Descriptive and Genetic Models for Lunar Ice Deposits Consistent with Current Remote Sensing Data

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No, and Yes

1. The orbital data have severe limitations

M^3, LAMP [and Trailblazer] only seeing 100s of microns beneath the surface
Neutron spectroscopy resolution 10–50 km/pixel
Radar can’t distinguish ice and buried rocks

2. No ground truth exists for any of the orbital data

Not close to level of knowledge of terrestrial mineral deposits

Can we form good explanations for lunar ice deposits based on current data?

No, and Yes

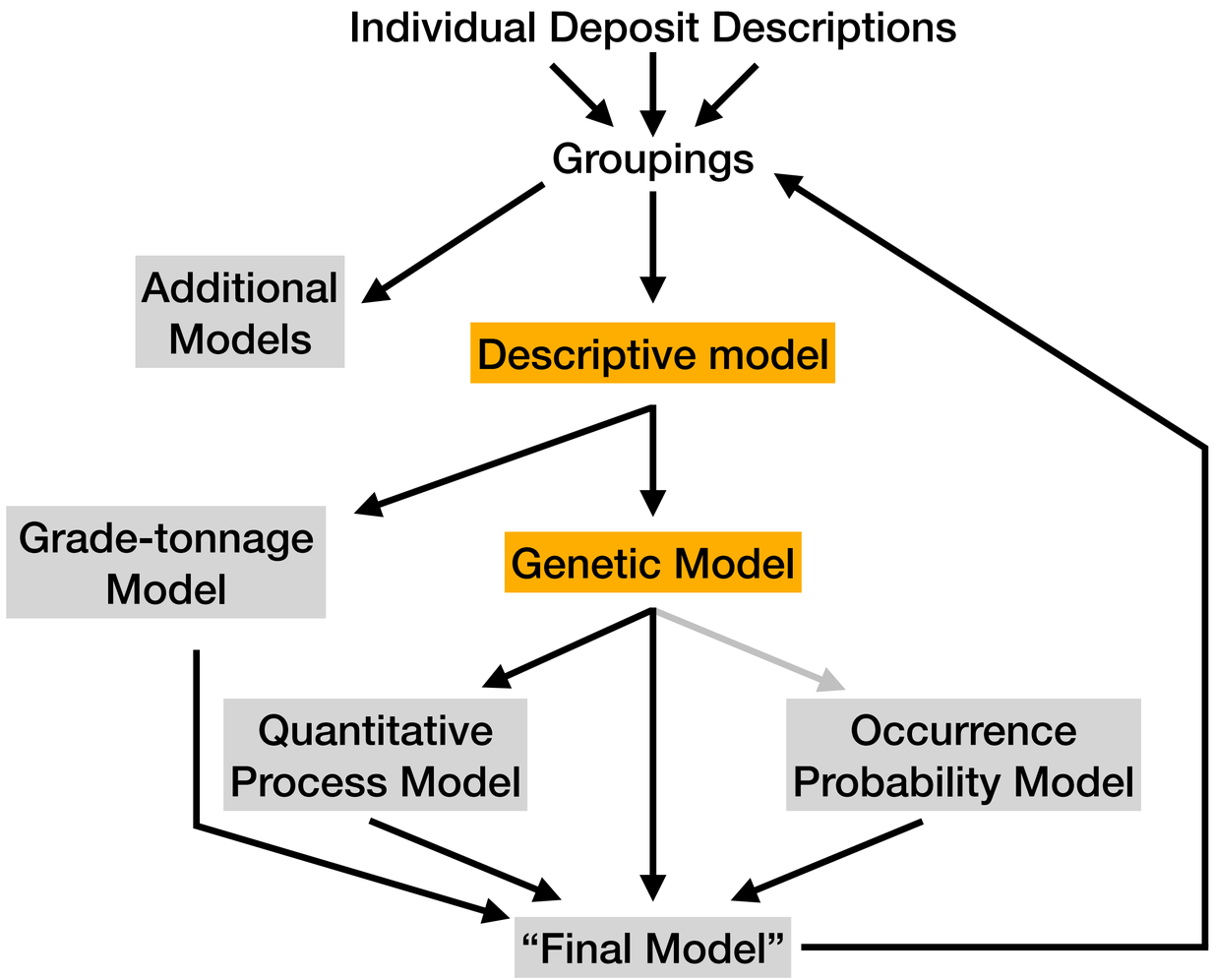
1. Remote sensing data have both a positive & negative component

What do they suggest is there?
What is precluded that they would detect if it were there?

