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The Moon

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INTRODUCTION

S.R. Taylor [1982] wrote a book that summarized the Moon as we knew it at the start of the quadrennium. Since then lunar science has continued (perhaps to the surprise of many), and provided us with many new ideas and "facts" about the Moon and its past and present environment. Lunar science is not moribund. Some aspects have received insufficient attention despite the potential for advances. For instance, there has been little experimental phase petrology relevant to lunar rocks. Some fields lack the possibility of new data, e.g., geophysics (although reinspection of the data continues). But the lunar samples provide a continuing resource from which some of the Moon's secrets can, with careful work, be revealed, and terrestrial spectroscopic observations provide new data. Most important, perhaps, is that the framework for interpreting data is continually being improved, so that our level of sophistication is continually increased. Lessons from terrestrial and meteorite studies are used to elucidate our lunar data, and in return, the Moon remains a major proving ground for ideas about the evolved bodies of the solar system. In this review, prominence is given to two major developments which have taken place in the last quadrennium: interest in and a possible consensus on the origin of the Moon; and the recognition and study of meteorites from the Moon. Less space is devoted to more "traditional" topics, not because they are actually less important to lunar science, but because the advances are less dramatic.

THE ORIGIN OF THE MOON

The Apollo mission samples demonstrated that the Moon is a differentiated, evolved body, and not the primitive, cold body which Urey had supposed. No clear reading of lunar origin came from early Apollo science, which did however provide clues and constraints by better characterizing the Moon, including demonstrating a very hot early period, an age the same as the Earth, and oxygen isotopes lying on the Earth's mass fractionation line but differing from most meteorites. There followed a period during which little attention was paid to the origin of the Moon. However, during the last quadrennium, the origin of the Moon became a very active field of study, and the hypothesis that the Moon was produced following the impact of a large (Mars-sized?) body into the Earth emerged as a front-runner. This interest stems from work inspired by the Conference on the Origin of the Moon held in Kona, Hawaii, in October, 1984, itself inspired by the Lunar and Planetary Sample Team, and cosponsored by the Lunar and Planetary Institute, NASA, and the Division of Planetary Sciences of the American Astronomical Society. The conference produced an abstract volume [*Hartmann et al.*, 1984] and a book of pertinent papers [*Hartmann et al.*, 1986]. Three important review papers on the origin of the Moon have been written [*Wood*, 1986; *Boss*, 1986*a*; *Stevenson*, 1986].

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The collisional ejection hypothesis invokes a catastrophic collison late in or after the formation of the Earth, ejection of material to produce a disk of material (not a fully-formed Moon), and a coalescence of this material to produce the Moon [e.g., *Wood*, 1986; *Hartmann*, 1986]. There are several variants of this basic model: for instance, the collision need not be singular [e.g., *Ringwood*, 1986*a,b*]; and *Boss* [1986*b*] suggested that spin up of the Earth by an oblique large-body impact could cause mass shedding of mantle material, contributing to the disk. The concept of collisional impact is not new, as it derives from *Hartmann and Davis* [1975] and *Cameron and Ward* [1976]. What really happened was a conflation of developments: (1) a realization that the traditional hypotheses of capture, fission, and coaccretion could not explain the Moon's features or were in some way implausible; indeed, collisional ejection appears to be the only mechanism which is not ruled out by dynamical constraints [*Boss and Peale*, 1986]; (2) development of a better understanding of the growth of planets from planetesimals and the dynamics of the early solar system, which shows that large body impacts would be both possible and expected [*Wetherill*, 1986; *Hartmann and Vail*, 1986], rather than *ad hoc* as previously supposed; (3) the stimulation of the conference focussed attention on the hypothesis [*Hartmann et al.*, 1986]. While the hypothesis is now popular, it has not been proven, and it is not clear that it satisfies, or can satisfy, all observational data. Important calculations, for instance on emplacement of ejecta into Earth orbit rather than its reaccretion or total loss, and on three-dimensional simulations of impact, are in progress [review in *Stevenson*, 1986]. The improvement in computing facilities over the last decade have been very important in making the calculations necessary to amplify and constrain the hypothesis.

