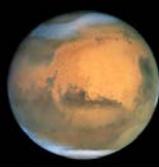


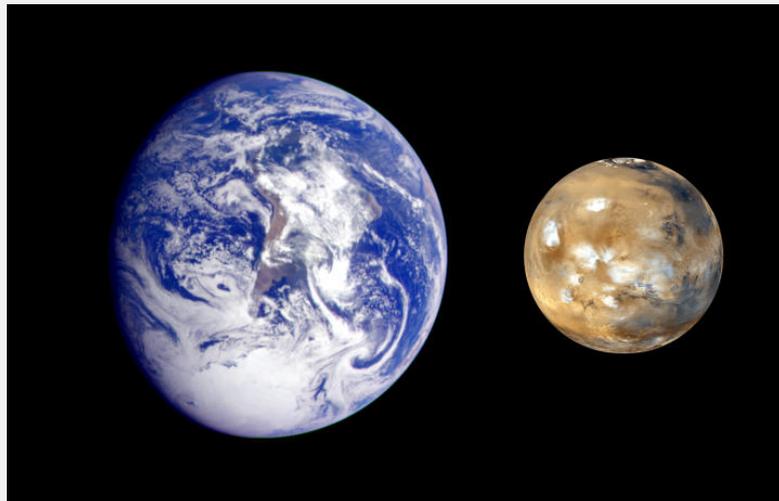


**JPL**



*Solar System Exploration @ 50*

***Mars after 50 Years of Space Exploration:  
Then, Now and Beyond***



***Richard W. Zurek***  
*JPL Mars Office Chief Scientist*  
*Jet Propulsion Laboratory*  
*California Institute of Technology*

# *Mars Exploration*

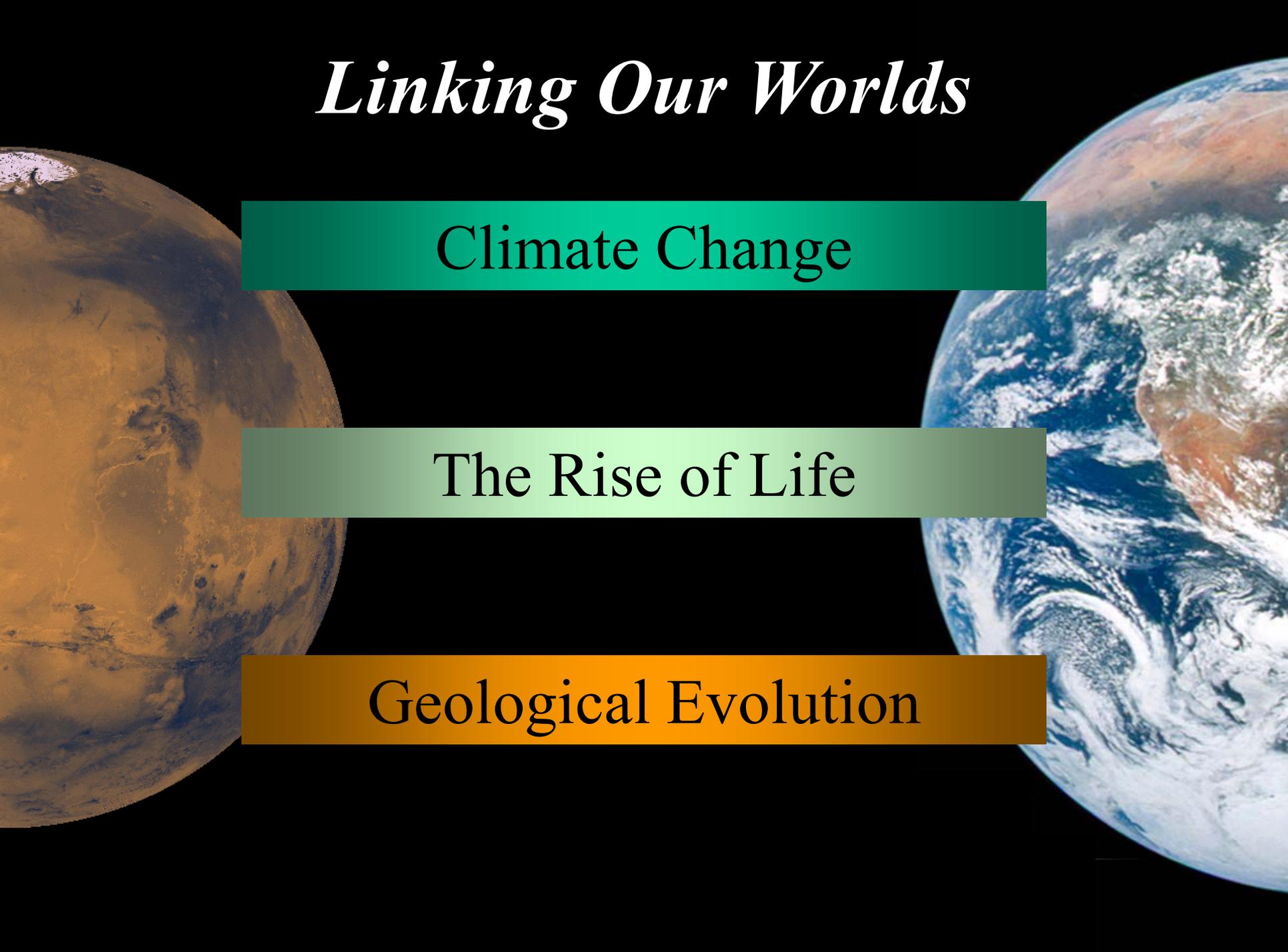


*Solar System Exploration @ 50*

- **Persistent themes**
- **Background**
  - **Lowellian View**
- **The *First Wave* of Exploring Mars from Space**
  - **Strategy: *Fly-by Recon* => *Orbital Recon* => *Land***
  - **U. S. Mariners and Vikings**
  - **Soviet Mars and Zond s/c**
- **The *Second Wave* of Exploring Mars from Space:**
  - **The Modern Mars Exploration Program**
  - **Strategy: *Orbiter-Lander Synergy & Ground Mobility***
- **Our view(s) of Mars Today**
- **Next Steps in Mars Exploration**

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# *Linking Our Worlds*



Climate Change

The Rise of Life

Geological Evolution

# *Mars as an older Earth - P. Lowell*



*Solar System Exploration @ 50*

## *The view of Mars at the beginning of the 20th Century*

*Both Earth and Mars had:*

- **Seasons and Seasonal Change**
  - Polar caps that come and go seasonally
  - Changes in color, also with season: the “Wave of Darkening”
- **Atmospheres**
  - Mars less air than Earth, but enough for life (~10% of Earth’ s)
- **Active Water Cycles: clouds, ice caps**
- **Similar length of day: Moderate diurnal variations**
- **Same evolutionary path--Mars was just older**
  - Losing atmospheric and surface water over time
  - A heavily eroded desert planet (no mountains)
- **Abodes of Life**
  - **Intelligent life: The canals were a vast engineering scheme to distribute the water from the poles to elsewhere on the planet**



# *Mars at the Start of the Space Age*



*Solar System Exploration @ 50*

## *Earth-based*

- **Many doubts about the classical arguments for Martian life**
  - **Color of the dark areas: not green**
  - **Seasonal changes in visual albedo: winds removing dust**
  - **Ability of dark areas to re-emerge after dust storms: winds again?**
  - **Existence of canals discredited with improving image resolution**
  - **Early doubts about whether Mars was in the “habitability zone”**
- **Atmospheres**
  - **Mars atmosphere much thinner than Earth’s**
    - **CO<sub>2</sub> measurement => < 10% of Earth’s total atmospheric column**
    - **Yes, there was some water vapor**

*Mariner 4 successfully launches in 1964 and initiates the age of Mars exploration by spacecraft*

# *Mars: First Wave of the Space Age*



*Solar System Exploration @ 50*

## *1964 – 1981 (US Program)*

### *Mariner 4, 6-7: Mars as the Moon*

- Heavily cratered surface => Mars as the Moon
- Total atmospheric pressure ~ 4 mbars (< 1% Earth), almost all CO<sub>2</sub>

### *Mariner 9: A Dynamic Planet once again*

- Planetary Dichotomy: Heavily cratered highlands in the south and less cratered lowlands in the north
- Massive volcanoes, giant rifts, vast channels, and valley networks
- Planet-wide dust storms

