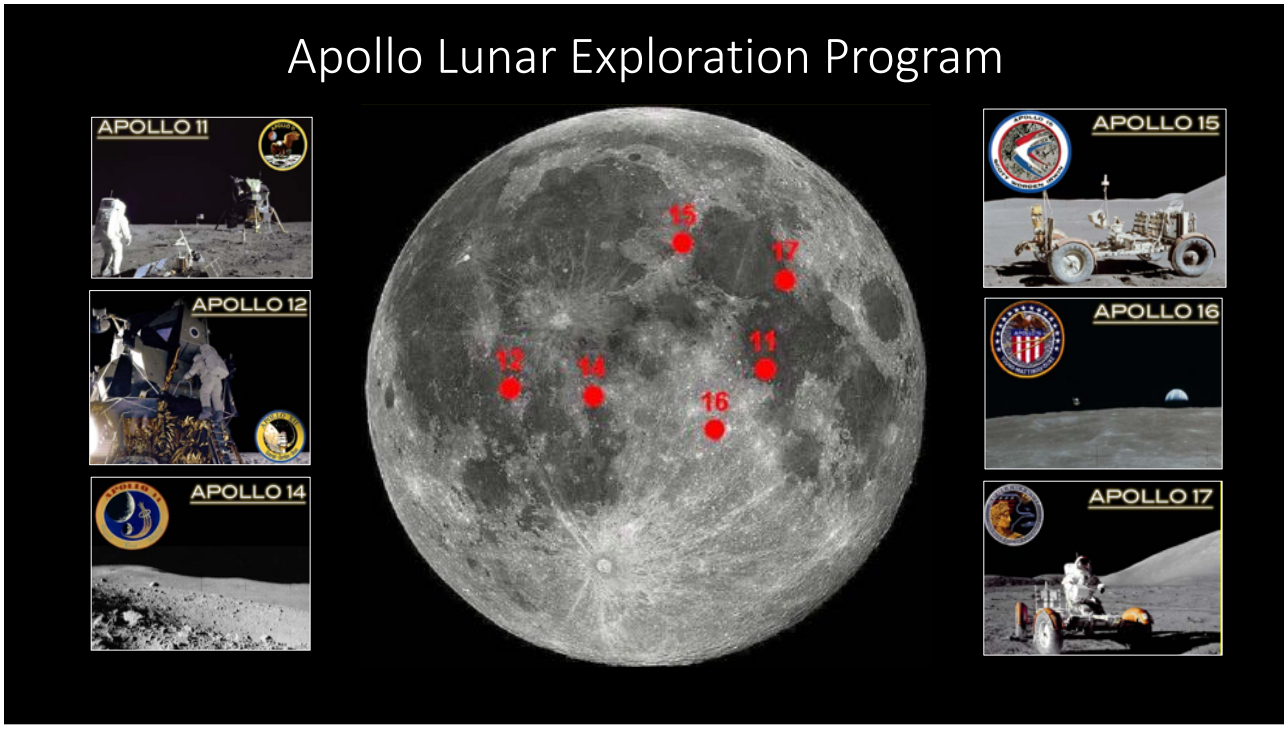
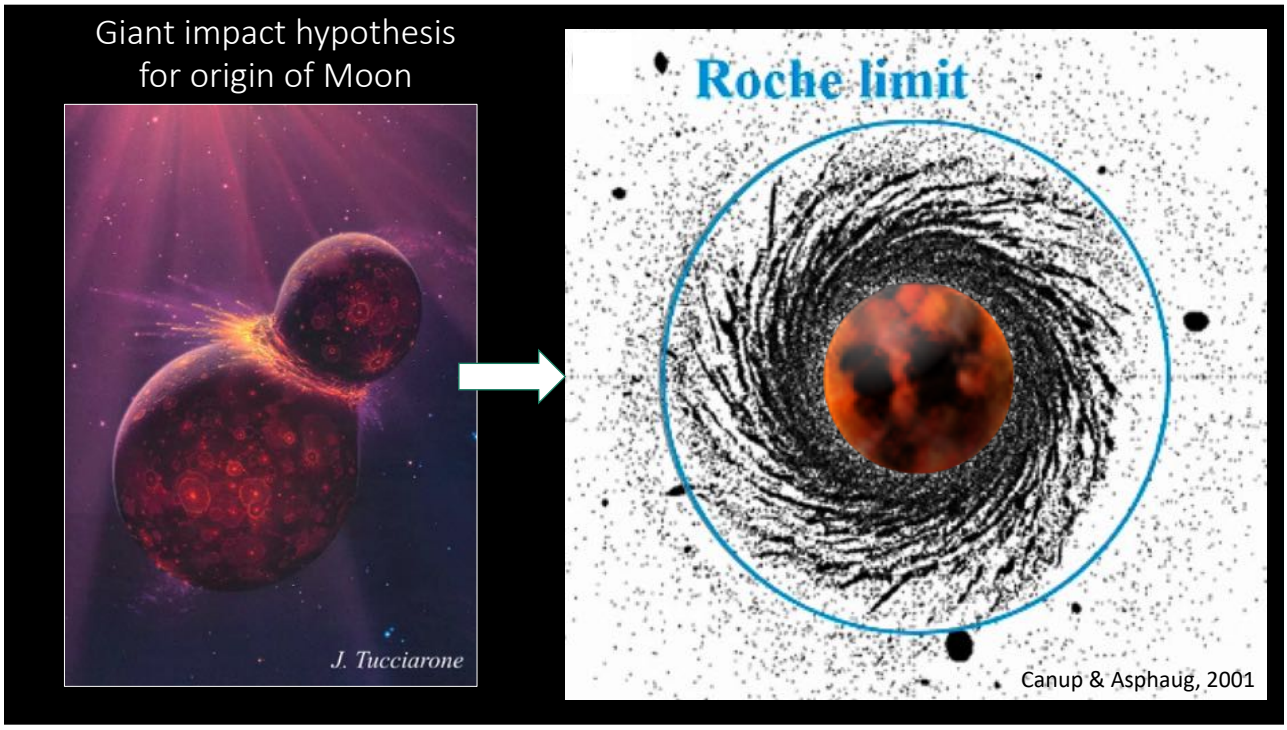

NASA
Exploration of the Moon
and then onto Mars
James L. Green
NASA Scientist & Senior Advisor
MASPG
February 16, 2022

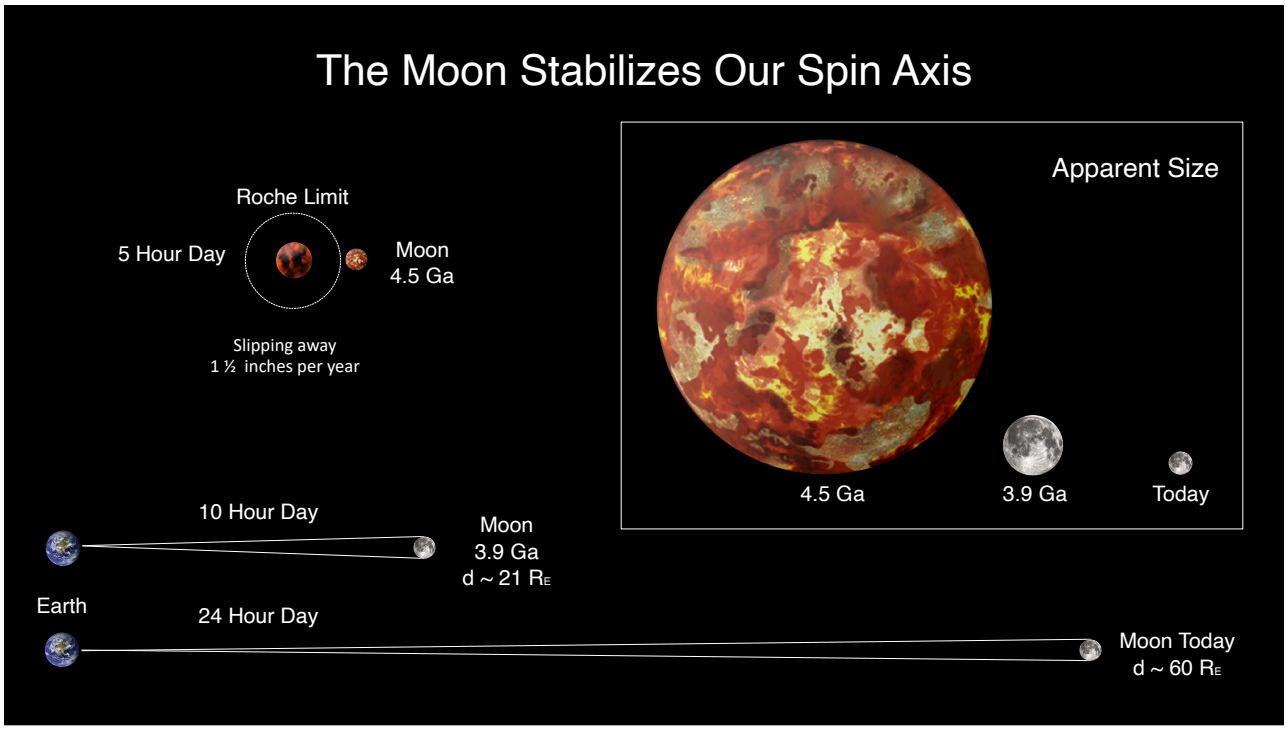
1


Apollo Lunar Exploration Program
APOLLO 11
APOLLO 12
APOLLO 14
APOLLO 15
APOLLO 16
APOLLO 17
15
17
12
14
11
16

2


Giant impact hypothesis
for origin of Moon
J. Tucciarone
Roche limit
Canup & Asphaug, 2001

3


The Moon Stabilizes Our Spin Axis
Roche Limit
5 Hour Day
Moon
4.5 Ga
Slipping away
1 ½ inches per year
Apparent Size
4.5 Ga
3.9 Ga
Today
10 Hour Day
Moon
3.9 Ga
d ~ 21 RE
Earth
24 Hour Day
Moon Today
d ~ 60 RE

4

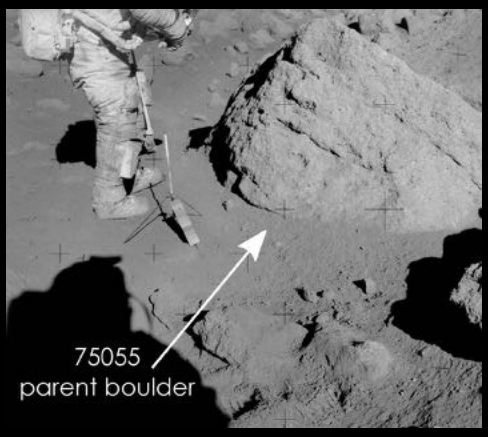
Magnetic History

<300 Ma ~650 Ma ~2 Ga Today

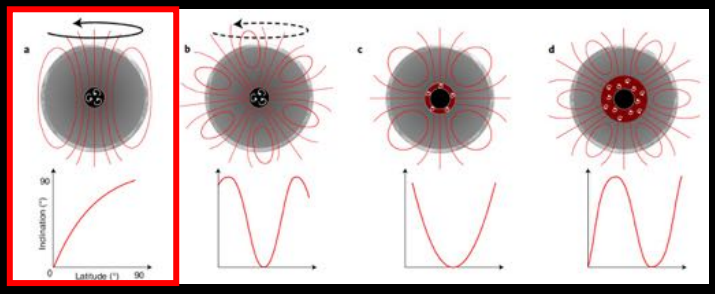
Adapted from Mighani et al., *Sci. Adv.*, 2020

5

What is the Orientation of the Lunar Internal Field?

