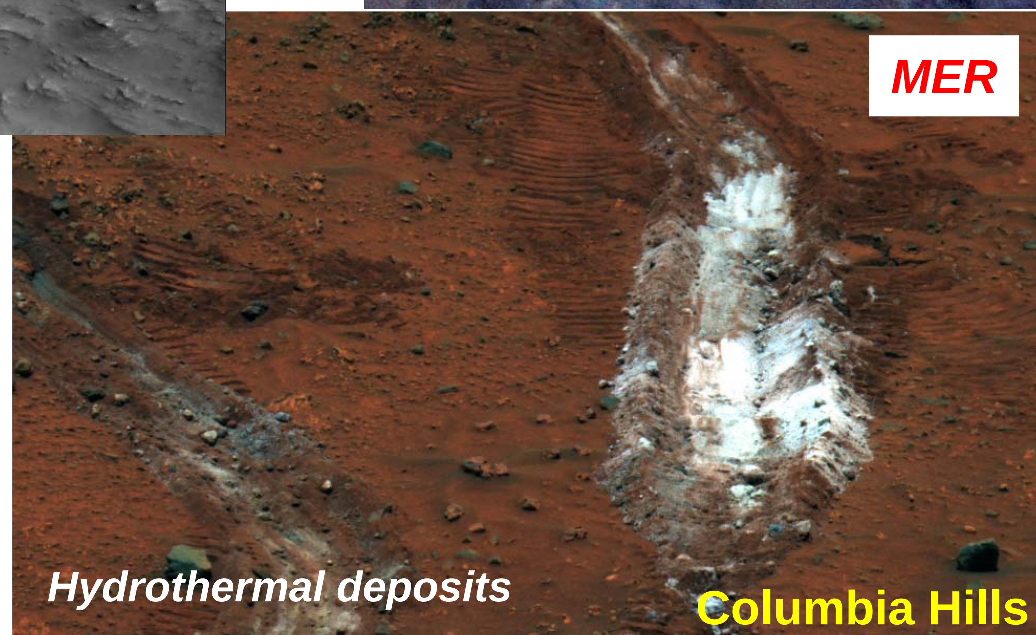
Past Decade Results:

Evidence for Water/Rock Interaction



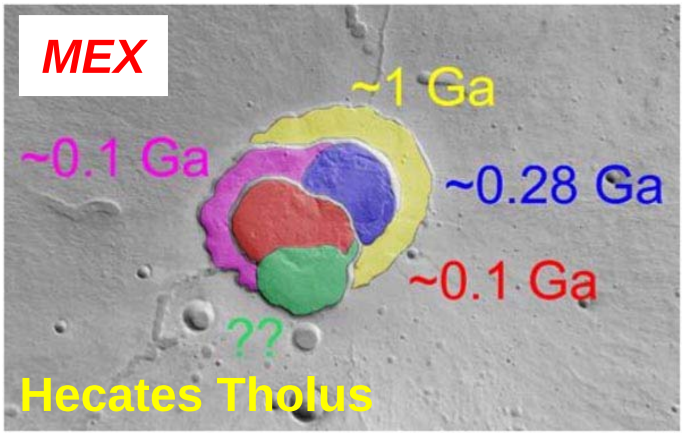


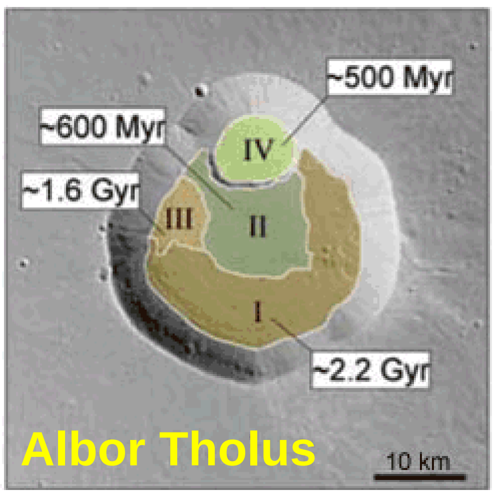




Past Decade Results:

