**IMPACT-GENERATED POROSITY AT DEPTH WITHIN THE LUNAR CRUST.** S. E. Wiggins\(^1\), B. C. Johnson\(^2\), G. S. Collins\(^3\), T. J. Bowling\(^3\), H. J. Melosh\(^4\), and E. A. Silber\(^1\). \(^1\)Department of Earth, Environmental, and Planetary Sciences, Brown University, 324 Brook Street, Providence, RI 02912, USA. (Sean_Wiggins@Brown.edu). \(^2\)Department of Earth Science and Engineering, Imperial College London, SW7 2BP, UK. \(^3\)Southwest Research Institute, 1050 Walnut Street, Boulder, CO 80304. \(^4\)Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, Indiana 47907, USA.

**Introduction:** Constraining the extent and magnitude of porosity created from impacts within the crust of differentiated bodies is crucial for understanding their thermal and magmatic evolution [1]. Here we focus on the Lunar highlands, a relatively pristine example of an early planetary crust. Recent investigations into the structure of the Lunar crust using GRAIL data have revealed that the crust is \(~\text{12\%}\) porous down to several kilometers and exhibits a significant porosity of \(~\text{5\%}\) down to a depth of \(~\text{20\ km}\) [2,3]. In previous lunar impact simulations, porosity has only been created during crater collapse through shear failure, neglecting the creation of porosity due to pure tensile failure [4]. Although these simulations [1] may explain observed residual Bouguer anomaly of craters [5], they do not produce porosity at depths much greater than the transient crater depth. Here we employ a method to compute the creation of porosity due to tension in combination with an implementation of the Grady-Kipp fragmentation model [6,7] to examine how tensile failure influences the creation of porosity at significant depths within the Lunar crust.

**Methods:** We simulated spheroidal basalt impactors striking a Moonlike target at 15 km/s using the iSALE-2D shock physics code [8,9,10]. We varied the diameter of impactors from 1 km to 10 km, while keeping a resolution of 10 cells per projectile radius. We use the ANEOS equations of state of basalt for both the impactor and the target [11]. The Weibull parameters used for the Grady-Kipp fragmentation implementation are \(k=10^{10}\) and \(m=9.5\) [6]. We estimate porosity generation using both the dilatancy model of [5] and a new routine that estimates fracture porosity created in tension. When material goes into tension, a common approach in shock physics codes such as iSALE is to cap the (negative) pressure at the minimum pressure determined by the material strength envelope, but leave the material density unchanged and hence thermodynamically inconsistent. The basic principle behind the new tensile fracture porosity routine is to insert porosity into material under excess tension, whilst keeping the bulk material density (and mass) constant. This raises the density and pressure in the solid component, relieving tension in the bulk. The amount of porosity inserted is sufficient to increase the bulk (negative) pressure to lie on the (strain-rate dependent) yield envelope.

**Results:** The expanding shock wave that is produced by an impact is followed by a release wave, known as the rarefaction wave. The rarefaction wave can produce tensile stresses within the target material which generates porosity as material fragments. Tensile hoop stresses are also generated as material moves outward away from the symmetry axis. Fig. 1A & 1B (1 km diameter impactors, with and without the new routine, respectively) show hemispherical zones where material was tensionally damaged by the rarefaction wave. The zones are characterized by a rapid decline of porosity with depth. In Fig. 1A the near-surface areas have porosity of \(~\text{10\%}\), whereas the porosity at a depth of several projectile diameters ranges from \(~\text{0.01\%}\) to \(~\text{0.1\%}\). In Fig. 1B, however, the porosity is low at the surface, decreases rapidly with depth, and hits the minimum porosity of \(~\text{0.01\%}\) at much shallower depths compared to Fig. 1B. Fig. 2A & 2B (10 km diameter impactor, with and without the new routine, respectively) highlights the importance of overburden pressure and its effect on the creation of porosity at significant depths. Unlike the smaller diameter runs the 10 km diameter impactor run lacks a hemispherical zone of porosity, because the compressive overburden pressure is too large for the rarefaction wave to overcome and cause tensile failure. However, the 10 km diameter impactor is still able to create porosity on the order of \(~\text{0.1\%}\) down to depths of \(~\text{100\ km}\). Both Fig. 1 & 2 highlight the importance of tracking porosity created solely in tension, as the new routine generates porosities an order of magnitude higher than previously simulated at significant depths.

The 1 km impactor diameter simulations produce low porosities to depths of \(~\text{20\ km}\). This is significantly deeper than porosity created during transient crater collapse. Since this porous material is relatively deep and only created by tensile forces, porosity is unlikely to be crushed out by successive impacts, as is the case for shallow shear induced porosity. Therefore, we propose that the high porosity within the lunar crust may be replicated using a combination of Grady-Kipp fragmentation and the new tensile porosity routine with successive impacts or an already porous target. This would bridge the gap that currently exists in hydrocode simulations and estimates of porosity as a function of depth based on GRAIL data. Future work will focus specifically on
successive impacts and a pre-impact porous target to test the hypothesis that tensionally created porosity at depth is additive. By taking the results of that future work and combining it with a cratered terrain evolution model (CTEM) model such as the one given in [13] the porosity profiles obtained from GRAIL data may be replicated, thus demonstrating a process that can create significant porosity at depth. Further work will be done to identify the exact sources of tensile stresses that damage material, such as the rarefaction wave or hoop stresses. Better understanding the source of tensile stress can help map out stress fields which can then be compared with terrestrial crater fracture patterns [14].


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Figure 1 (Above). Material colored according to porosity. The 1 km impactor diameter simulations with and without the new tensile porosity routine are given in A and B respectively. The grey colored material is material with 0% porosity.

Figure 2 (Below). Material colored according to porosity for the 10 km diameter impactor simulations with and without the new tensile porosity routine (A & B respectively). The grey colored material is material with 0% porosity. The shape of the porosity fields are different than those shown in Fig. 1 due to the greater influence from compressive overburden pressure.