Sm = 0.631 ppm, Nd = 1.2 ppm, again as per [7]; Figs. 2 and 3) that has an extremely elevated $\varepsilon_{Nd}$ (+8 at 3.84 Ga) and the lowest Sr initial ratio (0.69910) at 3.84 Ga. However, it is not likely that these two components remained distinct over a period of 500 Ma, when the interior of the Moon was still hot [10]. Recrystallization of the cumulate-trapped liquid pile could have occurred, yielding a source that was heterogeneous in trace elements on the scale of meters. Due to the low Sm/Nd ratio of the trapped liquid relative to the cumulate, those portions of the mantle that contained a larger proportion of this component would evolve with more enriched isotopic signatures.

**Melting of the Source to Achieve High-Ti Mare Basalts:** After an extended period of evolution (e.g., >0.5 Ga), earliest melting of the trapped liquid-cumulate pair would probably affect regions that were relatively enriched in the LILE (containing heat-producing elements U, Th, and K). Therefore, those regions that trapped the largest proportion of residual LMO liquid would melt first. Melts of these regions would exhibit relatively enriched isotopic signatures. Later melting would tap regions with less trapped liquid and would yield more isotopically depleted melts. Obviously, the degrees of enrichment and depletion of the melts are highly dependent upon the proportion of trapped liquid and the extent of melting of the cumulate + trapped-liquid pile. However, the trapped-liquid component is LILE-enriched (generally by at least an order of magnitude over the mafic cumulate) and would have originally consisted of low-temperature melting phases that would readily remelt. Therefore, even a small proportion (e.g., 1%) in the cumulate pile will greatly affect the isotopic signature of initial derived melts. However, because of its small proportion, the trapped liquid would have a lesser effect (inversely proportional to the degree of melting) on the major-element composition of the melt.

The low $^{147}Sm/^{144}Nd$ of this KREEPy trapped liquid, in concert with the relatively high abundances of Sm and Nd, obviates a large proportion of trapped liquid in the source (Fig. 2). This is illustrated in Fig. 2, where small proportions (≤5%) of trapped liquid have been added to a model high-Ti adcumulate. This addition of trapped liquid has the effect of lowering the Sm/Nd ratio, yet increasing the abundances of Sm and Nd, thereby leading to a viable cumulate source region. Again, only 2–3% of trapped liquid is required in the source for modal melting, and less if the trapped liquid is an early melting component (if the source was not recrystallized).

This can be further appreciated by looking at the parent/daughter ratios of the high-Ti basalts (Fig. 4, diagonally hatched areas). Simple two-component mixing of a high-Ti "adcumulate" source with varying percentages of KREEPy trapped liquid (where sample 15382 represents the KREEPy liquid) yields a curve of chemical mixtures. The compositions of the high-Ti basalts from both Apollo 11 and Apollo 17 lie along this curve. Any source that contains residual mafic minerals, such as pigeonite, clinopyroxene, and olivine, would be more depleted (lower in $^{87}Rb/^{86}Sr$ and higher in $^{147}Sm/^{144}Nd$) than the basalts from which it was generated. Therefore, the field of permissible sources (shaded) indicates <1.5% trapped liquid. Although this trapped KREEPy liquid is minor in volume, it controls the radiogenic isotope signature of the derived melt.

Similar calculations to discern the proportion of KREEP in these basalts were performed by Hughes et al. [11] and Paces et al. [4]. Both groups concluded that small percentages (generally <1%) of a Rb-, Sr-, and REE-enriched component, with high Rb/Sr and low Sm/Nd ratios, are required to explain the compositions of parental magmas for the high-Ti basalts. However, both groups envisioned this component as distal to the cumulate source and added to the source prior to its fusion, but not cogenetic with its inception. Paces et al. [4] pointed out the problems inherent in such a scenario, but neither group explored the possibility of an ancient KREEPy reservoir that was spatially associated with the cumulate source—as trapped intercumulus liquid from the late stage of evolution of the LMO—since its inception over 4.4 Ga.