Mars Still Active Today

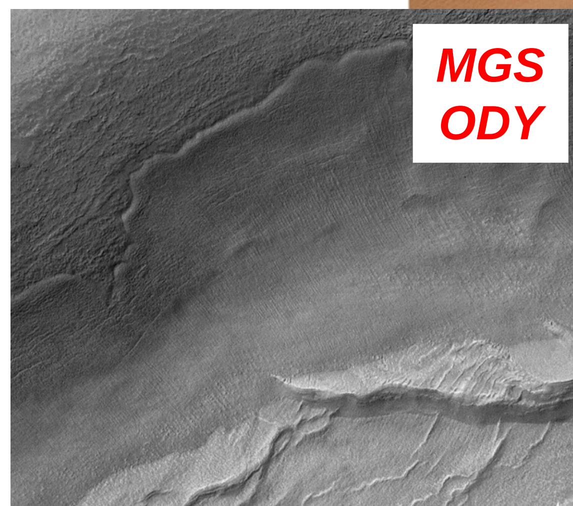


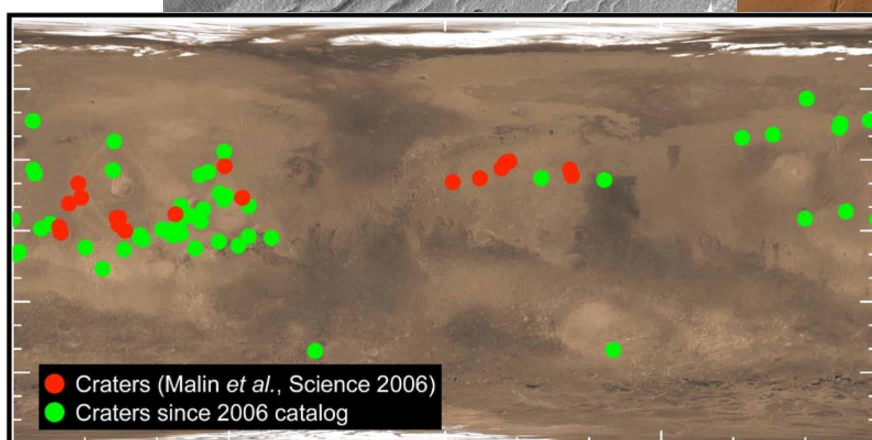


Lava Flows

Volcanic activity spans most or all of martian geologic history

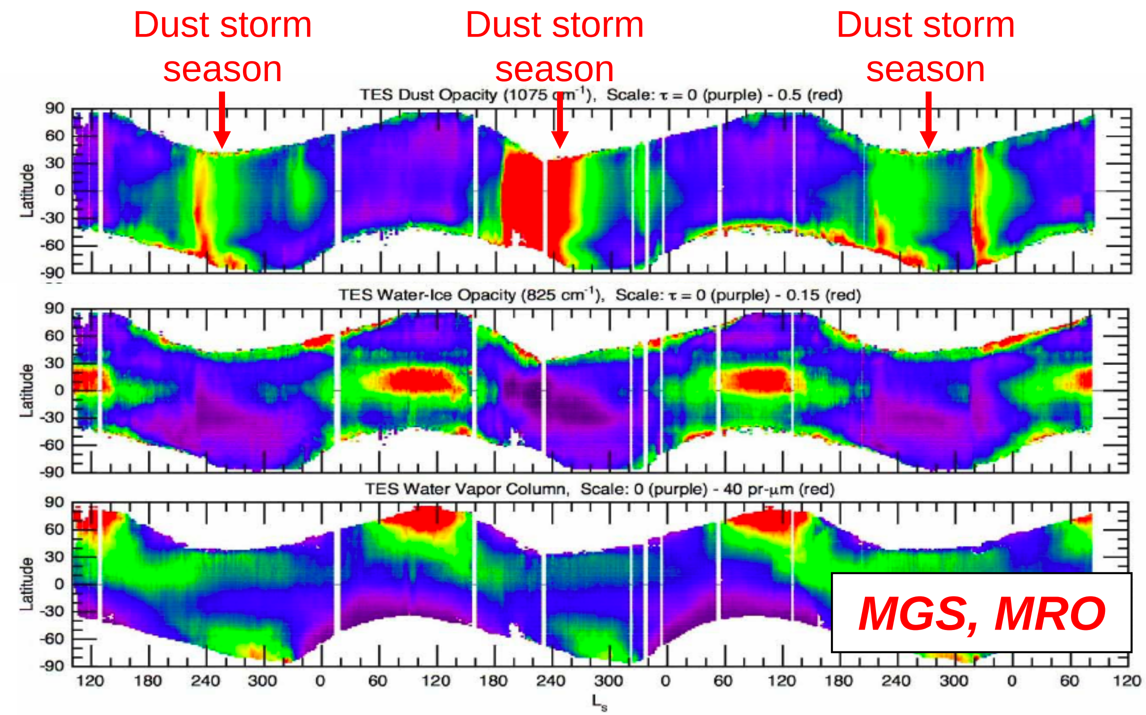
Mid-latitude mantles and gullies



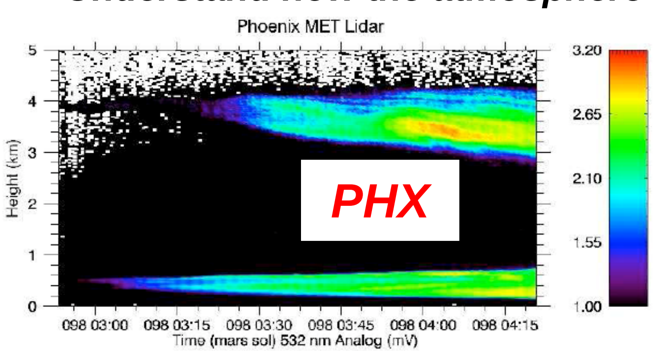


New Impact Craters

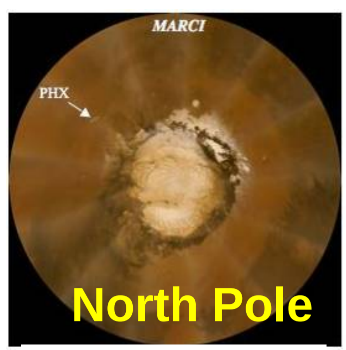
Past Decade Results:
Atmosphere and Climate Results



