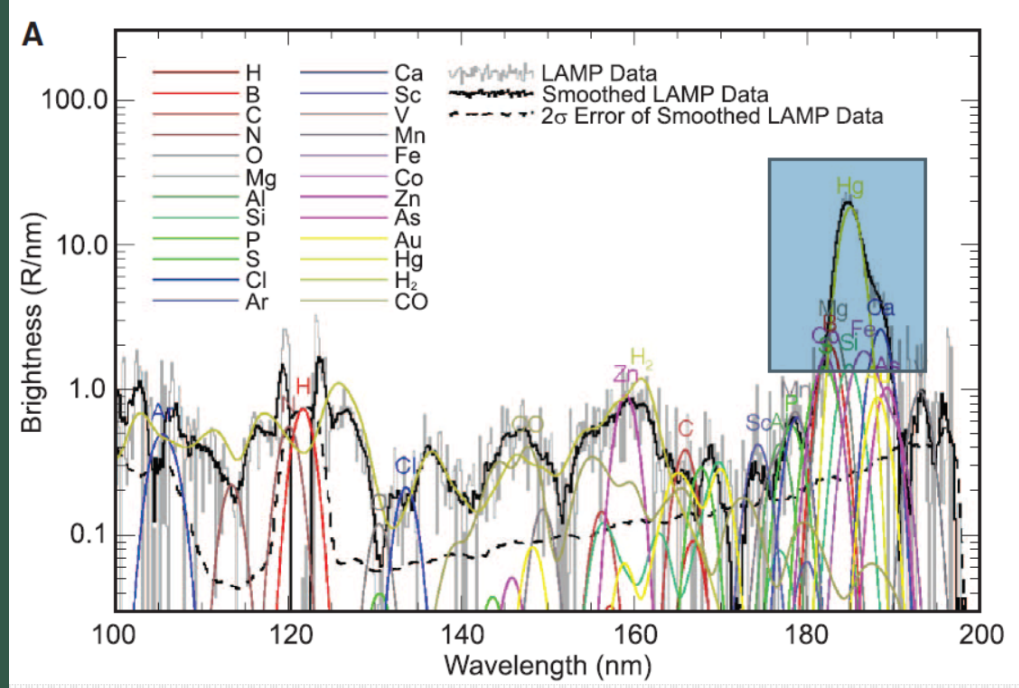
The Moon:

Strategic Knowledge Gaps I Have Known

Mercury (Hg)

- Concentrations up to about 0.5% (5,000 ppm) measured in LCROSS experiment
- George Reed developed concentration model: regolith depleted in Hg compared to pristine rocks; concentrated in polar craters
- Concentrations exceed environmental standards on Earth
- XRF device would be able to detect

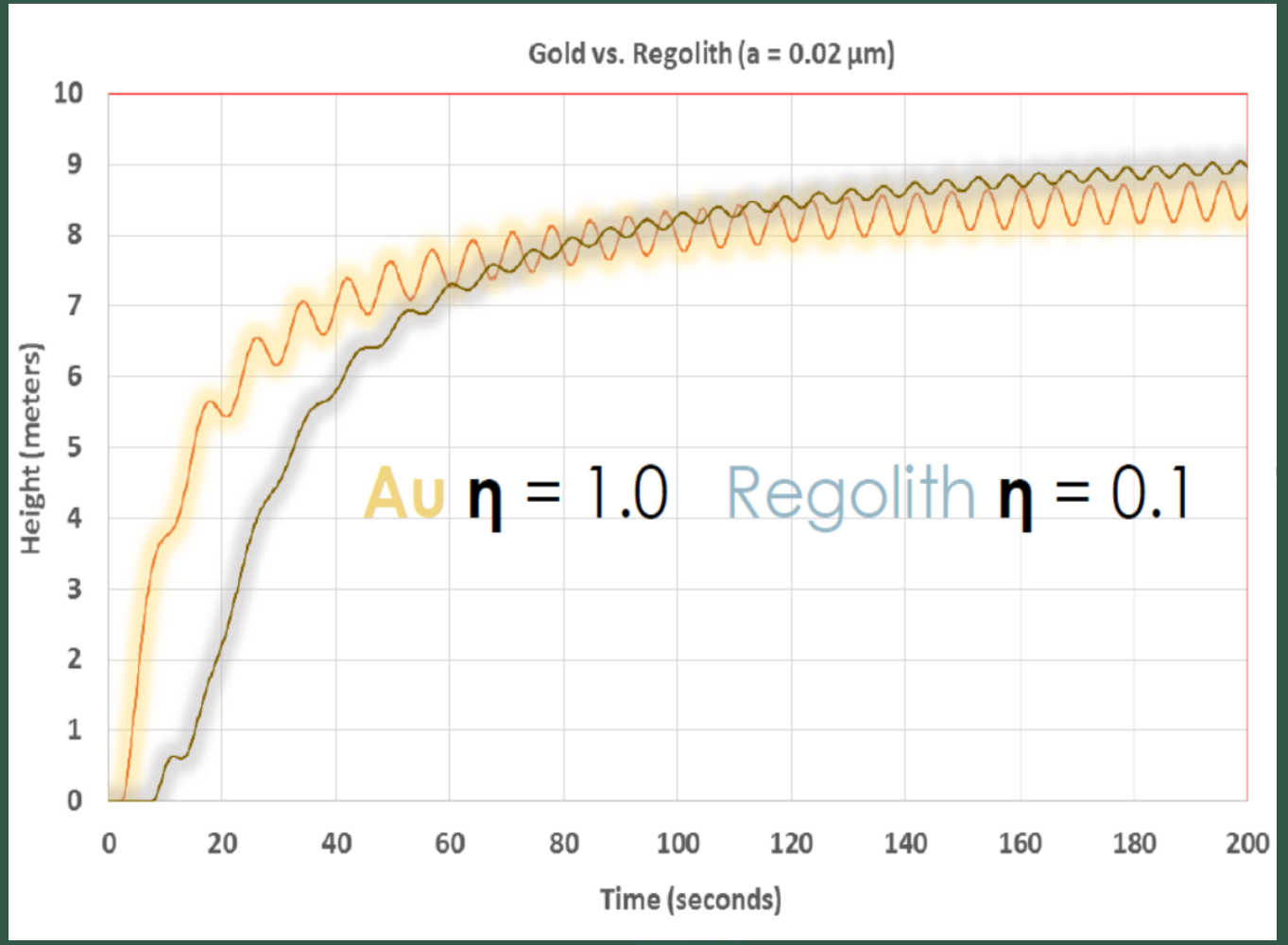


Land use	Soil Guideline Value (mg kg^{-1} DW) [1,2]		
	Elemental Hg [4]	Inorganic Hg^{2+}	Methyl Hg^{+} [4]
Residential	1.0	170	11
Allotment	26 [3]	80	8
Commercial	26 [3]	3,600	410

[1] Based on a sandy loam soil (Environment Agency, 2009b) and 6% SOM.
[2] Figures are rounded to one or two significant figures.

