A Study of Martian Mid-Latitude Water Ice Using Observations and Modeling of Terraced Craters

Ali M. Bramson[1], S. Byrne[1], S. Sutton[1], N. E. Putzig[2], E. Martellato[3], G. Cremonese[3], J. J. Plaut[4] and J. W. Holt[5]

[1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ (contact: bramson@lpl.arizona.edu), [2]Southwest Research Institute, Boulder, CO, [3]INAF-Astronomical Observatory of Padova, Padova, Italy, [4]Jet Propulsion Laboratory, Pasadena, CA, [5]Institute for Geophysics, University of Texas at Austin, Austin, TX

30 Second Summary

- Terraced craters suggest a change in material strengths while subsurface SHARAD radar reflections appear due to changes in dielectric properties.
- We have mapped the locations of terraced craters and SHARAD reflectors, which are widespread across Arcadia Planitia on Mars.
- Comparing the delay times of these subsurface radar reflections with the depths of terraces in these craters yields dielectric constant estimates of 3.3-3.6, which suggest a water ice-rich (~80%) layer decameters thick with ~20% lithic material (either mixed into the ice or as a regolith layer on top) if no porosity. The layer is ~60% ice if 20% porous.
- Modeling of impact crater formation into an icy layered target demonstrates a water ice layer (covered by a layer of basaltic regolith) is likely responsible for the doubly-terraced crater morphology. The best fits are obtained when the ice has porosity <30%.

I. Introduction

- There is abundant evidence for excess water ice (ice that exceeds the pore space of the regolith) in the mid-latitudes: ice exposed in recent impact craters, scallops, thermokarstically expanded craters, and ice at the Phoenix excavation site.
- Understanding the distribution and composition (pure, dirty or porous) of this ice will lead to a better understanding of the mechanism(s) and climate that emplaced this ice.
- Craters and SHARAD radargrams are independent mechanisms for probing the subsurface to study this ice and both show extensive layering (presumably of this ice) across Arcadia Planitia.
- We constrain the depth of a widespread interface using HiRISE Digital Terrain Models of the terraced craters. Knowledge of its depth allows the radar data to be interpreted in terms of dielectric properties and constrain the composition of the layer.
- Comparing models of crater formation to crater topography allows us to test a variety of properties for the subsurface layers (thicknesses, porosities, strengths) as well as projectile sizes and speeds for insight into impact conditions.

II. Observations

Terraced Craters

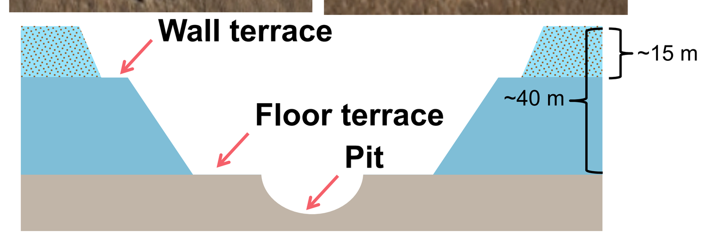


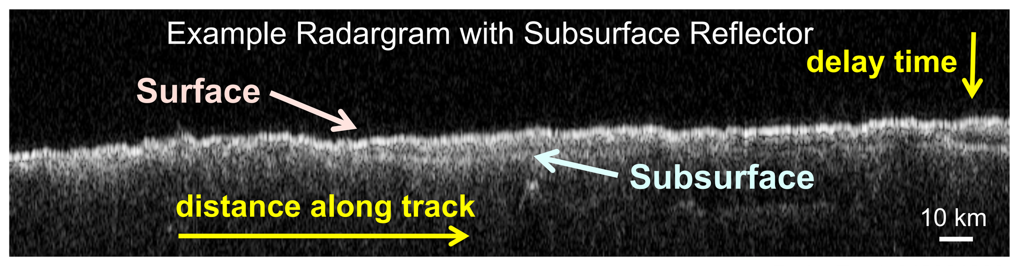
Diagram showing the typical double-terrace structure of the smaller, shallower "wall terrace" and the wider, deeper "floor terrace".

