Water and Hydrogen Resources on the Moon, Mercury, and Mars*

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Abstract

Water ice and other volatiles are vital in sustaining human settlement in space. Hydrogen and oxygen extracted from water by hydrogen-oxide reactions can be used as propellants on short-range interplanetary missions in the inner Solar System prior to developing more advanced propulsion systems for long-range interplanetary missions to follow. Water ice and other volatiles occur in polar areas on Mercury and the Moon, the two major airless bodies in the inner Solar System. As a consequence of their low obliquity, polar areas on Mercury and the Moon contain a large number of permanently shadowed, topographically low areas in crater floors. These permanently shadowed areas are cold traps for volatiles that accumulated over the past one to two billion years (1 to 2 Ga) from impacts from volatile-rich comets and asteroids. Evidence for water ice at the Moon's poles is based on (1) polarized radar signatures, first detected by the Clementine probe in 1994 and later measured in refined detail by the Mini-SAR synthetic aperture radar on the Chandrayaan-1 probe in 2009, (2) neutron scattering signatures that indicate hydrogen, detected by the Lunar Prospector Mission in 1999 and confirmed by subsequent missions, (3) spectral reflectance data, imaged by the Moon Mineralogy Mapper, and (4) detection of hydroxyl ions from ultraviolet emission spectra in a dust- and ice-plume generated from impact of the upper stage of the LRO Centaur rocket. Approximately 600 million metric tons of ice exists in the region of the Moon's North Pole. This amount of ice could yield sufficient hydrogen and oxygen for daily launches of a space shuttle for 2200 years. Martian water-ice resources far exceed those on the Moon and Mercury. Water ice occurs in abundance on Mars in polar ice caps, shallow permafrost, and in layered terrain adjacent to the poles. Martian permafrost, which holds more water ice than the poles, occurs as tropical mountain glaciers and in polygonal terrain with morphologies similar to those of terrestrial periglacial features. Subsurface ice on Mars has an areal distribution exceeding 20 million square kilometers, whereas the polar caps, although 2.7 and 3.1 km thick at the North and South Poles, respectively, each encompass an area >1 million square kilometers.

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Water and Hydrogen Resources on the Moon, Mercury, and Mars

William A. Ambrose

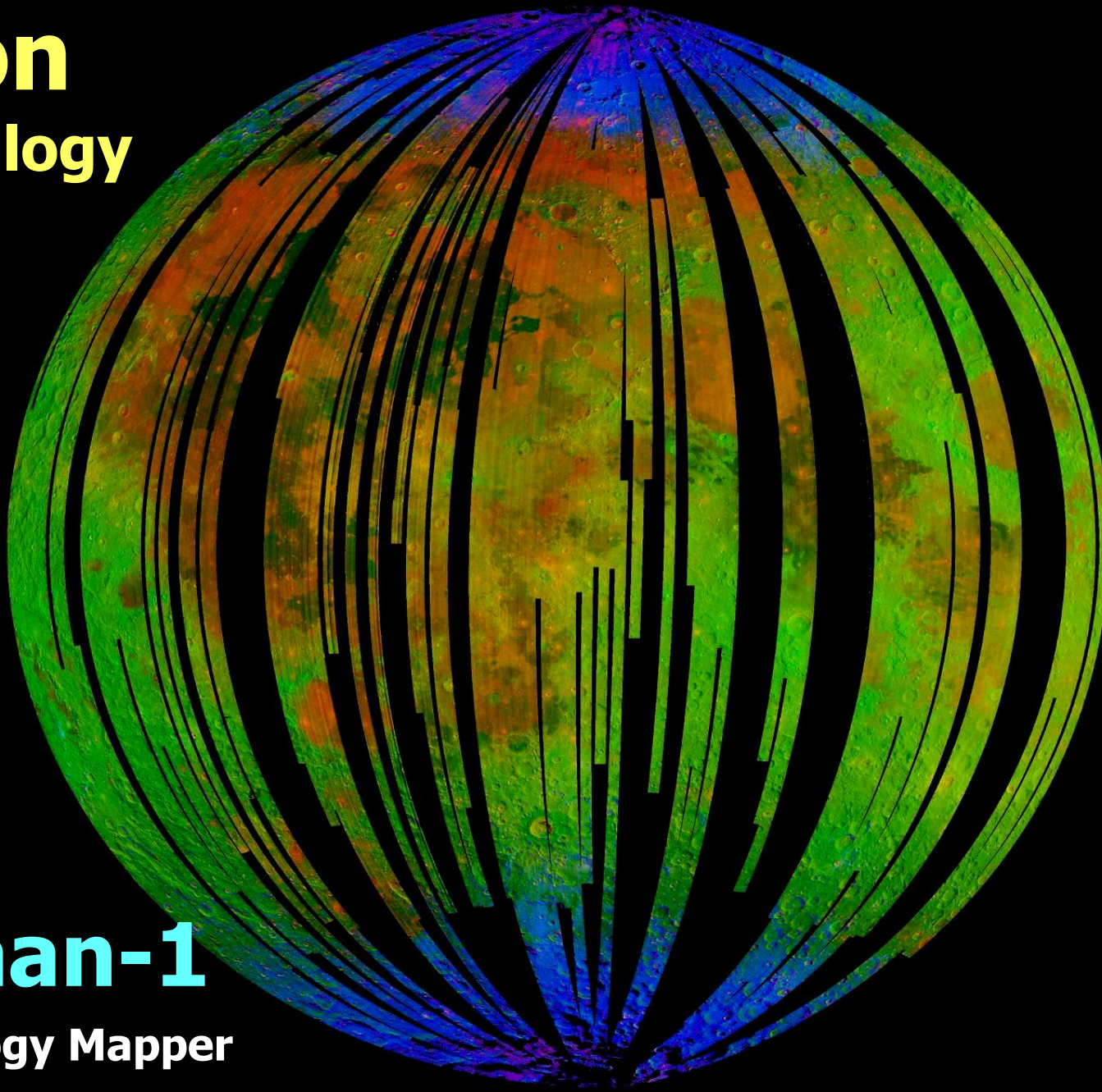
AAPG Annual Convention
April 9, 2014

BUREAU OF ECONOMIC GEOLOGY

Outline

- **Strategic Importance**
  - *-Sustaining Human Settlement*
  - *-Manufacture of Propellants for Transportation*
- **The Moon**
  - *-Non-Polar Areas (Endogenic and Exogenic Volatiles)*
  - *-Polar Areas*
- **Mercury**
  - *-Polar Areas*
- **Mars**
  - *-Atmosphere*
  - *-Ice Caps*
  - *-Permafrost*
  - *-Glacial Debris Aprons*
  - *-Gullies*