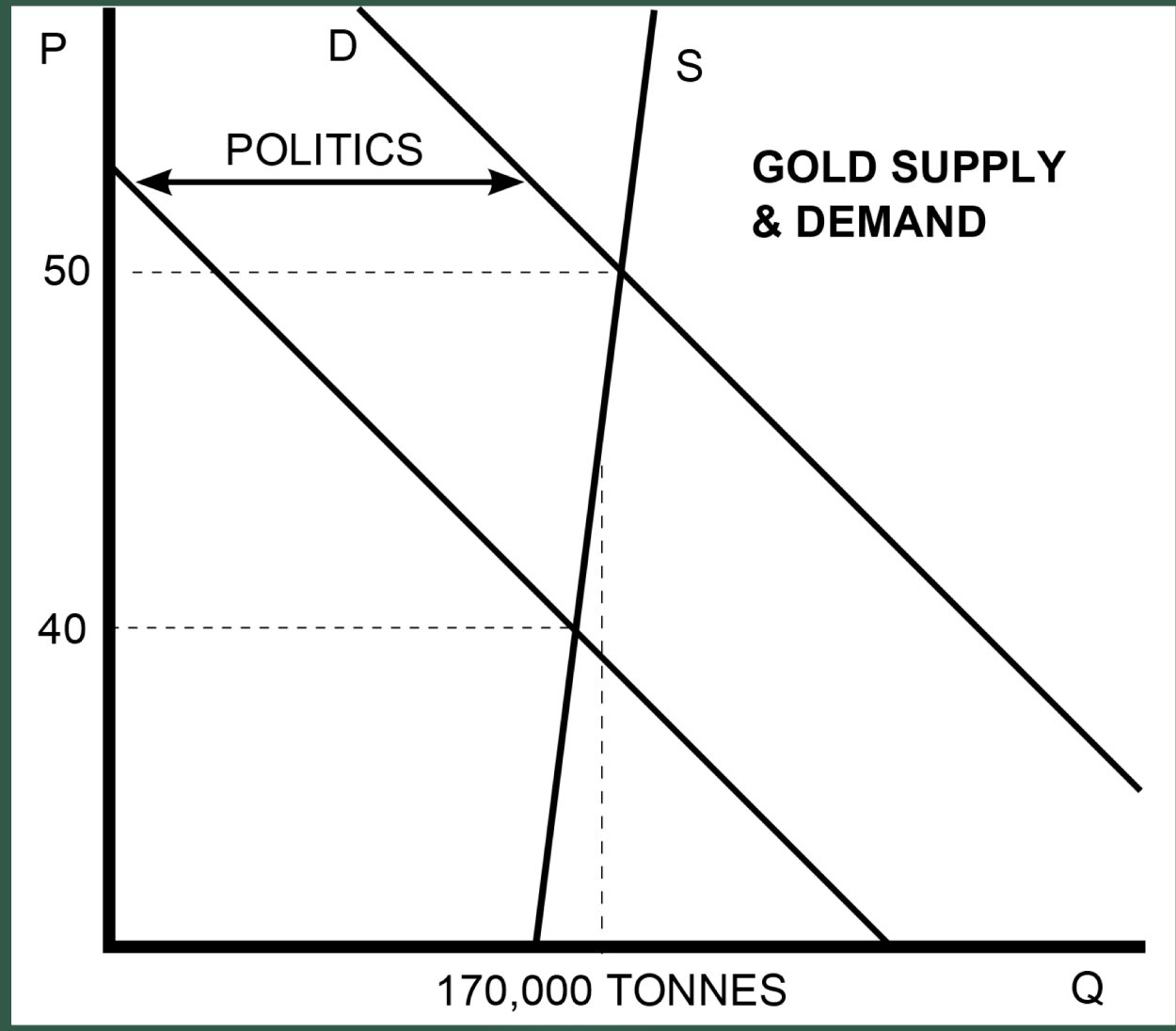
Gold (Au)

- LCROSS also detected about 0.5% Au (5 ppt)
- Possibly represents “electrostatic placer deposits”
- Numerical simulations show that gold dust is preferentially transported due to high photoelectric efficiency
- Pristine rocks relatively enriched in gold compared to regolith
- Gold offers one of the few extraterrestrial “anchor industries”



Economics of Gold

- Price of gold driven by political demand cycles
- Gold supply highly inelastic
- Very hard to drive down price due to over-supply
- 2,000 tonnes per year of platinum production would crash the price
- But 2,000 tonnes of gold per year would generate a revenue stream on order of $100 BILLION
- May not even have to bring it back

