HASP compositions are cordierite- or mullite-normative, and contain excess Al_2O_3 and SiO_2 after using all of the Ca, Na, and K to make normative feldspar.

Results and Discussion: The compositions of the 107 glasses analyzed from sample 72501 and the 115 from 78221 are plotted in Figs. 1 and 2. The compositions range from nearly 95% refractory components to others composed entirely of more volatile components. HASP compositions comprise ~75% of the total glasses analyzed in each sample. The group 1 HASP glasses comprise ~6% of the total analyses from both 72501 and 78221. The group 1 HASP compositions are the most refractory and the most volatile-depleted of all the analyzed glasses. A cluster of high-Ti glasses were included within group 1 and plot about the origin in Fig. 1. The group 1 high-Ti glasses contain little Ca or Al, but nonetheless have undergone extreme volatile loss in the form of nearly complete removal of Fe from what was once ilmenite (Table 1). The other group 1 members are probably derived from mostly anorthositic material that has lost most of its original SiO_2 content. All but one of the 72501 group 1 HASPs are high-Ti glasses, whereas 78221 contains a larger proportion of the Ca- and Al-rich members of this group (Table 1).

The group 2 HASP glasses span a much wider compositional range in both samples, and comprise 29% of the analyses from 72501 and 27% of those from 78221. These have undergone a lesser degree of volatile loss than those of group 1, and generally retain significant amounts of SiO_2 and FeO, even though considerable amounts of these components have been lost. The average composition of group 2 glasses (in wt%) from both samples is given in Table 1. The similarity in both the relative proportions and the average compositions of the group 2 HASP glasses in these two samples reflects the similarities in bulk soil composition and soil maturity at these two sites. We note that glasses fractionated to the extent of the group 1 and 2 HASP compositions seem to occur only among the finest size fractions.

The group 3 HASP glasses have the least fractionated compositions. The glasses of this compositional type in both samples comprise a larger proportion of the analyzed population than does any other single group (44% of 72501 and nearly 42% of 78221), and the average composition of this group is very similar in both samples (Table 1).

The high-Si glasses are comprised of the relatively volatile elements and are compositionally complementary to the HASP glasses. These compositions make up 13% of the 72501 analyses and 11% of the 78221 population. The compositions of these glasses in both samples span the range from nearly pure SiO_2, sometimes with other associated volatiles such as Na, K, P, and S, to other Si-rich compositions with high Fe concentrations (Table 1). It is believed that the compositions of this group represent the recondensation of impact-generated vapors [3]. As with most of the HASP glasses, these Si-rich compositions are only found among the finest size fractions of lunar soils. This suggests that such extreme fractionations only occur at sizes where the surface-area-to-volume ratio is high enough to allow the degree of melting and vaporization required to produce these unusual compositions.

In both samples, the glasses of basaltic composition constitute a relatively small group, being just over 8% of the analyses from 72501 and nearly 14% of those from 78221. These compositions display little or no observable volatile loss. The average composition of this group (in wt%) from both samples is given in Table 1.

Conclusions: We found that the majority of the analyzed glasses in both soils either have refractory compositions resulting from volatile loss, or are volatile-rich condensates of impact-generated vapors. In both samples, the three HASP groups comprise ~75% or more of the total number of analyzed glasses. The HASP glasses are derived from the bulk soil and from the feldspathic component of the soils through the loss of major amounts of Si and lesser quantities of Fe and alkalis. The Si-rich glasses rival the number of the unfractionated basaltic glasses. The pronounced fractionations (volatilization and condensation) that occur in the submicrometer size range result from the large surface-area-to-volume ratio of the glasses.

This is the first report of high-Ti glasses from lunar soils. Considering all high-Ti glasses from both samples together, a trend is observed that begins with Fe-Ti-rich compositions and extends to glasses that consist of nearly pure TiO_2. We conclude that these compositions originate by the loss of Fe from ilmenite, which is the dominant Ti-rich oxide at the Apollo 17 site. These high-Ti glasses are one of the few types of impact glasses derived from a specific mineral constituent of lunar soils.

