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Mineralogy, petrology, and chemical composition of lunar samples 15085, 15256, 15271, 15471, 15475, 15476, 15535, 15555, and 15556

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Abstract—Chemical analyses have been made of seven Apollo 15 rocks and one sample of Apollo 15 fines. The rocks, all of mare basalt composition, range from olivine-normative to slightly quartz-normative compositions, and vary considerably in grain size and texture. The principal minerals in all of them are plagioclase (average An_{90}) and pyroxenes (pigeonite and augite). Most of the rocks contain some olivine; the quartz-normative ones contain no olivine, but have accessory tridymite and/or cristobalite. The basalts from the edge of Hadley Rille (15535, 15555, 15556) appear related to one another by olivine fractionation, whereas those from Dune Crater (15475, 15476) represent a compositionally distinct flow or flows. A rock from the Apennine Front (15256) compositionally is similar to the mare basalts, but is a heterogeneous welded breccia, presumably formed by impact on the mare surface and ejected to its Front site. The major-element composition of the fines at Dune Crater (15471) can be closely approximated by a mixture of 70% local basalt and 30% troctolite, suggesting that troctolite may be an important constituent of the pre-Imbrian crust.

INTRODUCTION

WE HAVE EXAMINED samples of the Apollo 15 collections as listed in the title. All but three of them are mare basalts of rather similar composition; 15271 and 15471 are $<$ 1 mm fines, and 15256 is a thoroughly welded impact breccia. Chemical analyses of all of them except 15271 are given in Table 1, along with the norms calculated therefrom.

Approximately 0.5 g of sample was taken for each of the chemical analyses. Silica, MgO, CaO, total iron as FeO, TiO_2, and MnO were determined according to the general procedure for silicate analysis (Peck, 1964). Aluminum was determined gravimetrically by precipitation with 8-hydroxyquinoline on an aliquot from the R_2O_3 solution after removal of interfering ions by means of the mercury electrode. Sodium and potassium were determined by flame photometry, and phosphorus and chromium colorimetrically with molybdenum blue (Boltz, 1958) and diphenylcarbazide (Sandell, 1954), respectively. Summations uniformly are somewhat greater than 100.00, except for the <325 mesh fraction of 15471,27; this feature has been noted by other analysts of lunar rocks. Some of this excess can be ascribed to the presence of metallic iron, whereas all iron is reported as FeO. It is also possible that Ti and Cr may be present in lower valence states than reported. It was noted that ignition of the samples in air results in a weight gain, evidently the result of combination with oxygen. Sulfur was not determined, in order to economize on the consumption of material; analyses reported by LSPET (1972) show about 0.07% S in the Apollo 15 rocks, equivalent to approximately 0.2% troilite.

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Table 1. Chemical analyses and norms of Apollo 15 samples (E. Jarosewich, analyst)

	15085,34	15256,10	15471,27	15471,27 (<325 mesh)	15475,33	15476,5	15535,32	15555,157	15556,26
SiO_2	46.39	45.32	46.43	46.22	48.32	48.46	44.46	44.75	46.18
TiO_2	3.07	2.54	1.61	1.65	1.57	1.75	2.19	2.07	2.64
Al_2O_3	5.79	9.20	13.43	15.35	9.23	9.54	8.68	8.67	9.85
Cr_2O_3	0.67	0.31	0.35	0.28	0.66	0.43	0.57	0.61	0.77
FeO	26.75	22.51	16.20	14.51	20.17	20.76	23.80	23.40	21.70
MnO	0.37	0.35	0.26	0.23	0.31	0.28	0.33	0.30	0.32
MgO	8.20	9.45	11.15	10.11	9.54	8.69	11.27	11.48	8.03
CaO	9.12	10.17	10.58	10.77	10.33	10.50	9.20	9.14	10.72
Na_2O	0.21	0.30	0.37	0.36	0.27	0.28	0.28	0.24	0.30
K_2O	0.07	0.12	0.17	0.18	0.05	0.07	0.04	0.05	0.09
P_2O_5	0.09	0.07	0.11	0.12	0.05	0.05	0.06	0.05	0.07
Total	100.73	100.34	100.66	99.78	100.50	100.81	100.88	100.76	100.67
Q	—	—	—	—	0.05	1.01	—	—	—
Or	0.41	0.71	1.00	1.06	0.30	0.41	0.24	0.30	0.53
Ab	1.78	2.54	3.13	3.05	2.28	2.37	2.37	2.03	2.54
An	14.65	23.40	34.48	39.74	23.83	24.57	22.31	22.43	25.27
Di	25.48	22.35	14.30	10.67	22.73	22.88	19.21	18.89	23.16
Hy	50.67	34.49	32.65	34.31	47.79	45.50	31.33	33.32	40.36
Ol	0.72	11.41	11.27	7.13	—	—	20.29	18.84	2.51
Cr	0.99	0.46	0.52	0.41	0.97	0.63	0.84	0.90	1.13
Il	5.83	4.82	3.06	3.13	2.98	3.32	4.16	3.93	5.01
Ap	0.21	0.16	0.25	0.28	0.12	0.12	0.14	0.12	0.16
Fem*	0.62	0.55	0.43	0.42	0.53	0.55	0.52	0.51	0.57

*Fem = FeO/(FeO + MgO) mole ratio in normative silicates.

