Lunar Pyroclastic Deposits and the Origin of the Moon[1]

Harrison H. Schmitt[2]

## Introduction: The Consensus

Debate over the origin and evolution of the Moon, and implications relative to the Earth, has remained lively and productive since the last human exploration of that small planet in 1972. More recently, issues related to the evolution of Mars, Venus and Mercury have received increasing attention from the planetary geology community and the public as many robotic missions have augmented the earlier lunar investigations. A number of generally accepted hypotheses relative to the history of the Moon and the terrestrial planets (e.g., Sputis 1996, Canup and Righter 2000, Taylor 2001, Warren 2003, Palme 2004), however, deserve intense questioning as data from many of the lunar samples suggest alternatives to some of these hypotheses. Further, how much do the known, probable and possible events in lunar history constrain what may have occurred on and in Mars? Or, indeed, do such events constrain what may have happened on and in the Earth?

Strong agreement exists that at 4.567 ± 0.001 Gyr ($T_0$) (Carlson and Lugmair 2000, Alexander et al 2001, Taylor 2001, Jacobsen 2003, Amelin et al 2004) a portion of an interstellar molecular cloud collapsed to form the solar nebula (Taylor 2001, Hester et al 2004). A sizable consensus also exists that a few tens of millions of years after $T_0$, the Moon belatedly came into existence as a result of a "giant impact" between the very young Earth and a chondritic asteroid that was 11 to 14 percent the mass of the Earth and gave a combined angular momentum of 110-120 percent of the current Earth-Moon system (Hartmann and Davis 1975, Cameron and Ward 1976, Hartmann 1986, Cameron 2002, Canup 2004, Palme 2004). This angular momentum would have been subject to later tidal dissipation to reach today's still unusually high value. Increasingly detailed hydrodynamic simulations (Canup 2004) of such a hypothetical collision indicates that, if it occurred, the impact angle and velocity of the impactor were around 45º and less than

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[2] Geologist, Apollo 17 Astronaut, Former U.S. Senator, Aerospace consultant and advisor, Former Chair NASA Advisory Council, author of "Return to the Moon," Member, new Committee of Correspondence.

4 km/sec, respectively. Under these conditions, about half of the ejected material would reach the velocities and trajectories outside the Roche limit that would be necessary for a stable orbit once aggregated as the Moon. The remaining material would re-impact the Earth.

The giant impact consensus holds that at the time of such a collision, both the Earth and the impactor would have been at least partially differentiated from their chondritic parent material by the separation of core-forming, iron-rich liquid. Some chemical differentiation in non-core material may also have taken place by a least partial crystallization of silicate-rich magma oceans created during the earlier accretion of the two bodies. This hypothetical lunar origin by giant impact primarily offers an explanation for the unusually high angular momentum of the Earth-Moon system (see Taylor 2001), and allows many of the lunar geochemical characteristics to be attributed to those of the hypothetical mantle of the original, at least partially differentiated, impactor. For example, the fifty percent higher iron content of the Moon relative to the Earth's mantle requires that at least 80-90 percent of the Moon be derived from the impactor rather than the core-depleted mantle of the Earth (Taylor 2001, Canup 2004).

The major, hypothetical consequences of such a Moon-forming, giant impact are presumed to be as follows: Most core-forming material in both bodies remained with or was quickly re-acquired by the Earth. The Moon formed through the rapid orbital re-aggregation of about one-half of the material ejected by the giant impact. Most of that material would have reached temperatures between 3000° and 5000° K, according to Canup's recent computer simulations (Canup 2004). 10-30 percent of material that formed the Moon vaporized during ejection and passed through a molten stage during condensation and re-aggregation into a coherent body, all in just a few days. Soon after or during re-aggregation, the lunar core formed (Agee 1991, Neal et al 2000b, Neal and Ely 2002) and a magma ocean existed above this core (Wood et al 1970, Smith et al 1970, Warren 1985).

## Moon Origin By Giant Impact Unlikely

The giant impact hypothesis for the origin of the Moon summarized above has become entrenched in the scientific literature, the popular scientific press, and as dogma in most academic institutions. The 2007 Space Science Board report, "The Scientific Context for the Exploration of the Moon," does not even suggest it should be tested in the future. Students and faculty alike are remarkably unquestioning about the hypothesis' basic premises. It is an attractive hypothesis, but too often implied as being more established than just a "hypothesis" by being called a "theory" (see also Wilson 2005). "Giant impact" clearly should be considered a hypothesis rather than a theory as it is based on computer modeling and simulations rather than also being objectively tested against all the geochemical data available from Apollo samples. Giant impact, however, remains an implicit if not explicit assumption that underlies most interpretations of new geochemical and geophysical data reported in the lunar science literature. The impact on the young Earth by a planetesimal less than fifteen percent its mass, of course, would be one way to explain the unusually high angular momentum of the Earth-Moon system. Further, some of the large-scale physical and orbital characteristics of the Earth and Moon can be reproduced convincingly in computer simulations (e.g. Canup 2004).