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ISOTOPIC AGES AND CHARACTERISTICS OF ANCIENT (PRE-SERENITATIS) CRUSTAL ROCKS AT APOLLO 17.
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Problems with the Isotopic Systematics in Lunar Samples: Four different decay schemes, K-Ar, Rb-Sr, Sm-Nd, and U-Pb, have predominantly been used for age determinations on lunar rocks. These radiometric systems are particularly useful because they have long half-lives that are on the same scale as most lunar rock ages, which is necessary in order to obtain the most precise ages [1]. However, none of these systems is without problems when applied to lunar samples. In order for any single radiometric system to yield a primary crystallization age, it must remain closed from the time of crystallization until the present, without addition or loss of either parent or daughter isotopes. After many years of isotopic work, investigators have come to realize that most lunar samples (nearly all ancient highland samples) have been metamorphosed and their isotopic systematics disturbed [2]. Many studies report completely reset and partially reset Ar-Ar ages—^{40}Ar loss readily occurs during impact metamorphism. However, some Ar-Ar ages agree quite well with other radiometric ages from the same sample, illustrating that Ar is not lost in some lunar samples. Reports of disturbances in the Rb-Sr and U-Pb systems [2–4] as well as the Sm-Nd system [3] are also prevalent in the lunar literature. Disturbed Rb-Sr isochron ages are normally explained by either mobility of both elements or mixing due to brecciation. The Sm-Nd system appears to be the most retentive, although some problems have also been noted. U-Pb and Th-Pb isochron ages typically date metamorphic events [5]. Fortunately, there are two U-Pb systems that can be compared simultaneously in a concordia diagram to "look through" disturbances. This attribute of the U-Pb systems is most desirable when working with lunar samples, and helps to identify both the age of the rock and the age of the disturbance. A major drawback of this approach is the necessity for initial Pb corrections in order to calculate radiogenic Pb/U ratios [5,6]. Initial Pb compositions are typically defined by the y-intercepts on U-Pb and Th-Pb isochron diagrams, but because most U-Pb and Th-Pb isochrons for lunar samples are disturbed, the initial Pb values are undefined and therefore must be assumed. This situation has been confronted with norite 78235 [5]. A possible solution to the problem is to use an age (hopefully accurate), perhaps determined using one of the other dating techniques, and back calculate what the initial Pb values must be in order to produce the same age with the two U-Pb systems. Whereas this procedure relies on an accurate age for the rock, the resulting initial Pb information can be used to characterize the source magma much the same as initial Sr and Nd values, and can have important implications for models of the petrogenesis of lunar magma sources through time.

Because the various isotopic systems are disturbed differently during metamorphism, most samples yield conflicting ages when using the different dating schemes on the same sample. Whereas the discrepancy in ages is usually interpreted as a result of open system behavior due to metamorphic disturbances that characterize lunar rocks, other factors may cause age disparity as well, including either the misuse of basic assumptions regarding the isotopic techniques (e.g., U-Pb), or a lack of understanding of lunar petrogenesis (isotopic closure ages vs. ages of crystallization), or a combination of these factors. One possibility that cannot be dismissed is whether the disparity in ages reflects very slow cooling and crystallizing of the parent magma, particularly at depth in the lunar crust, and therefore the differences in isotopic closure temperatures of the various radiometric systems rather than the age of crystallization of the rock [3]. The isotope data from samples collected at the Apollo 17 site have many of these problems, so that at present investigators have only a very limited reliable (as well as precise) isotope database to work from. Interpretations on the magmatic ages and origins of at least the ancient (pre-Serenitatis) rocks are therefore tentative at best.

