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The case for an Imbrium origin of the Apollo thorium-rich impact-melt breccias

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Abstract–Mafic, Th-rich impact-melt breccias, most of which are identified with the composition known as low-K Fra Mauro (LKFM), are the most common rock type in the nonmare regoliths of the Apollo lunar landing sites. The origin of mafic impact-melt breccias bears on many lunar problems: the nature of the late meteoroid bombardment (cataclysm); the spatial distribution of KREEP, both near the surface and at depth; the ages of the major basins; and the composition of the early crust of the nearside lunar highlands. Thus, it is crucial that the origin of mafic impact-melt breccias be accurately understood. Because of both intra- and intersite differences in compositions of mafic impact-melt breccia samples, apparent differences in crystallization age, and differences in siderophile-element ratios, previous studies have argued that either (1) most mafic impact-melt breccias are the products of several large craters local to the site at which they were found but that some are of basin origin or that (2) they are all from the Imbrium (Apollos 14 and 15), Nectaris (Apollo 16), and Serenitatis (Apollo 17) basins. Here, we reconsider the hypothesis that virtually all of the Th-rich, mafic impact-melt breccias from the Apollo missions are products of the Imbrium impact.

Ejecta deposit modeling based on modern crater scaling indicates that the Imbrium event produced ejecta deposits that average hundreds of meters thick or more at all Apollo highland sites, which is thicker than some previous estimates. Substantial amounts of Imbrium ejecta should have been sampled at every Apollo highland site. We suggest that the mafic impact-melt breccias may be the principal form of those ejecta. The Imbrium projectile impacted into Th-rich material that we regard as part of a unique, mafic, lunar geochemical province we call the High-Th Oval Region. Based on the surface distribution of Th, only basins within the High-Th Oval Region excavated Th-rich material; the Th concentrations of the highlands as observed by the Apollo orbiting γ-ray experiments are consistent with the estimates from ejecta modeling. Of the younger basin-forming impacts, only Imbrium was large enough to produce the copious amount of melt required by the ubiquitous presence of mafic impact-melt breccias in the Apollo-sampled regolith. The High-Th Oval Region still may have been molten or hot at shallow depths ~4 Ga ago when the Imbrium projectile struck. We reason that compositional heterogeneity of ejected melt breccia is to be expected under these circumstances. We argue that siderophile-element "fingerprints" of mafic impact-melt breccias are not inconsistent with production of all common types by a single projectile. We suggest that the narrow range of ages of 3.7–4.0 Ga for all successfully dated mafic impact-melt breccias may reflect a single event whose age is difficult to measure precisely, rather than a number of discrete impact events closely spaced in time, such that reported age variations among mafic impact-melt breccias reflect the ability to measure ^{40}Ar/^{39}Ar ages with greater precision than the accuracy with which measured portions of mafic impact-melt breccias have recorded the time of their formation.

INTRODUCTION

Impact-melt breccias are one of the most common rock types at the Apollo highland sites (Apollos 14, 15, 16, and 17). These breccias have a wide range of compositions, but most of them, the Th-rich breccias identified with the composition known as low-K Fra Mauro or LKFM (*e.g.*, Vaniman and Papike, 1980; BVSP, 1981), are relatively mafic and are the most common mafic lithology in nonmare regoliths. Because there are both inter- and intrasite differences in texture, composition, siderophile-element ratios, and reported crystallization ages among these breccias, a number of investigators have reasoned that at least some of them must have been formed by subbasin sized impacts (Simonds *et al.*, 1977; Spudis and Ryder, 1981; Ryder and Seymour, 1982; James *et al.*, 1984; McKinley *et al.*, 1984; Reimold and Nieber-Reimold, 1984; Ryder and Spudis, 1987; Korotev, 1987a, 1991; Dalrymple and Ryder, 1996). On the other hand, derivation of some types of mafic impact-melt breccias from basins has been advocated since early Apollo and post-Apollo days (*e.g.*, Ganapathy *et al.*, 1972; Wood, 1975; Hertogen *et al.*, 1977; Winzer *et al.*, 1977; Ryder and Wood, 1977) and is now accepted by most students of the subject (*e.g.*, Spudis, 1984, 1992; Lucey *et al.*, 1995; Warren, 1996). There are two main arguments in favor of the formation of mafic melt breccias in basins: (1) the breccias are substantially more mafic than nonmare regoliths (Fig. 1a), and, thus, they must have been formed by impacts large enough to penetrate the outer feldspathic crust and melt underlying mafic material (Ryder and Wood, 1977; Spudis and Davis, 1986); (2) the ratio of melt volume to crater volume increases with crater volume (Cintala and Grieve, 1994), and a substantial fraction of ejecta consists of melt only for basins and mainly just for the largest basins (Warren, 1996). Thus, simply from a probabilistic viewpoint, most impact-melt breccias were likely formed in one or more basins.

A popular hypothesis has been that mafic melt breccias from a given Apollo site come mainly from the basin that is nearest that site—Imbrium for Apollos 14 and 15, Nectaris and Imbrium for Apollo 16, and Serenitatis for Apollo 17. Spudis (1992) has suggested that virtually all mafic impact-melt breccias collected by the Apollo

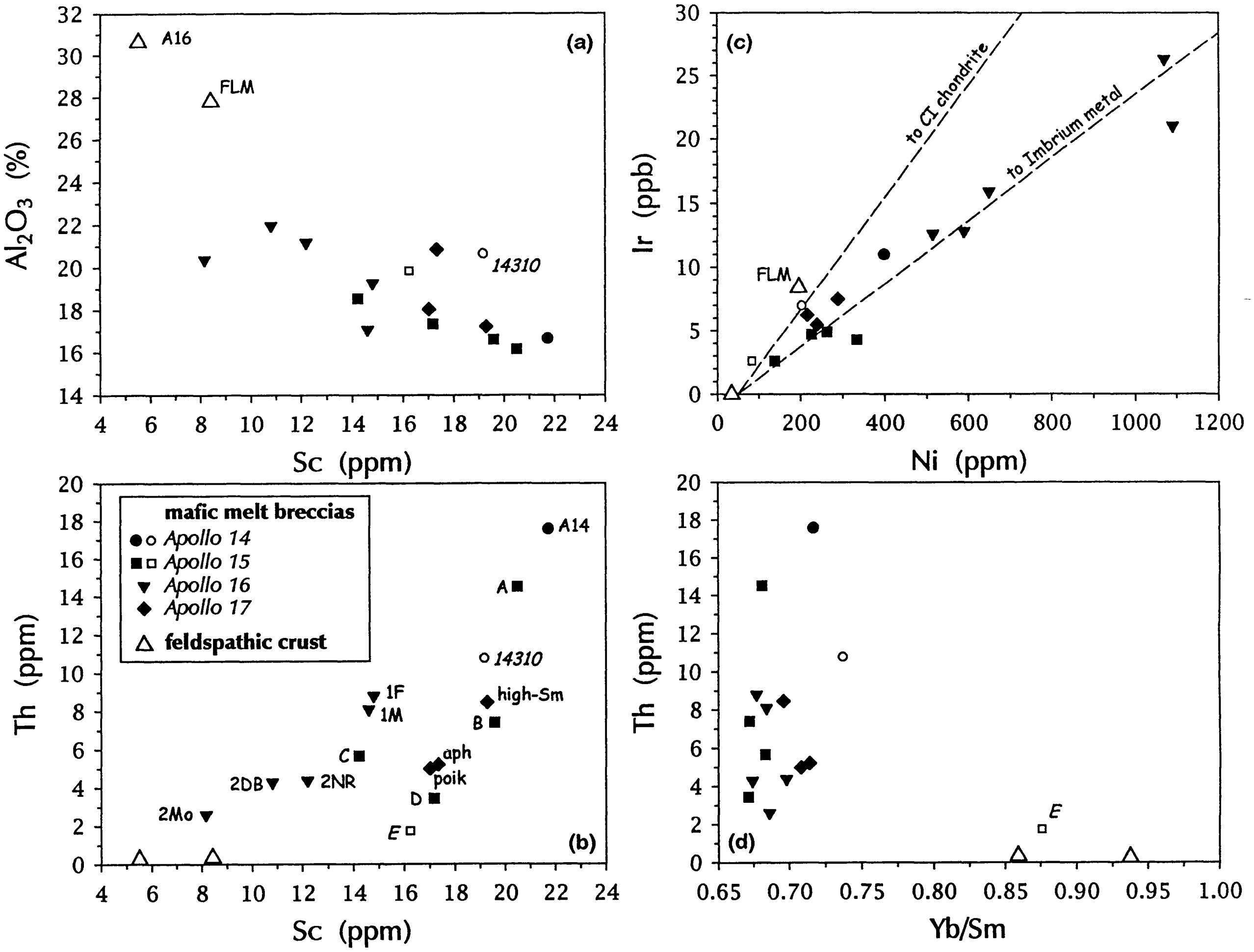

FIG. 1. Some element concentrations and ratios in Apollo mafic impact-melt breccias and a comparison to two estimates of typical upper feldspathic crust (large open triangles). The feldspathic crust point labeled A16 is an estimate of the pre-Imbrium crust at the Apollo 16 site (mean of columns 5 and 6 of Table 3 of Korotev, 1996); the point labeled FLM represents the mean composition of the four most feldspathic lunar meteorites (ALHA81005, Yamato 86032, MAC 88105, and QUE 93069; data from many literature sources). Each filled symbol represents the mean composition of a recognized compositional group (Spudis and Ryder, 1981; Ryder and Spudis, 1987; Lindstrom *et al.*, 1990; Korotev, 1994; Jolliff *et al.*, 1996). (a) Clast-poor sample 14310 and similar Apollo 14 rocks are excluded from consideration here because they are probably postbasin melts formed in a regolith dominated by mafic melt breccias but containing some mare material, hence the anomalously high Sc concentration. (b) All mafic impact-melt breccias are much richer in Th than typical feldspathic crust. Apollo 16 group 2Mo has anomalously low concentrations of Sc and Th (for a mafic melt breccia) because it contains a large component of troctolite, effectively diluting the KREEP component (Korotev, 1994, 1997a). (c) All five groups of Apollo 16 mafic melt breccias (filled triangles) are richer in siderophile elements than melt breccias from other sites. The dashed lines are mixing lines between meteoritic materials and meteorite-free lunar silicates containing 50 ppm Ni and essentially zero Ir. The "Imbrium metal" line is defined by the mean composition of metal from the Apollo 16 mafic melt breccias (Table 5 of Korotev, 1994). The feldspathic lunar meteorites (FLM) plot along the CI line because they are regolith breccias in which the siderophile elements are dominated mainly by chondritic materials (*e.g.*, Korotev *et al.*, 1996a). (d) Apollo 15 group E (small open square) of Lindstrom *et al.* (1990) is not included in the suite of mafic melt breccias discussed here because ratios of incompatible trace elements are significantly different from the KREEP-like ratios observed in the others.

missions were produced during formation of these three basins. At Apollo 17, in particular, the hypothesis of nearest-basin origin has become a dogma. For instance, Spudis and Ryder (1981) stated that "One of the few aspects of Apollo-landing-site geology on which there is virtual unanimity of opinion is the origin of the terra melt rocks collected at the Apollo 17 Taurus-Littrow landing site. These rocks [are]...representative of an ejecta sequence from a single large impact, which formed the Serenitatis basin.". This sentiment was echoed a decade later by Warren (1992), who stated that "the Serenitatis basin is the one lunar basin from which we confidently identify a suite of samples as pieces of the impact melt sheet..."

