The Effects of Low Thermal Conductivity Sand on the Relaxation of Titan's Craters

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(1) Summary

Saturn's moon Titan has only a few impact craters, all of which are many hundreds of meters shallower than expected. The majority of the craters are located adjacent to organic-rich sand seas and are thought to be shallow due to aeolian infill alone. We estimated that the thermal conductivity of Titan sand is very low, and determined that large amounts of sand will effectively raise the surface temperature in the crater bowl and under nearby dunes and aid viscous relaxation. Using finite element modeling, we found the relaxation times needed to achieve the current crater depth under different sand infill thicknesses, heat flows, and grain sizes. Although the majority of the shallowing is due to sand infill, the amount of sand required can be as low as half the depth change needed because of induced viscous relaxation. Increased sand infill, higher heat flows, and lower grain sizes result in shorter relaxation times.

(2) Introduction

Titan Lacks Impact Craters

- Less than 100 crater candidates have been identified on Titan [1]
- Only 8 are officially recognized: Ksa, Sinlap, Hano, Afekan, Menrva, Soi, Selk and Momoy
- With the exception of Hano, all of the official craters are found within 30° of Titan's equator, which is also the location of Titan's sand seas (Fig. 1)

Figure 1: Locations of Titan's Confirmed Craters

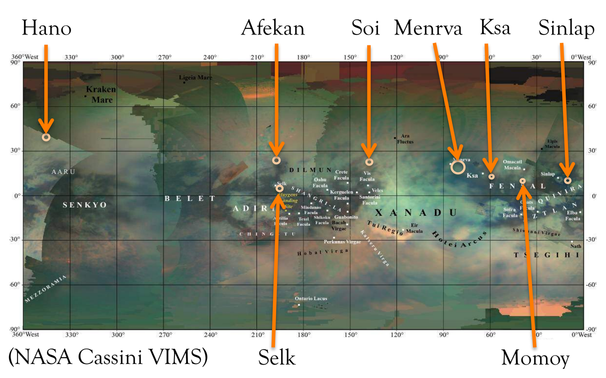
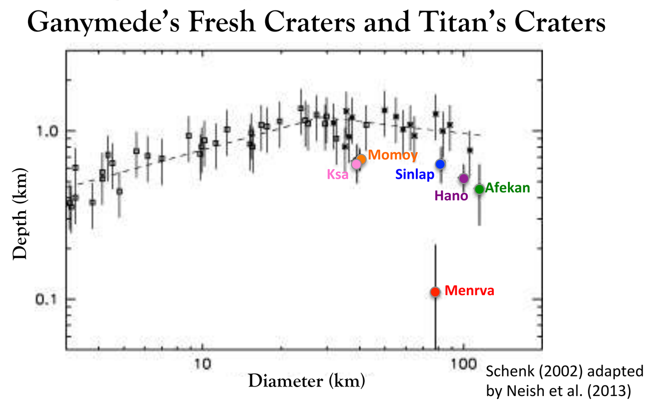


Figure 2: Depth-to-Diameter Plot for Ganymede's Fresh Craters and Titan's Craters



Titan's Identified Impact Craters are Shallow

- Titan is similar in composition and size to Jupiter's moon Ganymede, so the depth/diameter ratios of their unmodified impact craters is expected to be similar
- However, these craters are actually **shallow by many hundreds of meters in comparison with Ganymede** according to SARTopo data [2,3] (Fig. 2)

What Could Make Titan's Craters Shallow?

- **Erosion and deposition by methane or ethane rain**
  - GCMs predict that the equatorial regions are arid and rainstorms infrequent
  - This may be a more important process for removing craters at higher latitudes
- **Direct atmospheric sedimentation**
  - The most abundant solid photochemical product, acetylene, has a sedimentation rate of order 10 m/Gyr uniformly distributed over Titan [4]
  - It is unlikely that this alone could shallow the craters
- **Aeolian infill**
  - Most of the craters are located near the sand seas so they could be simply filled with sand [2],
  - This requires a lot of sand
- **Viscous relaxation**
  - Previously assumed to be an unimportant mechanism at Titan's low surface temperature of 94 K
- **Aeolian infill and subsequent viscous relaxation**
  - The low thermal conductivity of Titan's sand may effectively raise the surface temperature inside and adjacent to Titan's impact craters, aiding viscous relaxation
  - This reduces the amount of sand required to make Titan's craters shallow

We aim to determine if <u>both aeolian infill and subsequent relaxation</u> can relax Titan's craters to their current depth in timescales less than the estimated maximum dune age of 750 Myr [5]