Wetherill [1986] followed the natural orbital and collisional evolution of 500 initial planetesimals to planetary formation. Later accumulation in all simulations is characterized by giant impacts (up to 3× Mars size) which are sufficient to explain the large angular momentum of the Earth-Moon system (which is not explained by coaccreation). Such impacts can also explain the Earth's obliquity [*Hartmann and Vail*, 1986]. One problem with the collisional ejection hypothesis is showing how material can be emplaced into orbit (rather than reaccreted or lost). One way might be for the material to be vapor, not solid [*Cameron*, 1985, 1986; *Thompson and Stevenson*, 1983; *Stevenson*, 1986], so that gas pressure effects become important. Viscous stresses or gravitational torques can redistribute some angular momentum [*Stevenson*, 1986] to help achieve orbit. Such an expanding vapor model can place enough material into geocentric orbit to make the Moon [*Cameron*, 1985, 1986; *Stevenson*, 1986]. *Thompson and Stevenson* [1983] argued that the disk would remain hot and largely vaporized through most of its existence but nonetheless expand outside the Roche limit and cool within 100 years, and coalesce. The short time-scale of accretion and the relatively high temperature of the solids would produce a partly or wholly molten Moon. *Boss* [1986*b*] found that although dynamic fission was unlikely, spin up produced by tangential impact could have contributed substantial matter to a prelunar disk. *Durisen and Scott* [1984] had removed an objection to fission, but *Boss and Mizuni* [1985] found that planetary viscosities, even of molten bodies, are too high for natural fission to occur.

The postulated impact is beyond any human experience, and attempts to "scale" known impacts are probably doomed [*Stevenson,* 1986]. Numerical three-dimensional simulations are in their infancy [*Cameron,* 1985; *Benz et al.,* 1986*a,b*; *Kipp and Melosh,* 1986], and it would be premature to use the results as firm constraints.

The Moon's composition is at least roughly similar to that of the Earth's mantle [review by *Drake,* 1986*a*] and this evidence was a powerful motivator of the fission hypothesis. Some authors have suggested that the compositions are very similar indeed, e.g., *Ringwood* [1986*a,b*] believes that the siderophile patterns in the Earth are controlled by complex processes related to core formation and unique to the Earth; he also finds the lunar siderophile abundance patterns to be similar to the Earth's mantle. He thus postulates a number of large impacts into the Earth producing a ring of mantle-derived planetesimals. *Wänke and Dreibus* [1986] find the chemical similarities to be compelling. Others strongly disagree with supposed similarities [e.g., *Drake,* 1983, 1986*a,b*; *Taylor,* 1986; *Kreutzberger et al.,* 1986; and others in *Hartmann et al.,* 1986], finding differences in siderophiles, refractory elements, and Mg/Fe, among others. *Warren* [1986] however finds the Mg/Fe's to be similar, but because of fractional condensation of the ring, argues against the collisional ejection model. *Cameron* [1985, 1986] finds that most of the disk from a large impact is produced from the projectile, not the Earth. If so, then several chemical features become free parameters. Furthermore, both the Moon and the Earth's mantle could have changed by continued core formation and meteoritic infall since lunar origin [e.g., *Newsom,* 1984] so that the identification and significance of chemical similarities and differences remains an opaque yet potentially fruitful field. Nonetheless, lunar geology, petrology, chemistry, and physics must continue to work together toward as clear a picture as possible of the initial nature of the Moon.

The origin of the Moon appears to require a disk of volatile- and iron-depleted material in Earth orbit. The collisional model appears to produce that, but other methods have been invoked too, such as using differentiated bodies with separation of the metal-rich parts [reviewed and referenced in *Warren,* 1986, and others in *Hartmann et al.,* 1986]. The origin of the Moon is under intense study, and the field is largely in the realm of physics. The impact hypothesis is attractive because at present it has no strongly negative attributes, but that may be because it is still in primitive form; greater effort on the positive attributes is needed [*Stevenson,* 1986].

LUNAR METEORITES FROM ANTARCTICA

At the opening of the quadrennium, no lunar meteorites had been recognized. There are now four. Allan Hills 81005 was the first meteorite to be positively identified with a specific parent body [*Bogard,* 1983]. The other three are from the Japanese Yamato collection: Y-791197, Y-82192, and Y-82193 [*Yanai et al.,* 1984, 1986; *Yanai and Kojiima,* 1984, 1985]. All four lunar meteorites are rather small: 31, 52, 37, and 27 g respectively. Their significance far outweighs their mass, for they provide new information about the character and evolution of the Moon, and prove that rocks can be ejected from planetary bodies up to at least lunar size without melting or even appreciable shocking. Much of the work on ALHA 81005 was reported at the 14th Lunar and Planetary Science Conference [Abstracts for Special Session on Meteorites from Earth's Moon, *Lunar and Planetary Science XIV*] and in a special issue of *Geophysical Research Letters* [*Vol. 10, 9,* 1983]; much of the work on the other meteorites was presented in two Special Sessions on Lunar Meteorites at the Tenth and Eleventh Symposia on Antarctic Meteorites in Japan (Special Session: Lunar Meteorites, 1985, 1986).