Ancient Crustal Ages at the Apollo 17 Site: Samples collected mainly from large boulders ejected from the surrounding regions onto the Taurus-Littrow valley floor include some of the earliest-formed deep crustal cumulates, including the so-called "Mg-suite" of predominantly norites, gabbronorites, troctolites, and dunites. Most of the samples are brecciated such that individual lithologies and monomict clasts are not large enough or accessible enough for most isotopic age work. Consequently, there are only a handful of reliable radiometric ages from this suite of rocks. The following discussion will contain only those data from pristine, monomict, Apollo 17 highland samples. A more complete list of the data and discussion is given in [2]. Figure 1 compares the best of the radiometric ages (32 analyses) from 14 ancient, pristine Apollo 17 samples—some samples have as many as five different age determinations (e.g., troctolite 76535). The data are all from [2,6,7]. Perhaps the most important feature is that Ar-Ar ages are in almost every case younger than ages determined using the other three systems for the same sample. Some of the Ar-Ar ages are completely reset to the estimated age of the Serenitatis impact at ~3.95 Ga (e.g., 72255 and 77215), whereas others probably show partial resetting. Troctolite 76535 is perhaps the best preserved judging from the general concordance of the isotopic systems—three Ar-Ar ages cluster around 4.16 to 4.27 Ga, the older age agreeing generally with two published Pb-Pb isochron ages [6,8] and a Sm-Nd isochron age [9]. In contrast, norite 78235/6 illustrates the problems that exist in some lunar samples. Out of the four different dating schemes, concordance might exist between two of them. There is even a discrepancy from two results using the Sm-Nd system, suggesting isotopic disequilibrium is possible even on a small scale in this sample. If we assume the Ar-Ar results are basically disturbed (except perhaps 78155 and 76535) and use only the results from the other three dating techniques, the oldest rocks are probably the Mg-suite norite 78236 (assuming 4.425 Ga age) and dunite 72417 at ~4.45 Ga. These rocks are then followed by norite 77215 (~4.37 Ga), troctolite 76535 (~4.26 Ga), gabbronorite 73255 (~4.23 Ga), and