(3) Estimating the Thermal Conductivity of Titan Sand

- Titan sand is thought to be composed of a mixture of solid organic molecules that formed photochemically in the atmosphere [6]
- We estimate the thermal conductivity of the hydrocarbon sands by scaling the thermal conductivity of benzene and coals at temperatures and pressures relevant to Titan by a factor commiserate with the conductivity drop between particulate and solid silicates

Thermal conductivities:

- Organics such as solid benzene and coal: **0.25 - 0.55 W/mK**
- Quartz grains: **6 - 8 W/mK**
- Dry fine quartz sand: **0.24 - 0.4 W/mK**

Estimated organic sand thermal conductivity: 0.025 W/mK

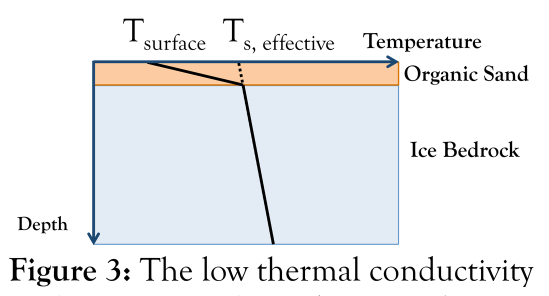


Figure 3: The low thermal conductivity of the organic-rich sand effectively raises the surface temperature of Titan.

(4) Methods: Estimating the Dune Field $T_{s,\ effective}$

Dunes adjacent to the craters influence the surrounding surface temperature profile.

To determine the $T_{s,\ effective}$ produced by the dune field:

- We used the Marc finite element package to produce meshes that crosscut 3 linear dunes with 5 surrounding interdune spaces
- Dunes assumed to have isosceles triangular shapes in cross-section
- Explored permutations of dune widths, interdune widths, and maximum dune heights (120-180 m) taken from global datasets [7]
- Interdune areas are held at 94 K and the $T_{s,\ effective}$ below the dunes is calculated using the estimated thermal conductivity of Titan sand and the sand thickness (Fig. 4)
- Dune scale << crater scale, so this is effectively the dune's Ts

The most representative $T_{s,\ effective}$ is about 100 K

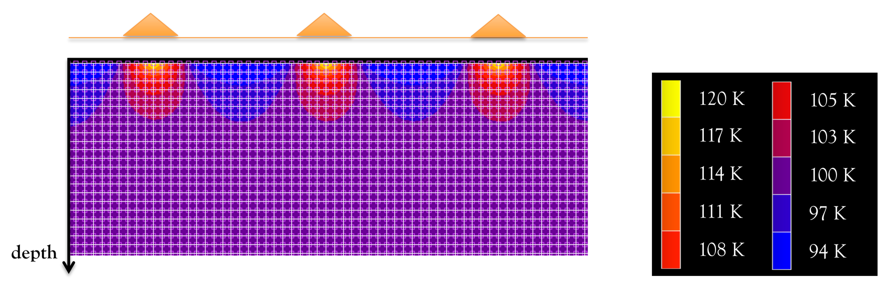


Figure 4: Example simulation with dune locations shown above (not to scale)

(5) Methods: Crater Relaxation Simulations

To Simulate Crater Relaxation:

- We used the Marc Finite Element Package using a mechanical simulation with a thermal simulation input [see 8] and determined the time needed to relax to the current depth (reduced by the thickness of sand infill)
- Crater topographic profiles provide: crater diameter, final depth, rim height [2]
- Initial crater depth constrained by Ganymede's fresh craters d/D [3]
- Distance to the adjacent dunes measured off of SAR imagery
- Planar, axisymmetric mesh

Thermal Simulation (Fig. 5):

- Applied basal heat flux: 4 mW/m^2 (today's estimate [9]) or 10 mW/m^2 (extreme value)
- Crater bowl $T_{s,\ effective}$ depends on sand infill thickness
- The $T_{s,\ effective}$ under the dune fields is 100 K
  - Minimum distance to dunes distance is used

Mechanical Simulation:

- Viscoelastic ductile ice rheology
  - GBS, diffusion, dislocation
- Two grain sizes: 1 mm and 0.1 mm
- Relaxation timescales up to 4 Gyr

