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VII. CRITICAL LUNAR QUESTIONS

Lunar stratigraphy

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The lunar scene is a continuous panorama of ancient impact physiography. Multi-ringed circular basins and smaller craters scar the Moon's highlands and provide evidence of a violent early history. Basin formation, the major material-transporting mechanism on the Moon, produces a deep inner depression, one or more benches, a basin rim, and radially lineated ejecta. Study of lunar photographs indicates that, on a relative age scale, subdued basin and crater features are older representations of younger, well-preserved forms. Absolute age dating of returned samples makes it feasible to calibrate this relative age scale. All the larger basins were formed during pre-Nectarian, Nectarian and Imbrian times, i.e. 4.6–3.9 Ga ago.

Following this major sculpturing episode, and during the Imbrian and Eratosthenian times, mare volcanism became the most important mode of deposition of lunar surface materials. Basaltic lavas from deep-seated sources flowed to partially fill the impact basins and cover their peripheral troughs and surrounding lowlands between 3.8 and 3.2 Ga ago. This occurred more frequently on the near side than on the far side, probably because the farside crust is thicker. During the past 1 Ga, i.e. Copernican time, only a small number of craters were formed in both highland and mare rocks.

Successes and failures of photogeologists in studying lunar stratigraphy provide the necessary lessons for understanding the geological history of the terrestrial planets. This is particularly true since both Mars and Mercury display many types of features in common with the Moon.

Introduction

The basic stratigraphic principles that have been successfully applied to the Moon are in some respects similar to those used on Earth. On the Moon (see El-Baz 1974), surface unit A is interpreted to be younger than unit B if unit A overlies B, if A cuts across B, or if A displays fewer craters of probable impact origin than unit B. In the past few years, problems of lunar stratigraphy did not arise from the application of these principles, but from misinterpretations of lunar surface morphologies.

Photographs and images taken by Luna, Lunar Orbiter, Zond, and Apollo indicate that the Moon is a well preserved museum of impact physiography. The global morphology of the Moon is controlled by the large features of impact origin known as multi-ring circular basins (figure 1). Materials of those basins and smaller craters compose most of the lunar terrae. Mare materials, of later volcanic origin, are concentrated in the basins, in their peripheral troughs, and in the nearby lowlands.

Thus, the main surface sculpturing mechanisms on the Moon appear to be meteoroid bombardment and the downslope movement of fine-grained debris from higher to lower levels, aided by tectonic and/or seismic shaking. In practice, this means that a study of fresh-appearing and young-looking features can help in understanding relatively older or more subdued forms.