**Summary:** The interpretation of cogenetic depleted and enriched reservoirs in the Moon is the consequence of events unique to the Moon. First, the late-stage LREE- and Rb-enriched residual liquid from a crystallizing LMO was trapped in variable and small proportions in the depleted upper mantle cumulates. A lack of recycling in the lunar environment would allow these reservoirs to diverge along separate isotopic evolutionary paths. This portion of the mantle would remain undisturbed for ≥0.5 Ga, prior to being melted to form the oldest high-Ti mare basalts. The isotopic character of the melts would be controlled by the degree of melting, as the least radiogenic reservoir would be melted first, i.e., that portion of the cumulate containing the greatest proportion of trapped liquid would melt first. The range in Sr and Nd isotopic ratios seen in basalts from Mare Tranquillitatis (Apollo 11) is due to melting of a clinopyroxene-pigeonite-ilmenite-olivine cumulate layer with variable proportions of trapped intercumulus liquid. Types B2 and B3 basalts were melted from a portion of the cumulate layer with intermediate amounts of trapped KREEPy liquid. Type B1 basalts from both Apollo 11 and 17 are melted from a "near-perfect" adcumulate portion of this layer. Apollo 12 ilmenite basalts represent the final known melting of this cumulate source, after it had been nearly exhausted of its ilmenite and trapped-liquid components. Type A basalts were probably extruded from a vent or vents near the Apollo 17 landing site [12] and could, therefore, represent melting of a similar source, albeit with the added complexity of neoKREEP assimilation.

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## BASALTIC IMPACT MELTS IN THE APOLLO COLLECTIONS: HOW MANY IMPACTS AND WHICH EVENTS ARE RECORDED?

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Many of the rocks in the Apollo collections from the lunar highlands are impact melt breccias of basaltic bulk composition [1–3]. They are known by a variety of names, including "low-K Fra Mauro basalt" [1], "VHA basalt" [2], and "basaltic impact melts" [3]. These rocks have been studied to understand the compositional nature of the lunar crust [1,4], to decipher the processes of large body impact [4], and to comprehend the record of impact bombardment of the Moon [5].

Study of terrestrial craters has led to a model for impact melt generation (e.g., [6]) whereby diverse target lithologies are totally, not partially, melted during impact. The impact melt makes up a few percent of the total volume of crater material; superheated silicate liquids of the impact melt have extremely low viscosities and mix intimately. This mixing thoroughly homogenizes the melt chemically during the excavation of the crater. Colder, unmelted debris is overridden by the melt sheet as the crater cavity grows. Incorporation of these cold clasts rapidly chills the melt, with zones of greater and lesser amounts of clasts being primarily responsible for modestly differing thermal regimes [6]. The net effect of this process is the production of a suite of rocks that have extreme chemical homogeneity, but wide petrographic diversity (see [7]).

Strict application of this model to the petrogenesis of basaltic impact melts from the Moon has some fairly significant consequences for how we interpret early lunar history. First, total amounts of impact melt are small, usually a few percent of the volume of ejecta (although this fraction may increase as a function of increasing crater size [8]), and such small total melt volumes facilitate rapid cooling. Thus, coarse-grained impact melts must come from the central parts of the melt sheets of relatively large (tens of kilometers) diameter craters [9]. Second, because the chemical composition of melt sheets is extremely homogeneous, the supposed wide chemical diversity of lunar melt compositions reflects the sampling of multiple melt sheets [3,10]. These melt sheets formed in a variety of craters, most of which occur close to or beneath the Apollo highland landing sites [3,9,11]. Third, impact melts are the only products of impact suitable for radiometric dating [5,12]; thus, because (1) only the ages of melt rocks should be considered in reconstructing the cratering rates and (2) the Apollo impact melts are from multiple events that formed large craters, the data from the Apollo samples are telling us that Moon underwent a cataclysmic bombardment about 3.8–3.9 Ga ago, at which time nearly all the Moon's craters and basins were formed [5].

These conclusions are significant to how we perceive the evolution of the Moon as a planetary object, yet few stop to consider that the paradigm of impact melt petrogenesis upon which this depends is itself an incomplete model based on the geology of some poorly preserved terrestrial craters and a few inferences about the physics of large impacts. In particular, the application of this model to the problem of the generation of basaltic impact melts on the Moon creates some difficulties in understanding all the lunar data. Are there really a large number of impact events represented by these melt rocks? What is the role of the largest impact structures (basins) in the genesis of basaltic impact melts?