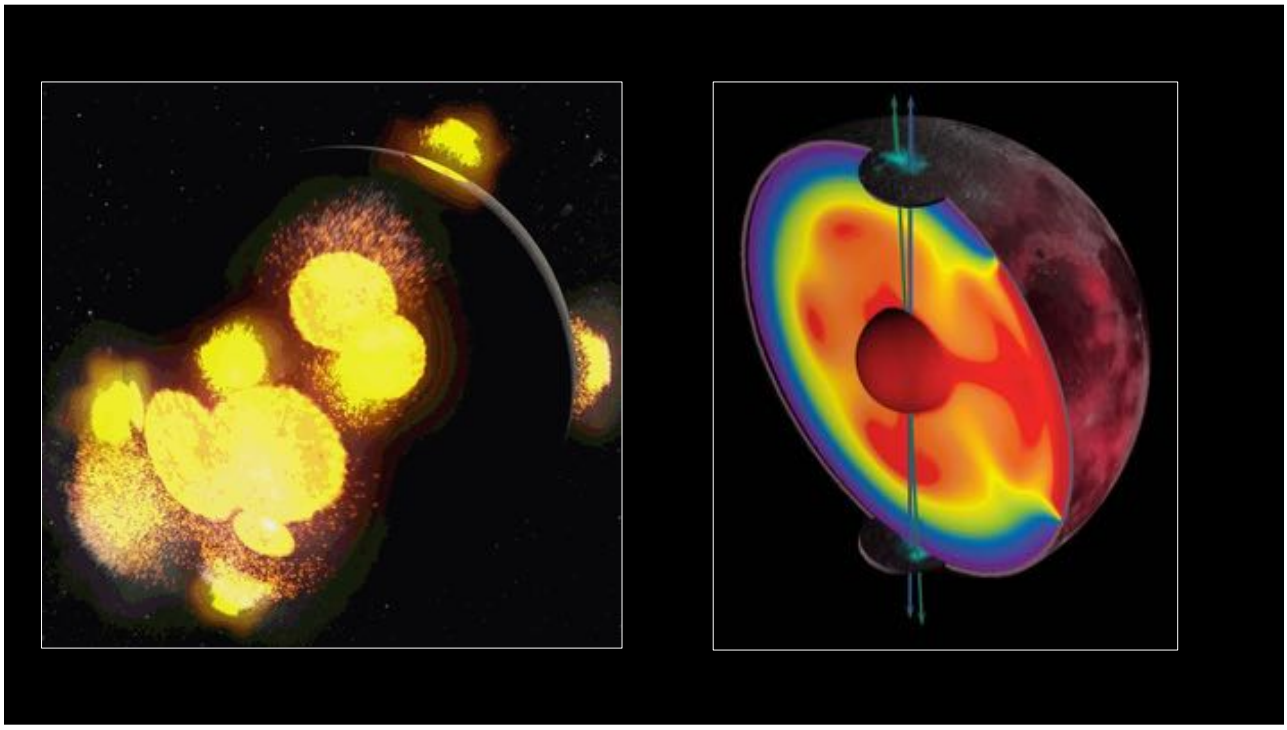


Nichols et al., *Nature Astron.*, 2021

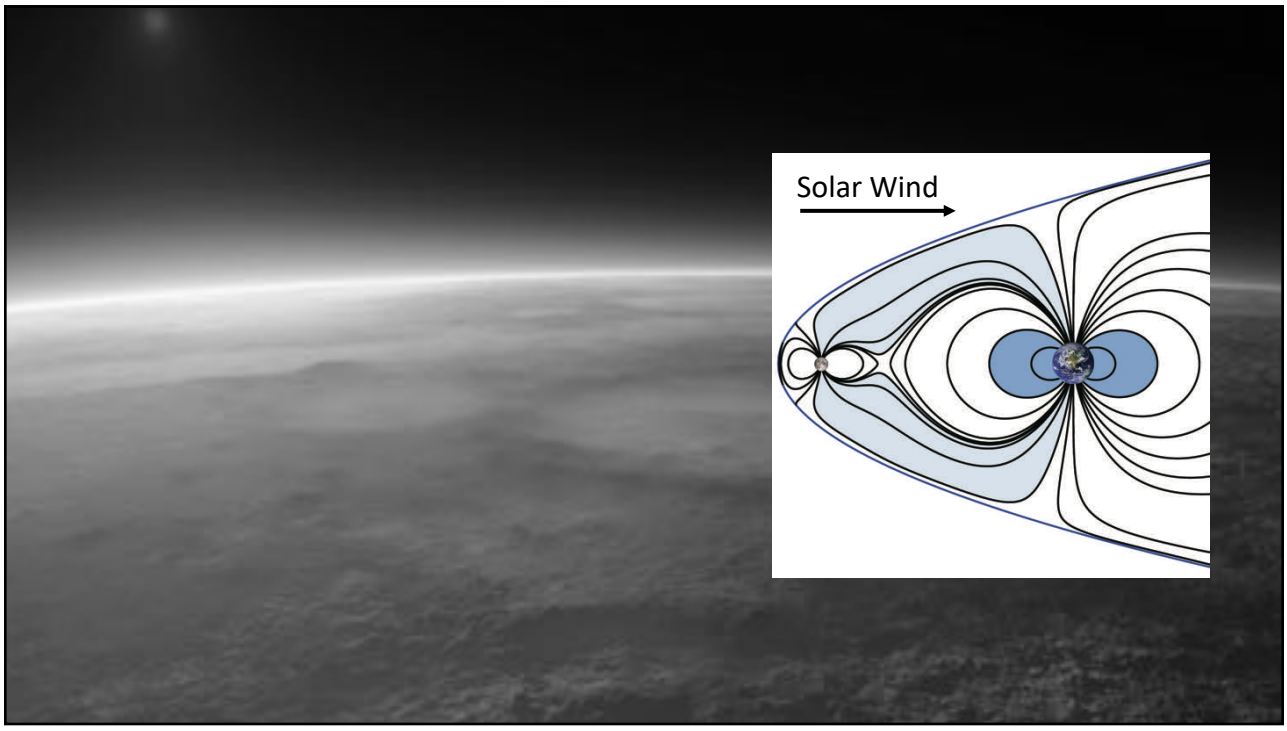


- The geometry of the Lunar field is largely unknown due to lack of knowledge of the orientation of most lunar samples
- However, recently analyzed Apollo 17 basalts are consistent with an axial symmetric dipole
- Some observations may indicate reversals or quadrupole moments