Modal analyses were made of most of the rocks by the point-counting technique. Generally the modal analyses were in good agreement with the normative composition, which is to be expected in view of the close correspondence between normative and observed mineralogy. Where discrepancies were found, they could be ascribed to sampling problems, as discussed in the following section. The close correspondence between normative and observed mineralogy is documented by the occurrence of tridymite and cristobalite. Of the two rocks with free SiO_2 in the norm, 15475 contains about 0.5% tridymite and 15476 about 0.7% cristobalite. The only other rock containing these minerals is 15085, which contains about 0.7% tridymite and 0.4% cristobalite; the norm shows slight undersaturation in SiO_2, equivalent to 0.7% olivine, but the discrepancy is small and well within possible analytical and sampling errors.

Trace element analyses on aliquots of the previously analysed samples are reported in Table 2. The technique used is described by Thompson and Bankston (1969). These analyses show that the fines (15471), compared to the rocks, are enriched in Ba, Ni, Pb, Rb, Sr, Y, and Zr, and are depleted in Cr and V; these trends are most marked in the <325 mesh fraction. The enrichment of Ni in the fines is consistent with a meteoritic increment in the material; a 1% increment of carbonaceous chondrite composition will increase the Ni concentration by approximately 100 ppm, but the Co concentration will increase by only 5 ppm and thus not readily be detected. Trace element variations within the crystalline rocks are not great; the porphyritic olivine basalts show higher concentrations of Ni and V and lower concentrations of Ba than the porphyritic clinopyroxene basalts. Rock 15476 shows

Table 2. Trace element analyses by direct-reading emission spectrometry, in ppm; precision and accuracy ±5–10%. Analyses are mean of four separate burns except 15471, which are mean of two separate burns. Ag < 1, Cd, Bi < 2, Zn < 10 ppm in all samples. (G. Thompson, analyst.)

	15085,34	15256,10	15471,27	15471,27 (<325 mesh)	15475,33	15476,5	15535,32	15555,157	15556,26
Rb	<5	<5	5	5	<5	<5	<5	<5	<5
Ba	87	41	120	150	47	63	38	30	50
Sr	92	88	115	125	96	98	83	83	102
Pb	2	<2	6	4	<2	<2	<2	<2	<2
Cu	18	11	10	19	6	7	8	17	10
Y	54	48	55	65	37	42	42	47	50
Zr	150	100	205	265	65	105	85	60	100
Co	49	46	40	37	56	37	52	66	46
Ni	45	60	160	225	50	27	70	70	65
Li	8	8	9	9	8	8	7	7	9
V	110	135	100	75	130	90	140	145	165
Cr	4600	4200	3600	3300	4500	3600	4800	4500	5200
Ga	5	4	4	2	3	3	3	3	5
B	5	3	2	1	4	2	4	3	3

significantly lower concentrations of Co, Cr, Ni, and V. The metabasalt 15256 does not show any anomalous concentrations of these trace elements.

SAMPLING PROBLEMS

We attempted to assess how representative our analyses are, in view of the small size of our subsample (0.5 g) and large grain size of some of the samples, especially 15085. Even a cursory appraisal of sampling statistics shows that such small subsamples cannot be even roughly representative of the whole for rocks like 15085. The size of subsamples required for representative analysis is proportional to the average volume of crystal (cube of the average grain size), and subsample size becomes prohibitively large (> 10 g) where average grain sizes exceed 2 mm. Average grain size for 15085 is greater than 3 mm, and our analysis thus has very low probability of being representative of the whole. The problem is less acute for the other samples, but our analyses of 15475, 15476, 15535, and 15555 must still be viewed with caution. On the other hand, our analyses of 15256 and 15556 are based on reasonably sized subsamples in view of their fine grain size (average <0.5 mm). For samples less than 0.5 mm average grain size, subsamples on the order of 0.10 grams could give reasonably meaningful results. An additional problem arises for 15256, a welded breccia, in that it contains mineral and rock clasts that commonly exceed 1 mm in maximum dimension, that is, it is not a petrologically homogeneous sample.

Some of the problems encountered in using nonrepresentative analyses can be well-demonstrated by comparing our analysis of 15085 with the others in Table 1 and with previous analyses of lunar basaltic rocks. Our analysis of 15085 is much lower in Al_2O_3 (5.79%) than practically all other lunar mare basalts. This is shown in Fig. 1, where we find a good direct correlation between the Fe/(Fe + Mg) ratio and total normative feldspar in most Apollo 12 and 15 mare basalts. Rock 15085 falls far off this trend for other Apollo 15 mare basalts. The analysis of 15076, also

