0.05) $\times$ 10^9 years age measured for another piece of this rock using the same method (*7*). The 3.28 $\times$ 10^9 years age indicates that the mare from which it came was filled with molten basalt and crystallized about 3.3 $\times$ 10^9 years ago. This basalt could, however, be a rather late stage flow in the Imbrium basin.

The data are still very limited, particularly from lunar highlands, but from evidence gathered so far we propose the following lunar chronology: (i) formation of at least a portion of the anorthositic crust occurred about 4.1 billion years ago; (ii) the Imbrium basin was formed about 3.8 billion years ago, as indicated by the Fra Mauro rocks (*8*); (iii) the filling of Mare Tranquillitatis occurred about 3.7 $\times$ 10^9 years ago (*9*); and (iv) that of Oceanus Procellarum, and possibly Mare Serenitatis, about 3.2 to 3.4 $\times$ 10^9 years ago (*10*). It would thus appear that the major mare surfaces on the moon were formed during the period 3.2 to 3.8 $\times$ 10^9 years ago and since then very little change has taken place in the major mare picture. The anorthosite age suggests that if the Wood *et al.* (*2*) model of evolution of lunar crust is correct, as much as 400 to 500 $\times$ 10^6 years were required for sufficient cooling to completely form the anorthosite layer which was subsequently penetrated by planetesimals to form the lunar maria. However, there is no evidence that there was a uniform layer of anorthosite over the entire moon.

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Mineralogic and Petrologic Study of Lunar Anorthosite Slide 15415,18

Abstract. *The anorthosite slide 15415,18 contains > 98 percent subhedral plagioclase (97 mole percent anorthite), two pyroxenes: diopsidic augite (46 percent wollastonite, 39 percent enstatite, 16 percent ferrosilite) with subsidiary (100) lamellae and grains of hypersthene (2.5 percent wollastonite, 58 percent enstatite, 39.5 percent ferrosilite), and traces of ilmenite. The pyroxene occurs interstitial to, and as small grains enclosed within, plagioclase. The textures and compositions of the phases appear compatible with an origin by concentration and adcumulus growth of plagioclase from a gabbroic anorthosite (or hyperaluminous) magma in a "plutonic" environment.*

The thin section of rock 15415 examined, approximately 26 mm^2 in area, is sketched in Fig. 1A. It is composed essentially of five or six subhedral plagioclase grains, the largest (incomplete) individual crystal being 3 by 2 mm. The edges of several other possibly large grains are present, together with smaller ($\sim$1 mm) fragments. Boundaries between the larger, roughly equant plagioclase grains are smooth and gently curved, with rounded corners. The effects of shock deformation are conspicuous, consisting of fracturing of the grains, offsetting and bending of some boundaries and twin lamellae, undulose extinction, and secondary twinning.

