Determining the Structural Stability of Lunar Lava Tubes

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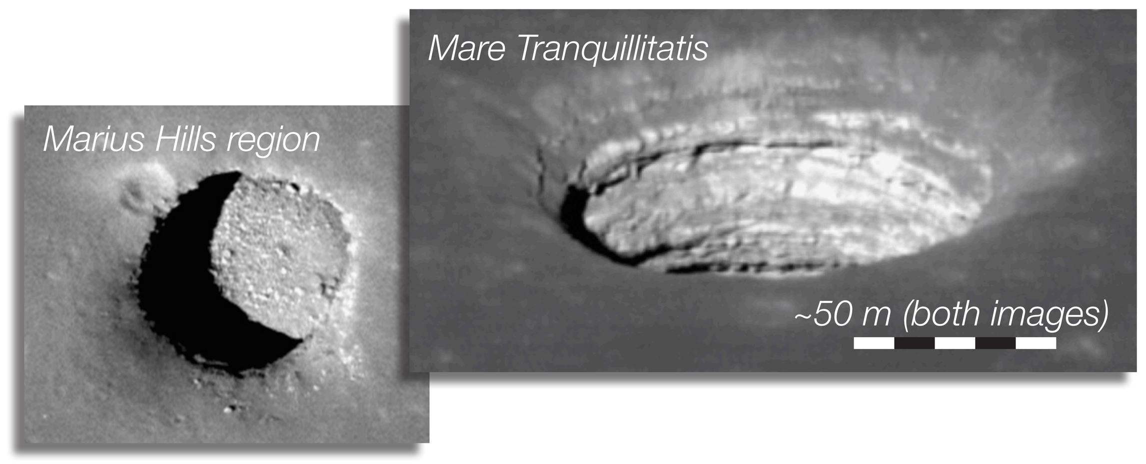
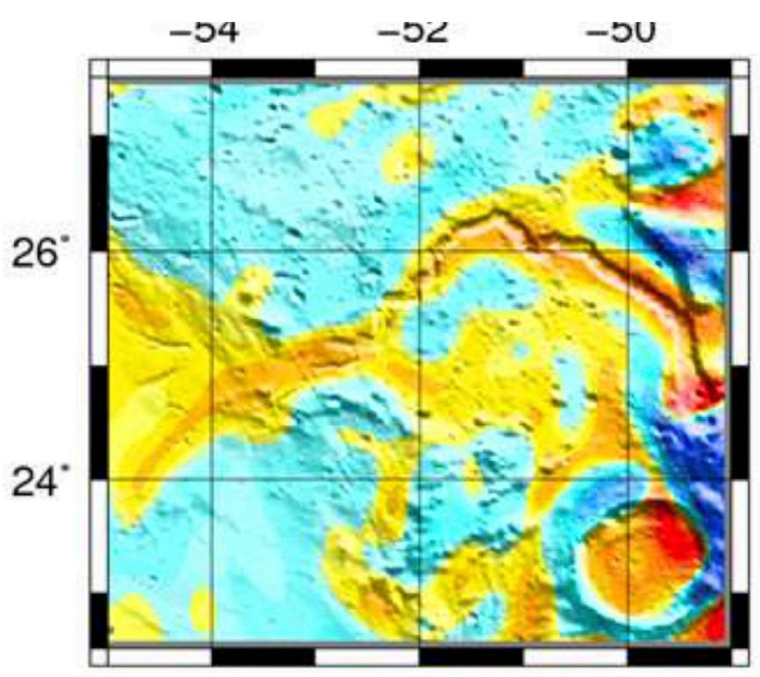
Introduction

