A Lunar Field Geologist's Perspective 30 Years Later: Shocking Revelations About the Moon, Mars and Earth

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Abstract

A number of conventional hypotheses relative to the Moon and the terrestrial planets deserve both questioning and unconventional thought based on the profound advances in planetary research in recent years. For example, elemental and isotopic data on the lower mantle of the Moon suggest that lunar origin by Giant Impact is unlikely. The apparent existence of a relatively undifferentiated lunar lower mantle indicates that all the terrestrial planets began with a cool chondritic proto-core on the order of 1200 km in radius. The proto-core of Mars may have been catastrophically displaced upwards by metallic core formation and its remnants may reside beneath the Southern Uplands. The terrestrial equivalents of the very large lunar basins, such as South Pole-Aitken and Procellarum, may have seeded the first continents through differentiation of thick, hydrous melt sheets, resulting in the late stage crystallization of zircons 4.4-4.2 billion years ago. Sampling of impact glasses indicating an apparent lunar cataclysm ~3.85 billion years ago may have been biased by late, young large basin-forming impacts that resurfaced the crust. Clay minerals probably were the dominant mineral species at the surfaces of the Earth and Mars during the periods of intense impact activity prior to 3.8 b.y. and may have been critical catalysts to the formation of complex organic molecules. Mars appears to have had both early and late oceans due to two major episodes of intense volcanic activity, the oldest triggered by metallic core formation and the youngest by remelting of the Martian mantle. And finally, the Martian water-ice boundary in the crust is probably the most stable, long-lived ecological niche for simple life forms.

Introduction

Debate over the origin and evolution of the Moon has remained lively and productive since the last human exploration 30 years ago. More recently, issues related to the evolution of Mars, Venus and Mercury increasingly get their share of our community's and the public's attention. A number of conventional hypotheses relative to the Moon and the terrestrial planets deserve both questioning and unconventional thought based on the profound advances in planetary research made by so many in recent years. How much do the known, probable and possible events in lunar history (Fig. 1) constrain what may have occurred on and in Mars (Fig. 2)? Or, indeed, on and in the Earth? Let's consider some possible headlines that might appear in the scientific press over the next few years.

Moon Origin By Giant Impact Unlikely!

The Giant Impact hypothesis for the origin of the Moon (Hartman and Davis, 1975; Hartman, 1986; Canup and Agnor, 2000) has become well entrenched in both the scientific literature and the popular scientific press and for good reason. It is an attractive hypothesis (but too often called a theory). The impact on the young Earth by a Mars-sized planetesimal primarily would explain the high angular momentum of the Earth-Moon system, and its large-scale physical characteristics can be reproduced convincingly in computer models. The timing of this proposed event now is constrained to have occurred within the first ~30 m.y. of solar system history (starting 4.57 b.y. ago) by the systematics of hafnium-182, an extinct isotope with a 9 m.y. half-life, and its daughter isotope tungsten-182 (Yin et al., 2002; Kleine et al., 2002). The estimated iron content of the Moon (Taylor and Esat, 1996) and hafnium/tungsten systematics (Jones and Palme, 2000) further constrain at least 90% of its parent to be the impactor rather than the differentiated Earth's mantle, assuming, of course, that the impactor had the composition of the Moon. This latter constraint essentially turns the Giant Impact hypothesis into an "impact assisted capture" hypothesis. A final constraint is that the impactor needed to have evolved as a large, co-orbiting planetesimal in the same oxygen isotope reservoir as did the Earth (Jones and Palme, 2000).

The major problem with the Giant Impact hypothesis is that the interior of the Moon is not cooperating. The lower lunar mantle, based on analyses of the Apollo 17 orange pyroclastic glass, has chondritic signatures for tungsten (Lee et al., 1997), lead (Nunes et al., 1994) and siderophile and chalcophile elements (Neal, 2001). Further, analysis of Apollo seismic data indicates a velocity discontinuity below about 550 km (Goins et al., 1981; Kahn et al., 2000). These data also suggest that the lower lunar mantle is significantly more aluminous that the upper mantle (Neal, 2001), suggesting that melting and fractional crystallization in the lower mantle was limited. If the Giant Impact hypothesis cannot explain this spectrum of geological evidence, alternatives to it should be considered.

The most plausible alternative to the Giant Impact hypothesis appears to be the capture of an independently evolved planetesimal co-orbiting the sun with the Earth (Alfvén and Arrhenius, 1972; Schmitt, 1991; Schmitt, 2003). It would seem that modeling studies of the pure "capture" hypothesis should be emphasized to see if the angular momentum constraint can be satisfied as it appears to be in "impact assisted capture."