6

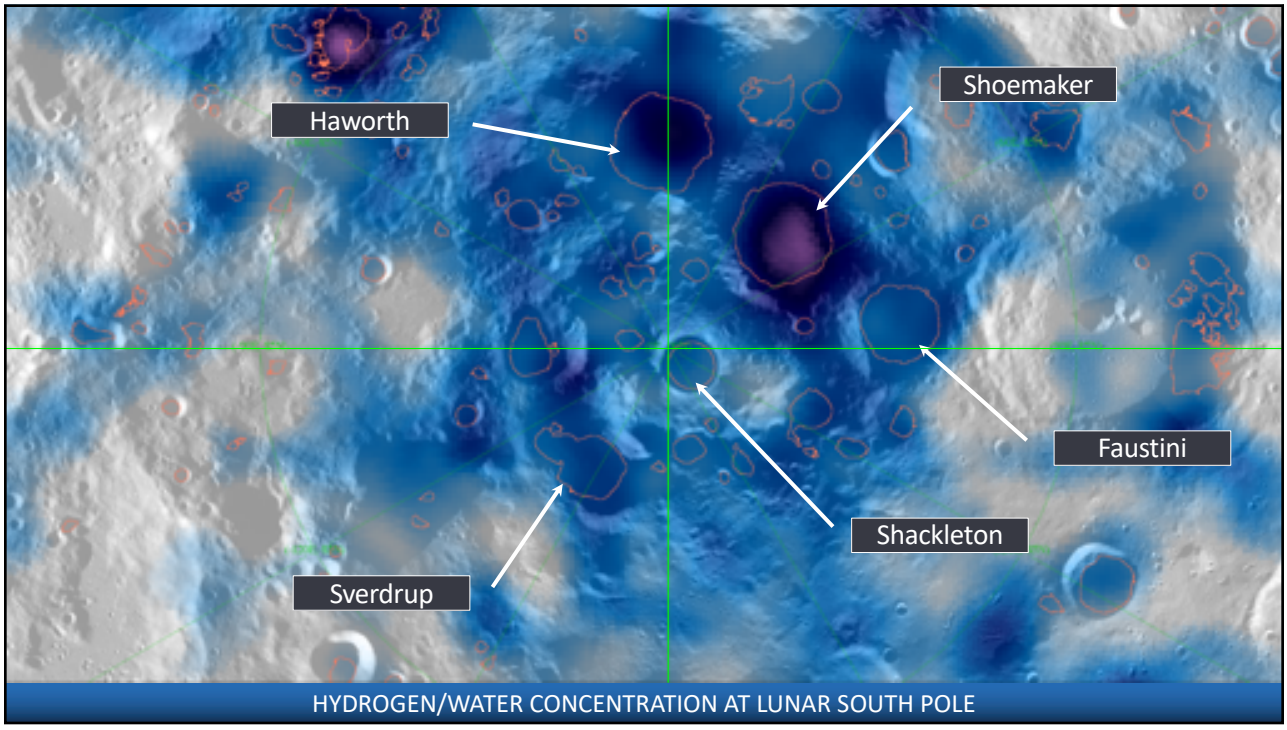


7

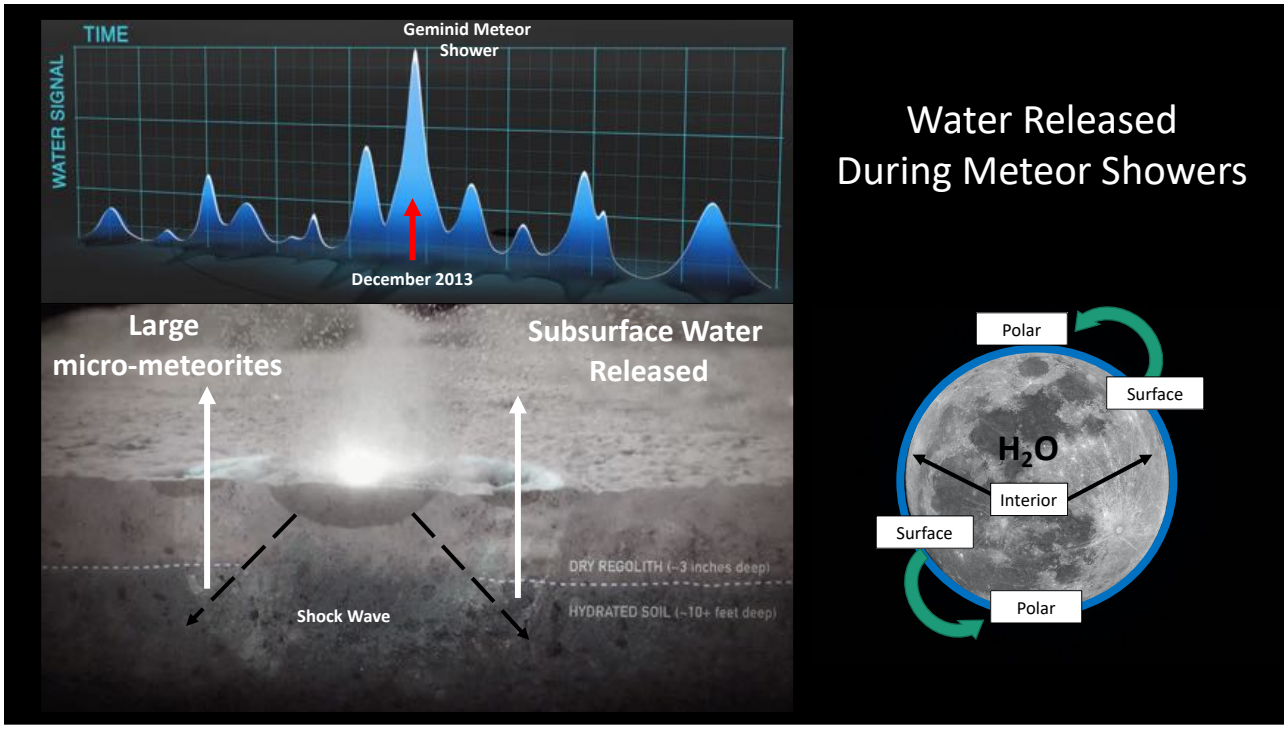


8

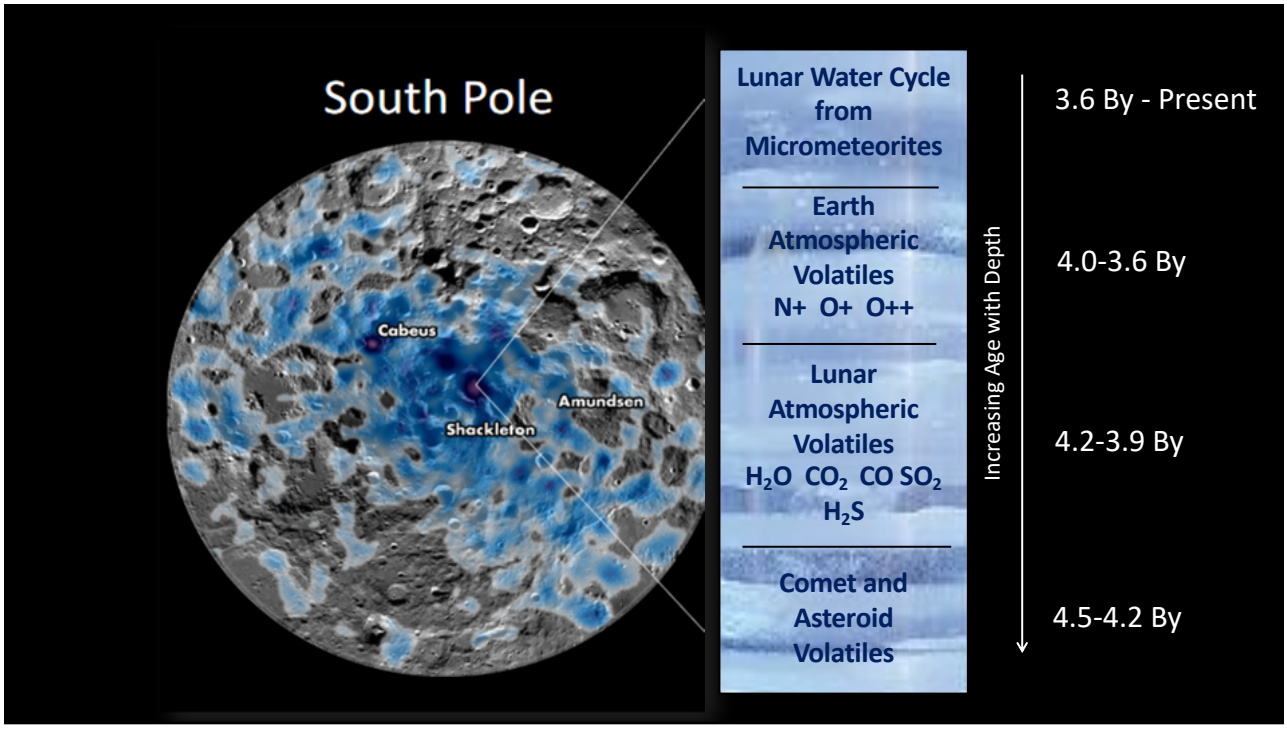
9


Haworth
Shoemaker
Faustini
Shackleton
Sverdrup
HYDROGEN/WATER CONCENTRATION AT LUNAR SOUTH POLE

10


TIME
WATER SIGNAL
Geminid Meteor Shower
December 2013
Large micro-meteorites
Subsurface Water Released
Shock Wave
DRY REGOLITH (~3 inches deep)
HYDRATED SOIL (~10+ feet deep)
Water Released During Meteor Showers
Polar
Surface
H_2O
Interior
Surface
Polar

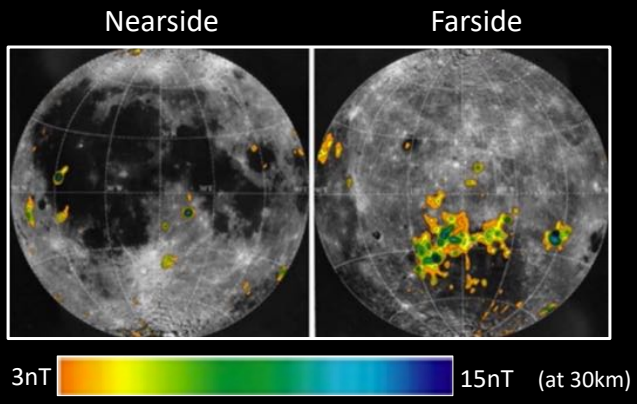
11


South Pole
Cabeus
Amundsen
Shackleton
Lunar Water Cycle from Micrometeorites
Earth Atmospheric Volatiles
N+ O+ O++
Lunar Atmospheric Volatiles
H_2O CO_2 CO SO_2 H_2S
Comet and Asteroid Volatiles
Increasing Age with Depth
3.6 By - Present
4.0-3.6 By
4.2-3.9 By
4.5-4.2 By

12

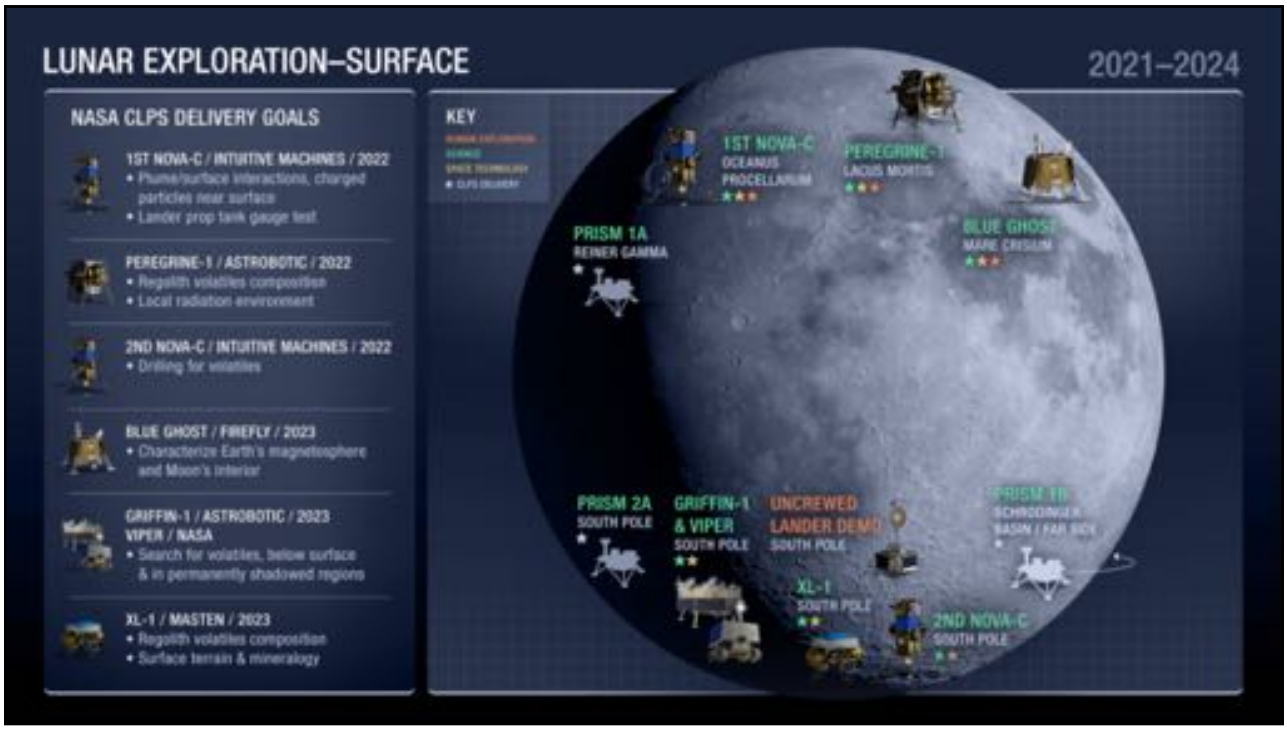
Magnetic Anomalies: Fe, Ni, and PGM

- Platinum group metals (PGM) are primarily located in SPA Basin
- PGM concentration in iron meteorites can reach 200 ppm



PGM	Value per kg
Platinum	$28,290
Palladium	$31,860
Osmium	$12,860
Iridium	$45,330
Rhodium	$72,660
Ruthenium	$8,038.05

13



14

Artemis Accords: International Guidelines

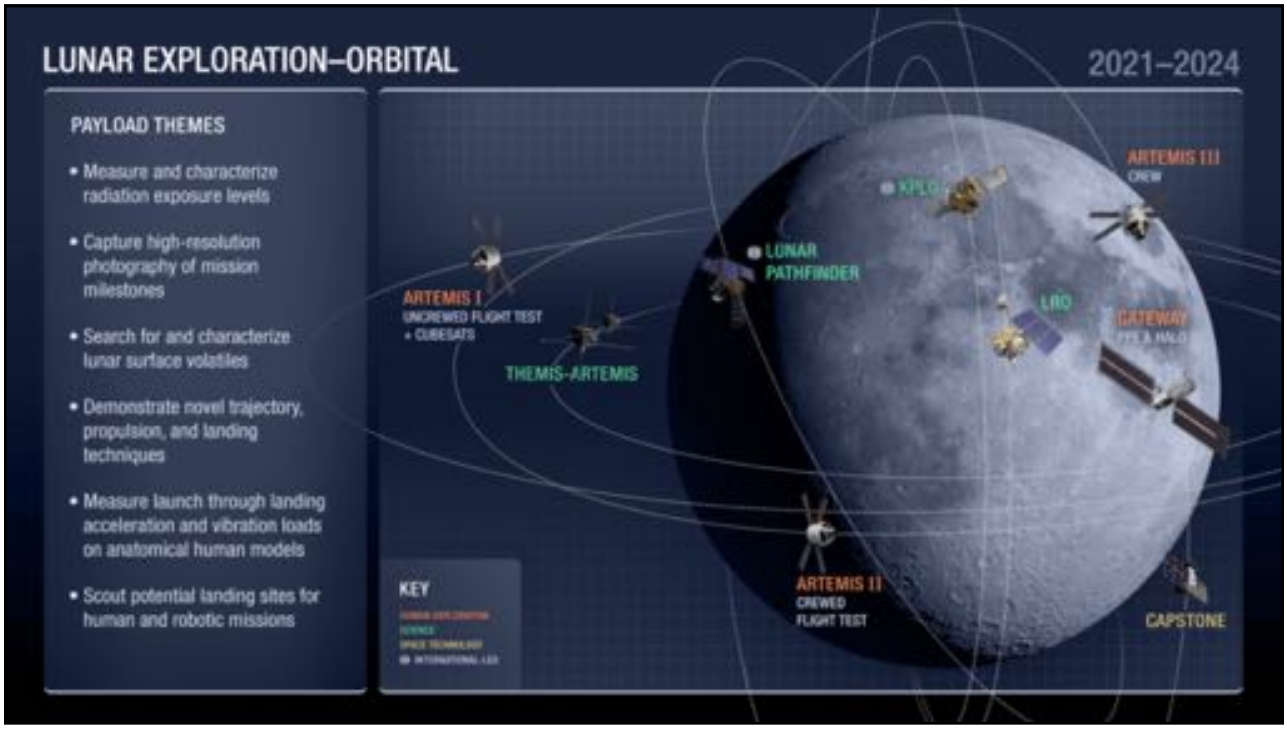
- Peaceful Purposes
- Transparency
- Interoperability
- Emergency Assistance
- Registration of Space Objects
- Release of Scientific Data
- Protecting Heritage
- Space Resources
- Deconfliction of Activities
- Orbital Debris and Spacecraft Disposal