ALHA 81005 was the last of 373 samples collected in the 1981-1982 season, in January, 1982. It was recognized as unique by its collector, John Schutt [*Marvin,* 1983]. Its unusual nature was described in initial processing [*Score,* 1982], and its similarity to some lunar rocks was observed in thin section [*Mason,* 1982]. Y-791197 was collected in November, 1979, but was not recognized as lunar until much later [*Yanai and Kojima,* 1984]. Y-82192 and Y-82193, collected close together, were recognized as probable lunar samples during their preliminary examination and are probably fragments of the same fall [*Yanai et al.,* 1986]. The evidence that these meteorites are lunar is manifold. The samples are all anorthositic regolith breccias, with the petrographic and chemical characteristics of lunar rocks, including Fe/Mn about 70, from the highlands [e.g., *Warren et al.,* 1983*c*; *Warren and Kallemeyn,* 1986; *Ostertag et al.,* 1985; *Lindstrom et al.,* 1985]. Perhaps most decisive are the oxygen isotope measurements on ALHA 81005 [*Mayeda et al.,* 1983] and Y-791197 [*Clayton et al.,* 1984]. Rare gas data for ALHA 81005 show relative and absolute abundances similar to lunar regoliths but unlike any known meteorites [*Bogard and Johnson,* 1983; *Eugster et al.,* 1985]; similar results were obtained for Y-791197 [*Takaoka,* 1985] and Y-82192 [*Takaoka,* 1986]. Lunar anorthositic samples have Pb isotopic signatures that are unique among all solar system materials: Their high $^{207/206}$Pb and $^{206/204}$Pb result from two stages of U-Pb evolution with high U/Pb from 4.5 to 3.9 Ga ago and a drastic decrease in this ratio at 3.9. Ga ago. ALHA 81005 [*Chen and Wasserburg,* 1985] and Y-791197 [*Nakamura et al.,* 1985] show these same Pb characteristics, providing strong independent evidence for their lunar origin. (Data for Y-82192 plot instead on the $^{207/204}$Pb versus $^{206/204}$Pb geochron, and thus are not similar to lunar data and the sample might be contaminated with meteoritic or terrestrial Pb; [*Nakamura et al.,* 1986]). Ar and Sr isotopic data for the Yamato meteorites also give indications that much of the material has the typical 3.9 Ga age of lunar highlands rocks [*Kaneoka and Takaoka,* 1985; *Nakamura et al.,* 1985; *Takaoka,* 1985]. *Nagata and Funaki* [1985] found Y-791197 to have uniquely lunar magnetic properties, including the coexistence of pure metallic iron and kamacite with 5-12% Ni. The absence of nuclear particle tracks in ALHA 81005 and Y-791197 [*Sutton and Crozaz,* 1983; *Crozaz,* 1985] and some cosmogenic nuclide data for all of them [*Nishiizumi et al.,* 1986] demonstrate a much shorter time in space than most meteorites. Thermoluminescence studies [*Sutton and Crozaz,* 1983; *Sutton,* 1985] also demonstrate transit times of less than 2500 years, if the loss of natural thermoluminescence is a result of shock heating during ejection rather than solar heating in near-sun orbit or heating during atmospheric entry.

All four meteorites are regolith breccias, containing varied clast types including glass, and with glassy matrices. However, except for Y-82192 and Y-82193, they are not petrographically or chemically identical. The KREEP component (with high incompatible element abundances with a distinct pattern) which characterizes most of the breccias and soils collected by the Apollo and Luna missions is lacking in all four meteorites [e.g., *Warren and Kallemeyn,* 1986; *Fukuoka et al.,* 1986] which have incompatible elements less than 2% those in KREEP. The lunar meteorites thus appear to have been derived from a location(s) distinct from the area sampled by spacecraft, and they are even possibly from the farside.

