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Mare Basalts on the Apennine Front and the Mare Stratigraphy of the Apollo 15 Landing Site

G. Ryder

Lunar and Planetary Institute, 3303 NASA Road One, Houston, TX 77058

Olivine-normative mare basalts are present on the Apennine Front as crystalline particles and shocked or shock-melted fragments. Picritic basalts, which may be related to the olivine-normative basalts by olivine accumulation, not only occur on the Front but such samples so far recognized are confined to it. Mare volcanic and impact glasses also occur on the Front; all are olivine-normative, though none are quite the equivalent of the typical olivine-normative mare group. The quartz-normative mare basalts are not present (or are extremely rare) on the Front either as crystalline basalts or shocked or glass equivalents. These observations are consistent with the olivine-normative mare basalts being both local and the youngest flows at the site, and the fragments being emplaced on the Front by impacts. The picritic basalts raise the distinct possibility that the olivine-normative basalts also ponded on the Front. An influx of olivine-normative basalts from exotic sources (e.g., a ray from Aristillus) is inconsistent with their abundance, their dominance in the mare soil chemistry, and their age, isotopic, and trace element similarities with the quartz-normative basalts. However, the thermal histories of the olivine-normative basalts require elucidation.

INTRODUCTION

The immediate subregolith bedrock of the plains that form Palus Putredinis at the Apollo 15 landing site is mare basalt, as shown by the volcanic landforms and the basalt samples collected (*ALGIT,* 1972). The collected mare basalt samples have long been recognized as forming two main groups, one olivine-normative, the other quartz-normative. The two groups cannot be easily related to each other by fractional crystallization or partial melting processes (e.g., *Rhodes and Hubbard,* 1973), despite their indistinguishable isotopic ages, initial isotopic ratios, and rare earth element patterns. An important geological constraint on the possible relationships of these two basalt types would be their stratigraphy: Are the olivine-normative basalts older or younger than the quartz-normative basalts, or are they even overlapping in age? Photographs of the west wall of Hadley Rille show several probable basalt units, totaling about 60 m thick (*ALGIT,* 1972) (Fig. 1). The lower reaches of the rille are talus covered. A new interpretation of the formation of Hadley Rille as a lava channel within a preexisting graben suggests that the mare flows at the site may be as little as 50 m thick (*Spudis et al.,* 1987).

The early accepted interpretation of the mare stratigraphy was that the olivine-normative basalts overlay the quartz-normative basalts (e.g., *ALGIT,* 1972; *Rhodes and Hubbard,* 1973). This conclusion was reached because most of the olivine-normative mare basalts were recovered from station 9A, high up on the edge of Hadley Rille, and two "bedrock" boulders sampled lower into the rille are quartz-normative basalts; moreover, the soil chemistry tended to converge on a high-Mg mare basalt component (*Rhodes and Hubbard,* 1973). However, in soil mixing model studies, *Korotev* (1987) found that the chemical arguments were not particularly definitive as to mare basalt type needed as a chemical component in the Front soils. The mixing problem is complicated by the presence of green pyroclastic mare glasses and by the uncertainty of the compositions of the highland components. Nonetheless, in the mare soils the chemical trends are clearly toward the olivine-normative basalts (*Korotev,* 1987); it is in the Front soils that the mare component becomes difficult to specify (R. Korotev, personal communication, 1987). *Grove* (1986), on the basis of the petrographic characteristics of the mare basalts, suggested radically different possibilities for the stratigraphy of the basalts

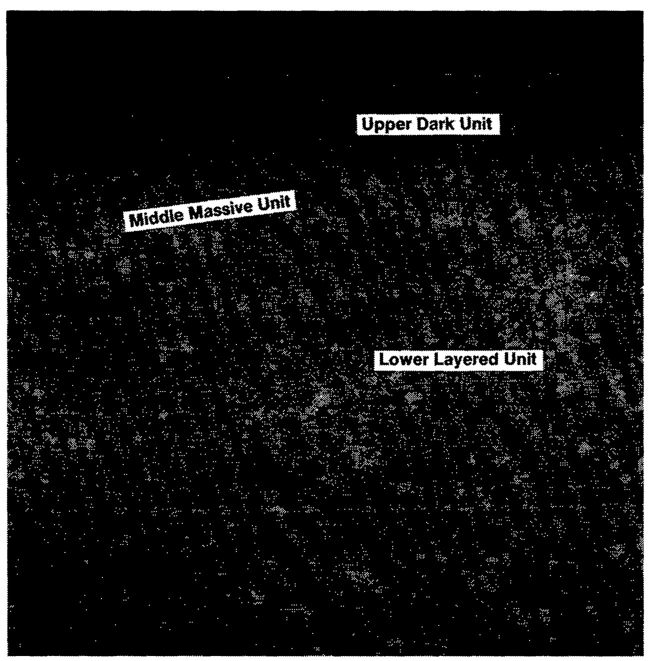

Fig. 1. Surface telephoto view of the west wall of Hadley Rille, showing at least three basalt units. The lower slopes are talus covered. AS15-89-12157.