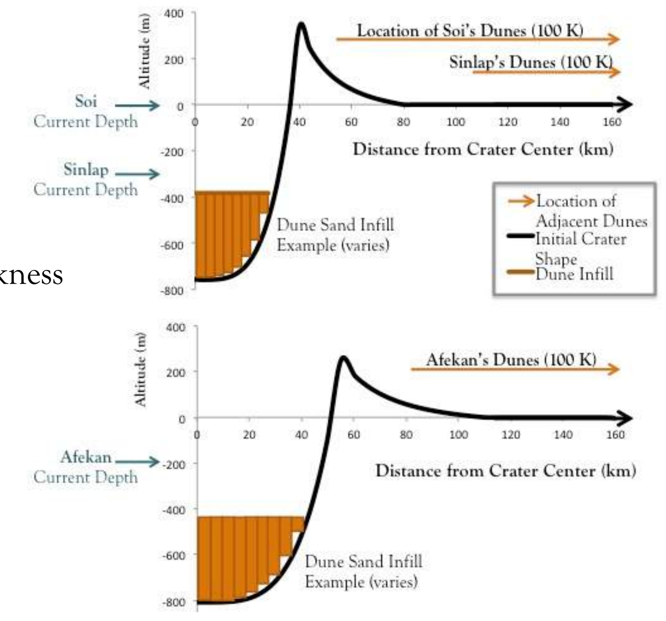
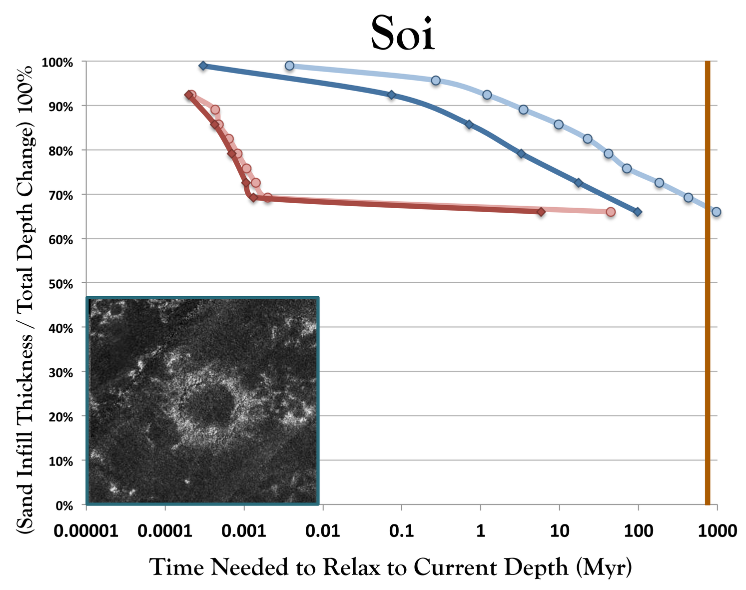
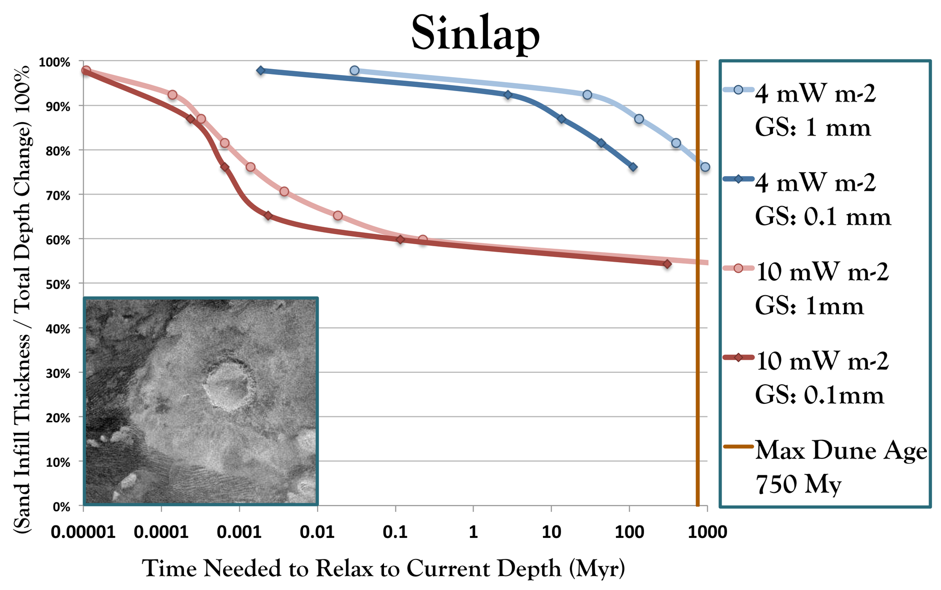
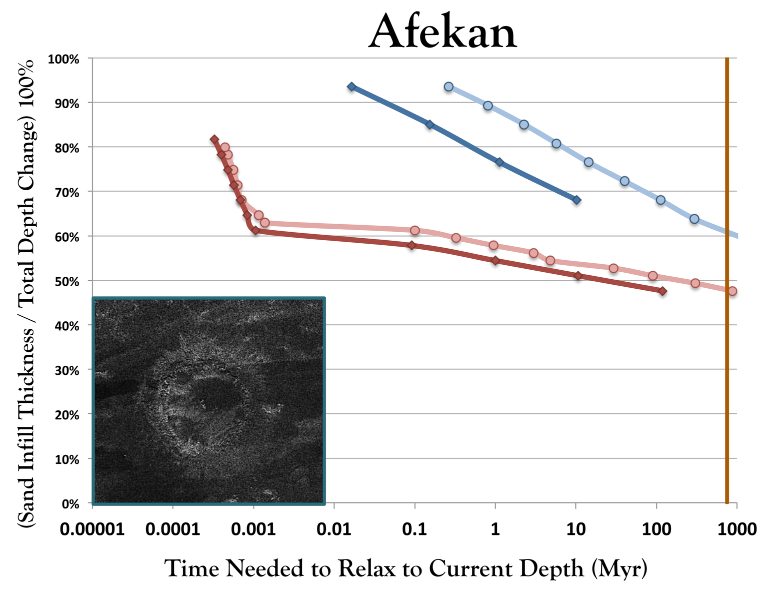