The Moon
Surface Mineralogy



Chandrayaan-1

NASA Moon Mineralogy Mapper
September 2009

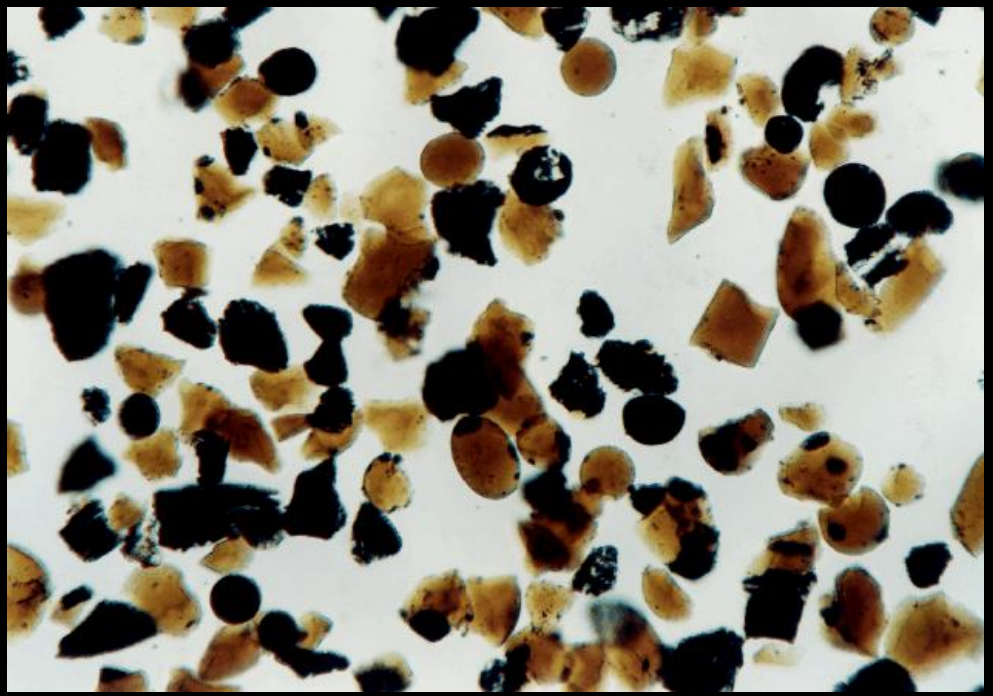
Lunar Energy Mineral Resources

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

Lunar Volatiles—Endogenic

Pyroclastics: 20-45 ppm water in some lunar glasses

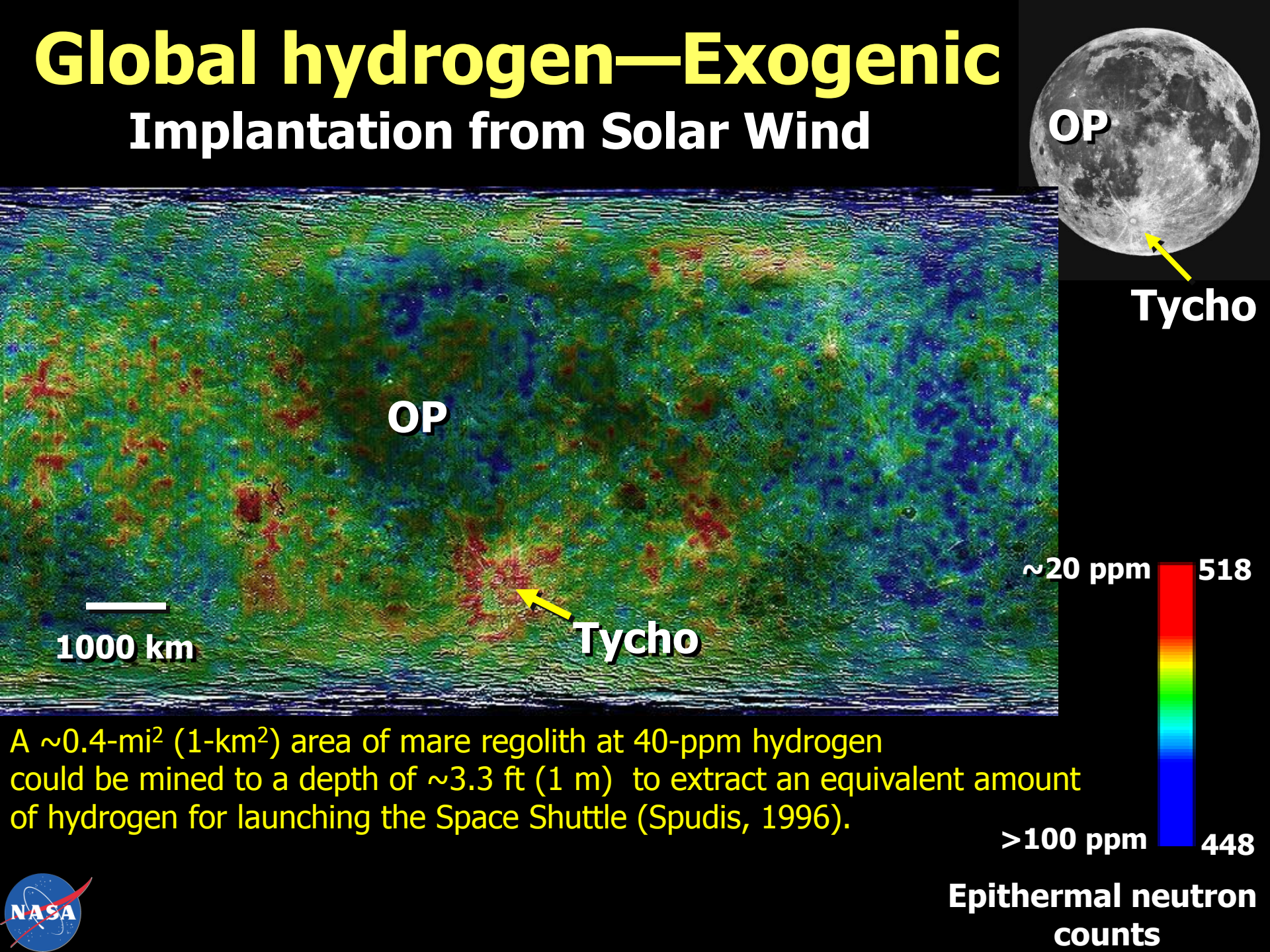
Pu'u O'o fire fountain
USGS (1985)



Volcanic Glass—Apollo 17
NASA (1972)

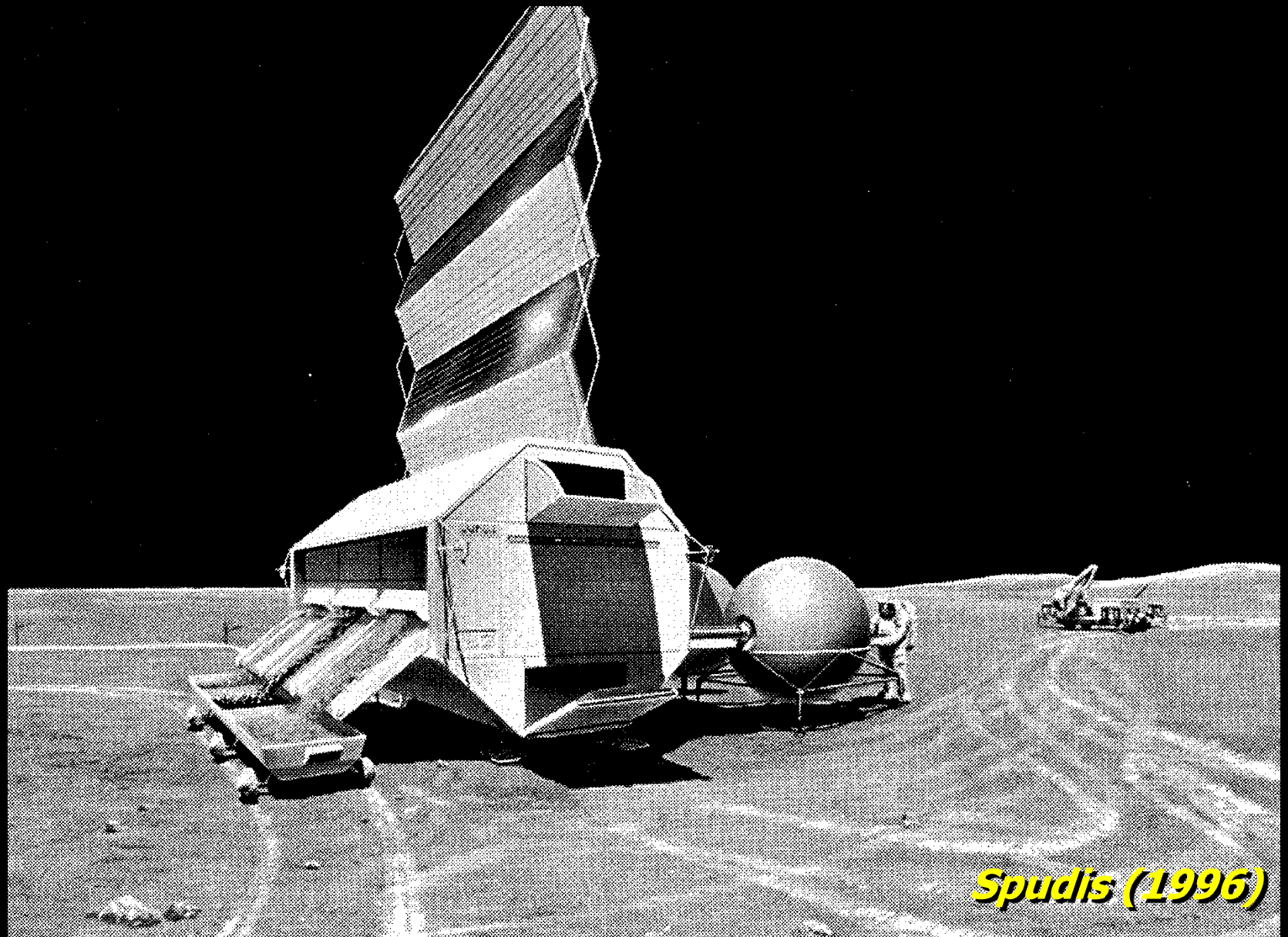
Global hydrogen—Exogenic

Implantation from Solar Wind



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).