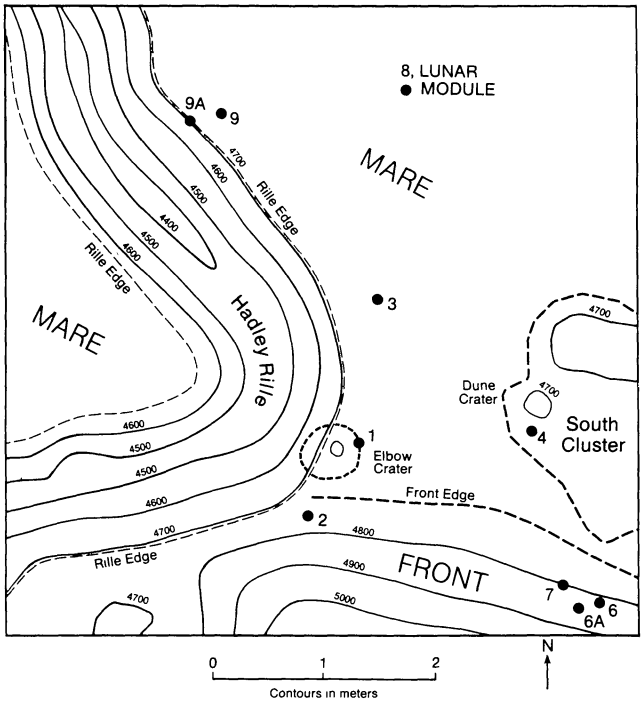

Fig. 2. Location map for the Apollo 15 landing site.

at the site: (1) The olivine-normative basalt fragments are exotic, transported in by a cratering event such as Aristillus or Autolycus; or (2) the olivine-normative basalts underlie the quartz-normative basalts and are only partly covered by them; for instance, they may form the northwest-trending ridge through the landing site.

Mare basalt fragments are also present on the Apennine Front at stations 6 and 7 (Fig. 2), a little more than 100 m above the mare plains. Most of them are fragments of volcanic flows, but a few are impact melted. In this paper I summarize the characteristics of these mare basalts and impact melts, *none of which belong to the quartz-normative group,* and discuss their significance for the mare stratigraphy of the Apollo 15 landing site. The discussion expands on that presented in *Ryder* (1986). I conclude that the olivine-normative basalts are local, and they are the youngest basalts at the site, in agreement with the original interpretation.

MARE BASALTS AMONG APENNINE FRONT SAMPLES

Rock and Rake Mare Basalt Fragments

The only individually-collected mare sample from the Apennine Front is 15256 (201 g), collected at station 6. However, this sample is a shock-produced, fine-grained, heterogeneous but clast-free melt (Fig. 3a) of olivine-normative mare basalt composition (e.g., *Rhodes and Hubbard,* 1973; B. Schuraytz and G. Ryder, in preparation), and is not an unaltered sample of a lava flow. Data for it are summarized in *Ryder* (1985). Sample 15256 is enriched in the very volatile elements Cd, In, Br, and Te compared with other olivine-normative mare basalts, according to the data of *Ganapathy et al.* (1973), but not in less-volatile elements such as Zn. It is not enriched in meteoritic siderophiles or KREEP elements. The target for the impact apparently was a pristine and rather average olivine-normative basalt flow(s).

The rake samples collected at station 7 include mare basalts. Chemical and petrographic data summarized by *Ryder* (1985) show that 15379, 15380, and 15384 are undoubtedly olivine-normative mare basalts, and sample 15381, a tiny unsectioned sample, is macroscopically similar to them. Picritic basalts 15385 and 15387 ("feldspathic peridotites" of *Dowty et al.,* 1973) are similar to each other and to some coarse-fines particles. These coarse-grained and much more olivine-rich samples are briefly discussed separately below with related particles.

Rake sample 15388 ("feldspathic microgabbro" of *Dowty et al.,* 1973) is coarse-grained but unusual in texture (Fig. 3b) and chemistry. It contains no olivine, has a positive Eu anomaly, and about 5% TiO_2 (*Laul and Schmitt,* 1973; *Ryder and Steele,* 1987). The only reasonable explanation of a positive Eu anomaly in lunar samples is that of plagioclase accumulation, and the chemistry suggests about 50% plagioclase accumulation from an olivine-normative mare basalt (*Ryder and Steele,* 1987). However, the high TiO_2 and lack of olivine require that first an olivine-normative magma evolved by olivine and pyroxene fractionation and then 15388 accumulated from it. Sample 15388 contains cristobalite, like the olivine-normative mare basalts, and not tridymite, which characterizes the residua of quartz-normative basalts. Its intergrown texture mimics that seen (rarely) in the olivine-normative basalt groundmasses, but not seen in the quartz-normative basalts. Sample 15388 is probably not related to the quartz-normative basalts, and it might not even be related to the olivine-normative basalts. Instead it might represent a distinct magma type of local or exotic origin; radiogenic isotope work currently in progress (J. Dasch, G. Ryder, and L. Nyquist, in preparation) might demonstrate such a distinction, or suggest a relationship with the olivine-normative mare basalts.