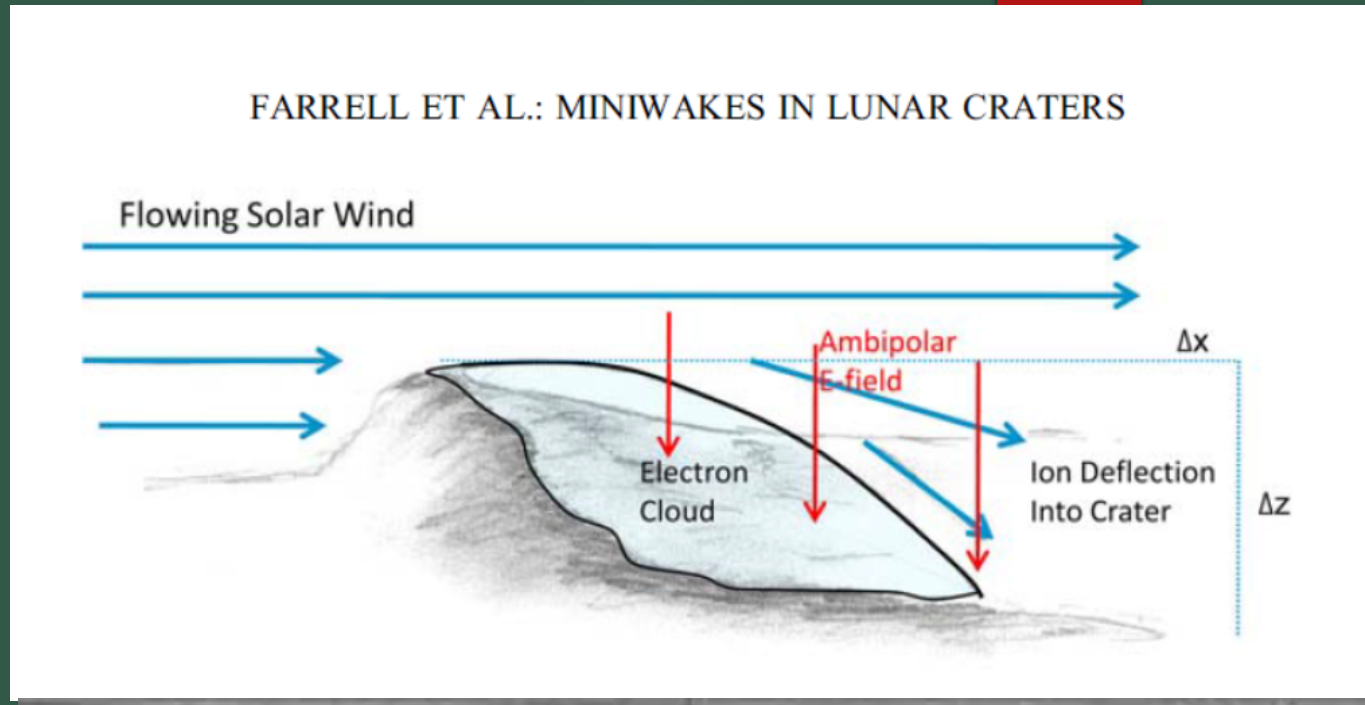


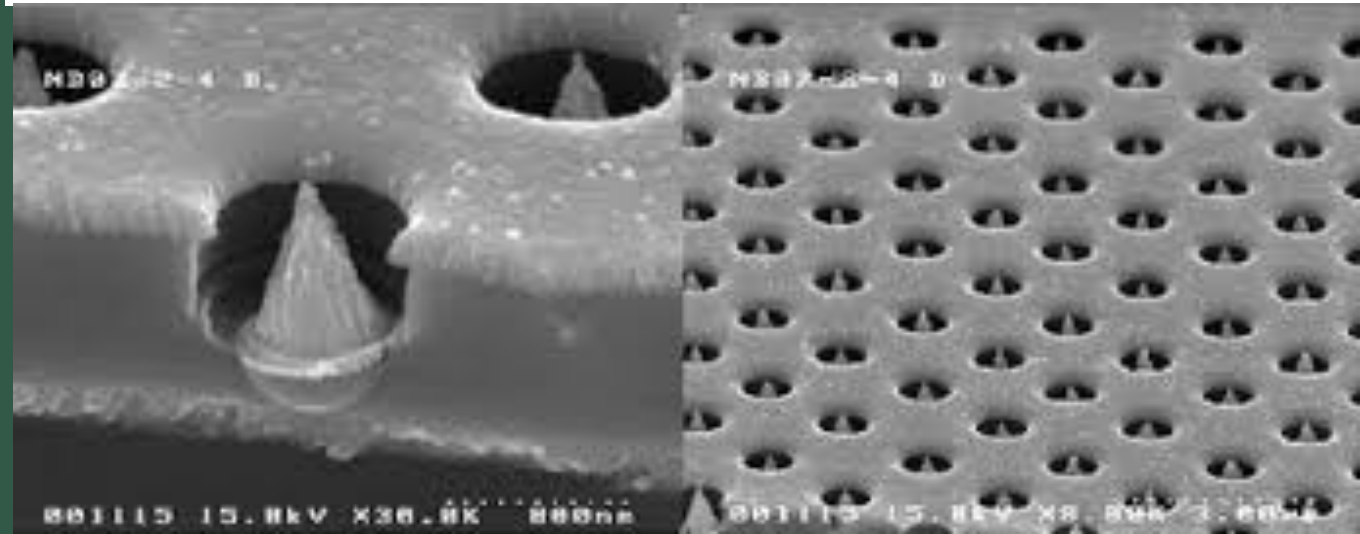
Monoatomic Hydrogen (H)

- Monoatomic H detected in LCROSS plume
- LCROSS plume apparently had more kinetic energy than did the impactor
- The theory (due to Randy Gladstone) is that crater so cold, solar wind protons get neutralized, but little chemistry happens after that
- The entire crater did not blow up, but it represents a potential hazard
- Could relieve refining energy budget

Tribocharging (static electricity)

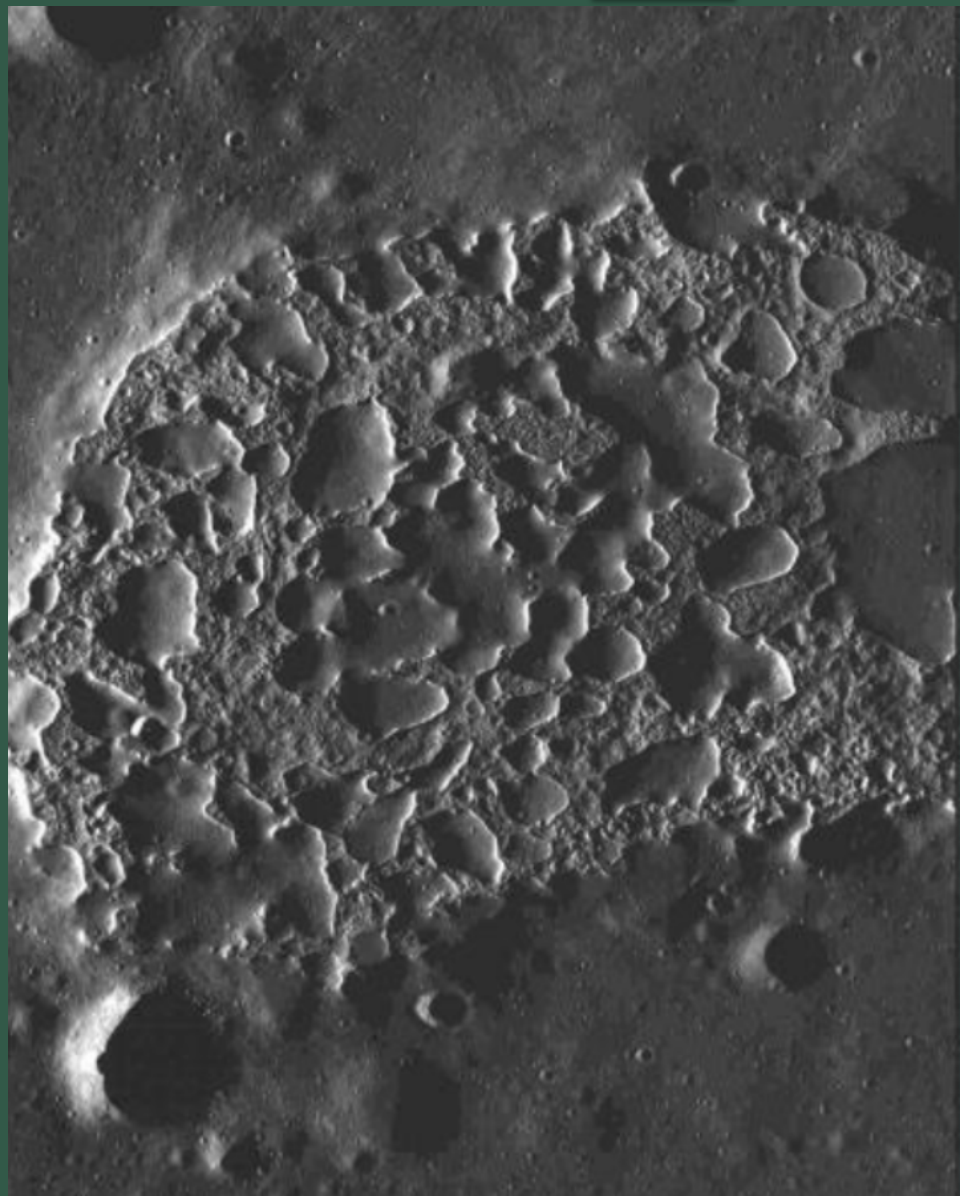
- Solar wind acts as the ground on the Moon
- Leeward edge of polar craters will build up electron clouds
- Metallic objects (rovers and astronauts) will tend to build up negative charge
- Charge dissipation times drastically increased
- Potential charge hazard
- Will also attract dust
- May want Spindt Arrays





