Living on the Moon: Lessons for Mars*

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Abstract

A variety of technical challenges await future human settlement of Mars, including (1) risks of ionizing radiation during long-term transit in interplanetary space, (2) aerobraking in the Martian atmosphere with potential Mars lander instabilities, (3) surface-radiation and weather hazards, and (4) resource extraction. These challenges can be best addressed with lunar missions that involve similar tasks to those on Mars—construction of living facilities, in situ resource utilization (ISRU), and protection from radiation both during transit and residence. The potential for exposure of astronauts to ionizing radiation with current chemical-propulsion technology is much less for 3-day Earth-to-Moon transit than for an Earth-to-Mars voyage (>200 days). However, Earth-to-Mars transit time could be reduced to <50 days with advanced ion rockets. Technology for shallow-subsurface habitations to reduce radiation and temperature flux has already been developed for the Moon. These habitations include inflatable dome structures and sinterhabs composed of lunar regolith fabricated on the lunar surface. Other shallow-subsurface habitations can be located in collapsed lava tubes, both of which occur on the Moon and Mars. Stress testing of these habitats on the Moon can result in more resilient structures for Mars. Lessons learned from resource extraction on the Moon can also be applied to Mars. Ice exists on both the Moon and Mars and can serve as raw material for both breathing atmosphere and for rocket fuel. However, it remains to be demonstrated that ice can be reliably collected, transported, and refined in a remote environment. Lunar metals such as titanium, magnesium, and iron occur in basaltic mare, and along with helium-3 and hydrogen (potential sources of rocket fuel), can be mined with currently available technology. Lunar orbital depots for fuel and life-support materials have benefits for mission economics and can also serve as temporary accumulation areas for materials transport to Earth's surface. Future advances in technology and planetary engineering on the Moon, a perfect proving ground, will offer humans a steppingstone to Mars, ultimately leading to a sustained human presence in space.

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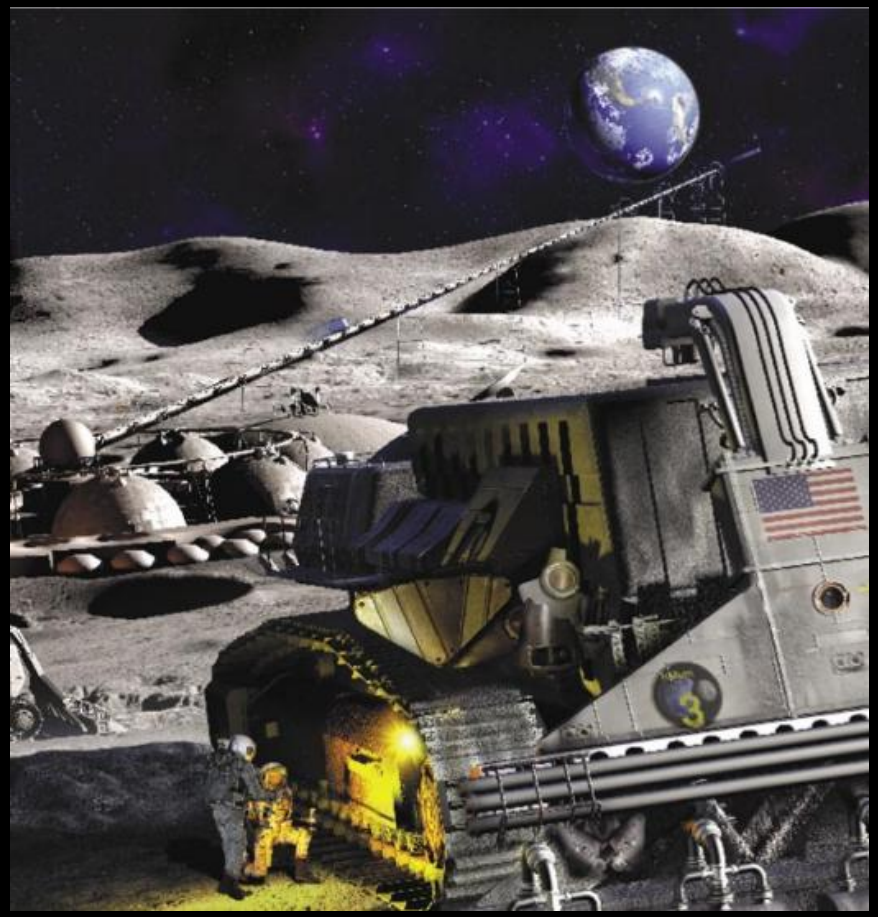
April 4, 2017

Bureau of Economic Geology



Schmitt (2004)

Return to the Moon

Earth's closest neighbor

-Three-day trip

-Technology already exists to return to the Moon

- Human missions: <0.1% surface area visited

Abundant resources

-Water and volatiles for human settlement and rocket fuel

-Metals for Moon Base and solar power facilities

Technology Development

-Settlements: Learning experiences for Mars

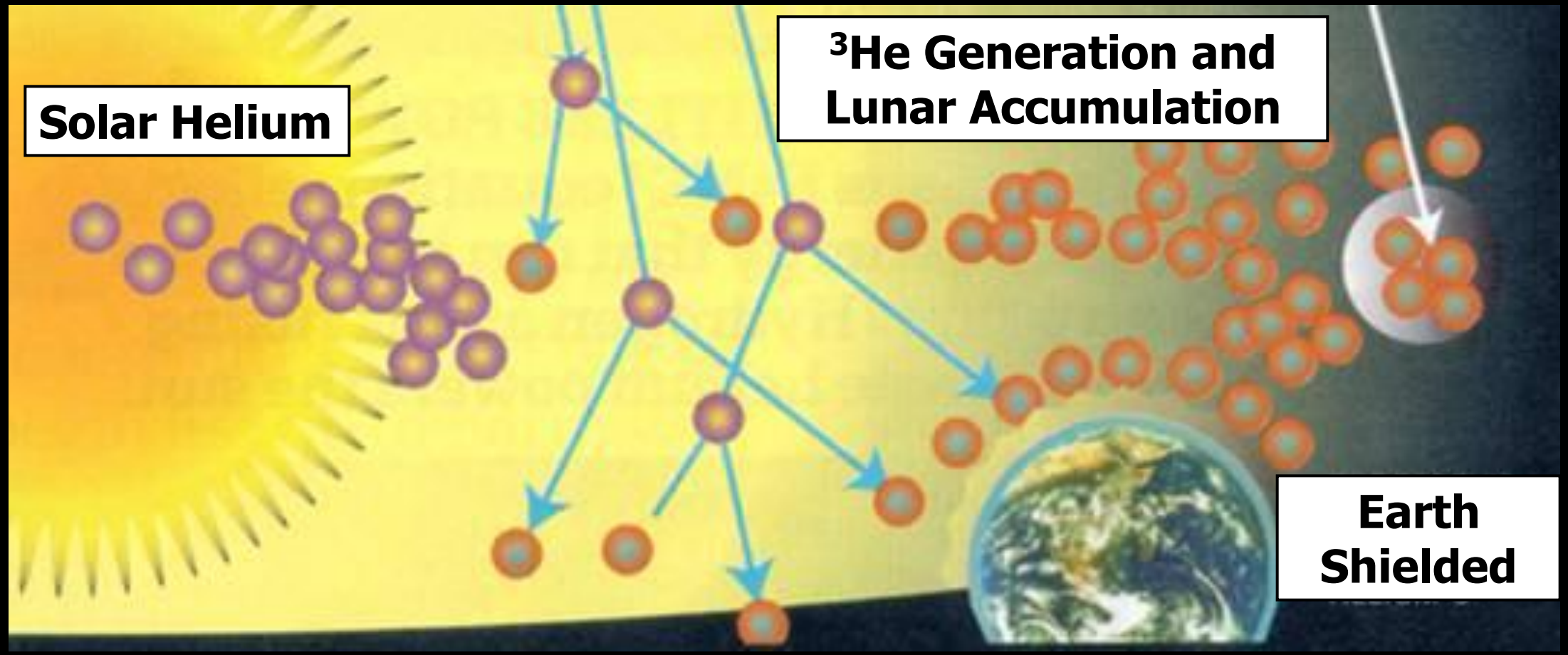
-Mining

-Space-power systems

Lunar Resources

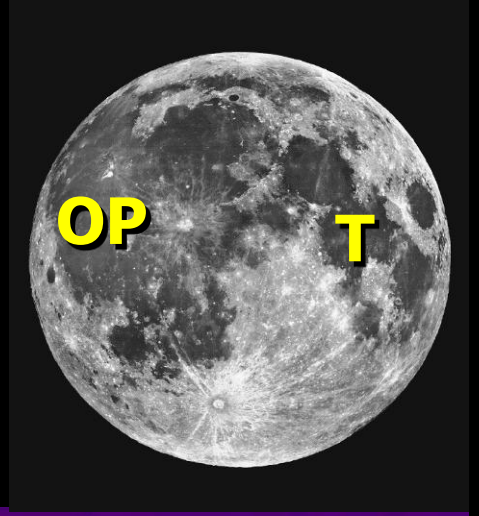
Resource	Use	Occurrence
Helium-3	Energy	Mature regolith
Hydrogen	Propellant, water	Mature regolith, poles
Oxygen	Propellant, air/water	Global
Nitrogen, carbon	Food and plastics	Breccias/regolith
Metals/bulk regolith Iron Titanium Aluminum	<u>Construction</u> Moon base Shielding Roads Solar power facility	Breccias/regolith