Fragments in Breccias

Mare basalts have been recognized only rarely in breccias from the Front. Regolith breccia 15459 (station 7) contains mare basalt clasts, including a prominent large one that is more mafic than most of the Apollo 15 basalts (*Ridley,* 1977; *Lindstrom,* 1986 and personal communication) and contains euhedral olivine crystals (Fig. 3c). It is more like the picritic basalts than like the normal olivine basalts in its major elements, but unlike the picritic basalts, it does not have lower incompatible trace elements. A second, smaller clast analyzed by Lindstrom is similar but is a little depleted in the trace elements. The large clast has age and isotopic characteristics very similar to those of the olivine- and quartz-normative basalts (*Stettler et al.,* 1973; *Nyquist et al.,* 1988) but may have slightly higher initial $^{87}Sr/^{86}Sr$ and a slightly younger age (*Nyquist et al.,* 1988). *Ridley* (1977) reported olivine in other mare basalt ("gabbro") clasts.

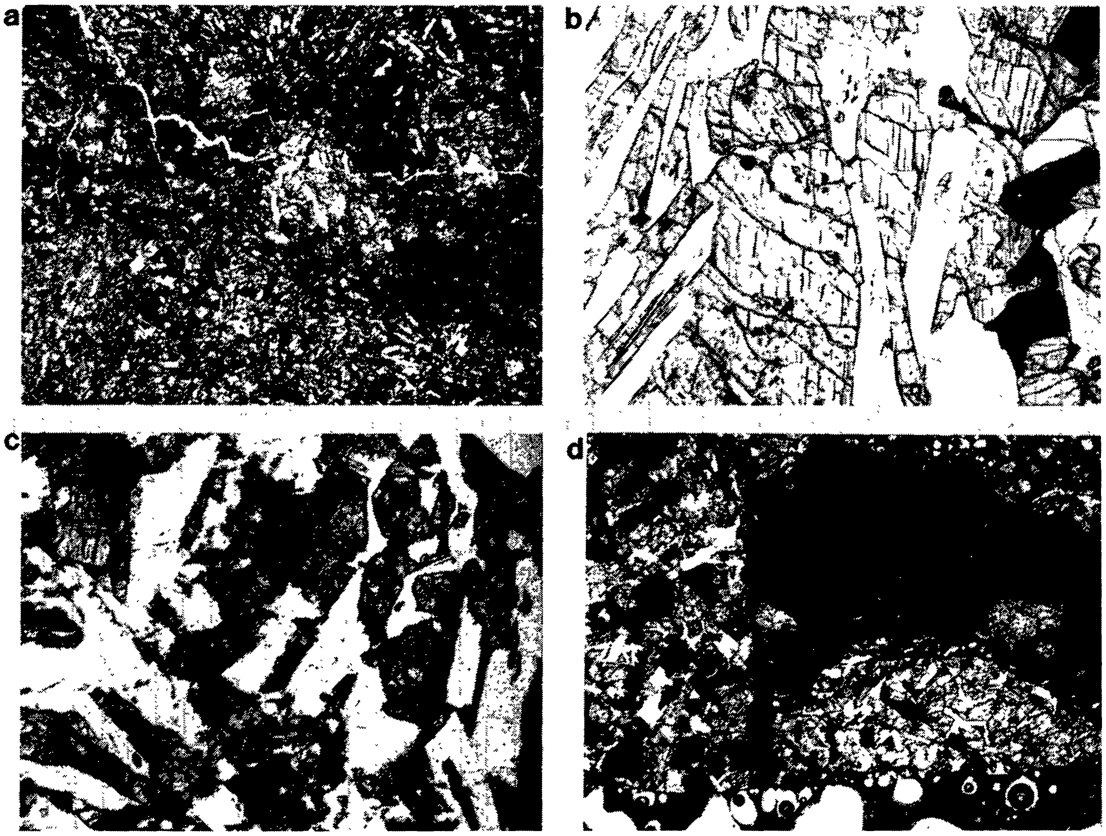

Fig. 3. Photomicrographs of crystalline mare materials from Apennine Front rocks. All plane transmitted light, all fields 2 mm wide. **(a)** 15256,47, an impact melt of olivine-normative mare basalt composition. **(b)** 15388,11, "feldspathic microgabbro," lacking olivine. **(c)** 15459,20, large, coarse olivine-bearing mare basalt clast, slightly cataclasized. **(d)** 15285,57, high-Ti mare basalt fragment and orange glass.