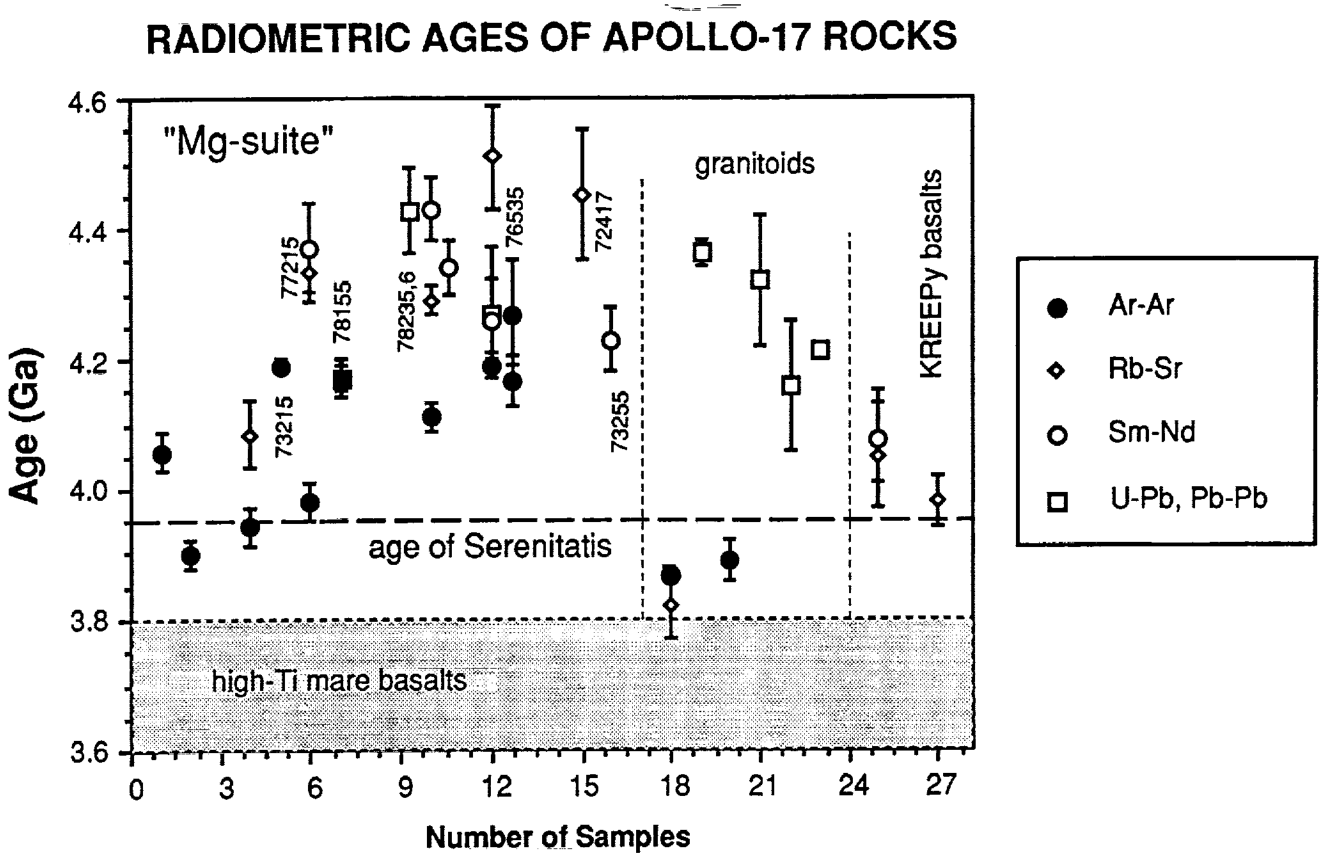

Fig. 1.

norites 73215 and 78155 (~4.17 Ga), although the latter may not be primary ages. Accepting these minimum estimates, Mg-suite formation appears to have continued from ~4.45 to ~4.15 Ga. However, depending on the investigator's interpretation of the isotopic age data, it is also possible to consider a much smaller magmatic interval. For example, we might question the Rb-Sr isochron age for dunite 72417, largely dependent on the mineral olivine, previously noted to be highly altered and possibly isotopically unreliable or disturbed [9] in some of these samples. A "best guess" Pb-Pb age of ~4.37 Ga was reported by [10] for 72415. Conflicting Sm-Nd isochron ages of 4.43 and 4.34 Ga are not supported by other isotopic age results (Fig. 1), resulting in some uncertainty of the true age of norite 78236. If we accept the younger age for this norite and assume that 73215 and 78155 are probably older than 4.17 Ga, then we find that most of the noritic-troctolitic (and probably dunitic) ages lie within a range of ~140 m.y. (4.37 to 4.23 Ga).