In detail, the principal arguments in support of the Serenitatis origin of the Apollo 17 poikilitic impact-melt breccias are summarized as follows (Rockow and Haskin, 1996): (1) The Apollo 17 site is at the eastern edge of the Serenitatis basin, so Serenitatis ejecta must be abundant (*e.g.*, Head 1979, 1992). (2) Photogeologists have interpreted the Taurus-Littrow massifs as uplifted blocks or ejecta deposits of Serenitatis origin; deposits having morphologies indicative of Imbrium sculpture or lineation appear to be minor or absent from the Apollo 17 site (*e.g.*, Wolfe and Reed, 1976; Spudis, 1993). (3) Of the two textural variants of mafic melt breccia occurring at the site, aphanitic and poikilitic, the poikilitic breccias appear to derive from outcrops high on the massifs. The poikilitic breccias are also more abundant and compositionally homogeneous. Thus, the poikilitic breccias have been regarded as the ones most likely to be samples of the Serenitatis melt sheet (*e.g.*, Dalrymple and Ryder, 1996). (4) The lithophile-element compositions of the Apollo 17 poikilitic impact-melt breccias are different from those of mafic impact-melt breccias from other Apollo sites, which is interpreted by some to mean that they represent one or more impacts different from those producing mafic impact-melt breccias at other sites (*e.g.*, Reed and Wolfe, 1975). (5) The Apollo 17 mafic melt breccias also have a unique siderophile-element fingerprint, presumably representing the unique impactor that formed them (*e.g.*, Morgan *et al.*, 1974; James, 1996). (6) The Apollo 17 poikilitic melt breccias yield older Ar-Ar ages than the Apollo 14 mafic impact-melt breccias and some of the Apollo 15 mafic impact-melt breccias (*e.g.*, Turner and Cadogan, 1975; Dalrymple and Ryder, 1993, 1996). (7) Early ejecta modeling indicated that Serenitatis ejecta would dominate the geology of the Taurus-Littrow site (*e.g.*, McGetchin *et al.*, 1973). In addition to those arguments, we note that the large size of the Apollo 17 poikilitic breccia boulders and the even larger deposits in the highland massifs from which they broke away, coupled with their relatively coarse matrix textures and inferred cooling history, are consistent with their being remnants of impact melt produced nearby and emplaced by a low-energy mechanism.

Despite this evidence, we find first-order properties of the Apollo 17 poikilitic breccias and other Apollo mafic impact-melt breccias that are puzzling to understand under the multiple-basin hypothesis of origin but are more easily explained if we assume a single-basin origin for most or all of them. The economy of explanation associated with a single-basin origin, however, requires that there be other explanations for several properties of mafic impact-melt breccias that previously have been explained by the nearest-basin hypothesis. It is the purpose of this paper to discuss the case for a single-basin origin, indicate complications that result from that hypothesis, and seek to resolve those complications in a manner consistent with the single-basin hypothesis. The hypothesis we examine here is an old one, namely, that the bulk of the Th-rich, mafic impact-melt breccias at the Apollo sites were produced by the Imbrium event (*e.g.*, Tera *et al.*, 1973, 1974; Evensen *et al.*, 1974; Reid *et al.*, 1977; Schaeffer and Schaeffer, 1977). The origin of the mafic impact-melt breccias bears on many lunar problems. These include the nature of the "cataclysm" (*e.g.*, Tera *et al.*, 1973, 1974; Ryder, 1990), the spatial distribution of KREEP near the surface and at depth (*e.g.*, Metzger *et al.*, 1973, 1974; Schonfeld and Meyer, 1973; Warren, 1988), the ages of the major basins (*e.g.*, Wilhelms, 1987; Nyquist and Shih, 1992; Deutsch and Stöffler, 1987; Dalrymple and Ryder, 1993, 1996), the nature of impact cratering, and the composition of the early crust of the nearside highlands (*e.g.*, Ryder and Wood, 1977; Korotev, 1996), so their origin is worth a further look. In our discussion, we focus on the Apollo 17 poikilitic breccias because, as noted above, these are the ones generally thought most unlikely to be of Imbrium origin.

We summarize our arguments and hypothesis as follows. The Imbrium event produced ejecta deposits that we expect to average hundreds of meters thick or more at all Apollo highland sites. Thus, it is probable that, at distances from Imbrium that correspond to those of the Apollos 14, 15, 16, and 17 sites, substantial amounts of Imbrium ejecta would have been sampled. Of the younger basin-forming impacts, the Imbrium event was the largest and was capable of ejecting quantities of melt consistent with the ubiquitous presence of mafic impact-melt breccias in the Apollo-sampled regolith. Imbrium ejecta are rich in Th whereas ejecta deposits of other basins are not (Haskin, 1998). As measured from orbit, the concentration of Th on the lunar surface generally decreases with distance from the Imbrium–Procellarum region. Thus, we speculate that the Imbrium projectile impacted into part of a unique, heterogeneous, mafic geochemical province, one known from remote sensing to have high Th concentrations, the "High-Th Oval Region" of Haskin (1998). Because the only abundant, Th-rich rocks in Apollo regoliths are mafic impact-melt breccias, these must be the principal ejecta from Imbrium. The proportions of melt in Imbrium ejecta would have been enhanced if the High-Th Oval Region was still partially molten or hot at shallow depths ~4 Ga ago when the Imbrium projectile struck (Haskin, 1998). Apollo 16 mafic melt breccias contain a high abundance (1–2%) of FeNi metal that is compositionally similar to metal in some iron meteorites. Metal of similar bulk composition occurs in lesser abundance in the mafic melt breccias of other Apollo sites. Thus, the bolide that formed the Imbrium basin was probably an iron meteorite.

We first define which lunar materials we include in the category of mafic impact-melt breccias. We then provide some results of modeling and the details of the observations that have led us to question the hypothesis of a nearest-basin origin and to reconsider the hypothesis of a single-basin origin. Finally, we discuss the observations that appear to support a nearest-basin origin and ways in which these observations might be consistent with a single-basin origin.

MAFIC IMPACT-MELT BRECCIAS: A DEFINITION

Lunar impact-melt breccias occur in a wide range of textures and compositions. Some have glassy or aphanitic matrices, whereas others are more coarsely crystalline. Clast proportions are highly variable. Concentrations of Al_2O_3 range from 13% to at least 32% (Taylor *et al.*, 1991; Stöffler *et al.*, 1985), which reflects the range in average compositions of the target areas of the impacts. Of concern here are those breccias on the mafic end of the range, namely, those that are more or less basaltic, noritic, or even troctolitic in chemical composition. We define mafic impact-melt breccias as those with 19–29% $TiO_2 + FeO + MgO$ (*i.e.*, 14–22% Al_2O_3, Fig. 1a); crystalline impact-melt breccias more mafic than this are virtually unknown. In the subsequent discussion, we implicitly restrict ourselves to that subset of mafic impact-melt breccias that have the following additional characteristics: (1) crystalline melt breccias (Stöffler *et al.*, 1980; Taylor *et al.*, 1991) that are not the products of remelting of a protolith dominated by older mafic impact-melt breccias, (2) relatively high concentrations of incompatible trace elements (*e.g.*, $\gtrsim$3 ppm Th; Fig. 1b), (3) relative abundances of incompatible trace elements that are similar to those of KREEP basalt, and (4) high concentrations of siderophile elements compared to lunar igneous rocks (*e.g.*, Ni: >150 μg/g; Fig. 1c). Among impact-melt breccias with <22% Al_2O_3, these restrictions eliminate only a few samples. Rocks eliminated by restriction (1) are not necessarily easy to identify, but some glassy breccias from Apollo 16 and Apollo 14 samples 14310 and 14276 (clast-poor crystalline rocks) are likely examples (*e.g.*, Taylor *et al.*, 1991). Restrictions (2), (3), and (4) together eliminate melt breccias of compositional group E of Apollo 15 (Lindstrom *et al.*, 1990). Such breccias are unusual compared to the others in having non-KREEP-like ratios of heavy to light rare earth elements (Fig. 1d) and low absolute concentrations of incompatible trace (Fig. 1b) and siderophile elements (Fig. 1c). We argue here that the typical, Th-rich (3–18 ppm), mafic impact-melt breccias are related by a common process and region of origin. The Apollo 15 group-E impact-melt breccias may be similarly related, but their unusual composition suggests that they are not. As presumably extrusive igneous rocks, Apollo 15 and 17 KREEP basalts are eliminated from our definition, despite their compositional similarity to mafic impact-melt breccias.

At Apollo 14, Apollo 17, and, to a lesser extent, Apollo 15, there is a compositional dichotomy between mafic and feldspathic impact-melt breccias. This is not the case at Apollo 16, where there is a continuum (with some clusters) from mafic to highly feldspathic. Our cutoff of 22% Al_2O_3 deliberately includes the impact-melt breccias associated with the Apollo 16 dimict breccias and feldspathic fragmental breccias of North Ray crater (*i.e.*, groups 2DB and 2NR of Korotev, 1994) and excludes samples (*e.g.*, 61016) that appear compositionally to be mixtures of mafic impact melt and feldspathic material. Samples of Apollo 16 groups 2DB and 2NR tend to form tight clusters on two-element concentration plots (1994) suggesting that their compositions represent compositions of fragment-laden melt; more feldspathic variants of the group-2 melt breccias or "VHA basalts" (*e.g.*, McKinley *et al.*, 1984; Spudis, 1984; Korotev, 1994) do not.

The mafic impact-melt breccias include rocks that have been given a variety of names, for example, LKFM (low-K Fra Mauro "basalt"), poikilitic breccias, basaltic impact melt, crystalline-matrix breccias (*e.g.*, Stöffler *et al.*, 1980; BVSP, 1981; Korotev, 1994). We prefer the term "mafic impact-melt breccia" because it is consistent with the recommended nomenclature of Stöffler *et al.* (1980) and is more accurately descriptive and less misleading than terms like "LKFM" or some kind of "basalt." For convenience and readability, however, we sometimes use the simpler term "mafic melt breccia" in the discussion below.

MODELING AND OBSERVATIONS SUGGESTING AN IMBRIUM ORIGIN

Ejecta Deposit Modeling

Our reconsideration of the source region of the mafic impact-melt breccias was initially prompted by new modeling of ejecta deposit thicknesses, based on modern equations of crater scaling (Holsapple and Schmidt, 1982; Housen *et al.*, 1983; Schmidt and Housen, 1987; Holsapple, 1993) and ballistic sedimentation (*e.g.*, Oberbeck, 1975). This led to a demonstration that the distribution of Th at the Moon's surface may be consistent with an origin as Imbrium ejecta (Haskin, 1998). We will refer to the new model as the model of Moss *et al.* (Moss and Haskin, 1994; Moss, Haskin, and McKinnon, unpubl. model, 1998; Haskin *et al.*, 1995).

The model of Moss *et al.* takes into account the mixing of primary ejecta fragments with the substrate onto which they fall to produce the final ejecta deposits (*e.g.*, Oberbeck *et al.*, 1974). The average results are similar to those of the model of Oberbeck *et al.* on which the model of Moss *et al.* is based, but the model of Moss *et al.* also provides a probability distribution for deposit thickness as a function of the area of sampling. Using that model, Moss *et al.* obtain the following estimates of the average areal distribution of deposit thickness and fractions of Imbrium ejecta in those deposits at the distance from Imbrium that corresponds to the location of the Taurus-Littrow Valley. On average, for the smallest presumed Imbrium transient crater (335 km radius; McGetchin *et al.*, 1973), the probability is 80% that the thickness of Imbrium deposits at the Apollo 17 site (4 transient crater radii from the center of Imbrium) lies between ~270 m to 2.5 km, and the probability that the thickness is <100 m is only <0.5%. Proportions of Imbrium material in the deposits are ~30%. For the largest presumed Imbrium transient crater, 485 km, the corresponding values are ~1.2 to 6.8 km. The probability that the thickness is <250 m is only <0.06%. At this distance (1300–1400 km, ~3 transient crater radii) from the Imbrium basin, the estimated deposit thicknesses should be valid to within better than a factor of two. Thus, it seems unlikely that the Apollo 17 crew could have missed collecting some Imbrium ejecta. Similar arguments can be made for the other Apollo highland sites.

