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Some petrological aspects of Imbrium stratigraphy†

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Petrochemical studies of clasts in breccias from Fra Mauro and Apennine Front provide insights into different structural levels of pre-Imbrium terra crust. Most of the Fra Mauro breccias and included clasts are 'kreep' basalts showing both igneous and cataclastic textures and are interpreted as the surface veneer of the terra crust. Similar samples were collected from the Apennine Front near Spur Crater, but they are mixed in with clasts of coarse, plutonic texture. One clast type is spinel pyroxenite whose mineralogy and petrochemistry are consistent with the original rock type being garnet pyroxenite. Such a mineral assemblage could only be stable at greater than 300 km depth, well within the lunar upper mantle. It is suggested that these clasts represent garnet pyroxenite xenoliths, emplaced within the lunar crust during early volcanism, that underwent a phase transition to spinel pyroxenite. Another clast type is plutonic norite, in which coarsely exsolved inverted pigeonite is associated with anorthitic plagioclase. Similar terrestrial rocks are found in Stillwater-type layered intrusions, and it is suggested that the lunar norites were parts of terra crustal layered complexes developed beneath a veneer of impact brecciated crust. Examples of the latter are illustrated by poikiloblastic-textured gabbroic anorthosite, with inverted pigeonite oikocrysts surrounding grains of plagioclase, augite, pigeonite, orthopyroxene, olivine and ilmenite. Application of mineral geothermometers indicates crystallization of these rocks below 1100 °C, temperatures that are well below the liquidus. Hence these textures probably developed largely by solid state recrystallization during impact-metamorphism.

Introduction

The depth of excavation of major lunar basins remains a contentious question. Extensive excavation of basins the size of Imbrium should have ejected samples of the lower lunar crust or possibly the upper mantle. We find no sample in the Imbrium ejecta at either the Apollo 14 or 15 site that can *unequivocally* be related to deep stratigraphic levels. This suggests that samples from Fra Mauro and the Apennine Front sampled relatively shallow crustal levels, although cratering studies indicate that Apennine Front samples would be from a *relatively* deeper level than those from the Fra Mauro site.

Attempts to reconstruct a pre-Imbrium stratigraphy for the upper terra crust, in even the most simplistic manner, are hampered by the lithologic complexity of the Imbrium breccias and thermal metamorphic overprinting. The most direct reflection of pre-Imbrium lithologies is provided by clasts in breccias. The clasts dominantly show fragmental textures, indicative of a terra crust already pervasively fragmented prior to the Imbrian event. Of the other clast types present at the Fra Mauro site, most have basaltic textures with very infrequent examples of coarse-grained rocks. The basaltic clasts are all 'kreep'-like in composition, as are most of the Fra Mauro samples, irrespective of texture. One might argue then that the Imbrium crust

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had a veneer of kreep basalt that was excavated to the Fra Mauro site during the Imbrian event. In comparison kreep basalts are not so prevalent at the Apennine Front, although they are still major clast types in the terra breccias. In addition other clasts are present with coarse textures which suggest a plutonic environment of formation, consistent with a deeper level of excavation at the Apennine Front.

Following, are descriptions of the petrochemistry of two Apennine Front breccias 15445, 15459, both ejected to the surface during excavation of Spur Crater. Discussion centres on the relevance of the various components of the breccias to pre-Imbrium stratigraphy.

Glass population

Breccia 15459 is a clast-laden, glass matrix breccia. The matrix contains numerous angular to spherical glass particles, which have been analysed by electron microprobe techniques. Average glass compositions and relative glass abundances are shown in table 1. Green glass with very little compositional variance dominated the glass population, as observed in several other Apollo 15 soils (Reid *et al.* 1972). Indeed the relative glass abundances for the breccia matrix are close to those estimated for soil samples collected near Spur Crater (table 1). Two

Table 1. Average glass compositions in 15459 matrix

	1	2	3	4	5	6	7	8	9
SiO_2	45.24	45.43	49.52	46.40	44.11	35.38	37.64	42.93	43.95
TiO_2	0.34	0.42	1.37	0.85	0.05	13.64	12.04	3.11	2.79
Al_2O_3	7.53	7.72	17.08	19.47	30.90	7.26	8.46	8.89	8.96
Cr_2O_3	0.45	0.43	0.19	0.17	0.03	0.64	0.48	0.46	0.46
FeO	19.51	19.61	9.37	8.34	3.53	21.42	19.93	21.72	21.10
MgO	17.55	17.49	9.07	12.49	3.51	12.10	10.49	12.37	12.30
CaO	8.23	8.34	10.65	11.39	17.23	7.66	8.81	8.68	9.02
Na_2O	0.13	0.12	0.63	0.53	0.13	0.52	0.54	0.39	0.27
K_2O	0.01	~0.01	0.50	0.18	0.01	0.14	0.13	0.08	0.05
Total	98.98	99.57	98.38	99.82	99.49	98.76	98.52	98.63	98.90

