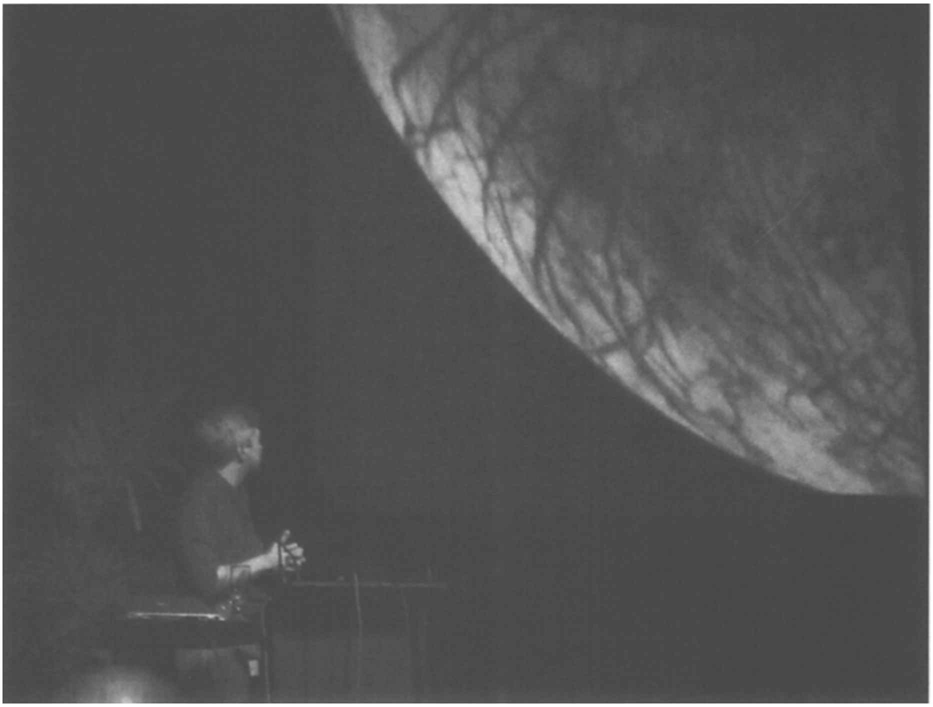
PLANETARY SCIENCE



(*photo: Michael Paine*)

Harrison Schmitt, first scientist to step foot on the moon, and some of those who might follow in his footsteps (*photo: Seth Shostak*)

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Life among the Craters

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1. Introduction

The Moon forms one end-member in the planetary mass series Earth–Venus–Mars–Mercury–Asteroids–Moon (Weissman 1999). Having a detailed understanding of the nature and evolution of the two end-members of this series, rather than of just the Earth, has increased the value of other data and inferences by orders of magnitude. As a consequence of obtaining an understanding of the evolution of a second planet, we now can look at other terrestrial planets with far greater insight than ever would have been possible otherwise (Fig. 1).

The record of impact activity on the Moon, particularly that between about 4.5 and 3.8 Gyr ago, represents a period of Earth history that spans the time when complex organic molecules became replicating life forms (Schmitt 1999; Mojzsis & Harrison 2000) and continents began to form. During the first 300 Myr of this period, the Moon's dry anorthositic crust was saturated with impacts capable of forming craters 60–70 km in diameter. On Earth, the pulverized and partially vitrified crust created by a similar saturation would have continuously reacted with water to create a wide spectrum of clay species (Ferris et al. 1996), the crystal structure of which may have been important as templates for organic synthesis. During this same interval, two and possibly more very large impact basins formed on the Moon, the terrestrial equivalent of which would have been larger and had thick interior melt-sheets due to the melting point suppression effect of terrestrial water. The differentiation of these melt-sheets would have yielded silica-rich disks thousands of kilometers in diameter and possibly tens of kilometers thick that became potential seeds for the aggregation of early continents. The existence of continental crust on Earth has now been placed at least 4.4 Gyr ago (Wilde et al. 2001) and consistent in time with the formation of very large lunar basins.

The next 400 Myr on the Moon saw about 50 large impact events that created basins at least 300 km in diameter plus many more below that size. On Earth, a much larger number of similar events may have delivered additional organic components as well as augmented initial continental material. The global effect, however, of such highly energetic and repeated impacts potentially would have both assisted and disturbed the final development of replicating life forms. In addition to formation of complex molecules in terrestrial environments (Huber & Wächtershäuser 1998), a continuing influx of organic chemicals also may have arrived as constituents of comets (Mumma 1996). Recent isotopic evidence of terrestrial biological processes about 3.8 Gyr ago (Mojzsis et al. 1996) is consistent with the end of large basin formation in the inner Solar System. Thus, the Moon gives us a window into the first one and one-half billion years of Earth history, a period that culminated with the first isotopic indications of biological processes that led to life on our home planet.

2. First Continents

The 2500 km diameter basin on the far side of the Moon (Wilhelms 1987), known as South Pole–Aitken, records an impact of an extraordinarily energetic object near the end of the period of smaller scale saturation cratering that followed the solidification of the lunar crust. South Pole–Aitken is just the most obvious manifestation of possibly four or five other such huge early impacts, including the 3200 km diameter front side basin, Procellarum (Schmitt 2003). On the basis of the degree to which ongoing saturation cratering has affected their impact morphologies, Schmitt (2003) estimates that the more highly degraded Procellarum basin formed at about 4.3 Gyr and South Pole–Aitken at about 4.2 Gyr. If the formation ages for South Pole–Aitken and Procellarum are about right, an explanation is suggested for the recent discovery of detrital zircon ($ZrSiO_4$) crystals of about the same ages in very old sedimentary rocks on Earth (Wilde et al. 2001).