Cartoon of typical double-terraced crater profile

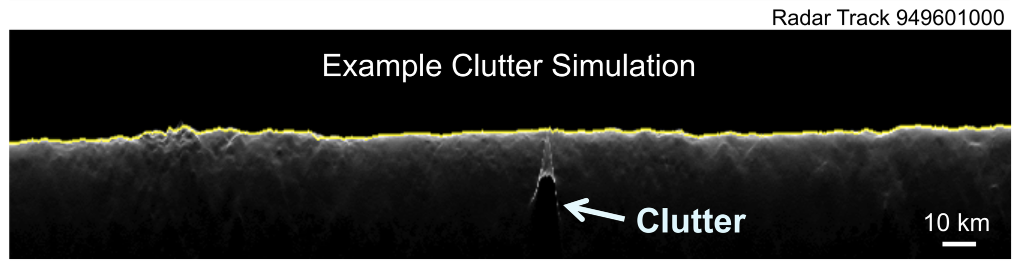
- Terraces within craters form due to changes in the strength of the target material at certain depths.
- We mapped the locations of terraced craters across Arcadia Planitia by searching 311 CTX images.
- Several have a double-terraced structure with a weak terrace closer to the surface (~15 m deep; either a change in the ice or due to a regolith layer on top) and a wider, deeper terrace (~40 m depth) indicative of a larger contrast in material strengths (likely the ice-crust interface).
- We obtained HiRISE stereo pairs for dozens of the craters and made Digital Terrain Models (DTMs) for 11 craters to measure the depths to terraces.

SHARAD Radar

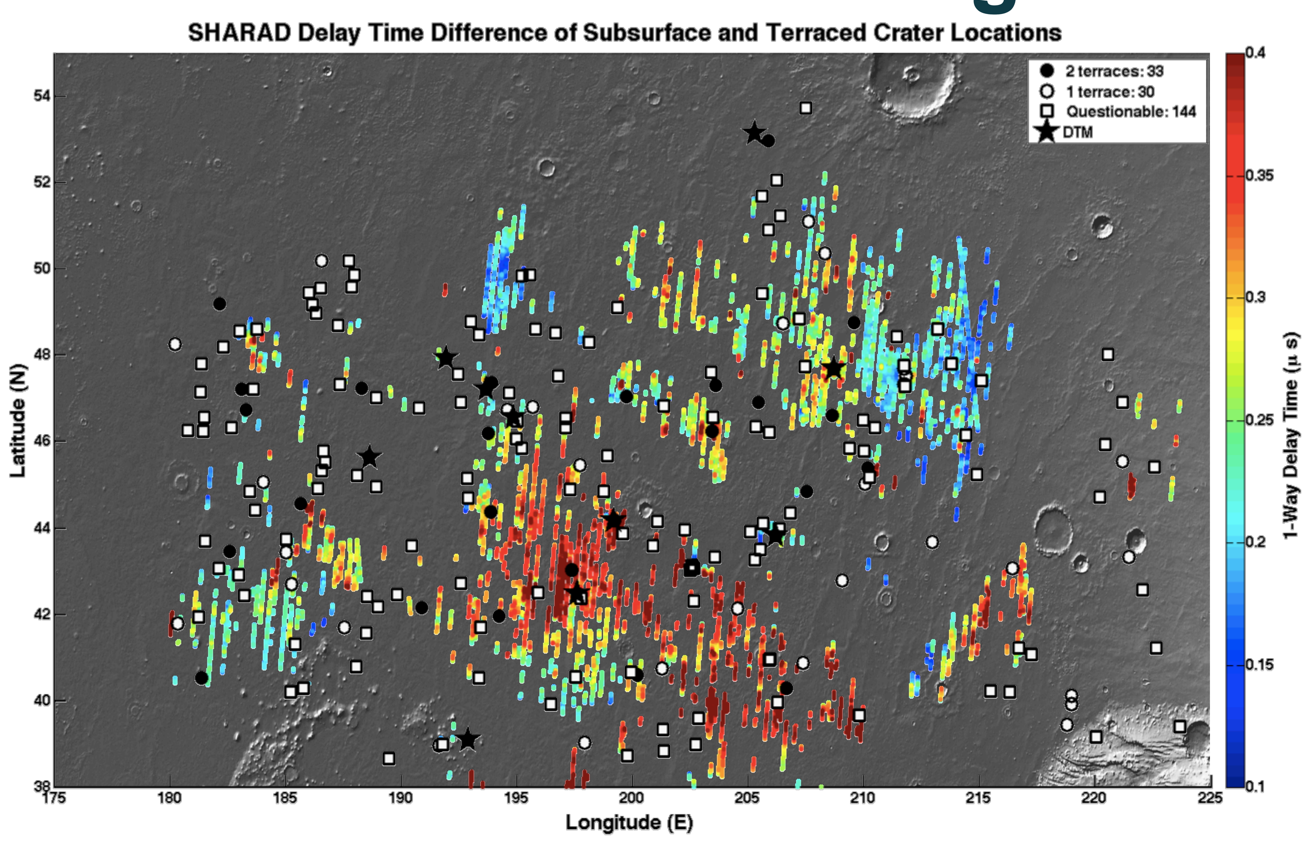
- Radar reflections indicate sharp change in the dielectric constant (relative dielectric permittivity) ε_r of the material.
  - The dielectric constant is a measure of how effectively an EM wave can move in a material.
  - Dielectric constants of common materials: Vacuum, Air ε_r: 1 Ice ε_r : ~3.15 Basalt ε_r: ~8
- We have mapped a subsurface reflector (originally detected and mapped by Plaut et al. LPSC 2009) in 277 SHARAD tracks across Arcadia Planitia by comparing the radargrams to clutter simulations (which simulate reflectors due to off-nadir topography).
- The reflector likely corresponds to the same interface as the floor terrace in the craters. The wall terrace is too shallow to be detected by SHARAD.