15

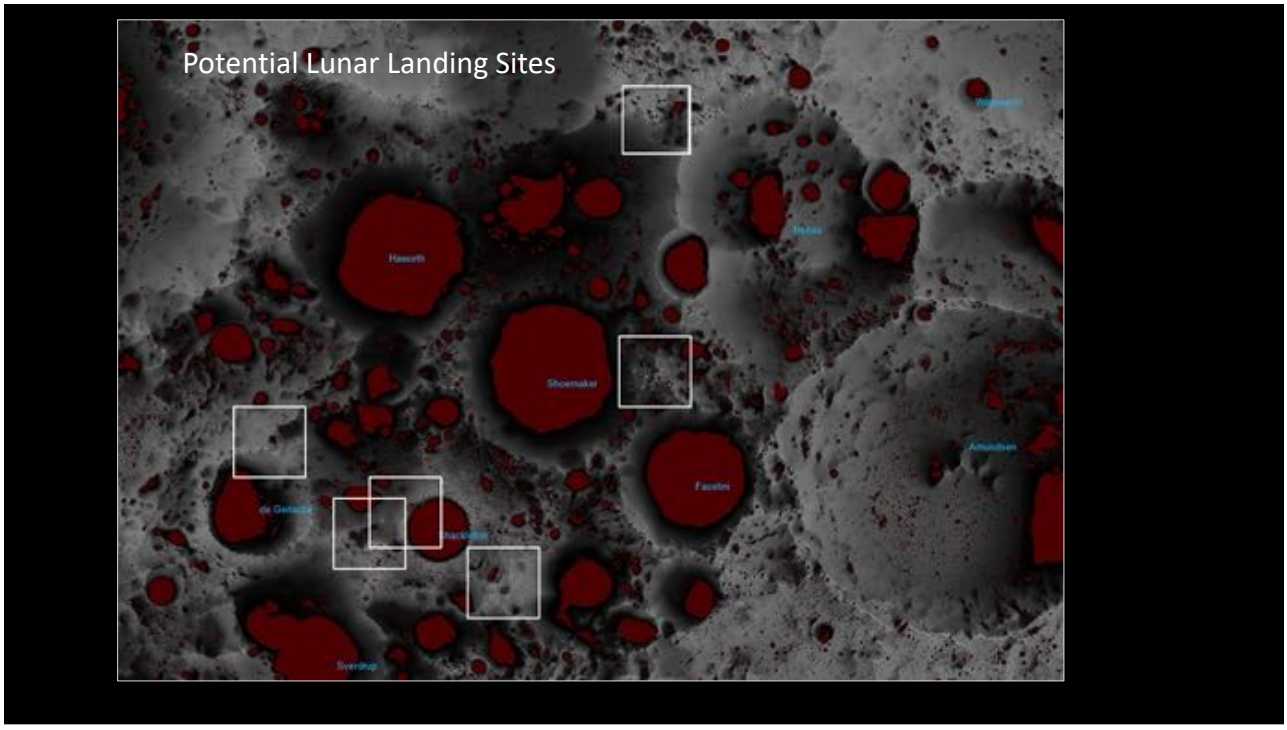
SLS and Orion

ORION

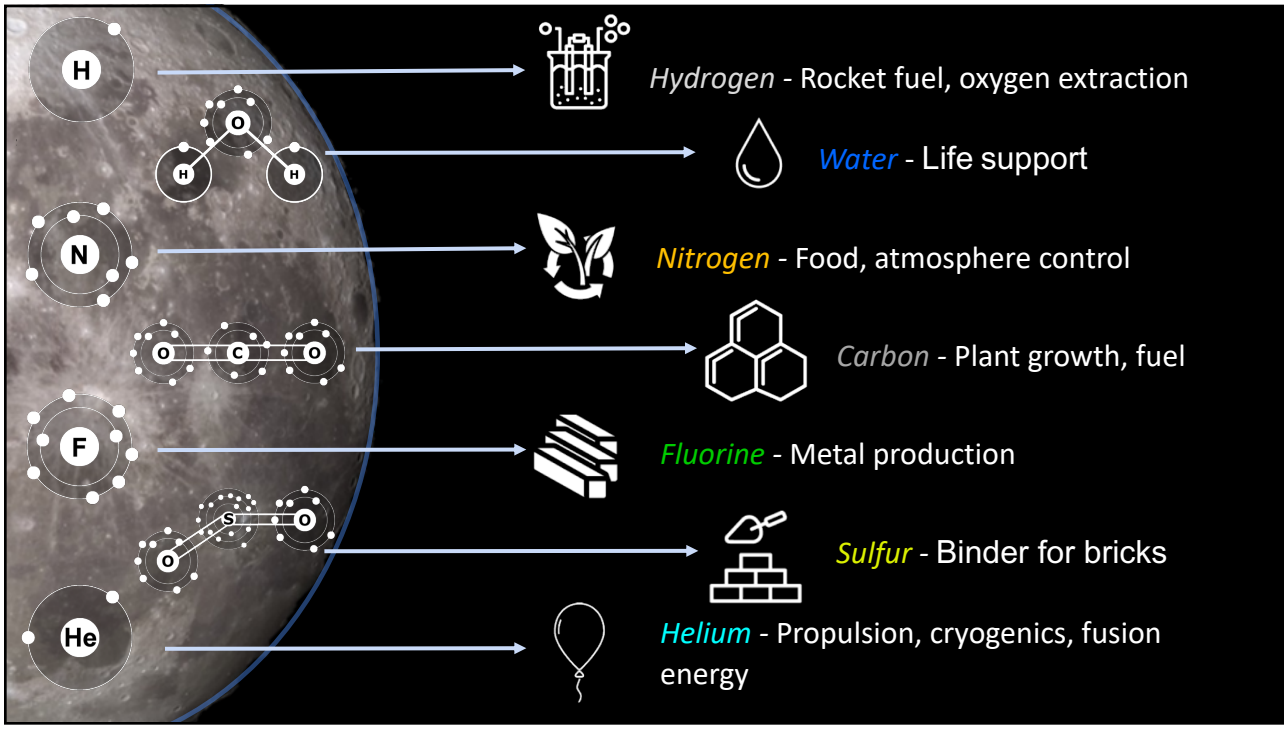
16


LUNAR EXPLORATION–ORBITAL
2021–2024
PAYLOAD THEMES
• Measure and characterize radiation exposure levels
• Capture high-resolution photography of mission milestones
• Search for and characterize lunar surface volatiles
• Demonstrate novel trajectory, propulsion, and landing techniques
• Measure launch through landing acceleration and vibration loads on anatomical human models
• Scout potential landing sites for human and robotic missions
KEY
ARTEMIS I
UNCREWED FLIGHT TEST
+ CUBESATS
THEMIS-ARTEMIS
LUNAR PATHFINDER
KPLO
ARTEMIS III
CREW
LRO
GATEWAY
ARTEMIS II
CREWED
FLIGHT TEST
CAPSTONE

17


Potential Lunar Landing Sites
Haworth
Shoemaker
Faustini
Amundsen
Nobile
Sverdrup

18


H
O
H
H
N
O
C
O
F
S
O
O
He
Hydrogen - Rocket fuel, oxygen extraction
Water - Life support
Nitrogen - Food, atmosphere control
Carbon - Plant growth, fuel
Fluorine - Metal production
Sulfur - Binder for bricks
Helium - Propulsion, cryogenics, fusion energy

19


Carbon - **Plant growth, fuel**
Nitrogen - **Food, atmosphere control**
Water - **Life support**
NASA

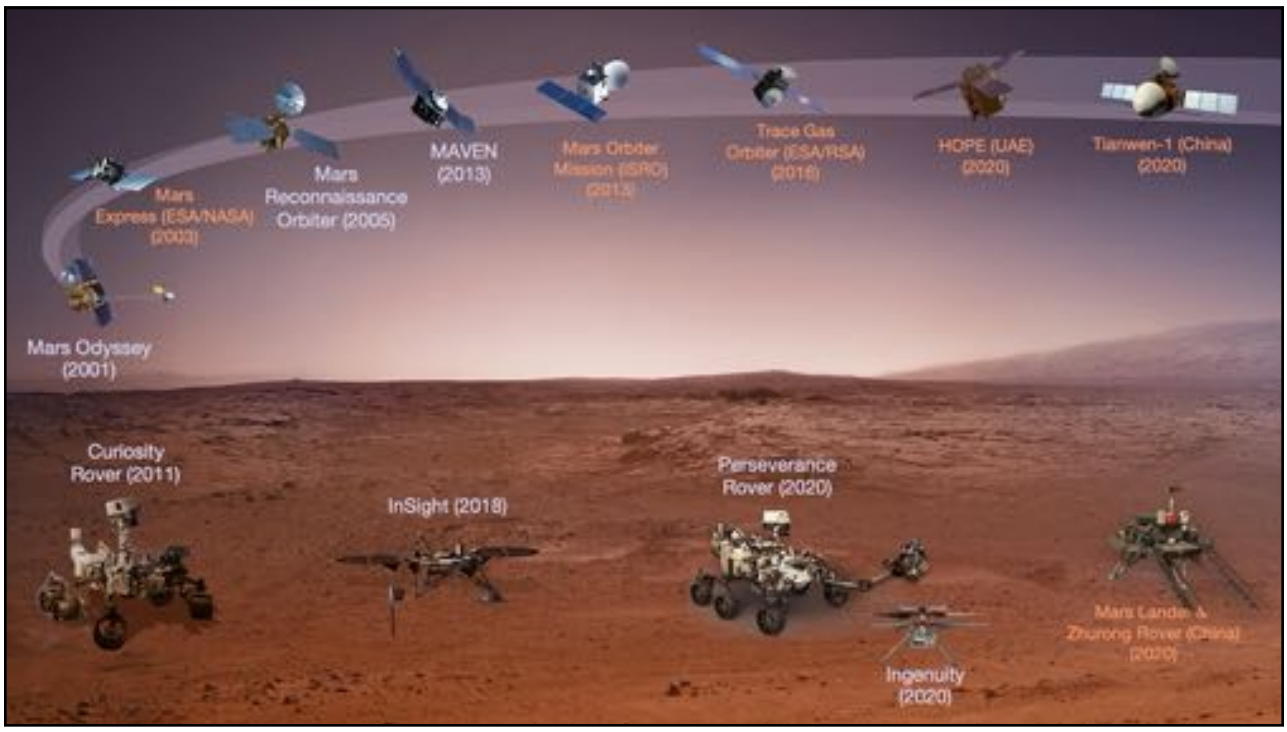
20


SCIENCE
HUMAN EXPLORATION AND OPERATIONS
SPACE TECHNOLOGY
21

21

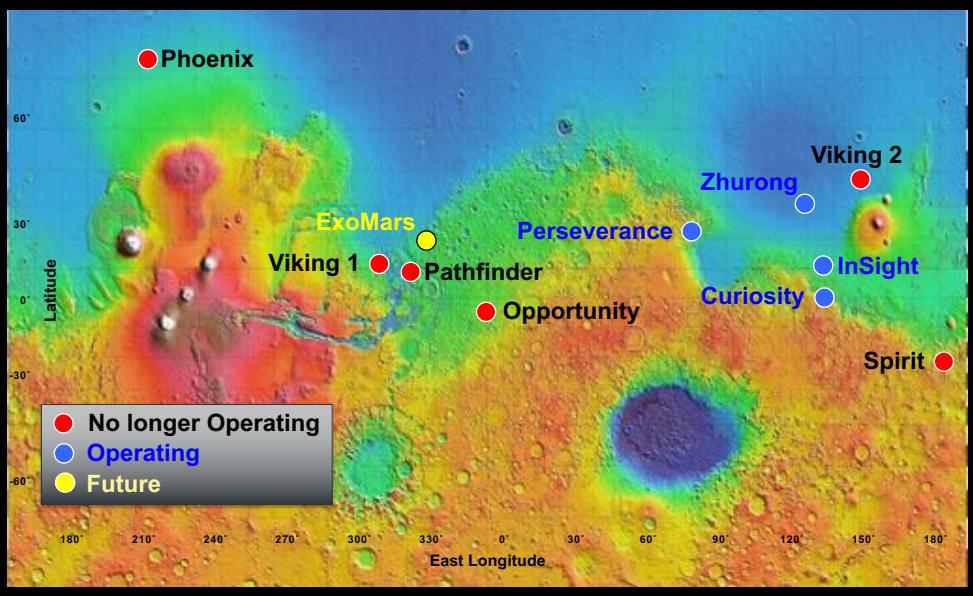

Future Moon
Science & Exploration
Living off the Land
Multi-planet Species
Fuel Depot
Mining
Manufacturing