The High Proportions of Mafic Impact-Melt Breccias in the Apollo Regoliths

In wondering just which material sampled from the Apollo 17 highlands seemed most likely to have come from Imbrium, we considered that the Imbrium component would probably be rich in Th, given that the Imbrium projectile impacted into a region observed to have anomalously high Th concentrations (Metzger *et al.*, 1977). We have postulated that the Imbrium impactor struck a unique, geochemical province produced during magmatic differentiation, a province we call the High-Th Oval Region (Haskin, 1998). Such a province was proposed by Evensen *et al.* (1974) and hinted at by Metzger *et al.* (1973) and Haines *et al.* (1978). The only Th-rich lithologies prevalent in the Apollo 17 regolith are the poikilitic and aphanitic impact-melt breccias (*e.g.*, Table 2 in Jolliff *et al.*, 1996). Thus, these melt breccias seem the most likely lithology to be Imbrium ejecta, if Imbrium ejecta are as common at the site as our modeling implies that they should be. Mafic melt breccias of similar composition are also common and are the principal carrier of Th in regoliths at the Apollos 14, 15, and 16 sites (Jolliff *et al.*, 1991; Korotev, 1987b, 1997b), although KREEP basalt may constitute a significant fraction of the Apollo 15 regolith. In our recent reconsideration of the source of the Apollo 16 mafic impact-melt breccias, various geochemical arguments led us to conclude that, despite their compositional diversity and despite the proximity of the site to the Nectaris basin, Imbrium was the most likely source region for all of them (Korotev, 1997b). At both Apollos 16 and 17, we are faced with a similar dilemma: If the Th-rich melt breccias are not the principal Imbrium component of the regolith, then either (1) the melt breccias are pre-Imbrium, local components that happen to be richer in Th and more mafic than any of the Imbrium components of the regolith or (2) there are few Imbrium ejecta at either site. The distribution of Th on the lunar surface argues against option (1), and our ejecta modeling argues against option (2). Thus, we are forced to consider seriously that the Apollo mafic impact-melt breccias are the principal ejecta product of the Imbrium impact.

Available evidence suggests that Th-rich, mafic impact-melt breccias are not common in regoliths that are distant from the Imbrium–Procellarum region. The concentration of Th on the lunar surface (Metzger *et al.*, 1977) generally decreases with distance from the Imbrium basin (Haskin, 1998). There is no evidence in our present data for the distribution of Th that any basin outside the High-Th Oval Region (*e.g.*, Serenitatis, Nectaris) ejected Th-rich material. Although Lucey *et al.* (1995) note that the interior of the South Pole Aitken basin contains ~10% FeO, which is a value consistent with the LKFM composition, it is not known whether this material has the high Th concentrations of the Apollo mafic melt breccias; regions of the continuous ejecta deposit from South Pole Aitken Basin do not (Haskin, 1998). None of the seven feldspathic lunar meteorites, all of which are breccias representing near-surface regoliths from presumably random impact sites in the highlands (*e.g.*, Warren, 1994), is rich in Th, and clasts of Th-rich materials are rare in these breccias. Among all lunar meteorites, only Calcalong Creek contains >1 ppm Th (4.6 ppm; Hill *et al.*, 1991).

The proportions of mafic impact-melt breccias in the Apollo soils fall within the ranges of the average proportions of primary Imbrium ejecta modeled in those regoliths (Table 1). The proportions of impact-melt breccias are, in fact, so high that our ejecta modeling is consistent with an Imbrium origin for the breccias only if much or most of the Imbrium ejecta was impact melt. This possibility is not unreasonable. The volume of impact melt (V) rises exponentially ($V \propto D^{3.85}$) with the diameter of the transient crater (D) (Grieve and Cintala, 1992; Cintala and Grieve, 1994), and, thus, most of the Moon's impact melt was produced by the few largest of the basin-forming impacts (Warren, 1996), of which Imbrium was the last to occur. Melt could constitute 25 to 30% (smallest to largest proposed Imbrium diameter) of the transient crater cavity volume (Cintala and Grieve, 1994) in an impact into a cold target. If the Imbrium target area was warm or perhaps partially molten as a result of the high concentrations of K, Th, and U (Spudis, 1984; Spudis *et al.*, 1984; Haskin, 1998), then we would expect an even larger volume of melt. Finally, if the Imbrium bolide was an iron, as we argue below, ~11% more impact melt would be produced than if it were a chondrite (Grieve and Cintala, 1992).

Photogeologic evidence suggests that some lunar craters may have been formed by secondary impact of melt ejected from basins (Schultz and Mendenhall, 1979), and theoretical considerations indicate that much of the Imbrium melt would have been ejected from the parent crater. Warren (1996) provided an estimate of the proportion of the ejecta that would consist of impact melt for such a case. If we assume that ~45% of the volume of the transient crater was ejected, then according to Warren's estimates, the proportion of melt in the ejecta would be ~35–40%. For the largest proposed Imbrium transient crater ($r = 485$ km), we estimate that the average ejecta deposits at the distance from Imbrium of the Taurus-Littrow Valley would have proportions of Imbrium material in the range ~50 to ~60%. If so, the expected proportion of melt from the Imbrium event in the ejecta deposit at the Apollo 17 site would be ~18–25%, and the proportion of impact-melt breccia would be at least 30% if the melt breccias consisted of 20% clasts, on average, which is our estimated minimum amount. The observed proportion of mafic melt breccias in highland regolith (*i.e.*, post-Imbrium, pre-mare) materials at the Apollo 17 site is not uniform; our observations range from ~26 to ~95% (Table 1). The estimated and observed proportions match more closely for the Apollos 14, 15, and 16 regoliths. An exact match is too much to expect for modeling of this type, but the magnitude should be about right, and it is. Again, the proportion of impact melt in the ejecta and, therefore, the regolith would be greater than expected from the modeling of Warren (1996) if the Imbrium target region was hot or partially molten when the Imbrium impact occurred.

Some Th-rich mafic impact-melt breccias may be produced by subbasin sized impacts. In particular, mafic impact-melt breccias produced by small impacts might be present in the regolith at the Apollo 14 site (*e.g.*, sample 14310; Fig. 1). Because that site lies within the High-Th Oval Region, the pre-Imbrium regolith would already have been mafic and rich in Th. Thus, Imbrium ejecta would have dug into a substrate as mafic and as rich or richer in Th than the ejecta themselves. Later, smaller impacts into the post-Imbrium regolith within the High-Th Oval Region could produce mafic impact-melt breccias. Because subbasin sized impacts produce relatively small proportions of impact melt, however, they cannot account for the high proportions of mafic impact-melt breccias observed in all Apollo highland regolith. The majority must be of basin impact origin.

The Prevalence of $Fe_{94}Ni_6$ Metal

A third observation that leads us to suspect that impact-melt breccias from different sites are related by a common impactor is the prevalence of $Fe_{94}Ni_6Co_{0.4}$ metal in the breccias. A discussion of this metal best begins with Apollo 16 breccias. Mafic melt breccias from Apollo 16 are distinct in that they have much higher concentrations of siderophile elements than mafic melt breccias from other sites (Fig. 1c). They also have the lowest Ir/Au ratios (Fig. 2). The carrier of the siderophile elements and the low-Ir/Au fingerprint in Apollo 16 melt breccias has been unambiguously identified as $Fe_{94}Ni_6Co_{0.4}$ metal (Wasson *et al.*, 1975; Korotev, 1987a, 1990, 1994) that is prevalent as grains in the breccias (Brecher *et al.*, 1973; Hewins and Goldstein, 1975; Misra and Taylor, 1975; James *et al.*, 1984). From mass balance considerations for Ni, Ir, and Au,

TABLE 1. Comparison of the average proportion of primary Imbrium ejecta at various highlands landing sites, as estimated from the model of Haskin *et al.* (1995), with estimates of the proportion of mafic impact-melt breccias in the nonmare regoliths of those sites.

	Primary Imbrium ejecta (%)		Mafic impact-melt breccias		
	Small	Large	(%)	Method, grain-size fraction, and samples	Source
Apollo 14	40	65	62	Particle count, 2–4 mm, 14161	1
Apollo 15, Apennine Front	75	90	60–80	Mass balance, range for <1 mm soils from stations 2, 6, and 7	2
			~60	Mass balance, most Sc-poor <1 mm soils from station-2 core 15007/8	3
Apollo 16, Cayley Plains	25	45	25–32	Mass balance, range of all mature <1 mm soils	4
Apollo 17, South Massif	30	55	41–52	Mass balance, range for <1 mm soils of stations 2, 2A, and 3	5
			85–95	Particle count, 2–4 mm, two station-2 soils	6
Apollo 17, North Massif	30	55	26–31	Mass balance, range for <1 mm soils of stations 6, 7, and 8	5
			43–45	Particle count, 2–4 mm, two station-6 soils	6
Luna 20	14	30	~9?	Particle count, ~0.5–1 mm, regolith core	7

For Apollos 15 and 17, "%mafic impact-melt breccia" values represent only the proportion of mafic impact-melt breccias among the nonmare lithologies or components because the mare materials (crystalline basalt, pyroclastic glass) are postbasin contaminants. "Small" and "large" indicate the smallest (335 km) and largest (485 km) proposed radii of the Imbrium transient crater; see text. Sources: (1) IMBx+IMR from Jolliff *et al.* (1991), normalized to regolith-breccia-free basis; (2) model of Duncan *et al.* (1975); (3) data of Korotev (1987b), model results of this work; (4) model results of Korotev (1997b); (5) model results of Korotev and Kremser (1992); (6) data from Jolliff *et al.* (1996); differences between (5) and (6) probably reflect actual differences with grain size (Jolliff *et al.*, 1996); (7) of the 44 particles of Fig. 6 of Swindle *et al.* (1991), four (9%) have compositions consistent with mafic impact-melt breccias (*i.e.*, >8 ppm Sm and >10 ppm Sc), although one of the particles, 22023,7J of Korotev and Haskin (1988), is known to be a regolith breccia.

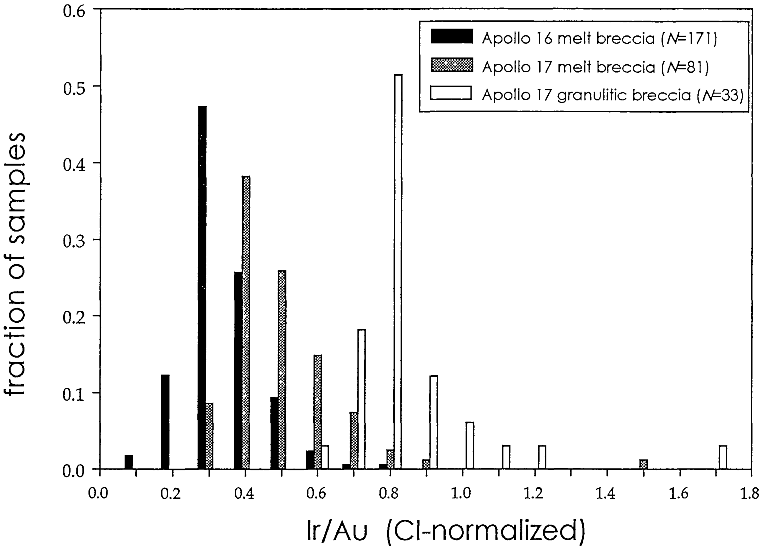

FIG. 2. Frequency of samples with a particular Ir/Au ratio. The plot shows that Apollo 17 mafic melt breccias have Ir/Au ratios intermediate to those of Apollo 16 mafic melt breccias and Apollo 17 granulitic breccias. Bars designated "melt breccias" are based on samples of mafic impact-melt breccias, with no distinction according to compositional group. All data are from this laboratory (Korotev, 1994; Jolliff *et al.*, 1996), which provides the advantage of eliminating interlaboratory bias and providing data for many more samples than are available from other laboratories but the disadvantage that both elements are determined imprecisely at low concentration. To increase the precision of this plot, only samples with >250 ppm Ni are included. On average, the Ir/Au ratio of the Apollo 16 breccias plotted here is known to ~15% and the Apollo 17 melt breccias, to ~35% (1σ). Thus, the spread in values at Apollo 16 (at least) is largely due to actual differences among the small samples. For Apollo 16, the average mass of the analyzed samples is 79 mg; for Apollo 17, the average mass is 28 mg. Iridium and Au concentrations are normalized by the concentration in CI chondrites (Anders and Grevesse, 1989).

the average concentration of metal in Apollo 16 mafic melt breccias must be very high, ranging from 1 to 2% depending on the type of breccia (Korotev, 1987a, 1994). The concentrations and ratios of Fe, Ni, Co, Ir, and Au in the metal are nonchondritic but fall within the range of group I and II iron meteorites (Korotev, 1987a; James, 1995). Because the siderophile elements are carried by metal grains of varying size and distribution, absolute concentrations of those elements vary considerably among small subsamples; thus, it is not uncommon for two small (~50 mg) subsamples of the same breccia to have absolute concentrations of siderophile elements that differ by a factor of ten.