Radar Track 949601000



III. Combining Observations



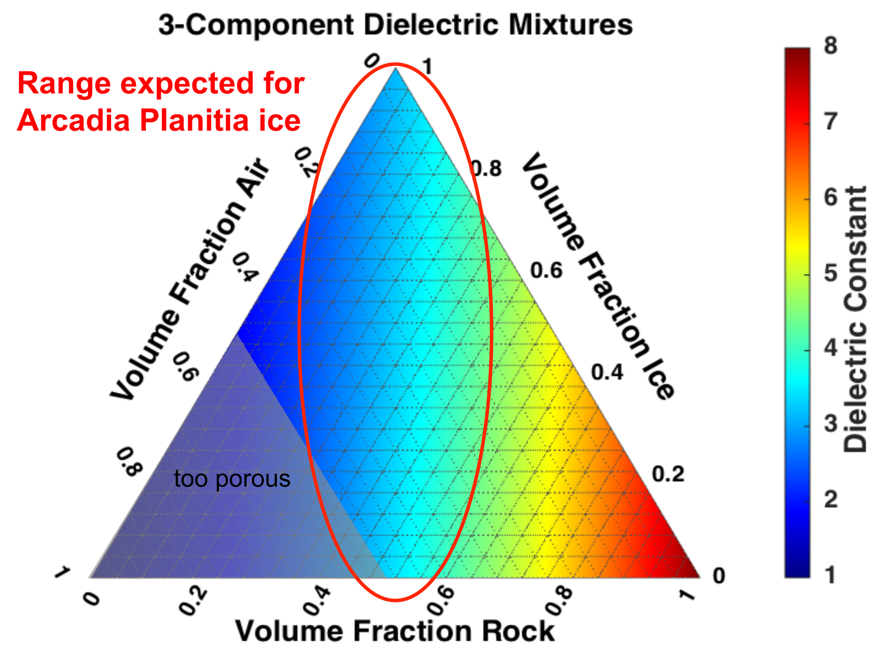
- The dielectric constant is related to radar propagation velocity in the equation below.
- We can use depths to crater terraces with SHARAD delay times to constrain the dielectric constant and thus the properties of the ice assuming the terrace corresponds to the same interface causing the radar reflector.

Floor terrace depths

$$v = \frac{\Delta x}{\Delta t} = \frac{c}{\sqrt{\varepsilon_r}}$$

Dielectric constant of subsurface layer

SHARAD 1-way delay times depth to subsurface reflector



Dielectric Mixing Models

$$\varepsilon_{mix}^{1/\gamma} = v_{rock}\varepsilon_{rock}^{1/\gamma} + v_{ice}\varepsilon_{ice}^{1/\gamma} + v_{air}\varepsilon_{air}^{1/\gamma}$$

Best-fit power-law exponent for sand-ice mixtures: γ = 2.7 [Stillman et al., 2010], where v is the volumetric fraction of that component in the mixture.

- 4 craters have two terraces *and* nearby radar reflectors.
- 3 of these craters give dielectric constants consistent with an ice-rich mixture (3.57, 3.49, 3.35) and one gives a higher dielectric constant (6.37), consistent with 60-80% basalt.
- Though, using the weighted mean of all radar returns within 15 km of each crater gives lower ε_r values, ranging from 2.6-2.7.
- We calculate errors in our dielectric constants of ~0.44-0.59.
- Thus the dielectric range expected for this ice is between ε_r = 2.6-3.6 but could extend as low as 2 or as high as 4.