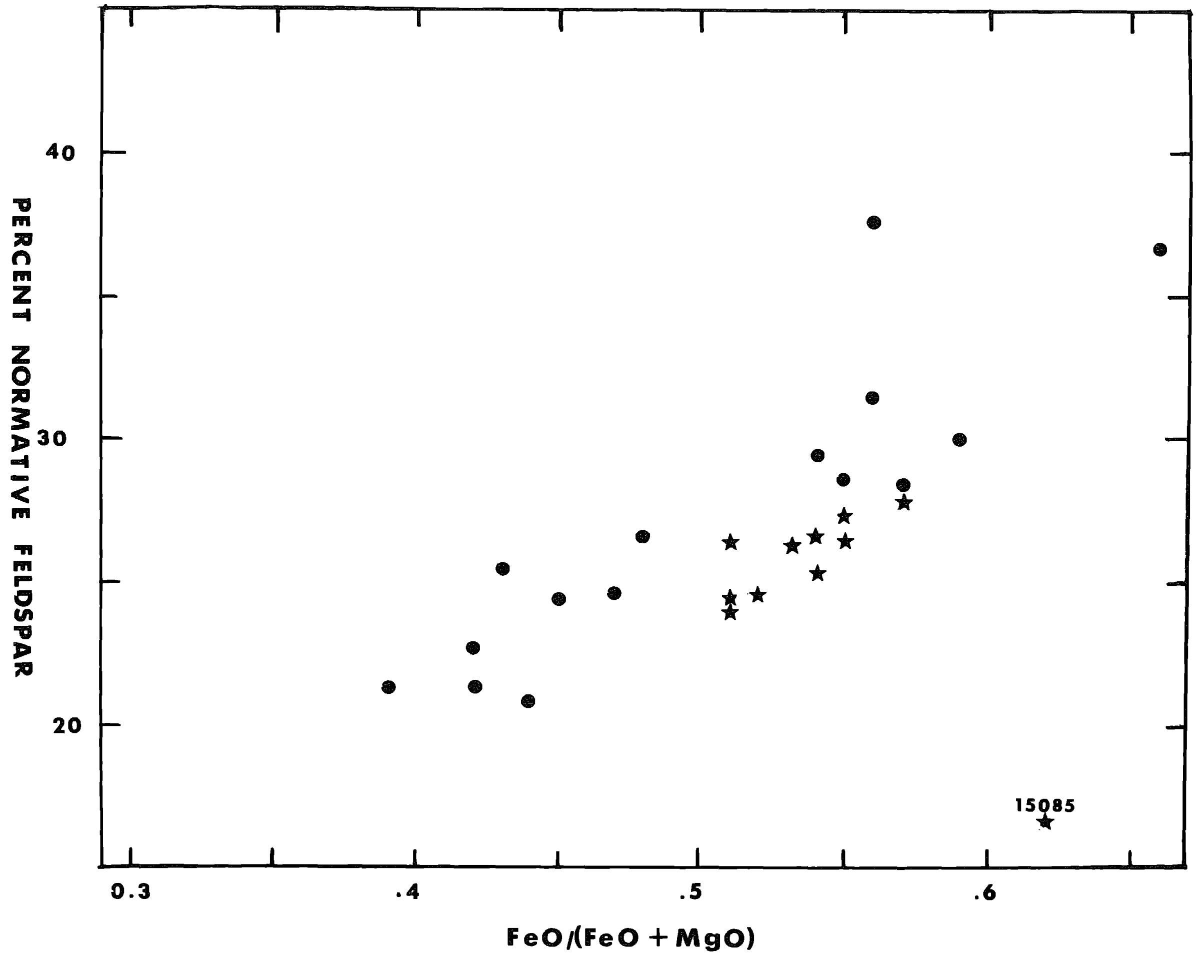

Fig. 1. In the Apollo 12 and 15 mare basalts, there is a rough direct correlation between Fe/(Fe + Mg) and total normative feldspar (An + Ab + Or). Some of the scatter in these data, like our result for 15085, is a result of sampling problems for coarse-grained rocks. Most samples that fall very far from this trend have average grain sizes greater than 1 mm. Stars: Apollo 15 analyses from LSPET (1972) and Jarosewich (this paper). Circles: Apollo 12 mare basalts.

a coarse-grained rock, departs significantly from this trend (LSPET, 1972), but not as much as our 15085 analysis.

There are significant variations in the major element analyses so far reported for rock 15555 (Table 3). The analysis by D. F. Nava (Schnetzler *et al.*, 1972) departs widely from the others for a number of elements, especially Al, Mg, and Ti. Sampling errors possibly are evident in the Fe/(Mg + Fe) ratio, reflecting variation in the olivine to pyroxene ratio, and in the up to 2 percent variation in alumina content, possibly reflecting differences in plagioclase contents of the subsamples, all of which are 0.5 g or less.

Much more meaningful analyses would be obtainable if subsamples were sized so as to be reasonably representative of the whole. This size would be prohibitively large for very coarse-grained samples, but would be reasonable for most mare basalts, normally less than 10 grams. Such a subsample ideally should be taken and powdered by the NASA curatorial facility and smaller aliquots of this could then be

Table 3. Different analyses* of 15555 (n.d. = not determined)

	1	2	3	4
SiO_2	44.75	43.82	44.24	45.0
TiO_2	2.07	2.63	2.26	1.60
Al_2O_3	8.67	7.45	8.48	9.37
Cr_2O_3	0.61	0.59	0.70	0.47
FeO	23.40	24.58	22.47	21.18
MnO	0.30	0.32	0.29	0.26
MgO	11.48	10.96	11.19	12.22
CaO	9.14	9.22	9.45	9.25
Na_2O	0.24	0.24	0.24	0.26
K_2O	0.05	0.04	0.03	0.03
P_2O_5	0.05	0.07	0.06	0.07
S	n.d.	0.06	0.05	n.d.
Fe/(Fe + Mg)	0.51	0.53	0.51	0.48

*Sources.