2. Ice was deposited & modified by geologic processes

These processes can be understood

Mineral deposit model types



Cox et al.

Descriptive model: Lunar Polar H_2O

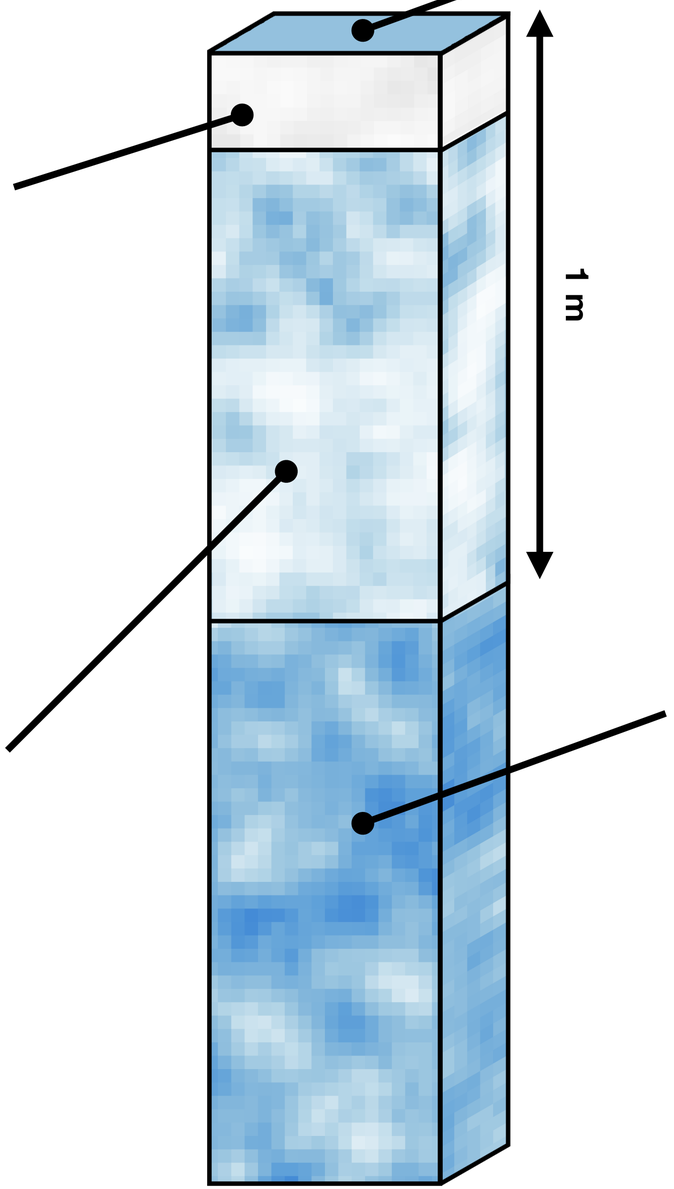
Patchy, low concentration “frost" at optical surface (LOLA, LAMP, M^3)

Lucey et al. 2004; Hayne et al. 2015; Fisher et al. 2017; Li et al. 2018

No large, Mars-like surface ice deposits (LOLA, ShadowCam)

Desiccated layer from 0 to 10±5 cm
THREE independent lines of evidence:
Neutron Spectroscopy
LADEE NMS
SELENE/Kaguya Spectral Profiler

Lawrence et al. 2006; Benna et al. 2019; Ohtake et al. 2024



~0.2–0.4 wt.% (maybe up to 2?)
from ~10 to 100 cm
(Neutron Spectroscopy)