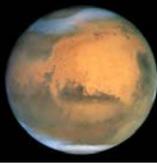
### *Viking: Life?*

- Experiments predicated on the assumption that if life exists somewhere on Mars, it will exist everywhere
- Orbiters revealed an annual atmospheric water cycle
- No confirmed biological activity; no organics in the soil

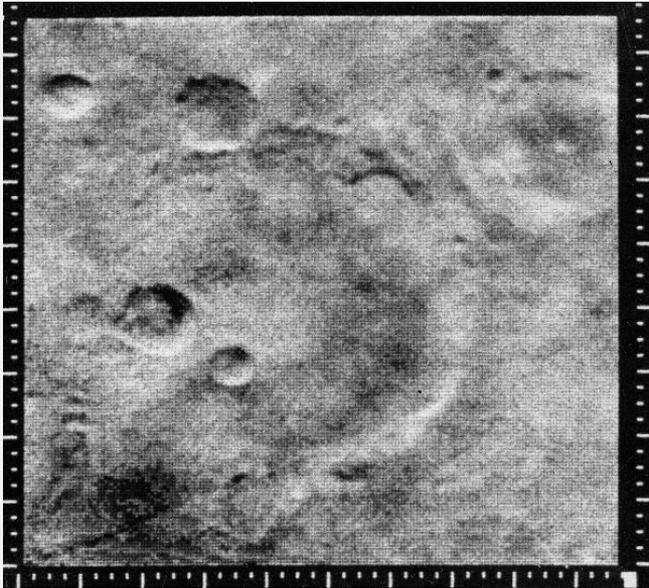


*Moon-like Mars:  
Heavily Cratered Highlands*

# *Early Views from Space*

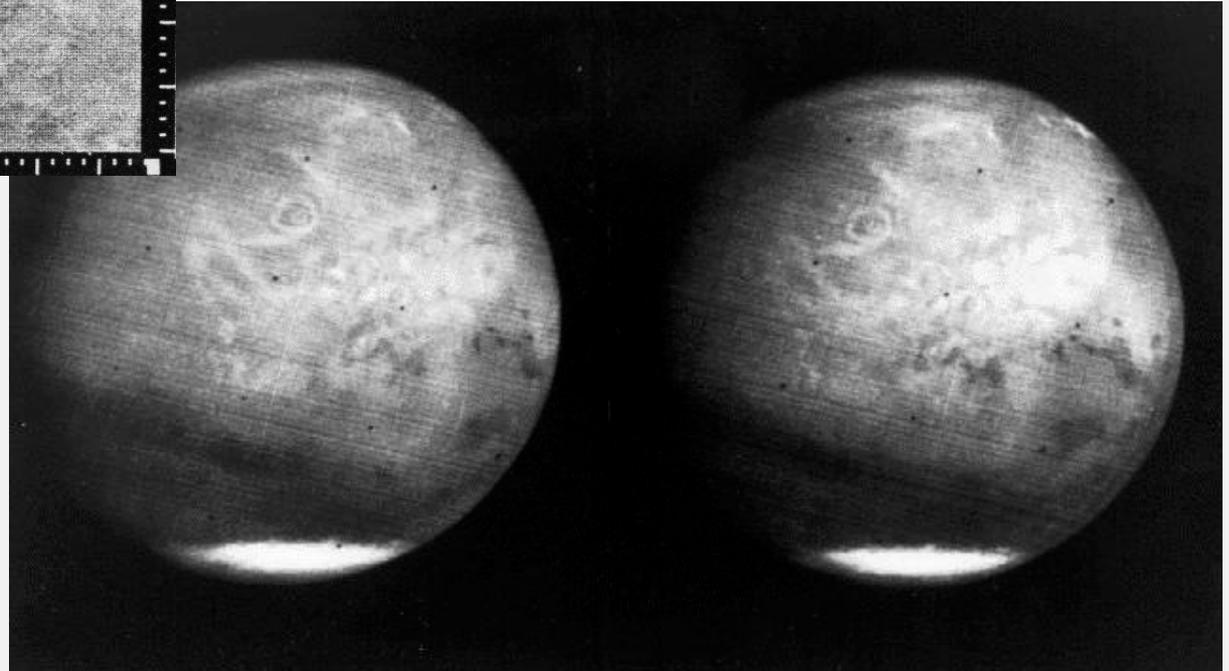


*Solar System Exploration @ 50*



**1965: Mariner 4 photos  
reveal a moonscape**  
**1969: Mariner 6 & 7 photos  
continue to puzzle**

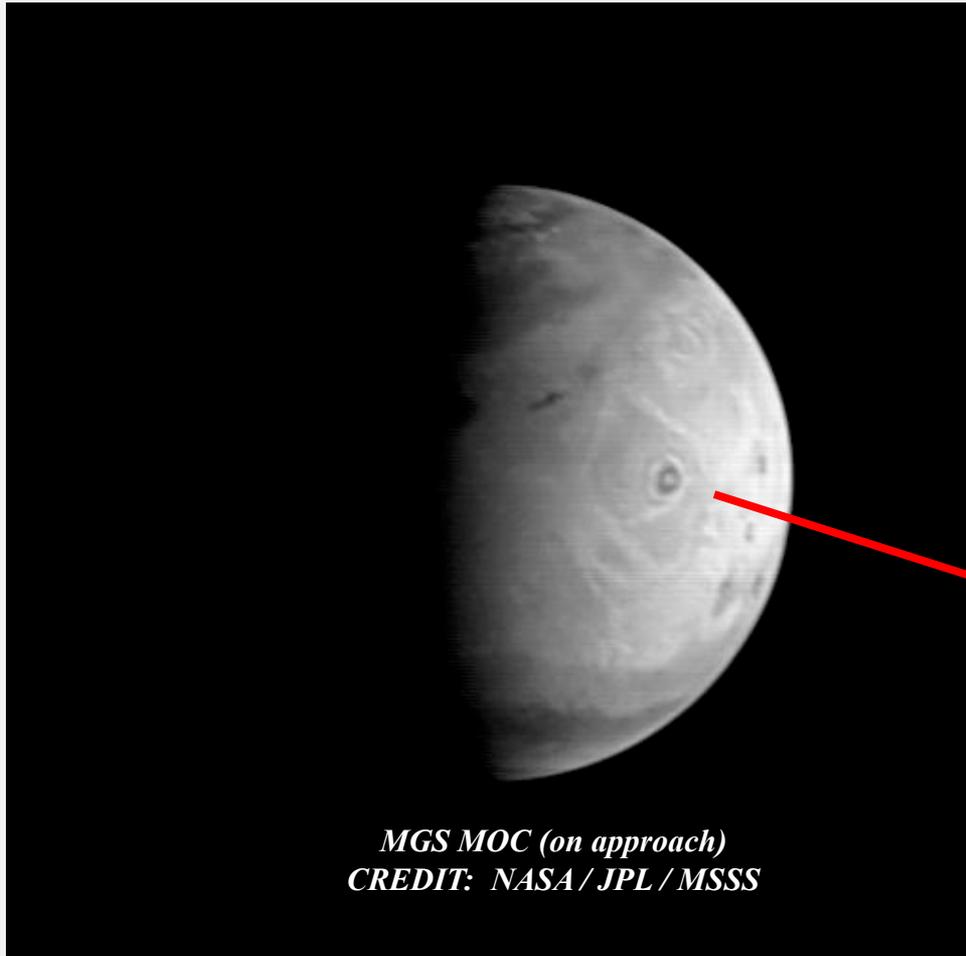