Helium-3 from the Solar Wind



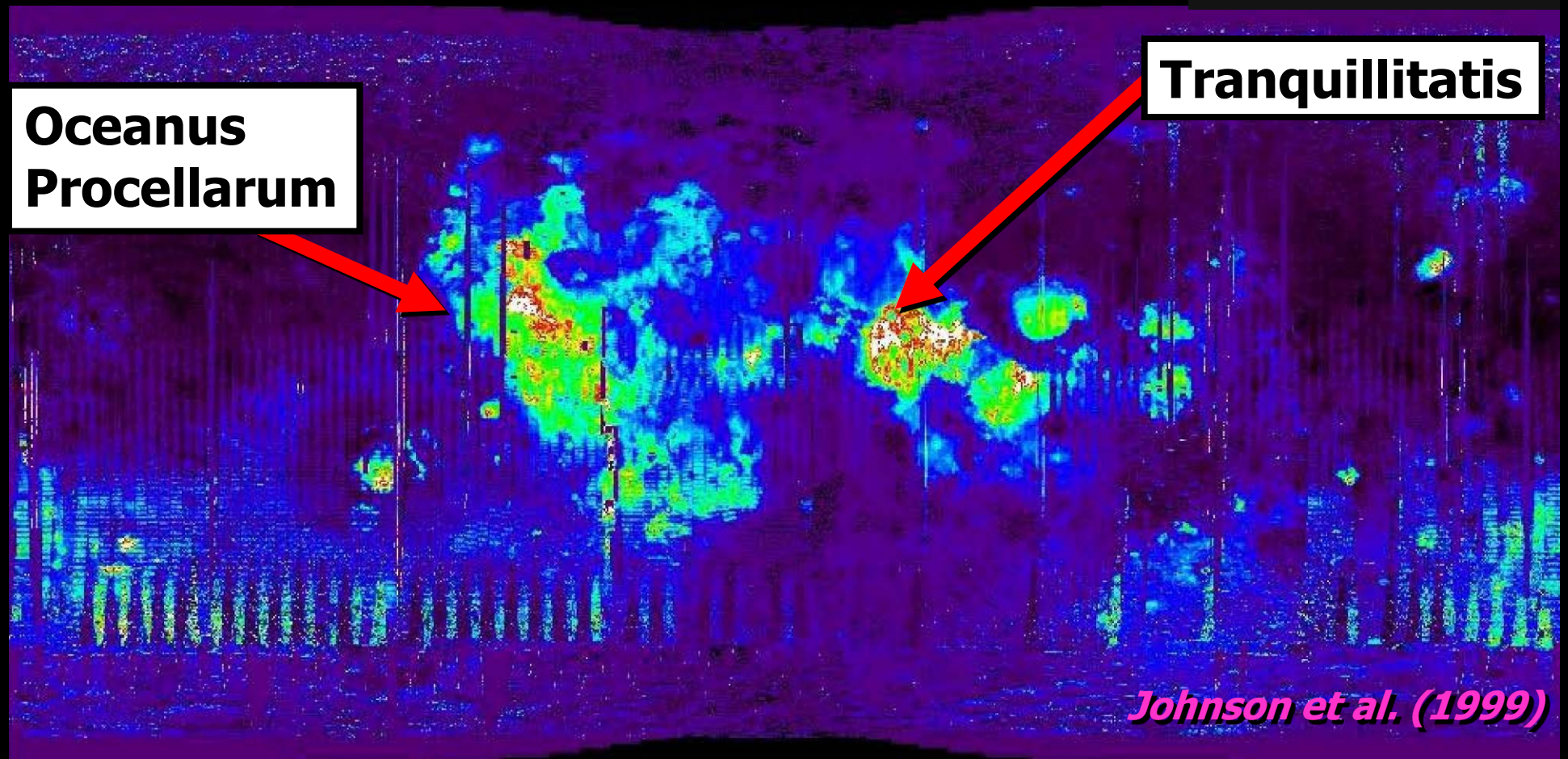
Modified from Schmitt (2004)

Lunar He-3 Distribution



>270,000 km^2 minable (high- and medium-grade)

Lewis (1996)

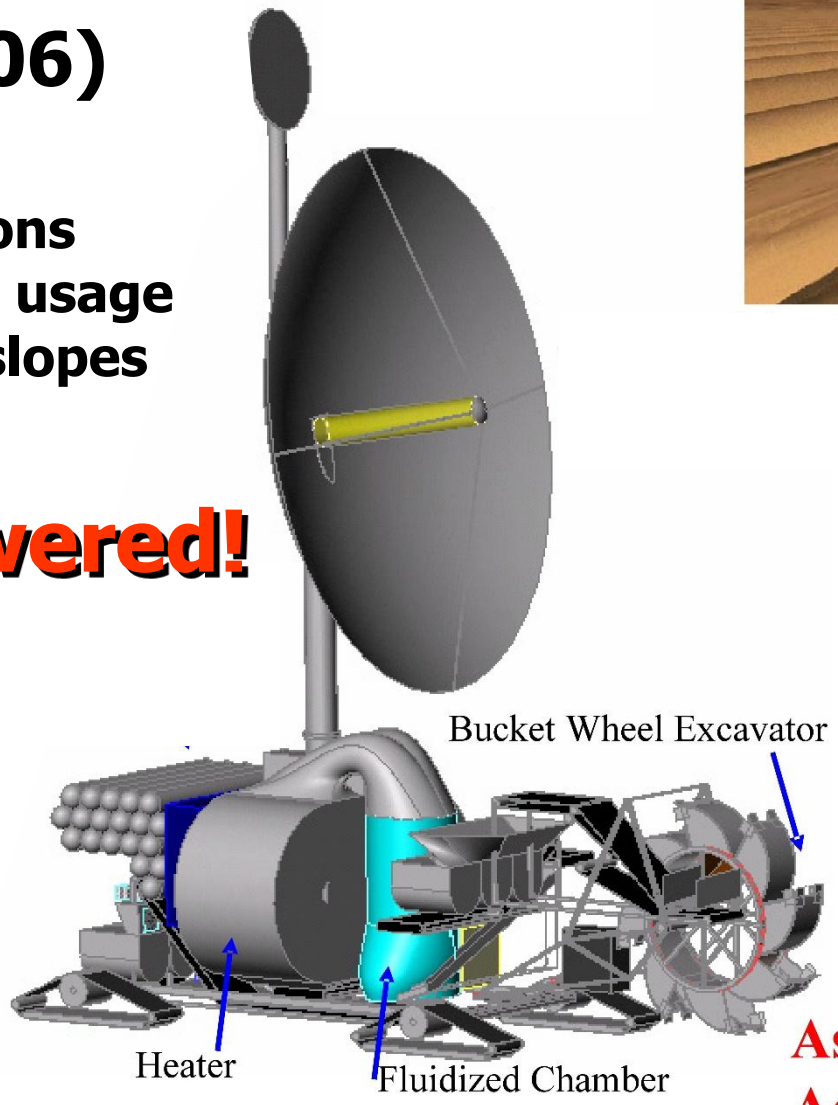


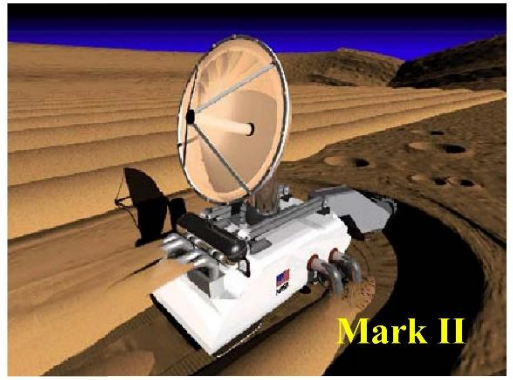
Lunar He-3 Mining

Matt Gujda et al. (2006)

Mass 9.7 tons
350 kW power usage
Handles 30 slopes

Solar Powered!



