APOLLO & THE GEOLOGY OF THE MOON:

UPDATE ON 28TH WILLIAM SMITH LECTURE, 1975-2015

The 1960s and 1970s saw two major revolutions in our understanding of the Earth: the delineation of the concept of plate tectonics and data from Apollo lunar samples proving the Moon recorded the early history of the inner Solar System. The prediction I made in the 28th William Smith Lecture that "the synthesis of the geology of Apollo will become one of the fundamental turning points in the history of all science" has proven to be correct. Forty years of Apollo sample and geophysical analysis and thought and debate within the lunar science community show that the dynamic evolution of the Solar System tied the early histories of the Moon, Earth and other planets closely together.

Additionally, new questions have arisen as information about the Moon has expanded. New and enhanced technologies have greatly increased the value of lunar sample analysis. It is the "gift that keeps on giving". Additionally, new remotely sensed data have expanded knowledge and questions to the lunar far side and poles.

In the William Smith Lecture forty years ago, I divided the history of the Moon into seven stages. What major new aspects of those stages exist today?

The Beginning Stage (4.567 Ga) has become more complicated with two competing hypotheses for the origin of the Moon. The more popular, model-based hypothesis is that the Moon formed as a consequence of the impact of a Mars-sized planetesimal on the young Earth. On the other hand, the proven existence of volatile reservoirs in the lunar mantle and increasingly more precise rock analyses showing identical or nearly identical lunar and terrestrial isotopic ratios in elemental systems ranging from oxygen to titanium, continue to encourage an alternative hypothesis — the Moon accreted as an independent planetesimal in the same planetary feeding zone as the Earth and was captured. I have long preferred this second alternative as the simpler explanation of the geochemical makeup of the Moon.

The Melted Shell (Magma Ocean) Stage (4.56 - ~4.4 Ga) resulted in a lunar interior consisting of an initial crust (~60 km), a fully differentiated upper mantle (~450 km), a possibly largely undifferentiated lower mantle or proto-core (~750 km), a fluid Fe-Ni-S outer core (~350 km), and a solid inner core (~150 km). Moonquakes associated with tidal stresses in the deep lower mantle and temperature estimates for those depths indicate the presence of distributed pockets of magma, probably Fe-Ni-S liquid. Recent considerations of the textures and iron isotopes in Apollo 17 samples of dunite and troctolite appear to confirm earlier suggestions that late in the fractional crystallization and differentiation of the magma ocean, the appearance of dense ilmenite-rich cumulates caused at least regional overturn of the earlier cumulate layers in the upper mantle. Also, a near side concentration of material rich in potassium, rare earth elements, phosphorus and thorium (KREEP+Th) in the area of thinnest crust indicates that the residual liquid (urKREEP) from magma ocean differentiation had accumulated beneath the crust in this region (Procellarum KREEP Terrain) and probably globally.

The Cratered Highlands Stage (~4.4 – ~4.1 Ga) left the crust saturated with craters ~60 km in diameter. It produced a mega-breccia zone at least 25 km deep. The Procellarum and South Pole-Aitken continental-scale basin-forming impact events, 3200 and 2500 km in diameter, respectively, occurred during this period. Evidence from Apollo 17 samples and those of other missions suggests that the Procellarum basin-forming impact occurred at about 4.35 Ga and triggered (1) movement of magma ocean residual liquid (urKREEP) toward the basin and into the crust, (2) the overturn of the upper mantle in this region, and (3) the partial re-melting of the mantle. The re-melting produced magmas that formed large plutons and dikes (Mg-suite) in the lower crust. The later formation of the South Pole-Aitken basin, possibly about 4.2 Ga, occurred after the far side crust had become strong enough to support major gravitational anomalies. Its ejecta blanket, superposed on that from the earlier Procellarum event, created the region with thickest crust, reaching about 100 km in thickness. On Earth, the melt sheets of these very large impacts may have differentiated into the first seeds of continental crust. Recently identified detrital zircons from Australia, as old as 4.4 Ga, may record such melt sheet differentiation.