*Mariners 4 & 7*  
*CREDIT: NASA/JPL*



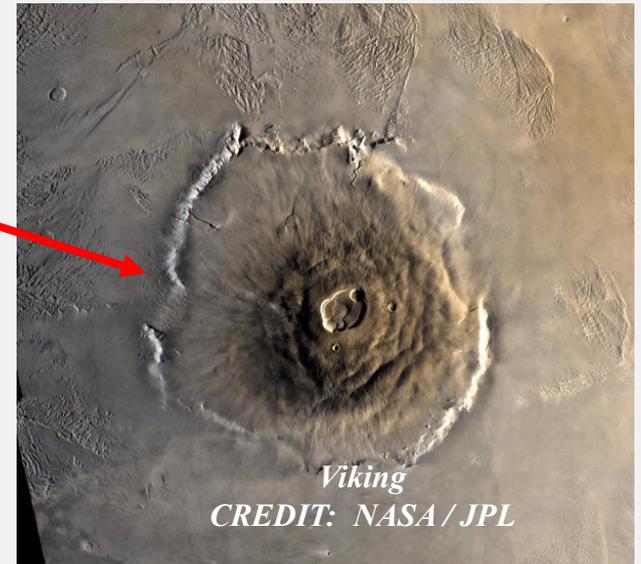
# *Now We Know!*



*Solar System Exploration @ 50*



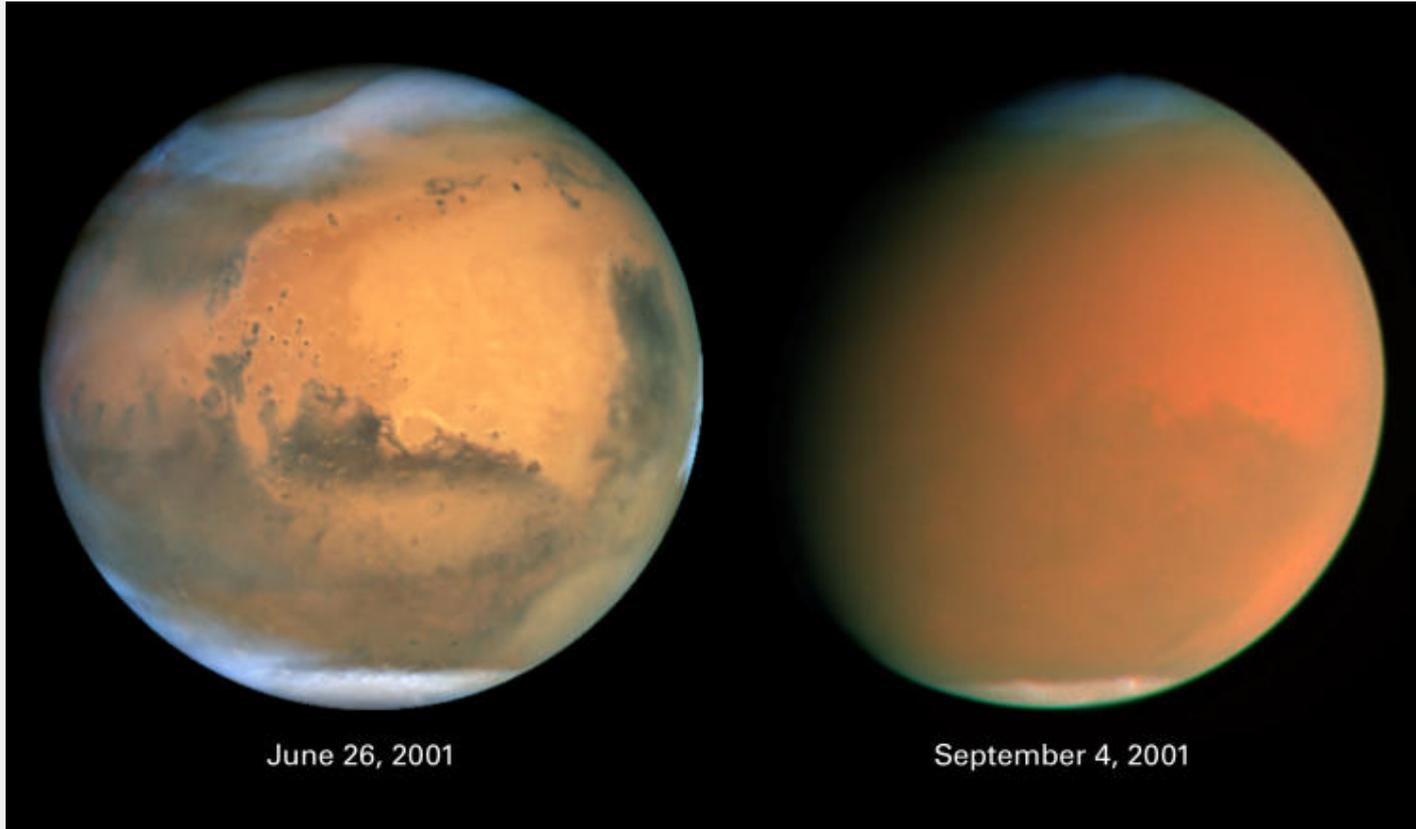
## *Olympus Mons*



# *HST View in 2001*



*Solar System Exploration @ 50*



June 26, 2001

September 4, 2001

*CREDIT: NASA/STScI/AURA/J. Bell & M. Wolff*

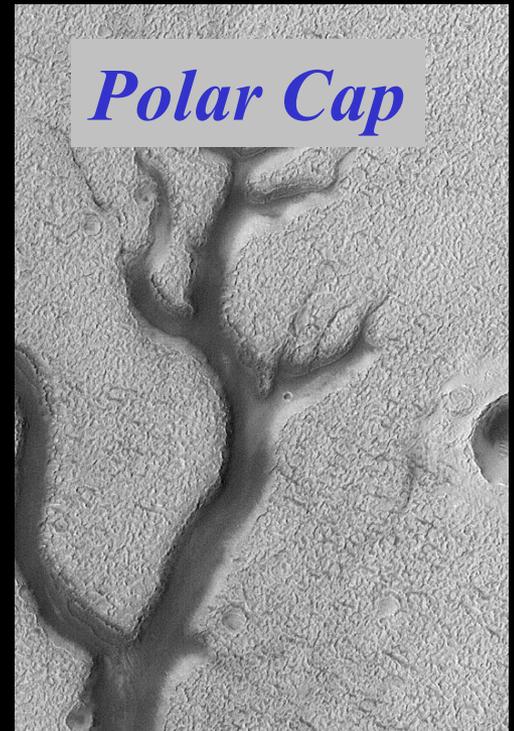


*Mariner 9*



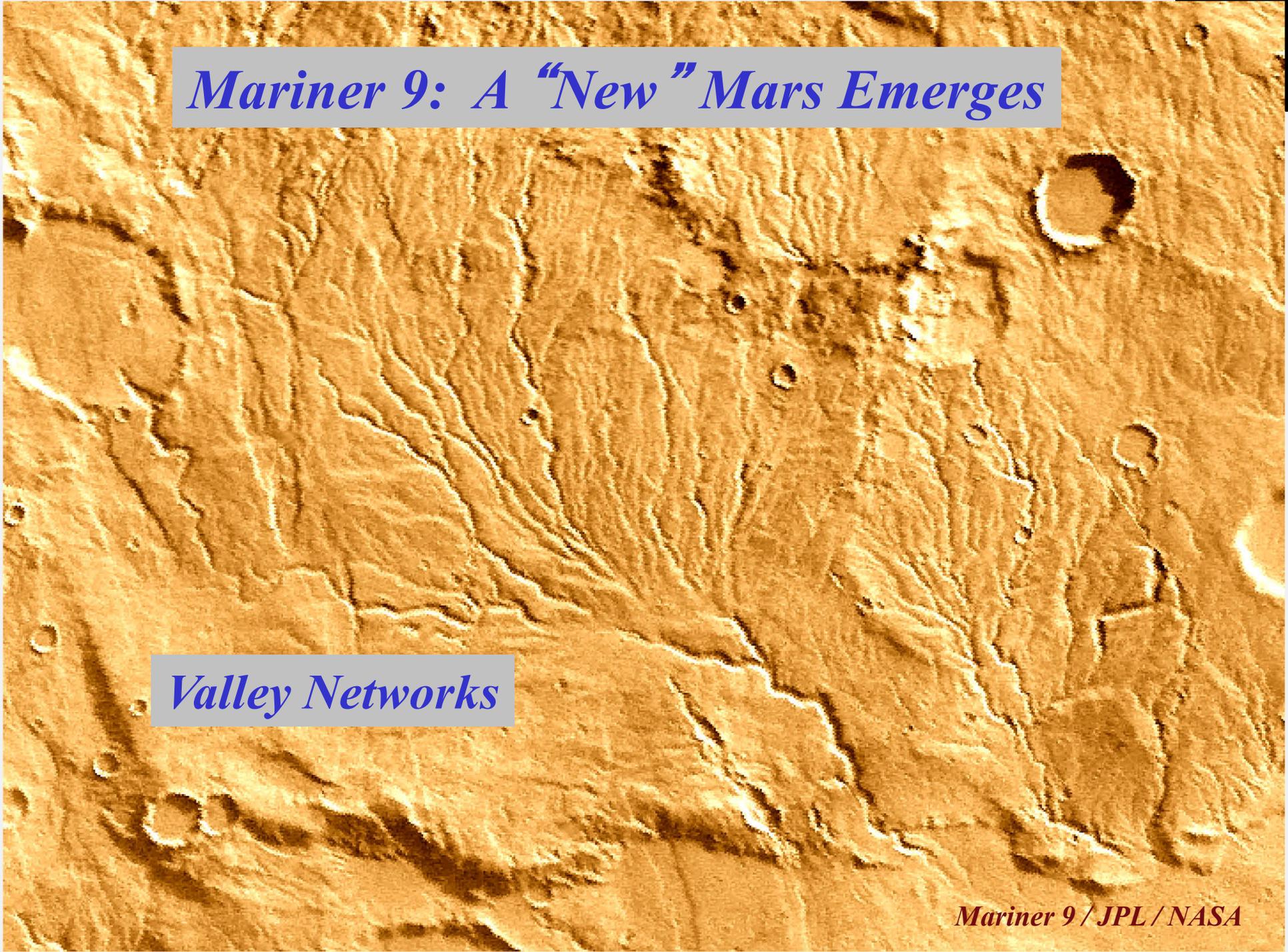
*Great Canyons*

*Mars Global Surveyor  
Images Courtesy of  
MSSS / JPL / NASA*



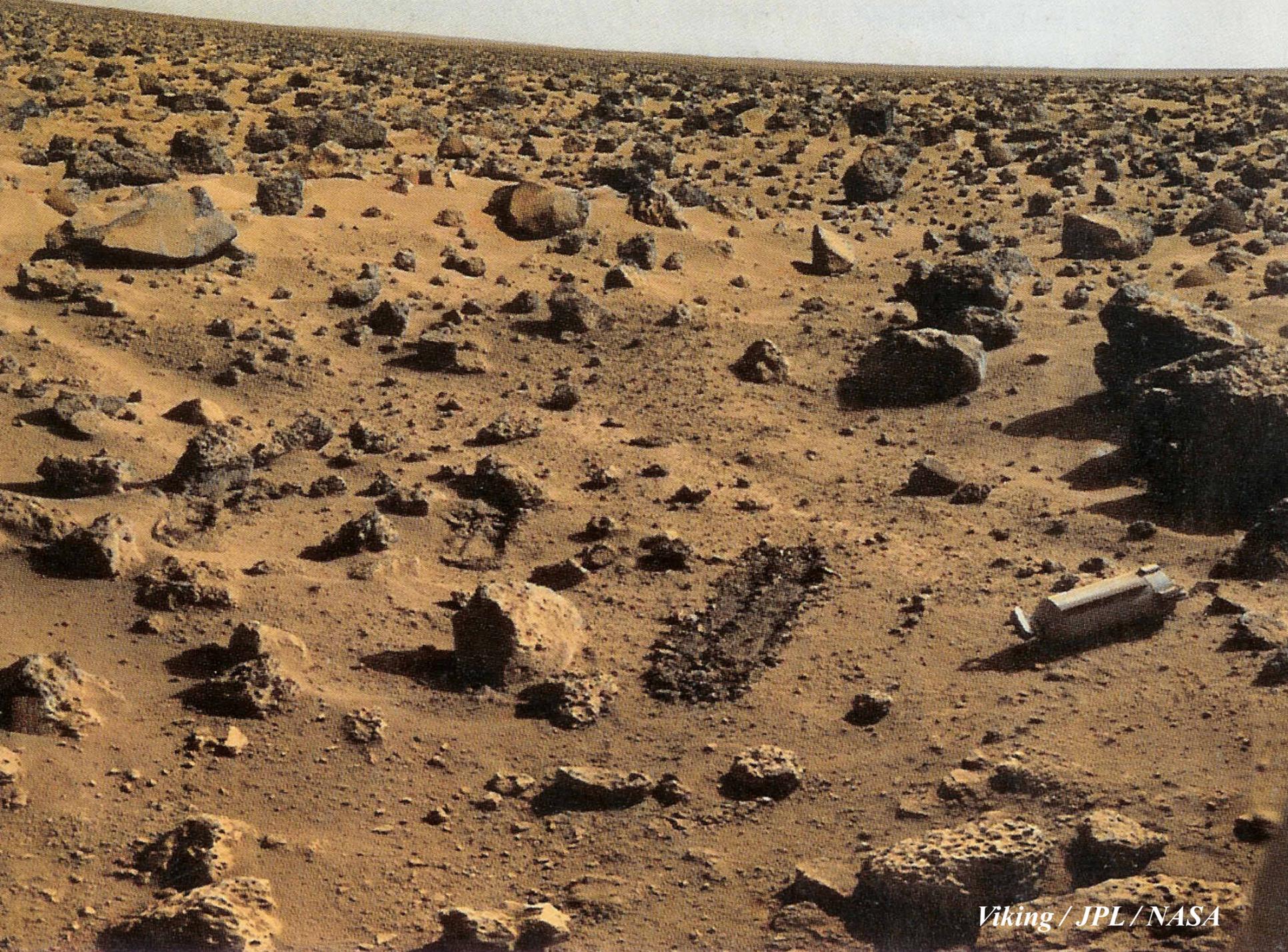
*Polar Cap*

*CREDIT: NASA / JPL*



*Mariner 9: A "New" Mars Emerges*

*Valley Networks*



# *Mars: 2<sup>nd</sup> Wave of the Space Age*



*Solar System Exploration @ 50*

**1992 – 2012+**

## *Mars Pathfinder and Mars Global Surveyor*

- **Successful Orbiter and Lander (with rover)!**
- **Global mapping of the Planet; site finding for MER**

## *Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter*

- **High spatial resolution imaging and monitoring; site finding for MSL**
- **Shallow ground ice in mid-to-high latitudes**
- **Diverse surface mineralogy points to diverse, potentially habitable ancient environments**