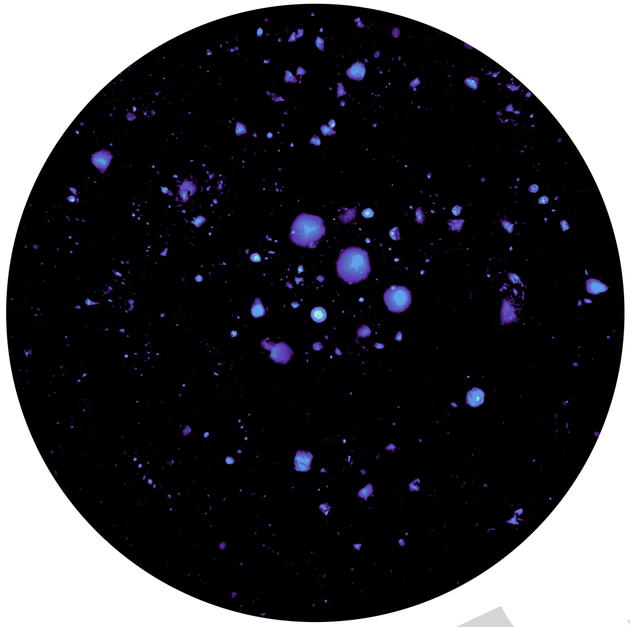
Feldman et al. 2000; Feldman et al. 2001; Lawrence et al. 2006; Teodoro et al. 2010; McClanahan et al. 2023

Higher concentration ice
(>5 wt.%?) >1 m deep,
mechanically stronger? (LCROSS)

Colaprete et al. 2010; Luchsinger et al. 2021

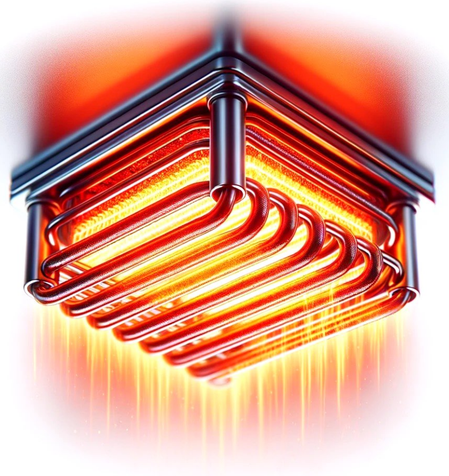
Genetic model

1. Cold traps emerge ~3.5 Ga and grow over time: ~50% by 2.1 Ga Schörghofer & Rufu 2023



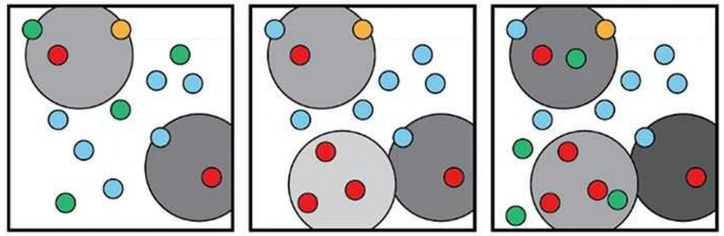
2. Episodic, transient collisional atmospheres (mostly from *asteroids*) deposit cm- to m-thick layers at cold trap surfaces as gas⇌solid deposition

3. Broiler model of erosion: micrometeoroids + sublimation + sputtering in upper ~mm. Gardening brings fresh ice in contact with broiler



Farrell et al. 2019

4. Excavation/burial by 10 m–1 km craters, and landslides create *modest* heterogeneity



Genetic model: lag deposits?

Dust

Electrostatic levitation

e.g., Colwell et al. 2007

Small meteoroids

Horányi et al. 2015; Wooden et al. 2016

Larger impacts

Popel et al. 2018; Berezhnoy et al. 2019

Complex organics

Carbonaceous infall

Haskin and Warren 1991; Tomas-Keprta et al. 2014

Radiation of C-bearing ices

Lucey 2000; Zhang and Paige 2009; Crites et al. 2013

Modeling lunar ice deposits

LPNS (2000) →

LCROSS (2009) →

LOLA, LAMP, M3 → (2014/15/18)

Study	Multiple deposition events?	Dimensions	Starting time or duration
Crider & Vondrak 2003a, b	No	1D	1 Gyr
Hurley et al. 2012	Yes (solar wind)	Multiple 1D columns	1 Gyr
Cannon and Britt 2020	No	3D	3.5 Gyr