The Large Basins Stage (~4.1 – ~3.8 Ga) resulted in at least 40 additional impact basins greater than 300 km in diameter. These basins, along with the earlier even larger basins, penetrated into the lower crust, incorporating Mg-suite rocks in their ejecta and distributing them across the Moon. The youngest large basins support mass concentrations (mascons) beneath their floors and mass deficiencies beneath their rims. This late lack of post-impact isostatic adjustment shows that the crust strengthened early in this stage, probably due to the final movement and crystallization of magma ocean residual liquid (urKREEP) in the lower crust stimulated by earlier basin-forming events. The creation of large basins appears to have been episodic, likely as a result of the dynamic re-positioning of the giant gas giant planets in the outer Solar System. Apollo 17 samples and other data indicate that a particularly active episode of basin formation occurred around 3.9 Ga with, for example, the Crisium, Serenitatis, Imbrium basins, and probably several other basins, formed in less than 100 My between 3.8 and 3.9 Ga. Regional magnetic anomalies and concentrations of light-colored swirls coincide with the antipodes of several these late basins.

The combined Cratered Highland and Large Basin Stages took place when the precursors to life on Earth (and possibly on Mars) were developing in the Hadean Eon. Although the Moon records that the Hadean was an extraordinarily violent period on Earth and Mars, the formation of abundant phyllosilicates, particularly smectites, from impact glass and debris in a water-rich environment may have provided the catalytic and structural base for the development of the biotic antecedents to life.

The Light-Colored Plains Stage, suggested in my original lecture, probably should be dropped as a separate stage. Increasingly, it appears that these plains had several origins related to debris flows of ejecta from Large Basin impacts and to lithic pyroclastic eruptions preceding mare basalt eruptions.

The Basaltic Maria Stage (3.9 – 3.0 Ga or later) consisted of pervasive eruption of a chemically, highly diverse suite of basaltic lavas that partially filled topographically low areas, particularly large impact basins. The partial melting of the upper mantle to produce the basalt magmas resulted from the accumulation of radioisotopic heat beneath the thermally insulating mega-breccia of the cratered highlands. Eruptions of largely hidden basalt flows and/or pyroclastic deposits (cryptomaria) preceded the main portion of this stage, but have been largely covered by ejecta from the last of the large basins. In many regions, particularly at the edge of large impact basins, the Stage also included late eruption of volatile-rich, highly mafic pyroclastic ash, including the Apollo 17 orange soil. The eruptive volatiles included indigenous water, halogens and non-ferrous metals as well as many other volatile elements. The existence of these pyroclastic volatiles, derived from deep reservoirs, may indicate a relatively undifferentiated, chondritic lower mantle.

The Quiet Crust Stage (3.0 Ga – to present) has consisted of relatively small impact crater formation, ranging in size from a few hundred km in diameter to dust. Apollo 17 samples, however, indicate that the flux of particles was variable, possibly the result of irregularly spaced collisions between bodies in the Asteroid Belt. As the Moon slowly cooled and contracted, thrust faulting has taken place in the crust, forming surface scarps and wrinkle ridges. Shallow moonquakes indicate that these faults continue to form. The surface debris layer or regolith created during this stage accumulated hundreds of ppm of solar wind hydrogen, carbon, nitrogen and helium. During this stage, re-volatilized hydrogen, water-ice and probably other volatiles gradually concentrated at high latitudes, disseminated throughout the regolith in areas of permanent shadow. Cometary impacts, pyroclastic eruptions, and solar wind hydrogen reactions with silicate oxygen may have been primary sources of water-ice in polar regolith. Additionally, the volatiles in the lunar regolith constitute future resources that can serve the Earth, lunar settlements, and future travelers to Mars. In fact, the helium includes a light isotope, helium-3, that is an ideal fuel for future fusion power production.

Clearly, each of the above stages of lunar history overlapped. As the lunar magma ocean crystallized, impacts saturated the still-forming crust, resulting in depletion of light elements relative to Earth. Large basins formed in the cratered highlands, only to be largely destroyed by continuing smaller impacts. Basalt eruptions began as large basins formed and appear to have continued to a lesser degree well into the Quiet Crust Stage.

This review covers only a small part of our current understanding of the origin and evolution of the Moon and its implications for Earth history. Much more has been learned in the last 40 years. Work continues with lunar samples, remotely sensed data, and the observations and photographs made by the Apollo astronauts. A return to the Moon as the training ground for trips to Mars also will add an immense reservoir of new knowledge and continue to enhance our understanding of Earth. I think William Smith would be proud of how we have built on his legacy and that of thousands of geologists who followed.