Terrestrial Planets Had Chondritic Before Metallic Cores!

Seismic, isotopic and elemental evidence, as discussed above, indicates that the lower mantle of the Moon, material below ~550 km, never melted significantly and is relatively undifferentiated. Logic then would suggest that the Moon and other terrestrial planets initially had early chondritic cores, or proto-cores, similar to that of the Moon or about

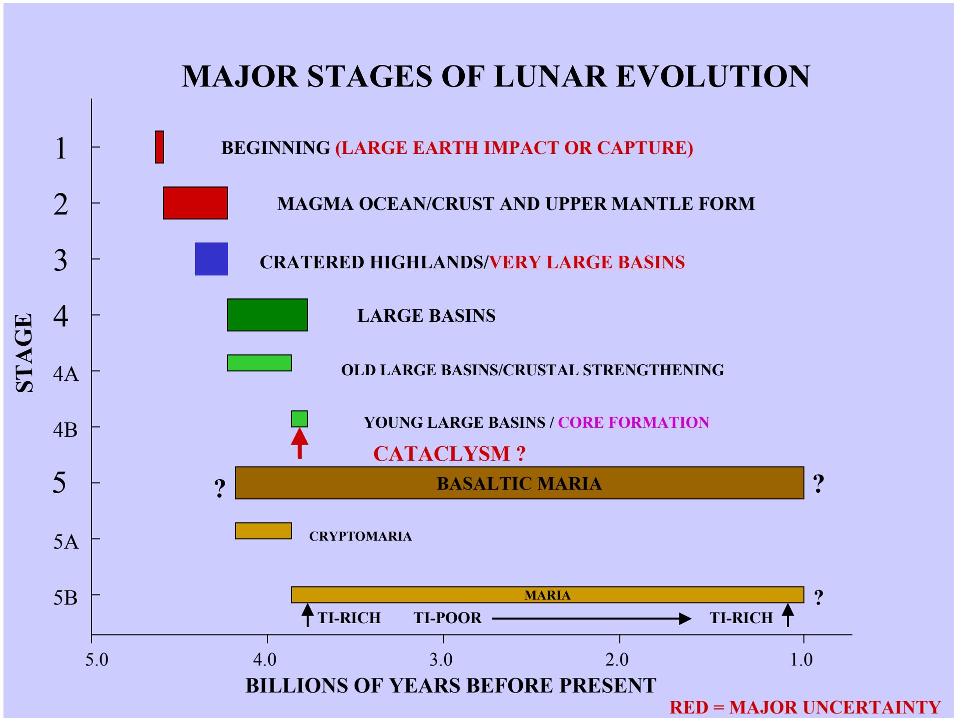

Figure 1. Graphical representation of the major stages of lunar evolution from Schmitt (2003).