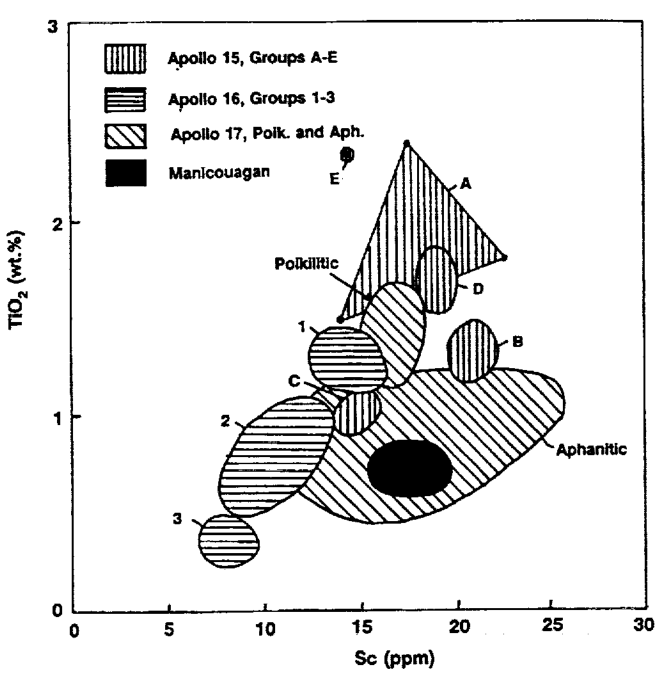


Fig. 1. Variation in Ti and Sc for basaltic impact melts of the Apollo 15, 16, and 17 landing sites (data from the literature). Impact melt sheet of the terrestrial Manicouagan Crater (black) shown for comparison. From [19].

One of the sites on the Moon where it is most appropriate to question the ruling paradigm for impact melting is the Apollo 17 Taurus-Littrow highlands [10,13]. The highland rocks from this site mostly consist of a variety of impact melt breccias, which have been broadly subdivided into two groups based on petrographic texture: the aphanitic and poikilitic melt rocks [6,11–17]. The aphanites appear to be a relatively heterogeneous group [11] and differ from the poikilitic melts in bulk composition [11,13], clast populations [11,14], and ages [15–17]. The group of melts collectively named "poikilitic" [16] are actually diverse texturally, having a variety of igneous textures, but showing remarkable chemical homogeneity [11]. In terms of chemical composition, the aphanites display considerable variation (Fig. 1), especially in comparison with the well studied Manicouagan impact melt (black in Fig. 1); the Apollo 17 poikilitic melts show chemical diversity comparable to that of Manicouagan Crater. These observations led Spudis and Ryder [11] to suggest that the two classes of melts formed in different impact events, with only the poikilitic melts being direct products of the Serenitatis impact. However, other workers preferred to interpret the aphanites as being a part of the Serenitatis Basin melt complex [13,14,17], the differences between the poikilitic and the aphanitic melts being attributable either to derivation of the latter from the margins of the melt sheet or early ejection [18] or the differences being considered insignificant [13,14].

Spudis and Ryder [11] noted an alternative interpretation of the Apollo 17 data: Our understanding of impact melt petrogenesis is incomplete and the terrestrial analogue should be applied to the Moon only with caution. Since that paper was written, a large amount of data has been collected for basaltic impact melts on the Moon: their compositions, their ages of formation, and their regional distribution and geological setting (summarized in [19]). In addition to data on Apollo 17 melt rocks, Fig. 1 also shows the principal melt groups found at other Apollo landing sites (these groups also appear well defined in plots other than Ti-Sc; see [19,20]). Note that with the exception of the Apollo 17 aphanites (and "group" A of Apollo 15, a three-member collection), the melt compositions appear to form diversity envelopes of size roughly comparable to each other and to the terrestrial Manicouagan impact melt sheet (Fig. 1). However, the groups also cluster *by site*, with the Apollo 16 melts making up a diffuse group with low Ti and Sc (groups 1–3, Fig. 1), the Apollo 17 melts having moderate Ti and high Sc (Poikilitic and Aphanitic, Fig. 1), and the Apollo 15 melts having high Ti and Sc (groups A–E, Fig. 1). Finally, note that if the melt groups are considered collectively by site, the resultant envelopes show diversity *no greater* than that displayed solely by the Apollo 17 aphanitic impact melts (Fig. 1).

In addition to these compositional data, we now understand several more things about basaltic impact melts on the Moon than we did 10 years ago. First, these impact melts are distinct in chemical composition from typical upper crust, as determined by remote sensing; they are both richer in KREEP and transition metals and are more mafic (less Al and more Mg) than the anorthositic composition of the upper crust [21,22]. Second, all these melts formed in a very short interval, between about 3.95 and 3.82 Ga ago [5,12–17]. Finally, each of these three Apollo sites is located within, on, or near the rims of three of the largest, youngest [23] basins on the lunar nearside: Apollo 17 occurs within the Serenitatis Basin [11,13], Apollo 15 is on the main rim of the Imbrium Basin [20,22,23], and Apollo 16 is on the backslope of the rim of the Nectaris Basin [19,23,24]. Each of these Apollo sites is in proximity to recognizable deposits of each basin; indeed, such deposits were high-priority sampling targets during these missions [23].