The lunar meteorites have similar incompatible element patterns, but different abundances, with Y-791197 having the highest (about 7× chondrites) and Y-82192 and Y-82193 having the lowest (2–3× chondrites) abundances [e.g., *Warren and Kallemyn,* 1986; *Lindstrom et al.,* 1985; *Ostertag et al.,* 1985; *Bischoff and Palme,* 1986; *Fukuoka et al.,* 1986; *Nakamura et al.,* 1986*a,b*]. The chondrite-normalized REE patterns are slightly enriched in light rare earth elements, and have positive Eu anomalies. The samples also differ in atomic Mg/(Mg+Fe): ALHA 81005~72, Y-82192~62–65, and Y-791197~0.60 [e.g., *Warren and Kallemeyn,* 1986; *Nakamura et al.,* 1986*a,b*]. (Most Apollo 16 regolith breccias fall between these extremes.) Y-791197 appears to be distinctly more enriched in volatiles such as Zn and Ga [*Ostertag et al.,* 1985; *Kaczaral et al.,* 1985; *Bischoff and Palme,* 1986] and some splits are among the most volatile-enriched lunar materials known [*Kaczaral et al.,* 1985]. The volatiles are probably of lunar, not terrestrial, origin.

ALHA 81005 contains abundant magnesian granulitic breccias and many hyperferroan anorthosite clasts, in a matrix which includes swirly brown glass [e.g., *Treiman and Drake,* 1983; *Ryder and Ostertag,* 1983; *Goodrich et al.,* 1984, 1985]. It also contains glass spheres and varied feldspathic melt breccias. *Treiman and Drake* [1983] recognized a mare basalt clast. Y-791197 contains much less glass and agglutinitic material [*Ostertag et al.,* 1985] and much less magnesian granulite [e.g., *Lindstrom et al.,* 1985]; mare basalt clasts have also been observed in Y-791197 [*Lindstrom et al.,* 1985]. Y-82192 and Y-82193 contain even less glass [*Bischoff and Palme,* 1986; *Takeda et al.,* 1986], and mare components do not seem to have been recognized in them. The mare component in the lunar meteorites is rare. Most of the clasts are of types generally recognized for Apollo and Luna highland samples, with the exception of a very small apatite-rich ferroan anorthositic troctolite fragment [*Goodrich et al.,* 1985] of complex igneous origin. The proportions are different in each [except the paired ones] and the absence of KREEP clasts is distinctive.

Solar-wind implanted gases in ALHA 81005 showed abundances and patterns similar to lunar regoliths, with exposure ages of more than 200 m.y. [*Bogard and Johnson,* 1983; *Eugster et al.,* 1985]. Y-791197 contains similar solar-wind gases [*Kaneoka and Takaoka,* 1985; *Takaoka,* 1985]. Both samples were probably irradiated near the lunar surface for several hundred million years. In contrast, the noble gas concentrations in Y-82192 are two orders of magnitude lower [*Takaoka,* 1986; *Weber et al.,* 1986]. Radiogenic ^{40}Ar was not lost recently, cosmic-ray irradiation ages are short in contrast with ALHA 81005 and Y-791197, and ^{131}Xe is not in excess, all indicating heavy shielding by burial (500 g/cm^2 or more) rather than impact loss [*Takaoka,* 1986]. There is really no indication that Y-82192 ever contained solar-wind gases; thus there are samples of lunar regolith which have never been exposed to the solar wind for any appreciable time [*Weber et al.,* 1986].

^{40}Ar-^{39}Ar studies on Y-791197 showed a high temperature age of 3.9–4.1 Ga for a clast, although half the ^{39}Ar was released at lower temperatures [*Kaneoka and Takaoka,* 1985]. Bulk samples (= matrix+clasts) of Y-82192 gave ^{40}Ar-^{39}Ar ages of 4.2 Ga for the high temperature release (90% of radiogenic Ar) and a K-Ar age of 4.0±0.4 Ga [*Kanaoka and Takaoka,* 1986; *Takaoka,* 1986]. Some of the lower temperature fractions gave ages older than 4.5 Ga and probably indicate contamination with terrestrial Ar [*Takaoka,* 1986]. *Weber et al.* [1986] reported an Ar age of 3.8.Ga. *Takahashi et al.* [1986] measured Rb and Sr isotopic ratios for materials in Y-791197, finding "isochrons" corresponding with 3.9 Ga ages, although the small spread in Rb/Sr gives large errors (0.3 Ga). The initial ^{87}Sr/^{86}Sr are very low and confirm the low KREEP abundances of the samples. The radiogenic isotope data are consistent with that part of the Moon represented by the samples having undergone an impact history similar to the Apollo and Luna sites. Clearly the redistribution of KREEP at 3.9 Ga was not global, nor can the common 3.9 Ga ages be ascribed to redistribution of KREEP by a single impact such as the Imbrium event.