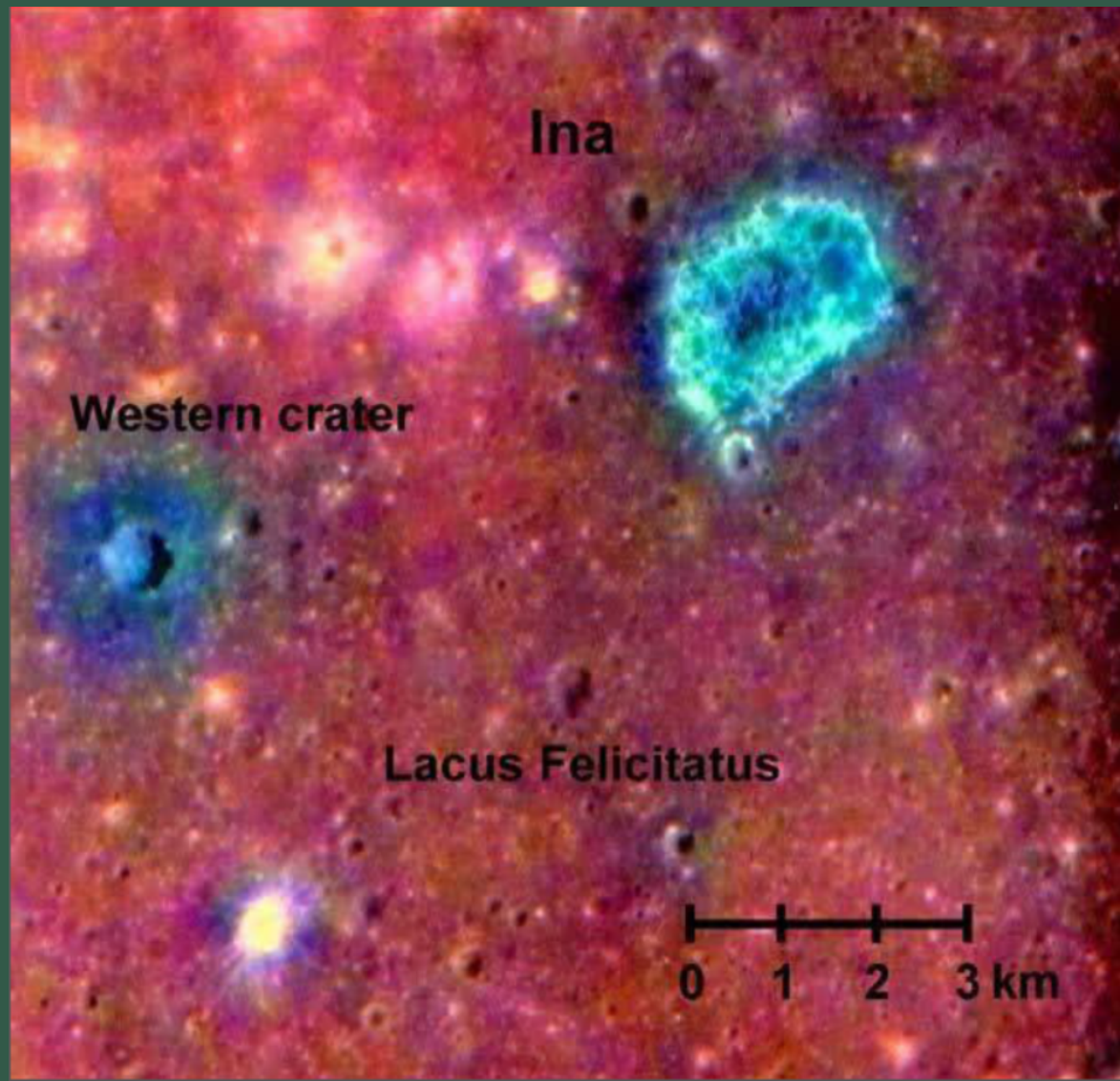
Low Latitude Sources of Volatiles —Overview

- Low latitude sources of volatiles would be highly desirable for obvious reasons
- Irregular maar-like pits (IMPs) are thought by Schultz et al. (in Nature) to be caused by outgassing events most likely involving H2O and CO2
- Schultz et al. also suggested that useful quantities of volatiles might be recovered from such areas
- Mix of volatiles discovered by LCROSS more like mix found in inner Solar System formation, rather than Oort Cloud, suggesting volatiles result of outgassing rather than cometary impacts



Low Latitude Sources of Volatiles —Energetics of H2O & CO2 about right

- My own research has suggested the energetics of an H2O/CO2 outgassing event are about right to account for 0.5 km debris apron
- The thing is, at the temperature and pressures required, any water would tend to condense, forming liquid water
- Accessible liquid water in outer space is the ultimate ISRU Holy Grail



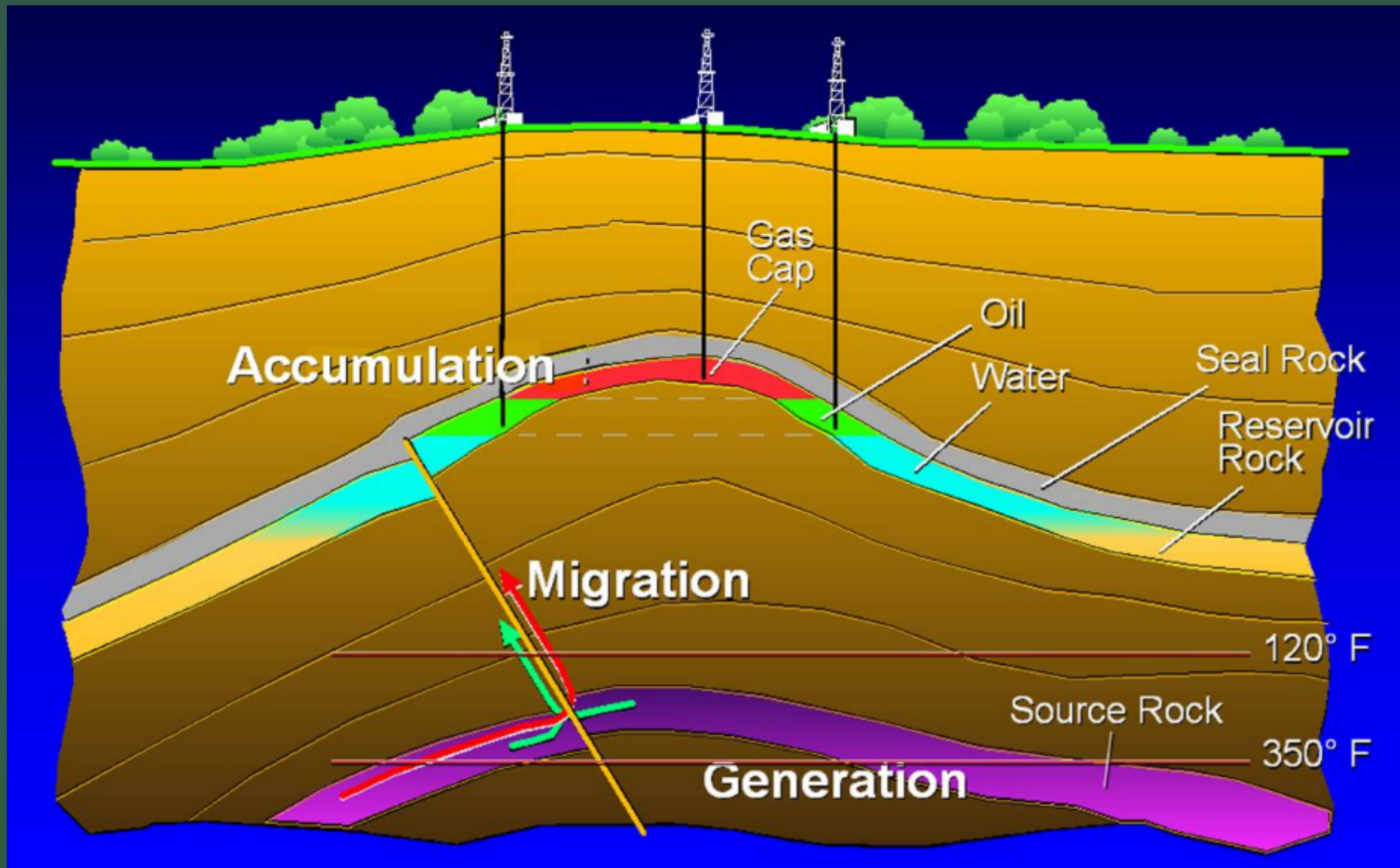
Low Latitude Sources of Volatiles —Volatile Deposits on Earth

- Three ingredients necessary to form classical volatile deposits on Earth:

1. Source Rock
2. Reservoir Rock
3. Cap Rock

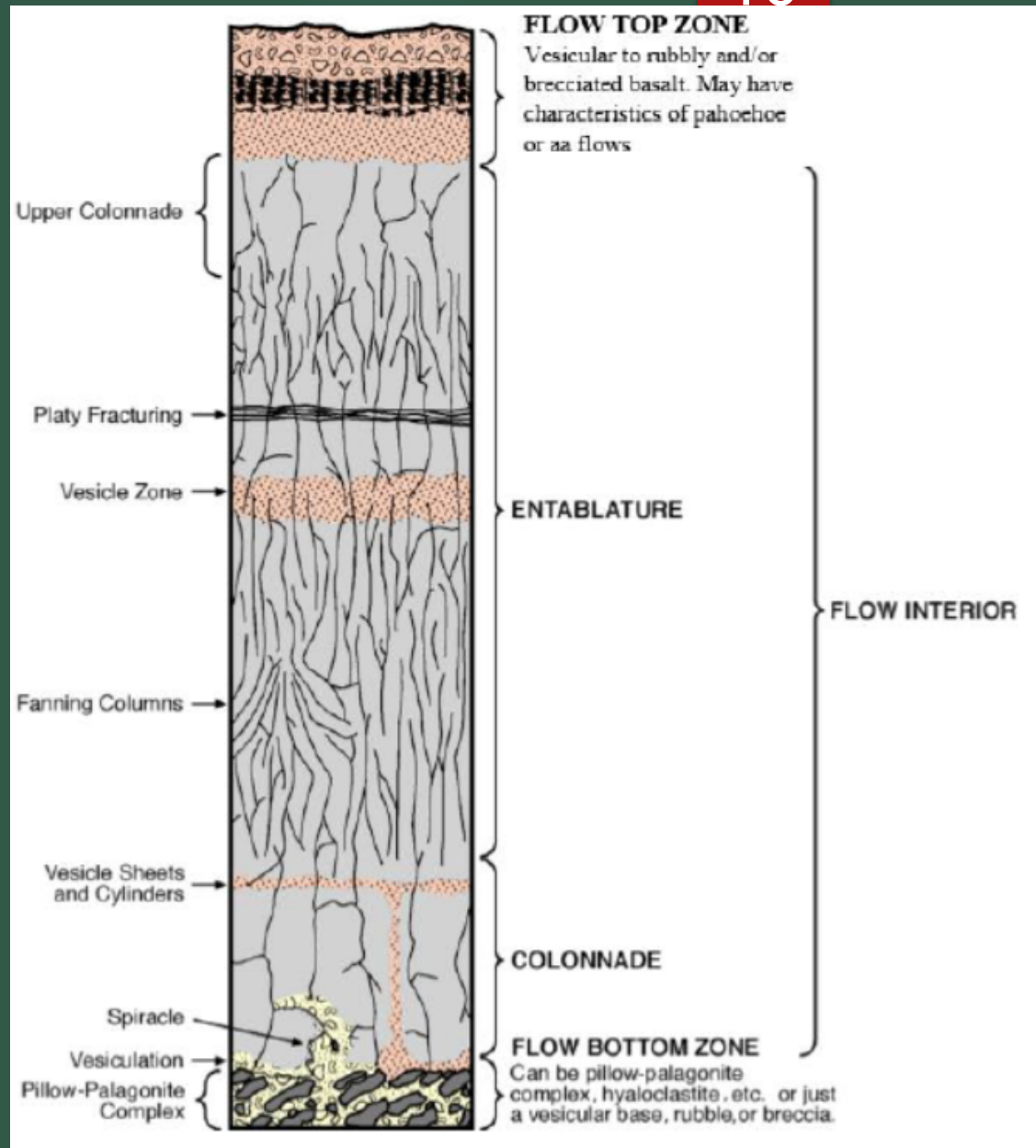
- Three Processes:

1. Generation
2. Migration
3. Accumulation



Low Latitude Sources of Volatiles Lunar "Sedimentary" Rocks

- Basalt flows in lunar maria functionally similar to sedimentary rocks: layers are formed
- Columbia River Basalt Group probably best studied lunar maria analog on Earth
- Top and bottom zone of lava flow cool faster
- As rocks contract, fractures happen, increasing porosity and permeability, thus forming effective reservoir rock
- Central interior cools much more slowly
- Flow interior has very low permeability, thus forming effect cap rock
- Natural gas has been produced from CRBG