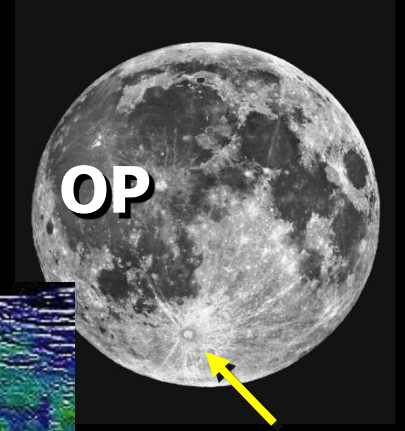


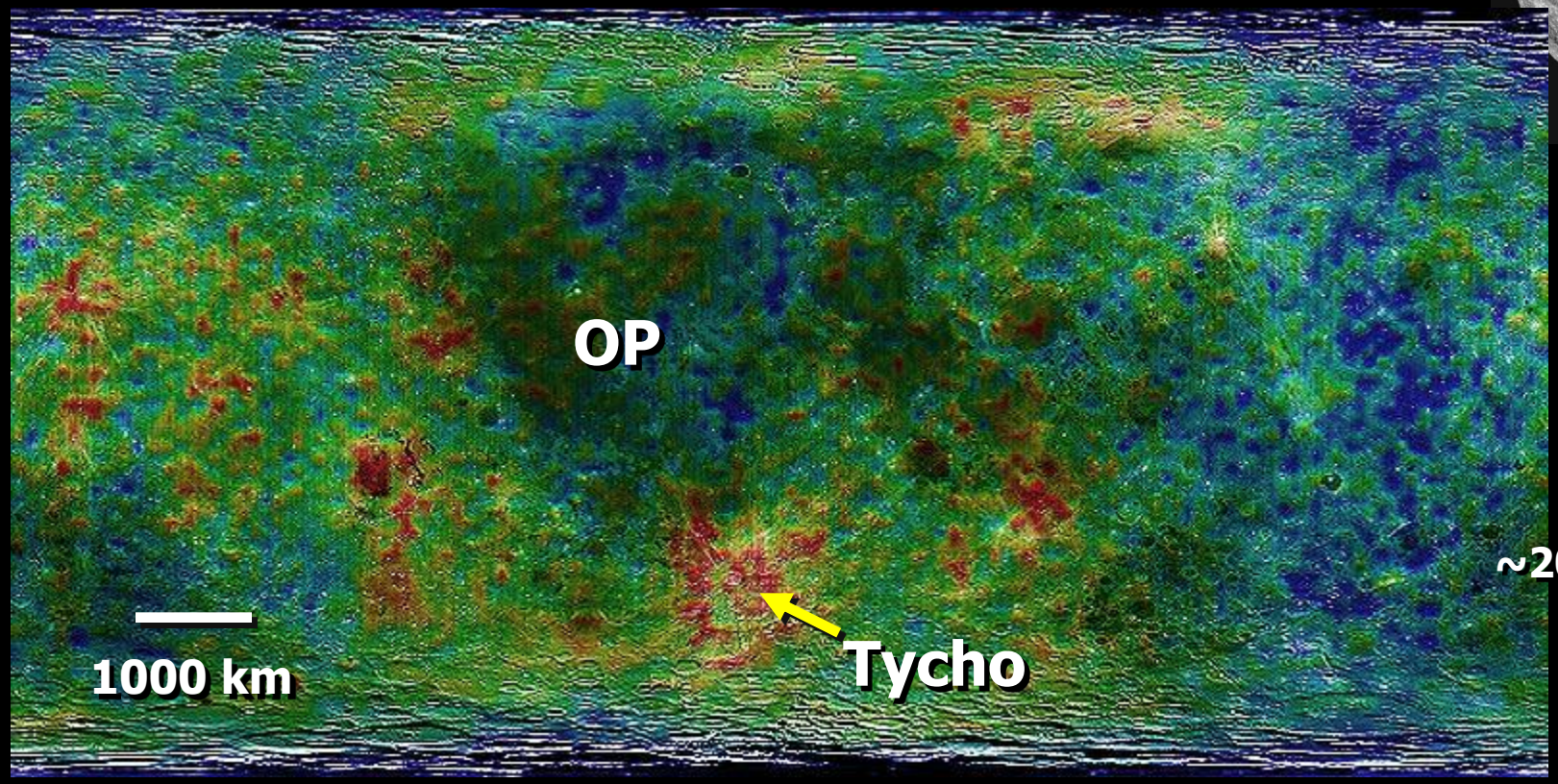
Mass of Volatiles Extracted (tonnes/yr @ 10ppb)	
H_2O	108.9
N_2	16.5
CO_2	56.1
H_2	201.3
^4He	102.3
CH_4	52.8
CO	62.7
^3He	0.033

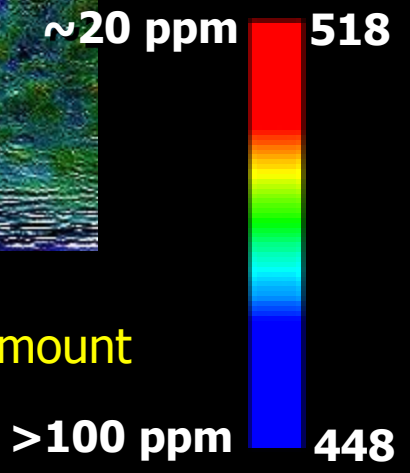
Assumed 10ppb!
Actual >20ppb

Surficial Hydrogen Distribution

Implantation from Solar Wind







Epithermal neutron counts

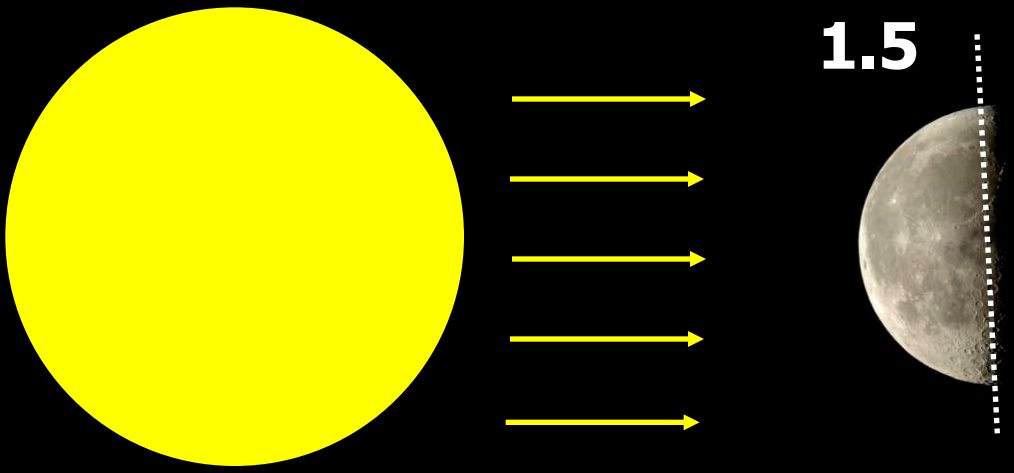
A ~0.4-mi^2 (1-km^2) area of mare regolith at 40-ppm hydrogen could be mined to a depth of ~3.3 ft (1 m) to extract an equivalent amount of hydrogen for launching the Space Shuttle (Spudis, 1996).

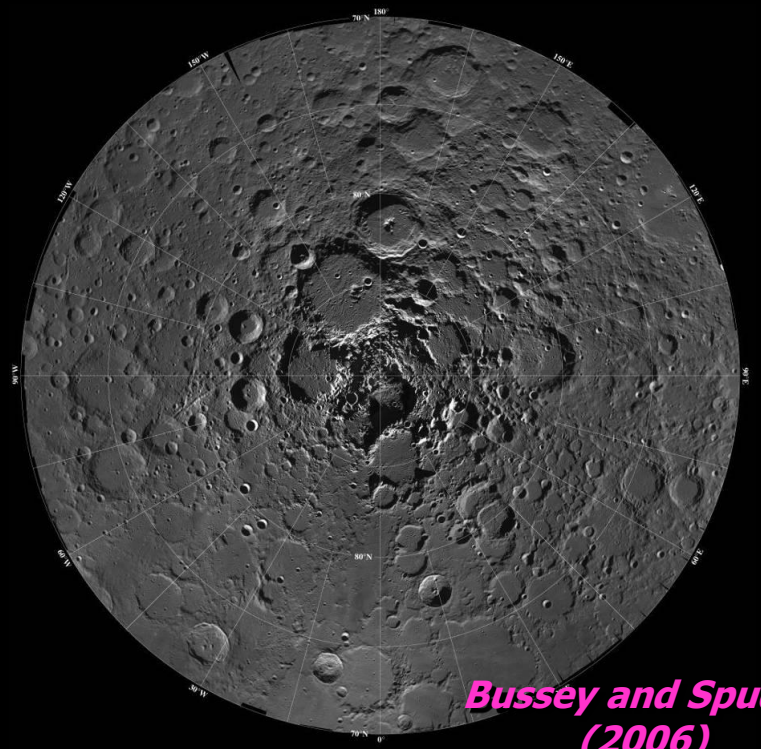
Volatiles at the Poles

Impacts from Comets

10^{13} kg water: past 2 Ga (Arnold, 1979)