Figure 5: Initial Crater Shapes & Dune Locations
Note: Sinlap and Soi have the same initial shape

(6) Results







Soi Results:

Assuming that Soi relaxed to approximately zero topography (current depth), it required a depth change of 758 m.

4 mW/m^2 Grain Size 0.1 mm:

500 m (66%) of sand infill aided the relaxation of the remaining 258 m of depth in 97 Myr
750 m (99%) of sand infill relaxed the remaining 8 m in 302 yr

10 mW/m^2 Grain Size 0.1 mm:

500 m (66%) of sand infill relaxed the remaining 258 m in 5.8 Myr
700 m (92%) of sand infill relaxed the remaining 58 m in 200 yr

Sinlap Results:

Sinlap relaxed to a depth of -301 m, requiring a depth change of 460 m.

4 mW/m^2 Grain Size 0.1 mm:

350 m (76%) of sand infill relaxed of the remaining 110 m in 112 Myr
450 m (98%) of sand infill relaxed the remaining 10 m in 187 yr

10 mW/m^2 Grain Size 0.1 mm:

250 m (54%) of sand infill relaxed the remaining 210 m in 305 Myr
450 m (98%) of sand infill relaxed the remaining 10 m in 9.8 yr

Afekan Results:

Afekan relaxed to a depth of -195 m, requiring a depth change of 588 m.

4 mW/m^2 Grain Size 1 mm:

375 m (64%) of sand infill relaxed of the remaining 213 m in 296 Myr
550 m (98%) of sand infill relaxed the remaining 38 m in 265 ky

10 mW/m^2 Grain Size 0.1 mm:

280 m (47%) of sand infill relaxed the remaining 308 m in 119 Myr
480 m (82%) of sand infill relaxed the remaining 108 m in 326 yr

Thinner sand infill thicknesses did not reach the current depth in less than 4 By and are not included in this plot

(7) Implications

- The major contributor to the shallowing of these three craters is sand infill, but instead of needing 758 m, 460 m, or 588 m of sand infill alone (100 % of the depth change), the low thermal conductivity sand may aid relaxation and only require a minimum of 47% of the depth to be sand at 10 mWm^2 and 64% at 4 mW/m^2
- Increasing sand infill increases the $T_{s,\ effective}$, which promotes viscous relaxation while also decreasing the distance that the crater must relax
- Higher heat flows and lower grain sizes result in faster relaxation, so increases in past heat flows may result in shallower craters
- The amount of time that the craters were filled with sand can constrain the value of the ratio of sand infill thickness / total depth change

[1] Wood C. A., et al. (2010) *Icarus*, 206, 168-172. [2] Neish C. D. et al. (2013) *Icarus*, 223, 82-90. [3] Schenk, P. (2002) *Nature*, 417, 419-421. [4] Toublanc, D. et al. (1995) *Icarus*, 113, 2-26. [5] Rodriguez, S. et al. (2014) *Icarus*, 230, 168-179. [6] Soderblom, L. A., et al. (2007) *Planetary & Space Sci.*, 55, 2015-2036. [7] Savage, C. J., et al. (2014) *Icarus*, 230, 180-190. [8] Dombard, A. J. and McKinnon, W. B. (2006) *JGR*, 111, E01001. [9] Sohl, F. et al. (2003) *JGR*, 108, E12.

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