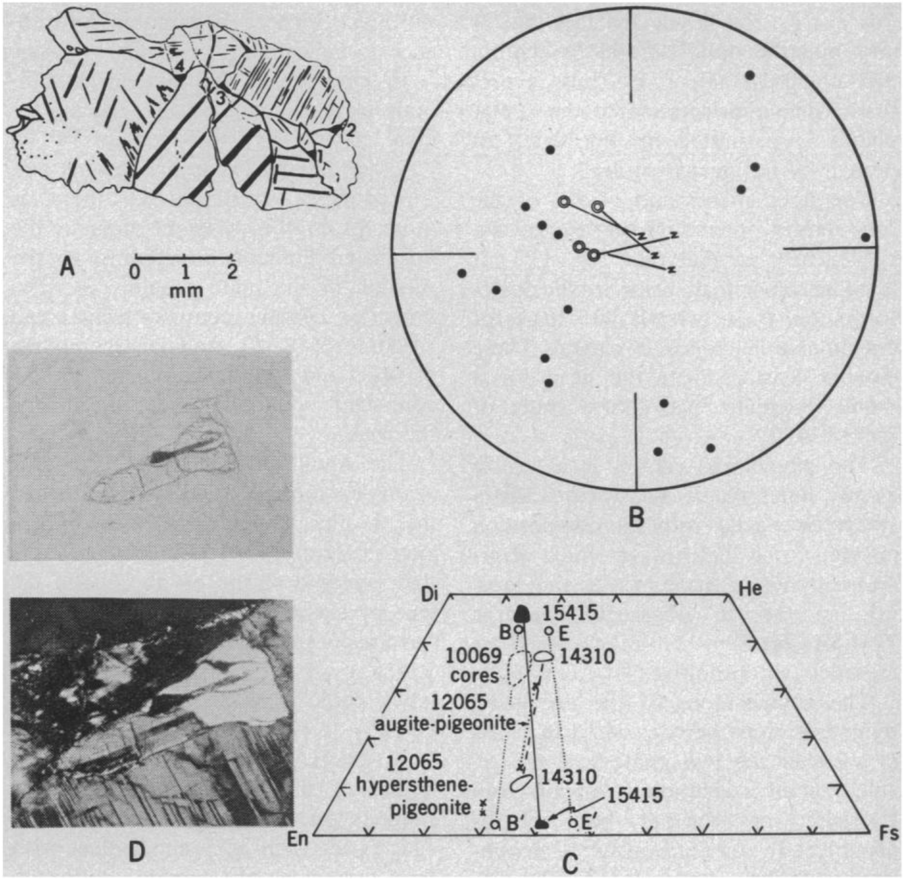
Diopsidic augite with exsolved hypersthene ($\sim$1 percent) is present as small anhedral triangular crystals (up to 250 μm), interstitial to the larger plagioclase grains. Small ilmenite grains are associated with some of these interstitial areas. Minute pyroxene crystals (< 50 μm) are also present as inclusions in two of the large plagioclase grains: they are quite numerous in one, and are apparently randomly oriented; they are fewer and partly oriented in the other.

Electron microprobe data on the composition of phases present are given in Table 1. The measured plagioclase compositions vary between about An_{96} (96 mole percent anorthite) and An_{98}; step-scanning across a grain with relatively symmetrical undulose extinction revealed slight compositional variation; the extinction irregularities are presumed to be due to strain. All twinning observed appeared to be polysynthetic; orientation on a universal stage revealed both normal (presumably albite) twinning in five of the 12 grains measured, and parallel (presumably periclase) twinning in 11 grains; $2V_x$ on four grains averaged 74°.

Systematic study of the feldspar grains was undertaken to test for any evidence of preferred orientation. Optical directions were readily obtained, and the orientations of the optic normal (Y) for at least one twin element in each of 12 grains is shown in Fig. 1B.

The bulk of the pyroxene present is diopsidic augite ($Wo_{46}En_{39}Fs_{16}$) (46 percent wollastonite, 39 percent enstatite, 16 percent ferrosilite); but all four of the larger interstitial grains could be seen to be composite, with small patches and thin lamellae (see Fig. 1D) of a second phase. Microprobe study revealed these to be hypersthene ($Wo_{2.5}En_{58}Fs_{39.5}$) and that even some of the very small pyroxene grains isolated in the plagioclase were in fact composite intergrowths of monoclinic and orthorhombic(?) pyroxene (see Table 1 and Fig. 1C). Universal stage measurements on the larger augitic pyroxenes gave $2V_z$=50°. The hypersthene lamellae are perpendicular to the optic plane of the monoclinic host and inferred to be parallel to

Fig. 1. (A) Drawing of slide 15415,18. Interstitial pyroxenes are indicated in solid black (larger grains are numbered 1 through 4); included grains are indicated as black dots. (B) Lower hemisphere stereographic projection. Solid circles are poles to the optic planes of plagioclase; double open circles are *c* axes of interstitial pyroxene grains, connected to Z optical directions, to indicate *a–c* planes. (C) Pyroxene quadrilateral showing the tie line and broad miscibility gap between the pair coexisting in rock 15415; Di, diopside; He, hedenbergite; En, enstatite; Fs, ferrosilite. Other lunar pyroxenes [samples 12065, 10069, and 14310 (*7*)] are shown for comparison; lines *B–B′* and lines *E–E′* are coexisting pyroxenes from a leucotroctolite and anorthosite in the Michikamau intrusion, Labrador (*3*). Data for sample 14310 are for a hypersthene-augite pair. (D) Photomicrographs of a 0.3-mm interstitial pyroxene grain (grain 3, Fig. 1A) in plane light (above) and crossed polars (below). The association is shown of diopsidic augite (analysis 4, Table 1) with (100) hypersthene lamellae to the left, hypersthene (analysis 3, Table 1) to the right, and black ilmenite (analysis 9, Table 1) in the center.