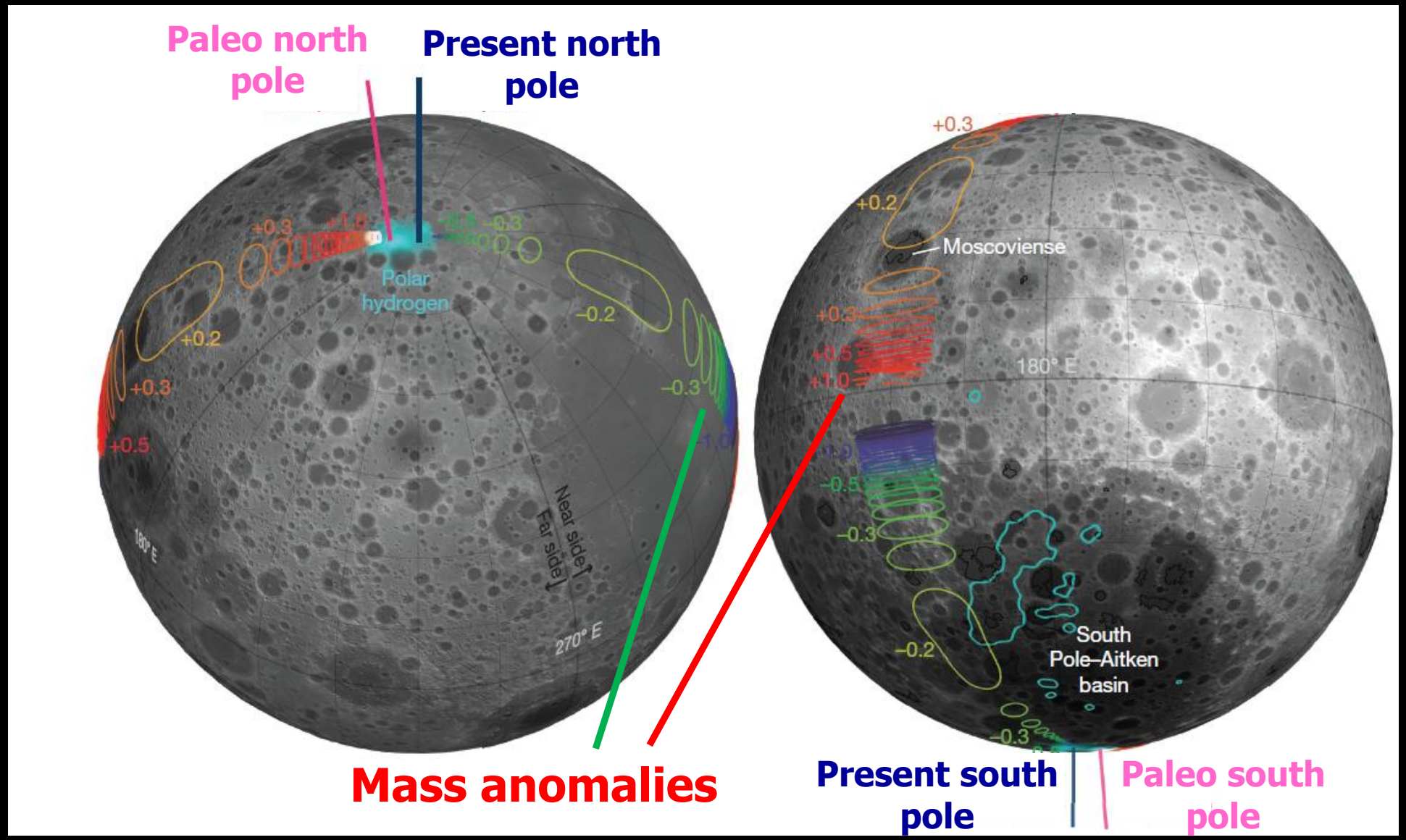
North Pole: Original estimate
~600 Mt of ice





Bussey and Spudis (2006)

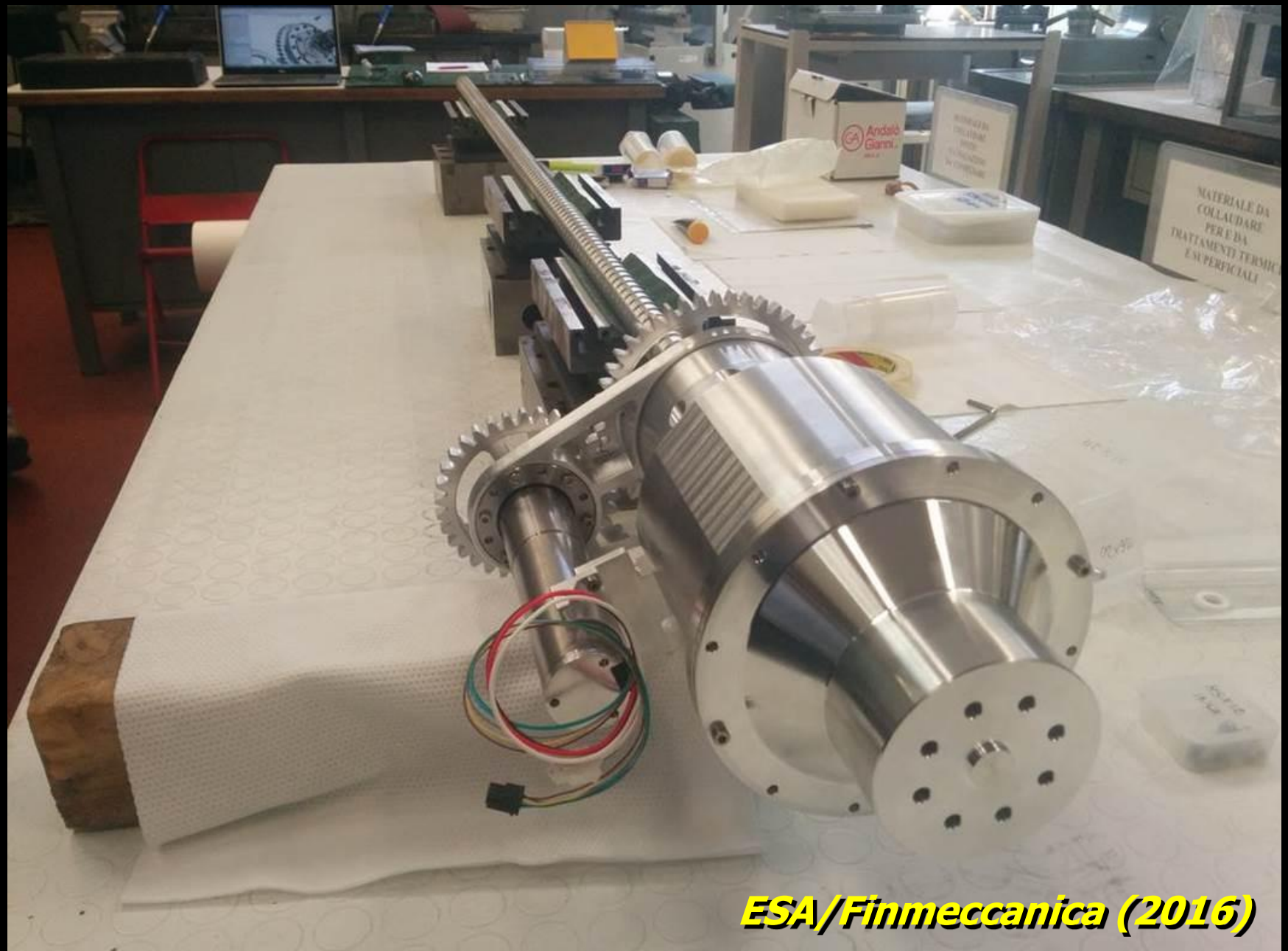
Off-axis Polar Hydrogen



Modified from Siegler et al. (2016)

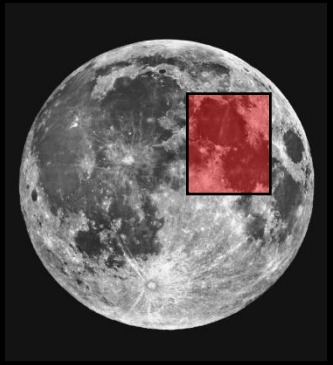
Lunar Ice Drill

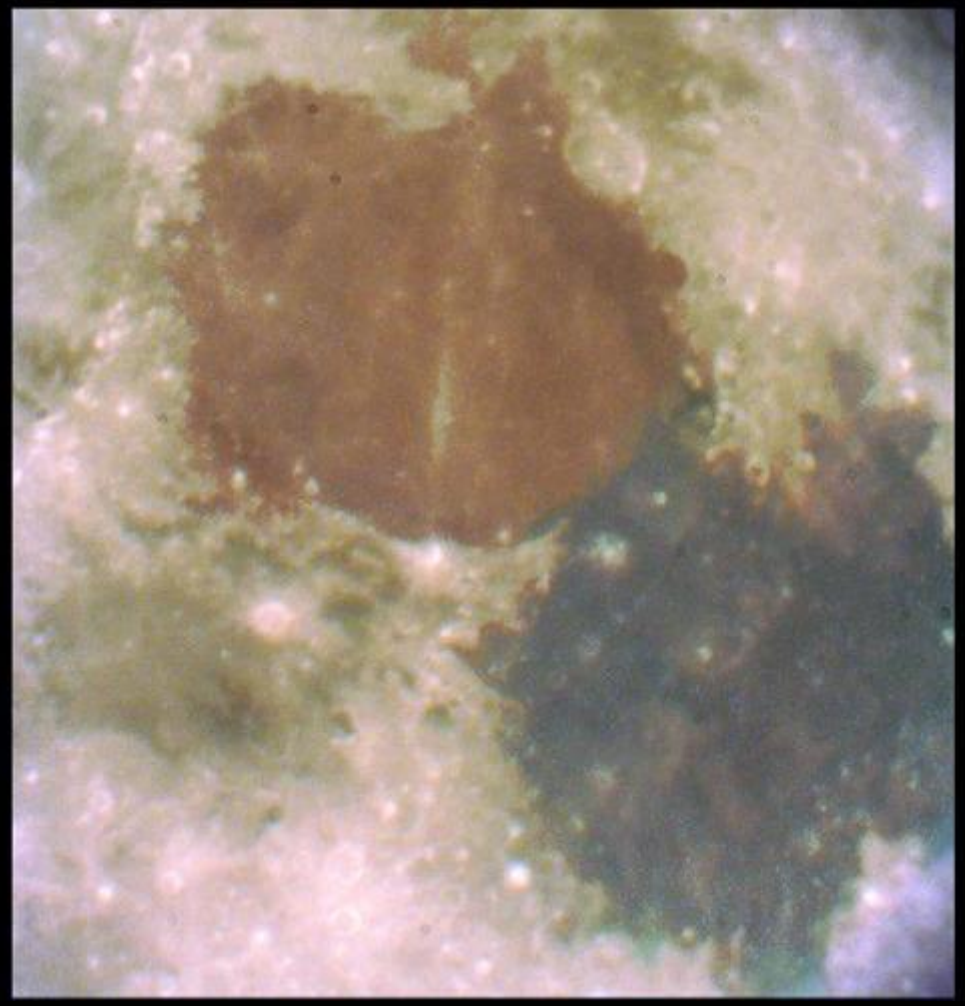
1-2 m depth of investigation
Luna-27 lander in 2020: -140°C