## *Mars Exploration Rovers: Spirit & Opportunity*

- **Evidence for past water activity on the ground and in the near-surface**

## *Phoenix*

- **Excavation of near-surface ice and salts at high latitudes**

## *Mars Science Laboratory – Curiosity*

- **Characterizing a potentially habitable site**

# *This Decade Mars Exploration*

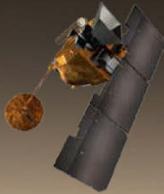
## *Launch Year*

1996



**Mars  
Global  
Surveyor**  
(mission completed)

2001



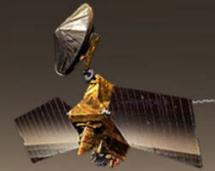
**Mars  
Odyssey**

2003



**Mars Express  
Collaboration**

2005



**Mars  
Reconnaissance  
Orbiter**

2007



**Phoenix**  
(mission completed)

2011



**Mars Science  
Laboratory**

**Mars  
Pathfinder**

**MEP Rovers  
*Spirit*  
*Opportunity***

# *Mars Pathfinder & Sojourner Rover*



*Solar System Exploration @ 50*

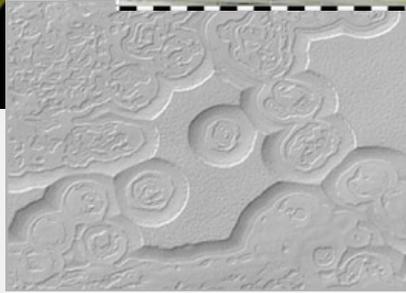
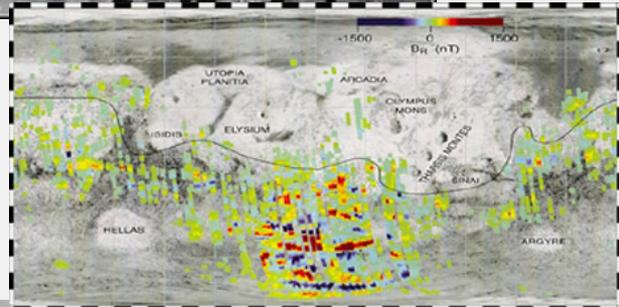
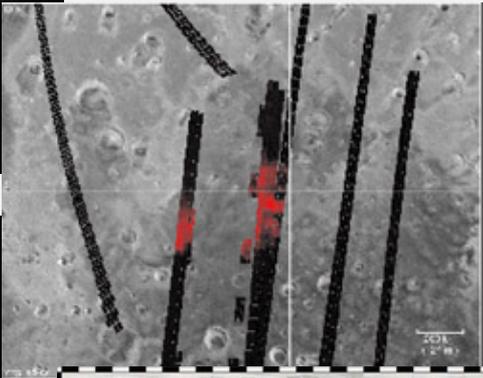
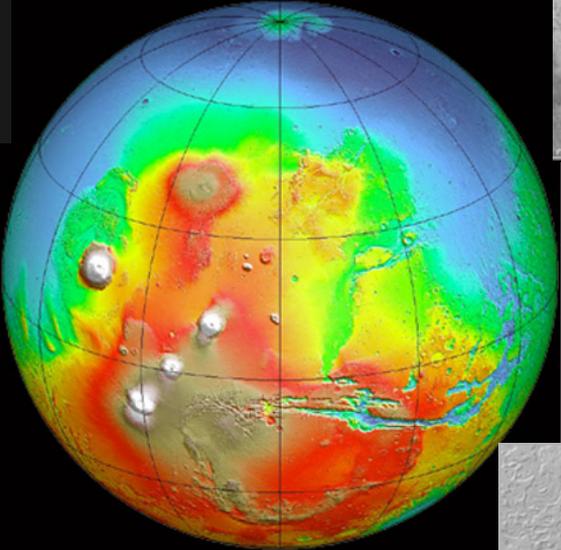
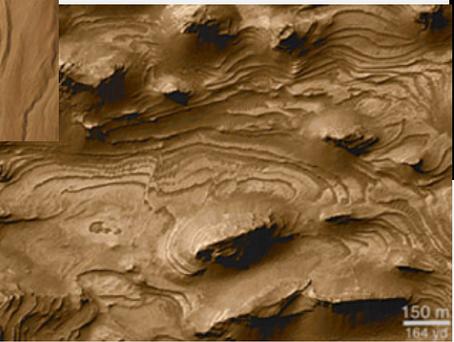
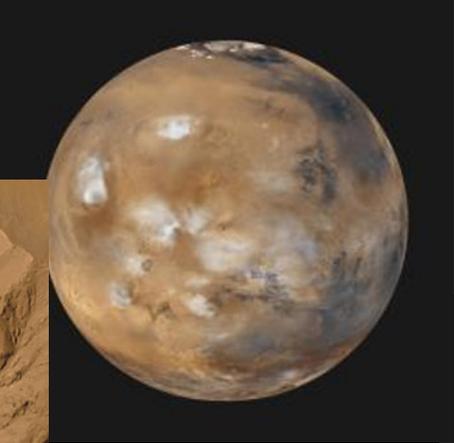


*CREDIT: NASA / JPL*

# *Mars Global Surveyor: A Science Catalyst for the Mars Exploration Program*



*Solar System Exploration @ 50*

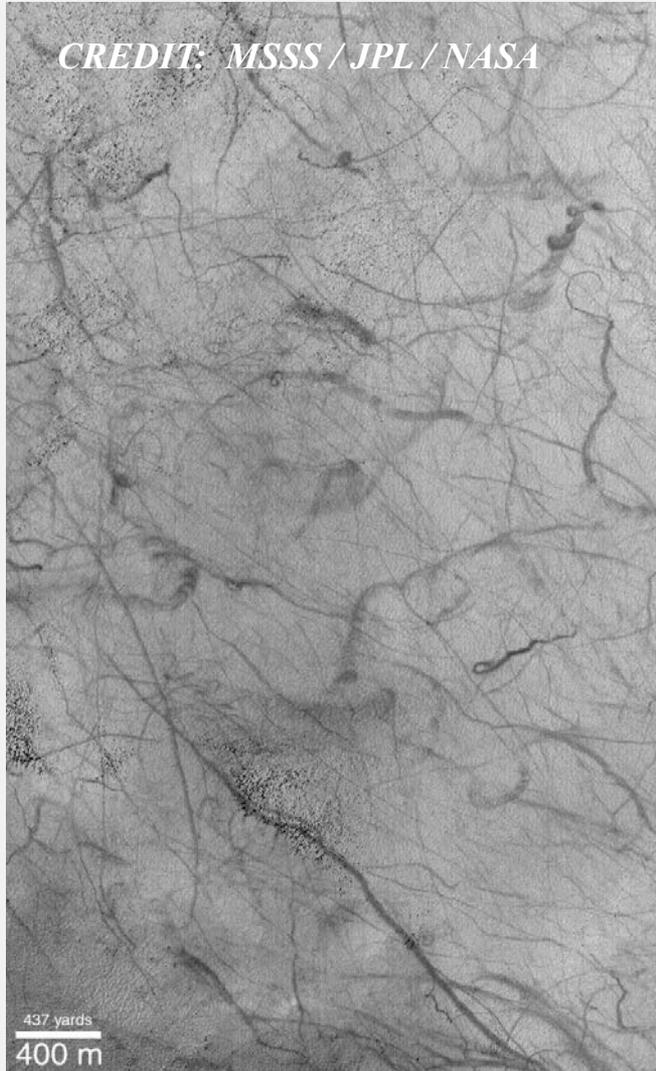


**MGS**  
**CREDITS: MSSS / GSFC / MIT**  
**JPL / NASA**

# How to Raise Dust on Mars



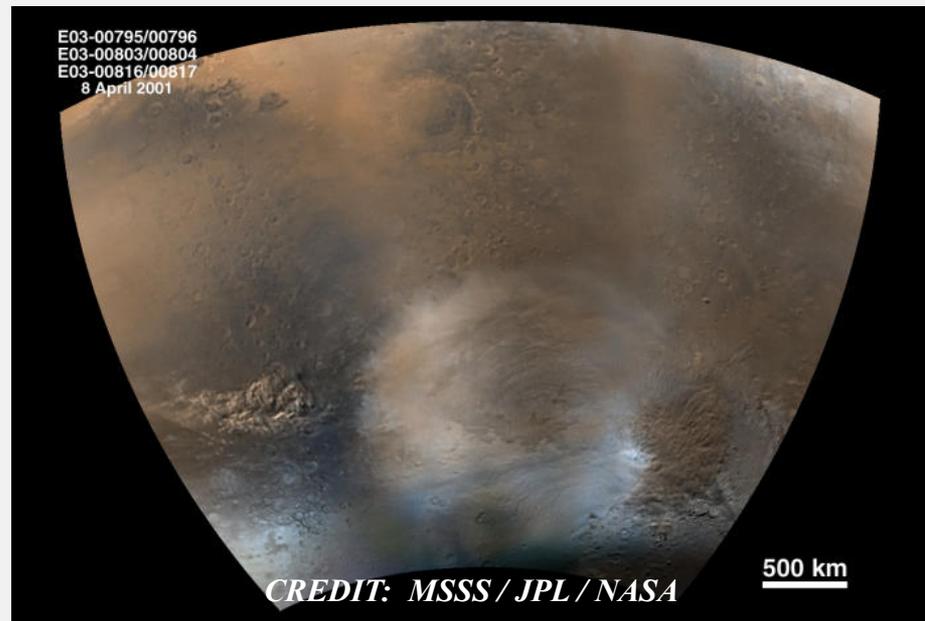
Solar System Exploration @ 50

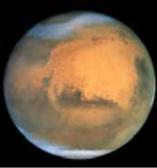


**MGS Mars Orbiter Camera (MOC)**

← *Dust Devil Tracks*

*Local Dust Storm at  
South Pole Cap Edge*





*Solar System Exploration @ 50*



Credit: NASA/JPL/University of Arizona

# Opportunity: Eagle Crater



*Solar System Exploration @ 50*



*MER*  
*CREDIT: NASA/JPL*

Martian  
“Blueberries”