Lunar Regolith Mining

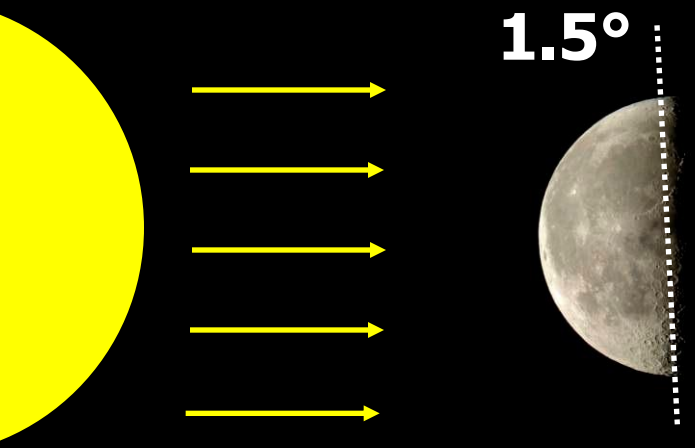


Volatiles at the Poles

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

North Pole: ~600 Mt of ice:

Daily launches of a space shuttle
For 2,200 years

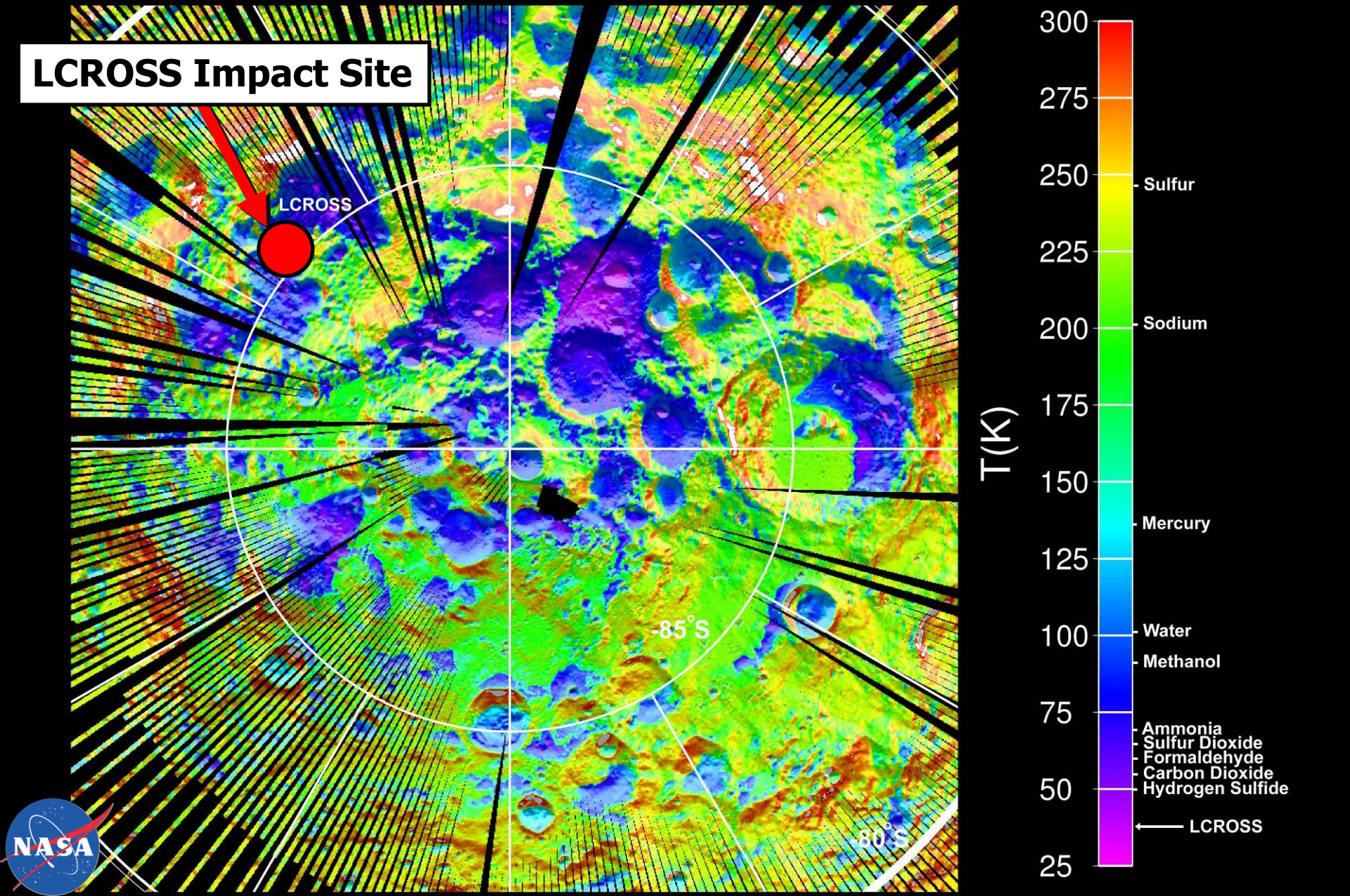


Bussey and Spudis (2006)