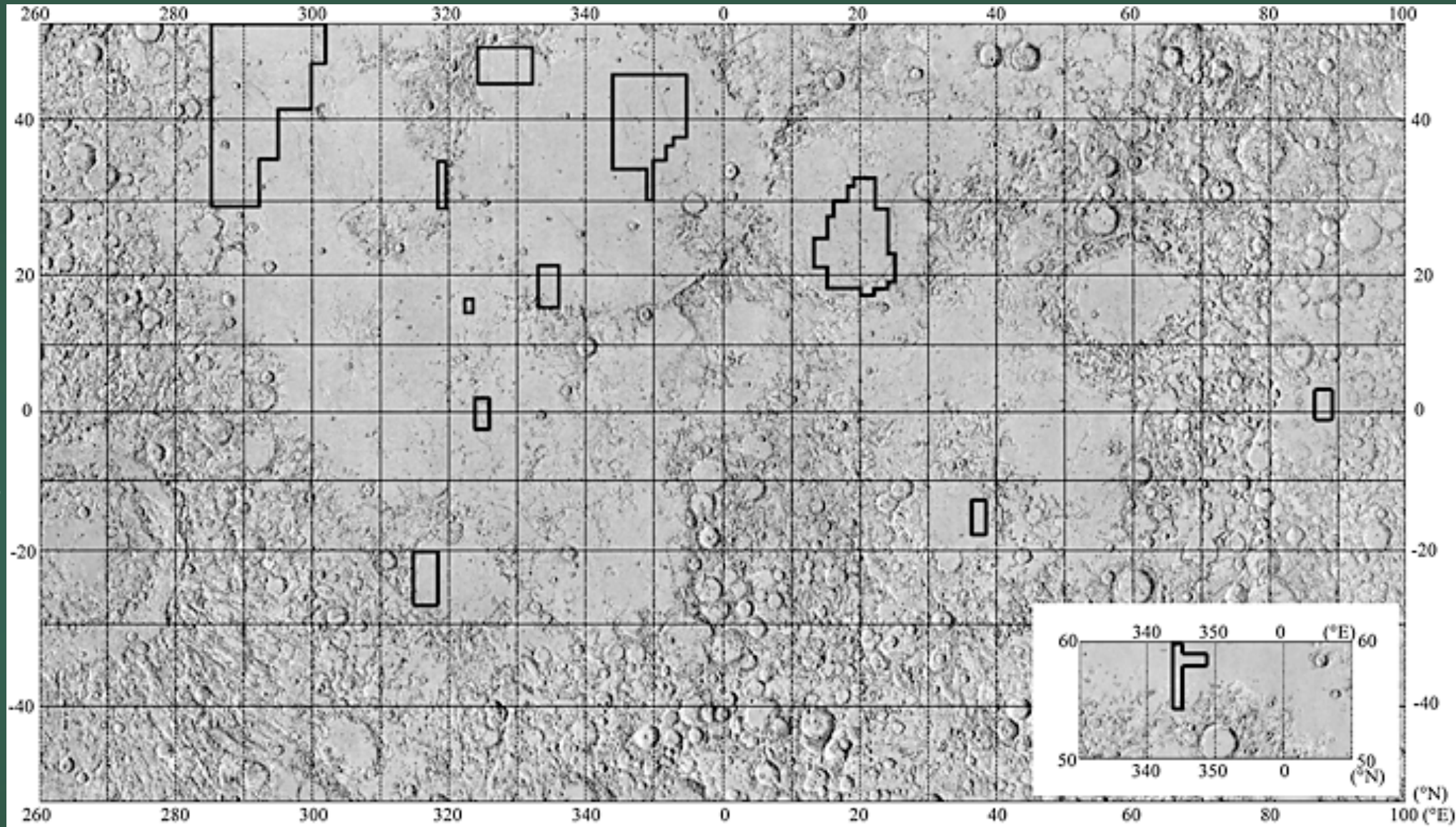


Low Latitude Sources of Volatiles —Prospecting for Volatiles

Kaguya Long Range Sounder (LRS) ground penetrating radar results

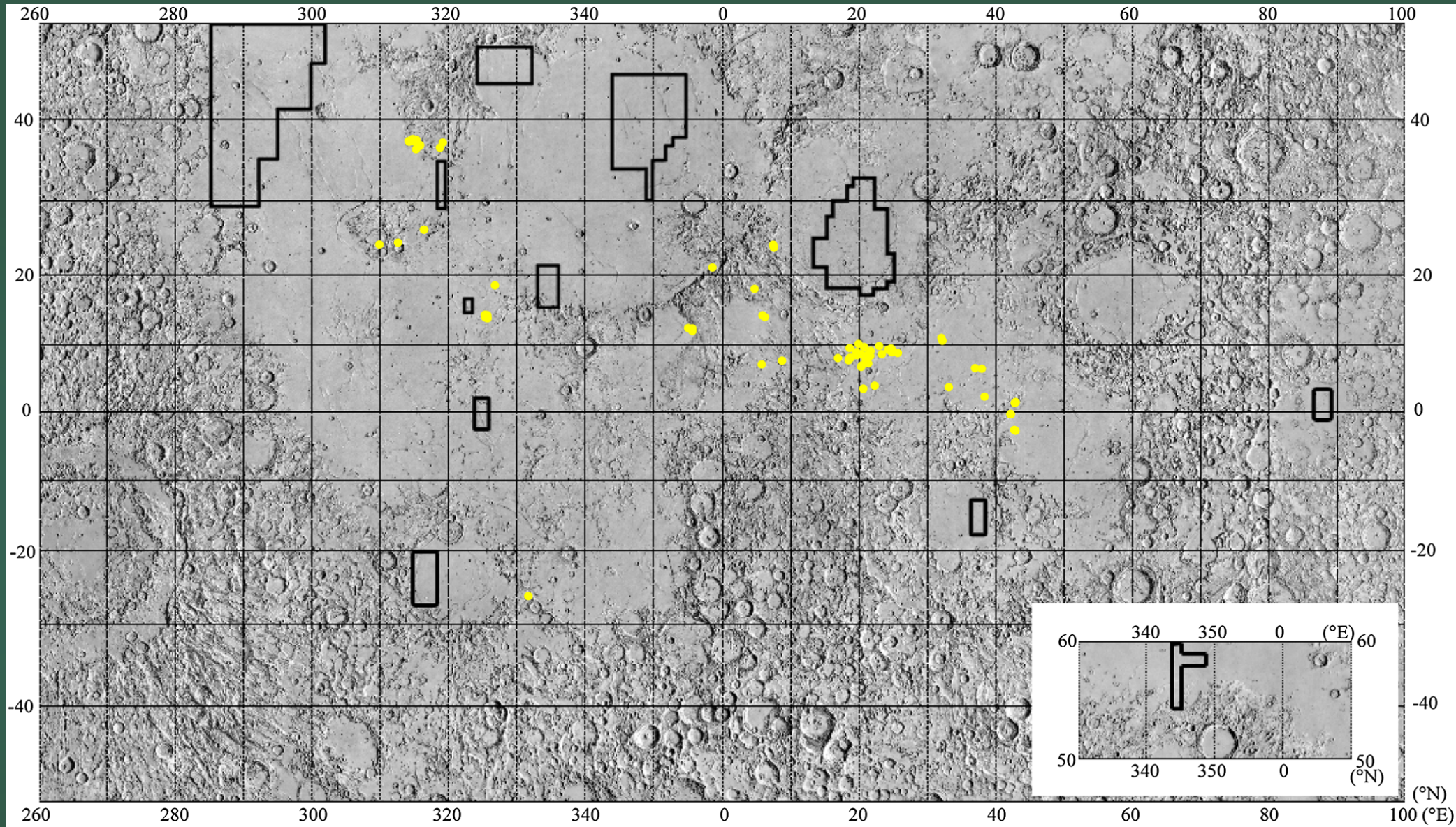
Black outlines mark areas where subsurface radar reflections were detected

Reflections found only in maria



Low Latitude Sources of Volatiles —IMPs versus Kaguya reflections

- No overlap between IMPs and Kaguya reflections
- OTOH… IMPs represent areas where volatiles are escaping!
- So maybe not so surprising



Low Latitude Sources of Volatiles —Why didn't LRS detect reflections everywhere?

- Basalt flows should always form in layers that are detectable
- Yutu rover detected reflections in zone outside of Kaguya LRS
- Orbital ground penetrating radar is very challenging
- Only the best reflections are likely to be detected