Metal of similar bulk composition (*i.e.*, 6 ± 2% Ni, 0.4 ± 0.2% Co) occurs at all Apollo sites. Such metal is found in the regoliths of Apollos 11 and 12 (Goldstein *et al.*, 1970; Goldstein and Yakowitz, 1971). It is prevalent in the Apollo 14 regolith (Goldstein *et al.*, 1972; Wlotzka *et al.*, 1972), the group-D mafic melt breccias (sample 15455) from Apollo 15 (Hewins and Goldstein, 1975), and the poikilitic melt breccias of Apollo 17 (Dymek *et al.*, 1976; Misra *et al.*, 1976). Unfortunately, data for other compositional groups of mafic melt breccia are lacking and, to our knowledge, no measurements have been made of Ir and Au concentrations or ratios in $Fe_{94}Ni_6$ metal grains in mafic melt breccias from sites other than Apollo 16. (Rock 14306 of Ganapathy *et al.*, 1974, which appears to be a regolith breccia, and soil 14163 of Wlotzka *et al.*, 1972, probably include metal from several sources; the sample of rock 14321 of Wlotzka *et al.*, 1972, is probably an igneous basalt.)

The ubiquity and uniformly high abundance of meteoritic metal in the Apollo 16 mafic melt breccias is the principal geochemical argument that all of the breccias were formed in one impact (Korotev, 1997b). The presence of compositionally similar metal in the melt breccias of other sites supports a single-impact hypothesis for all mafic melt breccias and poses a significant hurdle to any multiple-impact hypothesis.

RECONSIDERATION OF OBSERVATIONS THAT HAVE BEEN USED TO SUPPORT MULTIPLE-IMPACT HYPOTHESES

In this section, we discuss observations that have been used to advocate hypotheses that the Apollo mafic impact-melt breccias derive from more than one impact. We provide arguments for why these observations are not necessarily inconsistent with the Imbrium hypothesis.

Compositional Differences Among Mafic Impact-Melt Breccias

Although compositionally similar enough to each other to form a recognizable class of lunar polymict rocks (*i.e.*, the "LKFM melt breccias"), mafic impact-melt breccias differ in composition from landing site to landing site. For example, mafic melt breccias from Apollo 14 have the highest concentrations of incompatible trace elements, whereas those from Apollo 16 have the highest concentrations of siderophile elements and the highest Mg/Fe ratios; those from Apollos 15 and 17 are most similar to each other. Early data for Apollo 17 mafic melt breccias showed that their compositions differed from those of Apollo 14. Reed and Wolfe (1975) used the difference as evidence that ejecta from different impacts were being sampled at the two sites. Given the locations of the sites, it made sense to them to assign the Apollo 14 mafic melt breccias to Imbrium and the Apollo 17 mafic melt breccias to Serenitatis. At some landing sites, several compositionally distinct groups of mafic melt breccias have been identified (Fig. 1). Four or five compositional groups have been recognized or advocated among the Apollo 15 samples (Ryder and Spudis, 1987; Lindstrom *et al.*, 1990), five at Apollo 16 (Korotev, 1994), and three at Apollo 17 (Spudis and Ryder, 1981; Jolliff *et al.*, 1996). At some sites, certain compositional groups are texturally distinct from others. These differences have led many investigators to favor the idea that the various compositional groups, intrasite or intersite, each represent different impacts (*e.g.*, Spudis and Ryder, 1981; Ryder and Seymour, 1982; Reimold and Nieber-Reimold, 1984; Ryder, 1996; Dalrymple and Ryder, 1993). A necessary consequence of this idea is that because the number of compositional groupings exceeds the number of nearby basins, some if not most mafic melt breccias must then derive from impacts forming subbasin sized craters (Korotev, 1991).

An underlying assumption of the one-composition-per-impact hypothesis is that an impact homogenizes target material to produce melt of uniform composition. That assumption is supported by studies of intracrater melt sheets from small terrestrial craters. Melt breccias taken from within the Manicouagan and the Manson impact craters, for example, are impressively homogeneous (Phinney and Simonds, 1977; Floran *et al.*, 1978; Korotev *et al.*, 1996b). McCormick *et al.* (1989) showed that although breccia samples from different radial locations close to the rim of the Mistastin Lake crater have different clast populations, they have remarkably similar melt compositions. There is evidence, however, that melts ejected some distance away from an impact site are more variable in composition than melt within a melt sheet. Hörz *et al.* (1991) reported major compositional differences between tektites and tektite-like impact melts found around some terrestrial craters as compared to impact melt found within the craters. Haskin *et al.* (1980) found that the relative abundances of rare earth elements in dense glass from locations surrounding the Ries crater change systematically with radial angle and differ observably from the compositions of moldavites. All lunar mafic impact-melt breccias were collected from basin rims and well beyond. If they represent ejecta rather than portions of ponded melt sheets, as we propose, the better terrestrial analog to them may be tektites and dense glasses found external to terrestrial impact craters rather than melt breccias taken from within terrestrial craters.

A few investigators have emphasized the compositional similarities of all mafic melt breccias and have suggested or acknowledged that they all might have a common origin (*e.g.*, Reid *et al.*, 1977), as we suggest here. Spudis (1992) suggested that the existence of different compositionally distinct groupings of mafic melt breccia at a given site was not inconsistent with the idea that they all derived from a single basin. He assigned the Apollo 16 groups to the Nectaris impact, the Apollo 15 groups to the Imbrium impact, and the Apollo 17 groups to the Serenitatis impact, however, and did not suppose that the full range of compositions arose from a single impact, Imbrium, as we propose here. Similar assignments were made on the basis of differences in siderophile-element ratios (Hertogen *et al.*, 1977).

Especially for an impact crater the size of Imbrium, we can reasonably expect heterogeneity of ejected material that cools to become a crystalline melt breccia. First, there is the nature of the impact melt itself. Figure 3 is a schematic top view of a growing impact cavity as it expands outward through a hypothetical, heterogeneous terrain. There is no mechanism for mixing together those materials that are propelled outward with strong radial velocity components and, thus, no reason to believe that melt ejected radially outward from locations tens of kilometers and more apart should have a single composition. Early formed melt will have been ejected before the last melt is produced. Also, if the terrain sustaining the impact is heterogeneous on a scale that is small relative to the radius of impact-melt production, then there is no obvious reason why successive batches of melt ejected in a given direction or in different directions should all have the same composition. To the extent that melt reaching a single site (*e.g.*, Apollo 16 as opposed to Apollo 17) comes from a very limited region of the basin, that melt might show only limited compositional variability. Recent modeling by Warren (1996) supports the idea that most ejected impact melt retains source region compositional heterogeneity.

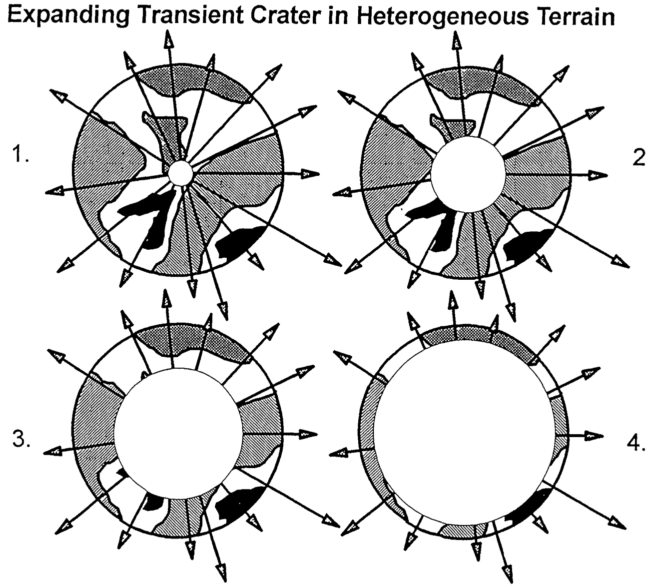

FIG. 3. Schematic representation of a transient crater expanding into a heterogeneous terrain, as viewed from above. If the distance scale is basin sized, there is no mechanism to homogenize melt impelled in one direction with melt impelled in a different direction or for melt produced near the point of impact and impelled in a particular direction to homogenize with melt produced farther outward from the point of impact impelled in the same direction. Thus the homogeneity of impact melt observed for melt sheets of terrestrial craters, as sampled within and on or near the crater rims, should not be expected for ejected melt from craters an order of magnitude greater in diameter.

Second, there are the clasts. Impact-melt breccias are physical mixtures of impact melt and entrained clasts. Although in compositional studies of such breccias efforts are made to avoid large clasts, it is likely that for some (if not all) mafic melt-breccia groups (*e.g.*, the Apollo 17 aphanitic breccias) the composition usually associated with that group is not that of the original melt but that of melt plus a suite of clasts (both dissolved and undissolved) that together may differ in composition from the original melt. If lunar mafic melt breccias are constructed from superheated melt (Simonds, 1975) and entrained clasts, then no subsample of the resulting breccia, no matter how small and carefully selected, can actually represent the original melt composition. Compositional uniformity among subsamples of a melt breccia is not strong evidence that the composition of the breccia is a melt composition. For example, in our own study of the crystalline impact-melt breccia from one region in the Manson impact structure, we were impressed that small (100 mg) subsamples that appeared so heterogeneous and clast-rich in thin section could all be so similar in composition (Korotev *et al.*, 1996b). In the model of Fig. 3, clastic material entrained in the melt as it moves outward will vary both in different directions and different distances along a vector from the point of impact.

The many-crater or several-basin hypotheses must overcome several obstacles. If many mafic melt breccias derive from subbasin sized craters, why are they so mafic, given the overall feldspathic nature of the lunar crust? How can mafic melt breccias be so common at the Apollo sites (Table 1) if the melt-volume to cavity-volume ratio is so much smaller for craters than for basins, as described in the previous section? At Apollo 16, how can different groups of mafic melt breccias, distinguished on the basis of lithophile-element concentrations, all contain FeNi metal of the same unusual composition (Korotev, 1994)?

Siderophile Elements

A distinguishing characteristic of all Apollo mafic impact-melt breccias is their relatively high concentrations of siderophile elements and their nonchondritic relative abundances of those elements. In particular, Ir/Au ratios in Apollo mafic melt breccias are at the low end of the range observed among all lunar polymict materials, ranging from ~0.25–0.5× the CI ratio (*e.g.*, Fig. 2). As is the case for Th and other incompatible elements, the mafic melt breccias are the principal and perhaps the only significant carrier of nonchondritic siderophile elements in Apollo highland regoliths.

