Impact Cratering: Relationship to Geological History of the Terrestrial Planets and Future Exploration Goals.

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In the first 50+ years of lunar and planetary exploration we have learned a substantial amount about the process of impact cratering, the manner in which it influences other processes, and the way impact craters can be used as probes and tools for understanding planetary evolution. In the early days of exploration there was a huge debate about the impact versus volcanic origin of lunar craters. This was quickly resolved by early results from field investigations and the Apollo missions, and subsequent exploration focused on the nature of the impact process through sample analysis and geological mapping of planetary landforms and surfaces. Also wildly uncertain were the ages of the major lunar surfaces, due to a poor understanding of the impact flux. Radiometric ages for the Apollo 11 basalts and crater counts for the surfaces began a long history of using impact craters as a tool to document lunar and planetary historical events as recorded in units that retained craters whose size-frequency distributions could be established. Samples collected from the Apollo landing sites provided ages for multiple surfaces spread over a significant part of the emplacement history of the maria. Unsampled were relatively young surfaces (less than ~3 billion years) and thus the details of the flux (and the absolute ages of units) remain tentative, and compelling arguments about changes in flux, or inferences about the waning and cessation of lunar volcanism continue to be speculative. Surprisingly, even the formation of the lunar crust (the magma ocean) was found to be related to impact processes and the very origin of the Moon was found to be due to the impact of a Mars-sized object into early Earth.

Variations in the nature of impact craters as a function of size quickly became a focus of study, with simple and complex craters, peak ring and multi-ring basins, and transitional landforms being described and interpreted. Extensive studies of terrestrial craters, experiments at the NASA Ames Vertical Gun, analysis of lunar samples, and quantitative modeling of the cratering process, all contributed to the fundamental understanding of the process, and how it varied with scale, velocity, angle of impact, projectile composition and target substrate. The large impact basins continued to fascinate workers because of their scale, approaching planetary radii, and the devastating influence they surely had in excavating material, melting huge quantities of rock, redistributing it to resurface hemisphere-scale areas, raising geotherms tens of kilometers and melting, if not excavating, sub-crustal mantle material. Improved equations of state made hydrocode models more realistic, and improved spatial and spectral resolution data image and spectroscopy data permitted cross-checks on observations and models. The advent of extremely high resolution gravity data (the GRAIL mission) “put the lunar crust in an x-ray machine” so that the subsurface structure of impact craters and basins could be observed. Furthermore these data confirmed that the lunar crust consisted of an impact-produced megaregolith, but further showed that the crust was fractured to great depth.

What was the nature of the lunar crust? Impact craters began to be used as drill holes to probe the crust and mantle by assessing the spectroscopic character of craters and basin, their ejecta and central peaks. These data served to establish the structure of the lunar crust and compare to models for magma ocean solidification and subsequent intrusion.

The degradation state of impact craters of all scales was used to assess relative chronology, and the processes, including impact cratering itself and volcanism, that were active in crater modification. The degradation state of smaller craters was used, in conjunction with models, to further assess the age of surfaces. The nature of impacts in cratering experiments in layered targets provided insights into the thickness of the regolith overlying mare basalts, and the development of regolith with time.

Cratering provided insights into the nature of the ascent and eruption of magma on the Moon. Volumes of extruded magma and the thickness of lava flows could be inferred from impact crater rim heights and depth diameter relationships, and the brecciated substructure of impact craters often resulted in intrusion of sills below the crater floor that uplifted and deformed the floor to produce floor-fractured craters. Impact basins served as huge depressions to accumulate lunar lavas, and basin structure was often called on to act as a contributing factor in the location of volcanic vents and deposits.

New insights into the role of the mode of emplacement of crater ejecta and secondary and tertiary cratering resulted in an increased awareness of the fact that ejecta can excavate many multiples of its own mass, and that the ejecta deposits are not simple "blankets", but a combination of primary and secondary/tertiary ejecta that changes as a function of increasing distance from the ejecta origin. The role of secondary craters in "polluting" the primary impact flux has become clear and attention to this factor is critical in the proper interpretation of impact crater size-frequency distribution age data.

These lunar-centric results have played out on other planets and satellites in the Solar System, and we have used the different characteristics and environments of these bodies to help understand the importance of a variety of variables. We have learned a lot about the cratering process and the use of impact craters in the first 50+ years of lunar and planetary exploration. How do these results inform us of the challenges and exploration goals for the future?

Future Exploration Goals: Among the many goals for future analysis and exploration are the following:

1) Dating Younger Surfaces and Nailing Down the Flux: Important goals are to date *in situ,* or return samples from, a variety of surfaces suspected to be in the younger portion of planetary history, and to fill the gaps in between others. Multiple targeted missions could accomplish these objectives. A very wide variety of lunar and planetary surfaces are available for exploration.

2) Understanding Impact Melt: What are the processes and scale-dependence of impact melting formation and evolution? Did Orientale and larger basins form impact melt seas? And if so, how much did they differentiate? Sample return missions to South Pole-Aitken and other basins would help address this question.

3) What is the Flux in Earliest History and What was the Nature of the Impactor Population(s)?: Targeted sample return missions to critical places on the Moon could establish the flux and also assess the nature and reality of the late heavy bombardment hypothesis

4) The Nature of Complex Craters: Targeted human and robotic exploration of Copernicus and Tycho would provide huge returns in all areas associated with the cratering process. Detailed mapping and sampling of central peaks, impact melts, crater rim deposits and ejecta, and the geophysics of the deeper structure, could provide a reference frame for the cratering process at these scales for application throughout the Solar System.

5) The Nature of Multi-Ring Impact Basins: Now is the time for a concentrated attack on the geology, petrology, mineralogy, geophysics and geochronology of a major impact basin. Apollo-scale human exploration sorties, coupled with robotic interpolation and extrapolation could accomplish this goal. A McMurdo-like lunar base within the Orientale basin could enhance this scientific exploration of the most well-preserved basin-scale structure in the Solar System.

The Moon is a nearby laboratory for the study of the impact cratering process and its relationship to the history of the Solar System. The next 50 years of exploration must concentrate on this goal.