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The structural stability of lunar lava tubes

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ABSTRACT

Mounting evidence from the SELENE, LRO, and GRAIL spacecraft suggests the presence of vacant lava tubes under the surface of the Moon. GRAIL evidence, in particular, suggests that some may be more than a kilometer in width. Such large sublunarean structures would be of great benefit to future human exploration of the Moon, providing shelter from the harsh environment at the surface—but could empty lava tubes of this size be stable under lunar conditions? And what is the largest size at which they could remain structurally sound? We address these questions by creating elasto-plastic finite element models of lava tubes using the Abaqus modeling software and examining where there is local material failure in the tube's roof. We assess the strength of the rock body using the Geological Strength Index method with values appropriate to the Moon, assign it a basaltic density derived from a modern re-analysis of lunar samples, and assume a 3:1 width-to-height ratio for the lava tube. Our results show that the stability of a lava tube depends on its width, its roof thickness, and whether the rock comprising the structure begins in a lithostatic or Poisson stress state. With a roof 2 m thick, lava tubes a kilometer or more in width can remain stable, supporting inferences from GRAIL observations. The theoretical maximum size of a lunar lava tube depends on a variety of factors, but given sufficient burial depth (500 m) and an initial lithostatic stress state, our results show that lava tubes up to 5 km wide may be able to remain structurally stable.

1. Introduction

Lunar lava tubes present an enticing target for future human lunar exploration. A vacant lava tube could provide astronauts shelter against small meteorite impacts, cosmic radiation, and the extreme temperature variations at the lunar surface (Hörz, 1985; Haruyama et al., 2012). Because lava tubes are by their nature found in the vicinity of volcanic vents, there may also be good local availability of volatile chemical species such as sulfur, iron, and oxygen, as well as pyroclastic debris which could be useful as a construction material (Coombs and Hawke, 1992). Their enclosed nature and limited exposure to the space environment may also make them possible storage locations for water and other ice deposits, useful sites for studying the stratigraphy of the lunar regolith and dust environment, and suitable sites for finding comparatively pristine examples of mantle-derived rocks near the surface (Haruyama et al., 2012). Locating and characterizing potential lunar lava tubes has therefore been a priority in the lunar science community for some time.

Lava tubes form when a channelized lava flow forms a roof either through the development of levees or the formation of a surficial crust, while the molten material underneath flows away and leaves a partially or completely vacant conduit (e.g. Cruikshank and Wood, 1971). Such features occur in numerous locations on Earth, and it has long been posited that they may also exist—or have existed—on the Moon. Through interpretation of images returned by Lunar Orbiter V, Oberbeck et al. (1969) were among the first to suggest that sinuous rilles such as those observed in northern Oceanus Procellarum and elsewhere may be the collapsed remains of lava tubes which formed during the emplacement of the maria. Numerous other studies during the Lunar Orbiter and Apollo mission eras supported this idea, and showed examples of similar processes occurring in Hawai'i (e.g. Cruikshank and Wood, 1971; Greeley, 1971; Oberbeck et al., 1972).

It is only recently that we have obtained direct evidence for the existence of uncollapsed voids beneath the lunar surface. In 2009, Haruyama et al. published their discovery of a 65 m-diameter

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vertical-walled hole in the Marius Hills region of the Moon, using data from the Terrain Camera and Multi-band Imager aboard the SElenological and ENgineering Explorer (SELENE) spacecraft. The following year, two additional pits were identified in SELENE data, in Mare Tranquilitatis and Mare Ingenii (Haruyama et al., 2010). Subsequent high-resolution imagery returned by the Lunar Reconnaissance Orbiter Camera (LRO/LROC) (Robinson et al., 2010) was then used not only to provide more detailed views of the pits discovered by Haruyama et al. (2009, 2010), but also to identify 150 additional pits at the lunar surface (Robinson et al., 2012). Overall, these openings are found to have widths ranging from 49 to 106 m, which represents a minimum size for the underlying void, and oblique views of the pits do show that the underlying cavern is wider than the hole in the surface in at least several cases (Ashley et al., 2011; Wagner and Robinson, 2014). Voids may also exist in areas such as the Al-Tusi impact melt pond near King Crater on the lunar far side, where skylights and sinuous fracture patterns have been found in high-resolution LROC images (Ashley et al., 2012), suggesting a lava tube collapse. Unfortunately, the size and shape of a void cannot be determined by the use of imagery alone (e.g. Robinson et al., 2012).