Anders and co-workers (*e.g.*, Morgan *et al.*, 1974; Hertogen *et al.*, 1977; Janssens *et al.*, 1978; Anders, 1978) proposed that the siderophile elements in highland breccias were mostly inherited from the projectile whose impacts formed those breccias. They argued that lunar breccias formed mainly or entirely in ancient, basin-forming impacts by bolides dissimilar to known chondrites. Relative abundances of siderophile elements differ among meteorite classes. Thus, siderophile-element ratios such as Ir/Au and Re/Au in the mafic melt breccias can, in principle, be used to "fingerprint" the different types of projectiles whose impacts created those breccias. Among the breccias from the Apollo sites, Anders and co-workers initially recognized six, then later nine, "ancient meteorite groups," each characterized by a distinct set of siderophile-element ratios (*i.e.*, fingerprints), distinguished mainly by their differing Ir/Au ratios (Hertogen *et al.*, 1977). In analogy with meteorites, several projectiles might have the same or similar siderophile-element fingerprints, but melt breccias with different siderophile-element fingerprints would, according to this hypothesis, require different projectile types.

Anders and co-workers attempted to assign the different ancient meteorite groups to specific basin-forming events. The siderophile-element fingerprint of breccias mostly from Apollos 14 and 15 composed the ancient meteorite group designated as 1L, which was assigned to Imbrium by the nearest-basin argument (Hertogen *et al.* 1977). Ancient meteorite group 1H was defined mostly by Apollo 16 mafic melt breccias (Fig. 2), which were assigned to Nectaris or to Unnamed B (a large but less-than-basin sized crater underlying the site; Hertogen *et al.*, 1977). Groups 1L and 1H had the lowest Ir/Au ratios and differed from each other in that group 1H (Apollo 16) had a higher Re/Au ratio. (Subsequent work has shown that the single Apollo 16 sample tentatively assigned to ancient meteorite group 1LL by Hertogen *et al.*, 1977, which has an even lower Ir/Au ratio, actually represents about six samples, those of (lithophile-element) compositional group 1M, Korotev, 1994.) Apollo 17 mafic melt breccias, with somewhat higher Ir/Au ratios (Fig. 2), fall mainly in ancient meteorite group 2, which was assigned to Serenitatis (Morgan *et al.*, 1974). Some Apollo 17 mafic melt breccias (aphanitic samples from station 2 boulders) fell in ancient meteorite group 3 (still somewhat higher Ir/Au ratio), which was presumed to represent a pre-Serenitatis impact (Higuchi and Morgan, 1975). Thus, Anders and co-workers proposed that differences in siderophile-element ratios were evidence that separate impacts had formed the highland breccias found at each of the Apollos 15, 16 and 17 sites.

As noted above, the carrier of the siderophile-element fingerprints in impact-melt breccias is FeNi metal. We recognize that there is much evidence that the metal in the melt breccias has equilibrated with lunar silicates during cooling of the impact melt and that the composition of the metal has been altered. Clearly, the excess W in the metal was acquired from lunar silicates (Wlotzka *et al.*, 1972), and we suspect that some of the apparent site-to-site variability in Ni/Co ratio of the metal is related to Co extracted from lunar silicates. However, as we have argued before (Korotev, 1987a, 1994), we doubt that equilibration processes or volatilization of Au (*e.g.*, Delano and Ringwood, 1978; Dreibus *et al.*, 1981; James, 1996) have much affected Ir/Au ratios in mafic melt breccias. Unbrecciated components of the Apollo 16 regolith have low siderophile-element concentrations (*e.g.*, Ni, Table 2 of Korotev, 1997b). Thus at Apollo 16, at least, the mass of Ir and Au contributed by the iron bolide forming the melt breccias far exceeds any reasonable amount of these elements that could have been contributed by materials in the target area. Gold concentrations cannot have been strongly influenced by volatilization because ratios of Au to Ni are nearly constant in most Ni-rich samples of mafic melt breccias; most arguments that are based on Ir/Au ratios could be made equally well using Ir/Ni ratios (*e.g.*, Fig. 1c). Of course, if one does not accept that (1) siderophile elements in mafic melt breccias derive mainly from the impactors that formed the breccias or (2) siderophile-element ratios of the impactors are essentially preserved in the breccias (*e.g.*, Delano and Ringwood, 1978; Wänke *et al.*, 1978; Ringwood *et al.*, 1987), then siderophile elements pose little or no impediment to the single-basin hypothesis for the origin of the breccias. In this section we show, however, that even if one accepts most of the arguments of Anders and co-workers, differences among siderophile-element ratios in the mafic melt breccias from different Apollo sites can still be consistent with an Imbrium origin for all of the breccias.

One such argument is heterogeneity of the impactor. Variation in Ir/Au ratios among melt breccia samples does not necessarily require multiple impacts, because a basin-forming projectile may not yield a single siderophile-element fingerprint if Ir/Au ratios are highly variable in the bolide, as in some classes of iron meteorites (Wasson, 1985). We have observed significant variation in Ir/Au ratios among small subsamples from a single sample of impact-melt breccia (Korotev, 1994). (Our own data on hundreds of samples of mafic melt breccias shows that Au/Ni ratios are nearly constant within analytical uncertainty but that Ir/Ni ratios and, thus, Ir/Au ratios can vary considerably.) This heterogeneity is a small-scale sampling problem that might reflect large-scale heterogeneity of the impactor. In regard to small differences among the fingerprints of ancient meteorite group 3 found in Apollo 17 aphanitic breccias, Higuchi and Morgan (1975) recognized that variation in composition of the impactor was a real possibility "since significant differences seem to occur even in bodies as small as 10–100 m, judging from terrestrial impactites" (*e.g.*, Mittlefehldt *et al.*, 1992). James (1996) identified a group of Apollo 17 samples from the station-6 boulder that differ from the main Apollo 17 group in having higher Ni/Ir ratios. She attributed those differences either to compositional variations in the lunar target or to heterogeneity in the impacting body.

Even without having to resort to arguments for projectile differentiation or unusual heterogeneity, however, we can still argue that it is not only possible but likely that siderophile elements contributed by the impact melt in all Apollo mafic impact-melt breccias are dominated by metal from a single bolide. Ratios of Ir to Au are distinctly higher in the mafic melt breccias of Apollo 17 than those of the other three sites, and this is one of the arguments that the Apollo 17 breccias were formed in a different basin (Morgan *et al.*, 1974). James (1995, 1996) suggested that the fingerprint of the Apollo 17 mafic melt breccias (both the poikilitic and aphanitic varieties) is that of EH chondrites. We suggest a different explanation: that Ir/Au ratios are higher in bulk samples of Apollo 17 mafic melt breccias because the breccias contain siderophile elements from two sources (1) the impactor, namely, an iron meteorite with a low Ir/Au ratio and (2) siderophile-element-rich clasts having a nearly chondritic Ir/Au ratio derived from an earlier impact. Granulitic breccias are feldspathic lithologies that commonly occur as clasts in the aphanitic breccias and less commonly in the poikilitic breccias (James, 1994); they are also fairly common in the Apollo 17 regolith (Jolliff *et al.*, 1996). Although feldspathic granulitic breccias occur at other sites, those from Apollo 17 are distinct in that they have high concentrations of siderophile elements, higher concentrations, in fact, than the those of the poikilitic and aphanitic melt breccias (Table 2). As in the impact-melt breccias, we believe that siderophile elements are carried mainly by metal grains in the granulitic breccias because we observe metal grains in thin sections of the samples, and absolute concentrations of siderophile elements vary greatly among small samples of Apollo 17 granulitic breccias (data of Jolliff *et al.*, 1996).

In Table 2, we show that the average composition of the Apollo 17 poikilitic melt breccias is equivalent to that of a mixture of 0.3% FeNi metal such as that occurring in the Apollo 16 mafic melt breccias (which in our hypothesis is metal from the Imbrium bolide), 16% granulitic breccia (magnesian variety; data of Jolliff *et al.*, 1996), and 84% of a hypothetical mafic-silicate component with negligible concentrations of siderophile elements. The mafic silicates component (column 2) is effectively the "melt" component in this example and probably represents a mixture dominated by some Th-rich material related to KREEP basalt but that probably includes a troctolite component and some minor components (Korotev, 1997a). Compositionally, it bears some resemblance to the Apollo 15 group-A and Apollo 14 mafic melt breccias. Qualitatively, the main point of Table 1 is illustrated in Fig. 2, but the figure shows an additional point. In most small subsamples of Apollo 17 mafic melt breccia, the siderophile elements are contributed subequally by fragments of metal from the impactor and of metal in the granulitic breccia clasts; thus, the Ir/Au ratio of Apollo 17 mafic melt breccias is intermediate. In a few samples, however, the Imbrium metal dominates, leading to Ir/Au ratios as low as those seen in Apollo 16 breccias. In a few other samples, the granulitic-breccia metal dominates, leading to values as high as those seen in the granulitic breccias. There is no sharp spike in the histogram which would correspond to a probable metal of intermediate composition.

James (1994) noted that the high siderophile-element concentrations of the granulitic breccias and the high abundance of granulitic-breccia clasts in the aphanitic melt breccias probably influences siderophile-element concentrations in the bulk breccias. We merely extend that idea to suggest that both the poikilitic and aphanitic breccias contain a component of granulitic breccia, but that in the poikilitic melt breccias that component is largely dissolved in the melt. The average proportion of that component in the poikilitic melts, 16% in the example of Table 2, is not an unreasonably large amount. It is possible that with consideration of other siderophile elements (*e.g.*, James, 1994, 1995), the example of Table 2 may not be so clear cut; but considering that granulitic breccias may not be the only siderophile-element-bearing clastic component of the melt breccias, it seems unlikely that the basic argument would be significantly compromised. As noted earlier, metal with the major element composition of that of the example of Table 2 (typical Apollo 16 metal) is observed in the Apollo 17 poikilitic melt breccias (Dymek *et al.*, 1976; Misra *et al.*, 1976).

TABLE 2. Example of mass balance for Apollo 17 poikilitic impact-melt breccias.

	Granulitic breccia 1	Mafic silicates 2	FeNi metal 3	Poik. Brec. Calc. 4	Poik. Brec. Obs. 5
f, %	15.8	83.9	0.285	100.	–
TiO_2, %	0.24	*1.75*	0	*1.51*	1.51
Al_2O_3, %	26.2	*16.6*	0	*18.1*	18.1
FeO_T, %	4.95	*9.45*	120.5	*9.1*	9.1
MgO, %	8.2	*13.6*	0	*12.7*	12.7
CaO, %	15.1	*10.4*	0	*11.1*	11.1
Sc, μg/g	7.4	*18.9*	0	*17.0*	17.0
Co, μg/g	34.1	*18.5*	3600	*31.2*	31.2
Sm, μg/g	1.5	*17.1*	0	*14.6*	14.6
Mg′, %	74.6	*71.9*	–	*71.4*	71.4
Ni, μg/g	443	50	60000	283	289
Ir, ng/g	20.5	0	1500	7.52	7.5
Au, ng/g	7.0	0	1300	4.81	4.8
$(Ir/Au)_{CI}$	0.85	–	0.34	0.46	0.46

1 = Average composition of 46 magnesian granulitic breccias (Jolliff *et al.*, 1996).
2 = Hypothetical, calculated composition. Lithophile elements (*italics*) are calculated by the difference from mass balance; siderophile-element concentrations are assumed.
3 = Average composition of metal in Apollo 16 dimict breccias (Korotev, 1994).
4 = Columns 1, 2, and 3 combined in mass fractions *f*.
5 = Average composition of 178 poikilitic impact-melt breccias (Jolliff *et al.*, 1996).