1. E. Jarosewich, this paper (0.5 g).
2. Chappell et al. (1972) (0.36 g).
3. LSPET (1972) (0.28 g).
4. Schnetzler et al. (1972) (0.5 g); D. F. Nava analyst.

distributed, rather than small rock chips, as has often been done. Analyses of small chips (< 1 g) of coarse-grained (> 1 mm) rocks give a large spread that does more to obscure than to reveal significant variations in lunar magmas.

PETROLOGY OF APOLLO 15 MARE BASALTS

In the following discussion, our analyses of 15256, 15475, 15476, 15535, 15555, and 15556 will be assumed to be representative of the whole rocks. The close agreement of our analyses of 15555, 15256, and 15471 (fines) with those of LSPET (1972) suggests that, in regard to sample size and analytical methods, both sets of analyses are meaningful. The samples considered include also 15016, 15058, 15076, and 15499, of which analyses from LSPET (1972) are available, bringing the total number of Apollo 15 mare basalt samples considered here to ten.

The samples from the Hadley Rille rim (Station 9A, samples 15535, 15555, 15556) appear related to one another by fractionation, with olivine as the dominant fractionating phase (Fig. 2). The samples from Dune Crater (15475, 15476, 15499) fall close to one another and off the Rille trend, presumably reflecting a different magmatic parent, and thus represent a flow or flows compositionally distinct from those sampled at the Rille. The basalt from the ALSEP site, 15058 (LSPET, 1972) appears to belong to the Dune Crater group, whereas 15016, from the mare surface, appears closer compositionally to the Rille basalts of Station 9A. The division into two major compositional groups correlates with topography. The lower FeO group (Fig. 2) corresponds to mare basalts nearer the Apennine Front and at slightly higher elevations than those from the ALSEP site and from the Rille.

The two analyses of basalts from Elbow Crater, 15085 and 15076, are of coarse-grained samples. One, 15085, as previously discussed, was of a chip too small to give meaningful results, and the other, 15076, also may have been too small to give meaningful results.