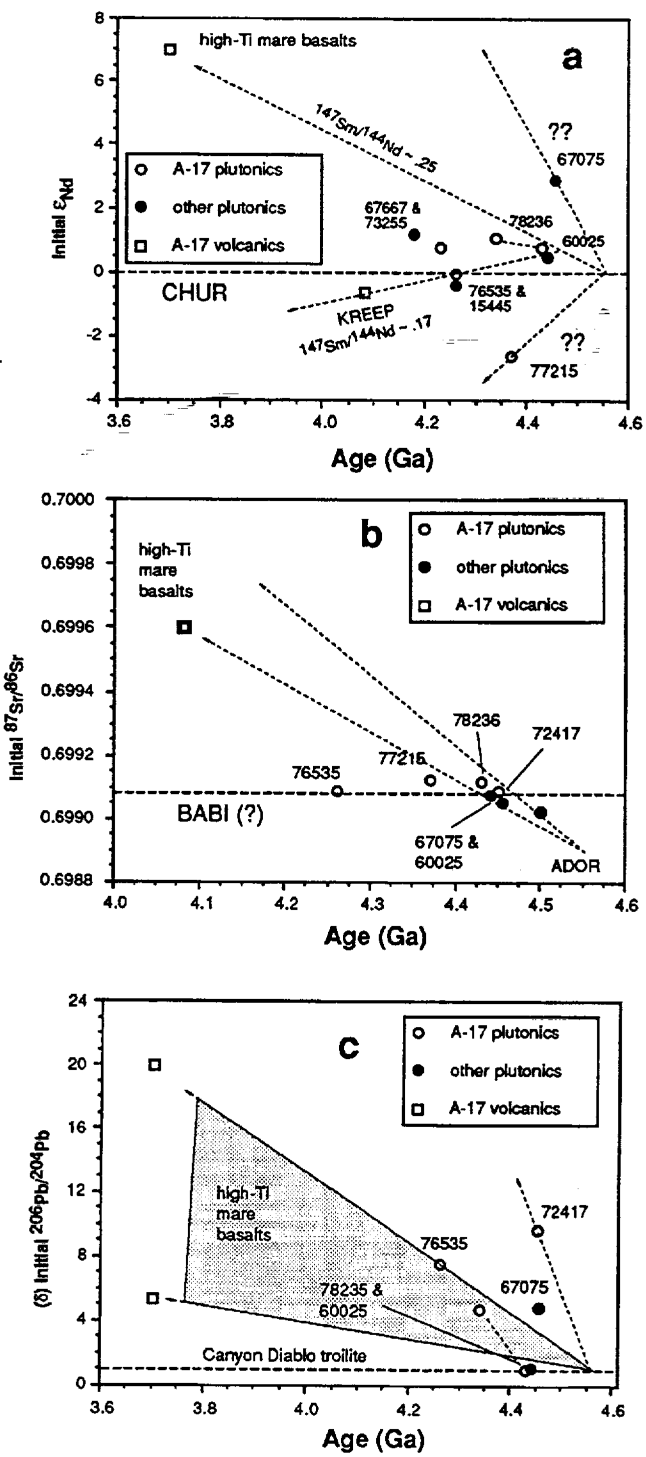

Fig. 2.

Pb-Pb analyses on U-Th-bearing minerals from granitic clasts separated from some of the breccias yield minimum ages between 4.36 and 4.16 Ga, indicating that granitic magmatism occurred contemporaneously with Mg-suite plutonism (Fig. 1), and all the episodes thus far discussed apparently predate KREEP basalt volcanism between 4.1 and 4.0 Ga. These results are interesting because concordant age results from the same sample, basalt 72275, using two different dating techniques, predate estimates for the Serenitatis impact event at ~3.95 Ga (Fig. 1). The isotopic systematics of these basalts were apparently unaffected by the basin-forming event. The KREEP basalts are also apparently at least ~150 m.y. older than the volumetrically dominant high-Ti mare basalts of the Apollo 17 site (Fig. 1). In any case, it should be obvious that there are too few reliable radiometric ages for any of the major ancient igneous rock types at Apollo 17 to feel confident about making any concluding remarks regarding their actual magmatic age durations.