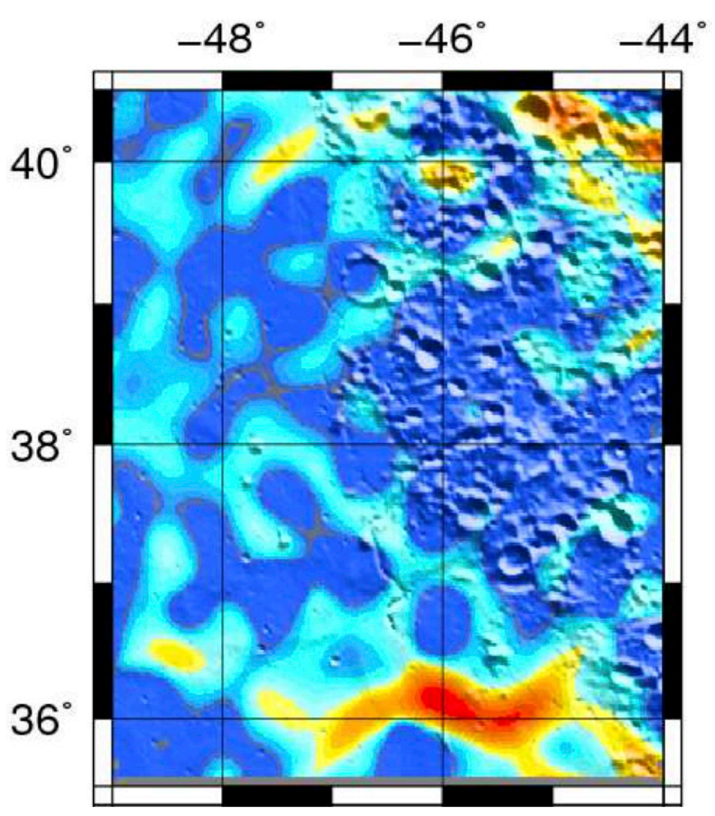
Lunar lava tubes are an enticing target for future **human lunar exploration**—they can provide shelter from meteorite impacts, cosmic radiation, and temperature extremes [1].



Lunar "skylights" were discovered in images returned by the **SELENE/ Kaguya** spacecraft [2,3]. Images from the **Lunar Reconnaissance Orbiter (LRO)** (↑) later confirmed the presence of those skylights and 150 others [4].



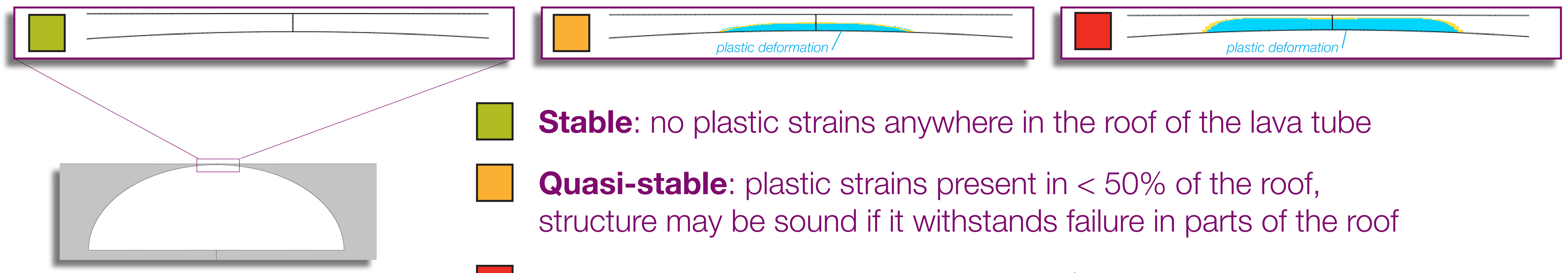
Gravity data from the twin **Gravity Recovery And Interior Laboratory (GRAIL)** spacecraft also points to the existence of large sublunarean voids. For example, **1–4 km wide** empty lava tubes which are **subsurface continuations of sinuous rilles** in Vallis Schröteri (↑) and Rima Sharp (↘) [5,6] are visible in the eigenvalues of the free-air gravity anomaly field. If this interpretation is correct, lunar lava tubes may be **much larger than any known terrestrial lava tube**, and larger than previous **estimates of their maximum size** [7]...



...but ***can empty lava tubes > 1 km wide remain structurally stable on the Moon?***