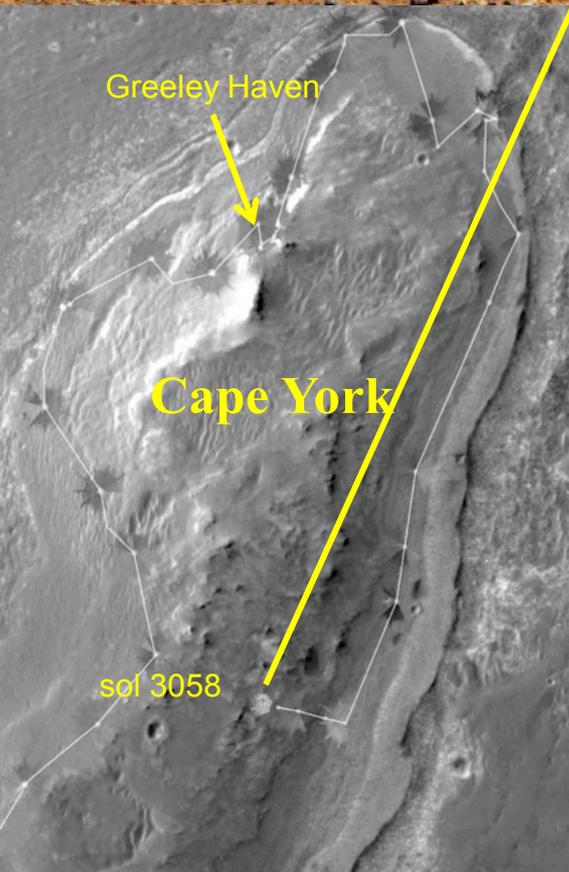
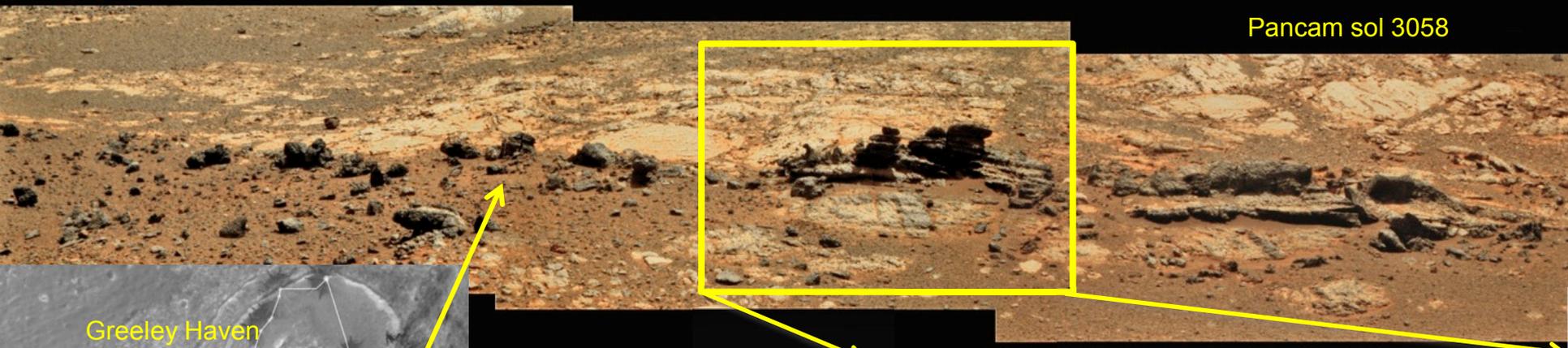


# Opportunity at Endeavour Crater

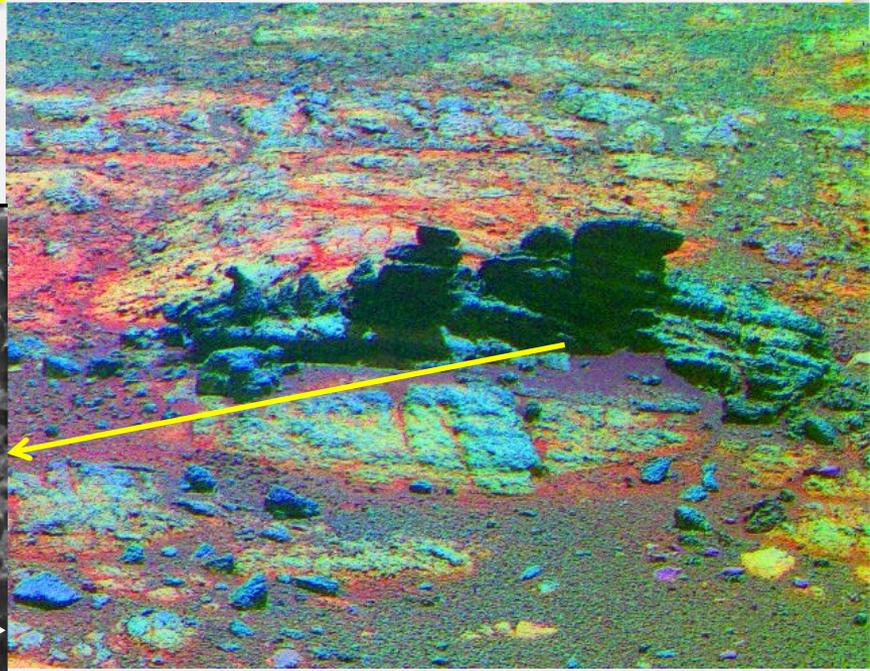
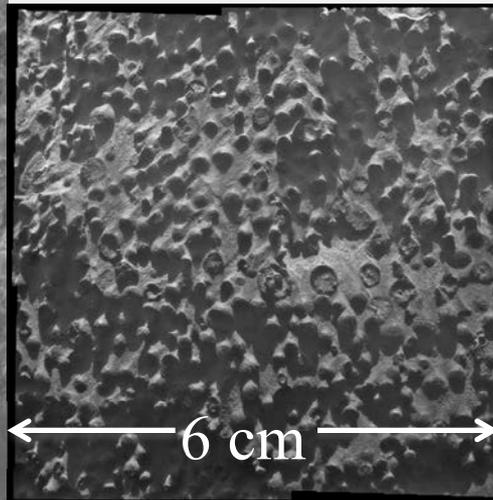


