DRILLING FOR WATER ON THE MOON:

THE ECONOMICAL WAY TO EXTRACT GAME-CHANGING AMOUNTS OF H2O.

LOTS OF WATER IN POLAR CRATERS

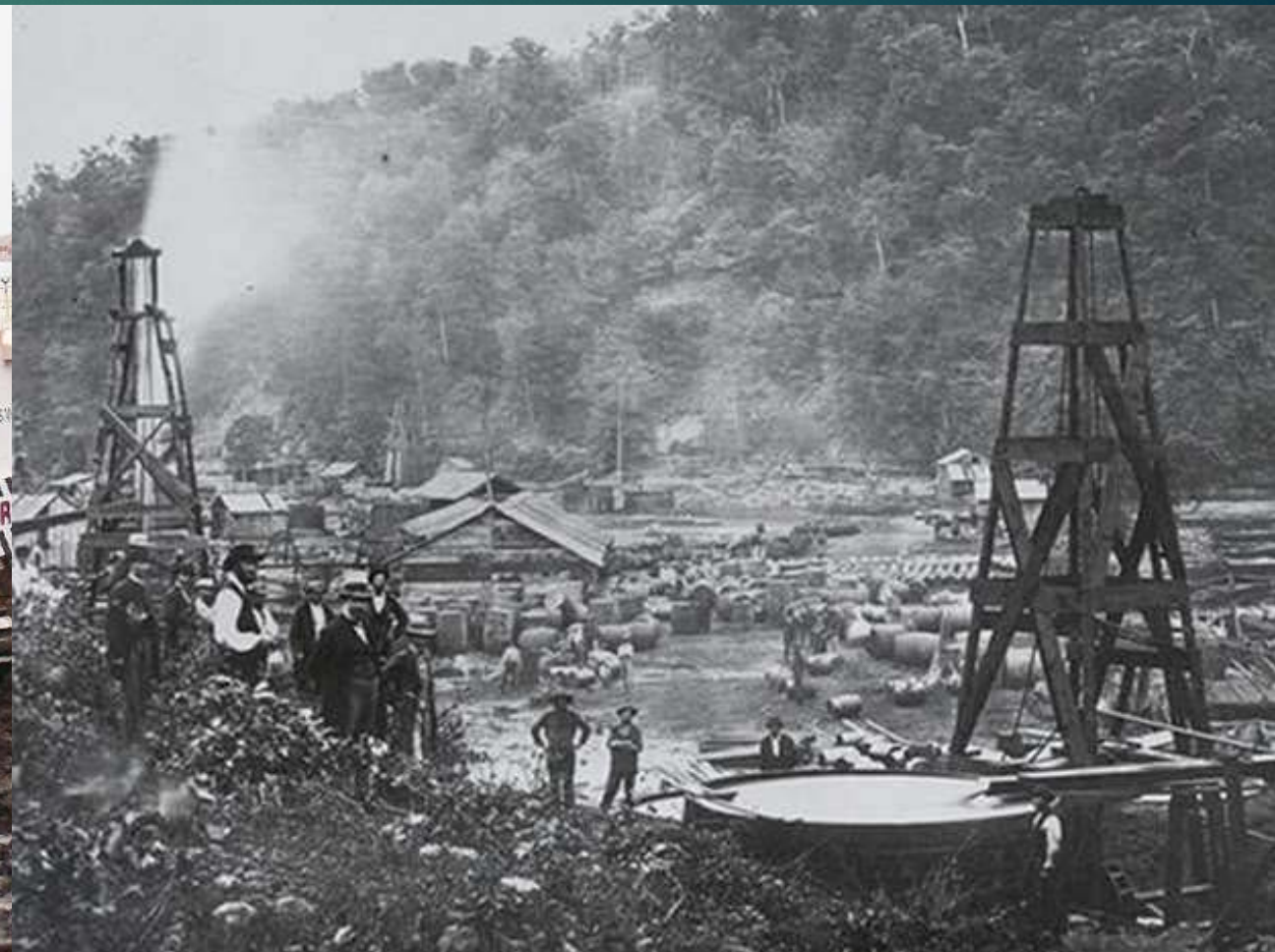
BUT….

1. High delta-v requirements
2. No line of sight communications
3. Extreme cold temperatures
4. Need for lots of heavy equipment
5. Why mine when you can drill ?!?