1, Green glass. 2, Average green glass composition in three Apollo 15 soils (Reid *et al.* 1972). 3, Medium-K kreep. 4, Low-K kreep. 5, 'Anorthositic' component. 6, High-Ti mare basalt. 7, 'Mare 4' glasses in Apollo 15 soils (Reid *et al.* 1972). 8, Mare glasses. 9, 'Mare 3' glasses in Apollo 15 soils (Reid *et al.* 1972).

Average abundances:	15459	A-15 soil
Green glass	43%	34%
Low-K kreep	13%	15%
Medium K kreep	20%	22%
'Anorthosite'	2%	
Mare	22% (High-Ti 2%)	22%

types of aluminous basaltic glass were observed, one type termed medium-K kreep (following the terminology of Reid *et al.* (1972)) and a second with lower K_2O, TiO_2 and higher Mg/Fe ratio, termed low-K kreep. The latter is synonymous with the low-alkali basalt composition of Prinz *et al.* (1973) and is representative of a compositional group found at most lunar landing sites (Ridley *et al.* 1973). Unlike kreep, samples of which have been described with unequivocal basaltic textures, low-K kreep has only been described as a glass or clasts with hornfelsic textures. Hence the significance of this composition as a pristine basaltic magma remains questionable. Particularly disturbing is the observation that the polymict matrix of 15459 has a *bulk* composition of low-K kreep, indicating that in at least one case, the composition arises by a mixture of several chemically distinct components.

The matrix also contains a high proportion of mare-like glasses, based upon their Fe/Mg ratio and TiO_2 content. Two types of mare glass have been distinguished, a high-Ti type (table 1), closely analogous to the 'Mare 4' glasses analysed from Apollo 15 soils (Reid *et al.* 1972), and a low-Ti type analogous to the 'Mare 3' glasses from Apollo 15 soil (Reid *et al.* 1972). This latter glass group is equivalent to the most magnesian olivine-normative mare basalt from Palus Putredinus (Rhodes & Hubbard 1973). No glasses were found equivalent to the Apollo 15 quartz-normative mare basalts. The high-Ti glasses (a minor component) have no basalt equivalent at the Apollo 15 site but have been observed at almost all Apollo landing sites (Reid *et al.* 1972). Chemically they are similar to, but somewhat more magnesian than, the olivine-normative Apollo 17 basalts.

An important point is the absence of glasses chemically equivalent to the 'highland basalt' or anorthositic gabbro component observed in abundance in most lunar soils, including those from the Apollo 15 site. Indeed the 'terra' component in 15459 glasses is of very minor importance, represented by only a few glasses of gabbroic anorthosite composition. This anachronism is the only major difference between glass abundances in the matrix of 15459 and Apennine Front soils.

Several observations can be made regarding the matrix data. The bulk composition of the matrix is similar to that of several Apennine Front soils. Together with the overall similarities in glass abundances in the matrix and soils, we might surmise that the breccia could have evolved by induration of a pre-existing local soil. From the individual, average glass compositions it is evident that green glass forms a dominant component in both Apennine Front soils and glass-laden breccias. The composition of green glass remains highly invariant, but its source still remains enigmatic. If the low-K kreep composition is representative of a basalt magma-type then it should play an important role in lunar petrogenesis. For instance, in appropriate equilibrium systems it clusters around peritectic points and hence schemes can be evolved relating to kreep magma and a spectrum of cumulate rocks, e.g. troctolites, norites, anorthosites. At present however, its rank as a magma type remains speculative.