Isotopic Characteristics of Ancient Apollo 17 Rocks: Implications for Their Petrogenesis: Assuming most of the ages given for pristine A-17 rocks are accurate, we can construct Nd, Sr, and Pb isotope evolution curves for the source(s) of these rocks (Fig. 2). With the exception of 77215, all ancient A-17 rocks plot between Nd isotopic evolution curves for the A-17 high-Ti basalts starting from a chondritic value at 4.56 Ga and a KREEP curve that is initiated at ~4.45 Ga (Fig. 2a). Several of the Mg-suite rocks, including troctolite 76535 and norite 15445, lie along the KREEP line, implying their derivation from KREEP-like sources. Depending on which age one prefers for norite 78235/6, it may either be part of an initial pile of mafic cumulates settling out of a lunar magma ocean (Nd isotopes similar to early plagioclase float, anorthosite 60025) or part of a later stack of cumulates, crystallizing from reservoirs with variable $^{147}Sm/^{144}Nd$ ~0.2. Younger gabbronorites, 67667 and 73255, may have formed similarly. Sources for the high-Ti mare basalts appear to have remained undisturbed with a $^{147}Sm/^{144}Nd$ ~0.25; however, these sources may have mixed isotopically with KREEP sources to produce sources for the younger plutonic rocks. The Sr isotope data do not help clarify the Nd data; however, the adherence of the Sr data to the BABI line indicates that all sources maintained an extremely low Rb/Sr value (Fig. 2b). The Sr evolution line for the high-Ti basalts does include within error some of the older A-17 plutonics as well as other ancient highland rocks, including anorthosites 67075 and 60025, dunite 72417, and norite 78236. These rocks all appear to have formed early, perhaps during differentiation of the lunar magma ocean. Troctolite 76535 lies off this line, just as it does on the Nd diagram. The Pb isotope data is too sparse and imprecise to make confident generalizations; however, again the coherence of the data between anorthosite 60025 and norite 78236 would suggest that Mg-suite rocks and anorthosites were both forming simultaneously during differentiation of the lunar magma ocean (Fig. 2c). The initial $^{206}Pb/^{204}Pb$ data is normalized to Canyon Diablo troilite (δ = 1). A large uncertainty on the 67075 data leaves this analysis in question, although an unpublished Sm-Nd internal isochron age of 4455 ± 140 Ma indicates that it was also formed early. An interesting line of ascent is indicated by anorthosite 60025, norite 78235/6, and troctolite 76535, suggesting derivation from magma sources that are progressively evolving to higher $^{238}U/^{204}Pb$ and corresponding initial $^{206}Pb/^{204}Pb$ values.

In summary, the lack of reliable as well as precise isotope data for Apollo 17 igneous rocks inhibits our ability to make confident statements regarding their ages and origins. However, the present state of isotopic art is progressing in the right direction, such that we should be able to obtain more precise data in the coming years, even with the present set of lunar samples. Nonetheless, its obvious that we need larger, pristine, monomict highland samples if we are to finally arrive at real answers.

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THE APOLLO 17 SAMPLES: THE MASSIFS AND LANDSLIDE. Graham Ryder, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058-1113, USA.

More than 50 kg of rock and regolith samples, a little less than half the total Apollo 17 sample mass, was collected from the highland stations at Taurus-Littrow. Twice as much material was collected from the North Massif as from the South Massif and its landslide. (The apparent disproportionate collecting at the mare sites is mainly a reflection of the large size of a few individual basalt samples.) Descriptions of the collection, documentation, and nature of the samples are given in [1–3]. A comprehensive catalog is currently being produced (Ryder, in preparation). Many of the samples have been intensely studied over the last 20 years and some of the rocks have become very familiar and depicted in popular works, particularly the dunite clast (72415), the troctolite sample (76535), and the station 6 boulder samples. Most of the boulder samples have been studied in Consortium mode, and many of the rake samples have received a basic petrological/geochemical characterization.

Sample Numbering: Samples from the South Massif are numbered 72xxx (station 2, but the 721xx samples are from LRV stops on the mare plains), 731xx (station 2 and 2a/LRV-4), and 732xx (station 3, on the landslide). Samples from the North Massif are numbered 76xxx, 77xxx, and 78xxx, with the second digit specifying the station, with the exception of a few LRV stop samples. Rock samples have numbers whose last digit is from 5 to 9; unsieved regolith (including cores) have last digits of 0, and sieved fractions end in 1 to 4 according to the size fraction.