OIL SANDS vs. OIL WELLS

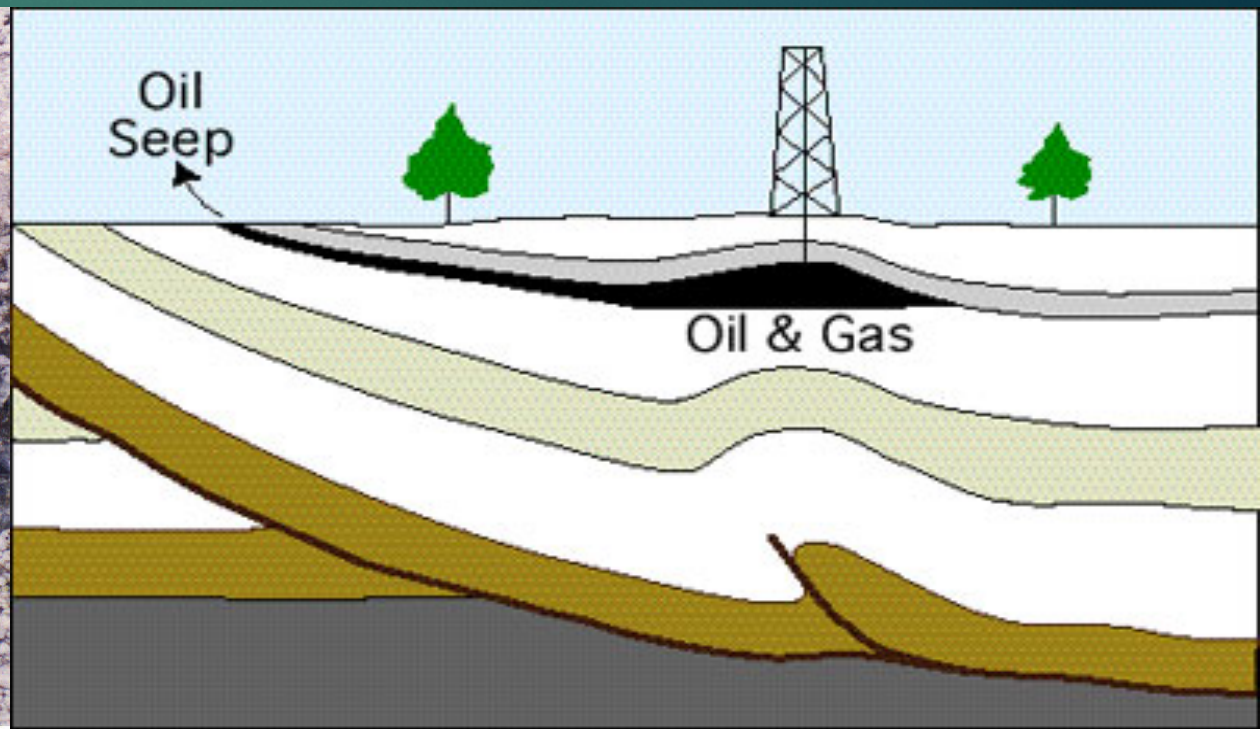
Alberta, Canada

Titusville, Pennsylvania



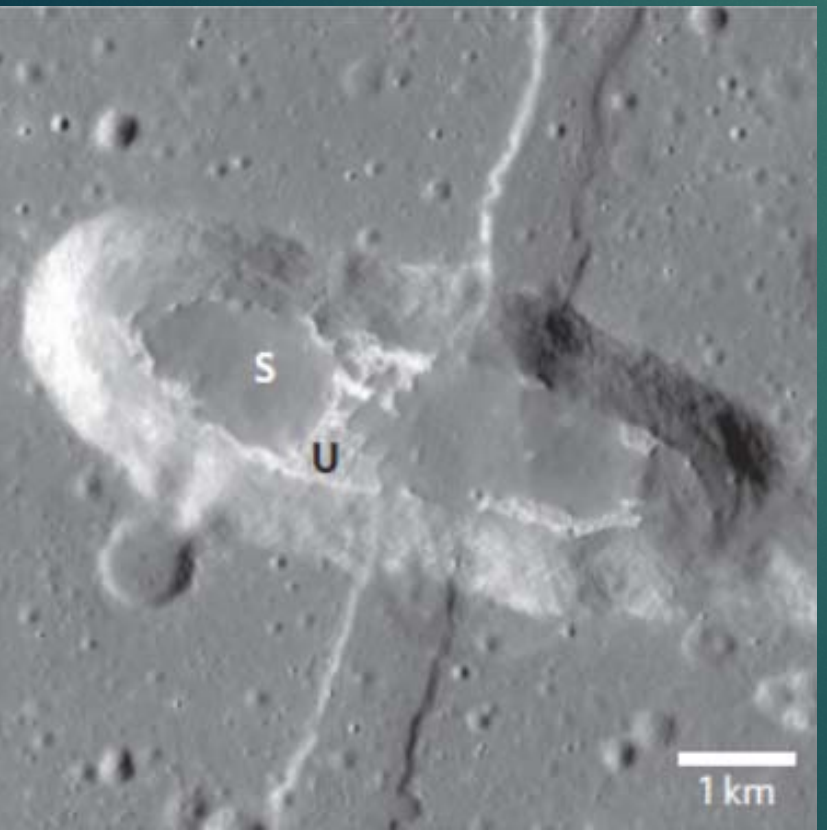
1ST EXPLORATION STRATEGY

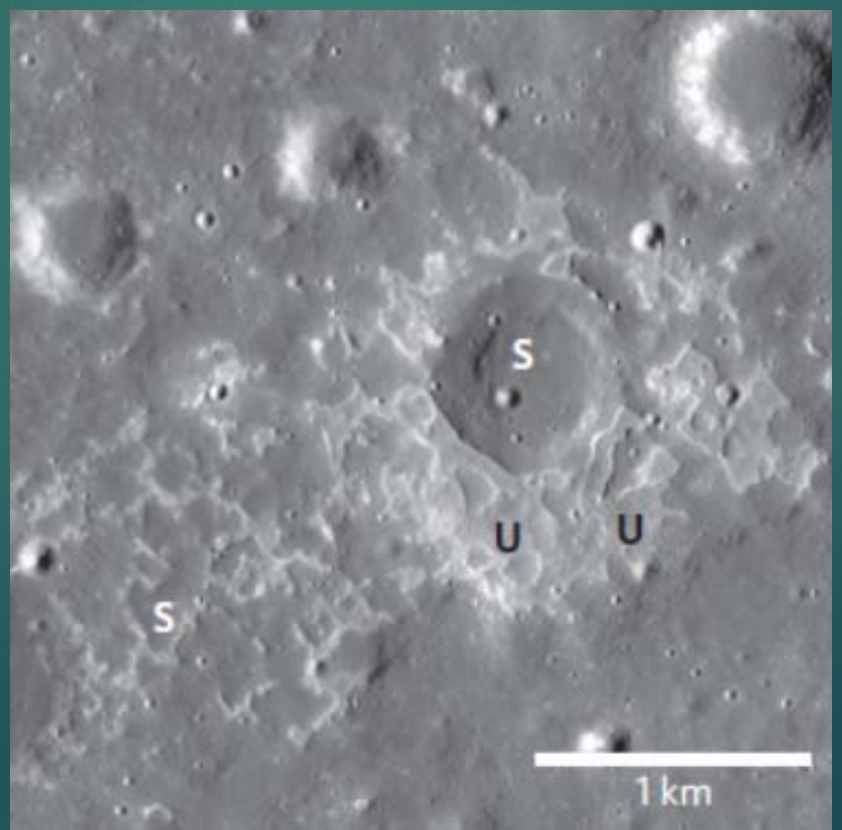
- Look for oil & gas seeps
- There you drill….

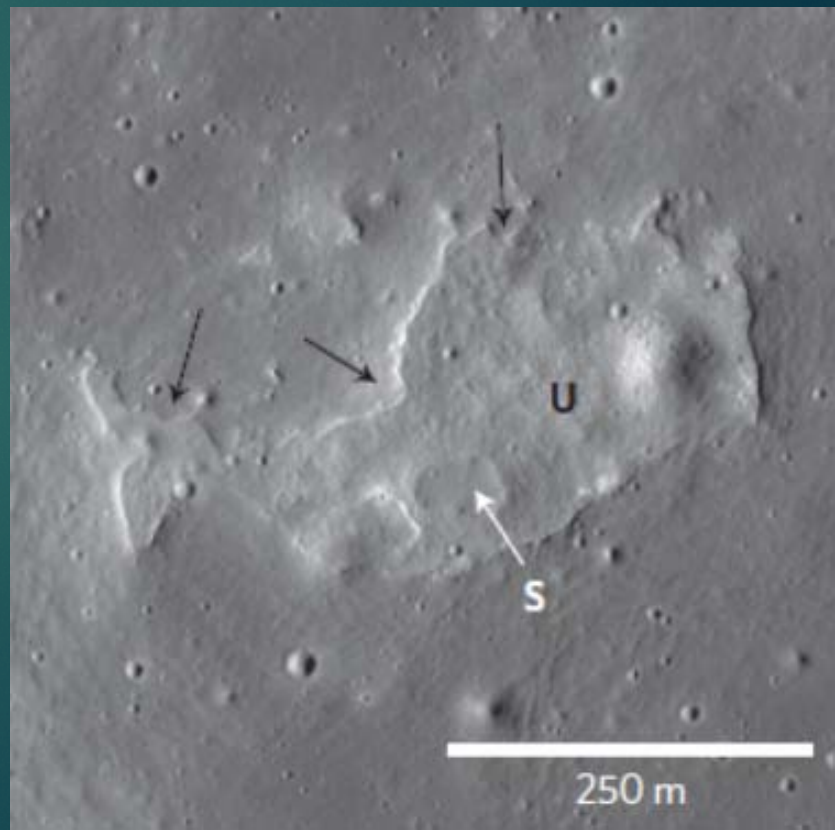


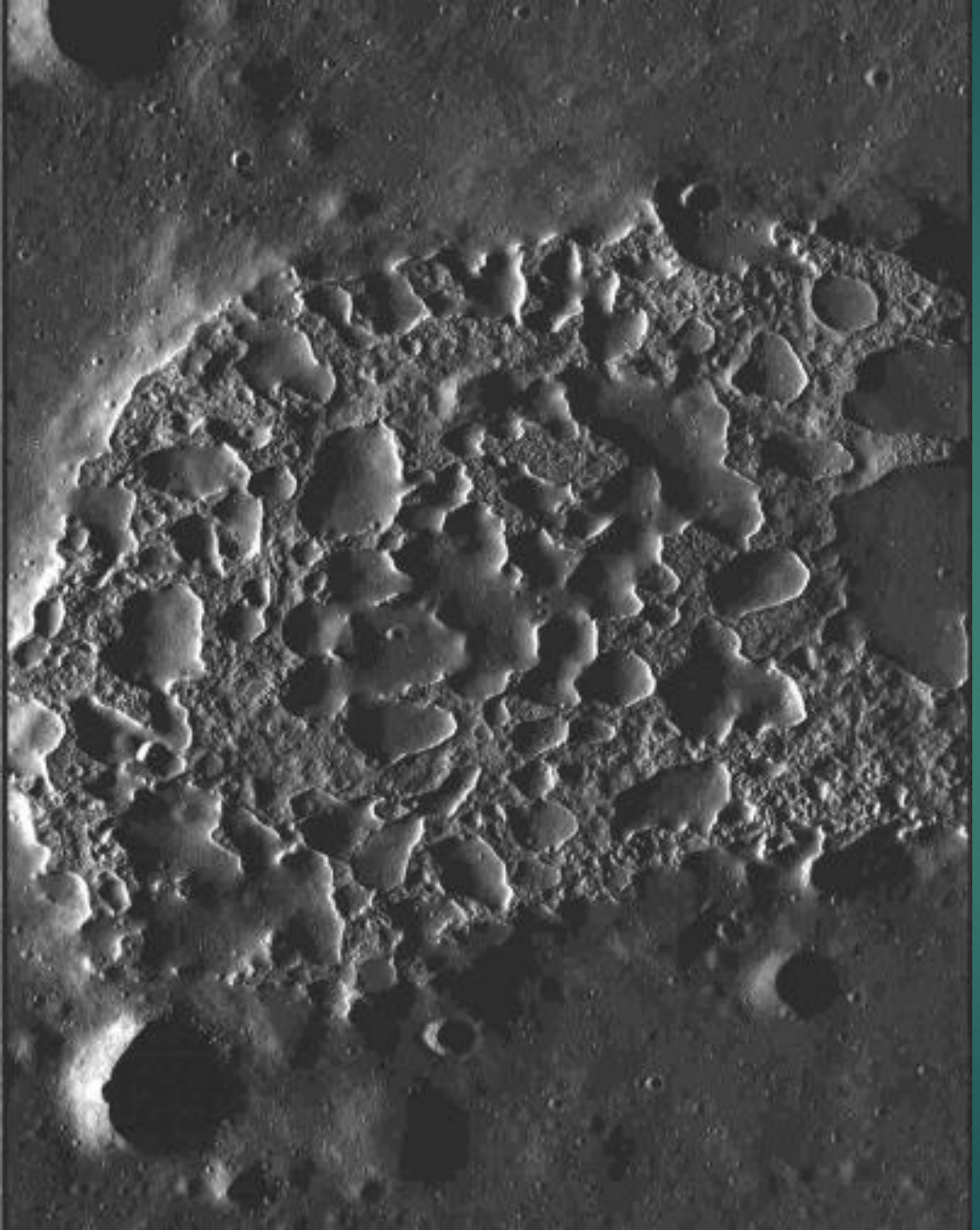
MENISCUS HOLLOWS

- a.k.a. Rimless Pits
- Irregular Mare Patches (IMPs)