22

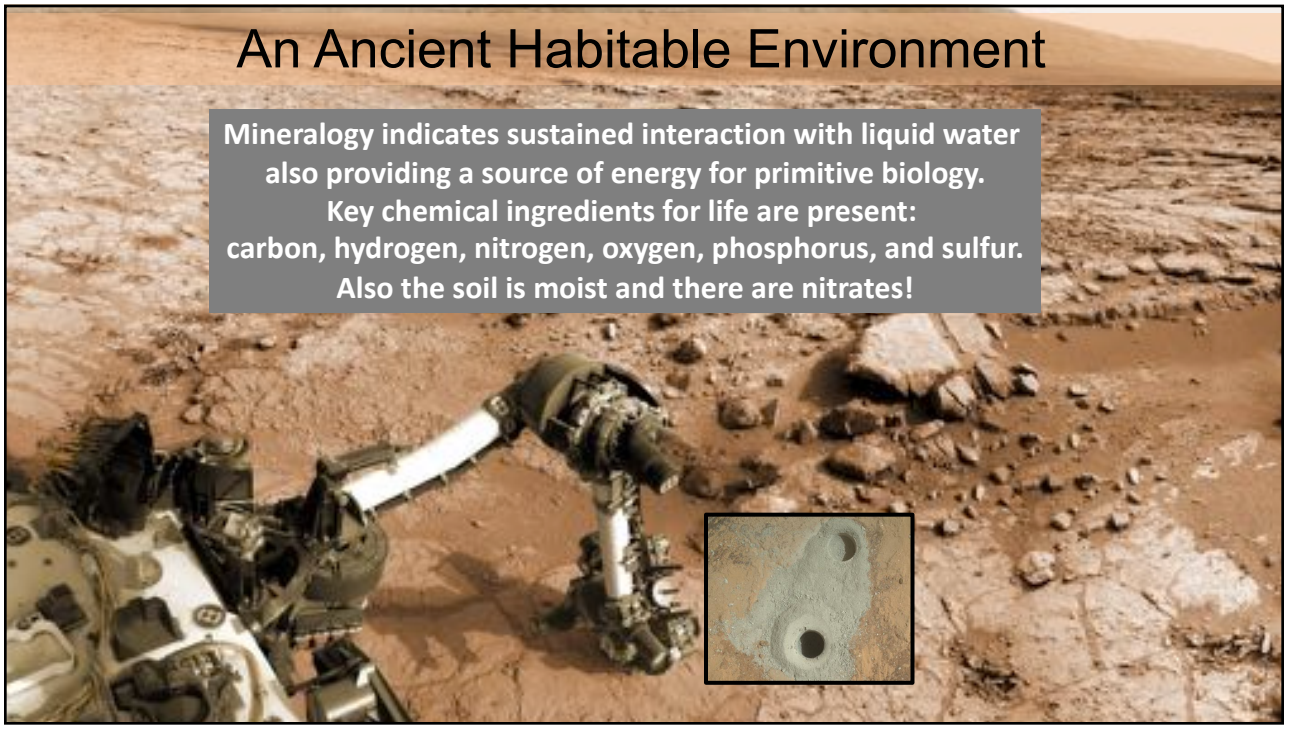


23

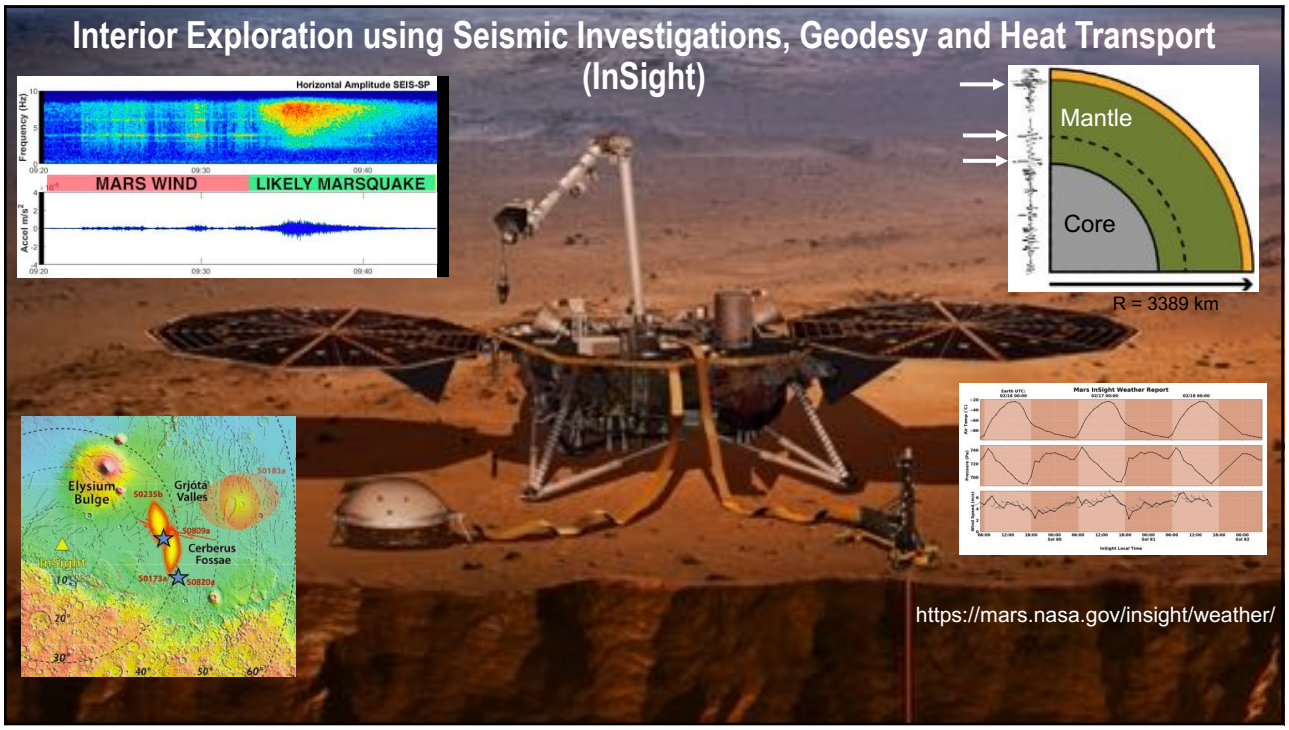
Location of the Landers and Rovers



24


An Ancient Habitable Environment
Mineralogy indicates sustained interaction with liquid water
also providing a source of energy for primitive biology.
Key chemical ingredients for life are present:
carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur.
Also the soil is moist and there are nitrates!

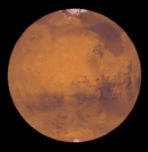
25


Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight)
Horizontal Amplitude SEIS-SP
Frequency (Hz)
MARS WIND
LIKELY MARSQUAKE
Accel m/s²
Mantle
Core
R = 3389 km
Elysium Bulge
Grjóta Valles
Cerberus Fossae
S0235b
S0183a
S0809a
S0173a
S0820a
InSight
Mars InSight Weather Report
https://mars.nasa.gov/insight/weather/

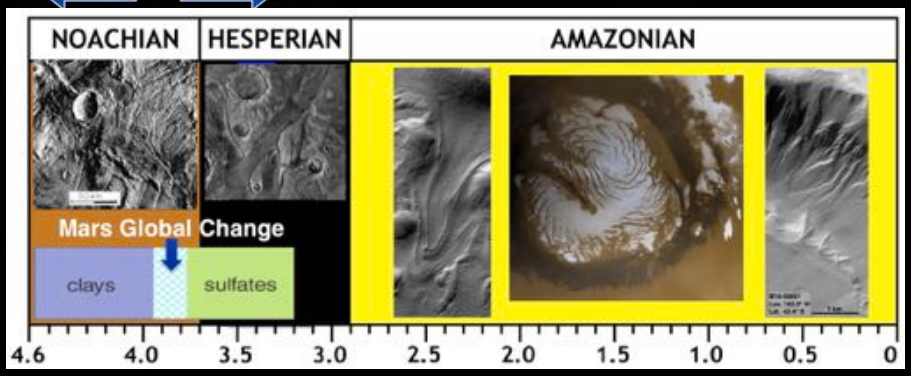
26

Ancient Water & Habitable Environments

Neutral pH Acidic



Anhydrous Ferric Oxides



Billions of Years

27

Where are these Discoveries Leading Us?

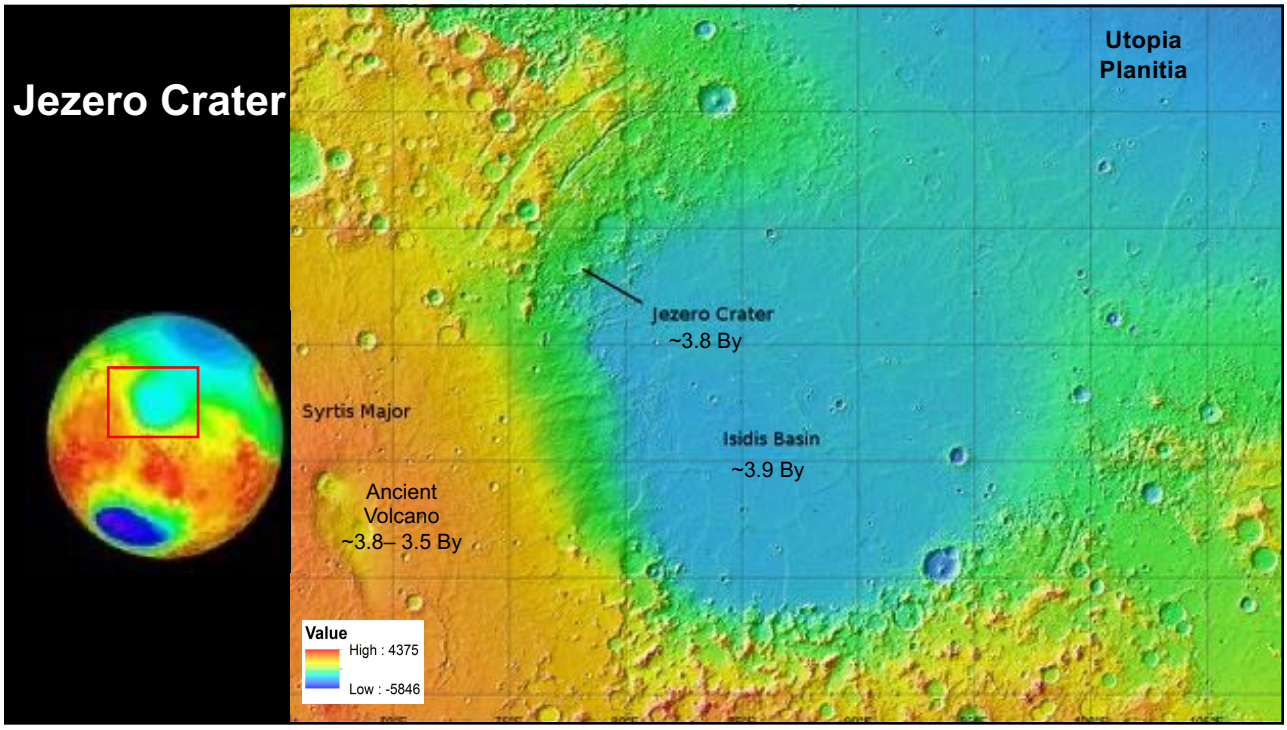
Ancient life - potential has increased

- Lots of signs of ancient liquid water: surface and underground
- Past geological environments that have reasonable potential to have preserved the evidence of life, had it existed
- Detection of complex organics has increased potential for preserved “fingerprints of life”

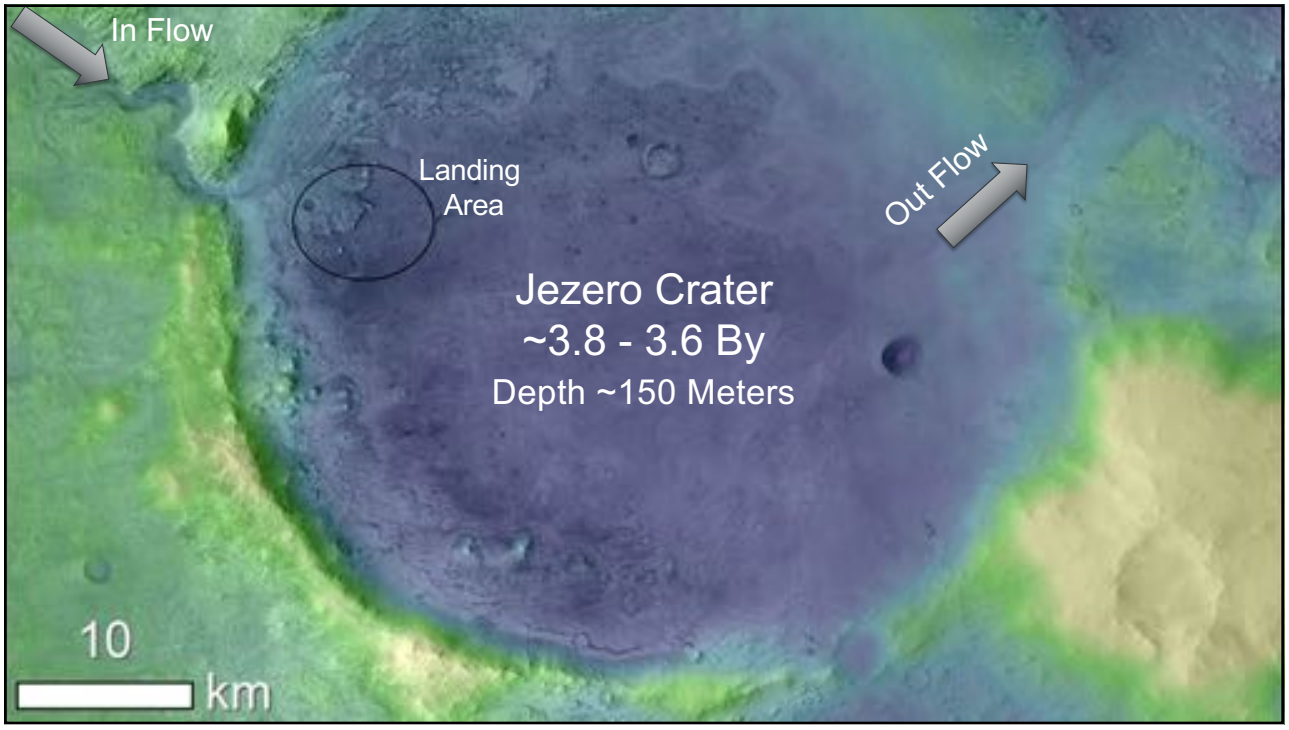
SUMMARY: We have a means to prioritize candidate sites, and reason to believe that the evidence we are seeking may be preserved and is within reach of our exploration systems.