View from the Moon's South Pole

Kaguya Photograph

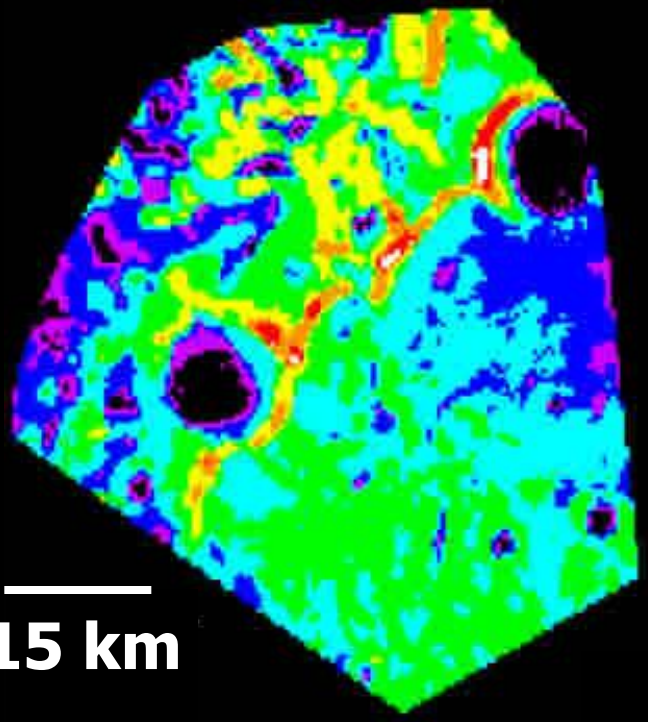
South Polar Temperature



Solar Illumination North Pole

Solar power

% Illumination



100

90-99

75-90

60-75

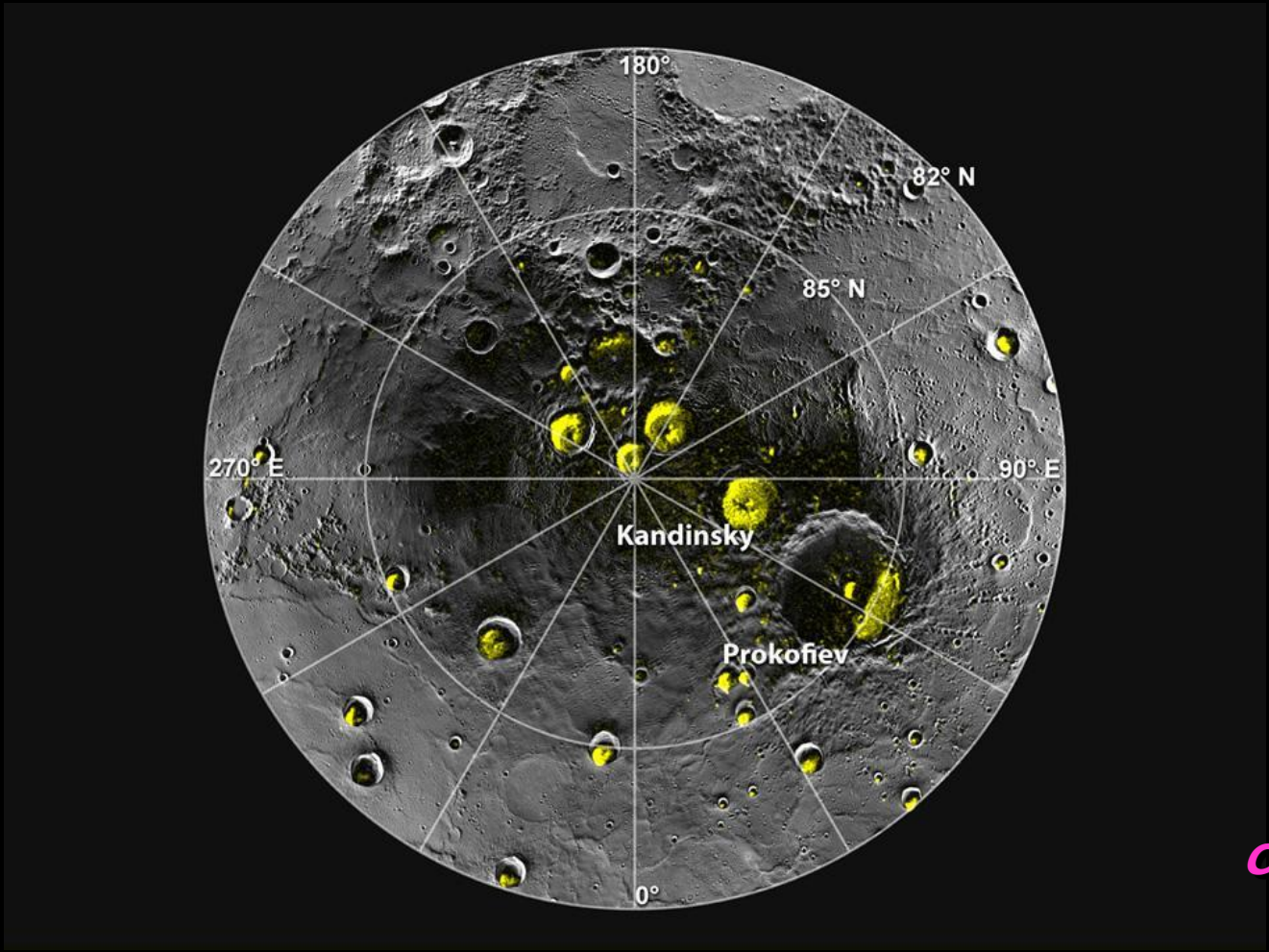
45-60

0

Bussey and Spudis (2006)

Mercury: Polar Ice

-Hydrogen (Neutron Spectrometer)—tens of cm
-Radar Reflectance Data at Near Infrared
-Topography and Temperature Data



Chabot et al. (2013)

Mars

- **Most Earth-Like Planet**

  -Second-closest planet (>200-d trip with conventional rocket)
  -Earthlike seasons; Day = 24 hrs, 37 minutes
  -As much land surface as the Earth

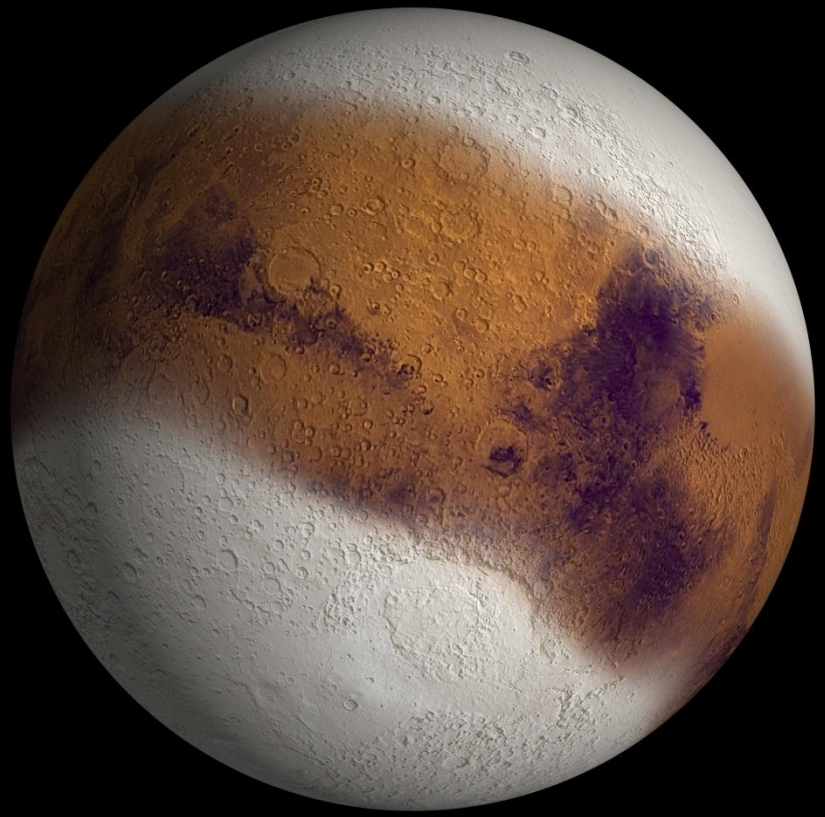
- **Abundant resources**

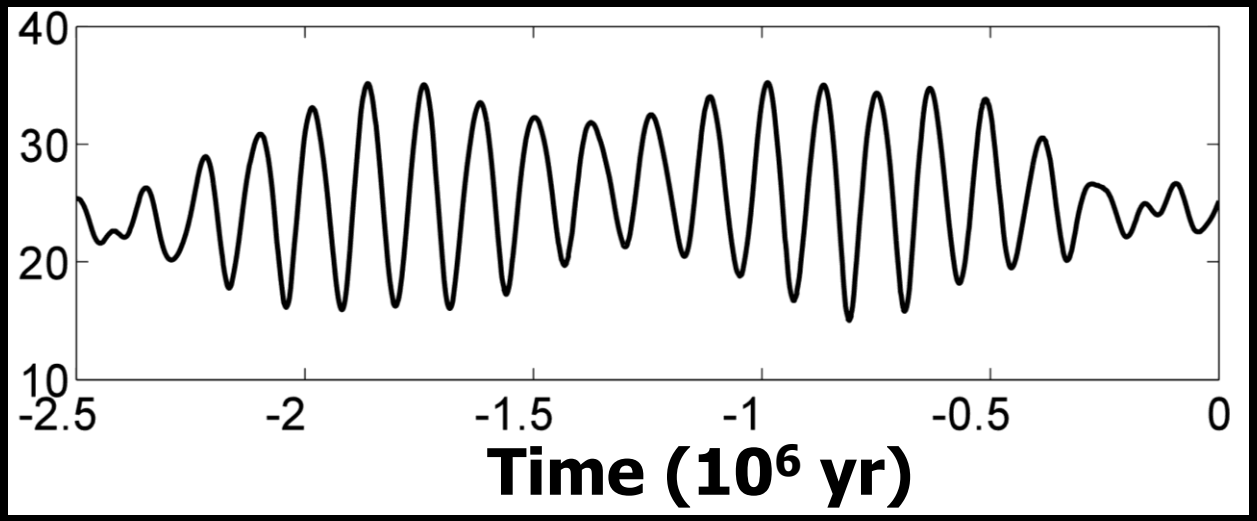
  -Water (Ice Caps and Permafrost)
  -Salts, volatiles, and metals
  -More carbon than the Moon (CO_2 atmosphere)

Mars

Water ice

-Atmosphere
-Ice caps
-Permafrost
-Fluvial , lacustrine deltas
-Glacial debris aprons
-Gullies