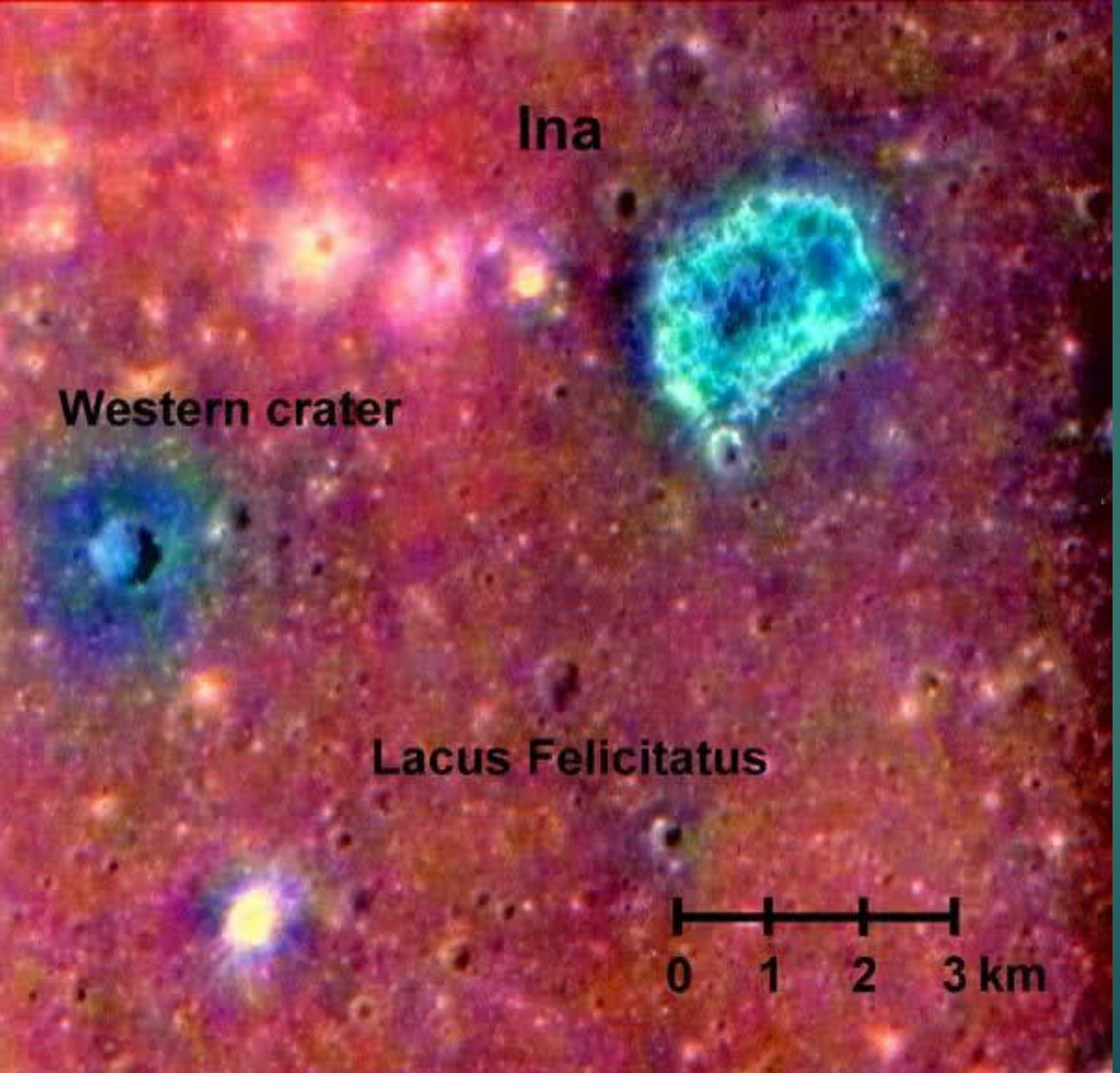






Ina D-caldera

- Approximately 3 km
- Characterized by numerous convex upward mounds
- Interspersed with blocky terrain



Reflectance Data:

- "Blue" color = fresh
- "Red" color = old

- Spectra similar to high Ti basalts exposed in very fresh craters

- Age: 10 my max

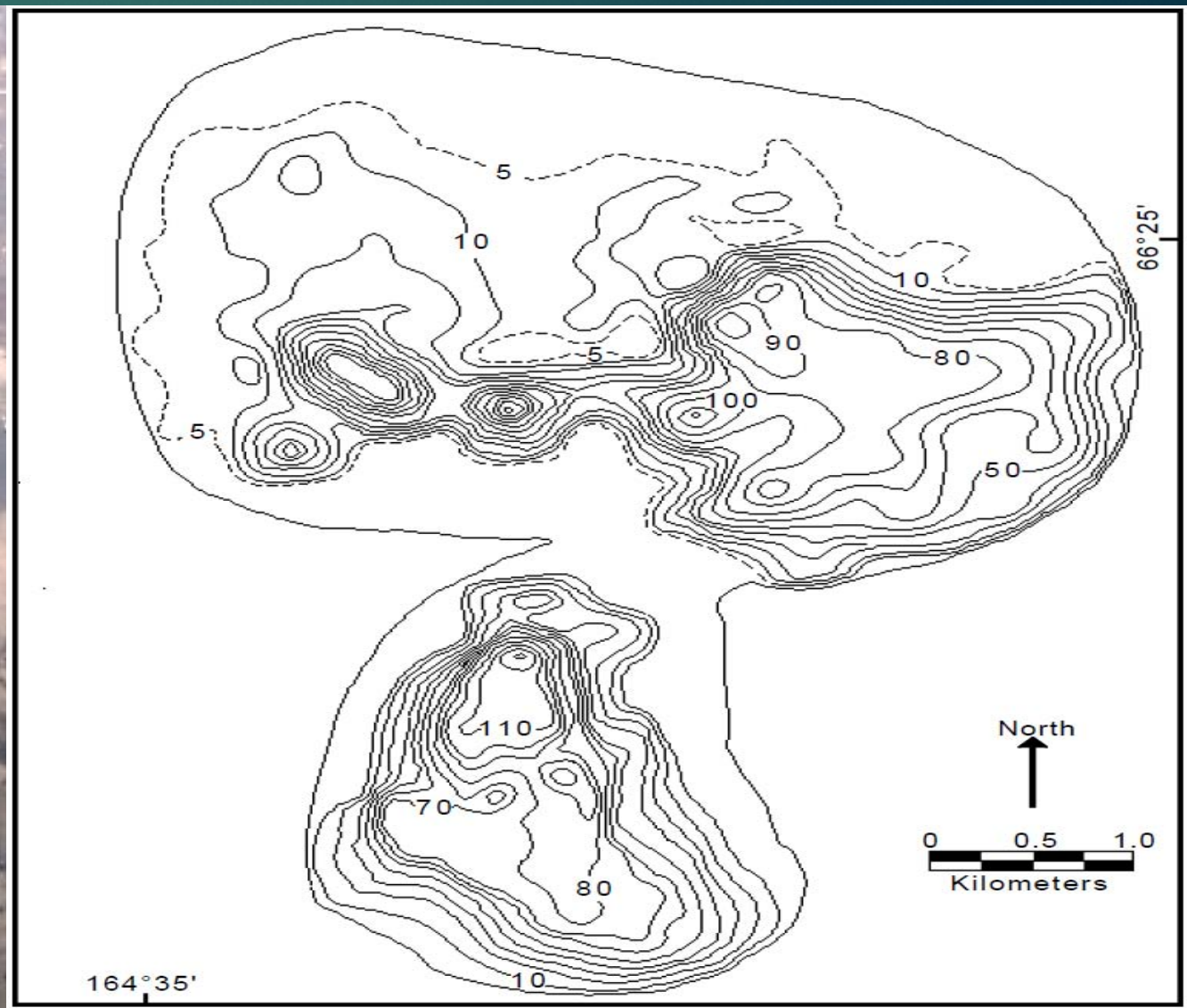
Tephra (debris) halo extends 500 m

$u = \blacksquare(d\,g/\sin 2\theta\ )\ \uparrow 1/2$

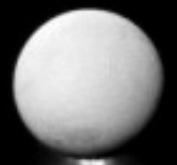
Launch angle: **45°** $V_e \approx 28\ m\ s^{-1}$