Regolith breccia 15285 from station 6 contains a fragment of high-Ti mare basalt petrographically similar to those from the Apollo 17 site (Fig. 3d). It is dominantly pyroxene with anhedral ilmenites and small amounts of lathy plagioclases. It was intruded by an orange impact glass prior to incorporation into 15285. No analyses of the basalt or the glass have been made, but most lunar orange glasses are high-Ti glasses, suggesting that the glass was produced by impact into a flow represented by the basalt clast.

Regolith breccia 15465 from Spur crater (station 7) contains small mare basalt fragments, constituting 20% of the crystalline rock fragments in 15465,7 (*Cameron and Delano,* 1973). Many of these are "similar to the large specimen 15555" (*Cameron and Delano,* 1973), which is an olivine-normative mare basalt. *Delano* (1972) noted pyroxene porphyritic fragments, but these are not referred to in *Cameron and Delano* (1973), and I saw none in thin sections.

Mare basalt fragments occur in a small rake sample (15383) that is largely glass. They are all deformed, with kink twin lamellae. A more precise determination of their composition awaits further inspection.

Coarse Fines Particles

Several of the 4-10-mm particles (coarse fines) sieved from regoliths from station 7 are mare basalts, although none have been recognized among station 6 or 6a coarse fines. Some were studied by *Powell et al.* (1973). (In the following, the split number is that for the first designation as a single particle rather than as one of several; subsequent split numbers are ignored.)

Sample 15314,14 was the largest of five similar-appearing basalt particles with a few percent yellow olivine crystals identified (*Powell,* 1972). It has a medium grain size with plagioclases and pyroxenes up to 1 mm long and is mildly shock cataclasized (Fig. 4a). According to *Powell et al.* (1973) 15314,14 is a distinct olivine-free variety that is actually quartz-normative, but my own inspection of thin sections shows that both cristobalite and early olivine are present. Hence the sample is some kind of olivine basalt, probably the typical olivine-normative basalt type, and the chemical analysis (on only a few tens of milligrams) is unrepresentatively pyroxene rich.

