The lunar Apollo missions: Enabling dating of planetary surfaces throughout the Solar System H. Hiesinger, Institut für Planetologie, Westfälische Wilhelms-Universität, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany (hiesinger@uni-muenster.de).

Introduction and Background: The Apollo missions were fundamentally important for understanding the stratigraphy of geologic events on the Moon and for dating planetary surfaces at least in the inner Solar System. Detailed investigations of the lunar surface have led to the definition of time-stratigraphic systems, i.e., the pre-Nectarian, Nectarian, Imbrian, Eratosthenian, and Copernican System [e.g., 1] that allow us to decipher the geologic record of the Moon and understand its history and evolution. Using the ejecta deposits of impact craters as a stratigraphic marker horizon similar to fossil beds on Earth, it is possible to construct a moon wide relative stratigraphy by investigating the superposition relationships of ejecta deposits [e.g., 2]. Additional application of the superposition criteria to mare basalt units [e.g., 3-5] provided relative ages for the entire lunar surface.

The Moon is unique in that it has been visited by 12 astronauts who carefully selected almost 400 kg of lunar samples and characterized in detail their geologic context. Together with the robotically collected samples of the Soviet Luna missions, these samples allow us to ground truth remote-sensing data of the landing sites (e.g., crater size-frequency distributions (CSFDs), crater degradation, mineralogy, composition) with well-documented samples that have been investigated and dated in great detail and with high accuracy in terrestrial laboratories [e.g., 6,7]. This opens an avenue of research that is only possible for the Moon for which we have samples from well-characterized landing sites. Although we have samples from Mars (SNC meteorites), the asteroid Vesta (HED meteorites), and likely several other unmatched parent bodies, we do not know specifically from where those meteorites were launched off the surfaces of their parent bodies, making it impossible to link their radiometric ages with CSFDs, i.e., to directly derive chronology functions for other planetary objects. Thus, understanding the lunar impact history and its extrapolation to other bodies is crucial for our understanding of the history and evolution of other terrestrial planets and possibly the entire Solar System, thus underlining the importance of the Apollo and Luna samples.

The calibration between landing site remote-sensing observations and samples enables us to derive absolute model ages (AMAs) and to extrapolate age determinations and compositional analyses to any area on the Moon covered by appropriate remote-sensing data. One fundamentally important result of such a calibration was the derivation of the lunar chronology function (CF) that links the cumulative CSFD at a certain reference diameter with the radiometric and exposure ages of lunar samples [e.g., 8-15]. This derivation of the lunar chronology function and its extrapolation to other planetary bodies is crucially important for the understanding of the Solar System. In fact, it enables us to not only study the geology of unsampled regions on the Moon, but also to date surfaces on other planetary bodies.

The Moon is also unique in that it allows us to study impact processes from mm-scale (craters on glass beads) to the largest impact basin in the Solar System, the 2,400 x 2,050 km South Pole-Aitken basin [16]. This is possible because we have samples and both high-resolution images taken by the astronauts on the surface, as well as images of the Apollo Metric and Panchromatic Cameras, the Lunar Reconnaissance Orbiter Camera, and the Kaguya Terrain Camera. Thus, we can determine the size-frequency distribution of impact craters on the lunar surface across a wide range of diameters, i.e., the lunar production function. Like the chronology function, the production function is of great importance because it describes the expected crater size-frequency measured on a geologic unit at a specific time, and is, when scaled, similar for all planetary bodies, that were exposed to the same projectile population, at least within the inner Solar System [e.g., 17-28].

The CSFD dating method generally yields robust results, but there are still several open questions related to the technique. For example, there is debate on the exact shapes of the production and chronology functions [e.g., 15], the existence of a lunar cataclysm [e.g., 29, 30], whether the lunar derived production and chronology functions can be extrapolated to the asteroid belt [e.g., 31] or the outer Solar System [e.g., 32], and on the effects of (self-)secondary cratering and target properties [e.g., 33, 34].

Selected results: On the basis of the lunar samples and the development of the CSFD dating method, many new insights into the history and evolution of the Moon became possible. For example, the application of the CSFD method allowed us to better understand the volcanic record of the Moon by systematically dating lunar mare basalts [e.g., 14, 35-36]. From these studies it became clear that the Moon was volcanically active for more than 3 Ga until about 1.2 Ga ago. The young basalts occur in the Procellarum KREEP terrain (PKT) that shows enhanced thorium concentrations. Provided the surface distribution of thorium reflects that of the mare basalt source regions, the higher thorium concentration might have allowed for late-stage eruptions in these regions while volcanism ceased earlier in colder regions of the Moon. Heavily debated are the ages of irregular mare patches that are either less than 100 Ma old [37] or as old as 3.5 Ga [38], although their crisp morphology seems to favor a relatively recent age. In addition, absolute model ages (AMAs) could be derived for volcanic constructs, i.e., domes that imply more silicic lava compositions and pyroclastic deposits [e.g., 39,40], both expanding our understanding of the lunar volcanic record.

The method also allowed us to better understand the tectonic history of the Moon. For example, based on LROC images more than 3000 small-scale lobate scarps have been identified and some of them have been dated [41-46]. The distribution and recent ages of these scarps imply that the Moon was deformed by tidal forces and the shrinking of the Moon within the last <100 Ma [41-46].

Finally, individual impact craters have been dated, which allows a better understanding of the local/regional stratigraphy by defining important stratigraphic benchmarks. For example, we now have AMAs for Jackson, Tycho, Copernicus, North Ray, Cone, King and many other craters [e.g., 47].

Conclusions: Even after 50 years, the Apollo missions and the returned samples are invaluable sources of information that enable new and exciting research with fundamental implications for our knowledge about the Moon. Thus, future lunar missions should thrive to return new samples, particularly from the South Pole-Aitken basin and should ultimately return humans to the Moon to continue the extremely successful accomplishments of the Apollo astronauts.

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