Launch angle: **80°** $V_e \approx 48\ m\ s^{-1}$

BEST TERRESTRIAL ANALOG: MAARS
Caused by phreatomagmatic eruptions



CRYOVOLCANOES



Enceladus plume

Also has ~3% CO_2

$v_e \approx 100\ m\ s^{-1}$

CO_2 driven eruptions on Earth

Limnic eruptions

Lake Nyos

Coldwater Geysers

Crystal Geyser

Lab Experiments

4000 frames / sec

Energetics of Cryovolcanos

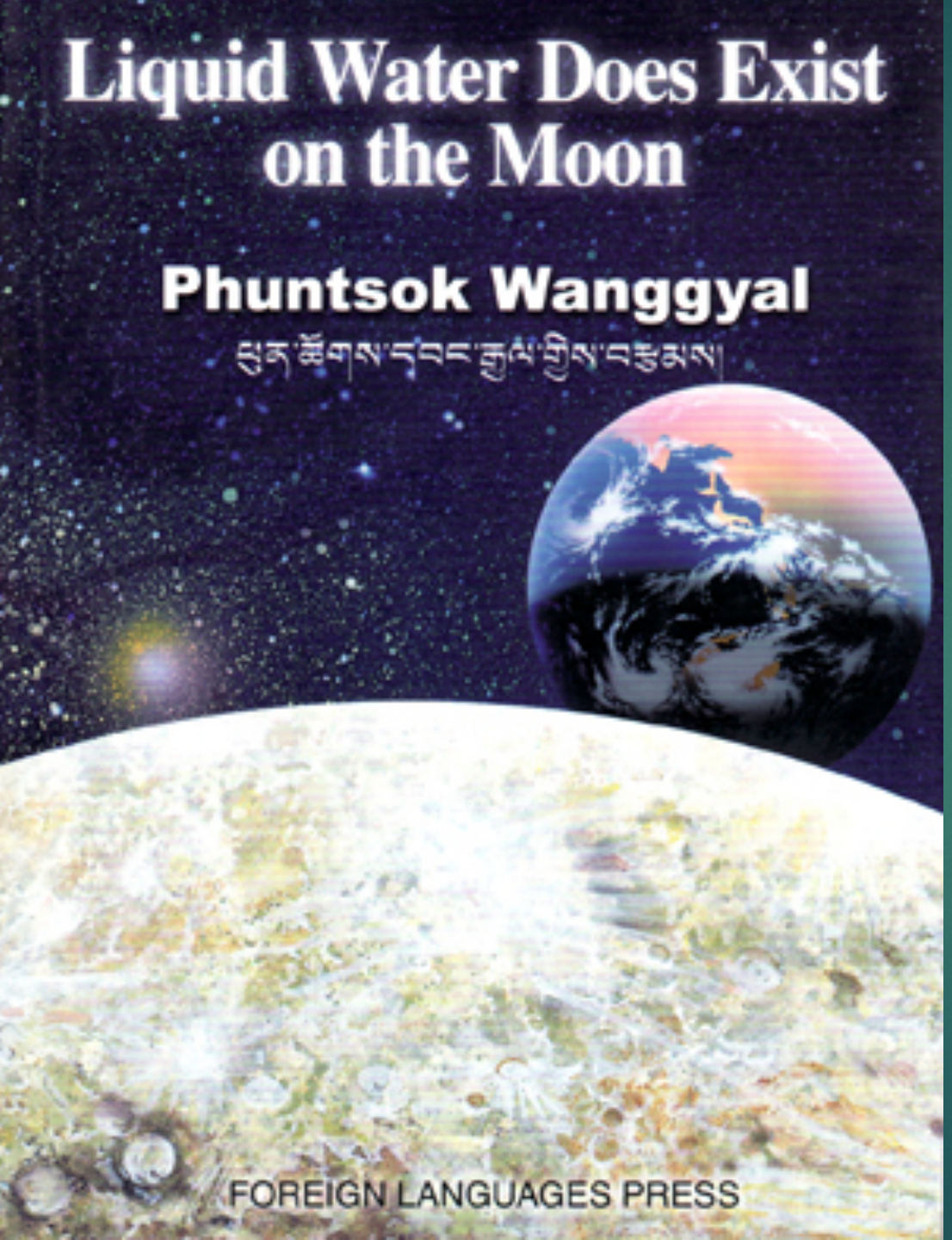
$$1/2\ u\uparrow 2 \approx \lambda P\downarrow 0\ /\rho\downarrow 0\ \left(\ln P\downarrow 0\ /P\downarrow out\ -1+P\downarrow out\ /P\downarrow 0\ \right)$$

CO_2 Ostwald coefficient ≈ 1.8

$u \approx$ 106 m s^{-1} for Lunar conditions

LIQUID WATER ON THE MOON?!?

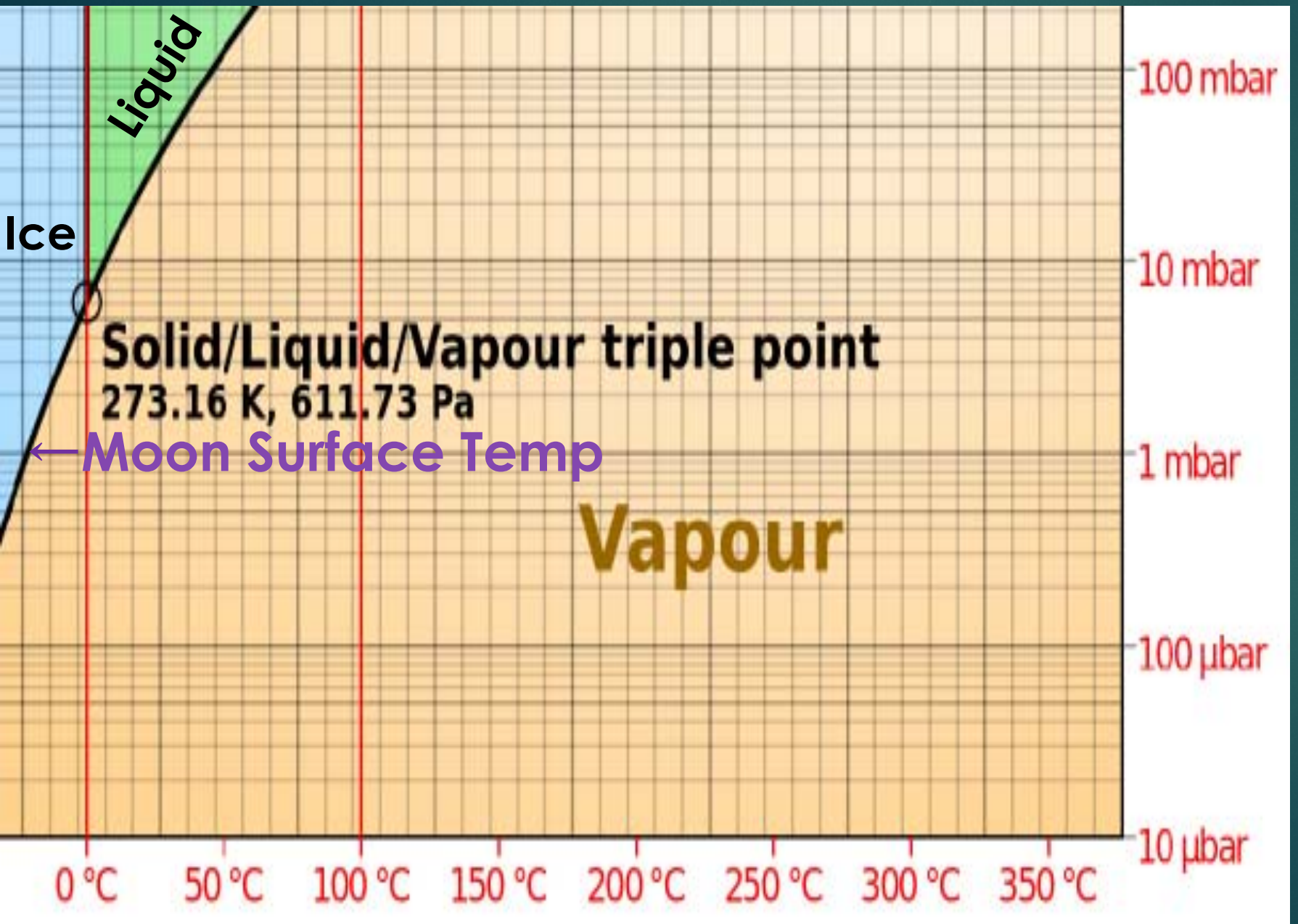
WTF?!?



- Figured it out while serving 18 year sentence in solitary confinement

- Was invited to NASA conference in 1990s

WATER PHASE DIAGRAM



P > overburden pressure: ½ bar and T > 0 C

Vapor diffuses thru regolith if P < 1 mbar

Vapor forms ice if T < 0 C and if P > 1 mbar

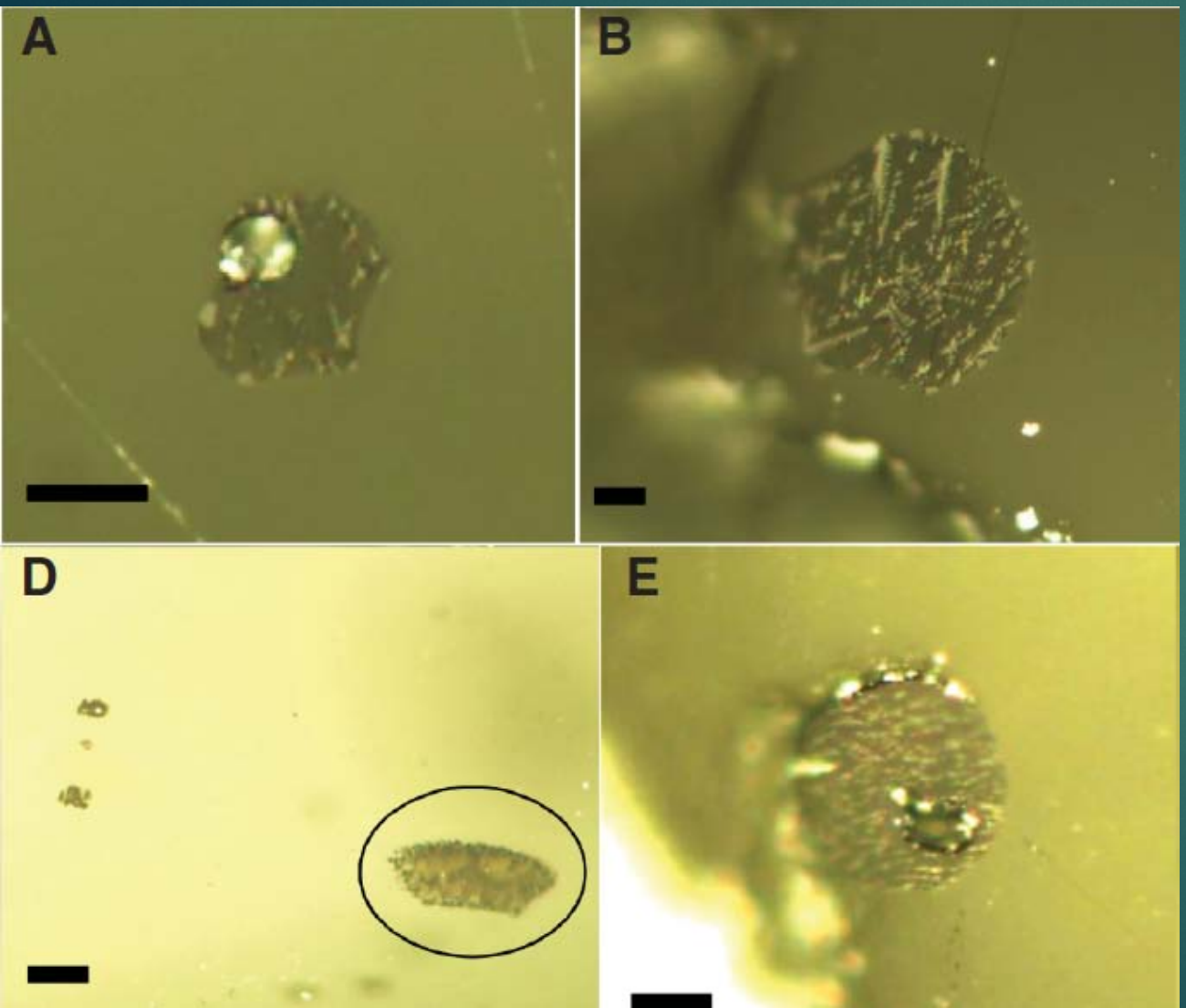
MAIN EFFECTS OF A PERMAFROST CAP

- Would form impermeable barrier
- Would increase tensile strength of regolith, thus increasing explosive force

What about MAPSIS/SHARAP results that show no H2O on Mars?