Gravity data, however, is particularly suited to the identification and characterization of subsurface density variations such as vacant lava tubes. Work by Chappaz et al. (2014a,b, 2016) and Sood et al. (2016a,b) has shown that lava tubes, buried craters, and other density anomalies can be located and characterized in the high-resolution datasets returned by NASA's Gravity Recovery And Interior Laboratory (GRAIL) mission (e.g. Zuber et al., 2013; Lemoine et al., 2014). Using a combination of techniques such as gravity anomaly Eigenvalue mapping, cross-correlation between observed gravity signals and those of hypothetical features, and forward modeling of the gravity anomalies caused by lava tubes, Chappaz et al. (2014a,b, 2016) have found possible sublunarean extensions of surface sinuous rilles at both Vallis Schröteri and Rima Sharp. In both cases, GRAIL observations were found to positively correlate with a buried tube 1–2 km in width. The depth and shape of these putative lava tubes cannot be explicitly determined from gravity data, however, as a tube even several hundred meters under the surface would produce a nearly identical GRAIL-observable gravity signature to one sitting centimeters under the surface since in both cases the spacecraft's altitude would be much greater than the feature's depth. While a collection of smaller lava tubes could also produce a gravity signature that would match GRAIL observations, the general pattern of volcanic flows on the Moon is one characterized by a relatively small number of high-volume flows. The interpretation favored here and in Chappaz et al. (2014a,b, 2016) and Sood et al. (2016a), therefore, is that these gravity anomalies are each caused by a single, large vacant lava tube buried at some non-zero distance under the surface.

The size of the lava tubes inferred by Chappaz et al. (2014a,b, 2016) is much larger than any known terrestrial examples, which reach a maximum of ~30 m in width (e.g. Greeley, 1971). Oberbeck et al. (1969) addressed the question of how large a lava tube could be on the Moon and remain structurally stable by modeling the roof of a lava tube as an elastic beam. Doing so, they found that a lava tube with a roof 65 m thick could remain stable at a width of $\lesssim$ 385 m, given a lunar basalt density of 2500 kg m^{-3}. They also suggest that lava tubes up to 500 m wide may be possible under lunar conditions, a number which has been frequently cited since that work was published; that calculation, however, uses a hypothetical vesicular basalt density of 1500 kg m^{-3}, well below the 3010–3270 kg m^{-3} density of that material which is now known from modern re-analysis of Apollo mare samples (Kiefer et al., 2012). Furthermore, while Oberbeck et al. (1969) mention that an arched roof would allow a larger stable tube or a thinner possible roof at a given tube width than the beam model used in their study, they do not quantify that effect.

In this study, we aim to constrain the maximum size at which vacant lava tubes could remain structurally stable under lunar gravity. More specifically, we seek to determine whether the large lava tubes inferred from analysis of GRAIL data by Chappaz et al. (2014a,b, 2016) are mechanically plausible, leaving aside the mechanisms for forming tubes of that scale. Our methods incorporate numerical modeling techniques of a scale not available to investigations of similar questions performed during the Apollo era, as well as modern knowledge about the densities of lunar rocks and the behavior and failure mechanisms of large rock bodies in general.

2. Modeling techniques

We approach the question of lava tube stability through the use of finite element models built in the *Abaqus* software suite (version 6.12; http://www.simulia.com/solutions). Our models assume plane-strain conditions and are symmetric about the tube's longitudinal axis for the sake of computational simplicity. Models were verified against analytic results for simple cases (e.g. gravitational self-compression of a block) and were found to be accurate to within 1%. Zero-motion boundary conditions are set at the far lateral and bottom edges of the model, which are placed sufficiently far away (20 tube widths) so as not to influence our model results. In every model, we ensure that there are 20 elements through the thickness of the lava tube's roof, and then adjust other mesh parameters to ensure suitable element aspect ratios (< 10:1). Our general model setup and an example mesh are shown in Fig. 1. We do not model the formation of the lava tube itself, but instead investigate the stability of the completed structure under various potential lunar conditions.

The primary variables in this study are the width of the lava tube, the thickness of the lava tube's roof, and the pre-existing stress state of the material. The shape of the tubes is held at a constant 3:1 width-to-height ratio, mimicking the general non-circular arched shape of terrestrial lava tubes while remaining somewhat close to the circular cross-section used in Chappaz et al. (2014a,b, 2016) such that our models do not grossly over-predict the width of the tube responsible for a particular gravity deficit. The fixed aspect ratio also means that we are varying the tube's volume linearly by adjusting only the width, which is useful for comparison with analyses of GRAIL data since these scales with the volume of the void space. While this single aspect ratio cannot represent the various lava tube shapes on the Moon or elsewhere, focusing on a single shape also enables efficient exploration of parameter space in terms of width, roof thickness, and initial stress state (see next paragraph). Because these structures are buried, the roof thickness is in one sense equivalent to the depth to which a lava tube has been buried by one or more flows after its initial formation. It can also be considered as the thickness of the thinnest layer within the lava tube's roof, however, by analogy to terrestrial caves in bedded rock which tend to collapse when individual beds start to fail (e.g. Ford and Williams, 1994; Palmer, 2007). We therefore test a range of roof thickness values from 1 to 500 m that includes both the range of layer thicknesses seen in the walls of lunar skylights (~1–12 m) (Robinson et al., 2012) and a thickness comparable to the larger flows in Oceanus Procellarum (~600 m) (Wieder et al., 2010). Our modeled lava tube widths range from 250 m to 10 km, representing a size slightly smaller than the maximum size calculated by Oberbeck et al. (1969) and the approximate present-day width of the widest part of Vallis Schröteri, respectively. With our assumed width-to-height ratio, this range also includes lava tubes with heights similar to the ~100–150 m depths of observed skylights.