Solar System Exploration @ 50

Pancam sol 3058



**MER-B**

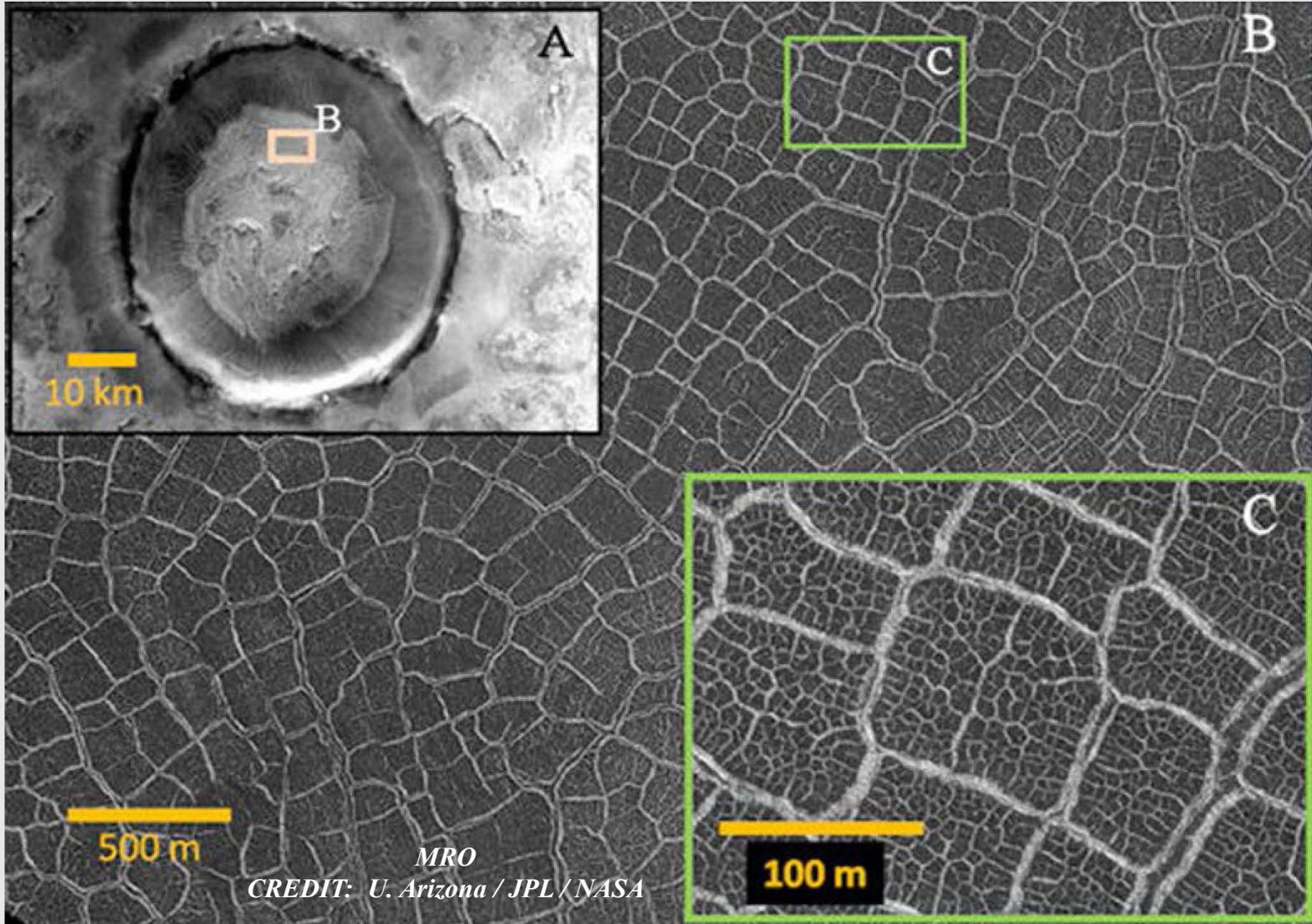


spectral principal component stretch 22

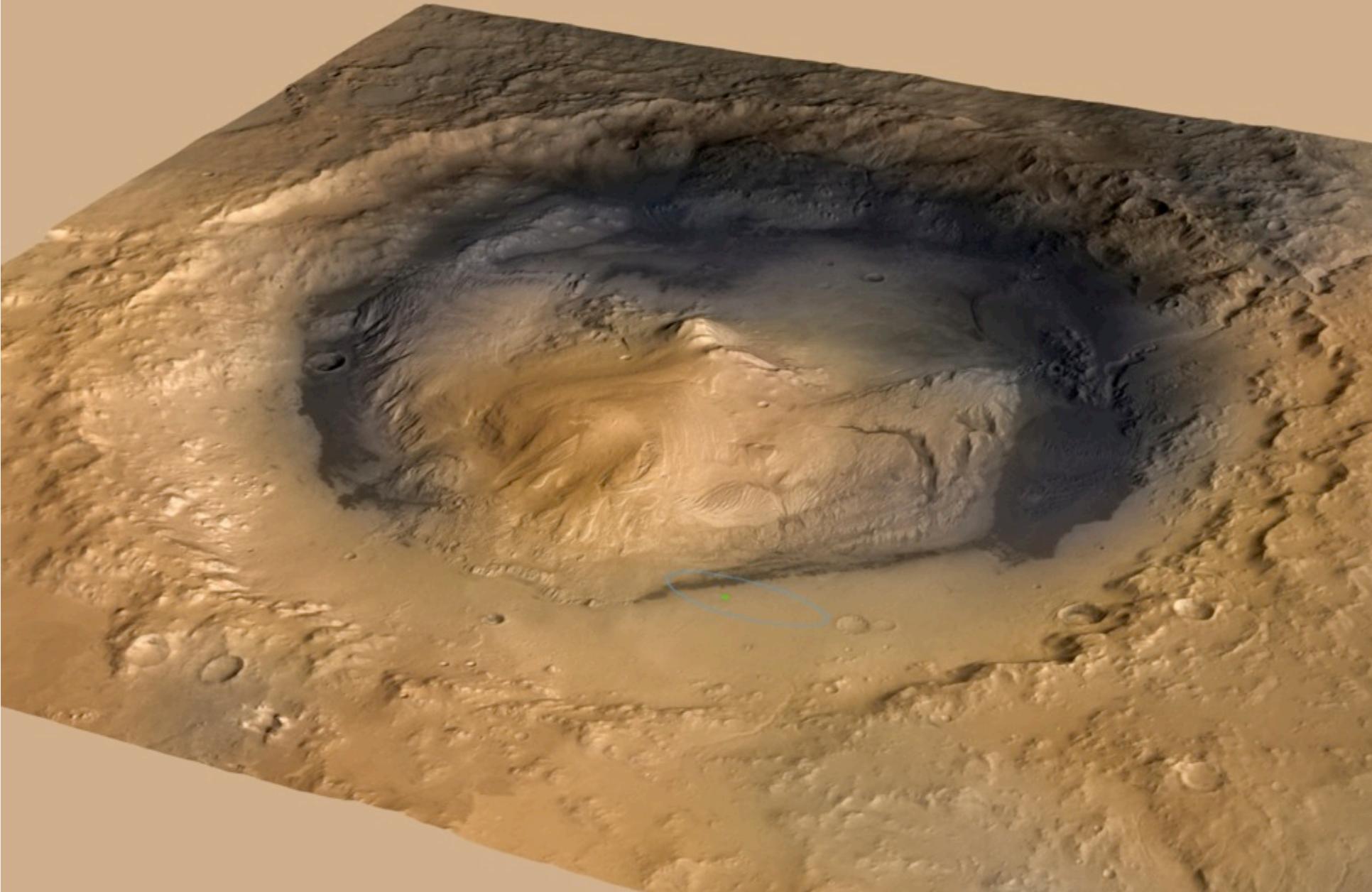
# Mars Patterned Ground



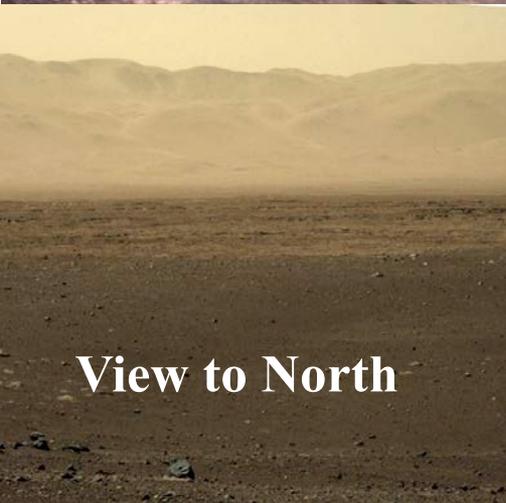
Solar System Exploration @ 50



# *Gale Crater and Mount Sharp*



# *Foothills of Mt. Sharp*



**View to North**

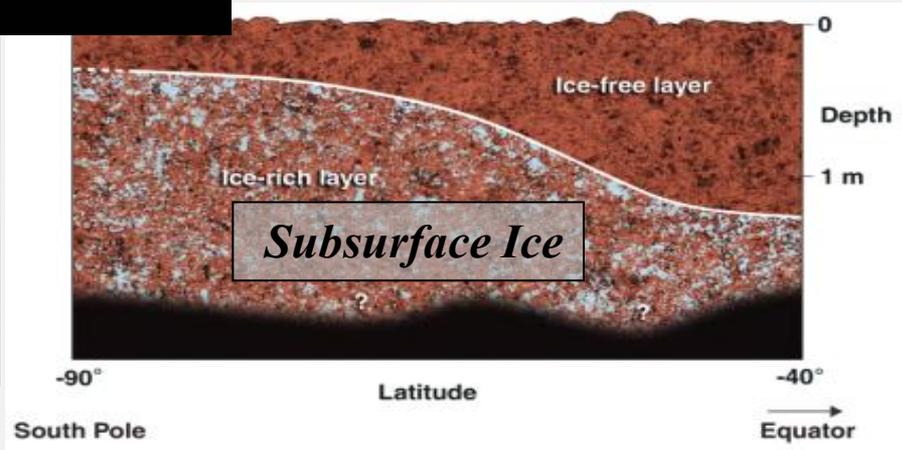
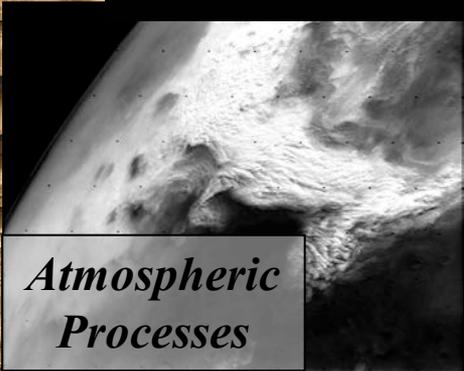
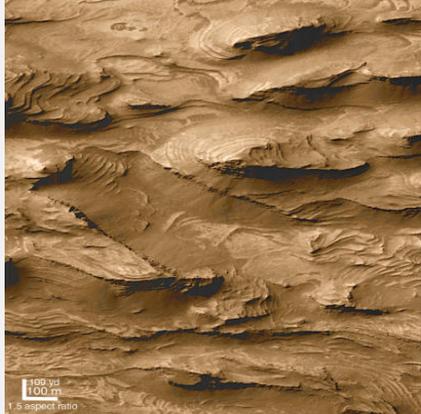
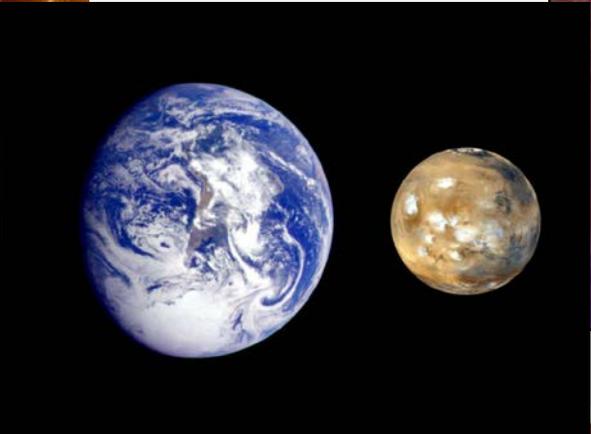
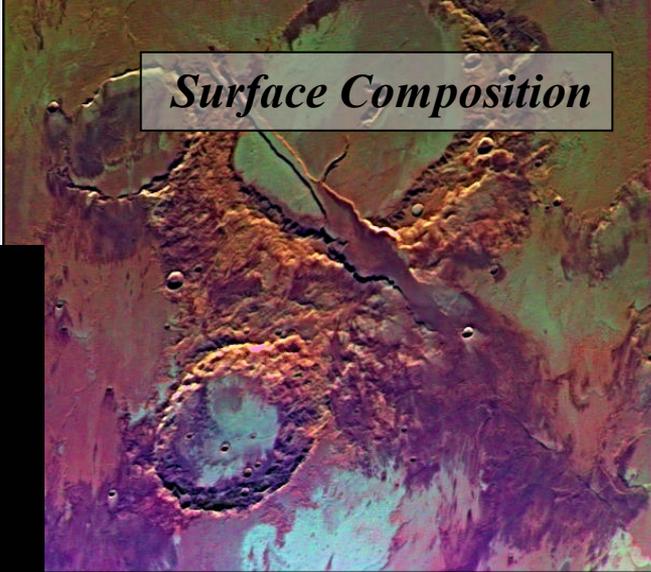
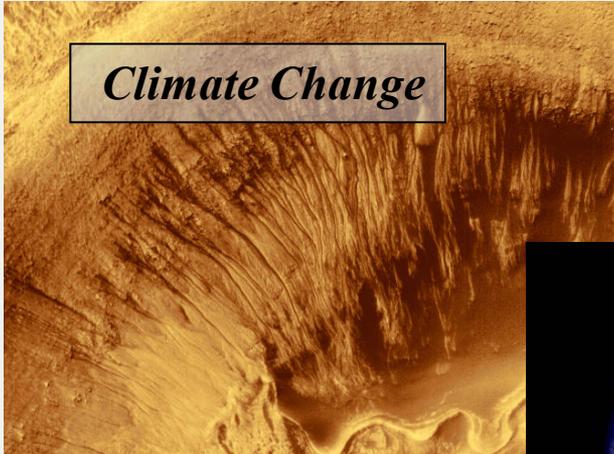
*Credit: MastCam / MSSS / JPL / NASA*

# Mars: A Complex Planet



Solar System Exploration @ 50

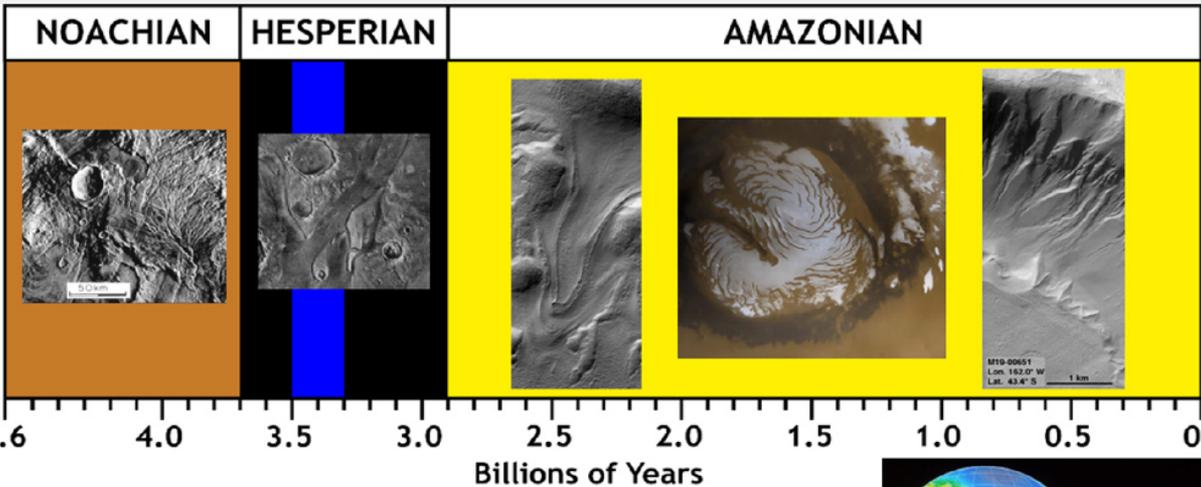
## Comparative Planetology



# Mars Planetary Evolution



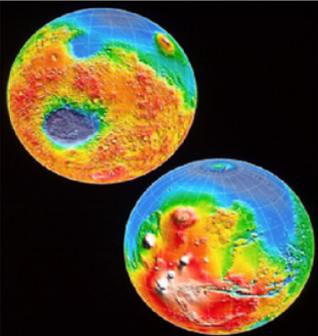
Solar System Exploration @ 50



- Heavy impact bombardment.
- Valley networks.
- "Warm/Wet" early Mars?

- Volcanism.
- Outflow channels.
- Oceans?
- South circumpolar deposits.

- Low impact rates.
- Tharsis volcanism continues.
- Outflow channels continue.
- Late-stage polar caps.
- "Cold/Dry" late Mars.



All Missions

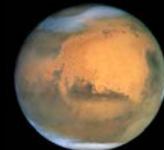
## Hydrous Mineralogy Changed Over Time

- 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

# Mars: A Planet Changing Today



*Solar System Exploration @ 50*

*Possible Brine Flows?*