Ice Homogenization

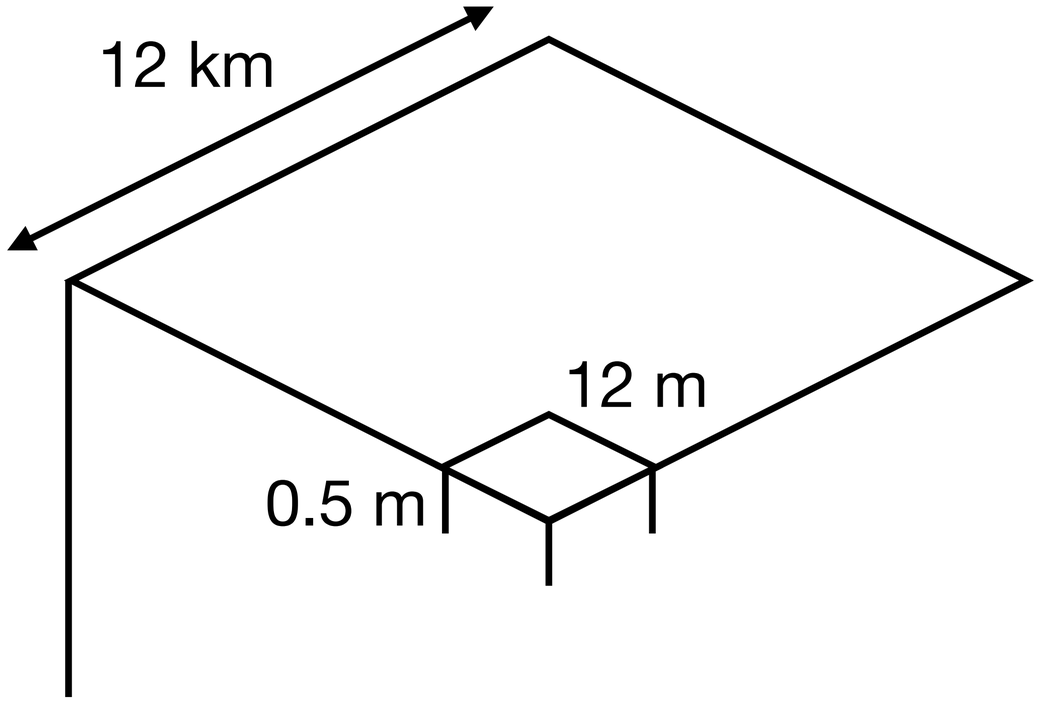
Cannon et al. 2020	Yes (impact, volcanic)	Multiple 1D columns	4.25 Ga
Wilcoski et al. 2022	Yes (volcanic)	Multiple 1D columns	4–2 Ga
Tai Udovicic et al. 2023	Yes (impact, volcanic)	Multiple 1D columns	4.25 Ga