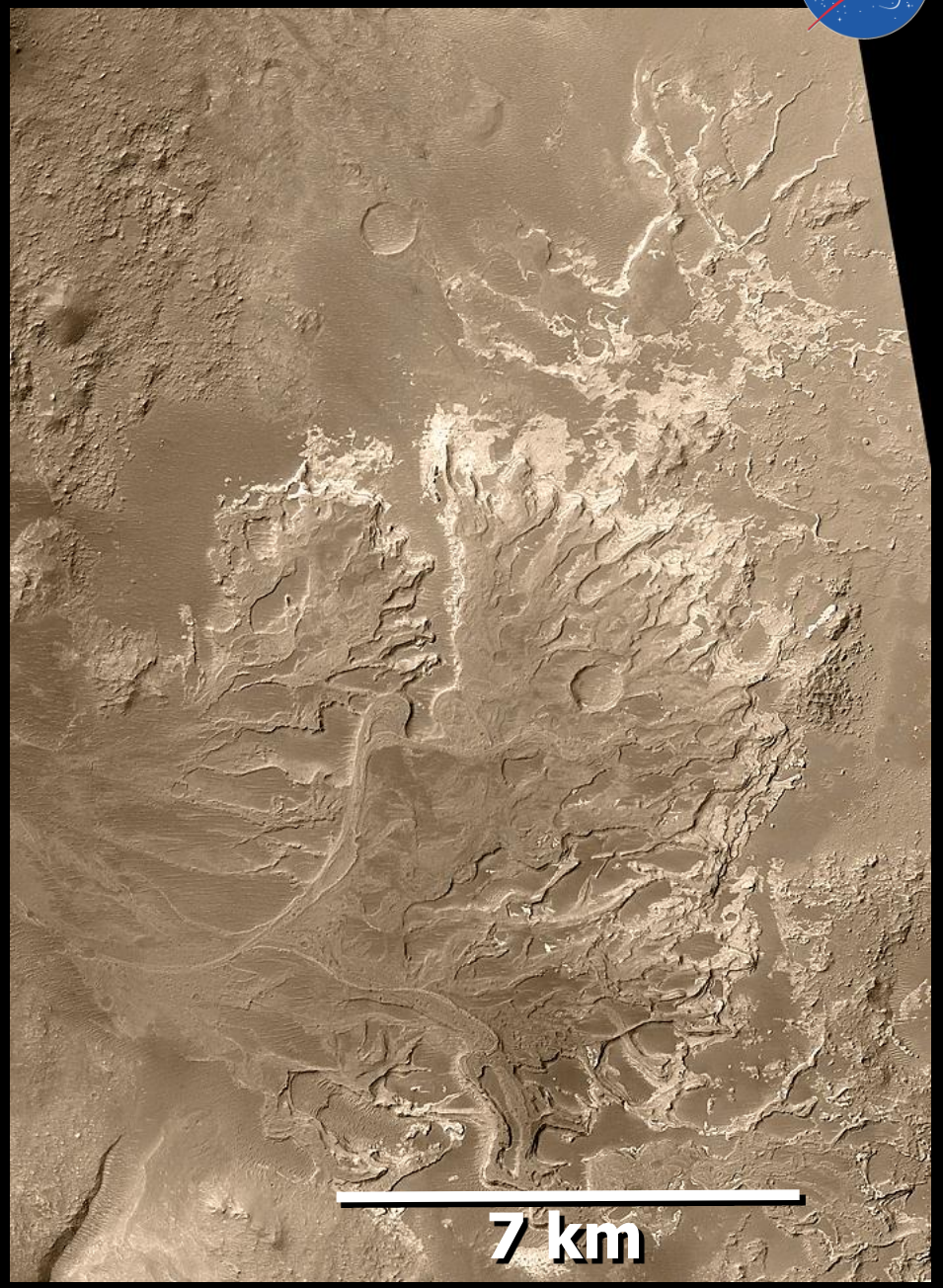




Schörghofer (2009)

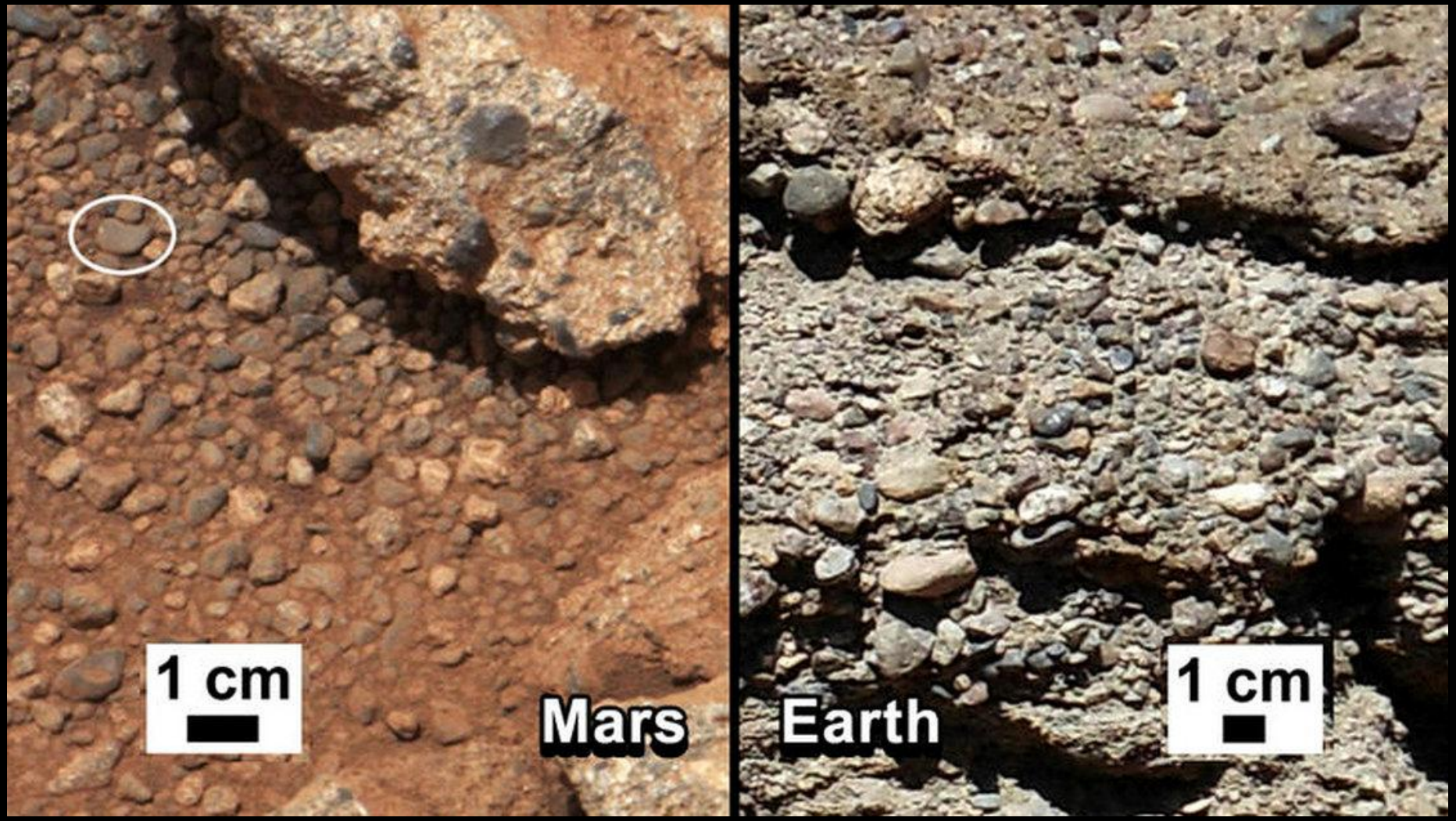
Deltas

Holden Delta



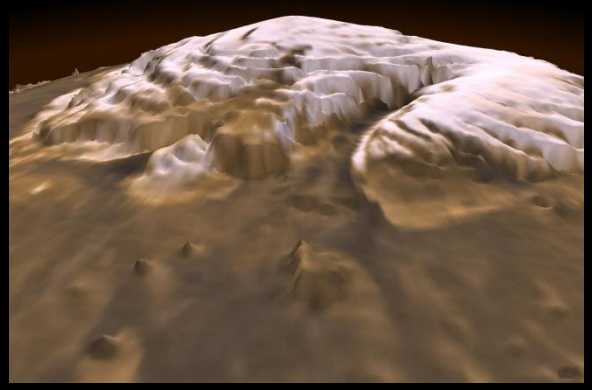
Alluvial-Fan Gravels

Curiosity Photo

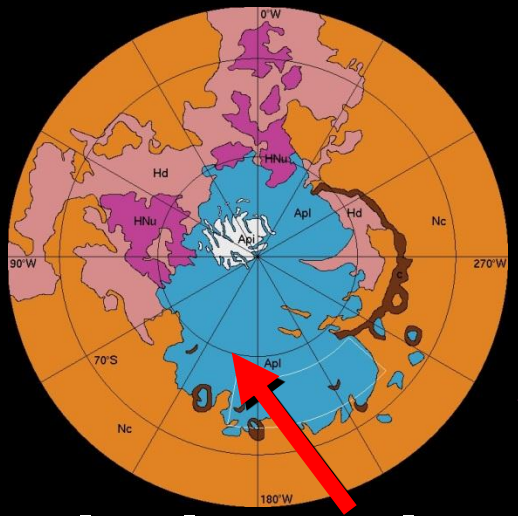


Mars: Water Ice Distribution

Kieffer et al. (1992)

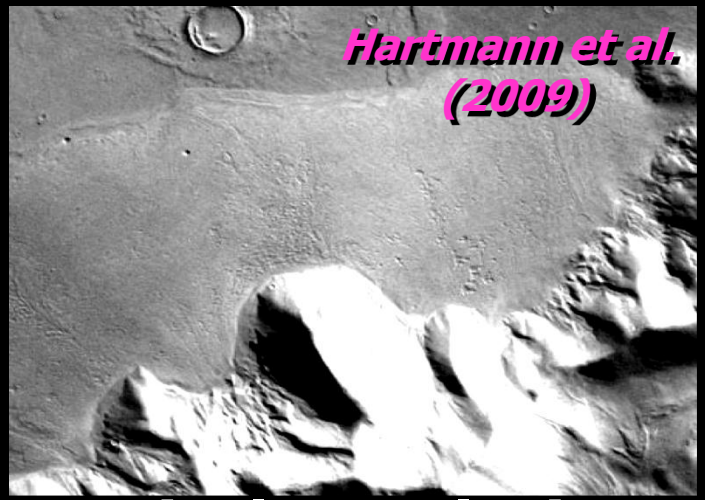


Polar caps
0.925 x 10^6 km^2

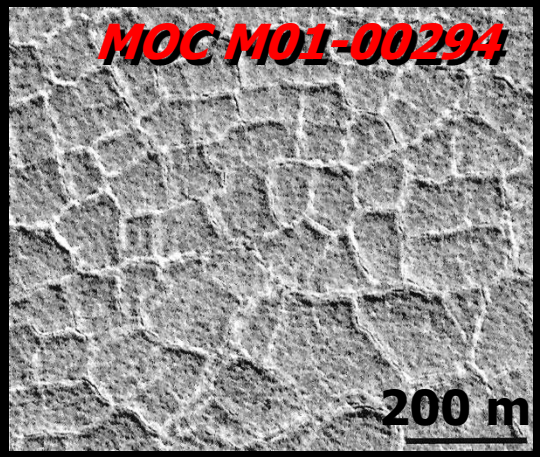


Tanaka (2005)