(100). Orientation of this plane with respect to the optic plane defined the *c* axis; the angle between the Z direction and the *c* axis in three grains averaged 38°. The Z direction in each of the four interstitial pyroxene grains (Fig. 1A) is almost perpendicular to the thin section, giving apparently low birefringence. The optic planes and *c* axes of these grains are very nearly parallel (see Fig. 1B).

Ilmenite occurs as very small grains (brownish-gray in reflected light) at the borders of or enclosed within the interstitial pyroxene crystals (Fig. 1D). Chemically (Table 1), the ilmenite appears to be fairly pure.

The small size of the sample studied must be borne in mind when one is attempting to judge if the fabric data have any possible significance. Furthermore, the primary texture and fabric have been obscured by bending and fracturing associated with the shock deformation.

The orientation of the plagioclase optic normals (Fig. 1B) can be considered to suggest a planar distribution. The potential textural significance of

Table 1. Microprobe analyses of minerals in rock 15415,18; analyses 1 and 2, plagioclase; analyses 3, 4, 5, 6, 7, and 8, coexisting Ca-poor and Ca-rich pyroxene pairs; analyses 3, 4, 5, and 6, interstitial material; analyses 7 and 8, small grain enclosed in plagioclase; analyses 9 and 10, ilmenite. Data for the oxides are percentages by weight; data for elements are atomic proportions.

Component	Analysis number									
	1	2	3	4	5	6	7	8	9	10
SiO_2	44.19	43.92	52.88	53.42	52.35	52.36	52.71	53.00	0.13	0.10
Al_2O_3	35.77	36.24	0.51	0.68	0.47	0.86	0.28	0.75	.08	.09
FeO	0.16	.09	25.22	9.70	24.47	10.22	24.18	9.01	44.37	44.18
MnO	.01	.01	0.52	0.24	0.52	0.24	0.54	0.23	0.62	0.63
MgO			20.26	13.83	20.57	15.58	20.36	14.47	.98	.96
CaO	19.66	19.49	1.02	22.14	1.53	21.09	1.33	22.33	.28	.38
Na_2O	0.22	0.26		0.03		0.02		0.01	.02	
TiO_2	0.01	.01	0.26	.36	0.25	.52	0.17	.45	50.91	50.40
Cr_2O_3	.03	.03	.20	.19	.17	.26	.11	.21	0.06	0.07
Total	100.1	100.1	100.9	100.6	100.3	101.2	99.7	100.5	97.5	96.8
Si	2.04	2.03	1.98	1.98	1.97	1.94	1.99	1.97		
Al	1.95	1.97	0.02	0.03	0.02	0.04	0.01	0.03		
Ti			.01	.01	.01	.01	.01	.01	0.99	0.98
Cr			.01	.01	.01	.01		.01		
Mg			1.13	.77	1.16	.86	1.15	.80	.04	.04
Fe	0.01		0.79	.30	0.77	.32	0.76	.28	.96	.96
Mn			.02	.01	.02	.01	.02	.01	.01	.01
Ca	.97	0.97	.04	.88	.06	.84	.05	.89	.01	.01
Na	.02	.02								

this distribution lies in the fact that in anorthite the optic normal lies within 30° of the *a* axis (*1*). Thus, a preferred planar orientation of the (010) planes is permitted by the data, although by no means required.

The optic planes and *c* axes of the four larger interstitial pyroxenes are very nearly parallel (see Fig. 1B). It is conceivable that, prior to shock deformation, these crystals were parts of one interstitial poikilitic crystal. These data at least indicate the need for a more systematic petrofabric study of rock 15415.

The plagioclase (An_{97}) is as calcic as any lunar plagioclase yet described. It agrees exactly with the composition inferred to be that toward which plagioclase trends in mare basalts and regolith anorthositic fragments converge (*2*). In this sense, it may indeed be regarded as "primitive."