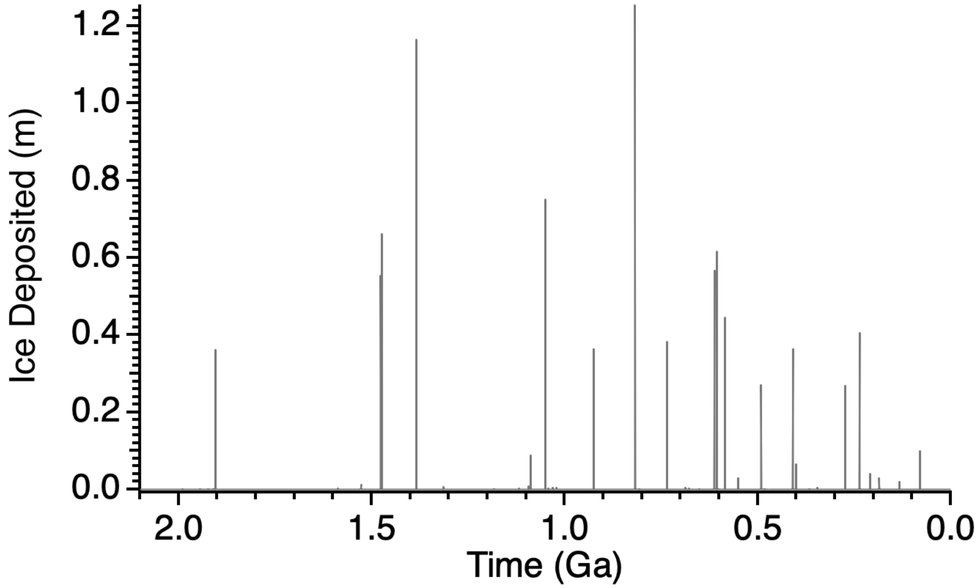
"Big ice" stratigraphies

ShadowCam (2023) →

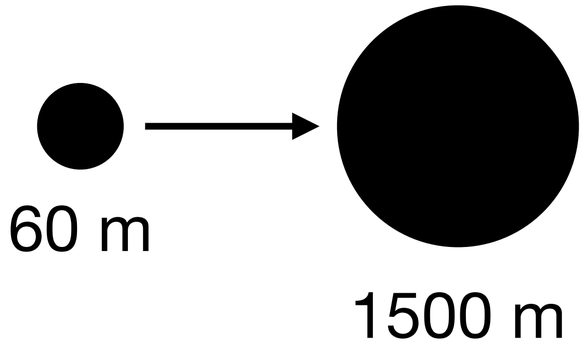
This work	Yes (impact)	3D	2.1 Ga

Modeling setup

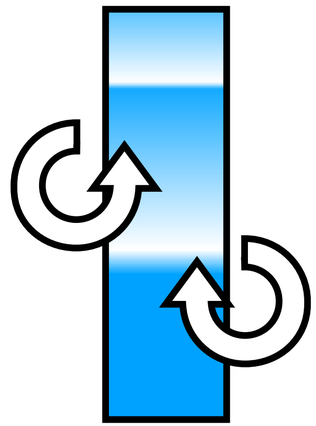




Explicitly modeled



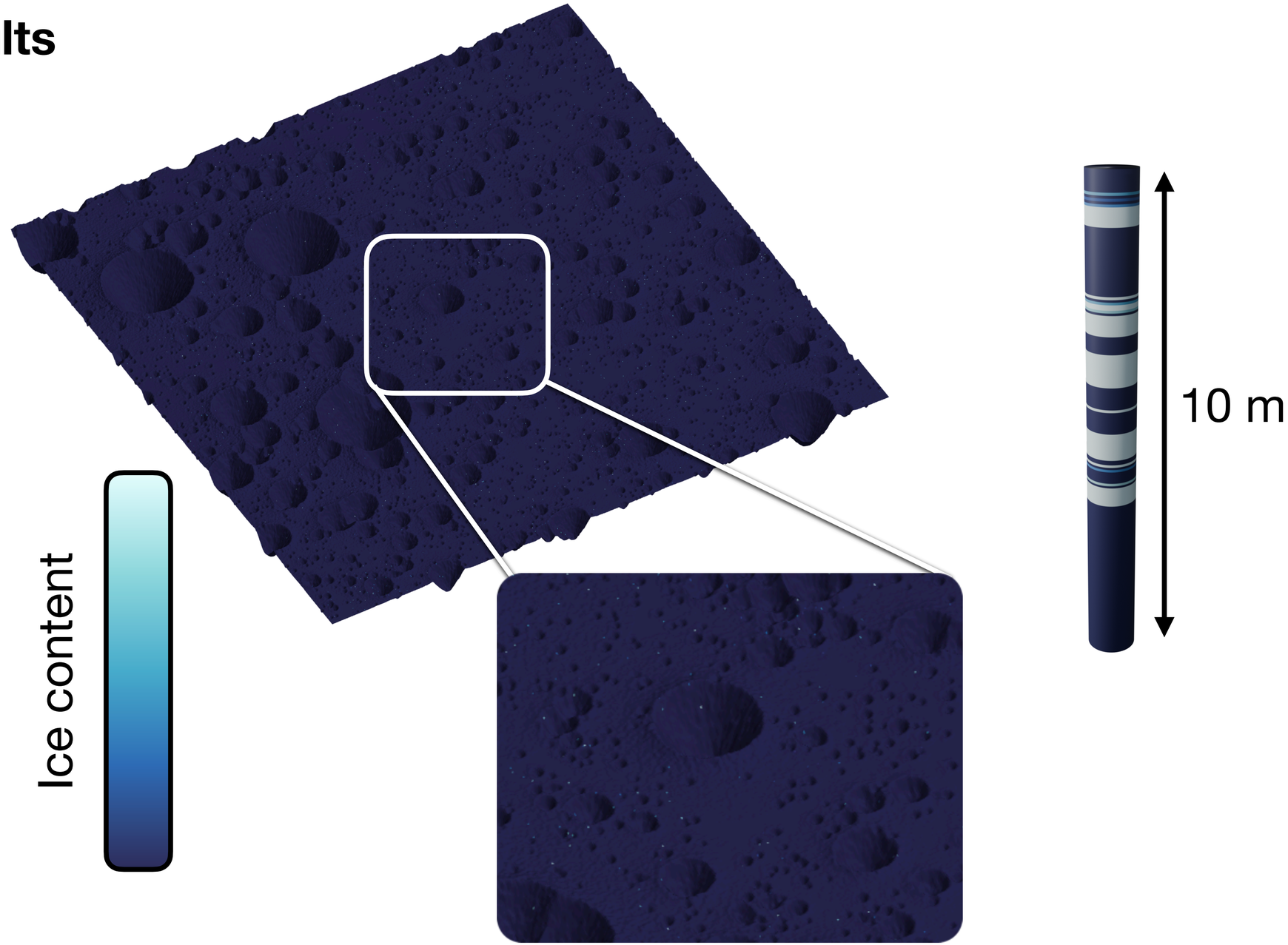
Gardening (5 cm res.)