- Wavelength = 25-50 meters
- Hasn't been done on the Moon AFAIK
- Horizontal resolution order of 1 km
- Vertical resolution order of 10 m
- Size of reservoir on order of one pixel

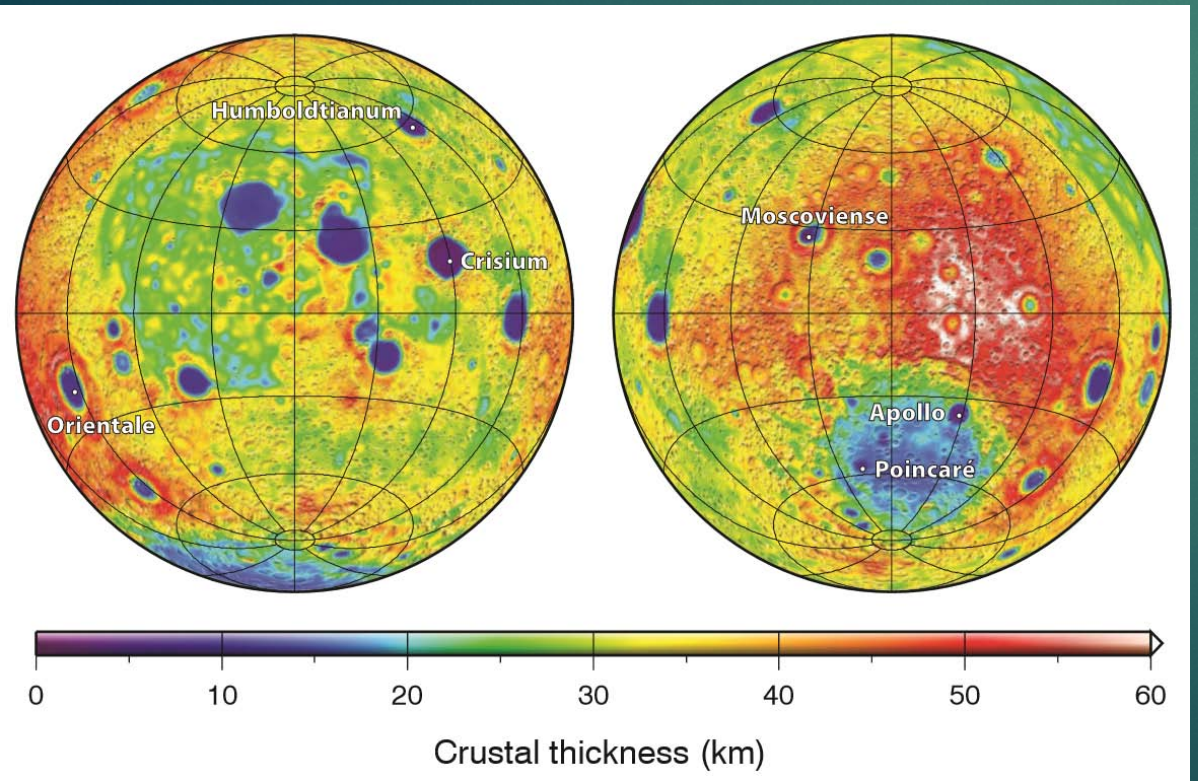
SOURCE ROCK: CRUST/MANTLE



- Melt inclusions show that lunar mantle/crust initially had as much water as Earth
- But water recycled on Earth due to plate subduction
- OTOH: no water lost on Moon through rifting