The lunar meteorites did not spend much time in space, according to track studies [*Sutton and Crozaz,* 1983; *Crozaz,* 1985], natural thermoluminescence [*Sutton and Crozaz,* 1983; *Sutton,* 1985], and cosmogenic nuclide exposure studies [*Tuniz et al.,* 1983; *Nishiizumi et al.,* 1986]. The cosmogenic nuclide data are a function of exposure on the Moon and in space, and residence time on the Earth. They indicate that ALHA 81005 was probably transported in less than 100,000 years. The cosmogenic nuclide data indicate terrestrial residence ages of 170,000 yr (±50,000 yr) for ALHA 81005 and less than 100,000 years for Y-791197, Y-82192, and Y-82193 [*Nishiizumi et al.,* 1986]. The ALHA 81005 data agree with the terrestrial age of more than 90,000 yr derived from ^{81}Kr data [*Eugster et al.,* 1985].

That the four meteorites were ejected from the Moon by impact is not in doubt. This ejection was accompanied by only minor shocking, less than 25 GPa [*Ryder and Ostertag,* 1983; *Ostertag et al.,* 1985]. This itself is significant, for it demonstrates that rocks can be ejected from large planets without melting. There had been dynamical objections to such removals, of particular significance to the origin of Shergottite meteorites as Mars samples, but the lunar demonstration has spurred the production of plausible physical models for such ejection [e.g., *Melosh,* 1985]. The question of whether the lunar meteorites represent one impact or more than one impact has not yet been answered, and the lunar location(s) are not established. The meteorites are similar but not identical to each other, and are more dissimilar in major element abundances than are Apollo 16 regolith breccias, which were collected in an area specifically chosen to straddle two separate formations [*Warren and Kallemeyn,* 1986]. Thus if all four were blasted off together, evidently they were not close together before the impact, or the impact was in an exceptionally heterogeneous area. The presence of mare basalts is one constraint on their origin. One possibility is Giordano Bruno, a very young crater according to its bright rays, which is 20 km in diameter (larger than the Apollo 16 traverse area) and in a complex highlands terrain [see *Ryder and Ostertag,* 1983].

MARE BASALTS

During the quadrennium, several advances were made in our understanding of the ages and magmatic processes of mare volcanism on the Moon. *Taylor et al.* [1983] reported the existence of a mare basalt more than 4.2 Ga old (Rb-Sr isochron), the oldest mare fragment then identified. Petrographically it is similar to some Apollo 12 basalts, but was a clast in an Apollo 14 breccia. In a study of more Apollo 14 mare basalts, *Dasch et al.* (manuscript in preparation) found a range of ages, including one sample 4.33 Ga old. At the other end of the age spectrum, *Schultz and Spudis* [1983] reported photogeological evidence for the youngest basalt flows visible, perhaps only 1.0 Ga old. Apollo 14 samples of mare basalts produced other new types. One set (5 groups) possibly formed by varied assimilation of KREEP [*Shervais et al.*, 1985*a*; *Dickinson et al.*, 1985]. Most are about 4.1 Ga old (*Dasch et al.*, manuscript in preparation). Another, a very-high K basalt, according to petrochemical [*Shervais et al.*, 1985*b*] and isotopic data [*Shih et al.*, 1986] appears to have selectively assimilated a granitic component; Rb-Sr, Ar-Ar, and Sm-Nd determinations show crystallization 3.8 Ga ago. Lu-Hf isotopic determinations on mare basalts [*Unruh et al.*, 1984] with Sm-Nd data suggest that mare basalts were derived by small (< 10%) degrees of partial melting of cumulate sources. Lu/Hf ratios are consistent with this scenario [*Fujimaki and Tatsumoto*, 1984]. However,the Lu/Hf data indicate that assimilation cannot be accepted as a major process in explaining the general diversity of lunar mare basalts. The prevalence or otherwise of contamination of various kinds in the chemistry of mare basalts is an active field; the fluid, high-temperature lavas could erode surface materials during extrusive flow. The possible multiple use of rilles (e.g., Hadley Rille at Apollo 15) could include such erosion, already postulated for terrestrial komatiites.

Volcanic glasses are seen to be important clues to the interior of the Moon, because they are more primitive than crystalline basalts, and some even contain volatiles from primitive reservoirs [review by *Delano*, 1986]. Phase relations suggest that these magmas come from rather deep in the mantle (400 km), particularly if the assumption of multiple saturation at melt removal is made. *Binder* [1985] has alternatively modelled mare magma compositions and isotopic characteristics with shallow melting (< 200 km) of large percentages, leaving generally olivine in the source, subsequent olivine (+ pyroxene) fractionation in shallow magma chambers, and crustal assimilations. The model, which is complex and includes trapped melt in the sources and remelting in convecting magma chambers, is claimed to account for trace chemical and radiogenic isotopic data for both mare basalts and pyroclastic glasses.