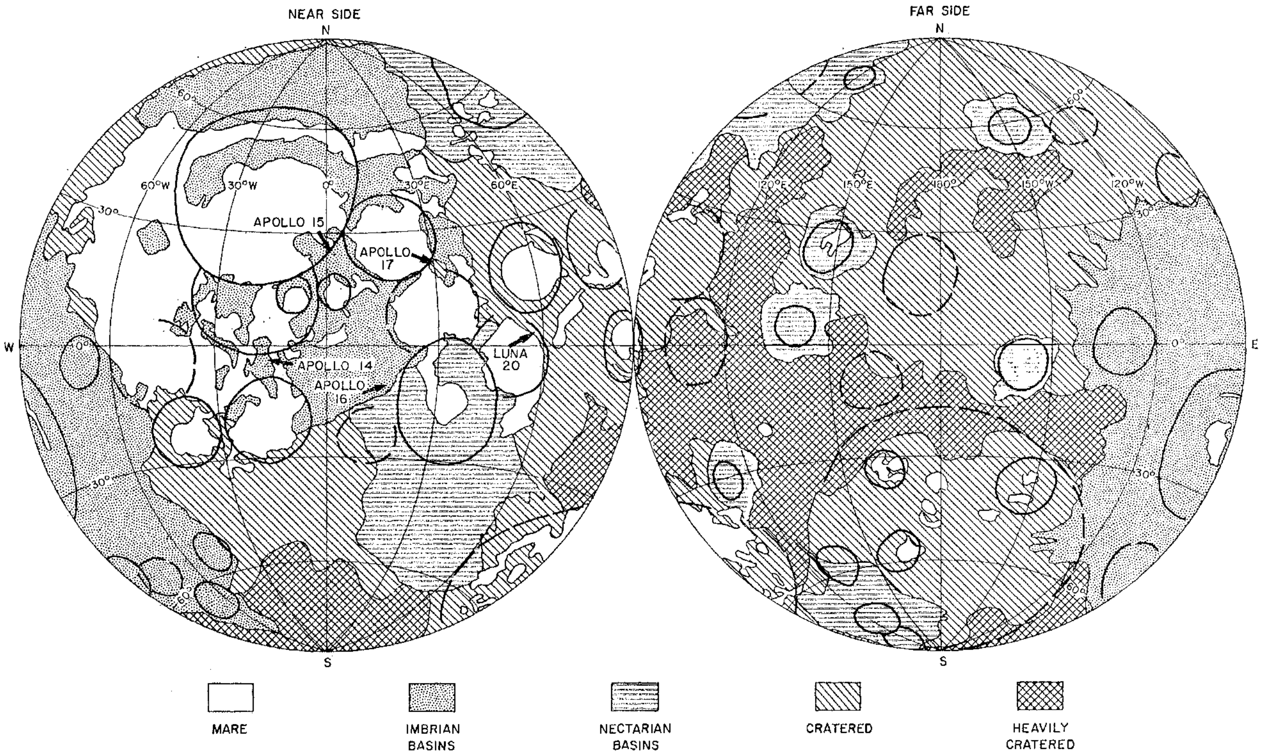

FIGURE 1. Thematic map of the major geologic provinces of the Moon. The map clearly shows that lunar physiography is controlled by the large, circular basins and their overlapping ejecta blankets. Mare materials are enclosed within the circular basins and their peripheral troughs. Note an asymmetry in the distribution of maria; more on the near side than on the far side. (After Howard *et al.* 1974.)

DISCUSSION

Although lunar stratigraphy is a relatively new field, several attempts have been made to classify features by relative age according to topographic and morphologic characteristics. The basic lunar stratigraphic sequence was first developed by Shoemaker & Hackman (1962) in an area that includes the southern part of the Imbrium basin. This sequence was later modified and applied to most of the near side of the Moon by the U.S. Geological Survey as summarized by McCauley (1967), Wilhelms (1970), Wilhelms & McCauley (1971), and Mutch (1972). Also, it was recently realized that the nearside lunar stratigraphy could be extended, with modifications, to the far side as well (El-Baz 1975).

The Moon-wide, time-stratigraphic sequence in order of decreasing relative ages is as follows:

Pre-Nectarian. All materials formed before the Nectaris basin and as long ago as the formation of the Moon are classed as pre-Nectarian. The majority of pre-Nectarian units are distinguished on the lunar far side. These include materials of very old and subdued basins, and mantled and subdued craters.

Nectarian system. This system includes all materials stratigraphically above, and including, Nectaris basin materials, and up to but not including Imbrium basin strata. Ejecta of the Nectaris basin that can be traced near the east limb region allow recognition of these materials as an important stratigraphic datum for the farside terrae. Some light-coloured plain units, particularly on the far side, are believed to be Nectarian in age.

Imbrian system. A large part of the lunar surface is occupied by ejecta surrounding both the Imbrium and Orientale basins. These form the lower and middle parts of the Imbrian System, respectively. They include the Fra Mauro Formation and several patches of light-coloured plains. Two-thirds of the mare materials belong to the Imbrian System, particularly in the eastern maria of Crisium, Fecunditatis, Tranquillitatis, Nectaris, and the dark annulus of Serenitatis, as well as most mare occurrences on the lunar far side.