Model results

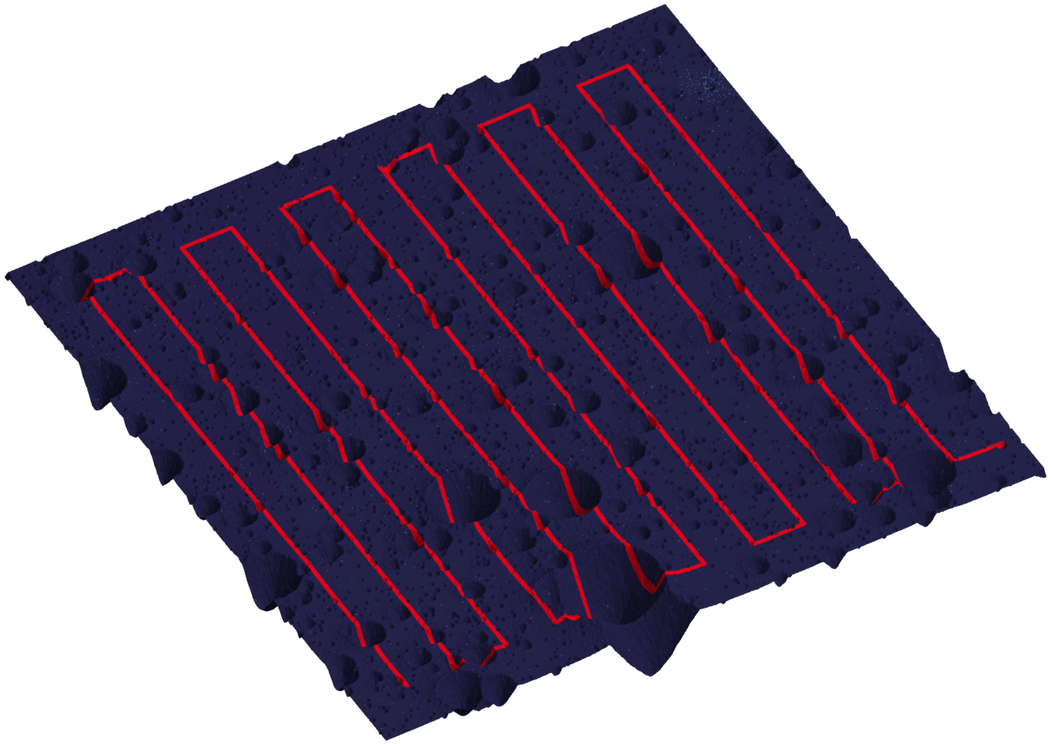
run #	spatially coherent surf. ice	patchy surface ice	desiccated layer	neutron below desiccated	high-purity >1 m
g7	1	1	1	1	1
g16	1	1	1	1	1
g8	1	1	0	1	1
g9	1	1	0	1	1
g19	1	1	0	1	1
g17	0	1	1	1	1
g23	0	1	1	1	1
g24	0	1	1	1	1
g26	0	1	1	1	1
g27	0	1	1	1	1
g28	1	0	1	1	1
g30	0	1	1	1	1
g14	1	1	0	0	1
g21	1	1	0	0	1
g20	1	0	1	0	1
g22	1	0	1	0	1
g25	1	0	1	0	1
g10	0	1	1	0	1
g4	0	1	0	1	1
g13	0	1	0	1	1
g15	0	1	0	1	1
g29	0	0	1	1	1
g1	1	0	1	0	0
g2	0	1	0	1	0
g3	0	1	0	0	1
g5	0	1	0	0	1
g6	0	1	0	0	1
g11	0	1	0	0	1
g12	0	0	1	0	1
g18	0	0	1	0	1

