NUMERICAL MODELING OF THE SOUTH POLE-AITKIN IMPACT. G. S. Collins[1] and H. J. Melosh[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA (email: gareth@lpl.arizona.edu).

Introduction: The South Pole-Aitkin (SPA) basin, on the far side of the Moon, is the largest and oldest impact structure still preserved in the solar system (Fig. 1). The crater is about 2500 km in diameter [1] and formed in the Pre-Nectarian era of lunar history, over 4 Gyr ago. At this time, the thermal state of the Moon was much hotter than it is today. Accretional energy from the rapidly forming Moon melted the outermost few hundred kilometers of the Moon. As this magma ocean differentiated and cooled a 60—100-km thick low-density crust formed at the surface; below this the residual melt, with a higher density, cooled to form the lunar mantle.

The giant SPA impact event punctured the Moon some time during the cooling of the magma ocean and thus provides a unique window for studying the lunar interior and the early formative processes of the Moon. The impact excavated otherwise inaccessible samples of the deep crust and (possibly) upper mantle, which has inspired proposed sample return missions. Furthermore, the thermal and rheologic state of the early Moon played a role in shaping the final structure of the basin. To aid in site selection for future sample return missions to the SPA basin, and to investigate the effect of thermal state on final crater structure, we performed some numerical simulations of the SPA impact event.

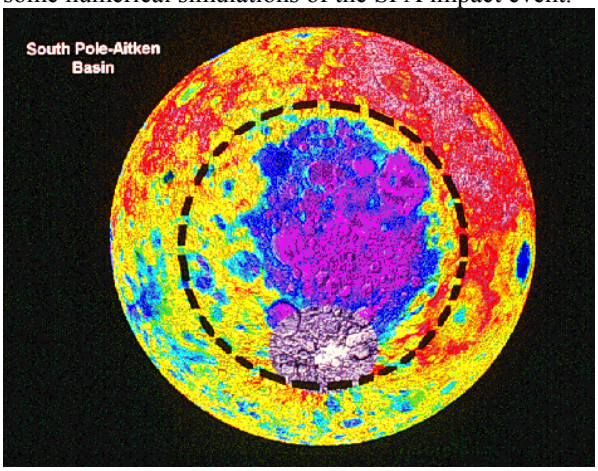

Figure 1: *Clementine topography image of the SPA basin. Purple is low; white is high. (Picture courtesy of NASA: the Clementine Project* [3]*).*

Previous Work: Despite the geologic significance of the SPA impact basin, little is known about this crater. Indeed, it was only recognized as an impact basin in the mid-70s, ten years after the first photographic and altimetry data from the lunar farside were obtained. Analysis of the pristine SPA crater morphology is extremely difficult due to its degradation; a plethora of subsequent impacts have scarred the surface and redistributed material in the interior of the basin. However, Clementine topography data show that much of the basin is now ~8 km below the Lunar geoid, and 3 possible ring structures are suggested [2]. The depth of the SPA basin is somewhat (~2 km) greater than that predicted by the depth/diameter relationship for other, well-imaged, smaller lunar basins [4]. However, the SPA basin is four times larger than the next largest lunar basin used in this study; hence, it is unclear whether the SPA basin is anomalously deep or not. The great depth of the SPA basin led several authors to conclude that negligible viscous relaxation of the impact basin has occurred [4, 5]. Although sparse, gravity data suggest that the basin is almost in isostatic equilibrium.

Numerical Modeling: We used the SALEB multi-material, multi-rheology hydrocode [6] to simulate the impact event that caused the SPA basin. Our models assumed a spherical Moon, 1738 km in radius, comprising an 80-km thick crust above a compositionally uniform interior. We used the ANEOS equation of state for granite (ρ =2.68 g/cc), to represent the crustal material and that for dunite (ρ =3.3 g/cc) to represent the lunar interior. Both whole-Moon, and half-space simulations were performed. In both cases, various temperature profiles with depth were investigated, from cases where a thin sub-crustal layer was at or close to the dunite melting temperature (magma ocean) to colder cases closer to estimates of the modern lunar geotherm [7].

Results: The resolution of our preliminary simulations (cell size = 5-10 km) precludes accurate analysis of the final crater morphology; for example, final crater depth, or identification of distinct structural rings. However, several important and insightful results are observed in our simulations. The assumed thermal state of the lunar interior in our simulations has a profound effect on the rheology of the target and, consequently, the structure and development of the impact crater. In general, the warmer the interior of the Moon, the weaker the target and hence the smaller the energy of the impact event required to generate the 2500-km final crater.

Figure 2 shows final crater profiles from two SPA impact simulations with different thermal states: a "hot" case, where the magma ocean has not fully cooled (Fig. 2a) and a "warm" case, where the magma ocean has completely cooled (Fig. 2b). In both cases, such an enormous volume of melt is generated that the central uplift is predominantly melt, or melt-rich material. This material flows off the central uplift during

collapse, filling much if not all of the basin with melt/melt-rich breccia.