Petrochemistry of selected clasts

(*a*) *Spinel-pyroxenite*

Ridley *et al.* (1973) have described a number of pink-spinel bearing clasts in a highly indurated breccia 15445. These clasts have cataclastic texture but relict unfragmented areas confirm the clasts originally were coarsely crystalline. The mineralogy is essentially olivine + orthopyroxene + spinel + plagioclase. Compositions of mineral phases are given in table 2. Trace element data for one of these clasts showed a rare earth element (r.e.e.) pattern with strong relative enrichment of heavy over light r.e.e. (Ridley *et al.* 1973). This pattern remains unique amongst lunar rocks, and leads to the suggestion that the clasts must originally have contained a high proportion of garnet. This can be achieved by the following reaction: $Mg_3Al_2Si_3O_{12} + Mg_2SiO_4 \rightleftharpoons MgAl_2O_4 + 4MgSiO_3$ which proceeds to the right with decreasing pressure. Hence we suggest the clast assemblage may originally have been pyrope-rich garnet +

forstoritic olivine + orthopyroxene. Recalculation of the mineral compositions suggests the following reaction has occurred:

$$\underset{\text{garnet}}{(Mg_{2.62}\,Fe_{0.38})\,(Al_{1.73}\,Gr_{0.27})\,(Si_{2.87}\,Al_{0.13})\,O_{12}} + \underset{\text{olivine}}{(Mg_{1.83}\,Fe_{0.17})\,(Si_{0.99}\,Al_{0.01})\,O_4} \rightleftharpoons$$

$$\underset{\text{spinel}}{(Mg_{0.79}Fe_{0.21})\,(Al_{1.73}\,Cr_{0.27})\,04} + 2\underset{\text{orthopyroxene}}{(Mg_{1.83}\,Fe_{0.17})\,(Si_{1.93}\,Al_{0.07})\,O_6}$$

Table 2. Composition and formulae for minerals in spinel pyroxenite clasts in 15445

	orthopyroxene	olivine	spinel
SiO_2	56.51	40.85	—
TiO_2	0.15	—	—
Al_2O_3	2.44	0.22	56.97
Cr_2O_3	—	—	13.40
FeO	5.70	8.55	9.52
MgO	35.67	50.20	20.10
CaO	< 0.01	< 0.01	—
Si	1.9276	0.9932	—
Ti	0.0036	—	—
Cr	—	—	0.2737
Al	0.0980	0.0058	1.7806
Fe	0.1621	0.1731	0.2053
Mg	1.8284	1.8310	0.7806
Ca	—	—	—
O	6.00	4.00	4.00

Enstatite	92	Forsterite	91	Spinel	79
Ferrosilite	8	Fayalite	9	Hercynite	8
				Chromite	13

It is interesting to note that this is almost identical to the isochemical change from garnet to spinel peridotite described by Reid & Dawson (1972) from terrestrial samples. Note also the garnet can be recalculated as 13 % almandine + 13 % knorringite + 74 % pyrope. The high Cr contents are also characteristic of terrestrial garnets enclosed within diamond (Meyer *et al.* 1972). The presence of plagioclase in the clasts could result from intercumulus growth of plagioclase if the original rock was a cumulate, although this would be incompatible with the original presence of garnet. Alternatively the plagioclase may reflect partial equilibration of the rock in a low pressure environment, in which original diopside was used up according to the reaction; diopside + spinel + orthopyroxene ⇌ plagioclase + olivine. This might account for the absence of diopside in the clasts. The limited data available for the bulk composition of one clast (7.2 % Al_2O_3, 31.1 % MgO; 1.9 % CaO) and mineral analyses, indicate an approximate mode of 59 % orthopyroxene + 24 % olivine + 7 % spinel + 10 % plagioclase. The mode indicates an original rock approximately equivalent to garnet pyroxenite and represents first evidence (although indirect) for a high pressure mineral assemblage among lunar samples. Experimental studies by Kushiro (1972) indicate that even under favourable conditions, i.e. a strongly aluminous environment, garnet is stabilized relative to spinel at depths greater than 320 km, consistent with pressure estimates from subsolidus experiments with terrestrial peridotites (Green & Ringwood 1967). Hence these clasts cannot have originated within the lunar crust unless the latter was subjected to high tectonic overpressures. We suggest that these clasts are fragments of samples from within the lunar mantle that were emplaced within the

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lunar crust, possibly as xenoliths in ascending magma. Within the crust they underwent one and probably two phase changes that stabilized spinel and then plagioclase. They were subsequently excavated during the formation of the Imbrium Basin and incorporated into the Imbrium ejecta blanket. We also note that the calculated mode, allowing for the crudeness of the technique, is that of a pyroxenite, consistent with models requiring a pyroxenitic mantle for the Moon.