GRAIL PROBE RESULTS

- Moon "fracked" down to 70-80 km



- Porosity average 12%
- Not enough water to fill all pore space

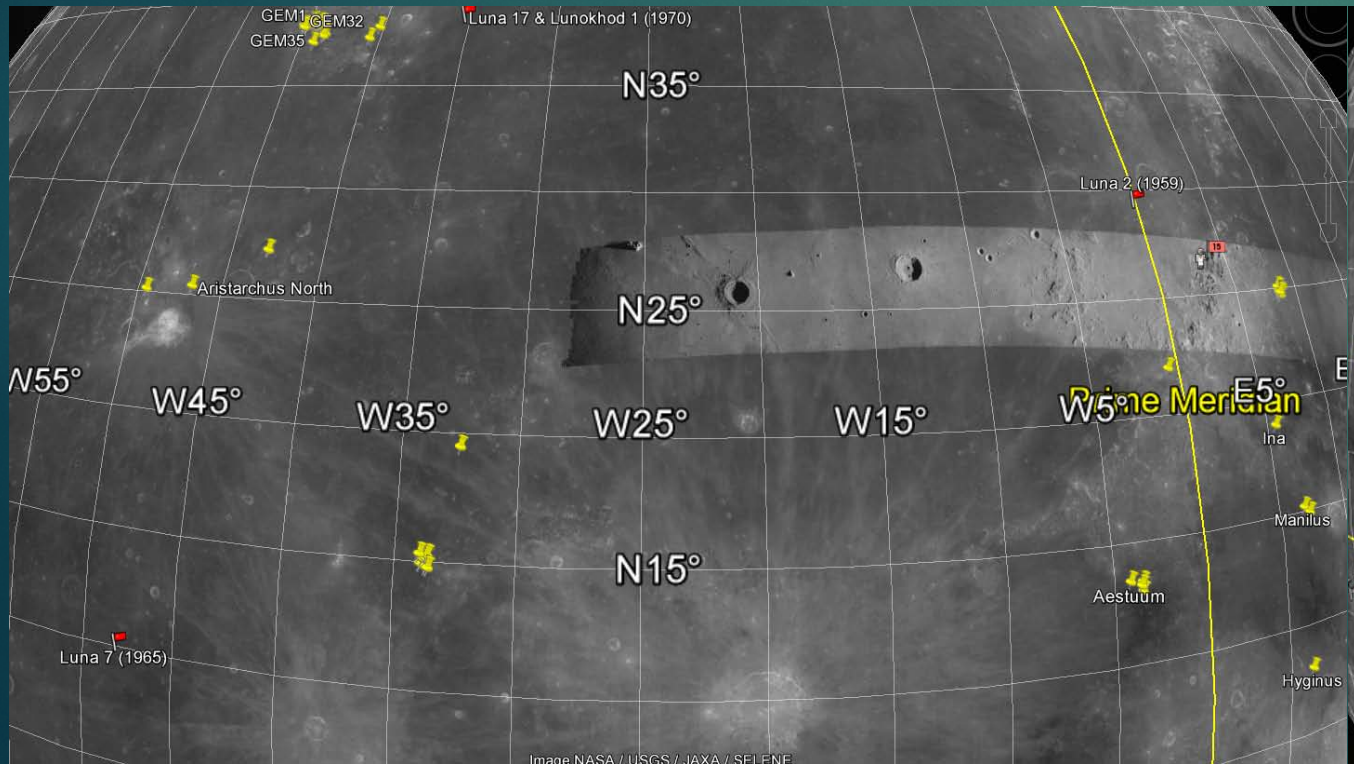
KOLA SUPERDEEP BOREHOLE

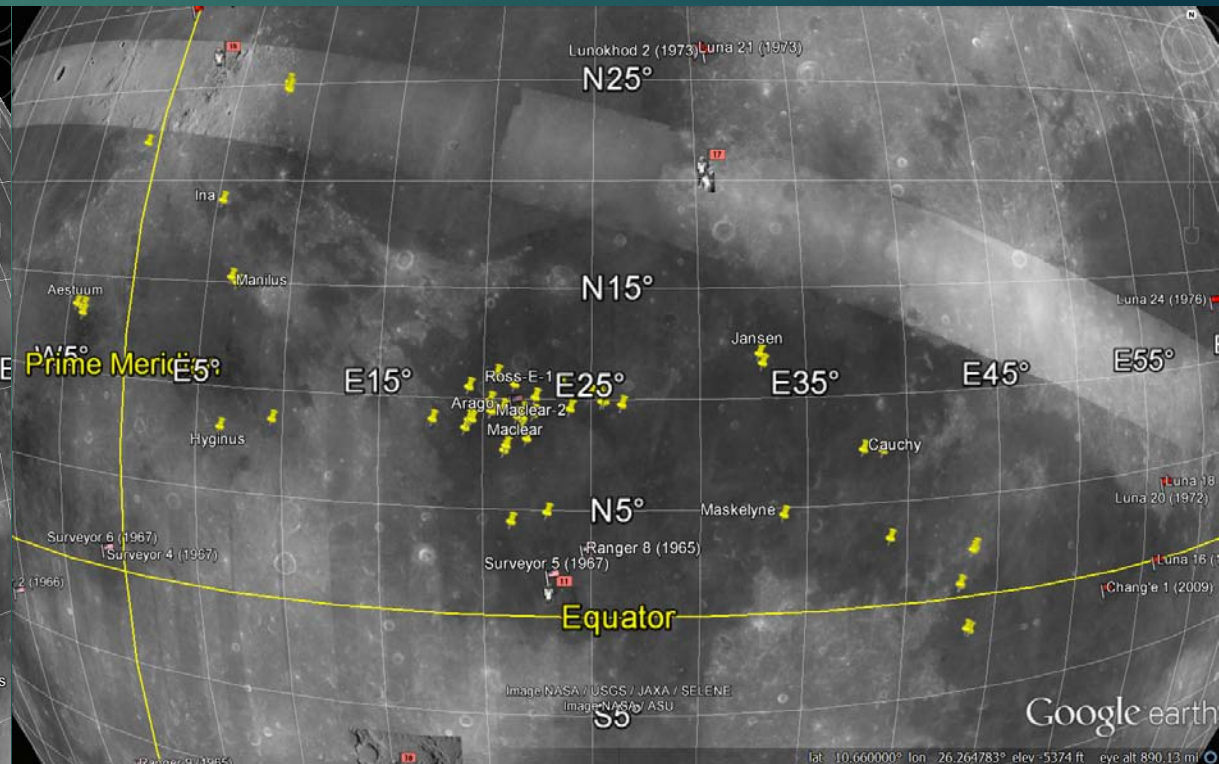
- 12 km hole roughly equivalent to lunar conditions at ~72 km depth

- Juvenile water found
- Water “boiling” w/ H2 gas
- s/b phreatic zone at base of lunar fracked zone

MENISCUS HOLLOWS LIMITED TO MARE BASALT REGIONS

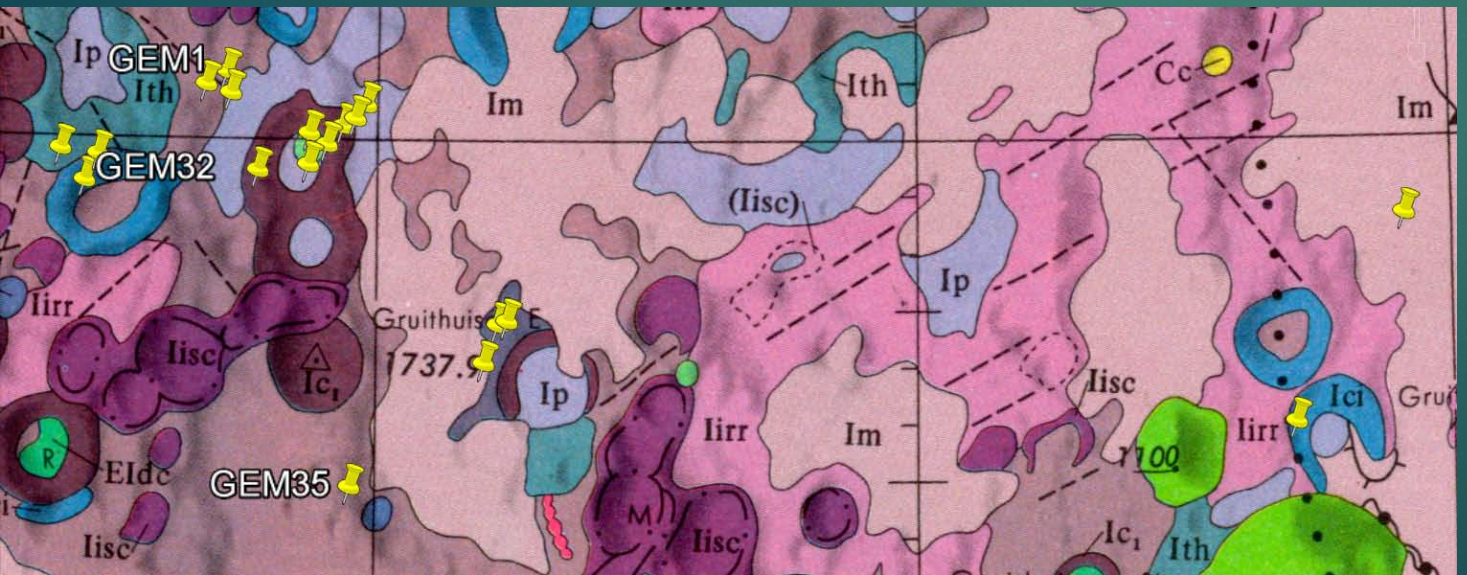
- 98 IMPs discovered so far
- 0 IMPs found in highland regions





No obvious geological pattern to IMP distribution

- They prefer proximity to tectonic features
- Limited to 38 degrees north latitude
- Very few found in southern hemisphere

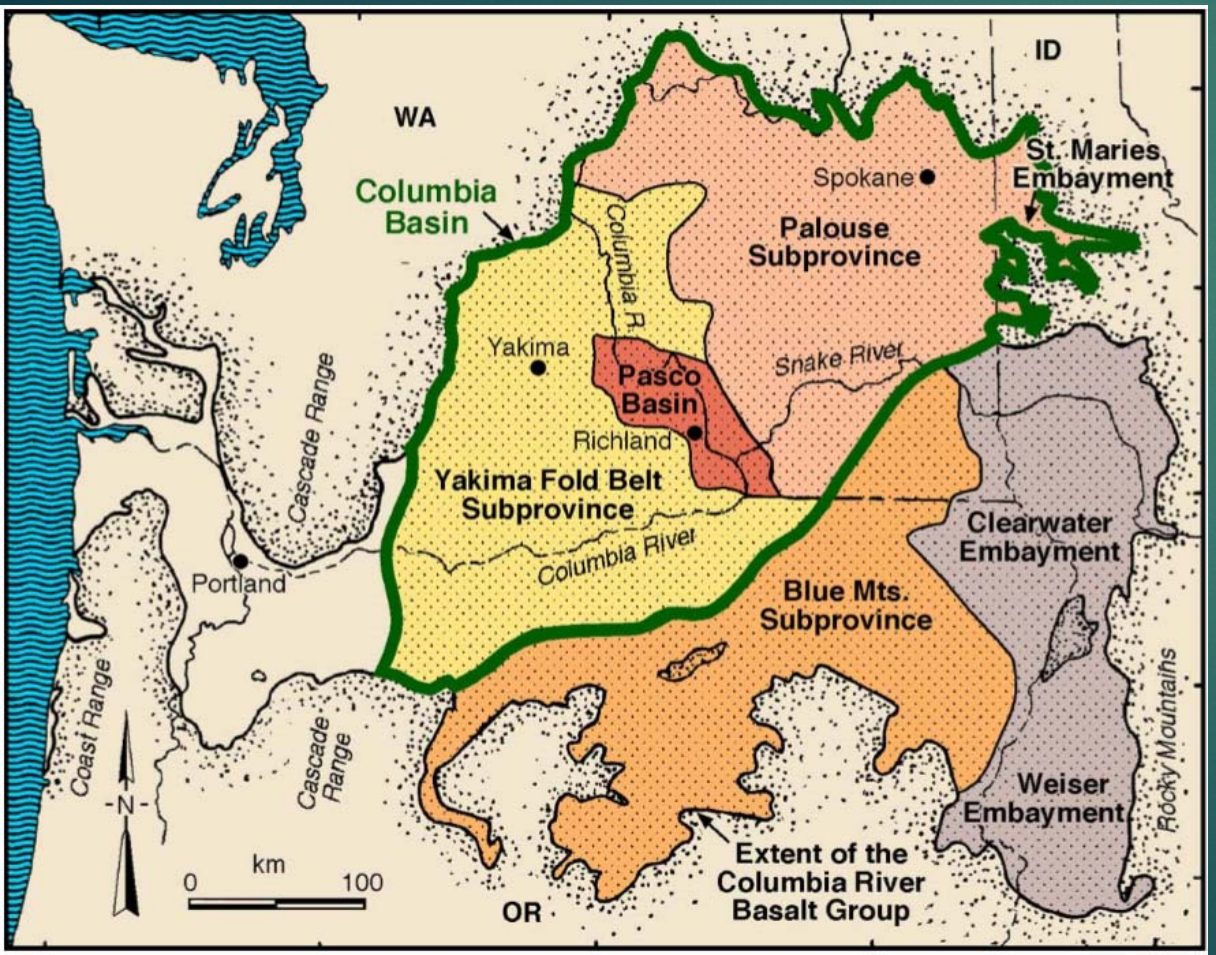


Implications of basalt habitat

- Probably, juvenile water from non-mare regions is long gone
- Rocks underlying basalt flows not fundamentally different from rest of Moon