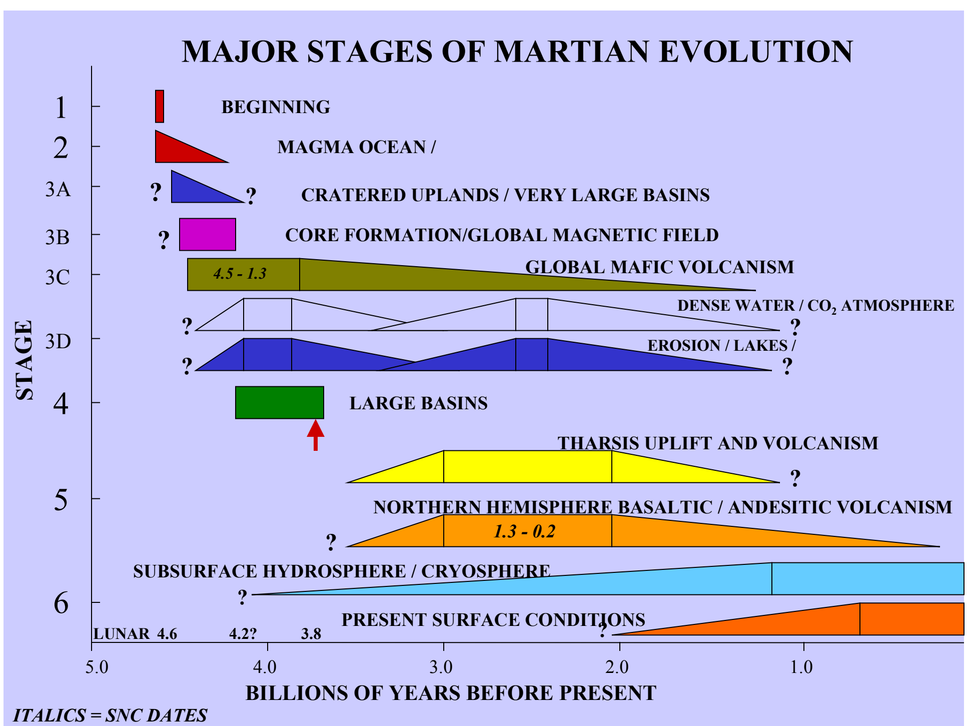

Figure 2. Graphical representation of the major stages of Martian evolution after Schmitt (2003).

1200 km in radius. The existence of such a cool proto-core beneath the magma oceans of the fully accreted terrestrial planets would delay, to varying degrees, the migration of iron-sulfur liquid to form metallic cores in these planets. In the case of the Moon, remnant magnetic fields at the antipodes of the four youngest large basins (Anderson and Wilhelms, 1979; Lin et al., 1988; Lin et al., 1998) suggest that core formation and an active dynamo-driven magnetic field were delayed by its proto-core until about 3.9 b.y., the estimated age of Nectaris, the oldest of these four basins (Wilhelms, Chapters 9-10).

Because of greater gravitational potential to drive core formation, and increased heating because of it, one would expect that there would have been progressively less delay than in the Moon in the sequence for Mercury, Mars, Venus, and Earth, respectively. This is contrary to the conclusions reached by Kleine (2002) and Yin (2002) in their analyses of hafnium-182/tungsten-182 systematics for samples potentially representative of the mantles of the Earth and Mars. The inconsistency may be, in part, the result of incomplete mixing after proto-core displacement. In fact, this possibility leads to the next predicted headline.

Mars Chondritic Core Lurking under Southern Uplands!

Remnant magnetic striping in the Southern Uplands of Mars (Connerney et al., 1999) occurred before the end of large basin formation ~3.8 billion years ago (Fig. 3) and probably before the last of the very large basins formed about at ~4.2 b.y. (Schmitt, 2003). These relationships indicate that metallic core formation and dynamo activation in Mars occurred significantly earlier than in the Moon. In Mars, unlike in the Earth, continuous convective mixing of the solidified mantle may not have broadly dispersed the displaced proto-core. The flattened remnants of that proto-core may now reside under the Southern Uplands, accounting in part for the apparently thicker Martian crust in that hemisphere. A offset of three kilometers in the center of mass, relative to the center of figure, toward the south pole of Mars (Smith and Zuber, 1996) and hemispheric differences in geological provenance also may be the result of selective displacement of the proto-core. In this context, there is increasing speculation on broad heterogeneity in the composition of the Earth's mantle (Albarède et al., 2000; Meibom and Frei, 2002; Bizzarro et al., 2002; Ballentine, 2002), some of which may record incomplete mixing of the Earth's proto-core after displacement during core formation.

Melt from Huge Impacts Produced First Continents!

The 2500 km diameter basin on the far side of the Moon (Wilhelms, 1987, p. 145), known as South Pole-Aitken, records an impact of an extraordinarily energetic object near the end of the period 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 b.y and South Pole-Aitken at about 4.2 b.y. 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, p. 157**;** 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 proto-continents 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 (Wilde et al., 2001; Mojzsis et al., 2001), consistent with this hydrous impact melt sheet hypothesis.

Lunar Cataclysm 3.9 B.Y. Ago Faked by Late Impacts!

The suggestion (Tera et al., 1974) that a "cataclysm" of impacts at about 3.85 b.y. was responsible for the vast majority of craters visible on the lunar surface has gained increasing adherents in recent years (Ryder, 1990; Ryder et al., 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 a few hundred kilometers in diameter. The primary rationale for the cataclysm hypothesis is the almost compete absence of impact glass older than ~3.9 b.y. 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 et al., 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 ~14 youngest of ~50 large impacts. Schmitt (1989) has discussed the clear temporal and geological distinctions between young and old large basins. The fresher appearing, so-called "mascon" basins (Muller and Sjogren, 1968) now represent these 14 impacts, that is, basins that have undergone little isostatic adjustment since they formed. Those such basins for which reasonable ages have been assigned (Wilhelms, 1987, Chapters 9-10), that is, Nectaris, Serenitatis, Imbrium and Orientale, range in age between 3.9 and 3.8 b.y., 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 and 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 young large basins, or they would not have been covered by basin ejecta. The cryptomaria eruptions, possibly the result of pressure release melting, also probably 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 m.y. long cataclysm at about 3.85 b.y. or a 400 m.y. period of large basin formation between 4.2 and 3.8 b.y., 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 breakup of the proto-planet 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 unraveling the evolution of the solar system and the terrestrial planets.