Model results

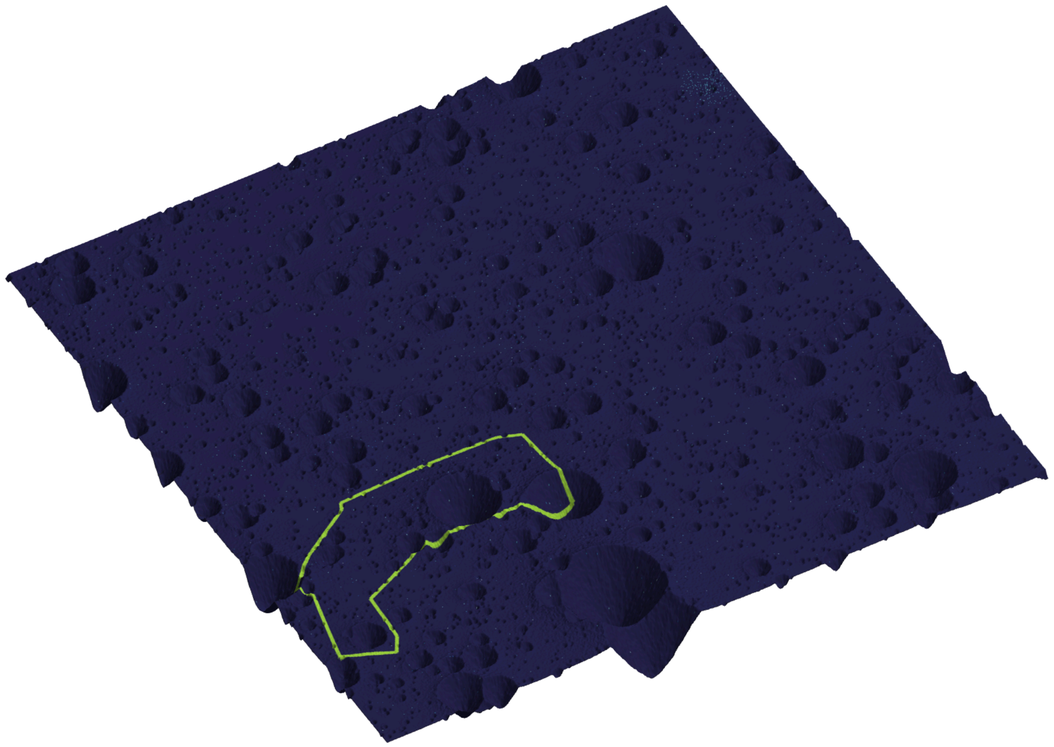


Application: prospecting campaign

No geologic model
133 km traverse
MSE: 29.5
(predicted vs. actual ice)



Geologic Model (translatable to Moon)
14.8 km optimized traverse
AMPL/CPLEX, custom PCTSP
MSE: 29.9



Testable Hypotheses

Model feature	Testable prediction
Episodic deposition of water	Multiple discrete subsurface layers with different thicknesses
Water sources dominated by asteroids	Mixture of volatile species and isotopic ratios should be dominantly chondritic
Deposition by global transient atmospheres	No significant variation from PSR to PSR except due to obliquity/TPW
Strong, top-down erosion of ice (broiler model)	Desiccated layer at surface, increasing ice content with depth
Heterogeneity at m to km scales controlled by impacts & landslides	Correlations of ice content with geologic mapping
Slow decline in obliquity over time	More ice in cold traps predicted to have emerged earlier

LCROSS

LAMP

ShadowCam

LPNS

LOLA

Mini-RF

LADEE NMS

M^3

LEND

Arecibo

Kaguya Spectral Profiler

Clementine bistatic radar