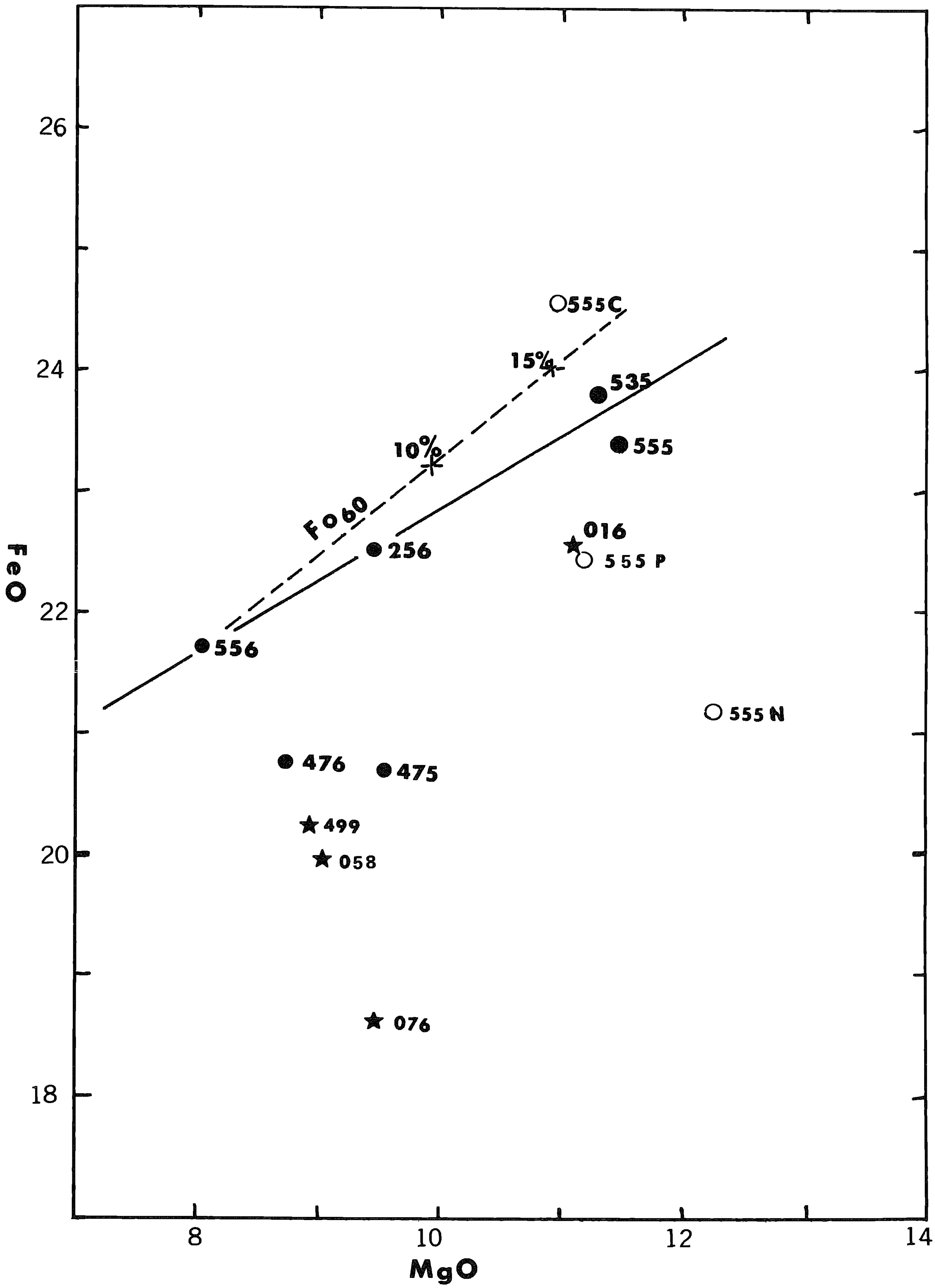

Fig. 2. The Apollo 15 mare basalts fall into at least two major groups. One group, those from near Hadley Rille (15535, 15555, and 15556) falls along a trend approximating an olivine fractionation trend, shown for addition of Fo_{60} to rock 15556. The other group, from Dune Crater and the ALSEP site, contain much less olivine, and cannot be simply related to those from Rille Station by olivine fractionation. Some of the divergence in 15555 analyses also is shown: 15555C from Chappell *et al.* (1972), 15555P from LSPET (1972), 15555N from Schnetzler *et al.* (1972).

The Apollo 15 mare basalts more closely resemble those of Apollo 12 than those of Apollo 11. They have low TiO_2 content and, like the Apollo 12 basalts, show evidences of olivine fractionation. So far, however, the analyses show much less compositional spread than those of Apollo 12 (e.g., Fig. 1). The age so far available, around 3.36 b.y. for 15555 (Podosek *et al.*, 1972), falls within the range of those for Apollo 12 basalts, suggesting that the volcanism at the Apollo 12 site was part of a very broad zone of volcanism, and one that led to the filling of Mare Imbrium as well as adjacent low areas.

Compositional trends are best shown by the results of analyses done by the same analyst, a not unexpected result and one noted for Apollo 12 samples by James and Wright (1972). Figure 3 shows this for our analyses and those of LSPET (1972). Both show an expected trend of increasing normative olivine with decreasing silica content, but our values are systematically displaced toward higher silica contents.

Sample 15555 has been studied extensively by us, whereas the others, some newly received, have not been examined in detail. Figure 4 shows the complex, and in places, oscillatory zoning in one of the large pigeonite-cored pyroxenes, presumably reflecting relative movement of crystal and magma during pyroxene growth. Hypothetically, movement of pyroxene into nearby magma already depleted by pyroxene growth accentuated zoning, giving a sharp increase in the Fe/Mg ratio. Movement in magma depleted in calcium by growth of plagioclase causes decrease in Ca content of the pyroxene at constant Mg. All these changes require some undercooling and slow diffusion rates of Ca, Mg, and Fe in the magma.

The olivine in 15555 commonly is enclosed in plagioclase, and is unusually iron-rich compared to that of other mare basalts, even for its most magnesian compositions (Fo_{58}). Coexisting pigeonite-cored pyroxene (approximately $Fs_{32}Wo_{11}En_{57}$) are too magnesian to have crystallized in equilibrium with such olivine. Chappell *et al.* (1972) note that a composition like 15555 would first crystallize olivine near Fo_{72}, and infer that the more iron-rich olivine reflects accumulation of about 20% olivine at a temperature around 1140°C. Figure 2 shows that addition of about 15% olivine near Fo_{60} to rock 15556 gives a reasonably good fit to the composition of rock 15555.

Rock 15256 is heterogeneous, and contains thoroughly welded mineral and rock clasts (Fig. 5). Large olivine clasts occur in some portions and typically have compositions around Fo_{65}. Some basaltic clasts are vitrophyric, with abundant olivine phenocrysts and microlites, typically ranging from Fo_{65} to Fo_{50}. Although texturally complex, this sample shows distinct mare basalt major element composition (Table 1 and Figs. 2 and 3) and falls on compositional trends established for the Rille basalts from Station 9A. We infer that it was ejected from the mare surface to its Front site by impact.

The trace elements contents (Table 2) can be compared with the proposed fractionation in the Rille series, in which we have included 15256 because of its close similarity in composition. If we assume that 15535 and 15555 are related to 15556 by the addition of 16% olivine, and 15256 by the addition of 7% olivine (Fig. 2), and further that olivine contains none of the incompatible elements, Ba, Sr, Zr, and K, we obtain the following model results, in ppm:

Ba	determined	50	38	30	41
	predicted	—	42	42	47
Sr	determined	102	83	83	88
	predicted	—	70	70	95
Zr	determined	100	85	60	100
	predicted	—	84	84	93
K	determined	900	400	500	1200
	predicted	—	760	760	840

There are some differences between predicted and determined values, although there is a general trend toward increasing incompatible element content with decreasing olivine content. The differences between the model and determined values may indicate (1) that the model is incorrect, that is, that each rock type represents an independent magma, or (2) the precision of the trace element determinations is inadequate for a comparison of this sort.