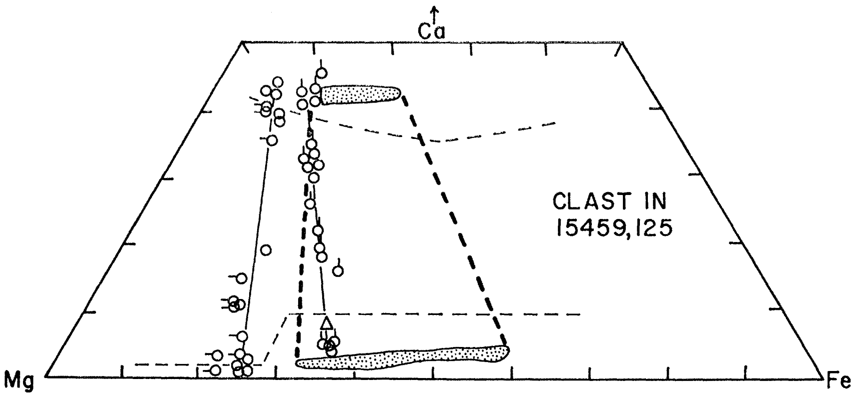

FIGURE 1. Composition of pyroxenes in clasts in breccia 15459. Solid lines are tie lines between coexisting Ca-rich and Ca-poor pyroxenes. Shaded areas are range in composition of exsolved pyroxenes in Apollo 16 breccias. Dashed lines are coexisting pyroxenes from the Skaergaard Intrusion. Circles with vertical bar are inverted pigeonites from a plutonic norite clast. Intermediate compositions represent analyses where the microprobe beam was unable to resolve host and lamellae. Triangle represents bulk analyses of inverted pigeonite. Circles with horizontal bars are exsolved orthopyroxene oikocrysts in a poikiloblastic clast. Circles represent coexisting orthopyroxene and augite chadacrysts in the same clast.

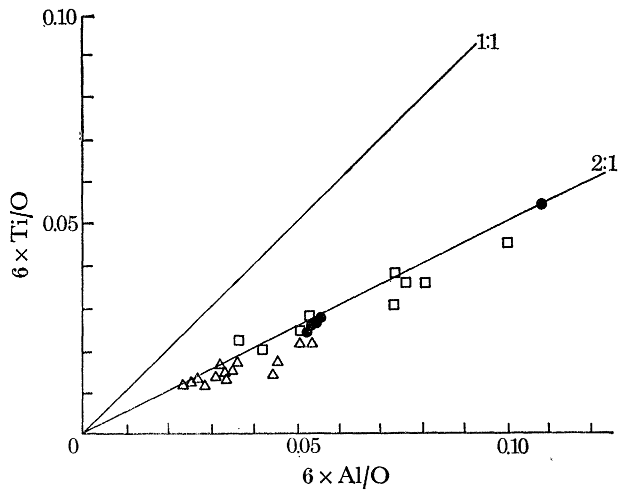

FIGURE 2. Ti-Al relations in pyroxenes plotted in figure 1. Note the close adherence to Al:Ti = 2:1 line indicating the presence of $R^{2+}TiAl_2O_6$ component. △, exsolved inverted pigeonites in plutonic norite; □, exsolved orthopyroxene oikocrysts; ●, coexisting orthopyroxene-augite chadacrysts in a poikiloblastic clast.

(*b*) *Norite*

Breccia 15459 contains clasts composed of coarse grains of calcic plagioclase and orthopyroxene. Coarse exsolution lamellae of augite occur parallel to 100 of the orthopyroxene with earlier exsolution parallel to 001 of an original pigeonite. Table 4 (anal. 9–10) and figures 1 and 2 indicate the chemical relations between pyroxenes in this type of clast. Similar pyroxenes have been described by Brown *et al.* (1973) from some Apollo 16 breccias, and Papike & Bence (1972) from an Apollo 14 breccia. The observation of pigeonite inverted to orthopyroxene, accompanied by exsolution of augite can be closely matched by terrestrial layered complexes of the Stillwater type. Together with the coarse-texture and simple mineralogy, all these features are consistent with the norites having developed by slow cooling of basic magma within the lunar crust. The bulk composition of the exsolved pyroxene is that of pigeonite with a low TiO_2 content. This contrasts with the titaniferous pigeonites crystallized from mare basalts, suggesting the parent magma was not of mare basalt composition. The presence of abundant plagioclase, together with the low TiO_2/Al_2O_3 ratio of the pyroxenes indicates an aluminous magma as a parent.