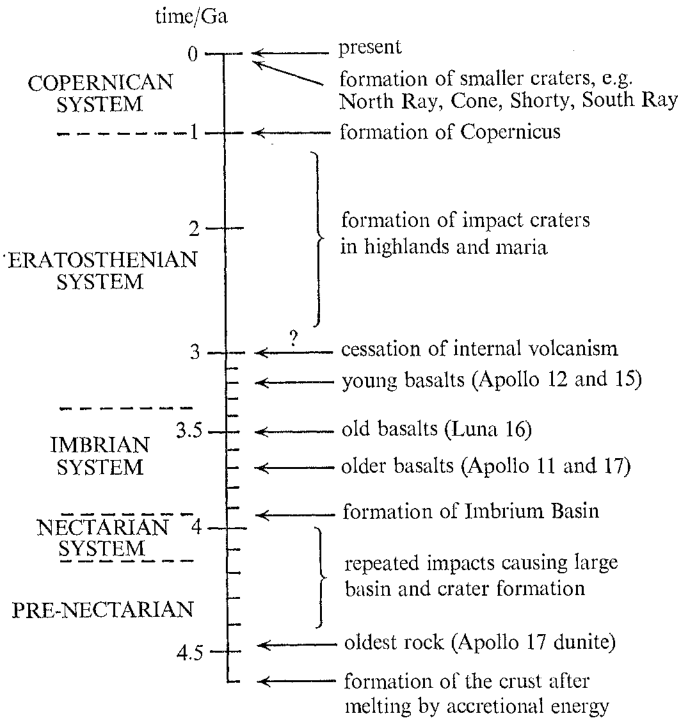

FIGURE 2. Schematic illustration of the evolution of the lunar surface. On the vertical line, the absolute time scale is given in billions of years as deduced from age and exposure dating of rock and soil samples. On the right, major events and eposides of material emplacement are shown; on the left is the lunar-wide, relative age scheme based mainly on photogeologic interpretations (after El-Baz 1975).

Eratosthenian system. This system includes materials of rayless craters such as Eratosthenes. Most of these are believed to have once displayed rays that are no longer visible because of mixing due to prolonged micrometeoroid bombardment and solar radiation. The system also includes about one-third of the mare materials on the lunar near side. These are generally concentrated in Oceanus Procellarum, in western Mare Imbrium, and possibly in the central region of Mare Serenitatis.

Copernican system. This is stratigraphically the highest and, hence, the youngest lunar time-scale unit. It includes materials of fresh-appearing, intermediate to high albedo, bright-rayed craters. The system also includes exposures of very high albedo material on the inner walls of craters and scarps. Brightness in these cases is believed to result from fresh exposure by mass wasting and downslope movement along relatively steep slopes. The Copernician System also includes isolated occurrences of relatively small, dark-halo craters. Although some of these are probably impact craters, others may be volcanic in origin.

Age dating of lunar samples returned by Luna and Apollo missions provided an opportunity for the construction of an absolute age timescale. The relative age timescale discussed above, which can effectively be applied to the entire Moon, may now be calibrated by absolute ages of rock and soil samples. An attempt is made in figure 2 to correlate the relative age scheme, derived mainly from photogeologic interpretations, with the absolute ages of lunar materials as reported by Tera *et al.* (1974).

Based on the model age of lunar soils, the Moon is assumed to have formed about 4.6 Ga ago. This age is comparable to the age of meteorites as well as to the age generally accepted for the Earth.

Little is known about the history of the lunar surface from the time of accretion of the Moon to the time of formation of a solid crust. However, there are indications that global planetary differentiation processes took place within the Moon between 4.6 and 4.3 Ga ago. As the solid crust was formed, it retained a record of the impacts that scarred its anorthositic rocks (pre-Nectarian time). From the time of formation of the Nectaris basin until prior to the formation of the Imbrium basin, many other impact scars were formed, resulting in major redistribution of terra materials (Nectarian time).

The formation of the Imbrium basin at about 3.95 Ga ago initiated the Imbrian System. A later impact created the Orientale basin and its ejecta blanket as well as numerous craters. These impacts also resulted in the deposition of light-coloured plains units, although a volcanic origin for some occurrences cannot be discounted.

Later in lunar history, volcanic eruptions resulted in the deposition of basaltic rocks. These basalts filled the basins and their peripheral troughs in successive flow units varying in age between 3.8 and 3.2 Ga (Imbrian to Eratosthenian time). The post-basalt history includes minor redistribution and mixing of lunar materials, mostly by impact craters, that continue to the present time (Copernican System).

Conclusions

(1) The basic principles of stratigraphy, just as they are applied on Earth, can be used to decipher the history and succession of lunar surface materials.

(2) Although not always possible, stratigraphy should be separated from genetic interpretations of morphological features of the Moon.

(3) The relative age scheme that is based on photogeologic interpretations can be successfully applied to the entire Moon.

(4) This relative age scheme can in part be calibrated by the absolute ages derived from radioactive dating of returned lunar samples.

It must be stated that the geochemical and geophysical sensors flown in lunar orbit on Apollo missions 15, 16 and 17 have provided important information that can profitably be used by lunar stratigraphers. Photogeologic interpretations alone are not sufficient to further develop lunar stratigraphy to maturity.

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