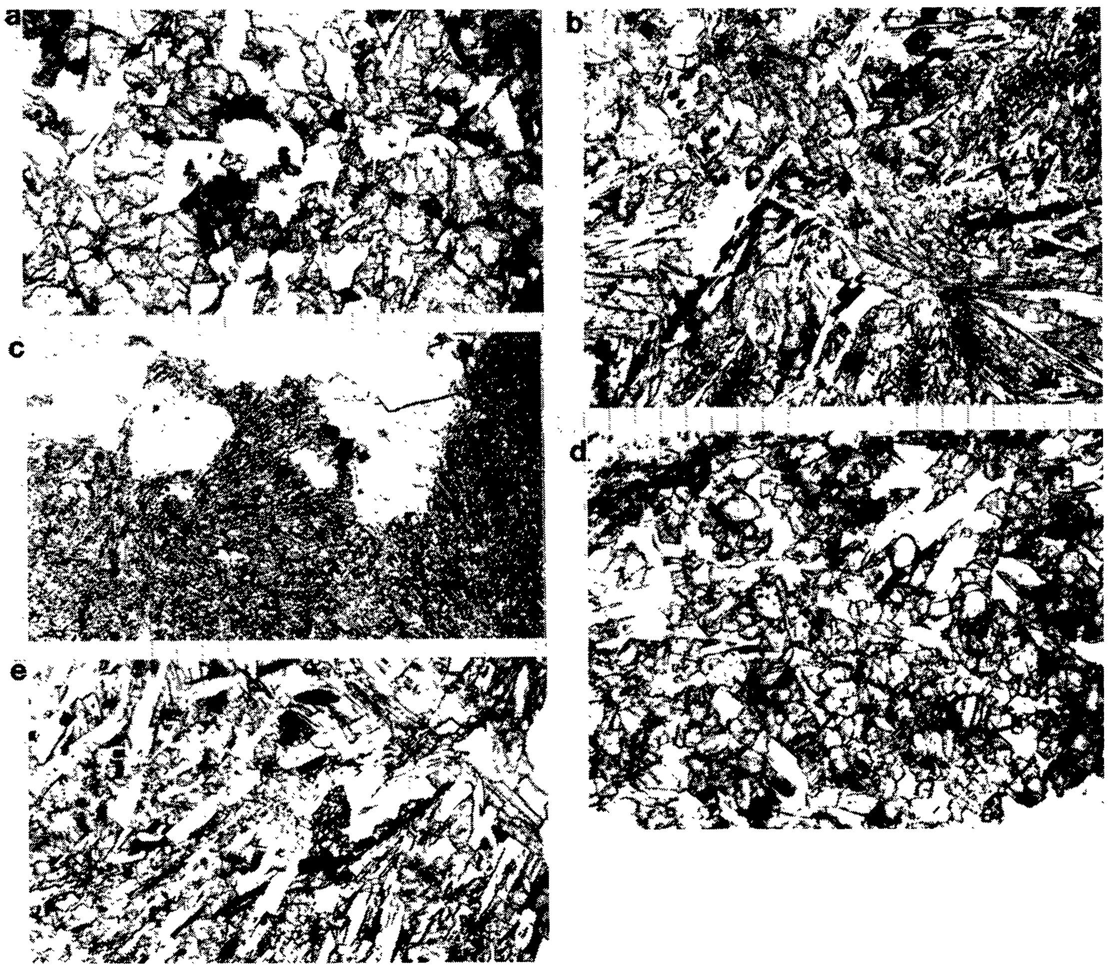

Fig. 4. Photomicrographs of crystalline mare materials from Apennine Front fines. All plane transmitted light, all fields 2 mm wide. **(a)** 15314,14,141, olivine-bearing mare basalt, somewhat cataclasized. Olivine is not distinct in this image. **(b)** 15314,3,94, olivine-bearing mare basalt with hollow plagioclases. Olivine is present in lower left. **(c)** 15314,28,98, porphyritic olivine basalt. Large olivine in upper left is partly resorbed but is not a clast. **(d)** 15434,26,117, olivine-normative mare basalt. **(e)** 15434,27,119, variolitic olivine basalt. Larger crystal in upper right is olivine.

Sample 15314,3 was distinguished by *Powell* (1972) from the five referred to in the previous paragraph, probably because yellow olivine was not visible. However, the thin section shows that it is a mare basalt with olivine phenocrysts set in a generally intrafasciculate-spherulitic groundmass consisting of plagioclase, pyroxene, and anhedral olivines (Fig. 4b). Interstitial areas contain cristobalite and fayalite. Although no chemical analysis has been made, the sample is almost certainly an olivine-normative mare basalt.

Sample 15314,28 is a fine-grained porphyritic olivine-normative mare basalt (Fig. 4c). The groundmass is mainly pyroxene, plagioclase, and ilmenite/ulvöspinel and silica (glass?). The groundmass contains rare resorbed olivines. *Simonds et al.* (1975) listed 20% olivine, 47% pyroxene, and 29% plagioclase for the sample. They interpreted it as an impact melt of mare basalt composition because of its unusual variolitic/poikilitic texture, but there is actually no evidence of an impact origin. The large olivines were interpreted as clasts by *Simonds et al.* (1975), but in an impact melt the clast population is usually more diverse and includes lithic fragments rather than displaying a single mineral type. The olivines look like phenocrysts, in some cases partially resorbed, rather than clasts, and the sample is likely to be a very rapidly-cooled olivine-normative mare basalt.

Sample 15434,26 has the fine- to medium-grained intergranular, plagioclase poikilitic texture common among the olivine-normative mare basalts (Fig. 4d). It has granular groundmass containing both olivine and late cristobalite, and there is no doubt that it belongs to the typical olivine-normative mare basalt group.

Sample 15434,27 has a variolitic or spherulitic texture (Fig. 4e). It contains some early olivine as well as cristobalite. The plagioclases include hollow varieties. Although there is no chemical analysis, it would appear that this sample is an olivine-normative mare basalt.

Fine Fines Particles

Mare basalt fragments also occur among finer regolith particles from the Apennine Front. *Cameron et al.* (1973) found three mare basalts, all olivine-normative, in their 2-4-mm allocation from station 6 regolith, but no other published data appear to provide any petrographic information on the fines. *Korotev* (1987) made partial chemical analyses of three 2-4-mm fragments from station 6 that are crystalline mare basalts, but the data are inadequate to make much distinction as to basalt type. The analyzed particles ranged from 3.5 mg to 5.1 mg, too small to be very representative of their parent rocks. Two appear similar to the local olivine- and quartz-normative basalts; the third is quite different in having higher REEs, FeO, and Sc, though perhaps only because it is an unrepresentative sample.

An inspection of a dozen or so thin sections in the Curatorial Thin Section Library shows that at least a few olivine-normative mare basalt fragments are present in each of the stations 6, 6a, and 7 regoliths in the fragments smaller than 4 mm. No pyroxene-vitrophyres or their coarser-grained quartz-normative mare basalt equivalents have been recognized among these fine fines.

Picritic Basalts

Rake samples 15385 and 15387 are distinctly more olivine-rich, both petrographically and chemically, than are the typical olivine-normative basalts (e.g., *Dowty et al.,* 1973), although they have the same age and isotopic characteristics (*Husain,* 1974; *Wiesmann and Hubbard,* 1975). They may be related to the olivine-normative basalts by the simple process of olivine accumulation (e.g., *Ryder and Steele,* 1987). One breccia fragment (in 15299; *Warren et al.,* 1987) and a coarse fine basalt particle (15274,3; *Ryder and Steele,* 1987) have almost identical chemistry. In addition, an impact melt in the 4-10-mm fines also has an almost identical chemistry (15274,4; G. Ryder, in preparation), suggesting that a target unit of some significant size existed that corresponded with the picritic basalt composition. These fragments are from both stations 6 and 7; no such compositions have been recorded from any of the mare regoliths.