Clearly, similar arguments could be applied to explain the minor differences in siderophile-element ratios among melt breccias from the other sites. The principal difference between Apollo 16 and the other sites is that at Apollo 16, concentrations of metal in the mafic melt breccias are high (1–2%), and the principal clastic component of the breccias, ferroan anorthosite, has low concentrations of siderophile elements. Thus in these breccias, the Ir/Au ratio is dominated by that of the metal associated originally with the melt phase. At the other sites, the concentration of FeNi metal is considerably lower in the melt breccias (0.3% in the example of Table 2), so any high-Ni clastic component (*e.g.*, granulitic breccias) can significantly alter the siderophile-element ratios of the bulk breccia. A definitive experiment may be to determine Ir and Au concentrations in individual metal grains from Apollo 17 melt breccias.

In summary, we suggest that the difference in siderophile-element ratios between bulk samples of mafic melt breccias from Apollo 17 and those from Apollos 14, 15, and 16 is largely a consequence of the siderophile-element composition of the clasts, not of the original impact melt, and that FeNi metal such as that in the Apollo 16 breccias, which we believe derives from the Imbrium impactor (Korotev, 1997b), occurs in all Apollo mafic melt breccias. Thus, we believe the siderophile-element ratios pose no obstacle to the single-basin hypothesis for the origin of the Apollo mafic impact-melt breccias and, in fact, support it.

Crystallization Ages

An overall similarity in ages of impact-melt breccias from all Apollo highland missions was obvious soon after the first Apollo 17 samples had been analyzed, and it has been given several interpretations. (1) On the assumption that the crystallization age of a melt breccia reflected the age of the nearest associated basin, then all associated basins formed during a short time interval, which implied a cataclysmic bombardment of the Moon with multiple, large projectiles at ~3.9 Ga (*e.g.*, Huneke *et al.*, 1973). (2) The ~3.9 Ga age for many basins marks the end of the era of bombardment by large projectiles rather than a spike in the bombardment history of the Moon. Prior to 3.9 Ga, large meteoroid impacts were so frequent and so intense that the ages of breccias were continuously reset (*e.g.*, Hartmann, 1975). (3) All dated melt breccias might be from or dominated by the last major impact to affect the Apollo sites, namely, the Imbrium impact (Schaeffer and Schaeffer, 1977). Whether the abundance of ages ~3.9 Ga represents a true cataclysm or just the end of early lunar bombardment is still actively debated (*e.g.*, Ryder, 1990). Interpretation (3) never gathered wide favor, but it is the only one consistent with the single-basin-origin hypothesis for the mafic melt breccias, so we reconsider it here.

A difference in crystallization ages among mafic melt breccias from different Apollo sites would be an obvious argument against a single-basin origin for all Apollo mafic impact-melt breccias. According to the nearest-basin hypothesis, and tempered somewhat by photogeologic observations, the bulk of the mafic melt breccias at the Apollos 14, 15, and possibly Apollo 16 sites would likely have been produced by the Imbrium event, some of those at the Apollo 16 site by the Nectaris event, and those at the Apollo 17 site by the Serenitatis event (*e.g.*, Spudis, 1992). Photogeologically, the Imbrium event is the most recent of these three, preceded by the Serenitatis event, which in turn was preceded by the Nectaris event. Under the nearest-basin hypothesis, we would anticipate therefore a pattern of ages for mafic melt breccias that was consistent with that order of basin formation. Numerous geochronological studies have been carried out to determine basin ages (*e.g.*, Nunes *et al.*, 1974; Schaeffer *et al.*, 1976; Maurer *et al.*, 1978; Deutsch and Stöffler, 1987; Stadermann *et al.*, 1991; Spudis *et al.*, 1991; Dalrymple and Ryder, 1993, 1996), and most of them have depended on measurements of mafic melt breccias.

Over the past decades, reported ages of the impact-melt breccias have been refined to high precision as methods of dating and interpretation have improved (*e.g.*, Deutsch and Stöffler, 1987; Stadermann *et al.*, 1991; Dalrymple and Ryder, 1993, 1996; summary by Nyquist and Shih, 1992). Great care has gone into interpreting results of age measurements (*e.g.*, Jessberger *et al.*, 1974, 1977). The most precise melt-breccia ages have been determined by the ^{40}Ar/^{39}Ar technique; these ages generally agree with those determined by other isotopic methods, but the other methods lack the precision of measurement of better than ~10 Ma, which is apparently required to distinguish among the ages of different basins. Geochronologists who have worked most extensively on the determination of basin ages by radiometric dating have concluded that the ages of mafic melt breccias from different Apollo sites are different from each other and are consistent with the relative basin ages as determined photogeologically, although they are not in full agreement on what the ages are.

To retain the single-basin hypothesis for the origin of the Apollo mafic impact-melt breccias, it is necessary either to find fault with those conclusions or to show that some other interpretation is possible. Because the purpose of this paper is to reconsider the single-basin hypothesis, we emphasize here some of the problems associated with determination of a crystallization age from an impact-melt breccia. First, there is a problem of identifying which samples of melt breccia were produced by the basin-forming event of interest; there is disagreement among geochronologists (and lunar geologists) on this point. Second, many samples do not yield good ages, and these are usually discounted by geochronologists rather than considered as a possible indication that melt breccias may not in general record basin ages faithfully. Third, there is the problem of interpreting what the range of good plateau ages means; we expand on this point below. Considering these problems, we suggest that there remains sufficient uncertainty in the determination and interpretation of melt-breccia ages that the single-basin hypothesis still can be seriously entertained. Put another way, if the other evidence for a single-basin origin for the Apollo mafic melt breccias were strong enough, then we believe that ways could be found to interpret the isotopic data in a manner that is harmonious with that hypothesis. We do not attempt a comprehensive review here, but we illustrate some of the difficulties we face in accepting that basin ages have been obtained as precisely as isotope ratios can be measured.

For dating the time of basin formation by the ^{40}Ar/^{39}Ar method, the ideal situation might be as follows: melt produced directly by the impact and clasts that dissolved in that melt would outgas completely; once the melt crystallized, the resulting rock would remain a closed system to K and the isotopes of Ar; clast-free samples would be measured to avoid any ^{40}Ar inherited from clasts. If these conditions were fulfilled, we could expect to see simple Ar plateaus and obtain a common, highly precise age for every group of melt rocks produced in a single basin. In Fig. 4, we show that this simple, straightforward situation does not occur. Given the complexity of the basin-forming processes, no geochronologist who has worked to determine melt breccia ages would expect it to occur, but it is nevertheless significant that it does not.

We call attention to three first-order observations from the histograms of Fig. 4: (1) mafic melt breccias from all sites collectively yield ages within a limited range, 3.7 to 4.0 Ga; (2) age determinations on melt breccias from any single Apollo site done in single laboratories of proven capability yield a range of ages; and (3) there is overlap such that age values within the narrow range of 3.850 ± 0.025 Ga have been obtained for melt breccias from all four Apollo highland sites, but there is no obvious significance to that particular age. It has not proved possible to select at random a sample of mafic melt breccia from a particular Apollo highland site and readily obtain to good precision the characteristic age of the melt breccias found at that site or even of the melt breccias in its own compositional category. There is no such single characteristic age, and many such samples yield poorly constrained ages or no age at all (poor plateaus). The range of ages obtained for mafic melt breccias from any particular Apollo site cannot represent a true spread of ages for a single impact event that was geologically instantaneous. Together, these observations mean that substantial interpretation of age values is required before a "basin age" can be stated or constrained.

Different lunar geochronologists have made different choices in assigning basin ages, although most of them might nevertheless agree that there is a succession of ages among the mafic melt breccias from different Apollo sites that is consistent with the photogeologically derived order of basin formation. Thus, much of the discussion in the literature has centered around which age of which melt-breccia sample corresponds most closely to the age of the basin believed to have produced the main ejecta deposits at the site, or which age places the best constraints on the age of that basin. Usually, the youngest plateau age for a group of closely related mafic impact-melt breccias is chosen as the upper limit of the age for the group; older ages are taken to reflect ^{40}Ar inherited from clasts (*e.g.*, Stadermann *et al.*, 1991), but application of that principle is sometimes complicated. Dalrymple and Ryder (1993) made precise, careful ^{40}Ar/^{39}Ar age measurements of 12 subsamples of Apollo 15 mafic impact-melt breccias. The analyzed suite comprised two subsamples from compositional group A, four from group B, three from group C, one from group D, one from group E, and one with a unique composition ("group Y"). Only seven of the twelve subsamples yielded acceptable age spectra (four from B, two from C, one from Y). Subsamples belonging to groups A and D and one sample from group C had complex age spectra and were interpreted to have been formed by or disturbed by impacts that did not completely reset the K-Ar isotopic system. The subsample from group E also did not have a plateau; its spectrum may be dominated

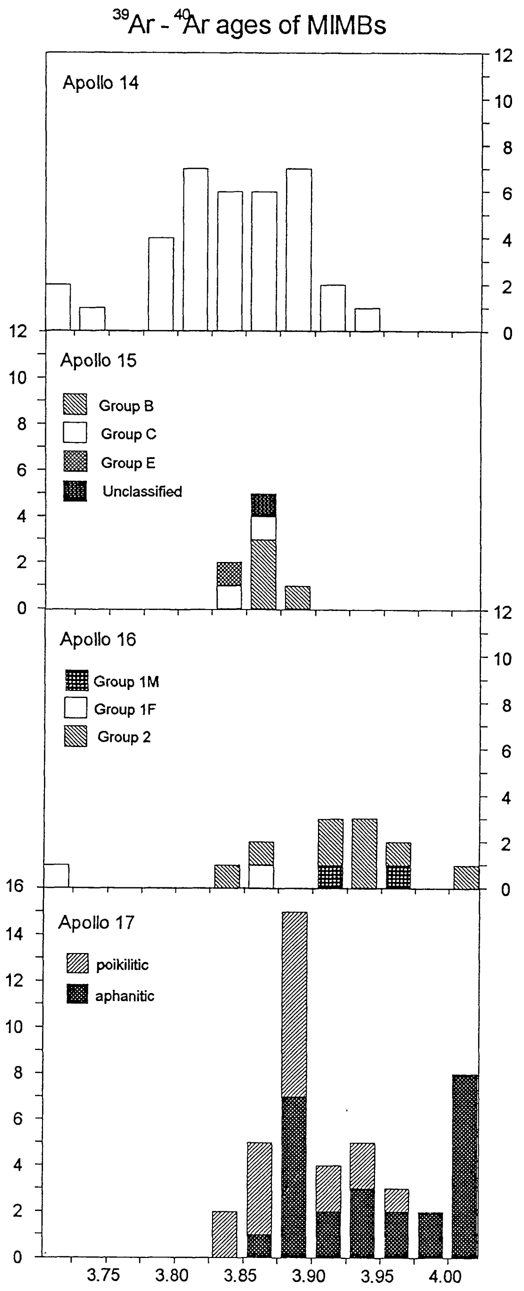

FIG. 4. Distributions of ^{39}Ar-^{40}Ar ages for mafic impact-melt breccias from Apollos 14, 15, 16, and 17. Although a histogram is not shown for Luna 20, a mafic impact-melt breccia from that site has been dated at 3.895 ± 0.017 Ga (Swindle *et al.*, 1991). Reported ages that did not use the decay constants of Steiger and Jager (1977) were revised according to the conversion factors of Dalrymple (1979). Many dated lunar samples lack a lithologic description; this is particularly true for Apollo 14. Table 10.1 in Wilhelms (1987) was used a guideline as to which dated Apollo 14 samples are melt breccias. Data sources: Apollo 14 = Alexander and Davis (1974), Alexander and Kahl (1974), Bernatowicz *et al.* (1978), Kirsten *et al.* (1972), Schaeffer and Schaeffer (1977), Stadermann *et al.* (1991), Stettler *et al.* (1973), Turner *et al.* (1971, 1972); Apollo 15 = Bogard *et al.* (1991) and Dalrymple and Ryder (1993); Apollo 16 = James (1981), Kirsten *et al.* (1973), Marvin *et al.* (1987), Maurer *et al.* (1978), Schaeffer and Husain (1973), Schaeffer and Schaeffer (1977), and Schaeffer *et al.* (1976); Apollo 17 = Cadogan and Turner (1976), Dalrymple and Ryder (1996), Eichhorn *et al.* (1978, 1979), Jessberger *et al.* (1976, 1977, 1978), Leich *et al.* (1975), Müller *et al.* (1977), Phinney *et al.* (1975), Staudacher *et al.* (1979), Stettler *et al.* (1974, 1975, 1978), and Turner and Cadogan (1975).

by many clasts. (Bogard *et al.*, 1991 gave an age of 3.85 ± 0.05 Ga for a sample that apparently belongs to group E, see Lindstrom *et al.*, 1990.) Five subsamples (three from compositional group B, one from group C, and one from group Y) gave the same age, 3.865 Ga (weighted mean), within measurement uncertainty (±5 Ma). A sixth subsample from group B gave a similar age but yielded a "peculiar double plateau." The seventh datable subsample, another from group C, gave a distinctly younger age, 3.836 ± 0.011 Ga. It seems noteworthy that samples belonging to the same compositional group did not all yield the same age or good plateaus.