Taking the compositional data (typified by Fig. 1) and the above considerations at face value, I suggest that most of the basaltic impact melts in the Apollo collections represent impact melt from the Nectaris (Apollo 16 groups), Serenitatis (Apollo 17 groups), and Imbrium (Apollo 15 groups) Basins. (From this assignment as basin melt, I exclude Apollo 16 group 3 melts and Apollo 15 group E melt, none of which are "basaltic" in the sense that term is used here (see above) and which are probably from local impacts [20,24].) I believe that the terrestrial Manicouagan Crater, while giving us important insight into certain processes during melt generation, is an incomplete guide to understanding the origin of basaltic impact melts in the Apollo collection. The paradigm of Manicouagan (and other terrestrial craters) has been taken too literally and has been applied incautiously and uncritically to the Moon. Basin formation is an impact event at scales that greatly exceed our experience [19]. There is no independent reason to believe that sheets of basin impact melt are as thoroughly homogenized as is the melt of the terrestrial Manicouagan Crater. Recent study of the impact melt rocks from the suspected K-T boundary crater, Chicxulub, indicates that significant variation in the chemical composition of impact melt may occur in basins on the Earth [25]. Moreover, both the great size of basin-forming impacts and the thermal conditions within the early Moon suggest great quantities of impact melt are generated, not only making complete chemical homogenization less likely, but possibly providing a heat source for a variety of geological effects, including thermal metamorphism of breccias (granulites).

If this scenario is correct, the implications for the geological evolution of the Moon are significant. First, we must revise our model of impact melt genesis and subsequent evolution; such revision, in slightly different contexts, has been proposed for some terrestrial craters [25,26] and impact process in general [27]. Second, the principal evidence for a lunar cataclysm [5] is weakened, although such a cratering history is not excluded in this reinterpretation. If most of the melt samples from these highland landing sites are in fact melt from the three basins listed above, the absence of old impact melts in the Apollo collection reflects dominance of those collections by melt samples from these latest basins (of the over 40 basins on the Moon, Nectaris, Serenitatis, and Imbrium are among the youngest dozen; [23]). However, the argument of Ryder [5] that old impact melts should have been sampled as *clastic debris* from the ejecta blankets of these basins is still valid and their absence remains a puzzling and troublesome fact in this interpretation (although no basin ejecta blanket is well characterized). Finally, the several small to moderately sized "local craters" that have long been invoked to explain the geology of Apollo sites (e.g., [11]) are much less important than often has been assumed [3,9]. Most of the basaltic melts from these sites are from basins, not local craters, a fact evident by virtue of their bulk composition, which cannot be made by small or moderately sized impacts into the local substrate [24]. The only alternative to a basin origin for these rocks is derivation by crater impact into targets far removed (tens of kilometers) from the Apollo sites; the rocks would then have to be ballistically transported to these sites by other impacts [24].

While differing significantly from conventional wisdom, this interpretation of the basaltic impact melts in the Apollo collections is consistent with what we know about the Moon and what we think we understand about the impact process, a field that continues to evolve with new knowledge, insights, and appreciation for the complexity of geological processes. Although this view of the Moon is not proven, I believe it to be a viable alternative that should be considered as we continue our study of the Moon and its complex and fascinating history.

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**FUTURE SCIENTIFIC EXPLORATION OF TAURUS-LITTROW.** G. Jeffrey Taylor, Planetary Geosciences, Department of Geology and Geophysics, SOEST, University of Hawaii, Honolulu HI 96822, USA.

The Apollo 17 site was surveyed with great skill and the collected samples have been studied thoroughly (but not completely) in the 20 years since. Ironically, the success of the field and sample studies makes the site an excellent candidate for a return mission. Rather than solving all the problems, the Apollo 17 mission provided a set of sophisticated questions that can be answered only by returning to the site and exploring further. This paper addresses the major unsolved problems in lunar science and points out the units at the Apollo 17 site that are most suitable for addressing each problem. It then discusses how crucial data can be obtained by robotic rovers and human field work. I conclude that, in general, the most important information can be obtained only by human exploration. The paper ends with some guesses about what we could have learned at the Apollo 17 site from a fairly sophisticated rover capable of *in situ* analyses, instead of sending people. This is an important question because the planned first return to the Moon's surface is a series of rover missions. As discussed below, it seems clear that we would not have learned as much as we did with expert human exploration, but we would not have come away empty handed.

**Unsolved Problems: Moonwide and at Taurus-Littrow:** *Primary differentiation.* It is widely supposed that the Moon was surrounded by an ocean of magma soon after it formed. Ferroan anorthosites formed from this system, accounting for the high Al content of the bulk upper crust. Because the magma ocean was global, accumulations of ferroan anorthosites ought to be global as well. If so,