The timing of this proposed event now is constrained to have occurred within the first ~30 Myr of solar system history, that is, ~30 Myr after $T_0$. This constraint has been established by the isotopic systematics of extinct $^{182}$Hf (9-Myr half-life) and its daughter stable isotope $^{182}$W (Yin et al 2002, Kleine et al 2002). ($^{182}$Hf differentiated between mineral phases during the fractional crystallization of the lunar magma ocean.) The estimated iron content of the Moon (Taylor and Esat 1996) as well as hafnium/tungsten systematics (Jones and Palme 2000) further constrain about ninety percent of the Moon's parent to be the impactor rather than the differentiated Earth's mantle, assuming, of course, that the impactor effectively had the composition of the Moon. This latter constraint essentially turns the giant impact hypothesis into an "impact assisted capture" hypothesis as the modern simulations clearly indicate. An additional critical constraint on this computer-based hypothesis is that the impactor needed to have evolved in the same oxygen isotopic reservoir as did the Earth (Jones and Palme 2000). Although chromium isotopic considerations suggest the same co-reservoir accretion (Palme 2001), broader chromium relationships, as well as oxygen isotope equivalence, suggest that the Moon's material may be more closely related to that of the HED meteorites (McSween, 1999) that appear to come from the Main Belt of asteroids (McSween 1999, Taylor 2001). Clearly, the original source of lunar materials is a subject for significant further study that takes into account all major variables, including thermal and dynamic accretionary history as a function of accreted planetesimal mass.

The major problem with the giant impact hypothesis lies with geochemical and geophysical information we have about the interior of the Moon below about 500km. Specifically, both the original and more recent analyses of Apollo seismic data indicate a velocity discontinuity below about 550km (Goins et al 1981, Kahn et al 2000). Kahn et al, as well as Neal (2001), interpret these velocity data as suggesting that the lower lunar mantle is significantly more aluminous than overlying upper mantle. If this interpretation is correct, then melting and fractional crystallization in Moon was limited to the highly differentiated upper mantle.

**The Importance of Lunar Pyroclastic Glasses**

The pyroclastic deposits of the valley of Taurus-Littrow provide our best field data base on these globally distributed materials (Schmitt, 1972 and 1973). Eruptions of basaltic lavas began in the valley and elsewhere throughout the Serenitatis basin soon after the Imbrium and Orientale ejecta arrived in the area. These eruptions began most probably at about 3.82 billion years or, statistically, between 3.88 and 3.57 billion years (Wolfe, et al, 1981). Early eruptions of basalt very probably came initially from many different vents in the extensively fractured lunar crust.

The Kovach active seismic system we deployed indicate a thickness of about 1175m (3854 feet) (Kovach, et al, 1973) for the titanium-rich, olivine basalt that partially filled the valley. The Talwani active gravimeter measurements made at many valley locations suggest that the basalt thickness might be as much 1400 m (4600 feet) (Cooper, et al, 1974). The predominance of coarse-grained mineral textures and systematic trends in chemical analyses of the basalts beneath the valley floor (Wolfe, et al, 1981) suggest that eruptions produced lava rapidly enough so that only one cooling unit of basalt was formed (Schmitt, 2003). The active seismic measurements of depths to changes in sound velocities supports this possibility with a velocity increase at about 248 meters (770 feet) probably representing the limit of deep fracturing beneath the clusters of secondary impact craters in the landing area. No evidence was found of decreased sound velocity caused by a zone of previously exposed, impact-generated regolith at this depth. Such a regolith zone would be expected if there had been any significant hiatus in basalt lava eruptions in the valley. Rather, the increase in sound velocity downward is consistent with just less fractured basalt.

Impact-generated regolith, probably averaging 5-10cm (2-5 inches) thick, formed on surface of the valley's basalt floor, but then, at about 3.48 billion years (Tera and Wasserberg, 1976), a new form of lava eruption occurred. Volatile-rich, "pyroclastic" lava fountains, probably reaching hundreds of meters above the surface, appeared along various fractures in the valley and elsewhere along much of the ~1000km (625 miles) east to south to southwestern edge of the Serenitatis Basin (Lucchitta and Schmitt, 1974; Schmitt, 1974 and 2003). As the gas-charged liquid lava rose into the lunar vacuum, it effervesced almost completely and, while in free fall back to the surface, each small fragment of liquid took the shape of small spheres, averaging about 40 microns (0.00004 inch) in diameter. Spheres near the outside of the erupting fountains and exposed to deep space quenched rapidly and became the orange glass beads. Those spheres inside the hot fountains cooled more slowly and partially crystallized, becoming the black beads. The blackness of the latter is largely the result of the crystallization of fine, dark needles of ilmenite, iron-titanium oxide [$FeTiO_3$]. At the future location of Shorty Crater, and probably throughout much of the valley, these lava fountains deposited discontinuous layers of both orange and black beads, totaling a few meters thick (Wolfe, et al, 1981; Schmitt, 2003). How much mixing between the orange and black beads occurred as they fell is unknown. The distinct black layer in the northwest wall of Shorty and observations from orbit of distinct red, orange, and black layers in craters walls elsewhere around Serenitatis suggest that mixing was not the rule.