ESA/Finmeccanica (2016)

Iron- and Titanium-Rich Basalts





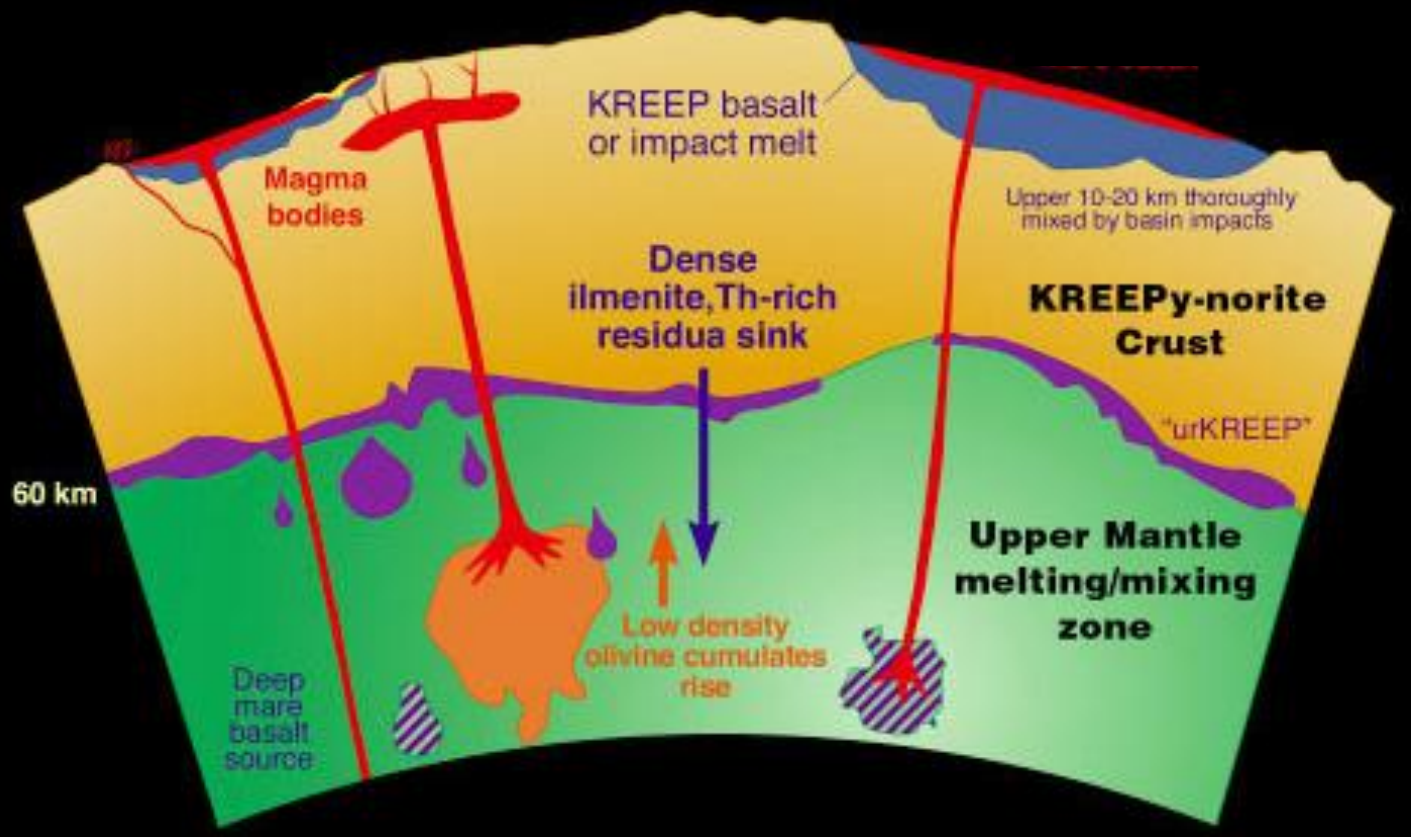
Serenitatis
Nectarian; Fe-Rich

Tranquillitatis
Pre-Nectarian; Ti-Rich

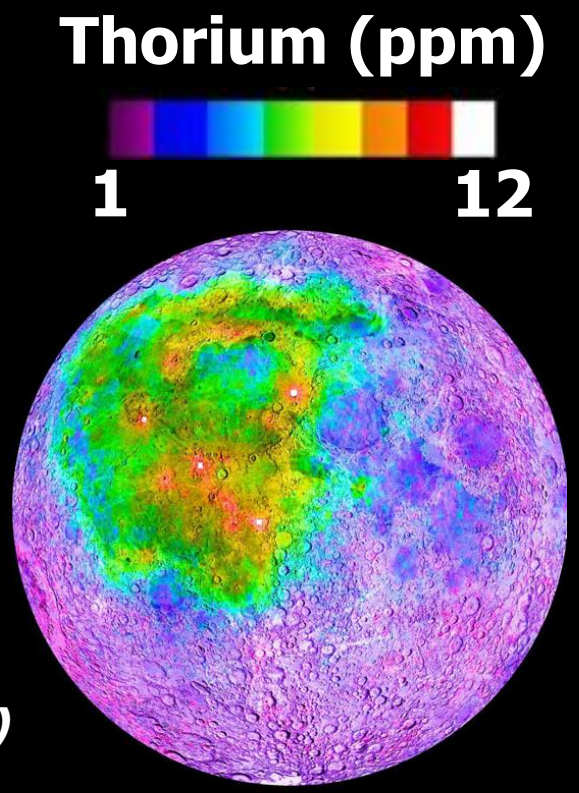
George Tarsoudis

Lunar Procellarum KREEP

(Potassium-REE-Phosphorus)



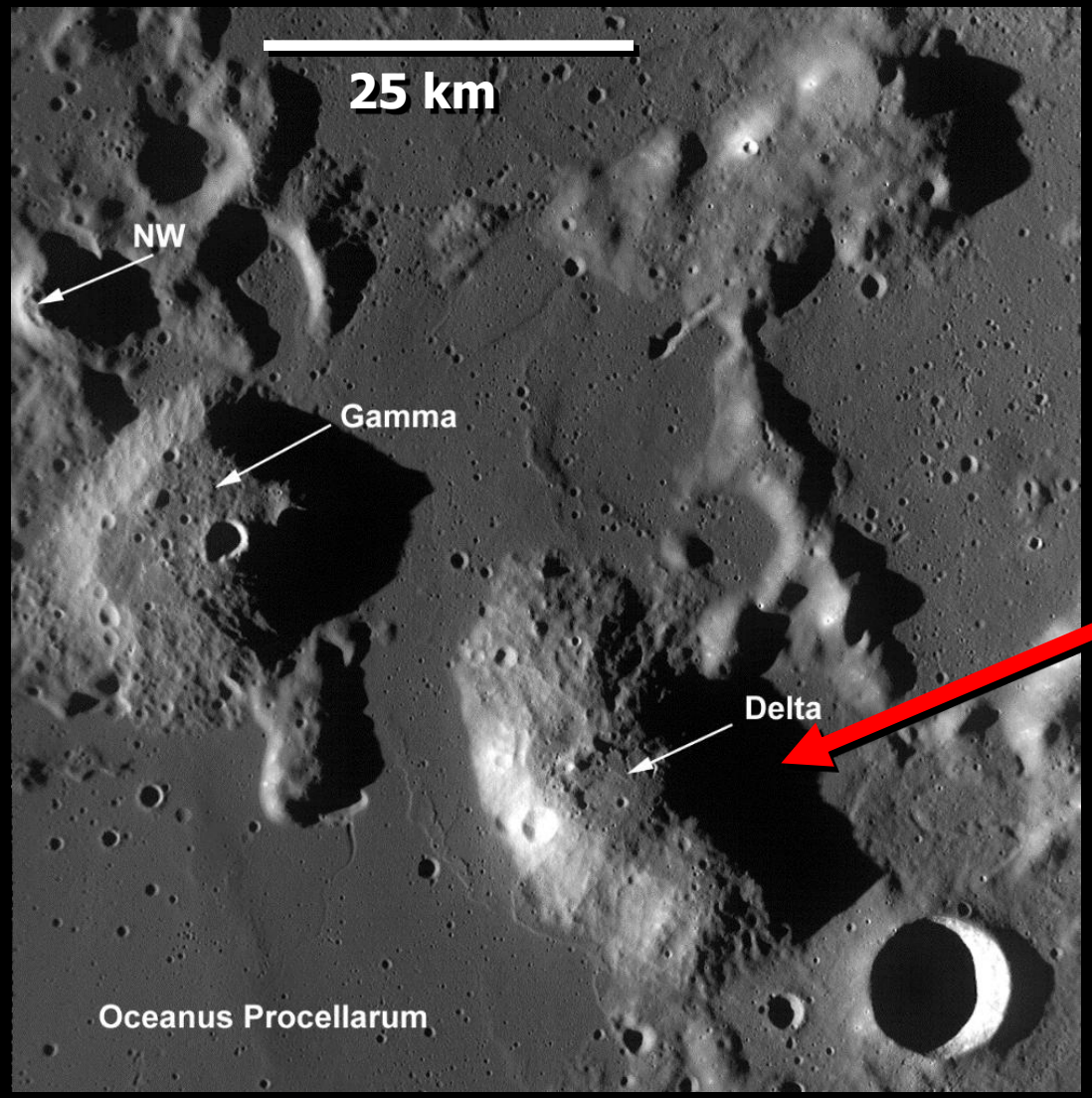
Jolliff et al. (2000)