Understand how the atmosphere works



Cloud, fog and storm dynamics

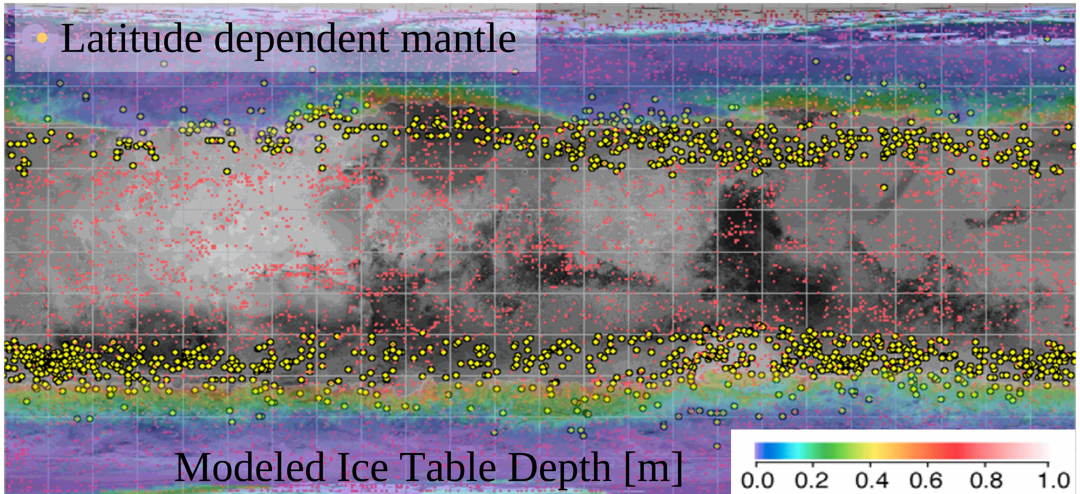


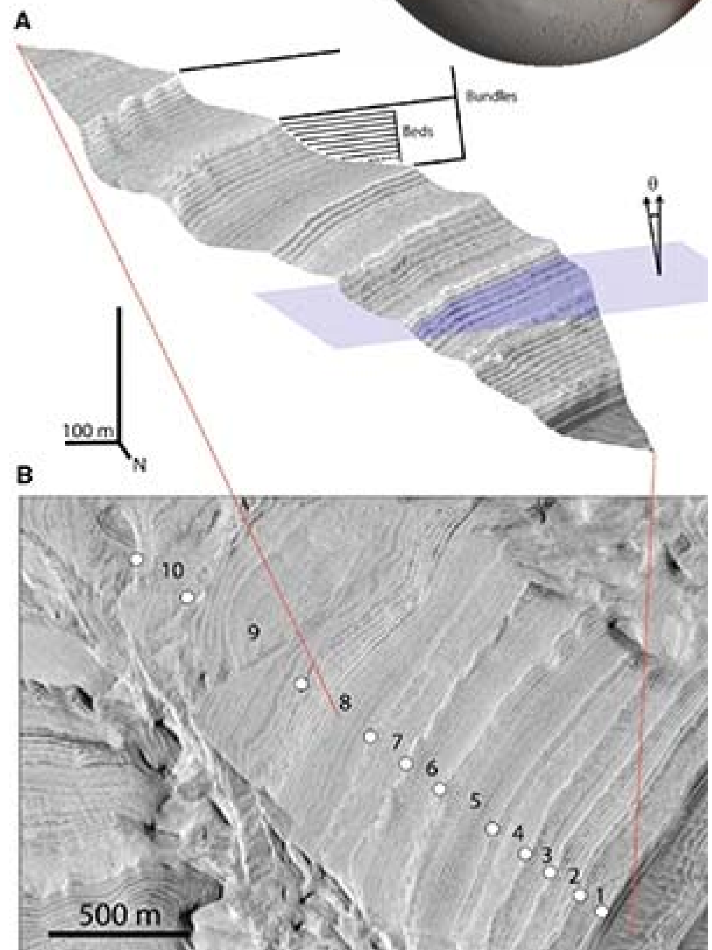
MEX, MRO

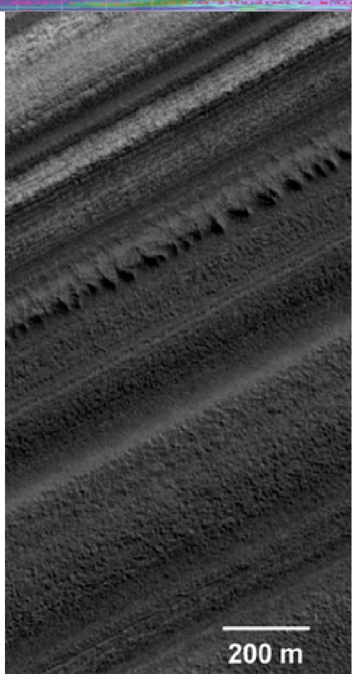
- **Climate change -- Past, recent and past: Understanding the process**
  - **Early wet (warm?) Mars (Noachian) has evolved to cold, dry Mars (Hesperian +)**
  - **Periodic change in last several million years**
- **Recent multi-year record of CO_2/water/dust; atmospheric dynamics [MGS, ODY, MEX, MRO]**
  - **Seasonal cycles and interannual variability**
- **SO_2, Argon, CH4, CO, etc.: Tracers of transport, chemistry, and surface-atmosphere interactions**

Past Decade Results:

Periodic Climate Change







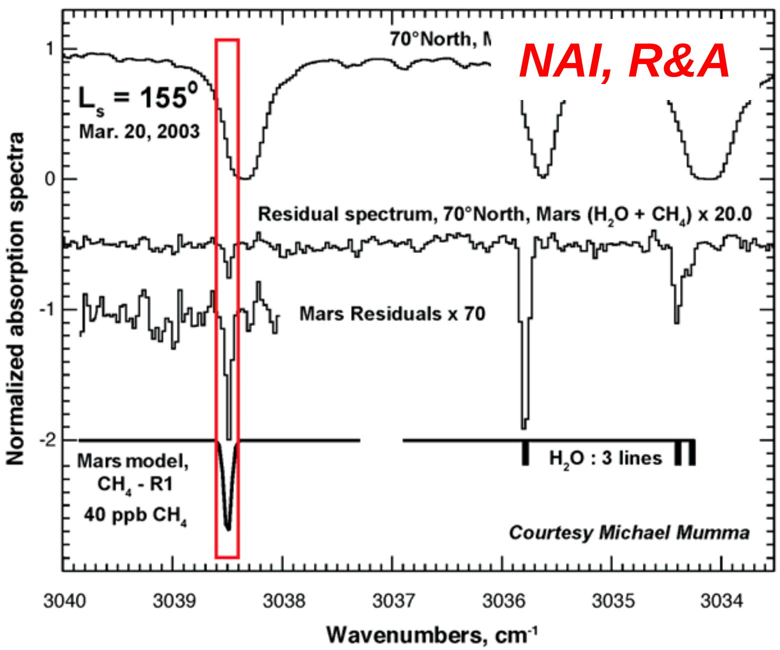
- **Volatile-rich, latitude dependent deposits (mantle, glaciers, gullies, viscous flow) coupled to orbitally-forced climate change**
- **Periodicity of layering in the north polar cap deposits as well as sedimentary deposits**

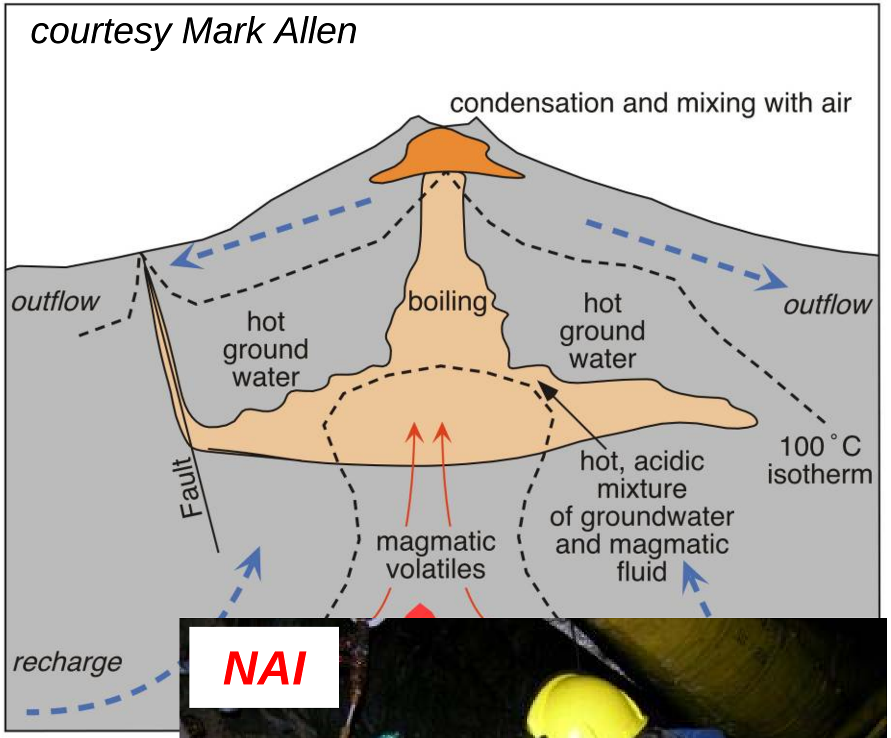
MGS, ODY, MEX MRO

Past Decade Results:

Modern Methane

Courtesy Mike Mumma





Detection of Methane on Mars

MEX NAI R&A

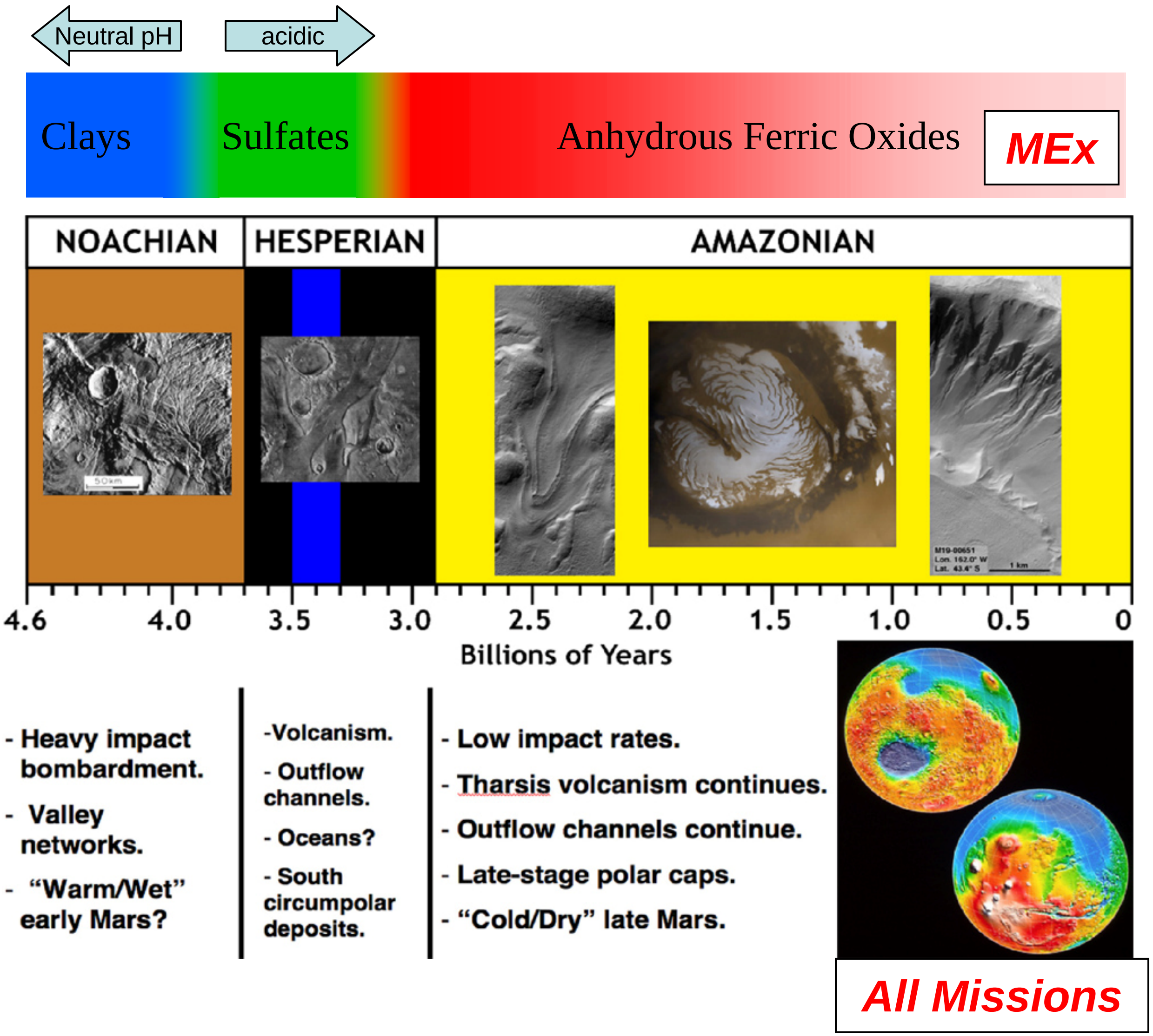
Abiotic?

Evidence of an active subsurface?

Biotic?

Past Decade Results:

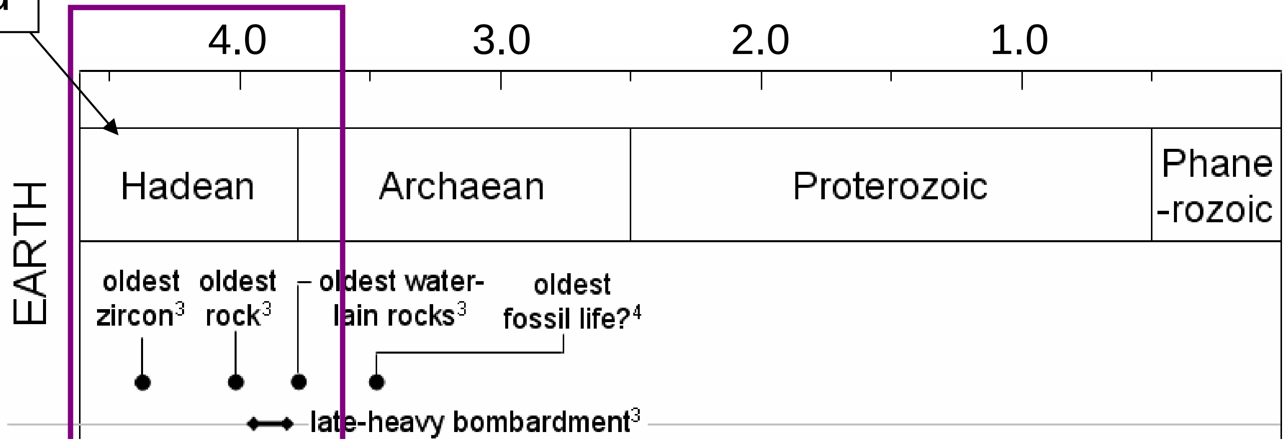
Mars Planetary Evolution



- **Hydrous Mineralogy Changed Over Time**
  - Phyllosilicate minerals (smectite clay, chlorite, kaolinite…) formed early
  - Evaporates dominated by sulfate formed later with opal/hydrated silica
  - Few hydrated mineral deposits since
- **Evolution of Aqueous, Fluvial and Glacial, Morphology with Time**
  - Valley networks, lake systems
  - Gullies
  - Viscous flow, glaciers, latitude dependant mantle