Polar layered terrain
1.8 x 10^6 km^2

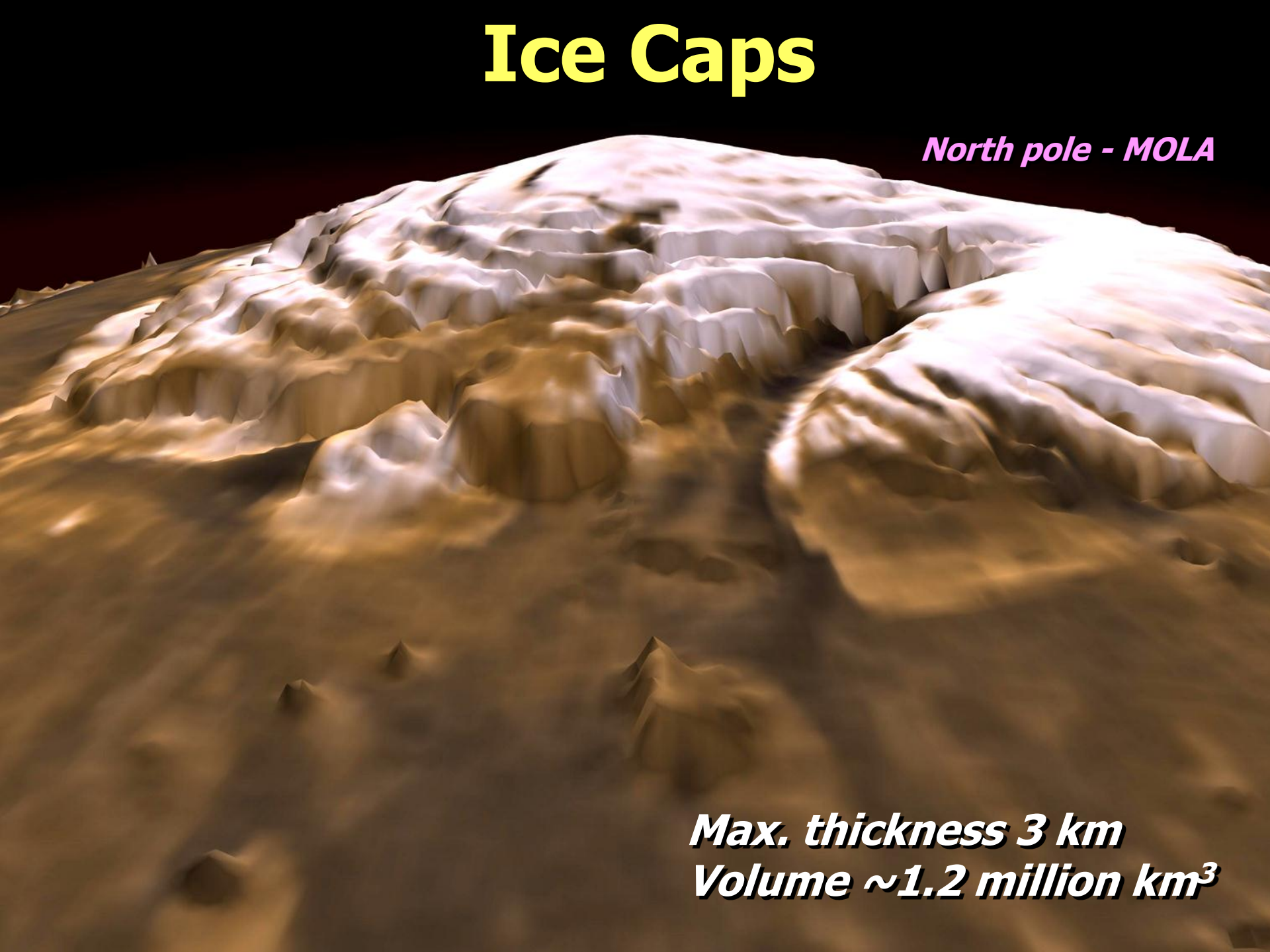


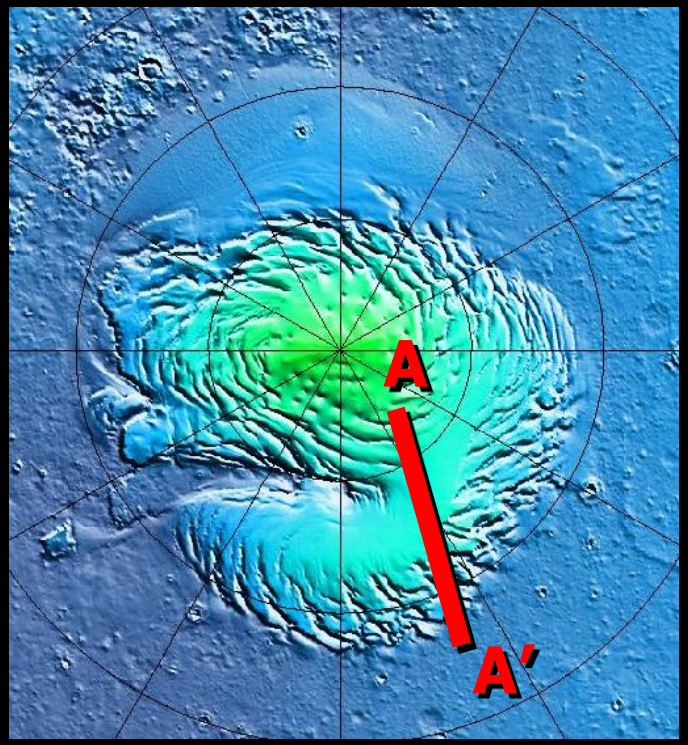
Tropical mt. glaciers
0.3 x 10^6 km^2



Subsurface ice
21 x 10^6 km^2

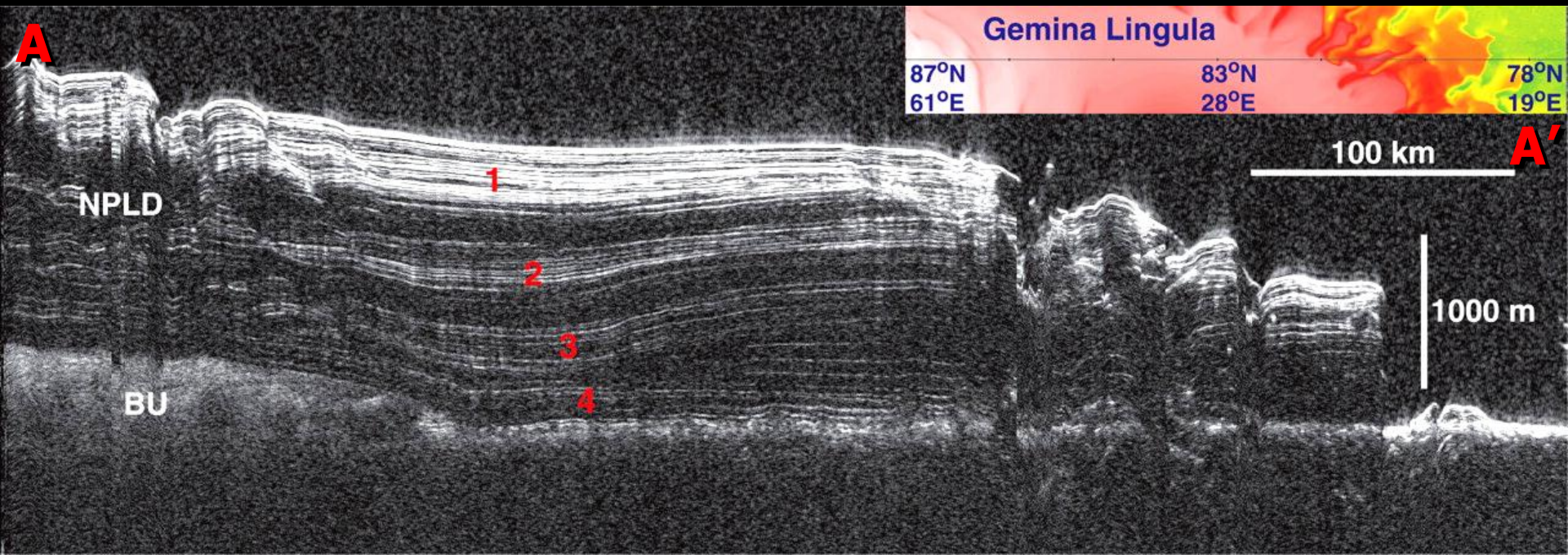
Ice Caps



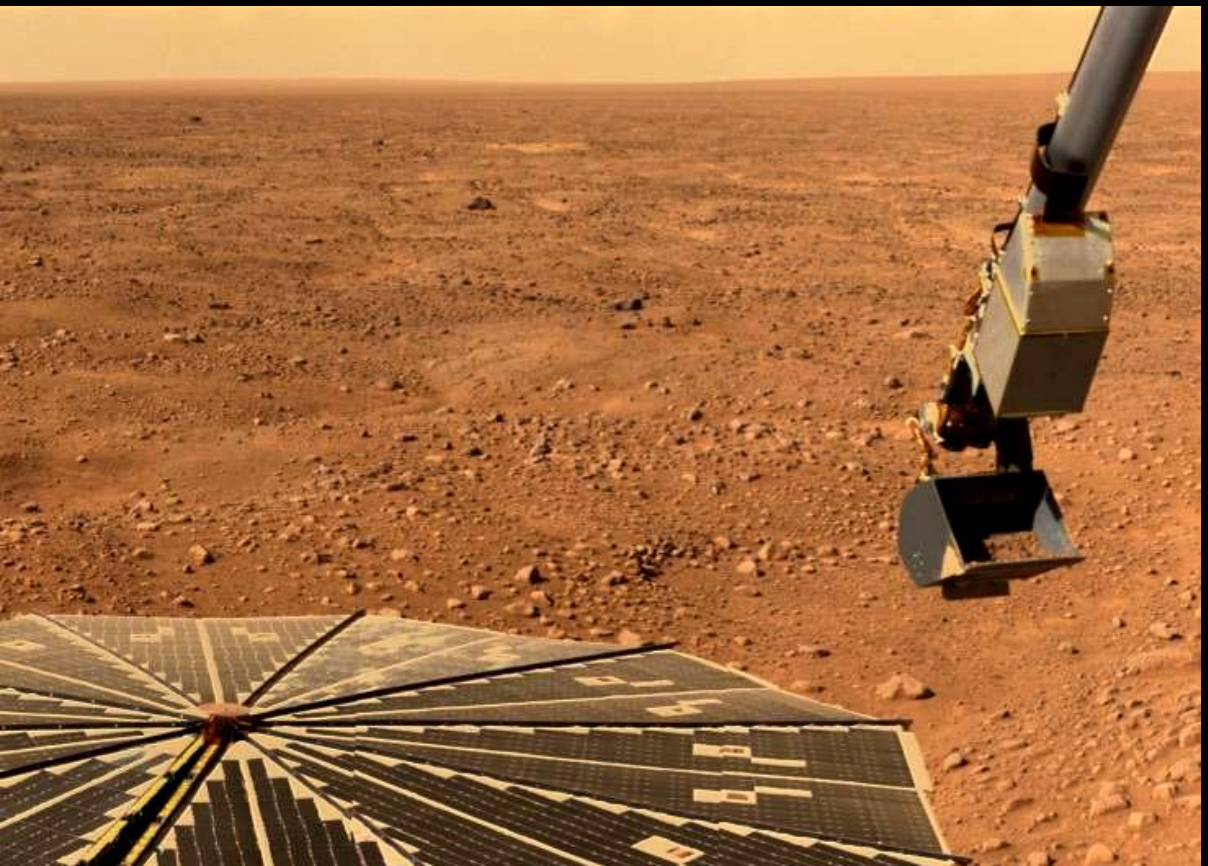


North Polar Cap Structure

Phillips et al. (2008)