APOLLO 15 FINES

Two samples of < 1 mm fines have been studied, 15271 from Station 6 on the Apennine Front and 15471 from Station 4 near the rim of Dune Crater. Two analyses of 15471 were made, one of an "as received" aliquot, and one of a < 325 mesh sieve fraction (< 0.043 mm grain size). These analyses (Table 1) are quite similar, as might be expected. The principal difference is a somewhat higher Al_2O_3 content in the <325 mesh fraction, giving a higher normative anorthite content. We have noted a similar enrichment in plagioclase content of the <325 mesh fraction of Apollo 11, 12, and 14 fines.

Significant differences were observed between the 15271 material and the 15471 material. Although the bulk composition of each is essentially basaltic, 15471 appears to be produced largely from local mare basalt with some admixture of feldspar-rich non-mare material, whereas 15271 represents a mixture of mare and non-mare material in subequal amounts. This interpretation is supported by our preliminary examination of coarser fines from these same locations.

Both samples consist largely of black cindery glass particles with minor amounts of mineral grains, and a few rock fragments in the coarsest (0.5–1 mm) fraction. A hand magnet provides a quick, if crude, separation of the glassy material, because it contains minute metal particles. The mineral fraction consists largely of plagioclase, pyroxenes, and olivine; in 15271 the plagioclase approximately is equal in abundance to the ferromagnesian minerals, whereas in 15471 the latter are considerably more abundant than plagioclase. The compositional ranges (determined by microprobe analysis) of the ferromagnesian minerals also are distinctive. In 15471 the ferromagnesian minerals consist of approximately 23% olivine (Fa_{28-58}, av. Fa_{39}), 3% orthopyroxene, 30% pigeonite, 21% subcalcic augite, 20% augite, and 3% ferrohedenbergite plus pyroxferroite. In 15271 they consist of 24% olivine in two distinct compositional ranges (about 6% Fa_{10-20}, 18% Fa_{44-50}), 16% orthopyroxene (Fs_{12-25}), 30% pigeonite, 14% subcalcic augite, 15% augite, and 1% ferrohedenbergite plus pyroxferroite. The magnesium-rich olivine and orthopyroxene in 15271 distinguish it clearly from 15471, and probably are derived from non-mare rocks. We have found these minerals in feldspar-rich basalt fragments in coarse fines 15272