IV. Modeling Crater Formation

iSale (Simplified Arbitrary Lagrangian Eulerian) Model

- Allows multiple materials and rheologies
- Modified from the SALE hydrocode [Amsden et al. 1980] to account for three target materials, various equations of state, various constitutive models and a porous-compaction model [Collins et al. 2004; Wünnemann & Ivanov 2003; Wünnemann et al. 2006]
- Is well tested against other hydrocodes [Pierazzo et al. 2008]

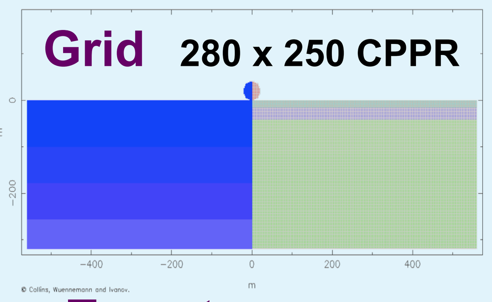
Components of the Model

- Differential equations established through conservation of momentum, mass and energy describe the dynamics of a continuous media
- Equation of State describes thermodynamic state (pressures, internal energies and densities)
- Strength Model describes response of a material to stresses that induce deviatoric deformations or changes of shape using elasticity, plasticity and fluid flow

Additional questions on the modeling can be directed to Dr. Elena Martellato: elena.martellato@oapd.inaf.it

SETUP

Grid 280 x 250 CPPR



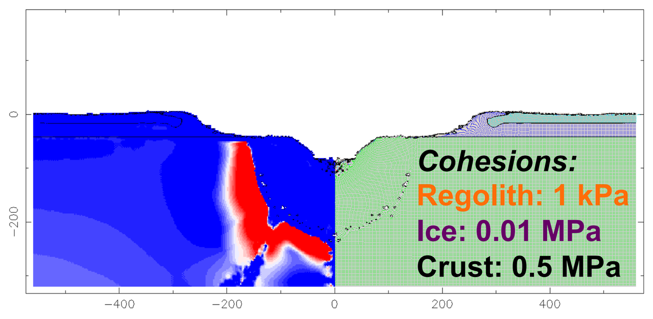
Projectile
- Radius = 20m
- Impact Velocity = 7 km/s
- Basalt (ANEOS, 10% porosity)

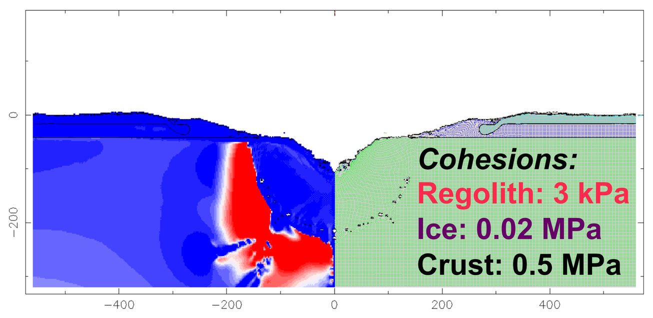
Target
- 0-17 m: Basalt (ANEOS; Drucker-Prager Model), Porosity = 5-50% (based on table below)
- 17-43 m: Ice (TILLOTSON EOS; Ice + Collins Model), Porosity = 5-50% (based on table below), Strength = 50 MPa
- 43-278 m: Basalt (ANEOS; Rock + Collins Model), Porosity = 10%, Strength = 10 MPa