Martian Permafrost
Phoenix Mission

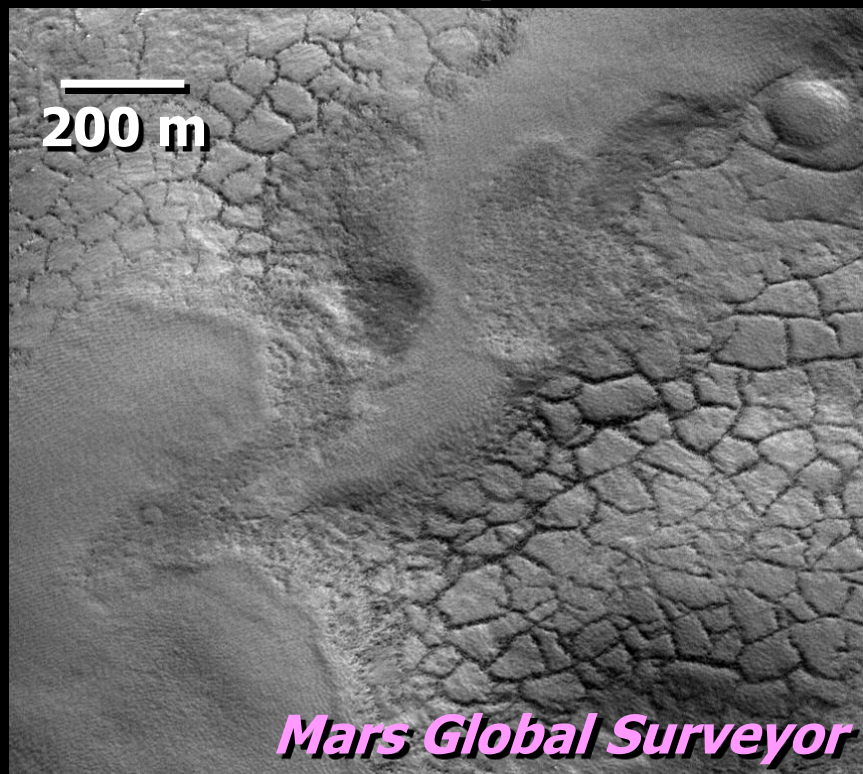


Patterned Ground

Mobile Permafrost

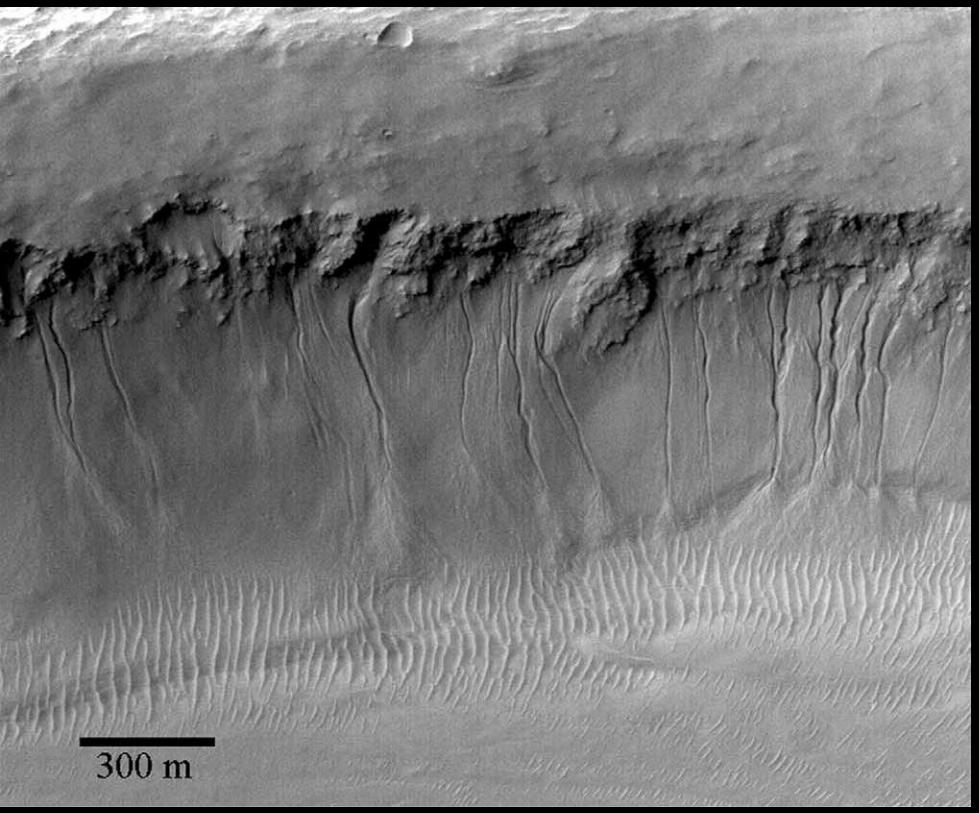
Northwest territories

Plains near Lyot Crater



Hillside Water Bursts

Mars

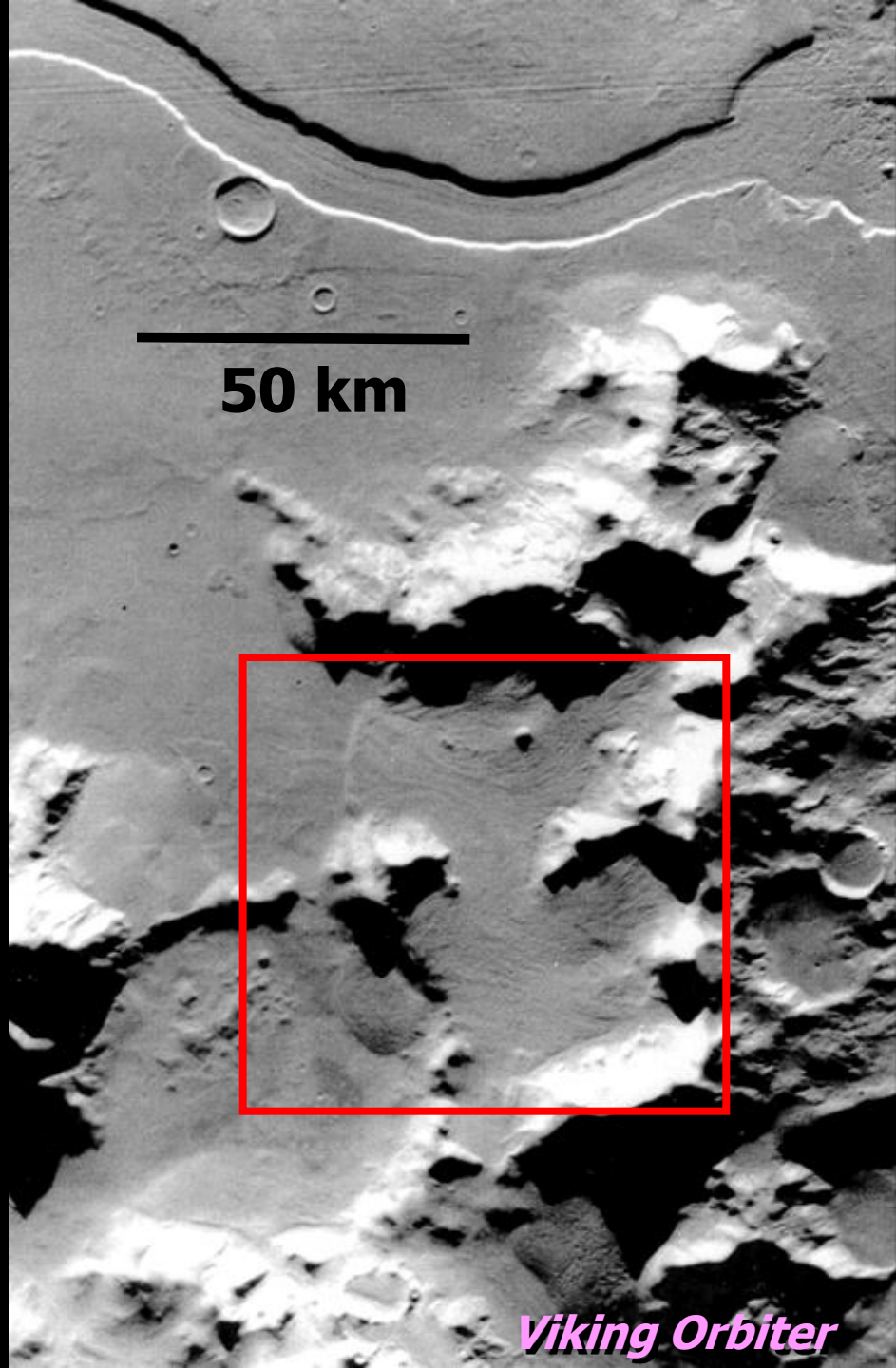


Hartmann et al. (2003)

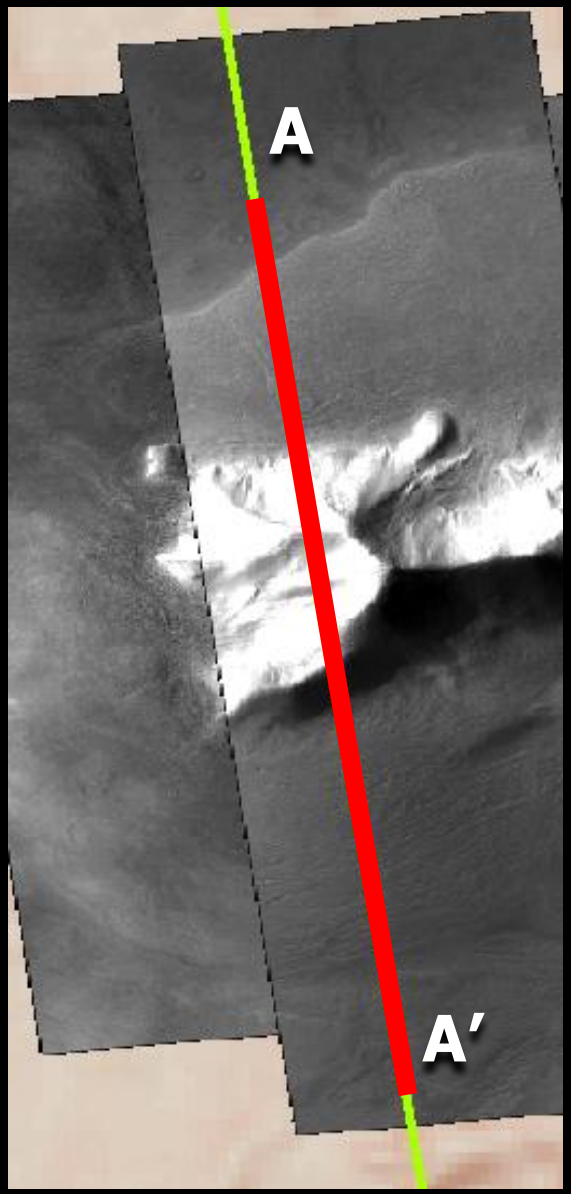
Iceland

Mid-Latitude Glacial Ice