Glasses

Glasses of mare basalt composition occur on the Apennine Front. Some are volcanic, such as the well-known green glasses (e.g., *Reid et al.,* 1973; *Delano,* 1979, 1986) that dominate the glass populations. Others are clearly of impact, hence possibly mixed origin. At least four of the glass groups found on the Front are volcanic (*Delano,* 1986). In addition to the very-low-Ti green glasses there is a high-Ti (13.8% TiO_2) red glass, a moderate-Ti (3.5% TiO_2) yellow glass, and an orange glass identical to the 74220 glasses. All these groups are found in regoliths and breccias along the Apennine Front.

Varied published data show similar groupings or clusterings of compositions of mare-related glasses at the Apollo 15 site (e.g., *Reid et al.,* 1973; *Best and Minkin,* 1972; *Engelhardt et al.,* 1973; *Ridley,* 1977). These groups, some possibly volcanic, others certainly of impact origin, are similar to the moderate TiO_2 group of volcanics or to slightly more Ti-rich versions of the crystalline olivine-normative basalts of the Apollo 15 site. These groups are all represented on the Apennine Front. All have normative olivine, and no glasses similar to the quartz-normative crystalline basalts have been identified. Similar groups of glasses were identified in regolith breccia 15459 from station 7 by *Ridley* (1977), who specifically stated that equivalents of the quartz-normative basalts were not found.

Yellow impact glasses are the most common. They are not identical in composition to the yellow volcanic glass. They appear to have a small but real range in major element compositions, and limited data suggests a much greater range in incompatible trace element compositions. Those from station 7 analysed by *Spangler and Delano* (1984) were 3.35 + 0.05 Ga old. These particular glasses had TiO_2 contents of 4.6-5.22% with less than 10% MgO. Other yellow glasses contain lower TiO_2 and higher MgO (e.g., Group 10 glasses; *Best and Minkin,* 1972, which averaged 3.6% TiO_2 and 12.6% MgO); these are probably volcanic. A yellow/orange glass sphere from Apennine Front coarse fines has 3.2% TiO_2 and 10.7% MgO (G. Ryder, unpublished data); although it has trace elements higher than local Apollo 15 KREEP basalts, it does not have a KREEP contamination signature. The yellow impact glass clod found at the Hadley Rille edge on the mare plain (station 9a; *Delano et al.,* 1982) has lower FeO and MgO and higher TiO_2; its trace element abundances are much higher than even the coarse fine particle, but still it bears no evidence for impact contamination with KREEP. Rather, it appears that these yellow glasses, while not necessarily pure volcanics, represent several mare compositions with varied trace element abundances fairly well. All contain normative olivine, but the compositions are not the same as the local olivine-normative basalts, nor can they be very easily related to them by simple petrogenetic schemes. Most are more Ti-rich, and many are even more Mg-rich than the most Mg-rich of the olivine-normative basalts, which have less than 12% MgO (B. Schuraytz and G. Ryder, in preparation). The chemical variation of these yellow impact glasses requires further detailed studies, similar to those of *Delano et al.* (1982), in order to understand their petrogenetic significance.

SUMMARY OF MARE BASALTS ON THE APENNINE FRONT

The descriptions given above from a survey of published data, inspection of thin sections, and some new analyses confirm the presence of mare basalts among samples collected from the Apennine Front. All of those for which data are available were extruded during the main phases of local mare basalt volcanism: Some at least correspond with local olivine-normative mare basalts in petrogenetic and isotopic characteristics, and the total percentage of mare basalt is very low. There is no indication that any of them are an integral part of the Apennine Front; the mare basalts are on the Front, not in the Front.

Most of the crystalline basalt fragments on the Front are very similar to the typical olivine-normative mare basalts, such as those collected at station 9a on the mare plain. In some cases they have been shocked or shock-melted but retain the olivine-normative mare basalt chemistry. Five samples are picritic basalts, unlike any basalts retrieved from the mare plain, but are probably related to the olivine-normative basalts by olivine accumulation. No quartz-normative basalt fragments have been reported except for one preliminary report (*Delano,* 1972), which was apparently not confirmed (*Cameron and Delano,* 1973). At least one fragment of high-Ti basalt has been observed.

Other mare-related components are glasses and have a wider variety of compositions. There are several varieties of volcanic glass (and the green glasses actually can be distinguished as five subgroups) (*Delano,* 1986). The impact glasses have a narrower range, from compositions rather like the typical olivine-normative basalts, though almost always slightly more Ti-and Mg-rich, to glasses with as much as 5% TiO_2. All of these mare-related glasses are olivine-normative, and no glasses even vaguely similar to the quartz-normative basalts have been reported from the Apennine Front. Indeed, published reports make no mention of such glasses even from the mare plains.