It is obvious that the origins of lunar mare basalts, and what they tell us about the lunar interior is not a closed book but an area of diverse opinion. More detailed data on mare magmas, particularly volcanic glasses, is necessary (and is partly being acquired) to allow better modelling to understand the varied processes at work. Unfortunately, many mare glass types occur only as dispersed pieces of glass, most too small for detailed studies [*Delano*, 1986]. Nonetheless, some detailed work is being done; *Spangler et al.* [1984] dated yellow volcanic glass from the Apollo 15 site as 3.62±0.07 Ga using a laser probe and the ^{40}Ar-^{39}Ar technique, and found two varieties of the Apollo 15 green glasses to be the same (3.41±0.12, 3.35±0.18 Ga) and in agreement with previous analyses. Isotopic analyses of the highly-volatile elements within rare vesicles in glasses have recently begun [*Barraclough and Marti*, 1985], and INAA analyses of individual groups of glasses is in progress (R. Schmitt group). The primitive components may be from the interior of the Moon, but the story is certainly complicated, for example, by the observation that the primitive Pb on the surface of the Apollo 15 green volcanic glass has a source different from that in its interior [*Tatsumoto et al.*, 1986]. These volcanic glasses are a potentially useful source of information, but the work required will not be easy to do.

IGNEOUS ROCKS OF THE LUNAR HIGHLANDS CRUST

The Moon has an igneously-differentiated crust 55–75 km thick. Its composition and evolution are important in constraining the Moon's bulk composition and origin. The diversity of the lunar highlands, both in the rock types it contains and its lateral variations, which has been known for some time [*Taylor*, 1982], has been emphasized in the last quadrennium. The report of a workshop on the igneous rocks of the lunar highlands was published in 1983 [*Longhi and Ryder*, 1983]. Since then, many new fragments of igneous rocks, small pieces of soils and breccias, have been found and their petrography and chemistry studied; there have been few isotopic studies. The rock types cover a wide range including granites (sensu lato) and dunite, as well as newly recognized types such as alkali gabbronorites and magnesian anorthosites [*Warren et al.*, 1983*a,b*, 1986*a*; *Lindstrom*, 1984; *Lindstrom et al.*, 1984; *Goodrich et al.*, 1986; *Warren and Kallemeyn*, 1984]. The lunar meteorites also produced an extreme variety of anorthosite which is hyperferroan [e.g., *Goodrich et al.*, 1984]. The Apollo 17 site remains devoid of ferroan anorthosites with the possible exception of one small fragment [*Warren et al.*, 1986*a*]. An Apollo 15 ferroan anorthosite fragment contains metal and higher siderophile element abundances than is usual, and indicates the uncertainty of any attempt to estimate the overall siderophile abundances of the igneous crust [*Warren et al.*, 1986*b*].

James and Flohr [1983] proposed a genetic distinction between gabbronorites, which have important amounts of high-Ca pyroxene, and the majority of the Mg-suite rocks, which have little or no high-Ca pyroxene. Alkali anorthosites [*Warren et al.*, 1983*b*; *Shervais et al.*, 1983] may be related to Mg-suite rocks or KREEP. Very evolved rock types have been found and analyzed: a granite clast from the Apollo 14 landing site studied by *Shih et al.* [1985] formed about 4.1 Ga ago (Rb-Sr, Sm-Nd) in the shallow crust and was excavated and heated 3.9 Ga ago (^{39}Ar-^{40}Ar). *Compston et al.* [1984] applied high resolution ion microprobe techniques to obtain older (> 4.3 Ga) U-Pb ages for zircons in evolved "granitic" lithologies. A 1 g sample of "felsite" has been discovered among Apollo 12 samples [*Warren et al.*, 1986*b*]. ^{40}Ar-^{39}Ar dating of an olivine-rich ferroan anorthosite fragment from breccia 67915 showed some memory of an age in excess of 4.1 Ga [*Marti et al.*, 1983].