Table 3. Spinels in 15459

	1	2	3	4	5	6	7
TiO_2	23.98	23.89	20.13	16.85	54.42	30.24	28.86
Al_2O_3	6.06	6.22	8.11	10.14	0.33	2.40	2.67
Cr_2O_3	16.99	17.74	23.44	26.73	0.49	7.14	8.80
FeO	47.47	47.19	44.00	40.10	40.56	61.18	58.45
MnO	0.39	0.39	0.39	0.36	0.36	0.38	0.35
MgO	3.35	3.40	3.37	3.48	3.92	0.35	0.37

	8	9	10	11	12	13
TiO_2	50.93	20.03	28.33	52.75	70.09	53.63
Al_2O_3	0.01	5.36	2.57	0.27	1.61	0.28
Cr_2O_3	0.37	24.94	7.97	0.11	7.78	0.03
FeO	46.64	49.83	59.68	40.45	9.18	40.92
MnO	0.28	0.38	0.38	0.44	0.03	0.47
MgO	0.47	0.92	0.51	4.16	2.29	4.27

1–5, Traverse from centre (1) to edge (5) of zoned spinel in, 124 (mare gabbro clast).
6–8, Traverse from centre (6) to edge (8) of spinel in recrystallized anorth. gabbro, 19.
9, 10, Small, individual grains in, 19.
11, Magnesian ilmenite in recrystallized poikilitic breccia.
12, Armalcolite in norite cumulate. Also contains 0.06% SiO_2, 3.19% CaO, 4.78, ZrO_2.
13, Magnesian ilmenite in recrystallized breccia, 123.

The pigeonite is more iron-rich than pigeonite crystallized initially from high-alumina basalts and is also associated with rare grains of zirconium-armalcolite (table 3). The latter is chemically distinct from armalcolite precipitated from mare basalts, but none the less reflects a magma with high titania activity. These observations suggest crystallization of the norite minerals from a terra magma already moderately fractionated, but not yet depleted in titanium.

Temperatures of equilibration of orthopyroxene host and augite lamellae can be estimated from the geothermometer of Wood & Banno (1973), resulting in a value of 990 °C. This value is only slightly lower than olivine-clinopyroxene equilibration temperatures estimated for several terrestrial layered intrusions (Powell & Powell 1974).

Since these clasts occur in breccias that are at least 3.9 Ga old, the original norites would have developed whilst the lunar crust was still subjected to largescale meteorite bombardment. Yet the clasts show no evidence for metamorphism or cataclasis, and hence the norites must have developed *beneath* the surface veneer of brecciated rock. The initial period of crustal evolution must have passed into a phase involving a global-scale development of the crust by the formation of true igneous cumulates protected from meteorite bombardment by a gradually thickening roof. The norites described here may belong to this phase of crustal development and were only excavated because the Imbrian event was unusually intense. As a consequence rocks with pristine igneous textures became intimately mixed with more surficial rocks that had suffered the effects of external bombardment. It is these latter types that are described in the following section.

(c) *Poikiloblastic gabbroic anorthosites*

Several white clasts in 15459 (e.g. 15459, 125 and 123) have well developed poikiloblastic textures defined by chadacrysts of plagioclase, orthopyroxene, pigeonite, olivine and augite

Table 4. Composition of pyroxenes in 15459

	1	2	3	4	5	6	7
SiO_2	54.07	53.06	51.26	51.52	52.54	51.81	50.62
TiO_2	0.23	0.50	0.87	1.21	0.39	0.76	0.89
Al_2O_3	0.80	1.76	2.30	1.58	0.86	1.69	1.79
Cr_2O_3	0.52	0.70	0.57	0.28	0.38	0.54	0.57
FeO	16.47	15.91	17.92	21.43	19.66	18.89	12.78
MnO	0.29	0.30	0.34	0.35	0.33	0.34	0.33
MgO	24.42	22.30	19.22	17.28	20.94	19.53	15.20
CaO	3.50	5.40	7.54	6.66	4.48	6.07	15.88
Na_2O	0.04	0.03	0.06	0.05	0.03	0.03	0.05
Si	1.969	1.948	1.915	1.942	1.965	1.941	1.933
Ti	0.006	0.014	0.025	0.034	0.011	0.021	0.026
Al	0.034	0.076	0.101	0.071	0.038	0.075	0.081
Cr	0.015	0.020	0.017	0.009	0.011	0.016	0.017
Fe	0.502	0.489	0.560	0.675	0.615	0.542	0.408
Mn	0.009	0.009	0.011	0.011	0.011	0.011	0.010
Mg	1.326	1.221	1.070	0.971	1.167	1.091	0.365
Ca	0.137	1.213	0.302	0.269	0.180	0.244	0.650
Na	0.003	0.002	0.004	0.004	0.002	0.002	0.003
Al-Cr/Ti	3.06	4.03	3.43	1.80	2.37	2.73	2.48