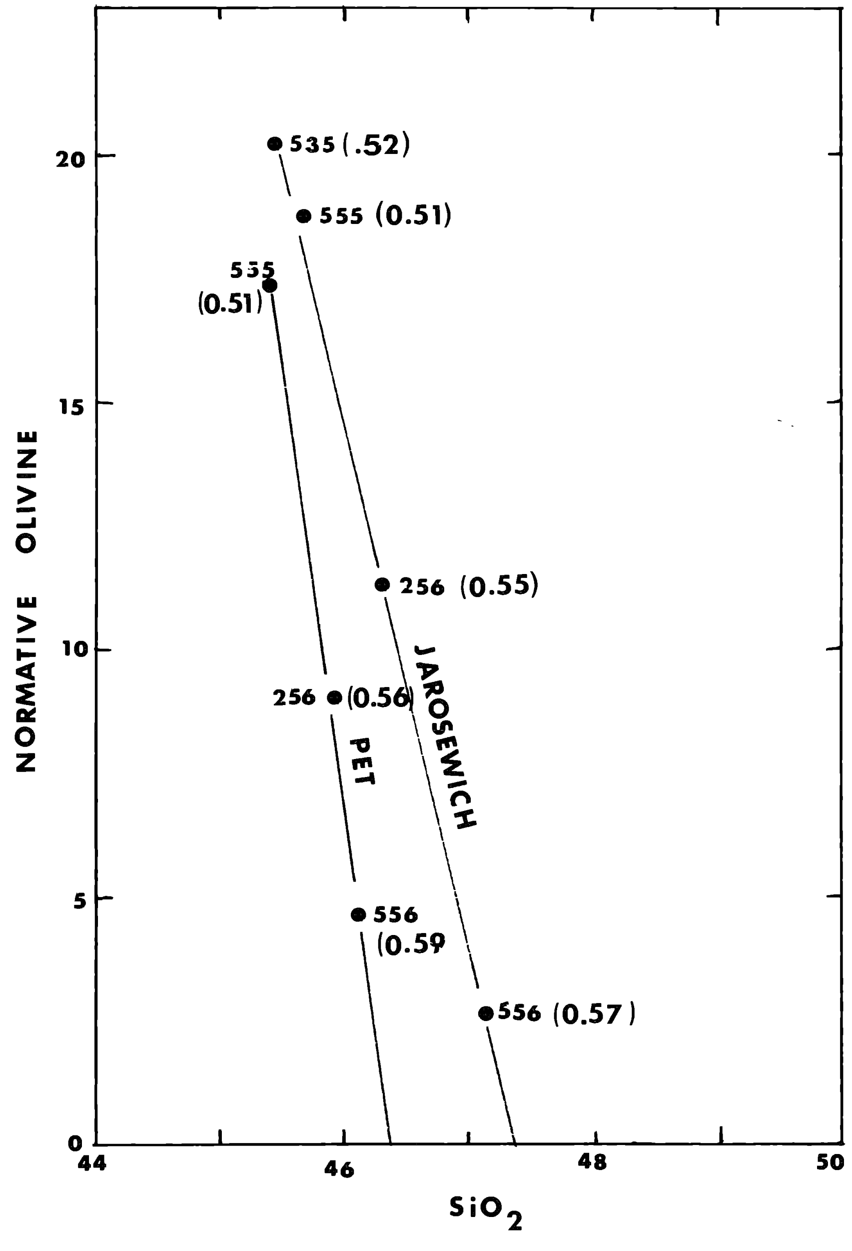

Fig. 3. Both LSPET (1972) and our major element analyses show a well-developed trend for normative olivine versus silica for the Rille basalts (Station 9A), but are systematically different in SiO_2 content. Numbers in parentheses are Fe/(Fe + Mg) in normative silicate, that is, with FeO in $FeTiO_3$ and $FeCr_2O_4$ subtracted. As expected in an olivine fractionation series, Fe/(Fe + Mg) decreases with increasing olivine content.

and 15273. Rare grains of red spinel were found in both 15271 and 15471; these probably have been derived from troctolitic rocks of non-mare origin (Mason *et al.*, 1972).

From our data it is possible to make a comparison between soil and rock compositions at Dune Crater (Station 4). The analyses of 15471 (< 1 mm fines) and rocks 15475 and 15476 are given in Table 1. These three samples were collected at the same place, described as approximately 28 m SSE of the rim crest of Dune Crater.

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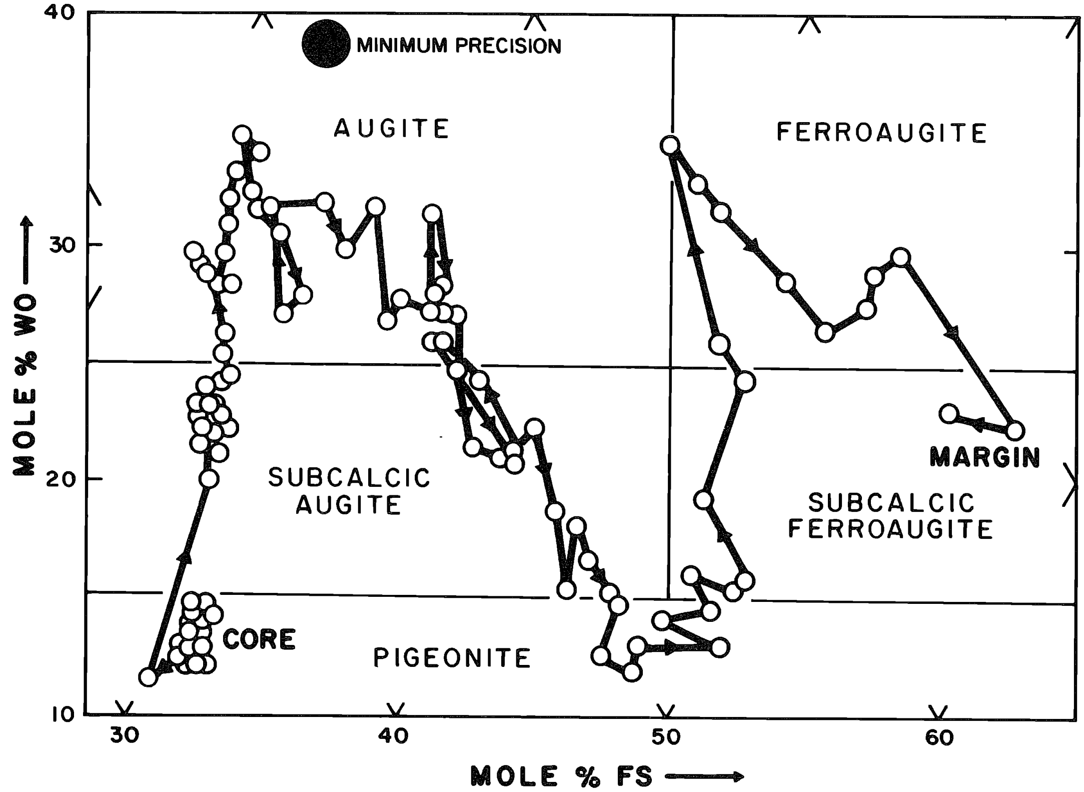

Fig. 4. Complex zoning, probably reflecting crystal growth during relative movement of crystal and magma either during turbulent flow or by crystal settling, is well-shown by large pyroxenes in 15555,29. Portion of the pyroxene ternary wollastonite (Wo), ferrosilite (Fs), enstatite (En).