It is clear that quartz-normative basalts, either as crystalline, shock-melted, or volcanic or impact glasses, must be rare, if not completely absent from the Apennine Front. This absence is in stark contrast to their predominance among individual rocks and boulders sampled on the mare plain (i.e., excluding the rake samples collected at station 9a, which bias the collection strongly toward olivine-normative basalts). Both mare basalt types are found at station 2, but that location is lower on the Front than stations 6, 6a, and 7 and must also have received material thrown out of Elbow crater. Elbow is on the mare plain and its ejecta contains quartz-normative basalts.

SOURCE OF OLIVINE-NORMATIVE MARE BASALTS ON THE APENNINE FRONT

The interpretation and implications of the simple observation that representatives of the olivine-normative mare basalt group occur on the Apennine Front, while representatives of the quartz-normatives either do not occur or are extremely rare, fall naturally into two domains: one in which the olivine-normative basalts originally flowed on the Front, 100 m above the plain, and another in which the olivine basalt fragments were transported from elsewhere by impact.

Mare Flows on the Front

A dark rim, or "high lava mark," on the side of Mt. Hadley is consistent with a drainback of lava leaving topographic highs draped with basalt (*Swann et al.,* 1972; *Swann,* 1986). Fragments of olivine-normative basalts on the Front would be consistent with ponding of its magma, and the variety of original textures displayed by the fragments would be consistent with the multiplicity of cooling environments to be expected with such ponding. *Grove* (1986) noted the poikilitic plagioclases in the groundmass of many olivine-normative basalts; the plagioclases surround subrounded olivines and pyroxenes. He suggested that these textures were most consistent with reheating by later flows. These textures are also similar to some found in the margins of some smaller basaltic intrusives, e.g., Skaergaard and Palisades. A lava pond would fulfill many of the conditions for reheating or perhaps continued heating. Most of the magma responsible for the heating would later have drained back into Hadley Rille (*Howard et al.,* 1972). A lava pond might also explain the picritic basalts on the Front, insofar as such an environment would be better for obtaining cumulates. Following accumulation, the lava drained off leaving the picrites stranded. Picrites would probably have also formed elsewhere in the pond, but would still be buried by the remaining olivine-normative basalts in the mare plain.

Another possibility for flow on the Front is that the lavas flooded the plain so fast from Hadley Rille that the magmas washed up briefly onto the Front, much as a tidal bore entering an estuary, as suggested (though not advocated) by *Spudis et al.* (1987). However, this seems rather an extreme possibility, even though it has been observed in terrestrial lava flow. A further possibility is that the Front was itself the vent area for the extrusion of the olivine-normative basalts (but not for the quartz-normative ones). However, there is no morphological evidence for a vent in this region, and Hadley Rille itself would have no significance for the olivine-normative basalts if such a vent had existed.

Impact Ejecta

Cameron et al. (1973) interpreted mare basalt fragments on the Front as probably thrown there by impacts from mare surfaces. Impact ejection does explain the shocked and shock-melted nature of several of the basalts, such as the single rock 15256. Such a derivation could be either a unique event or a continuous influx. If a single event deposited the basalts, then the target was not the Dune area, from which at least some quartz-normative basalts would be expected. An alternative is a single influx from some distance away, spraying both the Front and the mare plain with olivine-normative basalts. This is essentially one of the suggestions of *Grove* (1986). Such an event would have to be capable of transporting unshocked boulders as well as shocked rocks, and the target, judging from the shocked-melted samples, must have been solely olivine-normative basalt. The variety of textures and grain sizes in the target spot was very great. The significance of the picrites in such a model is unclear, but it would surely be coincidental that they were all found on the Front; they might alternatively have no relationship with the typical olivine-normative basalts. The mutual requirements of an impact large enough to spray the entire landing site with an exotic basalt type, yet small enough to have a target only of a suite of related olivine-normative basalts seems to me to be mutually exclusive. The introduction of an exotic basalt type that has the same age and isotopic characteristics as well as rare earth element patterns and abundances, as the local bedrock would also be quite coincidental. Furthermore, the chemistry of the regolith on the mare plain, particularly station 9 and 9a (which have the lowest abundances of nonmare components) is surely emphatic that there is so much olivine-normative basalt present that it must be local.

Rather than a single local or distant impact introducing olivine-normative mare basalt to the Apennine Front, the alternative of a continuous influx from local sources is more consistent with observations. The lack of quartz-normative basalts on the Front simply implies that the target area, i.e., in the mare plain near the Front and including the Dune crater region, is dominantly olivine-normative basalt in its upper part. There is nothing to support a contention that the olivine basalts are local yet underlie the quartz-normative basalts at the site. Interestingly, in the 2-4-mm fragments studied by *Cameron et al.* (1973) more than half the basalts were olivine-normative basalts, even at Dune crater; the regolith there lies on the same mixing line of olivine-normative basalts (rather than quartz-normative basalts) and highlands materials as other mare-rich soils.