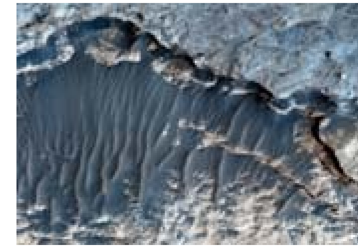
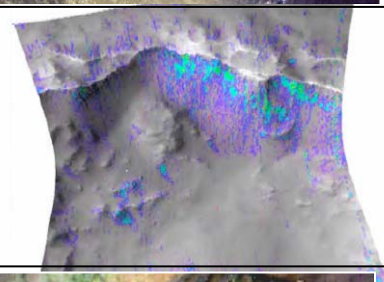
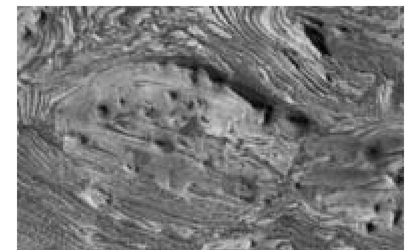
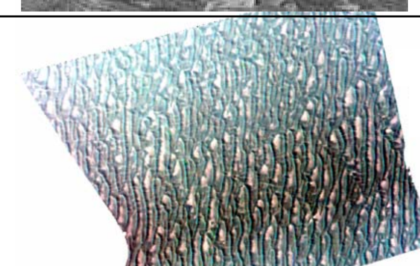
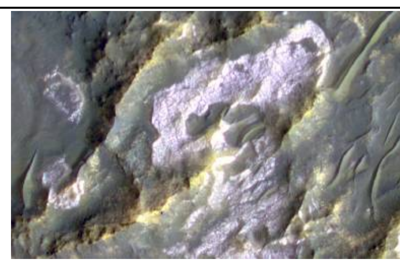
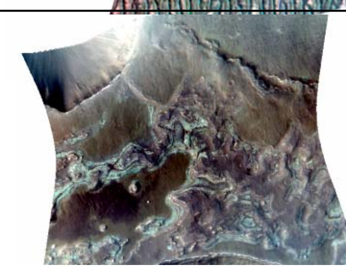
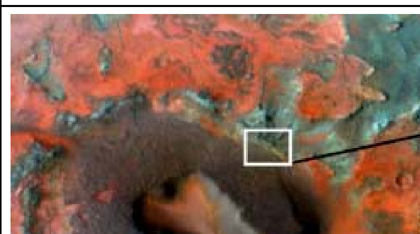
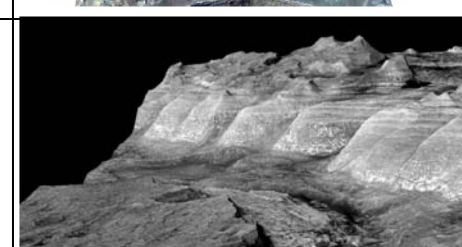
<<1% of rock record

GLOBAL GEOLOGIC TIMELINE



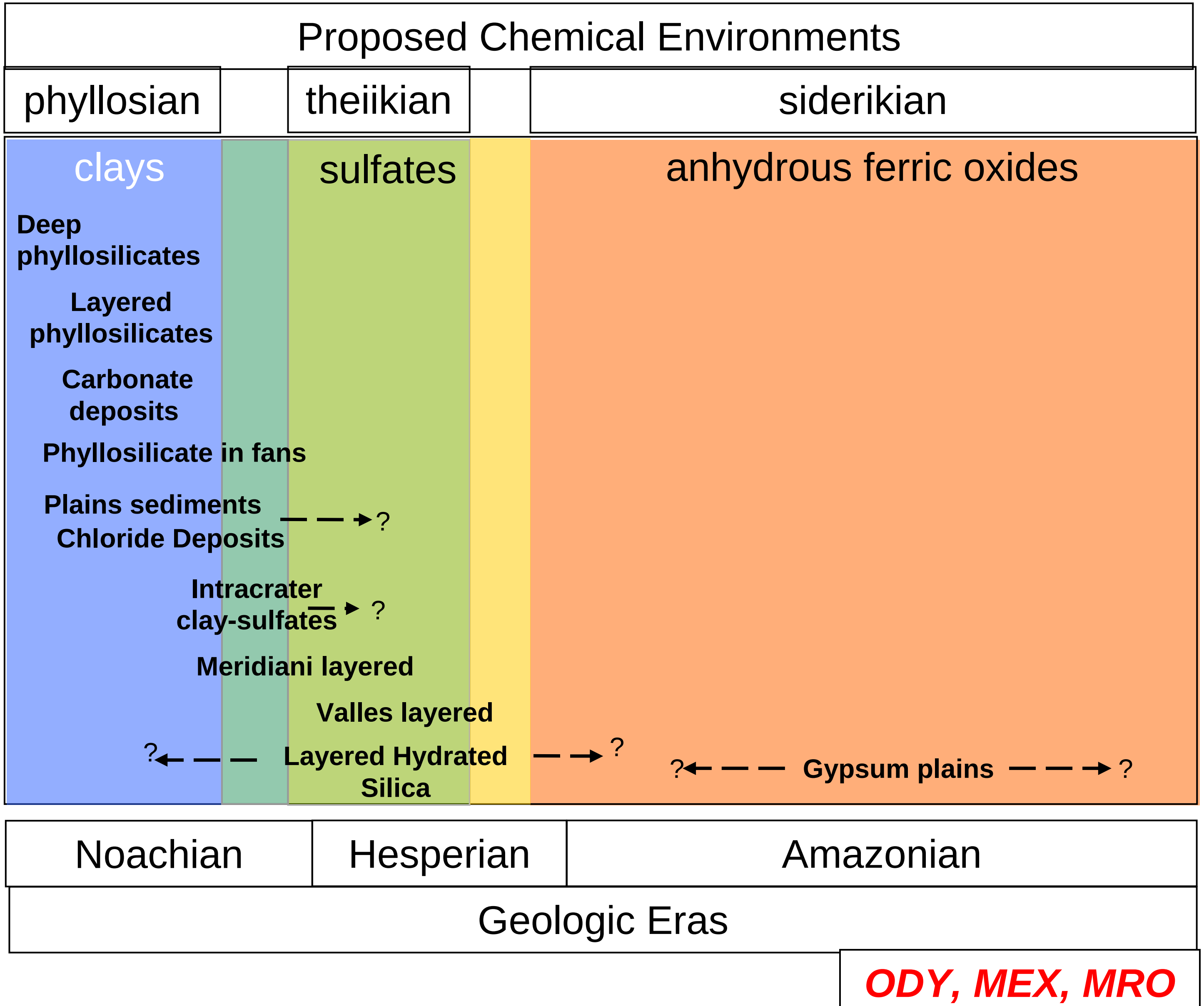
~50% of rock recor

Diverse Hydrous Mineral Deposits Recognized from Orbital Data: Murchie et al., 2009