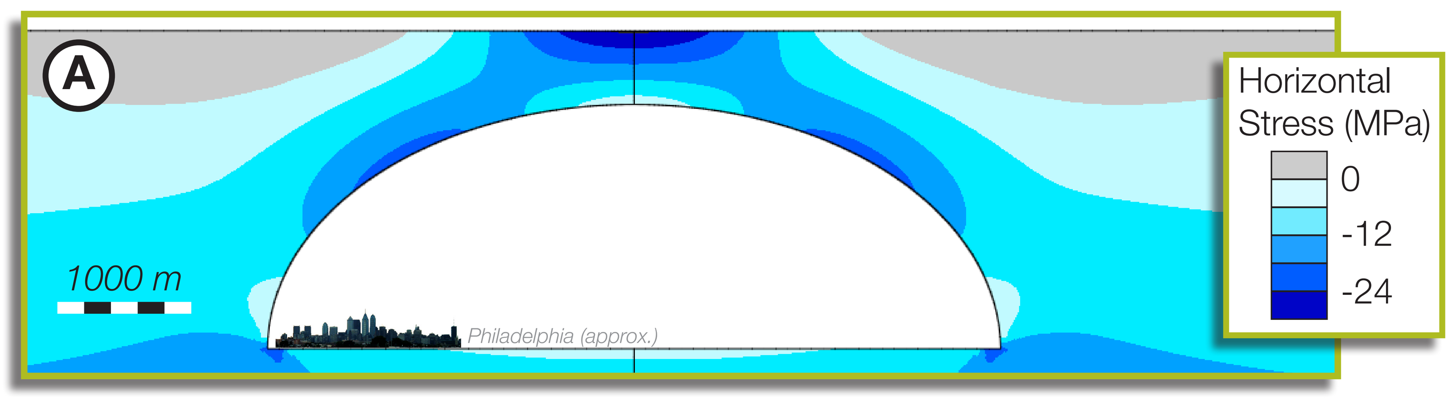
Methods

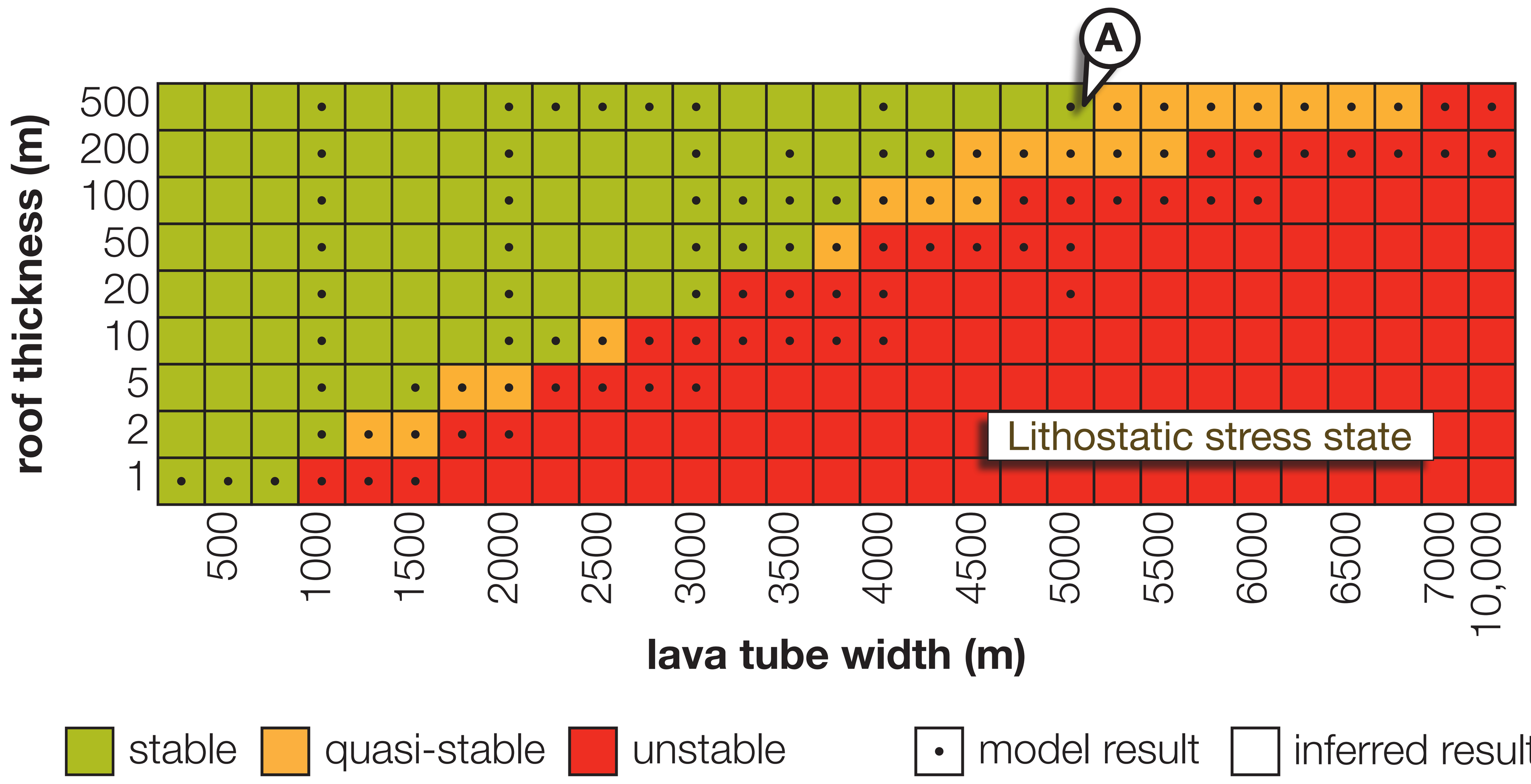
We use **finite element models** built in the *Abaqus* software suite assuming **plane-strain** conditions and **symmetry** about the tube's center. Tube failure is judged by the amount of material in the roof which exceeds a **Mohr-Coulomb plastic failure envelope** (↗).