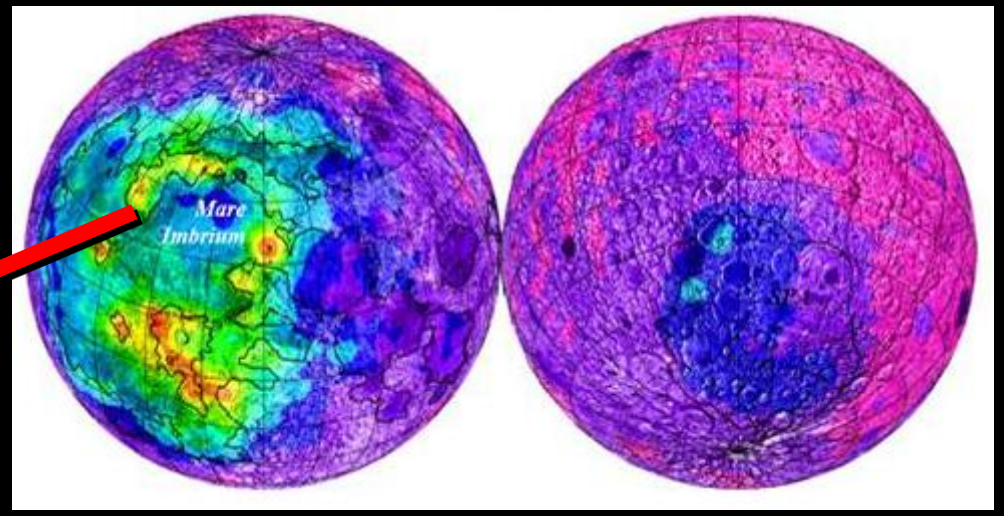
Spudis (2005)

Thorium: Silicic Domes

Mons Gruithuisen



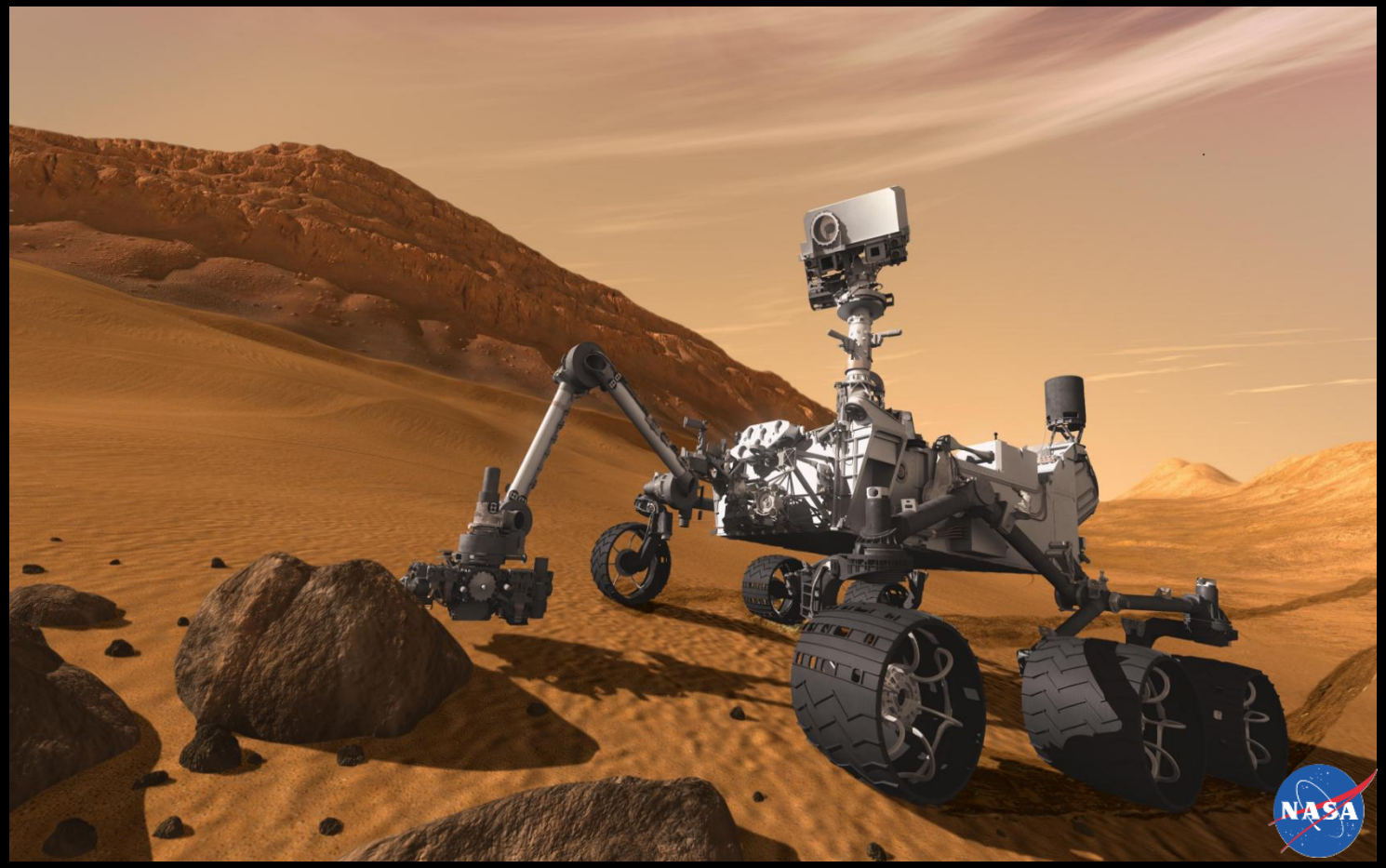
LOLA M117752970ME



>90 ppm

Yamashita (2009)

Surface Radiation Risks



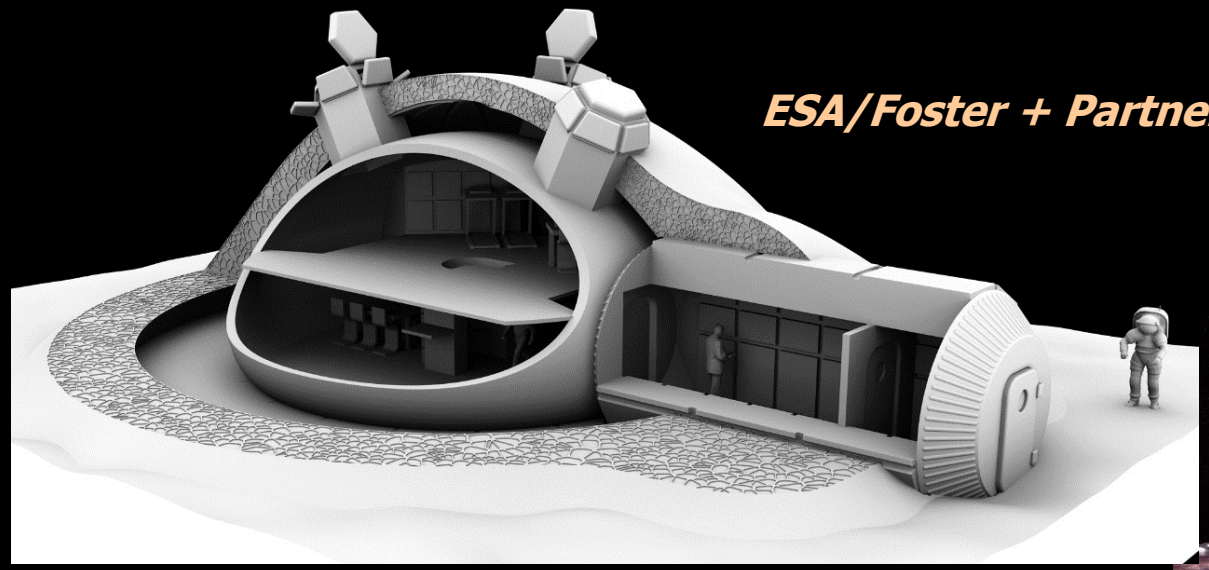
RAD on Mars Curiosity

Galactic Cosmic Rays, Solar Particle Events

Radiation equivalent to whole-body
Computed Axial Tomography (CAT) scan every 5 days
Lifetime cancer risk increase of 5%