Certainly there could be lateral variations such that either the olivine-normative basalt or the quartz-normative basalt is locally absent, but at present there is little evidence that this is the case. One exception might be regolith breccia boulder sample 15205 (*Dymek et al.,* 1974), which consists solely of Apollo 15 KREEP basalts and quartz-normative basalts; neither of the other highland components nor olivine-normative basalts are present. In the source region for the 15205 parent boulder, the quartz-normative basalts must have directly overlain the KREEP basalts. Olivine-normative basalts, if older, were missing from this location; if younger, then they were either missing or the 15205 precursor regolith was formed in the brief interval between the extrusion of the two basalt types.

CONCLUSIONS

There are mare basalts on the Apennine Front. Among the crystalline varieties, all are olivine-normative, and probably all are from the typical olivine-normative group from the landing site. A few actually confined to the Front are picritic; these are probably related to the olivine-normative basalts by olivine accumulation. A variety of glasses of both volcanic and impact origins occurs on the Front (as elsewhere), and all are olivine-normative. The quartz-normative basalts, predominant among individually-collected crystalline basalt samples on the mare plains, are not represented on the Front among crystalline basalt particles, shock melts, or glasses of any kind so far analyzed.

The volcanic glasses were presumably deposited directly by fire-fountaining onto the Front and by the impact glasses brought in as ejecta from unknown sources. A variety of basalts exists within the Upper Imbrian system within a few hundred kilometers of the landing site, both in the Imbrium and Serenitatis basins (e.g., *Whitford-Stark and Head,* 1980). These are likely to be sources contributing to the impact glasses, most of which are not represented among local rocks. The high-Ti basalt fragment in 15285 must also be an exotic fragment.

Both ponding of olivine-normative mare flows and the continuous impact influx from local sources are consistent with the presence of olivine-normative mare basalts and the absence of the quartz-normative basalts on the Front. Hypotheses in which the olivine-normative basalts are exotic

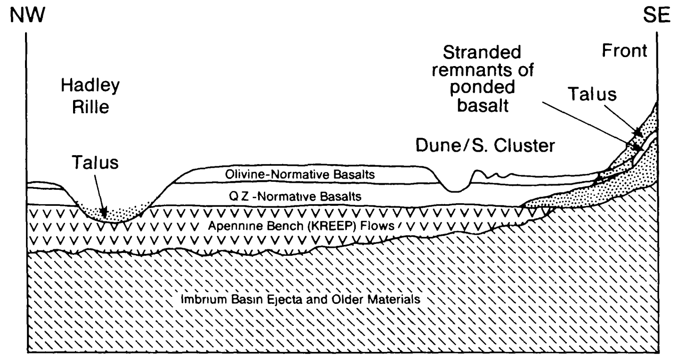

Fig. 5. Generalized cross-section of stratigraphy of the Apollo 15 landing site.

and deposited in impacts are inconsistent with the abundance of olivine-normative mare basalts in the soil from all collection sites. They also require the age, isotopic, and trace element similarities of the olivine-normative basalts and the quartz-normative basalts to be coincidental; although these similarities have not yet been adequately explained, it seems more likely that there is some relationship within a single volcanic system. The variety of textures present among the olivine-normative mare basalts on the Front, including the picritic basalts and the "reheated" textures (*Grove,* 1986), suggest ponding; the abundance of shocked and shock-melted samples suggest impact influx. It is quite possible that both occurred.

The impact influx and the dominance of olivine-normative mare basalts in the mare soil chemistry both require the olivine-normative mare basalts to be the uppermost flow at the site, as it certainly appears to be at station 9a. The stratigraphy of the site, according to this study and earlier work, is summarized in Fig. 5. The olivine-normative mare basalts, while indistinguishable in isotopic age from the quartz-normative basalts, are stratigraphically younger. The short time between extrusion of the two basalt types would severely limit the amount of impact gardening of the older quartz-normative basalt flows, only a thin regolith would have developed, few impact glasses of quartz-normative basalt would have formed, and little impact glass or basalt fragments would have been thrown onto the Apennine Front. The absence of vitrophyres of olivine-normative mare basalts, an objection of *Grove* (1986) to the "uppermost flow" model, can be explained by impact pulverization of the uppermost margin, and either reheating by ponding of the lowermost margin or lack of its exposure. Fine-grained samples (e.g., 15668 and 15314,28) do exist, even if vitrophyres do not. It may be difficult to produce more than a small amount of glassy material for such olivine-rich compositions, which crystallize readily. Dynamic cooling experiments on olivine-normative basalt compositions would be useful in determining their thermal histories.

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