NEXT STEPS: Mars Sample Return Campaign

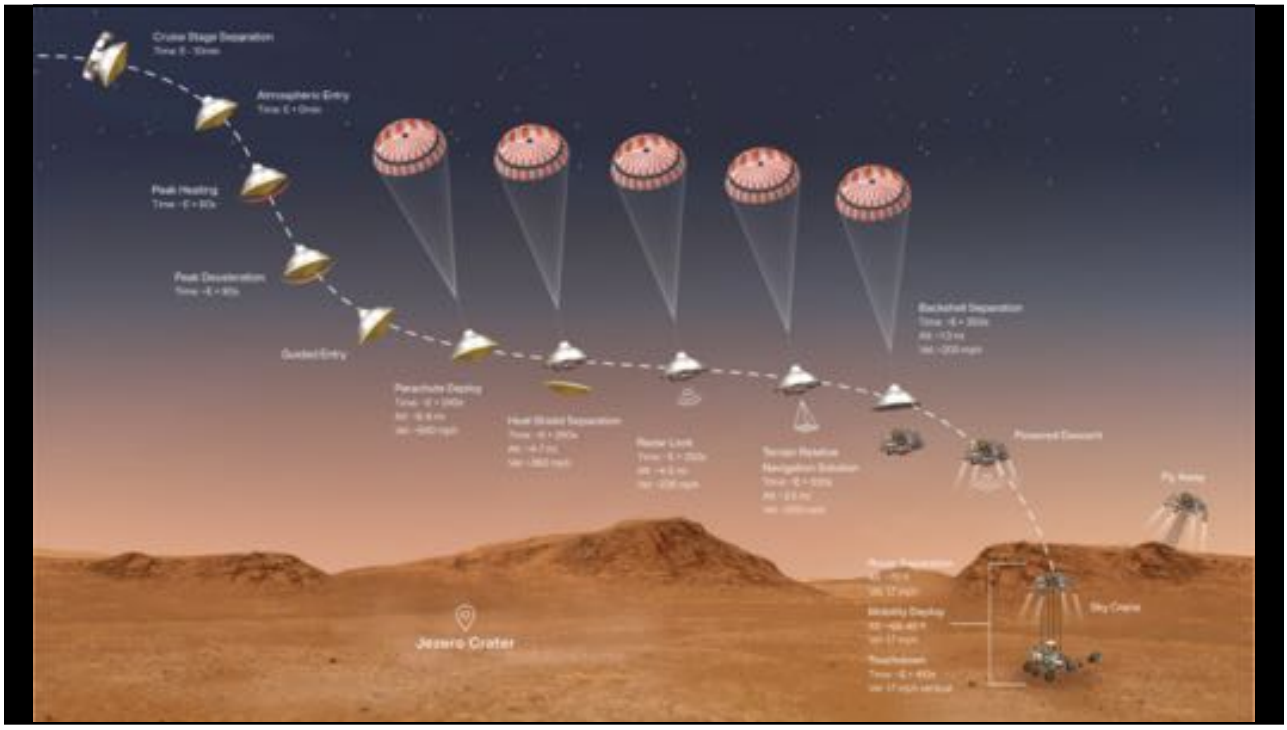
28


Jezero Crater
Utopia Planitia
Jezero Crater
~3.8 By
Syrtis Major
Isidis Basin
~3.9 By
Ancient Volcano
~3.8– 3.5 By
Value
High : 4375
Low : -5846

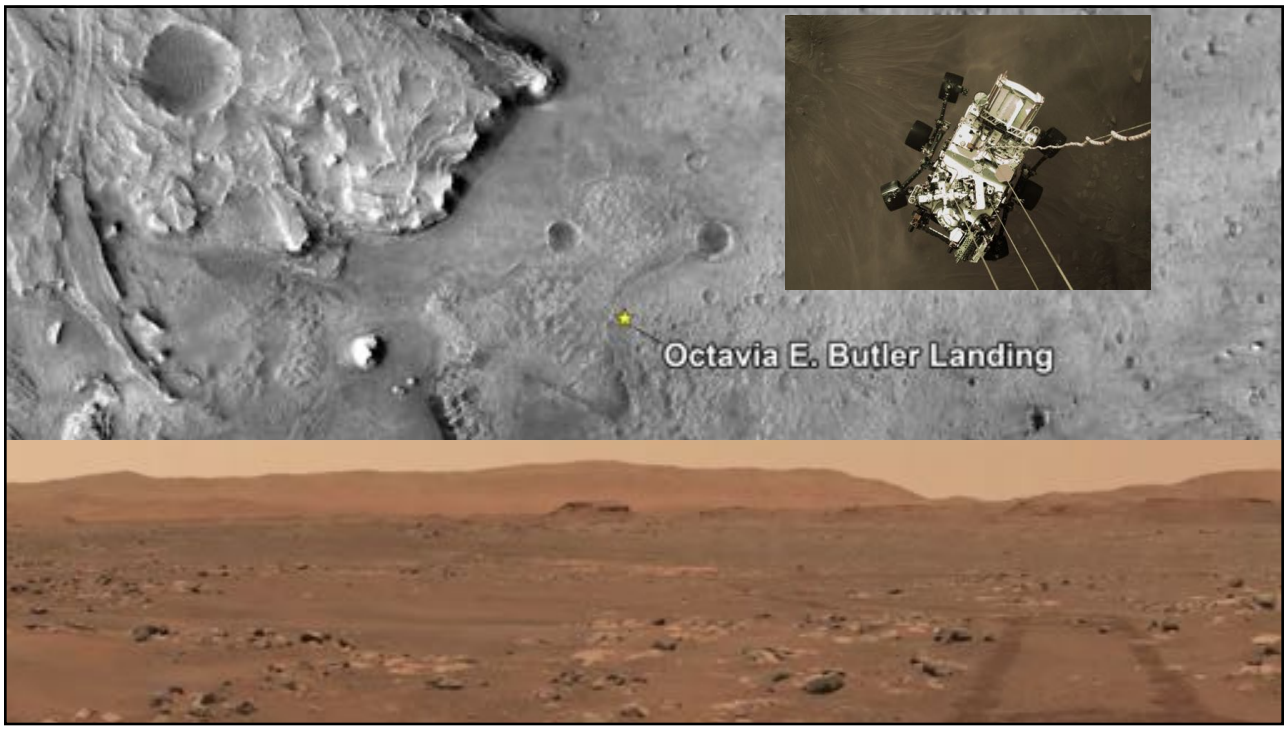
29


In Flow
Landing Area
Out Flow
Jezero Crater
~3.8 - 3.6 By
Depth ~150 Meters
10
km

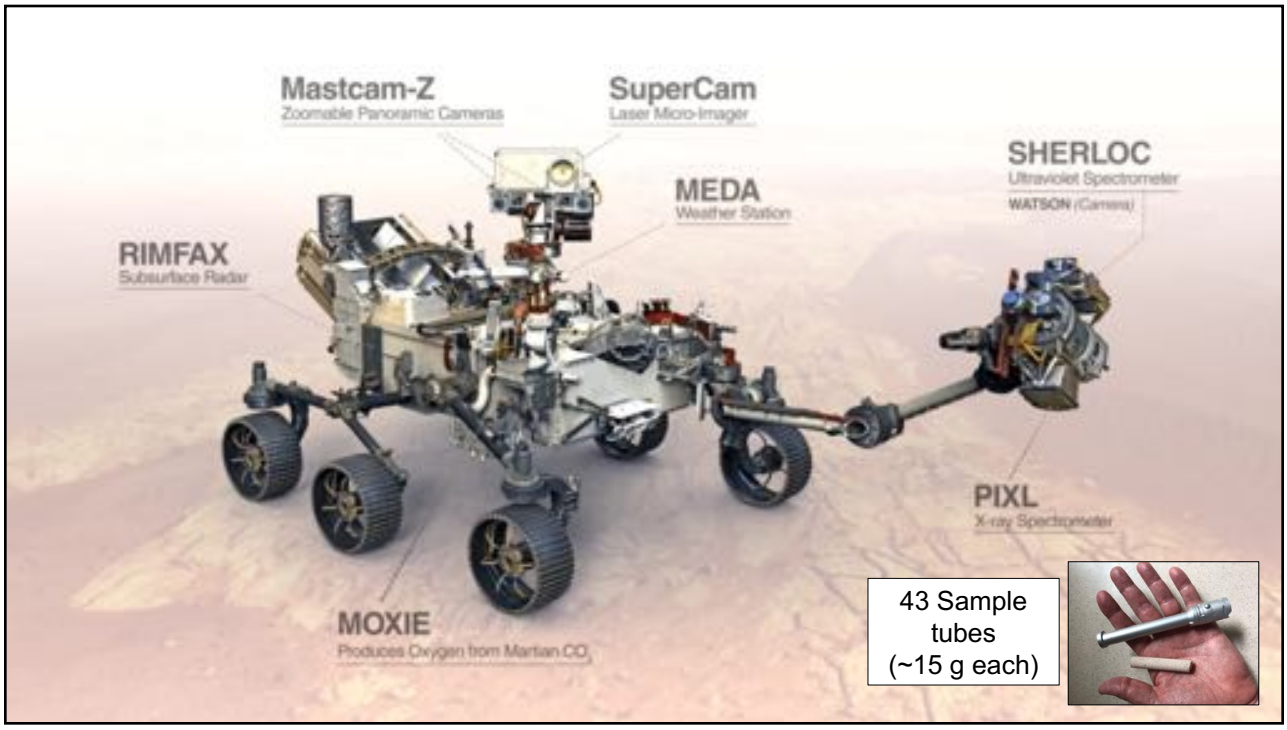
30


Cruise Stage Separation
Atmospheric Entry
Peak Heating
Peak Deceleration
Guided Entry
Parachute Deploy
Heat Shield Separation
Radar Lock
Backshell Separation
Powered Descent
Sky Crane
Jezero Crater