These newly-discovered rock fragments have been used in improving our understanding of the evolution of the lunar crust and the rock types within it. *Warren* [1985] gave an excellent review of lunar crustal igneous rocks and ideas about their origins and relationships, including concepts developed over the last few years. An important one of these was the partial replacement of the term "magma ocean" with the more general term "magmasphere," which hypothetically consists of a partially molten zone (magmifer; [*Shirley*, 1983]) and an overlying completely molten zone. A given model can have any proportion of the two. In *Shirley's* [1983] model the completely molten zone, which continually crystallized and was replenished, was never more than 7 km thick. Some form of a model with a magmasphere with a large-scale molten zone to produce the anorthositic crust first and then to complexly intrude it with mantle-derived but variously modified magmas (Mg-suite, KREEP) appears to fit the known rock characteristics and other constraints [e.g., *Warren,* 1985, 1986; *Palme et al.,* 1984]. Nonetheless alternatives for the production of the ferroan anorthosites have been seriously presented, including *Shirley's* [1983] replenishment model, diapiric anorthosites [*Longhi and Ashwal,* 1985] and serial magmatism [*Walker,* 1983]. There are compelling reasons to believe that the early lunar differentiation affected deep parts of the Moon, as summarized by *Warren* [1985]: the absence of mafic cumulates complementary to ferroan anorthosites, the Eu anomalies inferred for mare basalt sources (although these anomalies in the basalts themselves were explained instead by shallow-level crystallization and replenishment by *Walker* [1983]), and the high abundance of plagioclase in the crust, which is about 75% at the surface, among others. Assimilation of both ferroan anorthosites and KREEP-related materials may have modified the later products of the magmasphere [e.g., *Warren,* 1986]. It does not appear at all likely that the compositional diversity of the crustal rocks can be explained by differentiation during one magmatic event. The continued analysis of new highland rock types will improve our understanding of the lunar crustal evolution and how much, and in what way, the mantle was a part of the process. Emphasizing the difficulty of understanding lunar crustal formation are on-going analog studies of rocks from terrestrial intrusions. They suggest that we do not really know enough about the formation of rocks in terrestrial systems either [*Salpas et al.,* 1983; *Ryder and Spettel,* 1983].

POLYMICT ROCKS OF THE LUNAR HIGHLANDS CRUST

Most highlands rocks are not igneous but are some form of breccia. They range from friable fragmental breccias to coherent clast-free impact melts. They have been studied recently even as small bits from mare sites [*Simon et al.,* 1983, 1985*a*; *Laul,* 1986, *Laul et al.,* 1983]. Coarse fines from the Apollo 12 site confirmed the KREEPy, Apollo 14-like nature of the highlands crust there, including alkali anorthosites and norites; in contrast, ferroan anorthosites appear to be absent [*Simon and Papike,* 1985]. Conversely, at the Apollo 11 site, coarse fines showed the highlands to be fairly simlar to the Apollo 16 highlands [*Simon et al.,* 1983]. Breccias from Apollo 14 and 16 have been studied [e.g., *Shervais et al.,* 1983; *Heusser et al.,* 1985; *James et al.,* 1984; *Lindstrom and Lindstrom,* 1986] in an attempt to decipher the ancient components of the crust. Understanding the geology of the Apollo 16 landing site, particularly the origin and relationships of the photogeologically-defined units, the Cayley and Descartes Formations, is the goal of many petrochemical studies of both soils and breccias [e.g., *Spudis,* 1984; *Stöffler et al.,* 1985; *Basu and McKay,* 1984*a,b*; *Korotev et al.,* 1984; *McKinley et al.,* 1984; *Reimold et al.,* 1985; *See et al.,* 1986; *Morris et al.,* 1986]. *Stöffler et al.* [1985] studied the petrography and chemistry of many samples from North Ray Crater, applying their knowledge of crater dynamics to assess the immediate provenance of the samples from within the crater. Their interpretation is that a lower KREEP-poor section of the crater represents the Descartes Formation, which is Nectaris ejecta; a top section of KREEP-bearing rocks is Cayley and may be a distal facies of the Imbrium ejecta. They suggest from the clasts contents of the breccias that even Nectaris could be as young as 3.85 Ga old. *Basu and McKay* [1984] compared soils from Station 4 (high up on the Mountain) and Station 11 (also generally considered to be Descartes-derived) and found them to be different, although mixing suggests that neither is derived solely from its underlying unit. *Korotev et al.* [1984] also concluded that the Station 4 core soils were a complex mixture of Cayley, Descartes, and other materials, including mare basalt. There is as yet no consensual understanding of the origins of and differences between the Cayley Plains and the Descartes Mountains. Melt rocks are an important constituent at the site, although *Spudis* [1984] revised previous estimates down to 10%. There are three main chemical groups; the VHA (very high alumina) group, which occurs in dimict breccias, has been interpreted as the Nectaris melt [*Spudis,* 1984], but *McKinley et al.* [1984] suggested a much greater uncertainty. An even more aluminous group which is rather young (3.8 Ga, [e.g., *Deutsch and Stöffler,,* 1986] is similar in composition to the Apollo 16 fragmental breccias. The apparent lack of an appropriate young, large source crater lead *Deutsch and Stöffler* [1986] to propose the radical conclusion that Imbrium, whose ejecta they suggest obliterated the source crater, is less than 3.8 Ga old. The validity of this conclusion is far from established.