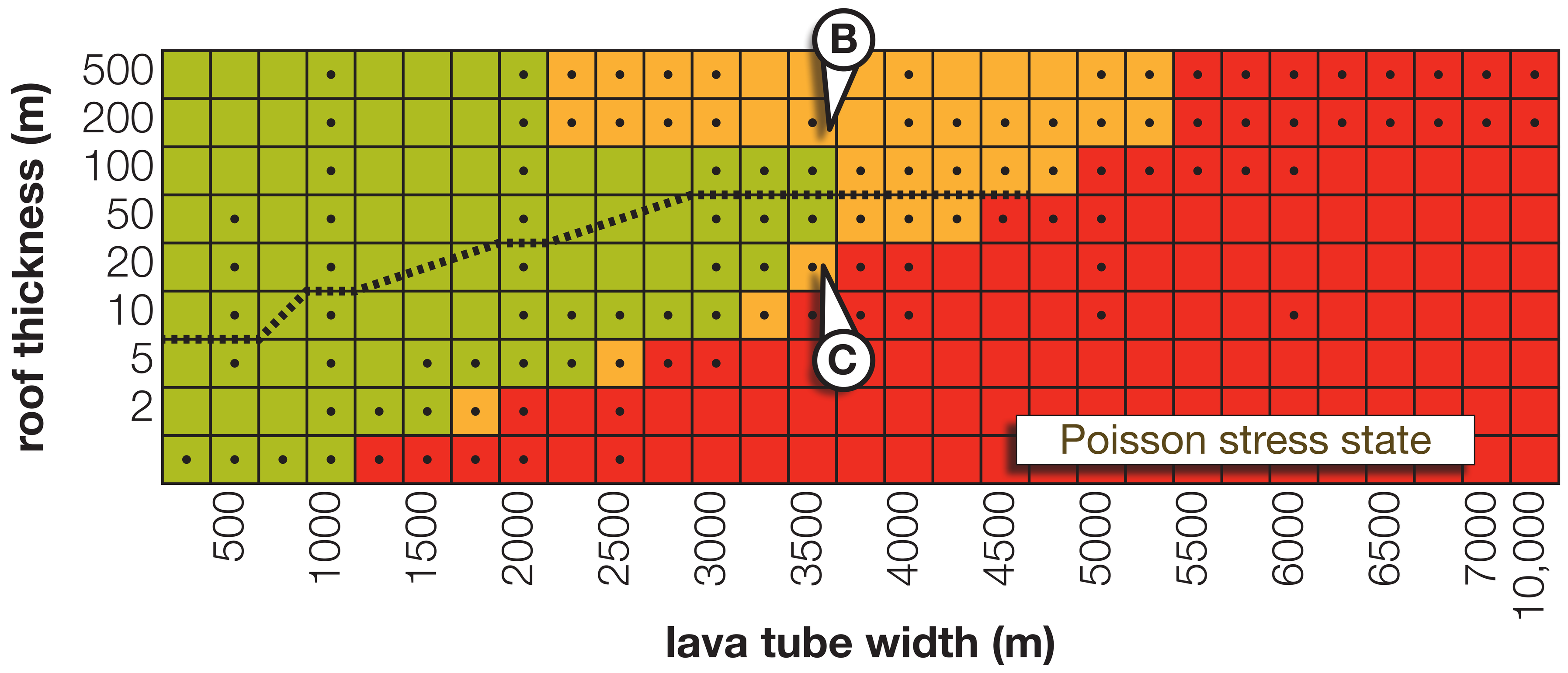


- **Stable**: no plastic strains anywhere in the roof of the lava tube
- **Quasi-stable**: plastic strains present in < 50% of the roof, structure may be sound if it withstands failure in parts of the roof
- **Unstable**: plastic strains through ≥ 50% of the roof