	8	9	10	11	12	13	14
SiO_2	50.39	53.86	51.43	52.00	53.23	53.88	50.85
TiO_2	1.90	0.83	1.23	0.50	0.44	0.97	2.15
Al_2O_3	2.50	1.22	1.74	1.00	0.76	1.54	2.91
Cr_2O_3	0.35	0.37	0.43	0.45	0.29	0.29	0.39
FeO	13.25	15.71	6.69	8.59	21.34	15.28	7.84
MnO	0.32	0.25	0.13	0.22	0.37	0.28	0.15
MgO	13.74	26.90	17.68	15.27	22.72	26.12	17.62
CaO	16.81	1.16	18.69	19.87	1.45	1.89	16.56
Na_2O	0.09	0.06	0.22	0.13	0.03	0.02	0.18
Si	1.908	1.943	1.921	1.967	1.966	1.944	1.890
Ti	0.054	0.023	0.036	0.014	0.012	0.026	0.060
Al	0.112	0.052	0.077	0.045	0.033	0.066	0.127
Cr	0.010	0.011	0.013	0.013	0.009	0.008	0.011
Fe	0.420	0.474	0.209	0.272	0.659	0.461	0.244
Mn	0.010	0.008	0.004	0.007	0.012	0.009	0.005
Mg	0.776	1.447	0.984	0.861	1.251	1.405	0.976
Ca	0.682	0.045	0.748	0.806	0.058	0.073	0.660
Na	0.006	0.004	0.016	0.009	0.002	0.001	0.013
Al-Cr/Ti	1.88	1.82	1.84	2.21	2.00	2.17	1.92

1–4, Typical zoning trend from core (1) to rim (4) for pigeonite in, 124 mare gabbro.
5–8, Typical zoning trend from core (5) to rim (8) of pigeonite-augite in, 124 mare gabbro.
9–10, Orthopyroxene (inverted pigeonite) host (9) to exsolved augite (10) in norite cumulate clast in, 125.
11–12, Host orthopyroxene (12) to finely exsolved augite (11) as oikocrysts in poikilitic clast in, 125.
13, 14, Homogeneous grains of orthopyroxene (13) and augite (14) in recrystallized, poikilitic clast in, 125.

surrounded by oikocrysts of unzoned orthopyroxene. Analyses of oikocrysts and chadacrysts are shown in table 4 and figures 1 and 2. The orthopyroxene oikocrysts contain thin exsolution lamellae of augite on (100). Crystallographic studies indicate the orthopyroxene has inverted from original pigeonite (Takeda 1972), but no (001) lamellae were observed. Exsolved oikocrysts are rarely observed in lunar poikiloblastic rocks, most of which are weakly zoned orthopyroxene or pigeonite (Simonds *et al.* 1973; Bence *et al.* 1973). McCallum *et al.* (1974) have described large orthopyroxene oikocrysts with coarse augite lamellae in gabbroic anorthosite 77017, and submicroscopic exsolution has been detected in 67955 (Hollister 1973). Presumably differing rates of cooling and varying bulk compositions result in the varying types of oikocrysts observed in lunar breccias.

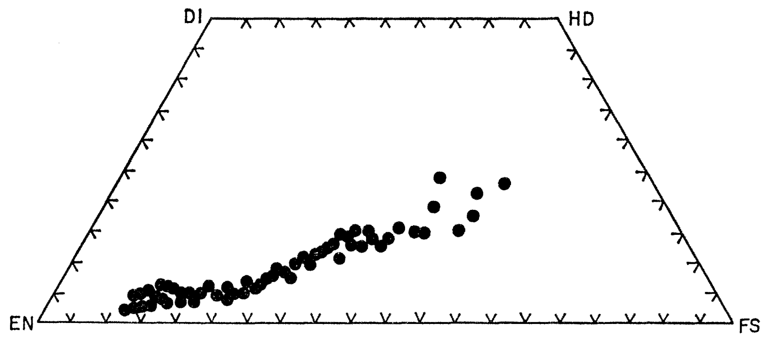

FIGURE 3. Variation in composition of pyroxenes in a diabasic-textured kreep norite clast 15459, 19. Note the continuity of pyroxene compositions from cores of aluminous bronzite to rims of intermediate pigeonite.