Noachian layered clays (type: Mawrth Vallis)		Noachian Meridiani-type layered deposits (type: Terra Meridiani)	
Deep Noachian phyllosilicates exposed in highland craters, chasma walls (type: Tyrrhena Terra)		Hesperian Valles-type layered deposits (type: Candor Chasma)	
Noachian intra-crater fans with phyllosilicate-rich layers (type: Jezero Crater)		Amazonian gypsum deposits (type: Olympia Undae)	
Noachian "glowing terrain" Chloride deposits (type: Terra Sirenum)		Thin Hesperian layered deposits with hydrated silica (type: Ophir Planum)	
Mg-Carbonate beds (type: Nili Fossae)		Interbedded sulfates and clays (type: Gale Crater)	

Past Decade Results:

Mars Planetary Evolution



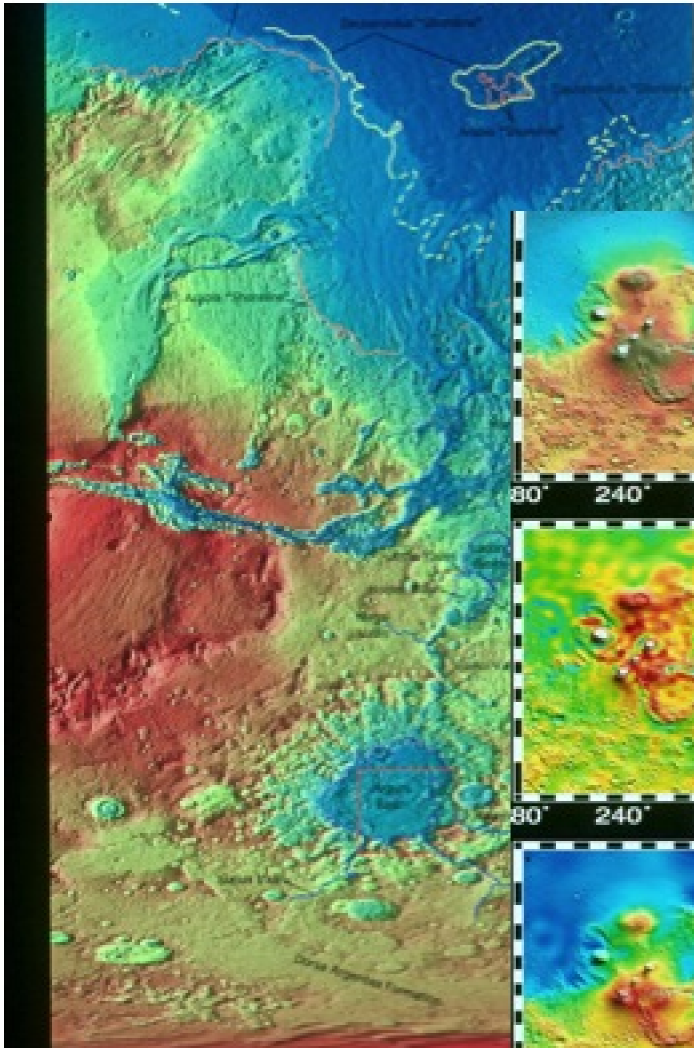
Coupled mineralogy and morphology define aqueous environments

Their character has evolved indicating changing environments

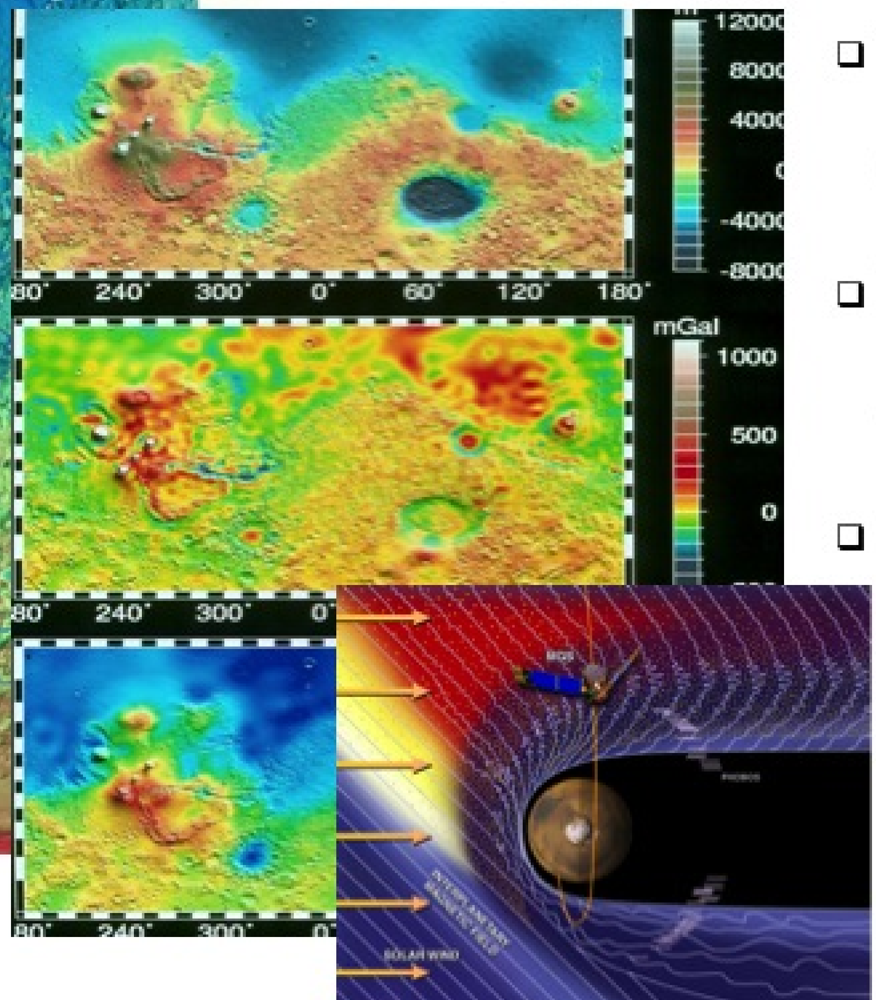
Data support the hypotheses but indicate greater complexity in local environments

Past Decadal Results:

Crustal Structure and History



- Best (30 km res) topographic model
  - Pole to pole slope controlling water transport, including northern depression



- Thick crust with near-isostatic compensation in rougher south
- Range of uncompensated gravity anomalies in smoother north
- Center of figure offset by nearly 3 km, indicating north pole ~6 km lower than south pole
- Evidence of early molten interior

MGS MRO

Major Questions for Mars and Planetary Science

1. **What is the early evolution of the terrestrial planets, including Earth? What is the role of water in the early evolution?**
2. **Origin and evolution of life?**
3. **What are the key processes for short- and long-term climate change on terrestrial planets?**
4. **What is the internal structure and origin of the terrestrial planets?**

Scientific Themes for Mars

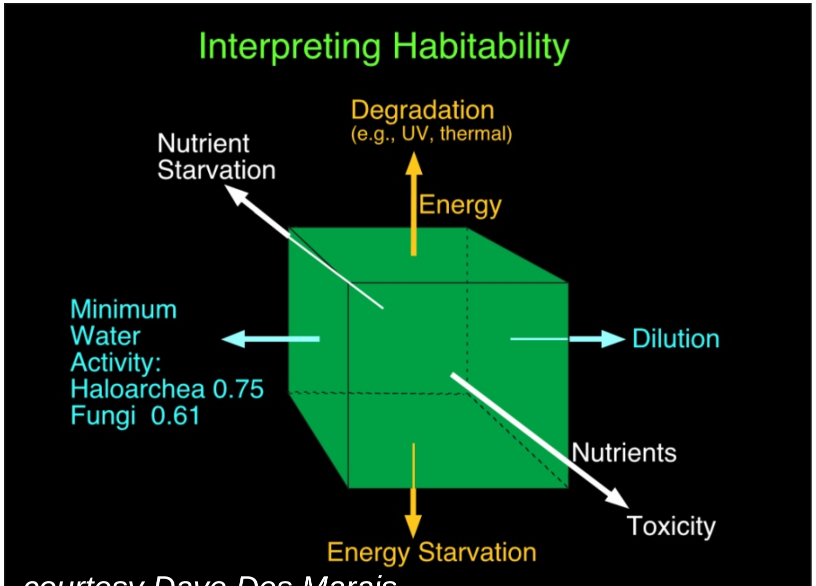
1. Early evolution of the terrestrial planets, including Earth

- **Mars retains history that has been completely erased from Earth (and Venus)**
  - Earth’s oldest rocks >3.5 billion years old are rare and usually altered; Mars rocks exist at 4.5 billion years (determined from dating Mars meteorites)
- ***This is the period of time when life evolved on Earth***
  - *As interpreted from chemical signatures in rock at 3.8 billion years; earliest microfossils are 3.0 billion years old.*

Ancient cratered surface of Mars (above)
and remaining Earth crust from same time period (below)

Scientific Themes for Mars
2. Origin and evolution of life questions

- **Ancient life—interpreted potential has increased**
  - Lots of ancient liquid water in diverse environments
  - Past geological environments that have reasonable potential to have preserved the evidence of life, had it existed.
  - Understanding variations in habitability potential is proving to be an effective search strategy
  - **SUMMARY**: We have a means to prioritize candidate sites, and reason to believe that the evidence we are seeking is within reach of our exploration.
- **Modern life—interpreted potential still exists**
  - Evidence of modern liquid water at surface is equivocal—probable liquid water in deep subsurface
  - Methane may be a critically important clue to subsurface biosphere
  - **SUMMARY**: We have not yet identified high-potential surface sites, and the deep subsurface is not yet within our reach.



courtesy Dave Des Marais

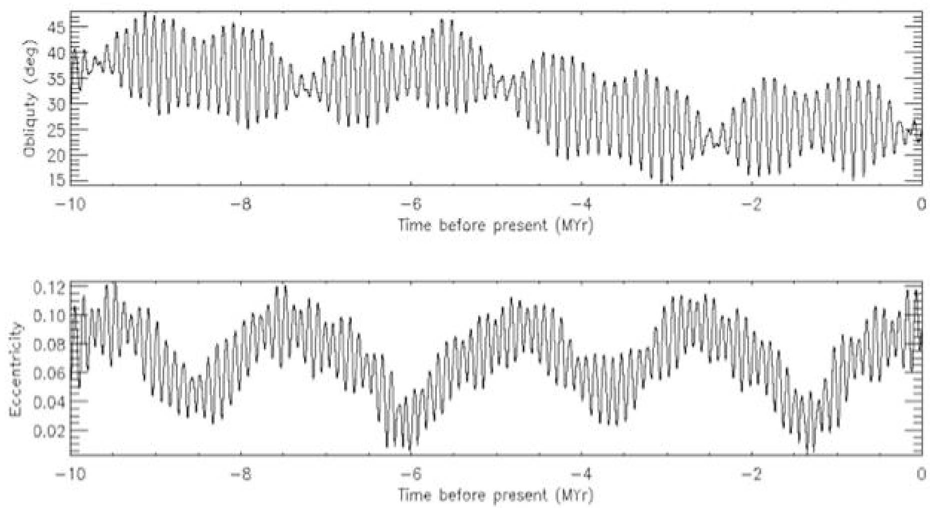
Scientific Themes for Mars
3. Short- and long-term climate change

❑ Preserved records of global environmental change

- Layered terrains in high- and low- latitudes indicative of cyclic changes related to orbital and axial variations
- Evidence of hydrous mineralogy changing from clays to sulfates to oxides. Mars morphology indicates water evolution over time in cooling environment.

❑ Modern climate may provide clues regarding solar forcing or internal process drivers of atmospheric escape

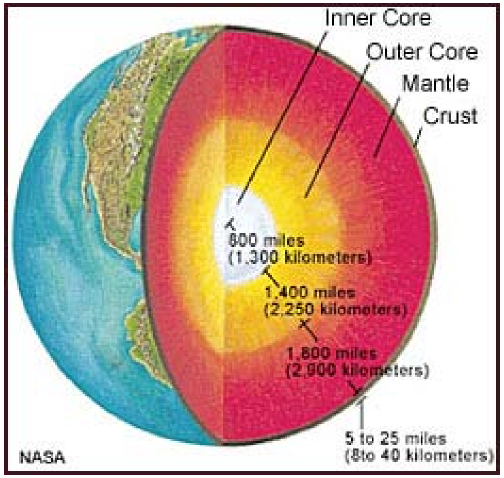
- We have observed a multi-year record of recent climate change
- The proposed MAVEN mission would establish the inventory of atmospheric trace gases to understand the internal and external processes that shaped Mars' atmosphere