Given that the range of compositions of the dated melt breccias exceeded their expectations for a homogenous melt sheet, Dalrymple and Ryder (1993) concluded that at least four or five impacts all occurring within a short interval of time were represented by the seven successfully dated subsamples of Apollo 15 mafic impact-melt breccia (an interpretation inconsistent with the premise described above that most mafic melt breccias are direct products of basin-sized impacts). Although they admitted that the melt breccias could not be assigned to any specific basin impact, Dalrymple and Ryder interpreted the ages as indicating that the Imbrium event is no older than ~3.87 Ga and probably no older than 3.84 Ga (the youngest age observed).

In contrast, Stadermann *et al.* argued that the Imbrium impact could be no older than the youngest Fra Mauro sample they analyzed, or 3.73 Ga. In their study of Apollo 14 mafic melt breccias, Stadermann *et al.* (1991) reported that clasts from sample 14063 (a breccia representing Cone Crater ejecta) ranged between 3.87 to 3.95 Ga in age. Ages of material from hand samples of mafic melt breccias taken from the regolith beyond the Cone Crater continuous ejecta deposit ranged between 3.73 and 3.85 Ga, however. Because the latter are found within the Fra Mauro Formation, an Imbrium deposit, Stadermann *et al.* argued that the Imbrium impact could be no older than the youngest Fra Mauro sample, or 3.73 Ga. Stadermann *et al.* cited the petrologic, impact-mechanical, and photogeological arguments of Deutsch and Stöffler (1987) to explain why the group of younger melt breccias at Apollo 14 could not have originated from local craters that postdate Imbrium. Dalrymple and Ryder (1993) dismissed those younger samples as local, post-Imbrium impact melts. They preferred a 3.85 Ga age for Imbrium based on their own age dates of the Apollo 15 samples and on the similar age (3.85 Ga) of Apollo 15 KREEP basalt fragments, which they regard as ejecta from the post-Imbrium Apennine Bench Formation. (Deutsch and Stöffler, 1987, interpreted the Apennine Bench to be a pre-Imbrium basement block that was displaced by Imbrium.) So, there is considerable margin in the interpretation of which samples represent a particular basin and which of those samples provide the best age for that basin.

Dalrymple and Ryder (1996) more recently made precise ^{40}Ar/^{39}Ar age measurements on 13 samples of mafic impact-melt breccias from Apollo 17. Of these, eight gave plateaus that they regarded as "good." Four of these came from aphanitic samples; three of them gave a tight average of 3.873 Ga, and one gave a value of 3.951 (±0.017) Ga. The other four came from poikilitic breccias. Of these, three gave a tight average value of 3.893 Ga, and one (subsample 73155,33e) gave a younger value of 3.853 (±0.016) Ga. Dalrymple and Ryder interpreted the average from the three poikilitic samples (3.893 ± 0.009) Ga as the age of the Serenitatis basin and argued for a different origin for the aphanitic breccias, whose average age for the three similar samples was younger (3.873 Ga, which happens to fall within the range found for the tight group of Apollo

15 mafic melt breccias; Dalrymple and Ryder, 1993). On this basis, they concluded that the Serenitatis impact occurred at least 20 Ma earlier than the Imbrium impact. Suppose that instead we assumed that the youngest age observed, that of 73155,33e, represented the age of the Serenitatis basin, as Dalrymple and Ryder (1993) did in determining the age of Imbrium. Then we might conclude that the mafic melt breccias at Apollo 15 and Apollo 17 had the same age! We note also that Dalrymple and Ryder (1996) included three subsamples of an Apollo 15 melt rock (15304) as a check for consistency between their Apollo 17 and Apollo 15 results. All three gave acceptable plateaus, but only two fell within the range observed earlier (Dalrymple and Ryder, 1993), and the third was thus dismissed.

In all their work, Dalrymple and Ryder (1993, 1996) have argued thoughtfully for their choices of which breccia ages should be used in determining basin ages, and we are not refuting their arguments here. The point we make is that substantial selection of data is required to obtain a basin age, and the choice of which samples and data properly provide that age and which do not is not an obvious one, at least to us. Given the many samples analyzed for which no plateaus are obtained or for which the age spectra are ambiguous, we suggest that, overall, the results of age measurements on mafic impact-melt breccias cast doubt on the ability of breccias to record precisely the ages of their basins of origin, which is a position that seems not to have been fully considered. We suggest that the precision of ^{40}Ar/^{39}Ar measurement may exceed the ability of melt breccias to record meaningful basin ages out to the limit of that precision. We also note that precise ages for melt breccias all rest on a single method, ^{40}Ar/^{39}Ar dating. There is not independent isotopic information that the age of lunar basin formation is actually recorded with a precision as good as a few percent in impact-melt breccias.

Argon plateaus, but not true basin ages, might be obtained, for example, if even the most clast-poor mafic impact-melt breccias had not fully outgassed on melting. Similar "ages" for mafic impact-melt breccias from a given mission might nonetheless occur because the proportion of unsupported ^{40}Ar might be about the same in some or most samples obtained from a particular location (*i.e.*, from a given unit of melt). A serious concern with this suggestion is whether ^{40}Ar/^{39}Ar geochronologists could unequivocally detect the small amount of unsupported ^{40}Ar required to produce an inaccurate age; this seems unlikely, because whole-rock plateaus and not single mineral plateaus were used (Dalrymple and Ryder, 1993, 1996). Only a little unsupported ^{40}Ar would be required. For example, Apollo 17 poikilitic impact-melt breccias contain ~0.22% K_2O, which corresponds to 0.22 ppm ^{40}K. Given their age of 3.9 Ga, the poikilitic mafic impact-melt breccias would have had 1.8 ppm ^{40}K at the time they formed. From decay of most of that ^{40}K, the breccias now contain 0.17 ppm of ^{40}Ar. An error of 10 Ma in age would occur if the impact-melt breccias now contain as little as $\sim 10 \times 10^{-4}$ ppm of unsupported ^{40}Ar. If the Imbrium target material also had 1.8 ppm ^{40}K at the time of the impact and at that time was only 100 Ma after formation of the source region of the impact, then the target material would have contained ~0.011 ppm ^{40}Ar; if 200 Ma old, 0.022 ppm ^{40}Ar; and if 400 Ma old, 0.046 ppm ^{40}Ar. These concentrations of ^{40}Ar range from 10 to 45× the amount required to produce a ~10 Ma error in age. The point is, not much of the target ^{40}Ar would have to be retained or acquired from other sources such as clasts to produce a significant error in the age of a mafic impact-melt breccia.

If, as suggested above, the Imbrium far-field ejecta consisted largely of melt, then the amounts of melt were so massive that the melt cannot be regarded as small droplets with high surface-to-volume ratios that might easily lose their ^{40}Ar, and the impact of that melt and rapid mixing with pre-Imbrium clastic material might have trapped a significant fraction of the ^{40}Ar from the Imbrium target material. The poikilitic texture suggests relatively slow cooling, in contrast to the rapidly cooled melt matrix of the aphanitic breccias. Perhaps the melt component mixed with too little clastic material to bring about rapid cooling. If slow cooling to produce the poikilitic mafic impact-melt breccias occurred within an ejecta pile that was more than a few meters thick, residual ^{40}Ar might not easily have been liberated from the melt. Additional ^{40}Ar might have come from the partial or complete digestion of clasts accompanied by failure of them to outgas. The extent of outgassing might have varied on a meter to tens of meter scale or greater but also on the submillimeter to centimeter scale depending on the size and proximity of clasts. For the single-basin hypothesis to be true, this or some other mechanism must cause errors in ^{40}Ar/^{39}Ar ages of mafic impact-melt breccias.

Given the overall situation, the conclusion that the Apollo 15 and Apollo 17 mafic melt breccias differ in age by as much as 53 Ma (Dalrymple an Ryder, 1996) is not compelling to us. We suggest that the tight range of ages obtained by Ar-Ar geochronology for most mafic melt breccias does not rule out the single-basin hypothesis but instead provides limited support for a common origin for those breccias at all sites.

Other Arguments

In the Introduction, we listed arguments used by others to advocate a Serenitatis origin for the Apollo 17 mafic impact-melt breccias, which we used as an example of the problem of determining the basin of origin of mafic impact-melt breccias. In presenting the case for an Imbrium origin for essentially all Apollo mafic melt breccias, we have addressed some of those arguments (numbers 3 through 7) and shown them not to refute an Imbrium-origin hypothesis. Here, we address briefly some remaining arguments.

Serenitatis is undeniably the closest basin to Apollo 17. The Taurus-Littrow Valley sits near the edge of the basin-filling maria, a location chosen by some investigators as marking the edge of the Serenitatis transient crater (Wolfe and Reed, 1976; Head, 1979). Based on its location, thick deposits of Serenitatis ejecta would be expected to occur at Apollo 17 (Wolfe and Reed, 1976). In basin-size impacts, melt typically spills over the edge of the crater to form sheets and pools (Ryder and Wood, 1977; Wilhelms, 1987; Warner *et al.*, 1976), so Serenitatis melt as well as fragmental ejecta deposits would reasonably be expected at Apollo 17. Such considerations led some sample investigators to conclude that the Serenitatis impact was the most likely source of the Apollo 17 mafic melt breccias (*e.g.*, the detailed discussion of James *et al.*, 1978). The proximity of Apollo 17 to Serenitatis, however, does not preclude the possibility that ejecta deposits from subsequent impacts, such as Imbrium, are also thick at Apollo 17. Proximity alone is insufficient to establish provenance.

Geomorphic features produced during the Serenitatis impact have been greatly modified and, in some cases, obliterated by the Imbrium event. The western rim of the Serenitatis basin was largely destroyed; the northern and southern rims are replete with obvious Imbrium sculpture (Wilhelms, 1987). Limited portions of the eastern rim, consisting of tall massifs such as North and South Massif and hummocky terrain such as the Sculptured Hills, presumably preserve Serenitatis features without obvious modification by the Imbrium event. The Taurus-Littrow massifs and Sculptured Hills were assigned a Serenitatis origin based on morphological comparisons with similar deposits located at the better preserved Orientale basin; the massifs and the Sculptured Hills were taken to be analogous to the Rook Mountains (about where the rim of transient cavity is presumed to have been) and the knobby terrain (an ejecta unit) of the Orientale basin (Head, 1974; Wolfe and Reed, 1976).