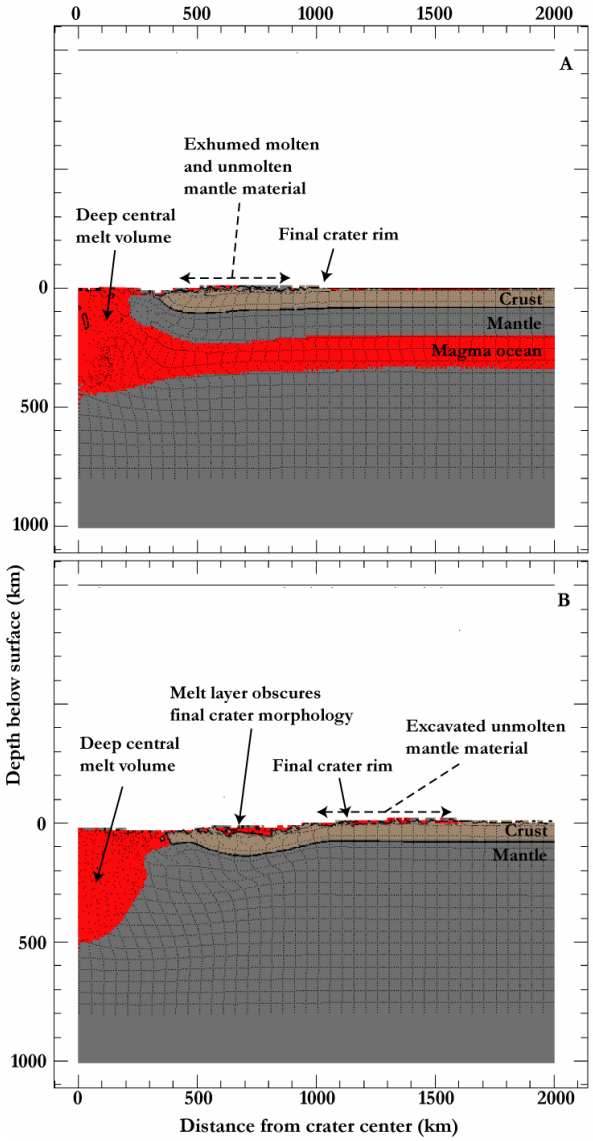

Figure 2: *Final crater structure from two simulations with different thermal states: a "hot" case, where the magma ocean has not fully cooled (A) and a "warm" case, where the magma ocean has completely cooled (B).*

The impact into the "hot Moon" required to form a final crater ~2500-km in diameter is much less energetic than that into the "warm Moon". The transient crater diameters for the two simulations are ~600 km and ~1000 km respectively. However, both events are energetic enough to strip all crustal material from the inner crater, and exhume mantle material and deposit it on the lunar surface. In the "warm Moon" case, the impact event is large enough that it excavates through the crust into mantle material, which is thrown out of the crater and deposited around the final crater rim. In the "hot Moon" case, the smaller impact event does not excavate below the base of the crust; however, mantle material is uplifted as part of the central uplift and then deposited onto the surface as the central uplift collapses back downward and outward.

Discussion: A reasonable model for the formation of the SPA basin can be obtained with a range of possible internal thermal states for the Moon, provided the energy of the impact is modified. More detailed numerical simulations and higher quality observational data are required to distinguish between different thermal states and the resulting crater structures. Nevertheless, several robust conclusions may be drawn from this study.

Our simulations suggest that immediately after impact, a deep and broad melt pool of predominantly mantle material lay in the inner region of the SPA basin. Outside of this, molten and unmolten mantle material, from either the collapsing central uplift or part of the ejecta curtain, smeared the floor of the crater. Below this lay inwardly-slumped, heavily fractured crustal material.

The removal of low-density crust in the crater center, which is observed in all our simulations, implies that the isostatic state of the final crater is deeper than that predicted for a uniform density target. Isostatic mass balance analysis inside and outside of the crater predicts that, for a crustal thickness of 80 km outside the basin and no crust inside the basin, the depth of the crater would be ~15 km. This is significantly greater than the observed crater depth; however, differentiation of the melt volume in the crater center would generate a low-density ceiling to the melt body, which could lower this value to agree with observation. Thus, we suggest that the current depth of the SPA basin is a direct result of the cratering process itself and does not preclude viscous relaxation.

Acknowledgements and References: We thank Boris Ivanov for developing SALEB. The financial support of NASA grant NAG5-11493 is gratefully acknowledged. [1] Wilhelms D. E. (1987) *The Geologic History of the Moon*. U.S. Government Printing Office, Washington, D. C. [2] Hiesinger H. and Head III J. W. (2003) Vernadsky/Brown Microsymposium 38, Abstract # MS101. [3] http://nssdc.gsfc.nasa.gov/planetary/clementine.html [4] Williams K. K. and Zuber M. T. (1997) *Icarus, 131*, 107-122. [5] Solomon S. C., Comer R. P. and Head J. W. (1982) *J. Geophys. Res. 87*, B5 3975-3992. [6] Ivanov B.A. and Artemieva N. (2002) In: *Catastrophic Events and Mass Extinctions: Impact and Beyond*. Geological Society of America, Special Paper 356: 619-630. [7] Solomon S. C. and Toksöz M. N. (1973) *Phys. Earth Planet. Interiors, 7*, 15-38.