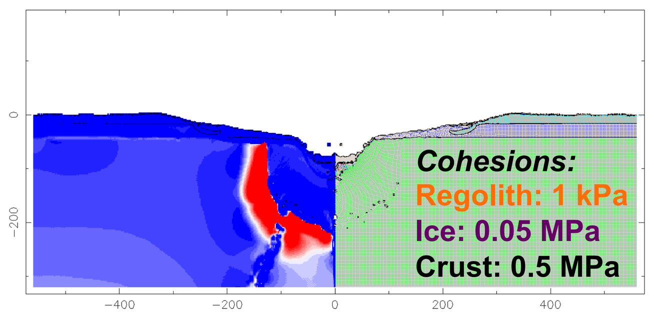
DIELECTRIC CONSTANTS		REGOLITH POROSITIES (17 meters regolith)										
		0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
ICE POROSITIES (26 meters ice for ice-crust interface depth of 43 m)	0%	4.80	4.63	4.46	4.29	4.13	3.97	3.82	3.68	3.53	3.40	3.26
	5%	4.69	4.52	4.35	4.19	4.03	3.88	3.73	3.58	3.44	3.30	3.17
	10%	4.59	4.41	4.25	4.09	3.93	3.78	3.63	3.49	3.35	3.21	3.09
	15%	4.48	4.31	4.15	3.99	3.83	3.68	3.54	3.40	3.26	3.13	3.00
	20%	4.38	4.21	4.05	3.89	3.74	3.59	3.45	3.31	3.17	3.04	2.91
	25%	4.28	4.11	3.95	3.79	3.64	3.50	3.36	3.22	3.09	2.96	2.83
	30%	4.18	4.01	3.85	3.70	3.55	3.41	3.27	3.13	3.00	2.87	2.75
	35%	4.08	3.92	3.76	3.61	3.46	3.32	3.18	3.05	2.92	2.79	2.67
	40%	3.98	3.82	3.67	3.52	3.37	3.23	3.10	2.96	2.84	2.71	2.59
	45%	3.89	3.73	3.58	3.43	3.29	3.15	3.01	2.88	2.76	2.64	2.52
	50%	3.80	3.64	3.49	3.34	3.20	3.06	2.93	2.80	2.68	2.56	2.44

Range of porosities that are consistent with dielectric constant measurements based on the radar and crater observations (yellow). Regolith porosity of 25% and ice porosity of 30% (orange) were used in the simulations below.

CASE 1 / BEST CASE / CASE 2

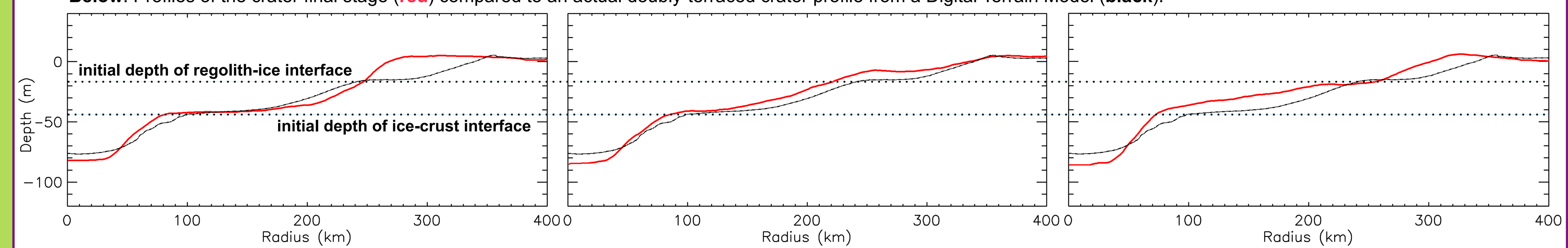






Above. Snapshots of the crater final stage: left side shows pressure contours (red = 10 MPa, blue = 1 MPa); right side shows the materials describing the target.

Below. Profiles of the crater final stage (red) compared to an actual doubly-terraced crater profile from a Digital Terrain Model (black).



This ratio of cohesions reproduces the floor terrace nicely but leads to no wall terrace.

The regolith-ice-crust cohesion ratio nicely reproduces the terraces, the rim and the pit.

The lower ice cohesion properly models the depth of the wall terrace but not the floor terrace.

V. Conclusions

- By combining crater terrace depths and SHARAD subsurface reflector delay times, we calculate the full expected range of dielectric constants (ε_r) for this layer to be between ~2 (corresponding to a maximum of 55% ice if mixed only with air) to ~4 (75% ice if mixed with lithic material) and includes the value of 3.15 corresponding to 100% ice.
- Using the radar delay times closest to each crater gives ε_r estimates of 3.3-3.6, which suggest a water ice-rich (80%) layer decameters thick with ~20% lithic material (either mixed into the ice or as a regolith layer on top) if no porosity.
- 2-layer and 3-layer models have been performed in order to best fit the HiRISE DTM profile of a doubly-terraced crater.
- Crater formation model results suggest that a 3-layer target is needed to account for both the floor terrace at the crust-ice interface and the subtler wall terrace, which likely stands at the base of a regolith layer.
- Porosities of the modeled ice and regolith are consistent with those expected from our dielectric constant measurements, with the best results obtained when the ice has a porosity lower than 30%.
- Material cohesion has a fundamental role in obtaining a good fit for both the terraces, the rim and the pit.

VI. Acknowledgements

- SeisWare International Inc. for free license of SeisWare software used in analyzing SHARAD data
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Department of Planetary Sciences Lunar and Planetary Laboratory

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