The compositions of the coexisting pyroxenes must be considered in terms of whether the two phases are the result only of exsolution (Ca-poor from Ca-rich), or whether both phases crystallized simultaneously. Calcium-poor pyroxene is present as (100) (?) lamellae in every interstitial diopsidic augite. In one grain, quite large Ca-poor pyroxene patches, optically continuous with the exsolution lamellae, are present. The largest hypersthene area, however, has an irregular, crystallographically nonrational boundary with the contiguous diopsidic augite and is not continuous with lamellae in the latter (Fig. 1D). X-ray area scans of this hypersthene suggest the presence in it of a trace of diopsidic blebs which may be the result of complementary exsolution, although no lamellar alignment is evident. Simultaneous crystallization of both phases is suggested by these data.

Although simultaneous crystallization of two pyroxenes remains uncertain, the wide miscibility gap between the presently coexisting pair is quite clear (Fig. 1C). The tie line crosses that for all similar lunar mare basalt pyroxenes but is similar to that in rocks from some terrestrial plutons bearing two pyroxenes (*3*). Although the Fe/Mg ratio is appropriate, there is no optical evidence that the Ca-poor pyroxene ever crystallized or exsolved as monoclinic pigeonite.

The compositions of the coexisting pair definitely indicate equilibration at relatively low temperatures, and possibly the original temperature of growth was not much higher. A "plutonic" provenance is indicated.

In contrast to the equivalent minerals in most mare basalts, the plagioclase has a very low content of Fe (*2*), and the pyroxene has low Al and Ti contents. Furthermore, there is more Cr in the pyroxene than in the associated ilmenite, in contrast to the relation in the mare basalts (*4*). The ilmenites contain comparatively small amounts of Cr_2O_3 and large amounts of MgO and MnO. These data are also consistent with a plutonic origin for the rock.

The Apollo 11 pyroxene cores (for example, sample 10069) lie athwart the tie line joining coexisting pyroxenes in sample 15415. It is conceivable that metamorphism of an Apollo 11 type pyroxene could give the interstitial ferromagnesian assemblage in sample 15415, or that incipient melting of the latter could give an Apollo 11 type liquid.

A priori, however, the interstitial nature of the larger pyroxene grains suggests their late-stage crystallization. This result is in apparent conflict with the presence of minute pyroxene grains, of nearly identical composition, randomly included in the plagioclase. Because these minute pyroxene grains do not appear to have a distribution crystallographically controlled by the feldspar, an exsolution origin is unlikely. We suggest instead that they may represent droplets of magma trapped within growing feldspar crystals (*5*), as the interstitial pyroxene plus ilmenite crystallized from liquid trapped between crystals. The low content of Cr in these isolated pockets suggests its low concentration in an undifferentiated parent magma consisting primarily of the components of anorthite and diopsidic augite.

The textural and compositional data presented here for this small sample are compatible with the interpretation that the rock represents a shock-metamorphosed fragment from a plutonic, adcumulus concentration of calcic plagioclase derived from a gabbroic anorthosite (or hyperaluminous basalt) magma (*6*).

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Lunar Anorthosite 15415: Texture, Mineralogy, and Metamorphic History

Abstract. *Lunar anorthosite 15415 consists almost entirely of anorthite (homogeneous anorthite 96.6 molecule percent), with accessory diopsidic augite and traces of hypersthene, ilmenite, and a silica mineral. The rock has had a complex metamorphic history. The texture reflects at least two episodes of shearing (followed by intense and partial recrystallization, respectively), one episode of cataclastic deformation, and one or more episodes of shattering and fragmentation.*

In the Apollo 11, 12, and 14 lunar samples, anorthosites and other feldspar-rich rocks form a minor, but significant, percentage of fragments in the size range 1 cm to 1 mm. These rocks are very different in composition and texture from typical mare basalts, and several authors (*1*) have suggested that the former are samples of highland rocks or primitive lunar crust or both. Sample 15415, collected by the Apollo 15 astronauts from the foot of Hadley Delta, is the largest fragment of anorthosite among the returned lunar samples. It is much coarser grained than most of the small chips of felds-