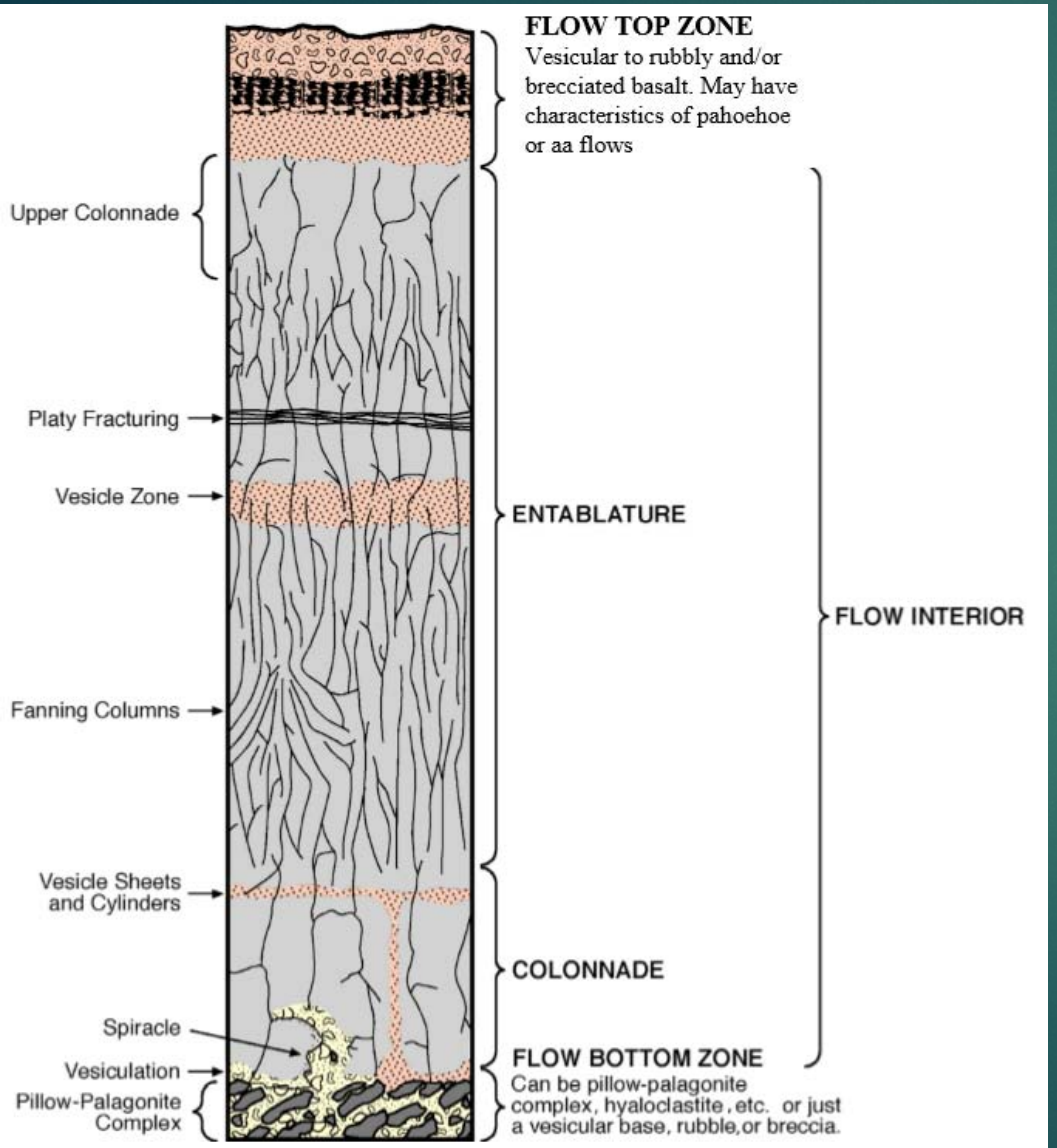
- The basalt flows could provide both reservoir rocks and stratigraphic traps

Columbia River Basalt Group (CRBG) provides good terrestrial analog



- Not nearly as big area-wise
- But thickness is comparable
- Has aquifers and natural gas deposits

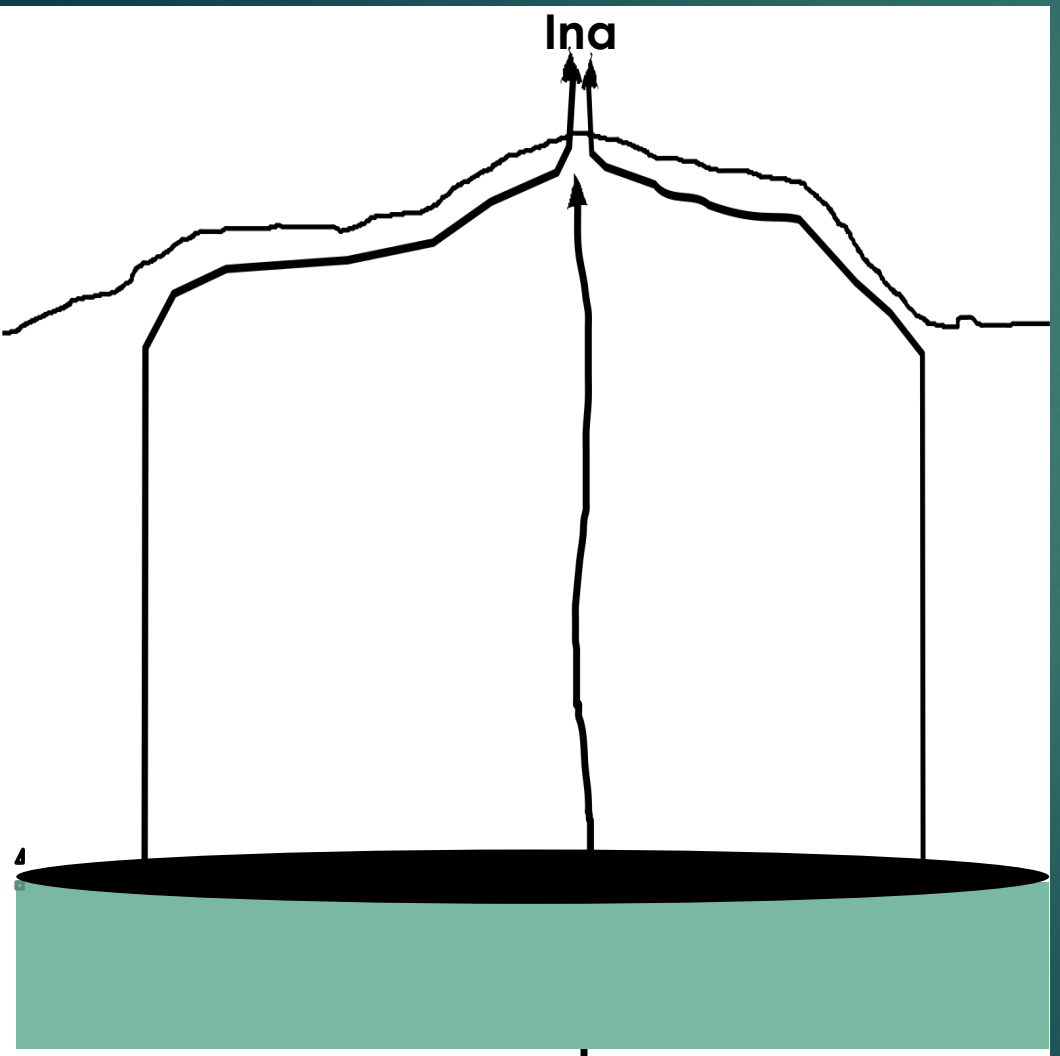
STRUCTURE OF BASALT FLOWS



- Top & bottom of flow are relatively porous
- AKA the “interflow zone”
- Interior (80%) is basically impermeable
- Faults provide avenues of fluid movement