*Global Dust Storm*



June 26, 2001



September 4, 2001

*New Gully Flows*



*Polar Cap Extent*

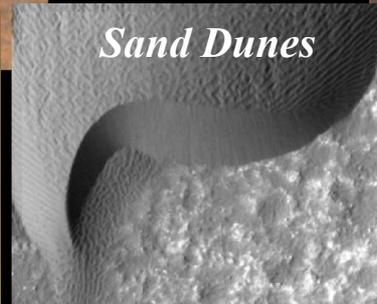


March 1999



January 2001

*Sand Dunes*



*Polar Cap Landslides*



*Credits: HST / MRO STSci / U. Arizona / JPL / NASA*

# *Why Mars?*



*Solar System Exploration @ 50*

- ***Mars: An Abode for Life?***
  - Mars is in the “habitable zone” with an early climate that had liquid water and sunlight on its surface, with basic elements to utilize
  - If life originated there, does it still exist? If life did not originate there, why not?
- ***Mars: Comparative Study with Earth***
  - The climate of Mars has changed profoundly over time
  - The record of that change is preserved in its surface morphology and composition. Mars was once wetter--and possibly warmer--with a much more active hydrological cycle
- ***Mars: A destination?***
  - Of all the planets, Mars is the most accessible
  - Astronauts could walk on its surface by-mid century

# Robots and Humans

DISCOVERY  
EXPLORATION

Climate History



Sample Selection



Ancient Water



Validate Paleo-Life

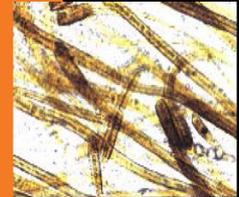


*3<sup>rd</sup> Wave of Space Exploration?*

Resources



Extant Life?



ROBOTICS ROBOTICS ROBOTICS HUMANS ROBOTICS & HUMANS



Reconnaissance



Site Selection



Sample Selection



Return Sample



Field Studies



Deep Drilling