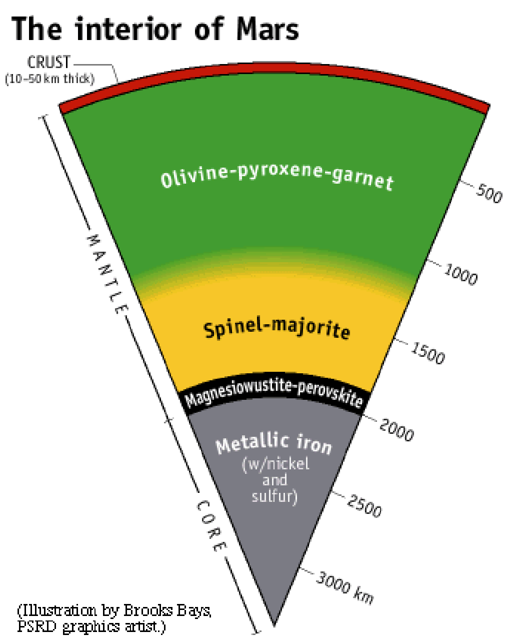


Scientific Themes for Mars

4. Internal structure and origin of the terrestrial planets

- **The internal structure of a planet provides clues to its origin and evolution**
  - Can follow up clues from remnant magnetism discovered by MGS.
- **To date, we have data for the Earth and some data for the Moon**
- **Mars offers an opportunity to obtain results on another terrestrial planet**
  - Intermediate in size between the Earth and Moon
  - May provide clues to early differentiation that are not available from more active planets like Earth and Venus

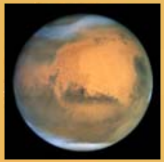




Interior of Mars figure from http://www.psrd.hawaii.edu/June04/martianMantle.html. Used with permission.

Should Mars be a Strategic Target for Human Exploration?

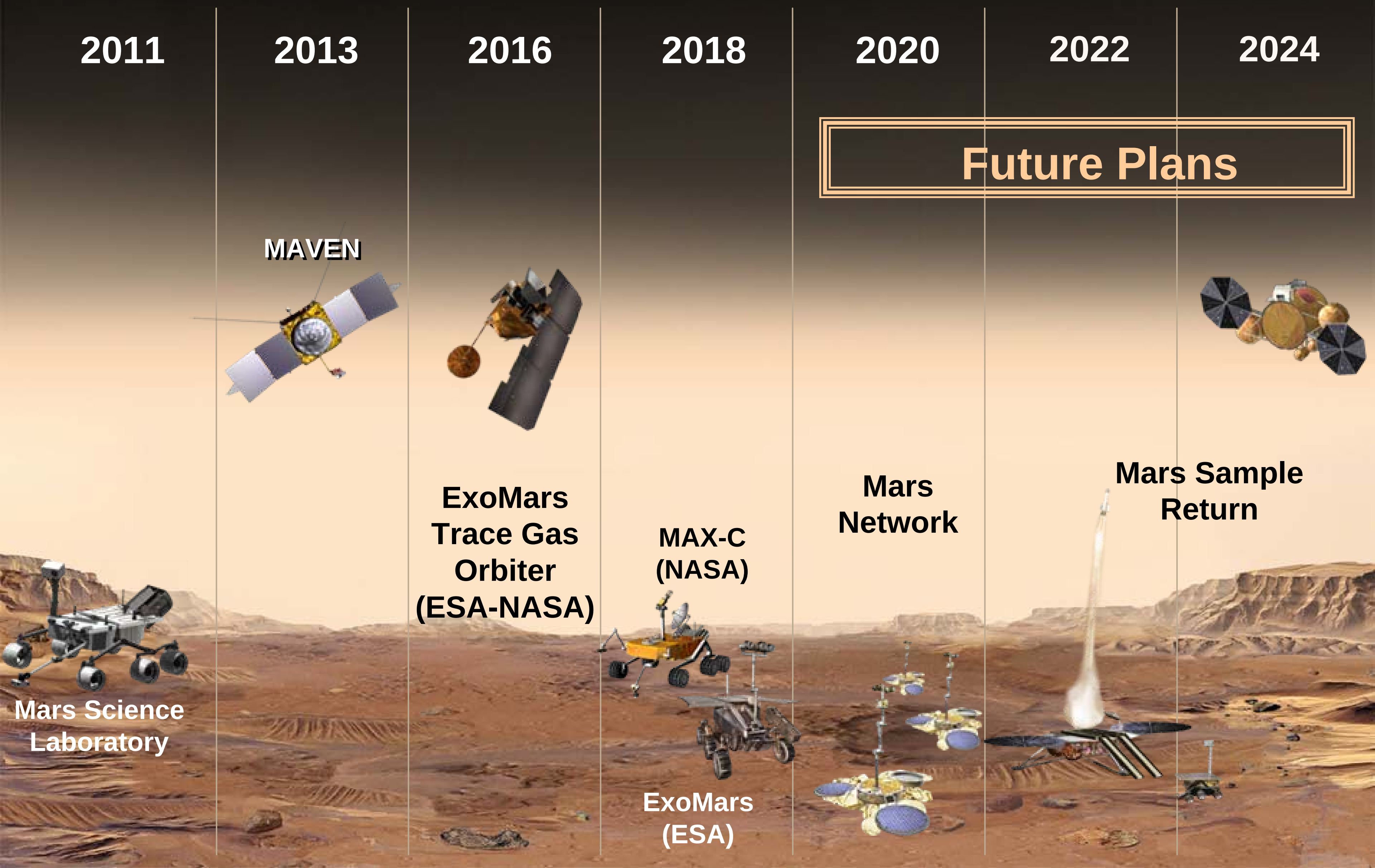
- ❑ Closest to Earth in terms of surface environment
- ❑ Close enough that we can credibly discuss reaching it with astronauts.
- ❑ Public fascination fuels student interest in science and technololgy.



Scientific Questions for the Next Decade

- What is the diversity and nature of aqueous geologic environments?
- What is the detailed mineralogy of the diverse suite of geologic units and what are their absolute ages?
- What caused the major transition from Early Mars to Middle Mars? (Phllyosian to Theiikian)
- Are reduced carbon compounds preserved and, if so, in what geologic environments?
- What is the complement of trace gases in the atmosphere and what are the processes that govern their origin, evolution, and fate?
- How does the planet interact with the space environment, and how has that affected its evolution? What is the record of climate change over the past 10, 100, and 1000 Myrs?
- What is the internal structure and activity?

International Exploration of Mars



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