CONCEPTUAL MODEL

← 30 kilometers →



← PERMAFROST CAP

← RESERVOIR

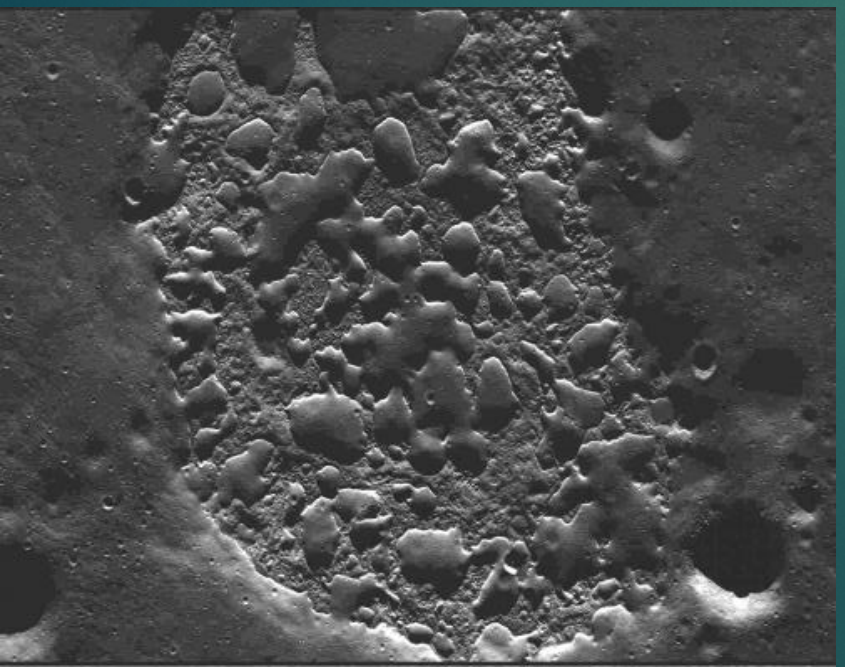
← HOT LOW PRESSURE ZONE
= WATER VAPOR

← SILL EPISODICALLY BREACHED

←PHREATIC ZONE

AMOUNT OF WATER REQUIRED TO EXCAVATE INA MENISCUS HOLLOW

$f=u↓0↑2 /u↓1↑2 -1$



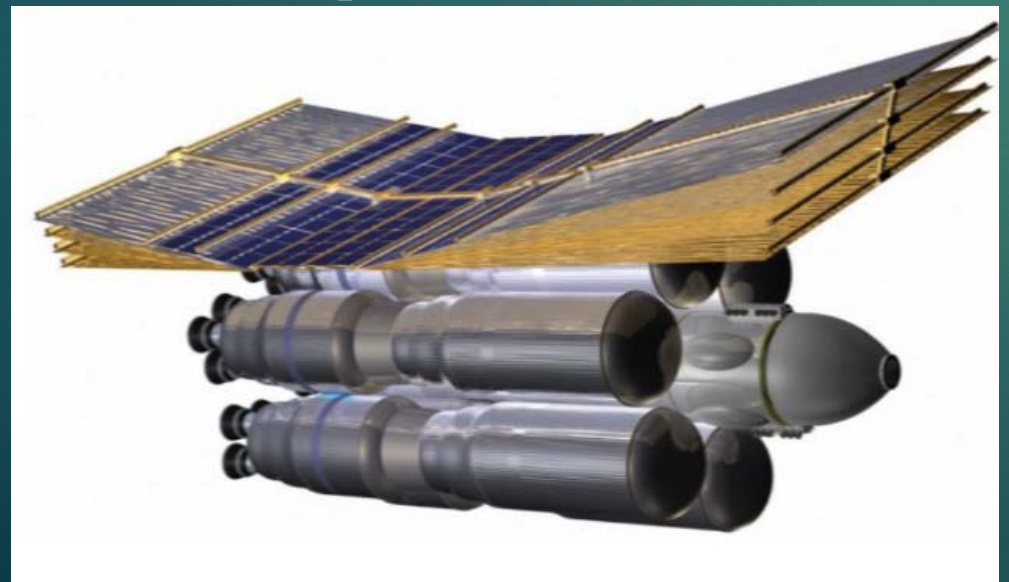
- Solve for v_e = 28 m s^{-1}
- 1 m^3 of H_2O can launch 6.5 m^3 to 28 m s^{-1}
- 10 m interflow zone w/ 20% porosity is typical
- Calculated volume = expected volume

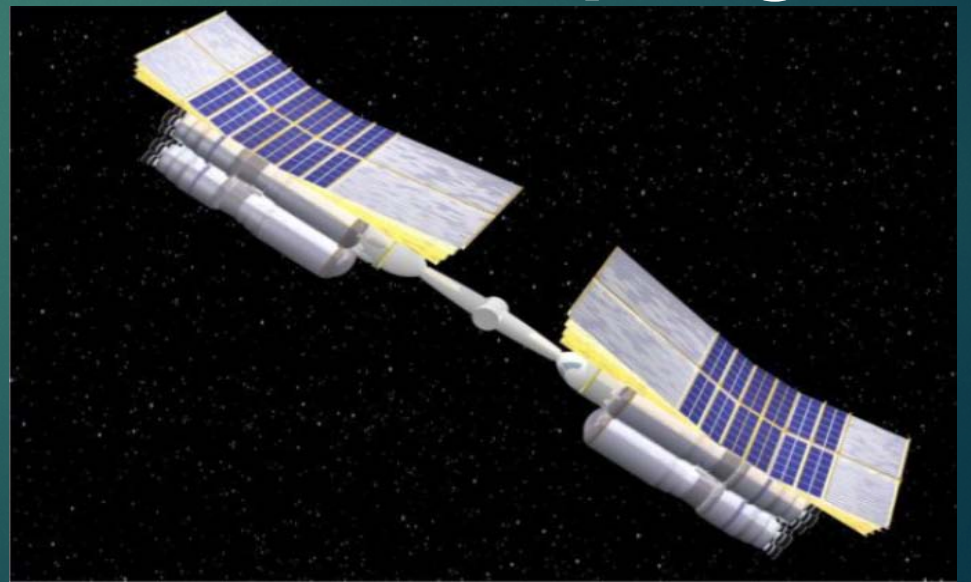
Volume estimate 1 km^2 IMP

- 1 km^2 reservoir with 10 m thick interflow zone with conservative 10% porosity could contain 1 million tonnes of water.
- Enough for 100 years at 10,000 tonnes/yr

Why we need 10,000 tonnes per year

- 1 t/yr → nice demo
- 10 t/yr → could launch ascent vehicle or two
- 100 t/yr → make a dent in lunar ops costs
- 1000 t/yr → render lunar station self sufficient
- 10,000 t/yr→abundant chemical Mars program





SIZE OF DRILLING RIGS

- Water well rigs on Earth mass ~3 mT
- Can be towed behind pickup truck
- Single person can run
- Might not be too hard to fully automate
- Can drill to 500 feet on Earth

BOTTOM LINE:

- a single well
- 4 inch diameter
- drilled by a 3 tonne piece of machinery
- could produce 10,000 t/yr
- conservative flow rate of 5 gpm
- minimal processing required
- You cannot beat that bang for your buck…

Cost of H2O at well head

ULA figures	
3000	mass of drill (kg)
$50,000	$ per kg
$150,000,000	cost per drill
$35,000	cost to move per kg
$105,000,000	cost to move drill to moon
$255,000,000	total cost for deployed drill
$9,000,000	annual cost
$25,500,000	amortized cost/per year
$34,500,000	total cost per year
10,000	annual production
$3,450	wellhead cost per tonne
$500,000	Moon surface price per ton
$496,550	profit per tonne
$4,965,500,000	annual revenue

EL FIN

ACKNOWLEDGMENTS:

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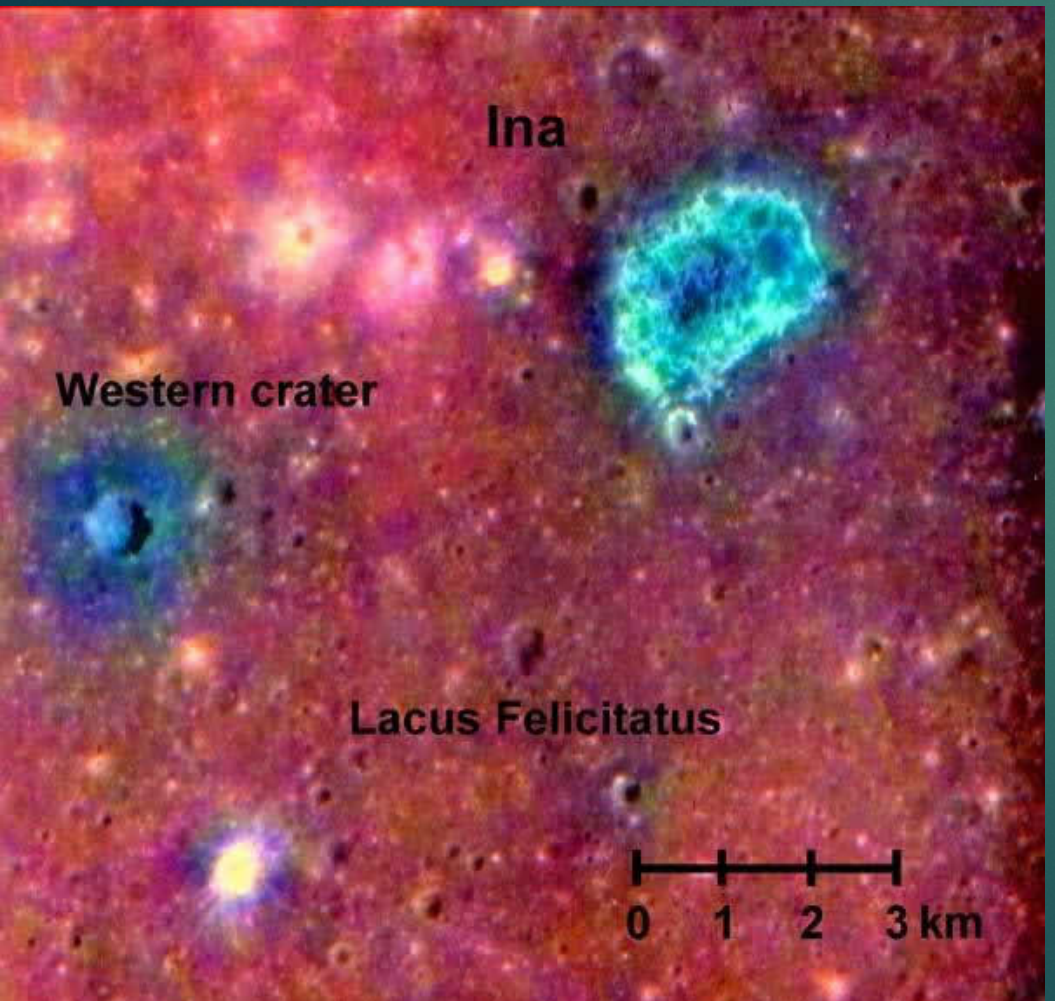
Hint: $503 out of $762 so far…

Alternative Hypothesis: "Menisci" are inflated lava flows



- Inflated lava flows on Earth are cracked
- Spectrographically similar to debris halo
- Law of superposition: upper layers younger

Alternative Hypothesis: Argon outgassing…

- Argon continuously forming all over the Moon: s/b hollows all over
- Yet meniscus hollows confined to mares
- If you need stratigraphy provided by basalt flows, then they should work for water too
- Ar will not form impermeable permafrost

Astrobiological Implications

- Life requires continuous habitat
- Posited lower phreatic zone probably too hot – order 200 C
- Would be scientific discovery of the century but kiss of death for ISRU