Zircon crystallizes from silica-rich igneous magmas in the late stages of crystallization when zirconium concentrations get sufficiently high due to most other minerals having crystallized. Late stage crystallization also tends to produce other silicate minerals that are characteristic of those that make up the Earth's continents. Early impacts on the continental scale of South Pole–Aitken and Procellarum, as well as possibly others (Wilhelms 1987; Schmitt 2003), occurring in water-rich environments such as the Earth and Mars, would create thick sheets of impact generated rock melt more than 2500 km across and many kilometers thick. As these magma sheets crystallized, zirconium concentrations may have reached levels that produced the zircons. Erosion of these protocontinents would release the zircon crystals for inclusion as sand grains in ancient sediments. As zircons are extremely hard and durable, they can survive several cycles of erosion. The very old terrestrial zircons that have been dated and had their oxygen isotopic ratios determined apparently formed in the presence of water (Mojzsis, Harrison, & Pidgeon 2001; Wilde et al. 2001), consistent with this hydrous impact melt sheet hypothesis.

3. Early Cratering

The suggestion (Tera, Papanstassiou, & Wasserburg 1974) that a "cataclysm" of impacts at about 3.85 Gyr was responsible for the vast majority of craters visible on the lunar surface has gained increasing adherents in recent years (Ryder 1990; Ryder, Koeberl, & Mojzsis 2000). In its most extreme manifestation, essentially all pre-maria impact cratering is attributed to this cataclysm. More modest proposals include only the 50 or so craters greater than about 300 hundred kilometers in diameter. The primary rationale for the cataclysm hypothesis is the almost compete absence of impact glass older than 3.9 Gyr in the Apollo sample collection and in lunar meteorites examined to date. The primary argument against this hypothesis is, of course, possible sampling bias in both the Apollo suite and the lunar meteorites (Schmitt 2001; Chapman, Cohen, & Grinspoon

2002). The possibility for sampling bias comes from the strong evidence that the surface of the Moon has been effectively resurfaced by debris thrown from and affected by the last 10 or more of 50 large impacts. Schmitt (1989) has discussed the clear temporal and geological distinctions between young and old large basins. The fresher-appearing, circular, so-called "mascon" basins (Muller & Sjogren 1968) now represent the last 14 impacts, that is, basins that have undergone little isostatic adjustment since they formed.

Those young large basins for which reasonable ages have been assigned (Wilhelms 1987), that is, Nectaris, Serenitatis, Imbrium, and Orientale, range in age between 3.9 and 3.8 Gyr, also the proposed period of cataclysm. Geologic mapping in the 1960s and 1970s (see Wilhelms 1987) had established that ejecta blankets and effects of secondary ejecta from these 14 impacts were widely distributed around the Moon. This fact has been more recently emphasized by the lunar-wide identification of "cryptomaria" (Bell & Hawke 1984; Antonenko 1999) through mapping the distribution of dark ejecta around small impact craters that penetrate overlying, lighter colored material. These pre-mare basalt volcanic eruptions clearly preceded the formation of the 14 youngest large basins, or they would not have been covered by basin ejecta. The cryptomaria eruptions, possibly the result of pressure release melting following large crater formation, also were temporally associated with and immediately followed the formation of the 35 old large basins, otherwise they would have been destroyed by such events.

Whether there was a 100 Myr-long cataclysm at about a 3.85 Gyr or 400 Myr period of large basin formation between 4.2 and 3.8 Gyr, it is clear that a discrete new source of impactors appeared in the Solar System (Schmitt 1999; Dones 2002). Of particular interest in this regard would be the break-up of the protoplanet of the main asteroid belt, the interaction of the gas giants with the Kuiper Belt, and the disturbance of the Öort Cloud by a passing stellar object. The identification of this impactor source is not only an intriguing challenge but also one with many implications to unravelling the evolution of the Solar System and the terrestrial planets.

4. Clay Minerals and Life

Prolonged and intense impact cratering took place in the inner Solar System from about 4.5 Gyr up to 3.8 Gyr following the solidification of magma oceans and is recorded, directly or indirectly, in existing planetary crusts. These impacts would have produced abundant glassy and pulverized silicate material in the upper several kilometers of those crusts. On the water-rich terrestrial planets, this material would alter rapidly to clay minerals, minerals with great variations in composition, structural dimensions, and environmental niches. Crystal structural patterns of broad variability on the surfaces of the clay mineral grains, possibly in association with sulfide minerals (Huber & Wächtershäuser 1998), may have assisted in the aggregation of complex organic molecules, possible precursors to the first replicating forms of such molecules (Ferris et al. 1996). Indeed, replication may have first been symbiotic with the forms, growth, and/or expansion of clay mineral structures.

The evidence of isotopic fractionation by organic processes associated with 3.8 Gyr terrestrial rocks (Mojzsis et al. 1996) may not be a timing coincidence. The end of the large basin forming events in the inner Solar System, based on lunar data, also appears to be at about 3.8 Gyr. Although simple organic replication, and possibly single cell organisms, may have existed on Earth prior to 3.8 Gyr, the catastrophic effects of large impacts may have prevented significant biological activity until after that time. The cratering history of the Moon has alerted us to the potential pervasiveness of clays on the early crusts of Earth, Mars, and Venus. Mars, therefore, may be the arrested crucible of early organic processes now lost to us on Earth.

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