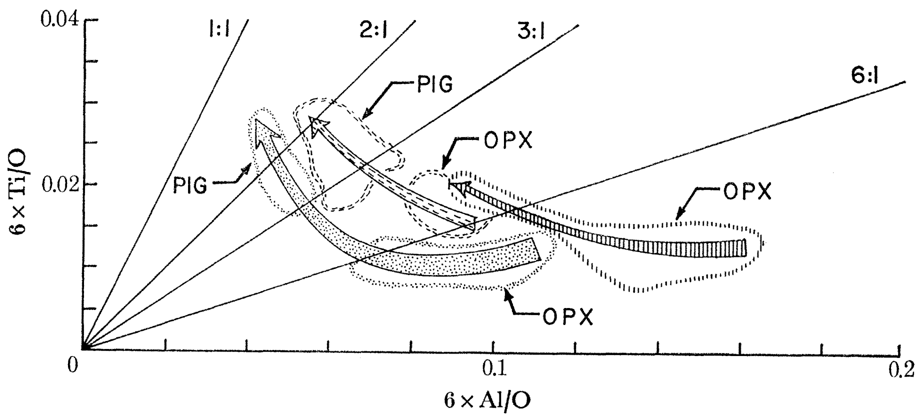

FIGURE 4. Ti-Al relations in pyroxenes plotted in figure 3. Note the core bronzites have Al:Ti > 6:1 indicating the presence of $R^{2+}Al_2Si\ O_6$ component reflecting high alumina activity in the basalt melt. During crystallization the Al:Ti ratios approach 2 and in some crystals < 2 suggesting the presence of divalent Cr or trivalent Ti.

The environment for formation of these poikiloblastic rocks is not well defined, although they are clearly widespread in the lunar highlands. Terrestrial experience indicates poikilitic textures may be produced by direct crystallization from a silicate melt or by subsolidus recrystallization during contact metamorphism. Similar textures are observed in terrestrial impact melts (Grieve *et al.* 1974), so that poikiloblastic lunar rocks may similarly be the product of meteorite bombardment. Nonetheless, much controversy has arisen over the interpretation of lunar poikiloblastic rocks in terms of an igneous versus metamorphic origin.

Temperatures of equilibration of minerals in some poikiloblastic rocks can be estimated by using several pyroxene geothermometers, and the olivine-climopyroxene geothermometer (Powell & Powell 1974). For 15459, 125 clasts the following temperatures (with largely unknown errors) were calculated: exsolved orthopyroxene oikocrysts: 1060 °C, orthopyroxene-augite chadacrysts: 1099 °C, olivine-augite chadacrysts: 990 °C. The presence of inverted pigeonite indicates cooling through the clinopyroxene-orthopyroxene inversion temperature. Extrapolation of the curve of Brown (1968) for W_0 = 7.6–8.9 suggests a temperature below 1100 °C, consistent with those calculated above.

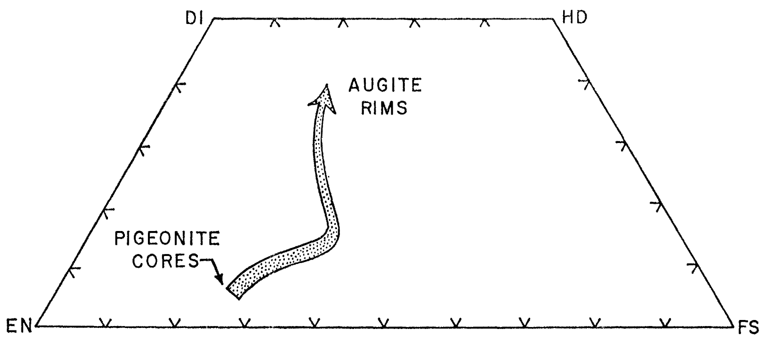

FIGURE 5. Zoning trend in clinopyroxenes from mare gabbro clast 15459, 124. There is a gradual change from core pigeonite, low-Ca augite to rims of augite with relatively minor non-enrichment. This contrasts with the strong iron enrichment in pyroxenes from Apollo 15 mare basalts, reflecting different rates of cooling.

We note that McCallum *et al.* (1974) estimated the crystallization temperature of 77017 to be 1050–1100 °C, and a temperature estimate based upon olivine-augite equilibrium gives 1010 °C. Temperatures calculated for other poikiloblastic rocks are as follows:

Diabasic areas in 60315, 63: 1102 °C (opx-cpx), 1072 °C (ol-cpx)

Poikiloblastic area in 60315, 63: 1254 °C (opx-cpx)

67955: 1093 °C

Generally, poikiloblastic rocks appear to have crystallized below 1100 °C. Even allowing for the variations in composition of individual rocks (they vary from 'kreep' basalt to anorthositic gabbro), this is well below the liquidus temperatures. Hence we prefer the interpretation that most poikiloblastic rocks crystallize in a metamorphic condition, possibly allowing for the presence of 5 % intergranular fluid.