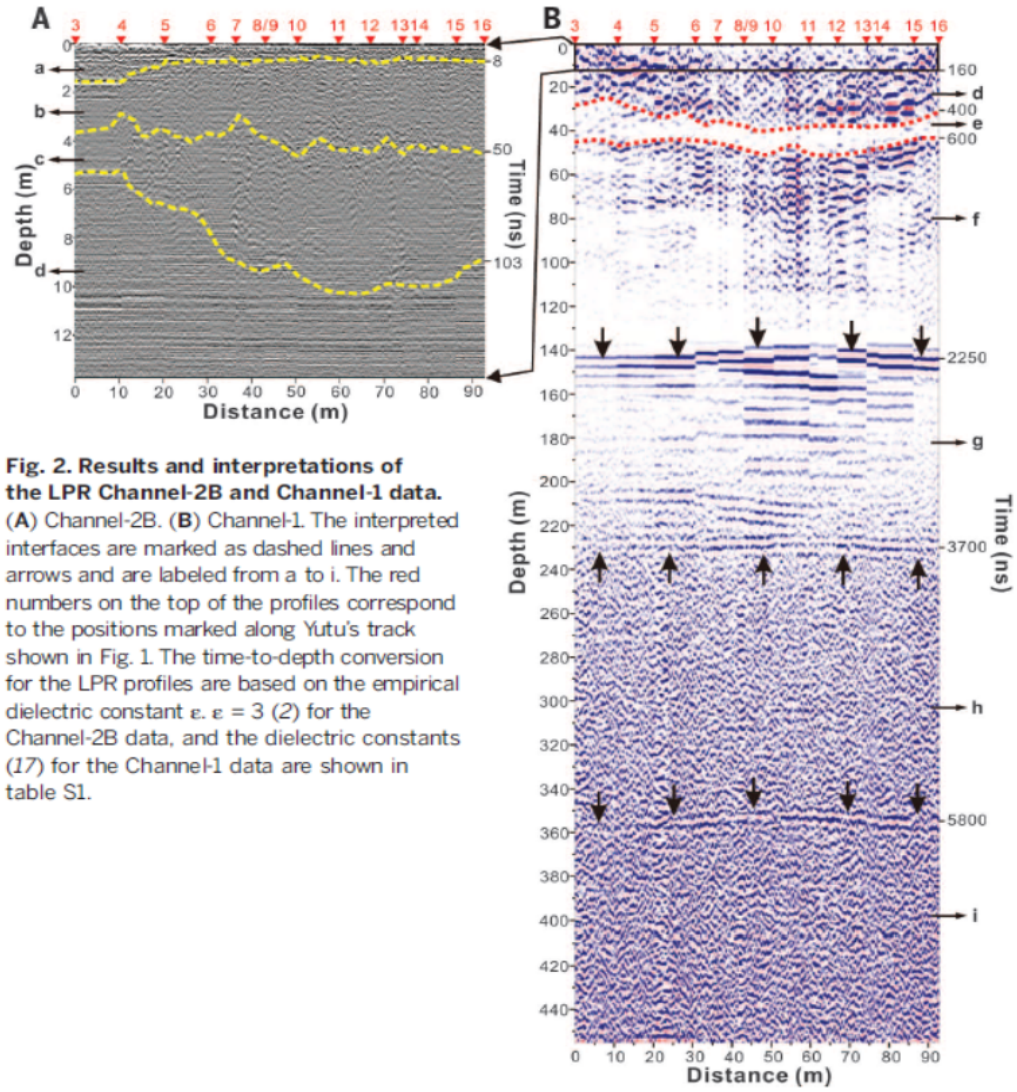


Fig. 2. Results and interpretations of the LPR Channel-2B and Channel-1 data. (**A**) Channel-2B. (**B**) Channel-1. The interpreted interfaces are marked as dashed lines and arrows and are labeled from a to i. The red numbers on the top of the profiles correspond to the positions marked along Yutu's track shown in Fig. 1. The time-to-depth conversion for the LPR profiles are based on the empirical dielectric constant ε. ε = 3 (*2*) for the Channel-2B data, and the dielectric constants (*17*) for the Channel-1 data are shown in table S1.

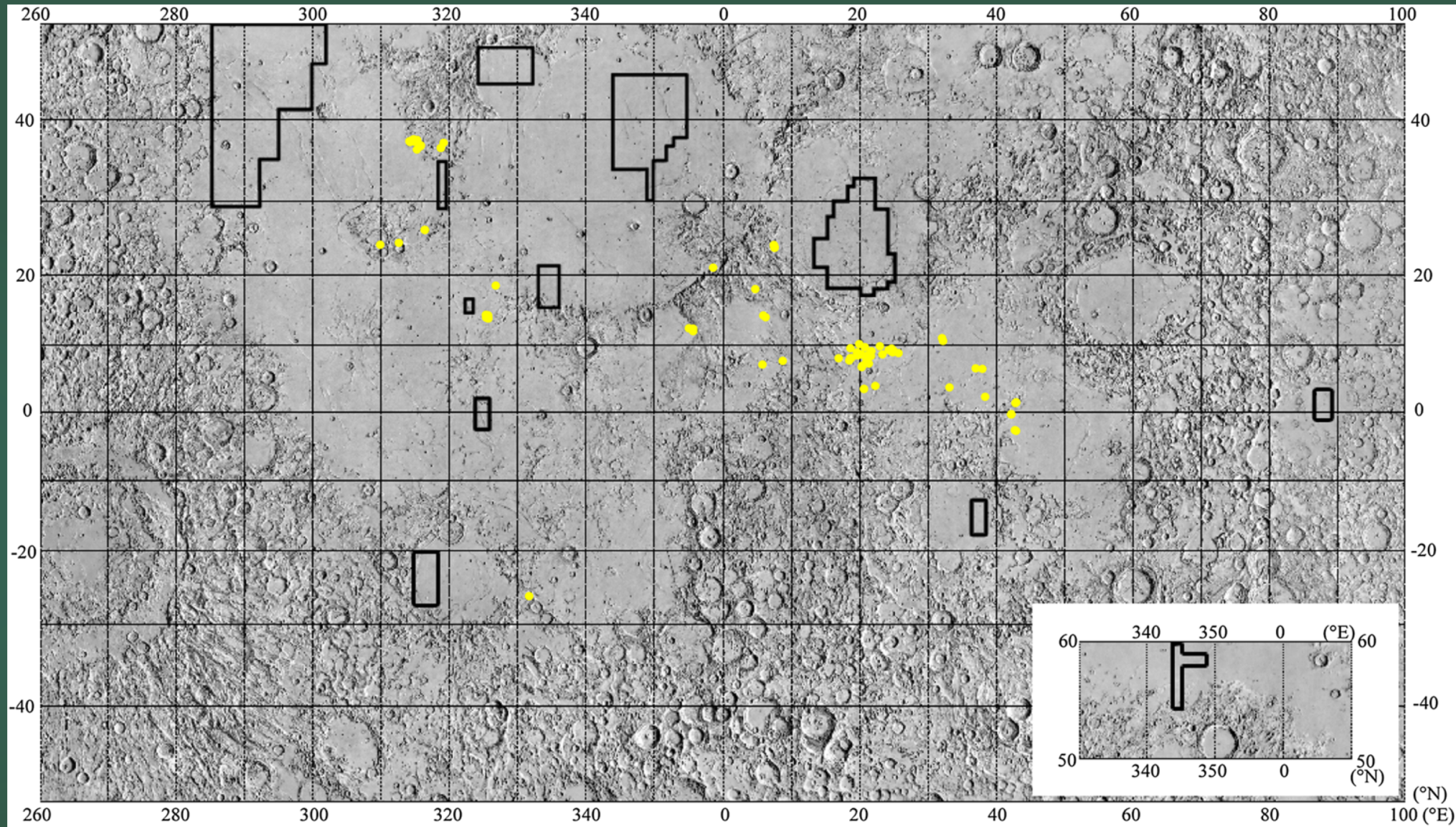
Low Latitude Sources of Volatiles —Ground Penetrating Radar Theory

- Reflections depend on changes in relative permittivity ε
- Changes in porosity have only marginal effect on ε if pore space is filled by vacuum
- If bulk ε is 5, and porosity is 0.2, then average ε is only 4.2—not a big difference
- Kaguya investigators thus propose buried regolith layer
- However, based on time of accumulation, the posited regolith layer is only ~0.5 to ~1.5 meters thick
- And GPR can only detect objects that are on the order of a wavelength
- LRS wavelength is 60 meters in space, maybe 20 meters in rock

- BUT: if pore space is filled with water (ε = 80) then average ε = 20—a big difference!