The lower lunar mantle, based on analyses of the non-glass component of Apollo 17 orange pyroclastic glass and Apollo 15 green pyroclastic glass, has chondritic isotopic and elemental signatures for tungsten (Lee et al 1997), lead (Nunes et al 1994), and siderophile and chalcophile elements (Neal 2001; Walker et al 2004). Samarium-neodymium (Synder et al 2000) and rhenium-osmium (Walker et al 2004) isotopic systems also are consistent with relatively undifferentiated, that is, chondritic sources for this component. Volatiles associated with coatings on beads of both orange and green glasses are enriched over associated basalts by factors greater than 100 in Cl, F, Br, Zn, Ge, Cd, Tl, and Ag and by factors greater than 10 in Pb, Ga, Sb, Bi, In, Au, Ni, Se, Te, and Cu (Wasson et al 1976; Krähenbühl 1980; Meyer 1989). Recent reports also suggest traces of water in the pyroclaseic glasses (Saal et al 2008) themselves although these studies need to be carefully replicated. Significant water in the phyroclastic plumes may not be consistent with the survival of glass beads for several billion years. These geochemical characteristics are not consistent with volatile retention during the 1000° to 5000° degree temperatures to which proto-lunar materials would have been subjected during a giant impact event. Some workers (Walker et al 2004) interpret chondritic material associated with pyroclastic glasses as being derived from post-magma ocean accretion (~150 Myr after $T_0$). This possibility of a late accretion source for the non-glass component appears highly unlikely based on the probable deep sources for these pyroclastic materials (Delano 1980, Heiken et al 1991) and the probable loss of such volatiles from the Moon because of extreme heating during any late accretionary impacts. An internal source also is supported by the close spatial association of the eruptions with deeply penetrating graben faults at the margins of large basins such as Serenitatis.

In addition to the above data from the pyroclastic glasses that are inconsistent with a giant impact origin, the ratios of rare earth elements and other refractory elements (Taylor 2001) also are inconsistent with the extremely high temperatures that modeling indicates would accompany such an origin. The rare earth elements show none of the fractionation that would be expected if temperatures in the proto-lunar materials reached significantly over 1100° and are present in their expected solar nebular ratios except as modified by the fractional crystallization of the magma ocean (Taylor and Esat, 1996). A lack of temperature fractionation in potassium isotopes (Humayun and Clayton 1995) also eliminates exposure to the high temperatures inherent in a giant impact.

## The Alternative to Giant Impact

If the giant impact hypothesis cannot explain the spectrum of geological evidence about the nature of the lower mantle outlined above, alternatives to that hypothesis should be considered. The most plausible alternative to the giant impact hypothesis appears to be the non-catastrophic capture of the Moon as an independently evolved planetesimal (Alfven and Arrhenius 1969 and 1972; Singer 1970, Schmitt 1991; Schmitt 2003). Capture of one body by another appears to have been common around the giant planets (Taylor 2001, Johnson and Lunine 2005). Those satellites with retrograde, inclined orbits, Triton around Neptune and Phoebe around Saturn, for example, appear to have been captured so a capture mechanism for the Moon probably exists that is not as improbable as many have stated (Kaula 1971, Spudis 1996, Cameron 2000, Taylor 2001).

General agreement exists that for any one encounter of two bodies in orbits around the Sun, the probability is low that capture will occur. On the other hand, after each such encounter the orbit of the smaller body changes significantly and moves in an ellipse that will create new encounters twice for every complete orbit of the Sun by the larger body. The overall probability of capture increases with time and, in fact. "may approach unity" (Alfven and Arrhenius 1972). Alfven and Arrhenius state as a general theorem, "if two bodies move in crossing orbits and they are not in resonance, the eventual result will be either a collision or a capture." There will be exceptions to this "theorem" but there are also many factors to be considered (Alfven and Arrhenius 1972, Singer 1986). For example, how would tidal interaction and accretion of possible pre-existing Earth satellites stabilize otherwise unstable post-capture orbits?

Although the internal geochemical and geophysical characteristics of the Moon suggest that capture is required, and physics appears to permit it, no modern modeling or simulation studies of such a dynamic interaction of the Earth and Moon have been published. In the capture alternative to giant impact, the Moon, like all the terrestrial planets, would probably would have begun its existence in heliocentric orbit in the inner solar system, possibly at one of the Earth-Sun stable libration points, L4 or L5 (Belbruno and Gott 2004), with the initial, relatively slow accretion of a cool, chondritic core. Independent accretion at a libration point, of course, would take place precisely in the same reservoir of oxygen isotopes that fed the Earth, as required by analyses of lunar and terrestrial rocks (Jones and Palme 2000). As the accreting proto-Moon reached a radius of about 1200km, roughly the current radius of the lower lunar mantle, a magma ocean formed from accreting material through a rapid rise in the conversion of kinetic and potential energy to heat. The ultimate mass of the Moon in the Earth's solar "feeding zone," as well as the Moon's ability to accrete the denser core material in the zone, would be limited by its competition with the more massive and gravitationally more attractive Earth.

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