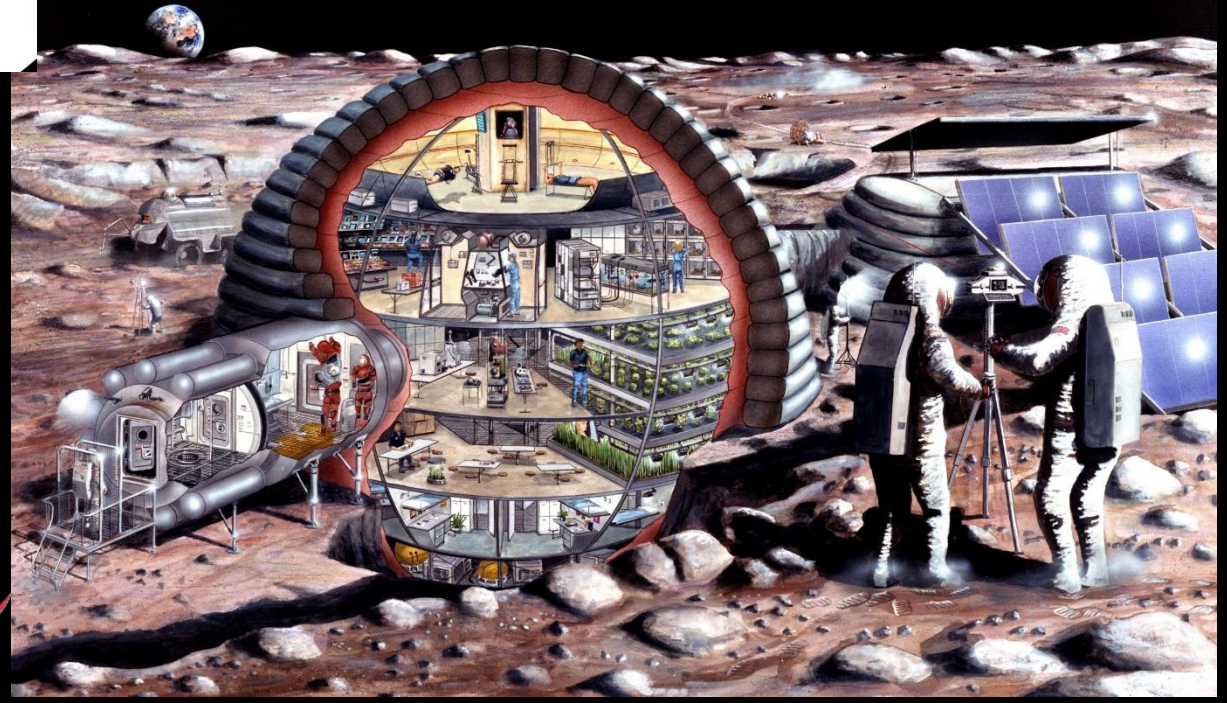
Lunar Base Designs

Sinterhab



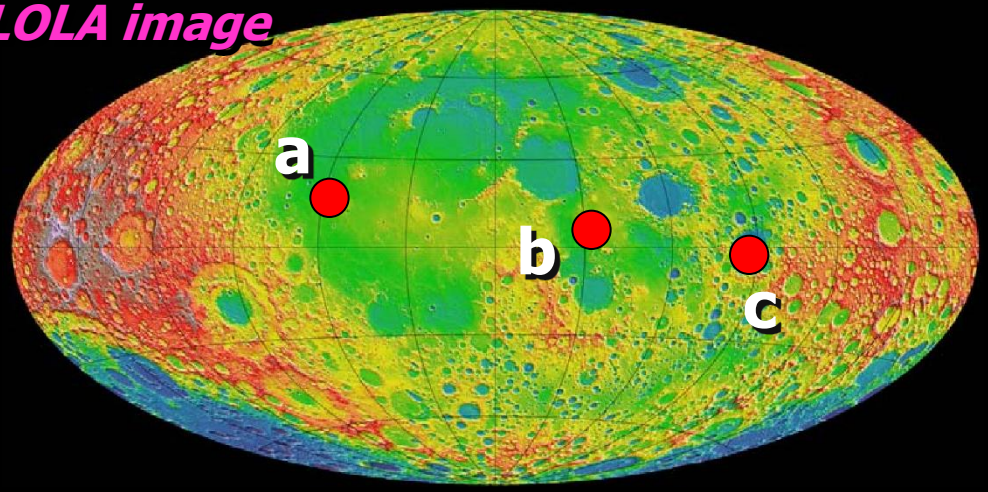
ESA/Foster + Partners (2013)

Inflatable Lunar Base

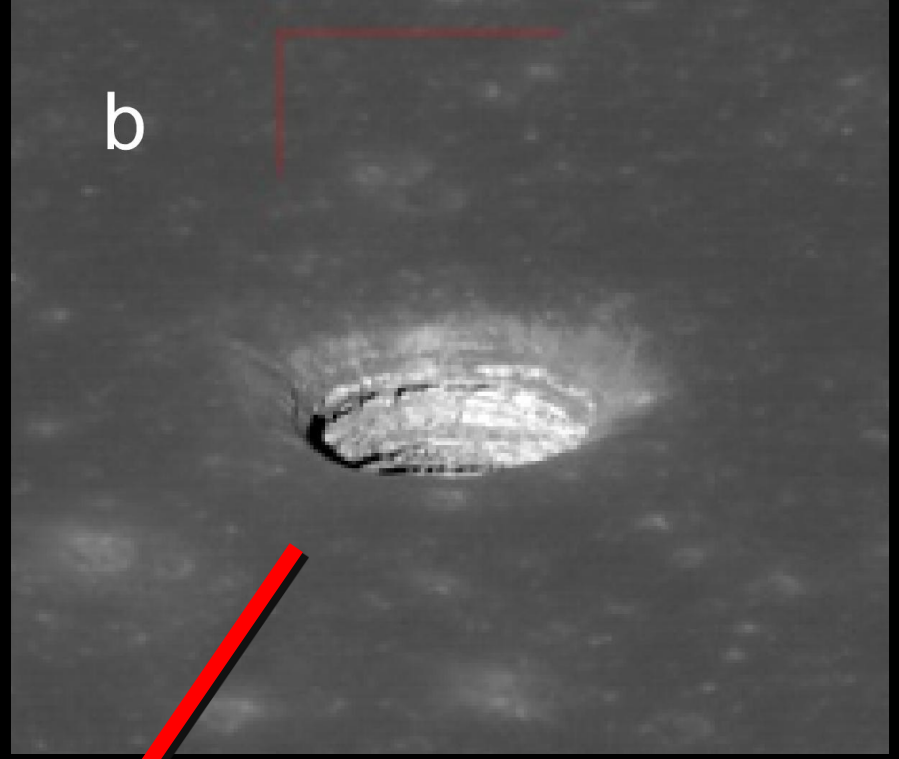


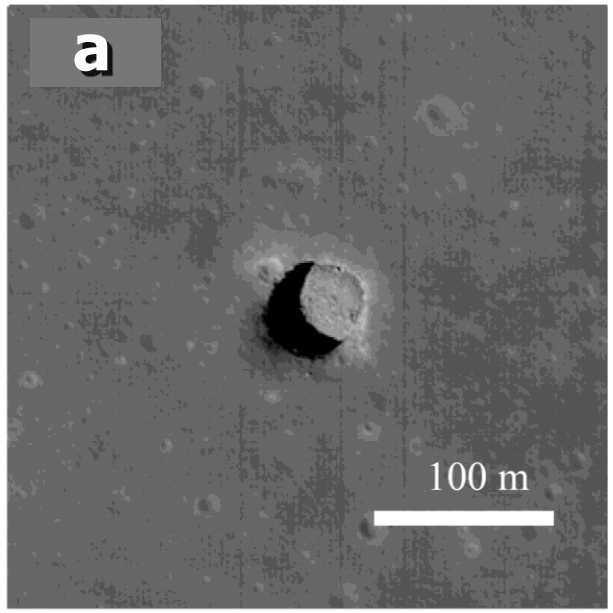
Lunar Pits

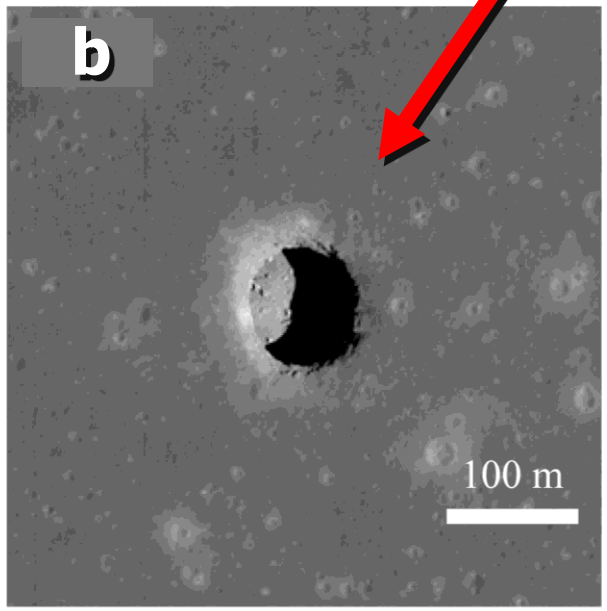
LOLA image

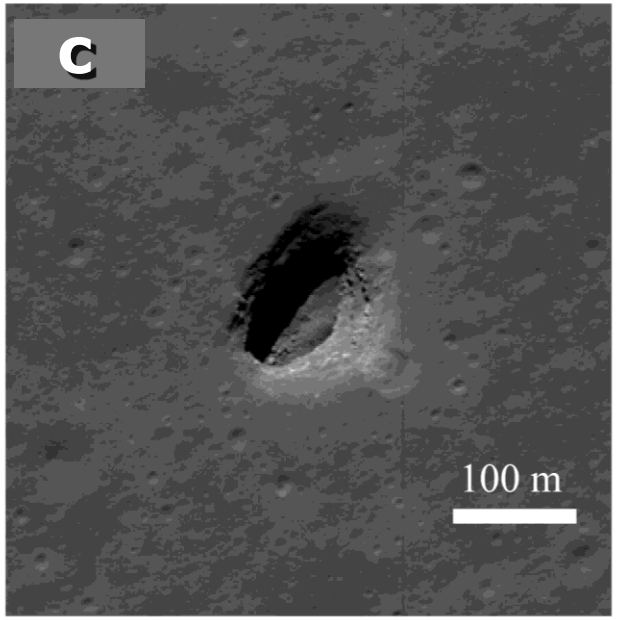


Modified from Haruyama et al. (2011)