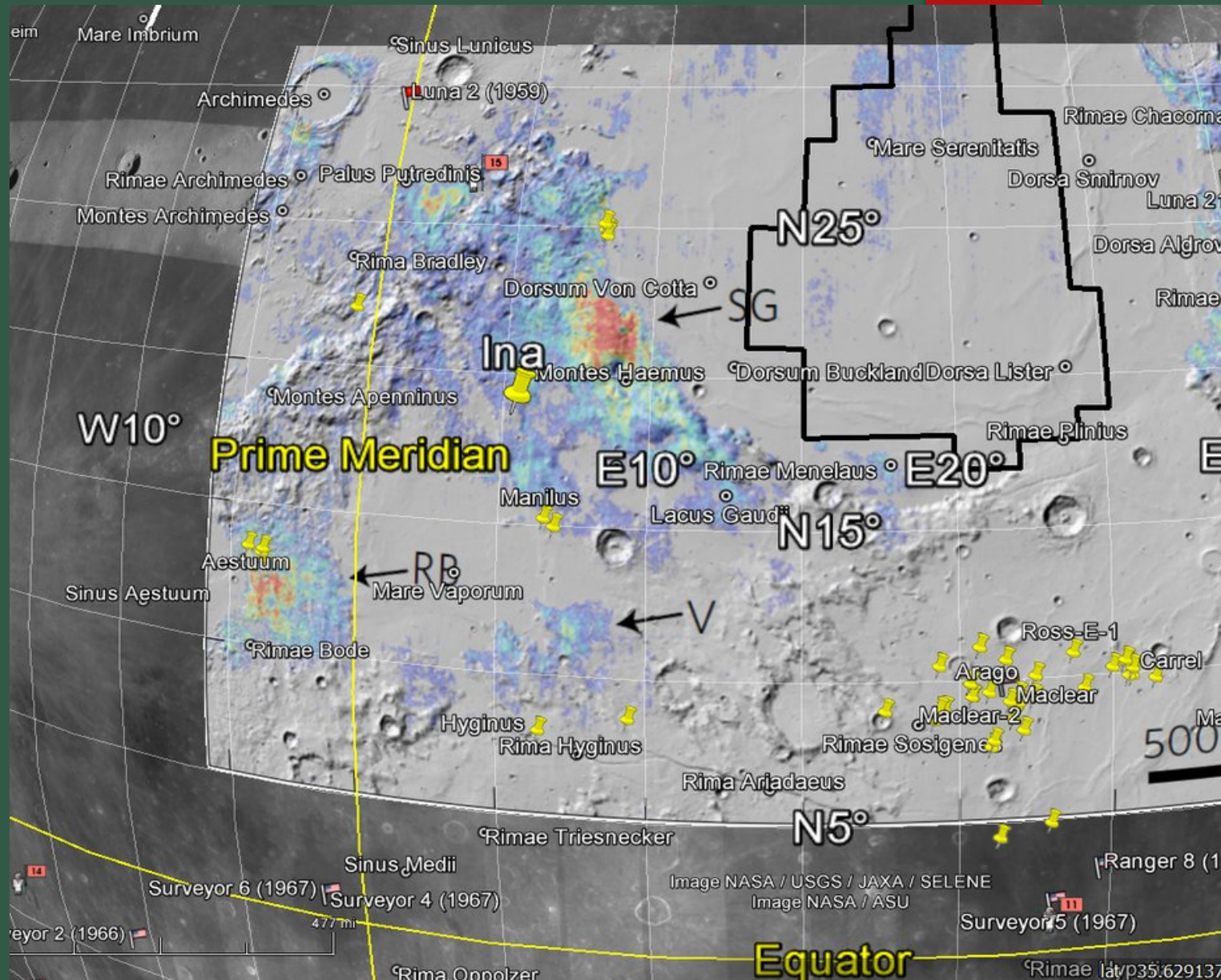
Low Latitude Sources of Volatiles —Kaguya LRS possible smoking gun?

- Kaguya LRS thus provides possible direct evidence of low latitude sources of volatiles
- Two smallish areas right on equator—no need to worry about launch windows



Low Latitude Sources of Volatiles —Source Rock

- Moon Mineralogy Mapper has identified major pyroclastic deposits of “glass beads”
- Beads average ~150+ ppm
- But beads indicate source rocks are about same as terrestrial MORB (order of 1%)
- Direct evidence of major juvenile water deposits
- Juvenile water deposits found on Earth in Kola Superdeep well
- Geographical juxtaposition is very intriguing



Low Latitude Sources of Volatiles —Where are the hydrated minerals?

- Lunar surface barely scratched so far
- IMPs have never been directly sampled
- Apollo samples did have trace amounts of phyllosilicates, but were chalked up to contamination
- Recent lunar meteorite examined apparently had dehydrated serpentine
- Premature to say there is definitely no hydrated minerals on the Moon

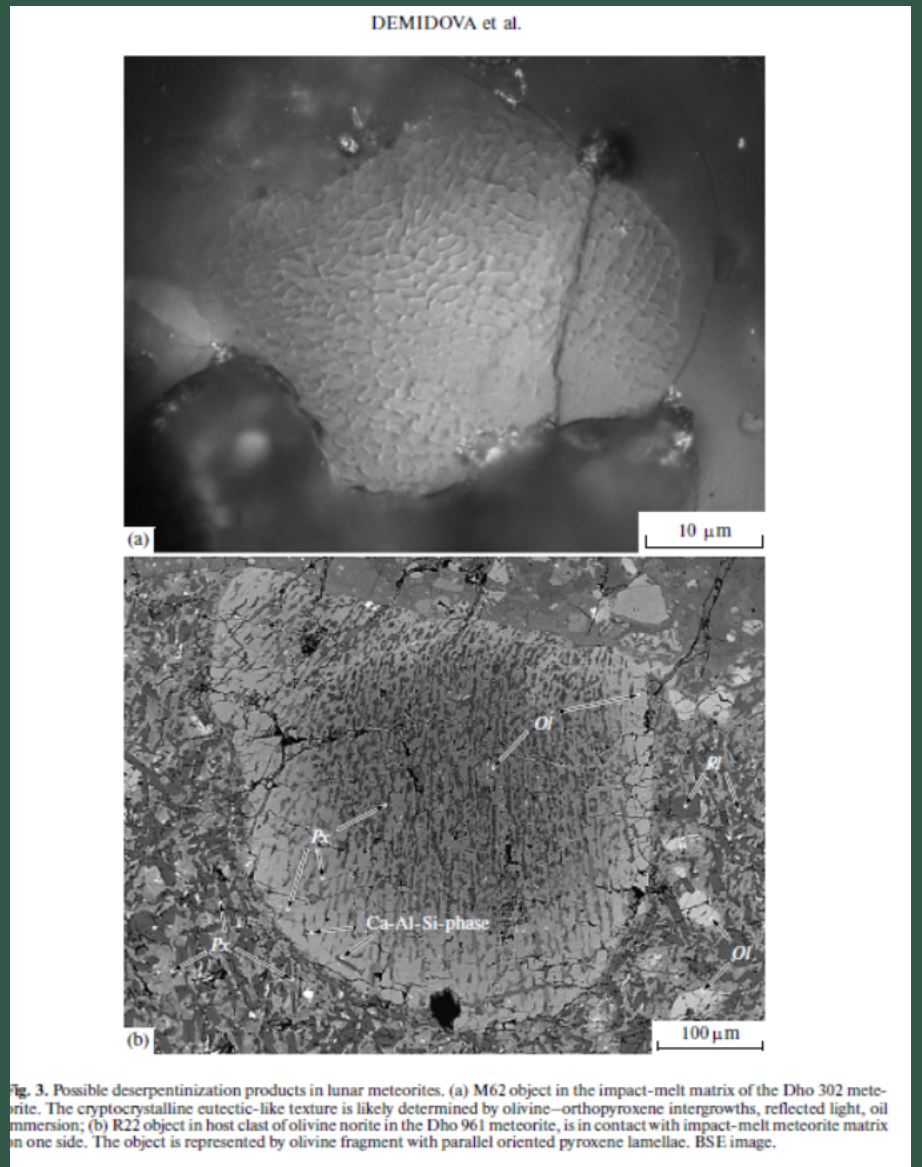


Fig. 3. Possible deserpentinization products in lunar meteorites. (a) M62 object in the impact-melt matrix of the Dho 302 meteorite. The cryptocrystalline eutectic-like texture is likely determined by olivine–orthopyroxene intergrowths, reflected light, oil immersion; (b) R22 object in host clast of olivine norite in the Dho 961 meteorite, is in contact with impact-melt meteorite matrix on one side. The object is represented by olivine fragment with parallel oriented pyroxene lamellae. BSE image.