Rock Sampling: Sampling of rocks at the Taurus-Littrow massifs was very comprehensive in style. Multiple rock samples were chipped from boulders of varied sizes ranging from less than a meter to the bus-sized station 6 boulder. The multiple samples were taken to evaluate the visible textural and possible chemical variations of the matrices of the boulders necessary to elucidate their origins, as well as to sample clasts that give insight to older lunar events. The station 7 boulder not only had different matrix textures visible during the field study, but also dikelets that cross-cut an extremely large clast as well. Different subsamples of boulders also had different exposure geometries, providing greater input to cosmic and solar radiation models. Individual documented (i.e., photographed *in situ*) and undocumented rock samples, not obviously directly related to boulders, were also collected. At several stations, samples were collected by raking with a 1-cm-separation rake. Two rake samples were taken at station 2, one at the base of the massif, a few meters from boulder 2, the other on the landslide 50 m away from the base. No rake sample was collected further out on the landslide. On the North Massif, rake samples were taken on the ejecta of a small crater at station 6, and on the rim of a small crater at station 8.

Regolith Sampling: Regolith samples were taken at all massif stations. Samples were taken of general regolith and of material on, under, and adjacent to boulders, mainly by scooping and some by trenching. A double drive tube (total about 70 cm depth) was collected on the light mantle at station 3, and a single drive tube on the North Massif at station 6, to a depth of about 37 cm.

Rock Types: The rock samples collected are different in character as a population from those collected on the Apollo 16 mission or from the Apennine Front on the Apollo 15 mission. In particular, all the larger boulders except boulder 1 at station 2 are very similar in chemistry and crystalline nature to each other, and to a very large proportion of the individual rock and rake samples collected. They have an aluminous basaltic composition with a KREEP incompatible element signature, falling in the general group of low-K Fra Mauro basalts (LKFM) originally defined for samples from the Apollo 14 site. They have crystalline melt matrices ranging from fine grained with olivine microphenocrysts (e.g., 76035) to poikilitic or ophitic (e.g., station 6 boulder). All of them contain mineral and lithic clasts (the latter mainly feldspathic granulites and pristine igneous fragments such as the dunite) and have meteoritic siderophile contamination, with the general similarity of Ir/Au about 1.5 (see summary in [4]). Radiogenic isotope data suggest a common age of around 3.87 Ga for the melting of these samples. The consensus is that these samples represent the impact melt produced by the Serenitatis Basin event. They dominate the sample collection in part because boulders were sampled in accordance with the field plans, and boulders tend to be from the coherent part of the Serenitatis rubble pile, which is the impact melt; older coherent units were broken up by the Serenitatis event.

Boulder 2 at station 2 is different in that it has a friable matrix consisting of a crushed volcanic KREEP basalt and aphanitic melt. This is texturally perhaps (but not chemically) the closest thing to the fragmental breccias at the Apollo 16 site. However, the bulk of boulder 1 consists of aphanitic melt alone, and these melts are different in chemistry from the "Serenitatis" melts, particularly in that they have much lower TiO_2. Some individual rocks collected on the light mantle are very similar to the boulder 1 aphanites, and one of them is a melt "bomb" [5]. As a group they have a clast population different from that of the "Serenitatis" melt (as well as a greater clast content); in particular, they contain more conspicuous granitic (or felsitic) fragments. If these aphanites do not represent an impact distinct from Serenitatis, then they must represent a substantially different phase of it than do the poikilitic rocks (see [4,6] for discussions). The radiogenic age of the aphanitic melts is indistinguishable from that of the poikilitic rocks.

Other impact melts of different composition are present in the Apollo 17 collection, but the range is not as great as that observed among Apollo 16 samples; extremely aluminous melts appear to be absent.

Feldspathic granulites (metamorphosed polymict breccias, most with more than 25% Al_2O_3) are fairly common as small clasts, but a few are individual rake or rock fragments as well. Far greater attention has been given to the pristine plutonic igneous rock fragments that occur both as clasts in the impact melt rocks and as