Preservation of Serenitatis features and lack of any clearly identifiable Imbrium structures at Apollo 17 were interpreted as indicating that ejecta deposits from Imbrium were thin or absent (Head, 1974; Wolfe and Reed, 1976). In fact, the Apollo 17 site was chosen in part to provide samples of pre-Imbrium material (Hinners, 1973). Photogeologists are not insistent on this interpretation, however. Wilhelms (1987) ascribes the origin of Apollo 17 mafic melt breccias to the Serenitatis event but notes the Imbrium radial features in the near vicinity of the Apollo 17 landing site and states that superposition of Imbrium ejecta on the Serenitatis massifs is consistent with the regional geology. Head (1992) points out that although the massifs are a Serenitatis-produced feature, there are numerous sources for the materials found at the Apollo 17 site. Some geomorphic features at Apollo 17 have been subsequently reevaluated. Spudis (1993) interprets the Sculptured Hills as partly Serenitatis and partly Imbrium ejecta. He speculates that the Sculptured Hills are partly composed of Serenitatis material where they grade into hummocky, intermassif deposits at the Apollo 17 site and mainly of Imbrium material where they grade into radially lineated terrain found inside the main rim of Serenitatis as defined by highland scarps, massifs, and the Vitruvius Front. From a photogeologic viewpoint, the presence of Imbrium material cannot be ruled out at the Apollo 17 site.

Another argument used in favor of a Serenitatis origin for the Apollo 17 melt breccias is the large size of the Apollo 17 poikilitic breccia boulders and the presumably extensive deposits in the highland massifs from which they broke away. The scale of their occurrence can be taken as evidence of extraction from the nearby Serenitatis basin by a low-energy mechanism that could keep a large body of melt intact, for example, flow of basin melt over the rim of the giant crater and onto the uplifted blocks of the basin ring. A highly energetic (ballistic) delivery mechanism, such as would be required for an Imbrium origin, would in the simplest scenario lead to the obliteration of any large bodies of impact melt on reimpact and would generate characteristic morphologies in the target terrain (secondary craters, lineations, as opposed to elevated, blocky topography). The predominantly poikilitic matrix textures of the Apollo 17 mafic impact-melt breccias also suggests slow cooling as would be expected in a thick body of melt. Textures reflecting rapid cooling and accretion or chaotic flow, as might be expected in the case of molten ejecta impacting the surface and incorporating cold regolith material, are observed in the Apollo 17 aphanitic breccias, which from a textural point of view might equally well have been produced by melt ejected from Serenitatis or Imbrium. Note that the chemical compositions of the poikilitic and the aphanitic mafic impact-melt breccias, including siderophile elements, are highly similar, however, and more similar to each other than either is to mafic impact-melt breccias from other Apollo sites. They are distinguishable mainly by a difference in TiO_2 and Eu concentrations (Spudis and Ryder, 1981; Jolliff *et al.*, 1996). They are not obviously from different sources. Even though the scale of occurrence of the Apollo 17 poikilitic melt breccias presents a good argument for why they should be of Serenitatis origin, we believe more needs to be understood about the mechanisms for formation of impact-melt breccias before it must be accepted as compelling. For example, the nature of the deposits that might form if massive quantities of melt fell onto a site has not been well thought out. Given the high energies and massive amounts of material transported, the depositional mechanisms for basin-produced ejecta may be significantly different from those of the smaller and better understood impact events for which we have direct terrestrial analogs and for which we believe we have a physically intuitive sense.

We have chosen to emphasize the Apollo 17 mafic impact-melt breccias throughout this paper because they seem the most difficult to reconcile with a single-basin origin for the Th-rich rocks of that type. We believe the single-basin hypothesis is still viable. We note, however, that even if we are eventually compelled to accept a Serenitatis origin for the Apollo 17 mafic impact-melt breccias, this does not negate a single-basin origin for most Th-rich mafic impact-melt breccias or the possibility that most of the Th at the Moon's surface was placed there as Imbrium ejecta (Haskin, 1998). Perhaps the Th-rich region of the Moon extends farther to the east than the boundaries tentatively chosen for the High-Th Oval Region (Haskin, 1998), at least at some depth, and the Serenitatis impact barely reached it, thus producing a Th-rich melt but no obvious Th-rich ejecta deposits.

SOME IMPLICATIONS AND SPECULATIONS

Except for the mafic melt breccias, most nonmare lithologies of the regoliths of both the Apollo 16 and Apollo 17 sites are feldspathic and poor in incompatible elements (*e.g.*, Korotev, 1997b; Jolliff *et al.*, 1996). Thus, if the mafic melt breccias at both sites are Imbrium ejecta, then Serenitatis and Nectaris ejecta must be largely feldspathic and free of KREEP, a corollary that is consistent with geochemical data obtained from orbit. Although beyond the scope of this paper, the hypothesis we propose here has important implications for the prebasin distribution of KREEP. In the words of Wetherill (1981), "The reason that Nectaris didn't excavate KREEP may simply be that there wasn't any there."

If all Apollo mafic melt breccias are Imbrium ejecta, then we have little idea of the absolute ages of Serenitatis and Nectaris. At Apollo 17, the granulitic breccias are a principal candidate for Serenitatis ejecta and some, at least, might be Serenitatis melt, although possibly metamorphosed (Cushing *et al.*, unpubl. data, 1998). Their bulk composition (~26% Al_2O_3) is reasonable for a section of upper crust. Their high concentrations of siderophile elements indicate that they are grossly contaminated with meteoritic debris from a bolide source other than that which contaminated the Apollos 14, 15, and 16 mafic melt breccias, perhaps the Serenitatis bolide. There are hints in the geochronologic data that the granulitic breccias of Apollos 16 and 17 are on the order of 4.2 Ga old (Kirsten and Horn, 1974; Turner and Cadogan, 1975; Maurer *et al.*, 1978; Dalrymple and Ryder, 1996).

If the Apollo 17 granulitic breccias are Serenitatis ejecta, then at least some of the clast load in the Apollo 17 mafic melt breccias probably derives not from the Imbrium target area as melt left the basin cavity but from the substrate onto which the Imbrium ejecta impacted. Our consideration above of both Ir/Au ratios and $^{40}Ar/^{39}Ar$ ages leads us to suspect that in the Apollo 17 poikilitic breccias, at least, a significant fraction of the breccia matrix is dissolved clasts. Following a suggestion by M. Cintala (pers. comm.), we consider that some of the heat for this dissolution might occur from conversion to heat of kinetic energy of infalling Imbrium ejecta. The launch velocity of material ejected at an angle of 30–40° from the Imbrium region to the Apollo 17 site is ~1.2 km/s. The kinetic energy of the material would be ~1440 J/g. A typical magnitude for the specific heat of mafic silicates is ~1.2 J/g/°C and for the heat of fusion is ~500 J/g (*e.g.*, Navrotsky, 1994). The total kinetic energy is, thus, about the amount needed to warm soil at 0 °C and melt a quarter of it. If the ejecta were already hot, say ~600 °C, then the conversion of the kinetic energy to heat would enable melting of the ejecta plus an additional ~40% of its mass in clastic material. The efficiency of conversion of kinetic energy of ejecta to heat is unknown but surely not close to 100%; much stirring and mixing occurs when the ejecta strike the surface. Nevertheless, enough kinetic energy may be converted to heat to account for the digestion by the primary ejecta of substantial clastic material in the ejecta deposit produced when hot or molten primary ejecta mix with the local substrate.

SUMMARY

During and soon after the Apollo missions, some investigators suggested that Th-rich materials in highland samples from all Apollo sites might be Imbrium ejecta (*e.g.*, Tera *et al.*, 1973; Evensen *et al.*, 1974; Reid *et al.*, 1977; Schaeffer and Schaeffer, 1977). This suggested origin has been out of fashion for some time, at least for the most common Th-bearing regolith materials, the mafic impact-melt breccias. We suggest that an Imbrium origin for the Apollo mafic impact-melt breccias is at least as defensible a hypothesis as one of local-basin origin (*e.g.*, Spudis and Ryder, 1981; Warren, 1992; Wilhelms, 1987). We offer a fresh discussion of it here. The principal arguments are as follows.

(1) Their ubiquity and high abundance at all Apollo highland sites requires that mafic impact-melt breccias are mainly of basin origin.

(2) Although mafic impact-melt breccias vary in composition both within Apollo sites and between Apollo sites, they form a recognizable compositional "supergroup" (alias: LKFM). If they are basin melts, then any sample found at the Apollos 14, 15, 16, and 17 sites was ejected from a basin. If so, we believe the extent of their compositional heterogeneity is reasonable for melt ejected from a single large basin excavated into heterogeneous terrain.

(3) Ejecta deposit modeling based on modern crater scaling indicates that Imbrium ejecta deposits should be hundreds of meters to kilometers deep at the Apollo sites most distant from Imbrium (Apollos 16 and 17). It appears that Imbrium ejecta should be abundant in highland regolith samples from those sites.

(4) The pattern of Th concentrations observed by the Apollo γ-ray experiments (*e.g.*, Metzger *et al.*, 1977) shows a large region of high-Th concentrations in the vicinity of the Imbrium–Procellarum region of the Moon. We regard this region, the High-Th Oval Region, as a unique, mafic geochemical province, a consequence of the Moon's igneous differentiation (Haskin, 1998).

(5) The surface distribution of Th outside of the High-Th Oval Region as observed by the Apollo orbiting γ-ray experiments is consistent with most of that Th residing in Imbrium ejecta from the High-Th Oval Region (Haskin, 1998).

(6) The proportions of mafic impact-melt breccias in the Apollo nonmare regoliths correspond reasonably to the proportions of Imbrium materials estimated by ejecta modeling to be in those regoliths but only if a high proportion of the Imbrium ejecta was melt. Among the younger lunar basin-forming events, only the Imbrium event could have produced such a high proportion of melt.

(7) The high proportion of melt in the Imbrium ejecta may have been enhanced by a still hot target area at shallow depths: a consequence of the high concentrations of heat-producing elements presumed for the High-Th Oval Region.

(8) Siderophile-element "fingerprints" of the impacting projectile based on Ir/Au ratios for mafic impact-melt breccias from Apollos 14, 16, and probably Apollo 15 are closely similar. They are different for Apollo 17 mafic impact-melt breccias, but the difference can be quantitatively explained by the presence (on average) of ~16% granulitic breccia clasts with high siderophile-element concentrations and a different fingerprint. Once the effects of the clasts are removed, the Apollo 17 fingerprint is very similar to those of the Apollos 14 and 16 mafic impact-melt breccias.

(9) The high abundance of $Fe_{94}Ni_6$ metal in the Apollo mafic impact-melt breccias, particularly those from Apollo 16, and the similarity in composition of that metal to iron meteorites of groups I and II suggest that all were formed by a single iron bolide.

(10) The ages of all mafic impact-melt breccias are similar, 3.9 ± 0.1 Ga. Highly precise, more detailed ages obtained by $^{40}Ar/^{39}Ar$ dating with uncertainties <0.1 Ga indicate age differences among mafic impact-melt breccia samples. The pattern of these differences, however, does not correlate in any straightforward way with different compositional groups or with assignment of formation times to different basins. We suggest that the impressive precision with which isotopic ages can be measured exceeds the accuracy with which mafic impact-melt breccias have recorded the times of their formation.

We conclude that the possibility of an Imbrium origin for most if not all Th-rich, mafic impact-melt breccias in the Apollo collection cannot be ruled out on the basis of any observations reported so far. It is supported by a wide variety of observations and accounts for some enigmas that are otherwise difficult to explain (Korotev, 1994, 1997b). It is important that it be taken seriously because of the importance of the origin of mafic impact-melt breccias to large-scale hypotheses about the Moon's evolution. These include the nature of the late meteoroid bombardment (cataclysm); the spatial distribution of KREEP, both near the surface and at depth; the ages of the major basins; and the composition of the early crust of the nearside highlands.

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