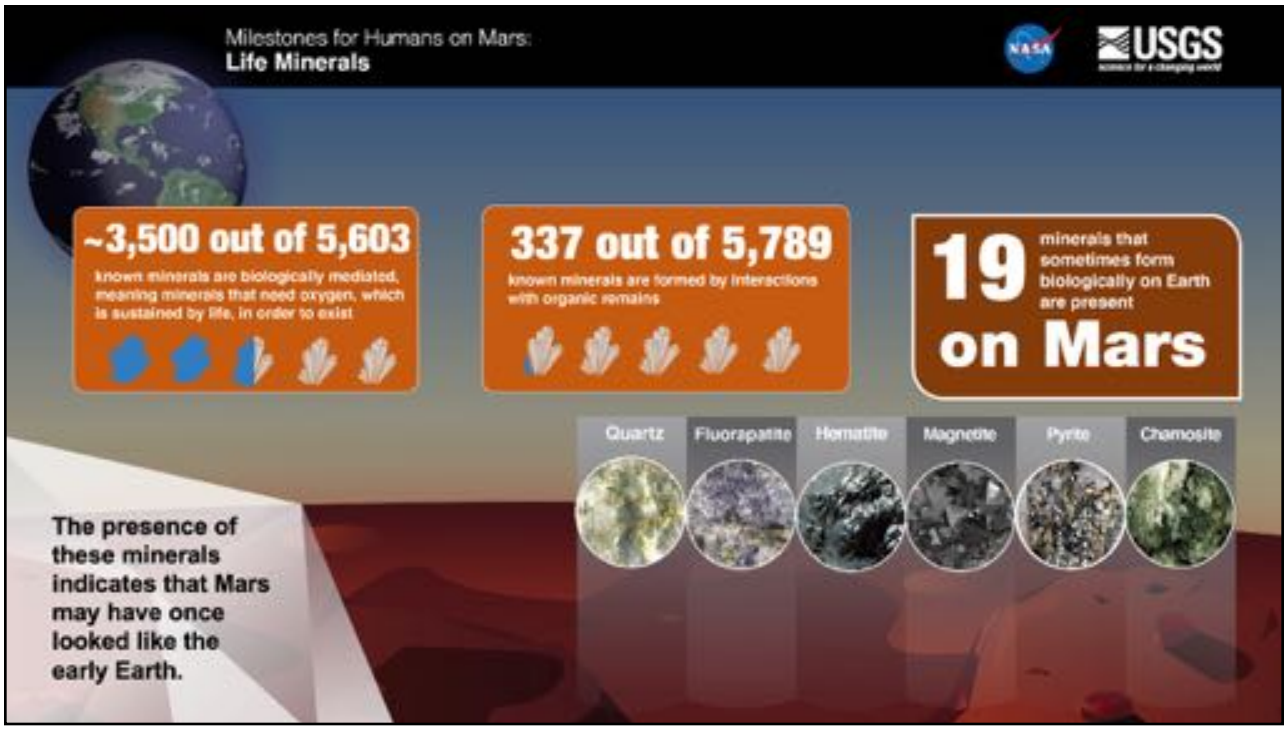
31


Octavia E. Butler Landing

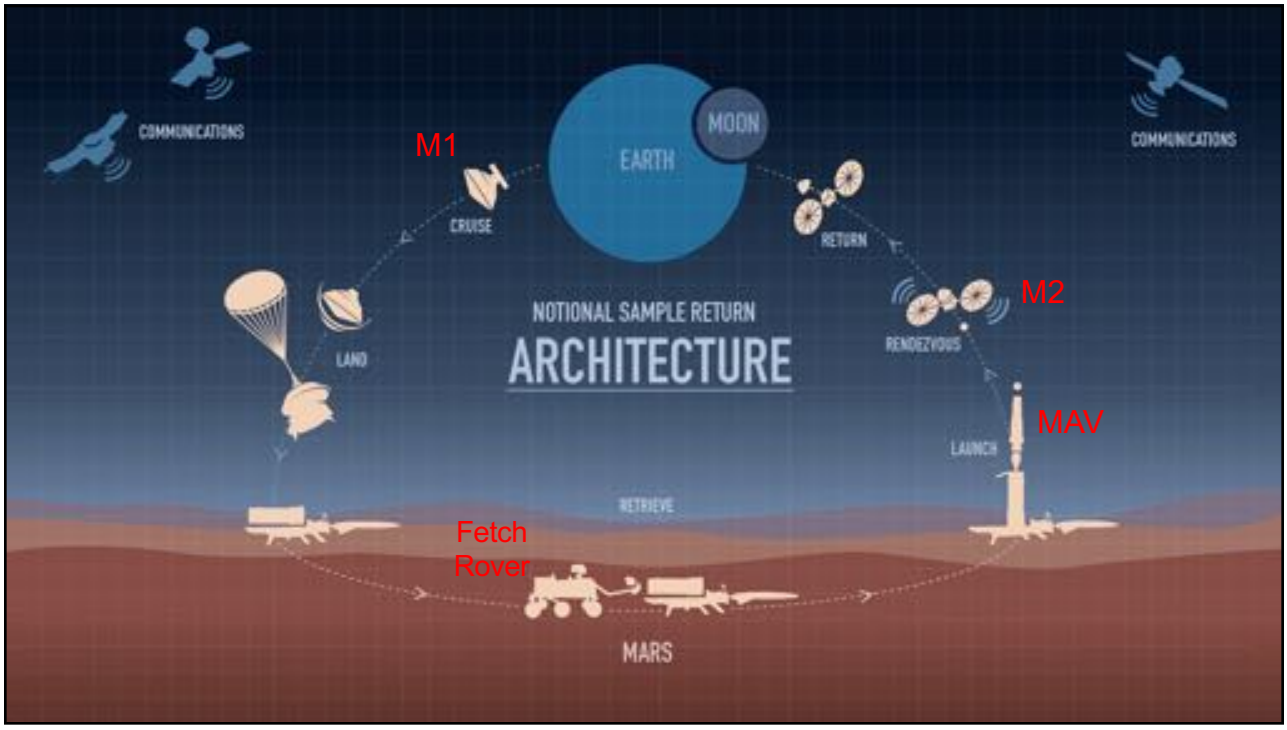
32


Mastcam-Z
Zoomable Panoramic Cameras
SuperCam
Laser Micro-Imager
SHERLOC
Ultraviolet Spectrometer
WATSON (Camera)
MEDA
Weather Station
RIMFAX
Subsurface Radar
PIXL
X-ray Spectrometer
MOXIE
Produces Oxygen from Martian CO2
43 Sample tubes (~15 g each)

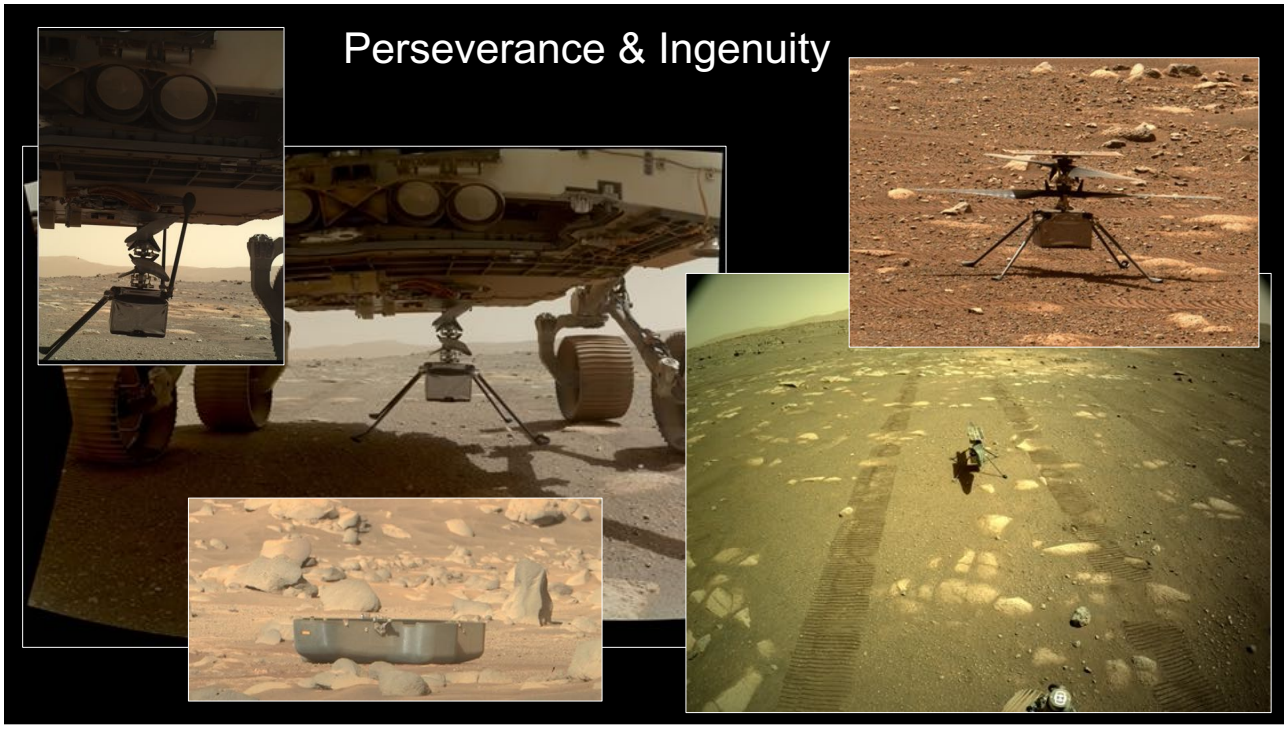
33


Milestones for Humans on Mars:
Life Minerals
NASA
USGS
~3,500 out of 5,603
known minerals are biologically mediated, meaning minerals that need oxygen, which is sustained by life, in order to exist
337 out of 5,789
known minerals are formed by interactions with organic remains
19
minerals that sometimes form biologically on Earth are present
on Mars
Quartz
Fluorapatite
Hematite
Magnetite
Pyrite
Chamosite
The presence of these minerals indicates that Mars may have once looked like the early Earth.

34


COMMUNICATIONS
M1
EARTH
MOON
COMMUNICATIONS
CRUISE
RETURN
LAND
NOTIONAL SAMPLE RETURN
ARCHITECTURE
M2
RENDEZVOUS
MAV
LAUNCH
RETRIEVE
Fetch
Rover
MARS

35


Perseverance & Ingenuity

36

Séítah From the Air

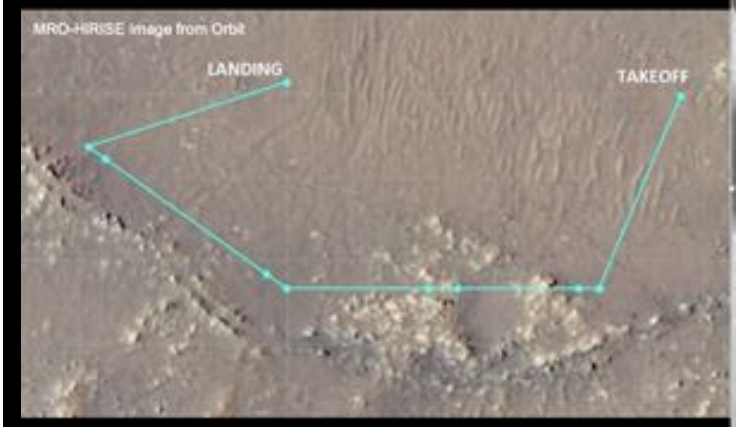
Flight #6 – May 22, 2021

- Demonstrated flight on Mars
- Test period completed with 5 flights of increasing complexity
- Transitioned from Technology Demonstration to Operations
  - Rover path planning – looking for hazards & special formations
  - Ground truth for HiRISE

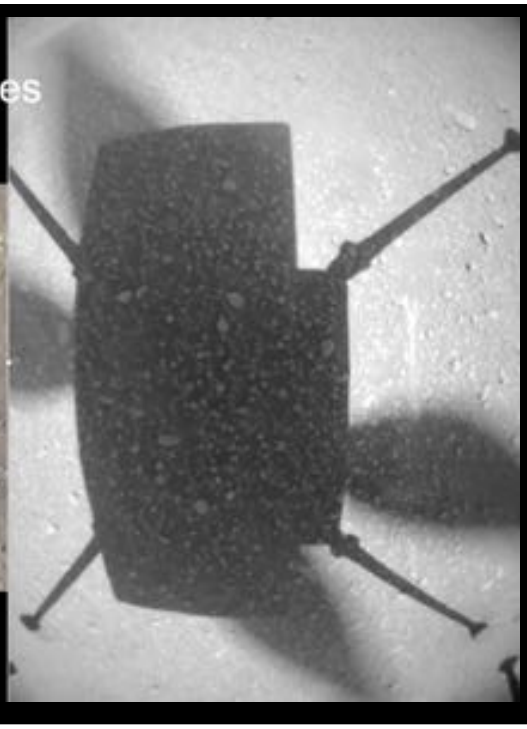
Flight	Sol	Date	Description	Height (m)	Tot. Distance(m)	Time(s)
1	58	4/19	Takeoff, hover, land	3m	0m	39.1s
2	61	4/22	Takeoff, 2m lateral, return, land	5m	4m	51.9s
3	64	4/25	50m out and back	5m	100m	80s
4	69	4/30	133m out and back	5m	271m	117s
5	76	5/7	Move to new landing site	10m	129m	108s
6	91	5/23	Fly southwest, image, land	10m	215m	140s
7	107	6/8	Fly south, image, land	10m	106m	62s