Clay Minerals Dominated Before Life Appeared!

Prolonged and intense impact cratering took place in the inner solar system from about 4.5 b.y. up to 3.8 b.y. following the solidification of magma oceans recorded by 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 and Wächtershäuser, 1998), may have assisted in the aggregation of complex organic molecules, possible precursors to the first replicating forms of such molecules (Ferris, 1996). Indeed, replication may have first been symbiotic with the forms, growth, and/or expansion of clay mineral structures. Tubular forms of clay minerals also may have been initially incorporated in the earliest single cell organisms to assist in the movement of fluid, only to be replaced later by organic compounds.

The evidence of isotopic fractionation by organic processes associated with with ~3.8 b.y. 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 also appears to be at about ~3.8 b.y. Although simple organic replication, and possibly single cell organisms, may have existed on Earth prior to ~3.8 b.y., 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.

Mars Had Both Early and Late Oceans!

Volcanic constructional features (Carr, 1996) and remnant magnetic striping (Connerney, 1999) identified in the Martian Southern Uplands, and partial erasure of the striping by very large impact crater formation, such as Hellas, indicates the early existence of surface or near-surface magmatic activity (see Fig. 2). Such activity may have been triggered by the upward displacement of Mars' chondritic proto-core discussed above and associated pressure release melting of that material and overlying Martian mantle.

Up to 3.8 b.y., intense impact cratering and solar wind erosion probably depleted primordial water initially retained at the Martian surface and in the atmosphere. Significant water reservoirs in the Martian mantle, however, would have been mobilized by early magmatic activity. First, the proto-core would have retained its primordial water if its displacement were catastrophic rather than gradual as may have been the case in the Moon. Secondly, high-pressure crystallization of hydrous silicates, particularly sodium-rich amphibole and mica, during the Martian magma ocean stage and their retention in the mantle would represent an additional water reservoir. Thus, water may have been introduced at high rates during the early volcanic episode.

Two possible strand lines for ancient oceans on Mars have been identified (Head et al., 1999), including one from a possible early northern ocean. This line has highly variable elevations, creating doubt as to its reality as an actual strand line. On the other hand, the variable elevations appear to be where a level line would have been most affected by uplift of the Tharsis bulge, and its antipodal response in Arabia Terra, and the Elysium uplift. As the effects of the Tharsis bulge post-date the large basin stage of impact cratering as well as the early volcanic period, this irregular, possible strand line may well be evidence of an early northern ocean. If the correlation of an early northern ocean with an early volcanic period is correct, it would indicate that this volcanism was after the formation of the very large basins that in aggregate form the Northern Lowlands of Mars but before the end of other large basin forming events.

More clearly evident than the strand line for an early northern ocean is a later one that post-dates the crustal deformation associated with the Tharsis-Arabia bulges. This second northern ocean has a well-defined and largely level strand line. Its water would have been evolved during Tharsis-Elysium eruptions and related volcanic activity and persisted after the major deformations associated with that activity. This ocean may have been in part re-mobilized water from the earlier ocean stored as ice and water in the Martian subsurface.

Simple Life Forms At Martian Ice-Water Boundary!

It has long been evident from geological evidence that water ice was present in much of the Martian subsurface at high latitudes and that liquid water (the hydrosphere) likely existed below this ice (the cryosphere) due to heat flow induced temperature increases with depth (Carr, 1996). The recent epithermal neutron data from Mars Odyssey more precisely defines the distribution of water ice (Boynton et al., 2002). The boundary region between the hydrosphere and the cryosphere of Mars is a stable, long-term ecological niche that could harbor simple life forms, including their evolutionary derivatives, since a more Earth-like environment disappeared from the Martian surface a few billion years ago. Certainly, this niche would be no more hostile to life than similar subsurface environments on Earth (Wharton, 2002).

Discussion

So there you have it - some headlines that may appear in our more public literature in the next quarter century. Sooner, if the first investors for a lunar helium-3 fusion power initiative step forward. In that way, we can have the return of science to the Moon and the human exploration of Mars largely paid for by power hungry Earthlings.

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