(*d*) *Mare gabbro*

Post-Imbrium reworking of 15459 is suggested by the presence of clasts of coarse mare gabbro, whose mineral chemistry is similar to the local 3.5 Ga mare basalts (tables 3, 4; figure 5). The gabbros are composed of zoned clinopyroxene + olivine + plagioclase + spinel + ilmenite. It is interesting to note that such coarse samples were not observed among the sampled mare basalts, but they can be chemically and texturally interpreted as the slowly-cooled equivalents of the olivine-normative mare basalts. At least some of the variation observed among the olivine basalts from Palus Putredinus has been ascribed to low-pressure fractional crystallization (Rhodes & Hubbard 1973). The presence of gabbro clasts clearly suggests that mare basalt magma did cool slowly enough to allow fractional crystallization to proceed.

Summary

Breccias collected from the rim of Spur Crater contain several distinct types of clast, most of which are stratigraphically related to the terra crust and presumably represent parts of the pre-Imbrium crust. Studies of the matrix components of one breccia, 15459, are consistent with it having developed by consolidation of a soil similar to the local soil along the Apennine Front.

Ultramafic clasts in breccia 15445 can be interpreted to originally contain garnet and are considered to have been garnet pyroxenites from the lunar mantle. Early volcanism may have introduced the pyroxenites into the crust as xenoliths where they underwent low-pressure sub-solidus re-equilibration.

Another clast population of plutonic norites have textures and mineral characteristics found in Stillwater-type layered complexes and may have developed by slow cooling within the terra crust beneath a protecting thick roof of impact-brecciated rock.

Yet another group of clasts have poikiloblastic textures as a result of impact metamorphism and may be members of the rock suite that formed the highly brecciated, shocked, annealed and recrystallized outer terra crust. However they differ from poikiloblastic rocks described from Apollo 16 and 17, in having several chadacryst phases and numerous unresorbed clasts. This and other textural evidence favour formation at lower temperature, followed by relatively slow cooling.

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References (Ridley)

Bence, A. E., Papike, J. J. & Delano, J. W. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* **4**, 597–611.

Brown, G. M., Peckett, A., Emeleus, C. H., Holland, J. G. & Phillips, R. 1973 *Lunar Sci.* **4**, 94–96.

Green, D. H. & Ringwood, A. E. 1967 *Contrib. Mineral. Petrol.* **15**, 103–190.

Grieve, R. A. F., Plant, A. G. & Dence, M. R. 1974 *Proc. Fifth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* **5**, 261–273.

Kushiro, I. 1972 *Lunar Sci.* **3**, 466–468.

Hollister, L. S. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl* **4**, 633–641.

McCallum, I. S., Mathez, A. E., Okamura, F. P. & Ghose, S. 1974 *Proc. Fifth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* **5**, 287–302.

Meyer, H. O. A. & Boyd, F. R. 1972 *Geochim. cosmochim. Acta* **36**, 1255–1274.

Papike, J. J. & Bence, A. E. 1972 *Earth Planet. Sci. Lett.* **14**, 176–182.

Powell, M. & Powell, R. 1974 An olivine-clinopyroxene geothermometer. *Contrib. Mineral. Petrol.* **48**, 249–263.

Prinz, M., Dowty, E. & Keil, K. 1973 *Geochim. cosmochim. Acta* **27**, 979–1006.

Reid, A. M. & Dawson, J. B. 1972 *Lithos* **5**, 115–124.

Reid, A. M., Warner, J., Ridley, W. J. & Brown, R. W. 1972 *Meteoritics* **7**, 395–415.

Rhodes, J. M. & Hubbard, N. J. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 2, *Geochim. cosmochim. Acta Suppl.* **4**, 1127–1148.

Ridley, W. I., Hubbard, N. J., Rhodes, J. M., Weismann, H. & Bansal, B. 1973 *J. Geol.* **81**, 621–631.

Ridley, W. I., Reid, A. M., Warner, J. L., Brown, R. W., Gsoley, R. S. & Donaldson, C. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* **4**, 309–321.

Simonds, C. H., Warner, J. L. & Phinney, W. C. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* **4**, 613–632.

Takeda, H. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* **4**, 875–885.

Wood, B. J. & Banno, S. 1973 *Contrib. Mineral. Petrol.* **42**, 109–124.

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