Lava Tubes on Earth

Craters of the Moon National Park

Layering

Filled

Mollica et al. (2011)

Open

U.S. National Park Service

Global Space Economy

$330 Billion in 2015

-Commercial activities: 76 percent
-Global navigation systems
-Infrastructure and support
-Transportation systems (ISS, Space Tourism)

NASA: $ 19.3 Billion: 2016 (0.5% US Federal Budget)

Falcon 9: May 18, 2015

Private Space Sector

Shackleton Energy Company: ***Ice Mining***
Bigelow Aerospace: ***Habitation Modules, Lunar Base***
SpaceX: ***Launch vehicles***
Odyssey Moon: ***Rovers***
Infinite Space Dynamics, Planetary Resources: ***NEAs***
Deep Space Industries: ***Space manufacturing, solar***
Mars One: ***Mars colonization***

Shackleton Energy Company

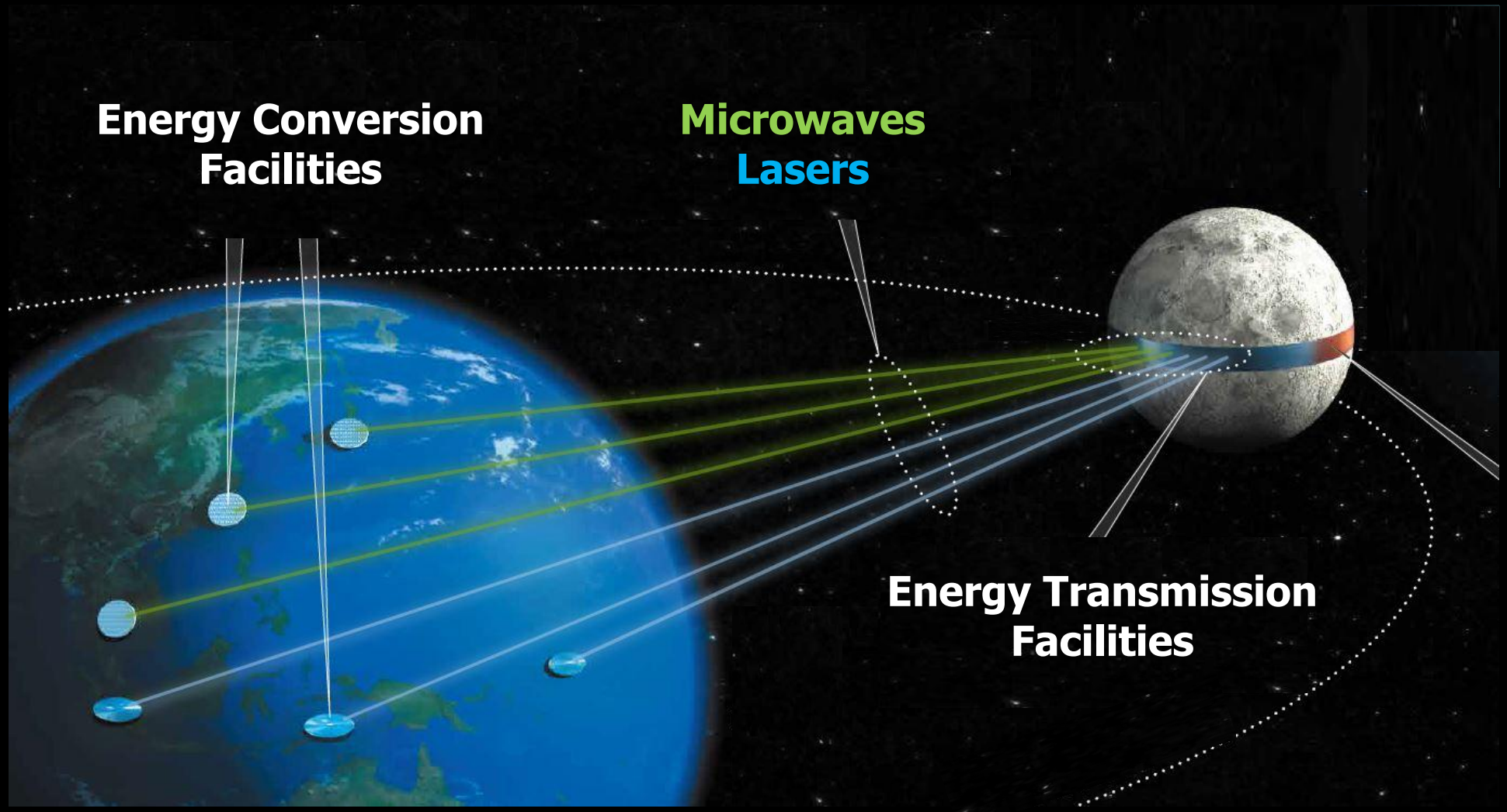
Located in Del Valle, Texas (Bill Stone, Founder)

Primary Goals:

- ***Mine lunar water ice and other volatiles***
- ***Produce and deploy rocket propellant***
- ***Provide space-based fuel depots***
- ***$25 B investment for infrastructure development***

Luna Ring: Shimizu Corporation

Construction beginning in 2035: Goal 13,000 TW power



Modified from Shimizu Corporation (2016)

Cislunar Space and Economic Potential

Modified from Duke et al. (2003); Kutter (2015)

LEO
Remote Sensing
Communications
Observations
Debris Mitigation
Propellant Transfer

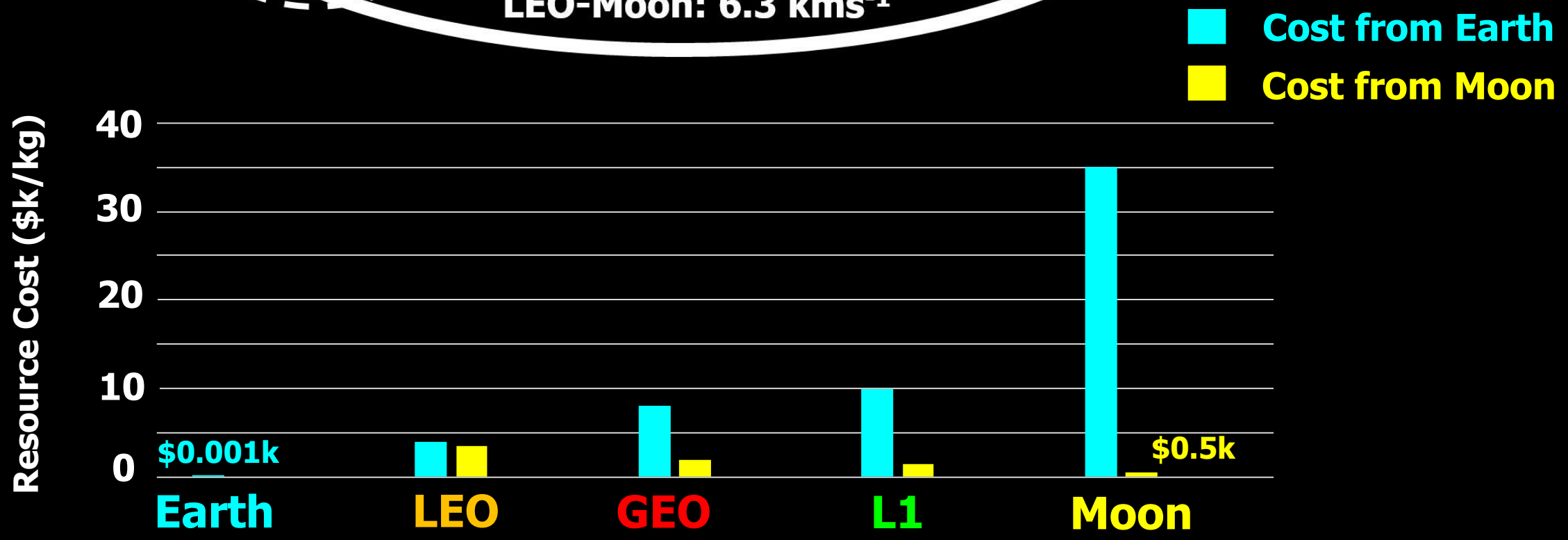
GEO
Communications
Solar Power
Observations
Satellite Life Extension

L1 and L2
Fuel Depot
Communication Link
Lunar Observations
Repair Station

Moon
Mining
Fuel Depots
Manufacturing
Habitations
Solar Power to Earth

Propellant Costs

Based on $3 million per ton at LEO
Kutter (2015)



Summary

Lunar Resource Base

-Hydrogen and Water
-Helium-3 and Metals

Human-Habitation Systems

-Mission Risks
-Radiation, Impact Flux, Fine-Grained Regolith

Transportation Systems and the Cislunar Economy

-Private Initiatives versus Government Funding
-Propellant Manufacture
-Energy Economies