37

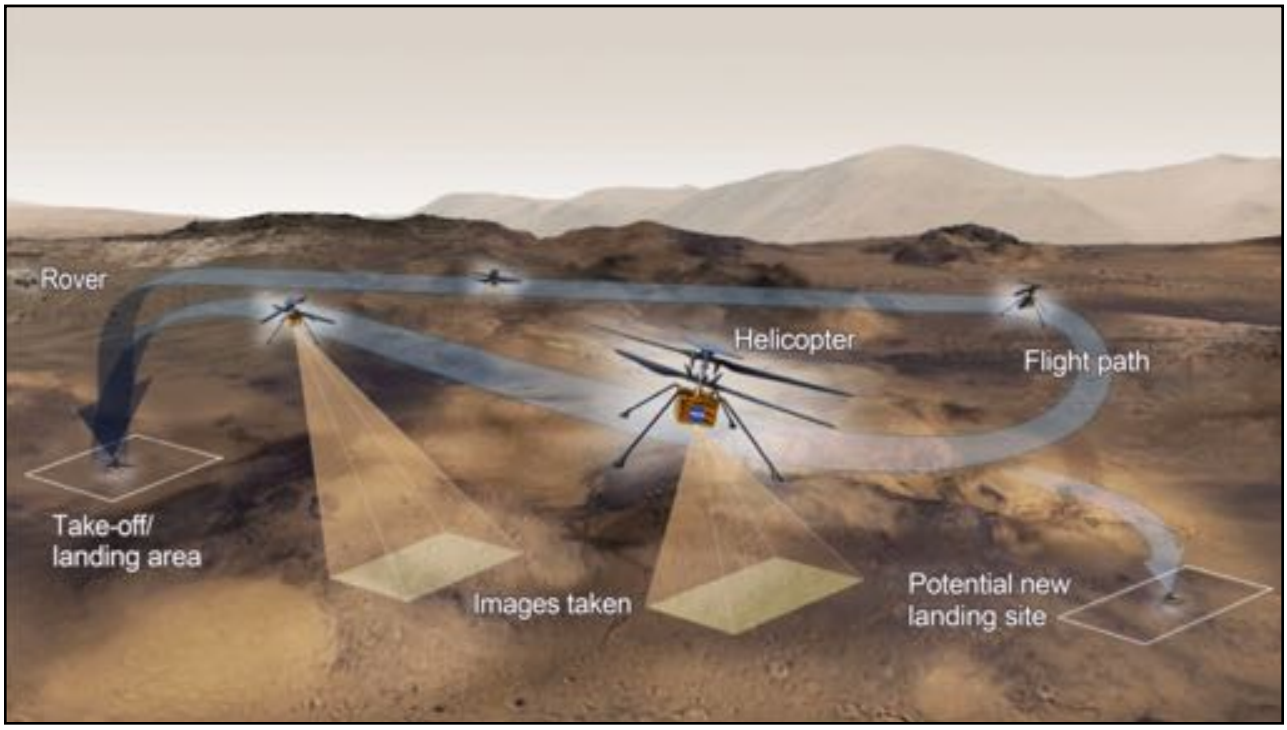
Target of the 10th Flight: Raised Ridges



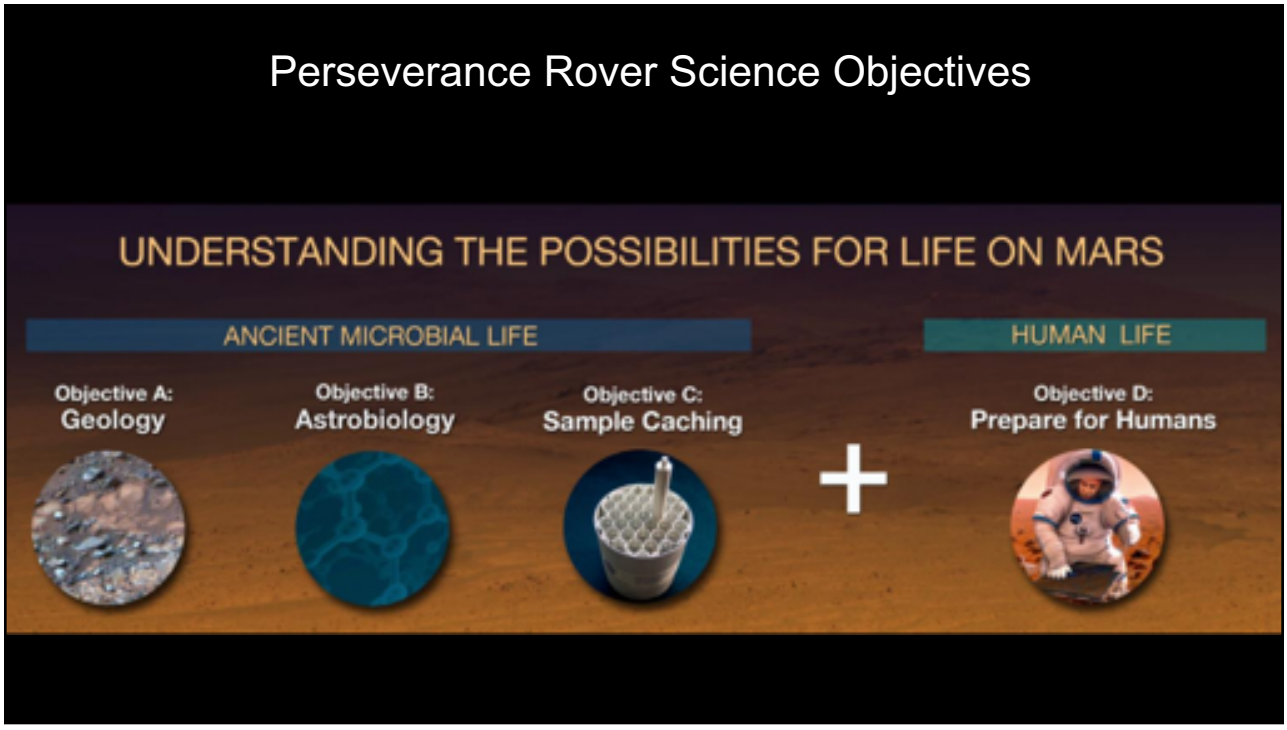
Ingenuity maneuvers at waypoints



38


Rover
Helicopter
Flight path
Take-off/
landing area
Images taken
Potential new
landing site

39

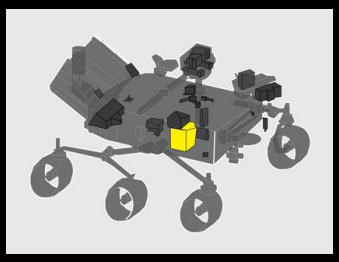

Perseverance Rover Science Objectives
UNDERSTANDING THE POSSIBILITIES FOR LIFE ON MARS
ANCIENT MICROBIAL LIFE
HUMAN LIFE
Objective A:
Geology
Objective B:
Astrobiology
Objective C:
Sample Caching
Objective D:
Prepare for Humans

40

Human Exploration on Mars

41

Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)



demonstration of technologies to enable propellant and consumable oxygen production from the Martian atmosphere. Collects CO_2 from the Martian atmosphere, then electrochemically splits the CO_2 molecules into O_2 and CO.

42

MOXIE makes 6-10 g of propellant-grade O_2 per hour from CO_2

- Can generate ~50% of what a person breathes
- Works remarkably well, hardly any differences from laboratory operation are seen

<u>Future</u>

- Need 25-30 kW power to produce 2-3 kg/hr of O_2
- Allow ~12 months to make enough O_2 to launch a crew of 4

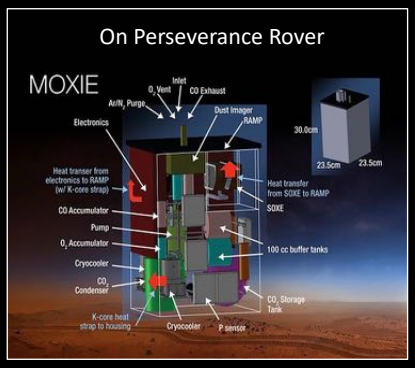
43

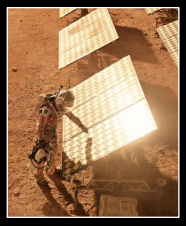
Elements for First Human Mars Mission

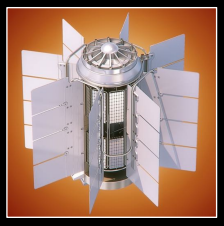
44

In-Situ Resource Utilization

- ISRU systems would turn Martian resources into plastics, metals and other construction materials for habits and 3-D printing
- Energy & Power systems: scaled fission reactors, solar and chemical fuels
- Massive amount of resources known to exist on Mars
  - Carbon Dioxide in the Atmosphere
  - Supply of Carbon and Oxygen
  - Sufficient Water





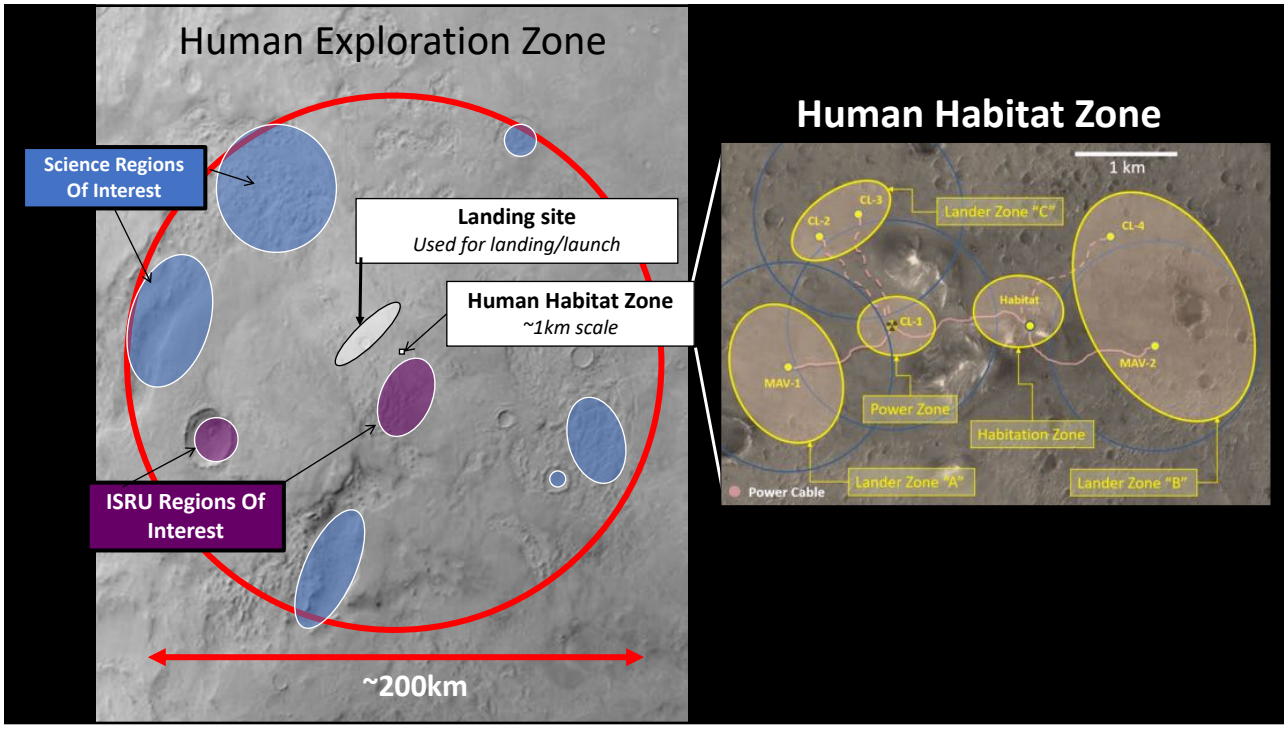


45

46


The Potential Future of Flying on Mars
Measurements:
- Imaging
- Temperature
- Pressure
- Humidity
- Microbes
Pascal Lee 2018

47


Human Exploration Zone
Science Regions Of Interest
Landing site
Used for landing/launch
Human Habitat Zone
~1km scale
ISRU Regions Of Interest
~200km
Human Habitat Zone
1 km
CL-1
CL-2
CL-3
CL-4
Habitat
MAV-1
MAV-2
Lander Zone "C"
Power Zone
Habitation Zone
Lander Zone "A"
Lander Zone "B"
Power Cable

48

49