The geology and petrology of the Apollo 15 landing site was the focus of a review covering its highland aspects from local petrology to basin formation, but also including mare volcanism, in a workshop in 1985 and related work [*Spudis and Ryder,* 1985, 1986]. Work stimulated by this workshop is in progress.

Lateral variations (and inferred depth variations) have been studied by reexamining the Apollo orbital data and interpreting it in the light of known petrology [e.g., *Davis and Spudis,* 1985]. New data from Earth-based spectroscopic measurements is also increasing our comprehension of lateral variations [e.g., *Spudis et al.,* 1984; *Lucey et al.,* 1986]. *Pieters and Wilhelms* [1985] obtained such data which implied the dominance of olivine in the central peak of Copernicus. Several studies have attempted to improve our understanding of craters, particularly the generation of large ones, including basins [e.g., *Croft,* 1985; *Spudis et al.,* 1984].

SEISMIC STRUCTURE AND THE LUNAR INTERIOR

There have been no new geophysical observations of the Moon, but *Nakamura* [1983] reported an improved analysis of the Apollo seismic data. The model which is most likely to represent reality is characterized by a velocity increase in the middle mantle (depth 400 km) rather than a decrease as had been estimated before. Geophysical constraints can and have been used to place constraints on the chemistry and mineralogy of the interior; such studies are now being revised on the basis of the *Nakamura* [1983] seismic profile [*Hood and Jones,* 1986; *Mueller and Phillips,* 1986]. In general, models that assume only upper mantle differentiation, that are more aluminous, have thermal gradients which are strong in the upper mantle but weak in the lower mantle, produce calculated velocity profiles more nearly matching the *Nakamura* [1983] velocity model, but are not unique. A small metallic core (1–4% lunar mass) in such models is needed to be consistent with the moment of inertia constraint. The inferred interior characteristics are important in establishing lunar evolution and origin.

LUNAR REGOLITH

For science, lunar regolith studies are really less concerned with the Moon than they are with exogenic processes, and so they will be barely considered here. The lunar regolith is produced by continuous impacting, and recent experimental simulations have clarified the processes of regolith production from rock. They have confirmed the role of preferential fusing of the finest fraction in producing agglutinitic glass [*Hörz et al.*, 1984; *Simon et al.*, 1985]. There have been several petrographic-chemical studies of soils and regolith breccias (which are lithified, fossil soils) [e.g., *Smith et al.*, 1985, *Simon et al.*, 1984, 1985*a*, and *McKay et al.*, 1986] as well as the characteristics of agglutinates [*Basu and McKay*, 1985; *McKay and Basu*, 1983; *Laul et al.*, 1984]. The interaction of the soil components with the solar wind and cosmic rays continues to be a productive field, in part improving our knowledge of the production rates themselves [e.g., *Nishiizumi et al.*, 1983, 1984*a,b*] for various nuclides, and in part providing clues to past histories of the solar wind [e.g., *Fourcade and Clayton*, 1984]. *Eugster et al.* [1985*a,b*] demonstrated the complex, multistage exposure history of lunar regolith.

THE FUTURE

One aspect that interests lunar scientists is new spacecraft missions to the Moon. A considerable amount of effort has been devoted to the emplacement of a manned base on the Moon, which would, of course, greatly increase knowledge about the Moon. This effort has included conferences and scholarly articles, and much of this is summarized in the collection of papers in *Mendell* [1986]. This volume covers transportation, logistic, scientific, and exploitational aspects of a lunar base. Of more immediate concern is the possibility of a lunar polar orbiter, which would be useful not only in planning a lunar base, but in understanding the Moon. Such a mission is prominent in NASA's plans, but like all planetary science missions, is currently something of an unknown. The Lunar Geoscience Observer would carry a battery of instruments, with luck could fly in the early 90's, and would contribute greatly to answering fundamental questions in lunar science [*LGO Science Workshop Members*, 1986]. A review of lunar science [*Lunar Geosciences Working Group*, 1986] acknowledges the continuing fundamental importance of lunar science in a planetary context, recommending that missions for both science and future manned lunar base support be given high priority by NASA. Lunar science was, in the previous quadrennium, perhaps in an interregnum; it now seems to be in an expansionary phase, adding to its breadth with studies of lunar samples aimed at their utility as well as their secrets about the universe.

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