The compositions of 15475 and 15476 essentially are identical, although the rocks differ somewhat in texture. The chemical composition of 15471 differs most notably from 15475 and 15476 in being higher in Al_2O_3 and MgO and lower in FeO and SiO_2. These facts can be accounted for by a higher content of plagioclase in the fines than in the local rocks, and the addition of a material with a relatively low FeO/(FeO + MgO) ratio and a low silica content—magnesian olivine is the obvious candidate. As far as the major components are concerned, a good match for 15471 is obtained by diluting the local rocks with 20% plagioclase (An_{90}) and 10% magnesium-rich olivine (Fa_{10}), as follows:

	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O
15476 (70%)	33.9	6.68	14.5	6.08	7.34	0.20
An_{90} (20%)	8.8	6.95	—	—	3.64	0.20
Fa_{10} (10%)	4.1	—	1.0	4.90	—	—
Sum	46.8	13.63	15.5	10.98	10.98	0.40
15471	46.4	13.43	16.2	11.15	10.58	0.37

Thus, the composition of a mixture of 30% troctolite and 70% local rock approximates closely the composition of the <1 mm fines. Although we did not find any olivine as magnesium-rich as Fa_{10} in our microprobe analyses of the 15471 minerals,

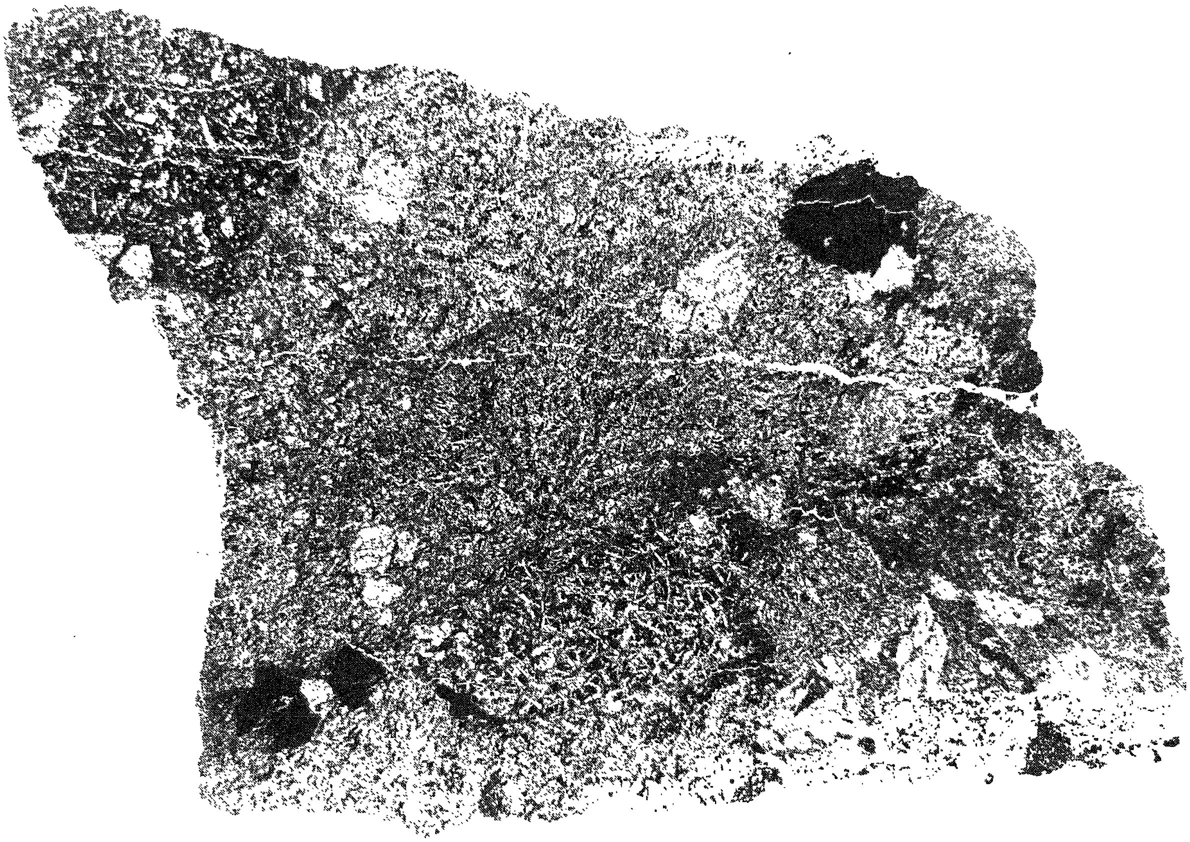

Fig. 5. Rock 15256 is a texturally heterogeneous, shock-altered rock, probably ejected to the Apennine Front from a mare impact site. Some clasts, upper left, possess a well-developed vitrophyric texture containing phenocrysts or microlites of olivine and less commonly of pyroxene. Maximum width of section (15256,20) is 12 mm. Dark areas are devitrified glass, with the glass probably produced by the impact event.

these analyses were made on the coarse grains (60–100 mesh) and thus may not be representative of the total mineral content.

We have made a preliminary examination of the coarse fines at this locality but have not so far identified any troctolite fragments. However, the coarse fines contain numerous complex breccia fragments that may well incorporate such material. In addition, as mentioned above, 15471 contains sporadic grains of pink spinel, which we have suggested originate in a troctolitic rock. We therefore believe that troctolites may be significant components of the pre-Imbrian crust.

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