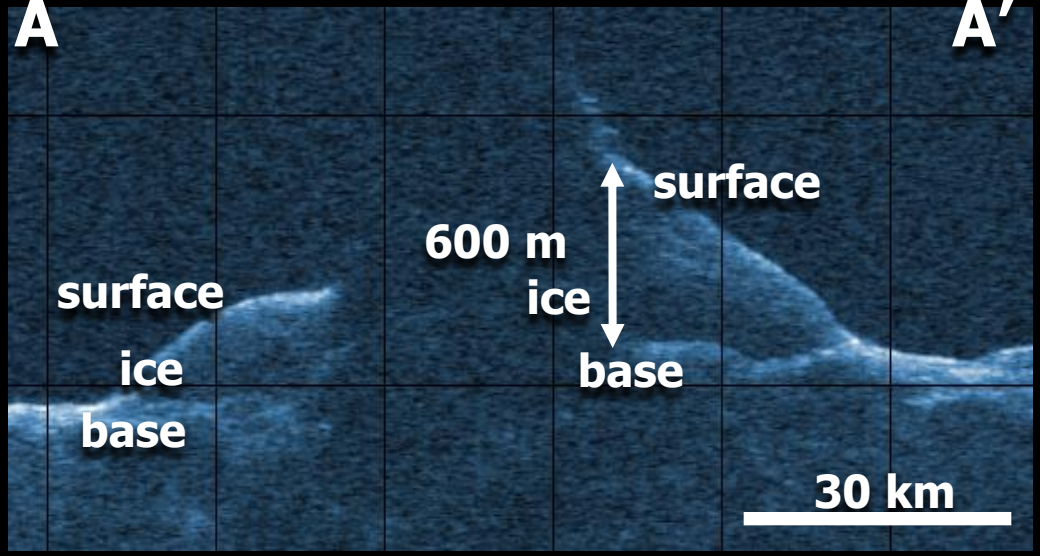
East of Hellas Planitia



Radar says: Lobate *not*-debris aprons



SHARAD data from MRO



Holt et al., *Science*, 2008

Radar observations indicate massive water ice

Not layered like polar deposits.

Hundreds of meters thick.

It's glacial ice!

This is a lot of ice...

vertical exaggeration 6:1

Holt et al., *Science*, 2008

Sunset on Mars