We vary the lava tube's **width** (up to the size of the **largest known lunar sinuous rilles**), **roof thickness** (from estimated **thicknesses of mare flows** in several different locations [4,8]) and pre-existing stress state. Models with a **lithostatic stress state** ($\sigma_x = \sigma_y = \sigma_z$) represent lava emplaced in one thick layer, while a **Poisson stress state** ($\sigma_x = \sigma_y = 1/3\ \sigma_z$) represents lava emplaced in many thin layers; the real stress state of the rock is likely somewhere between these two end-member cases.







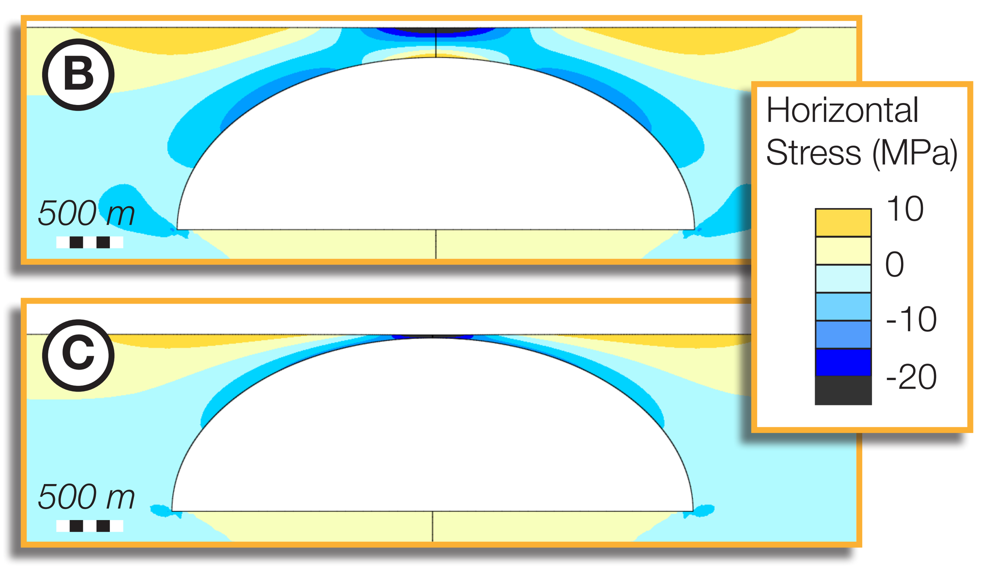
Results

Lithostatic stress state (↙)

- Structurally sound tubes up to **~5000 m wide** (A)
- Thicker roofs lead to larger stable tube sizes
- Thinner roofs like those of the **skylights** (~1–14 m) can still support tubes > **750 m across**
- **Fail in compression**, with plastic strains propagating downwards from the surface; this is the same mode of failure seen in **keystone arches** and many types of bridges.

Poisson stress state (↙)

- Stable lava tubes up to **~3500 m wide**, given a roof 50–100 m thick
- **Thicker-roofed tubes** (above the dashed black line) **fail via downwards flexure** of the roof (B), similar to the failure mode of **terrestrial caves in bedded rock**.
- Tubes with **thinner roofs** (below the dashed black line) **fail in compression** (C)



We are still exploring **regional tectonic stresses** and **cooling and contraction** of the lava tube. The modes of failure shown here, however, indicate that extensional far-field stresses may allow larger or thinner-roofed tubes.

Our results **support the possibility of several-kilometer-wide empty lava tubes** under the lunar surface. Our largest models are also at the **same scale as lunar sinuous rilles**, indicating that those features could have been covered lava tubes at some point in their history. The feasibility and mechanics of **actually forming lava tubes of this size**, however, **remains an open question.**

References & Acknowledgements

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