Crystallography of Some Lunar Plagioclases

Abstract. *Crystals of calcic bytownite from type B rocks have space group $I\bar{1}$ with c ≈ 14 angstroms. Bytownite crystals from type A rocks are more sodic and have space group $C\bar{1}$, c ≈ 7 angstroms. Cell parameters of eight bulk feldspar separates from crystalline rocks indicate that the range of angle gamma is about 23 times the standard error of measurement, and its value might be useful for estimation of composition. Cell parameters of seven ilmenites are close to those of pure $FeTiO_3$.*

Bulk bytownite separates were obtained from eight crystalline rocks by flotation of pulverized rock in bromoform (specific gravity 2.87). Suitable single crystals were removed from the chips and the separates before grinding, and single-crystal x-ray diffraction patterns were obtained by the Buerger precession method with MoKα radiation (50 kv, 20 ma). The 0*kl*, *h*0*l*, and *h*1*l* nets of crystals from rocks 10003, 10047, 10050, 10071, and 10072 were recorded with exposures of about 160 hours on Ilford G film. Crystals from type B rocks (10003, 10047, 10050) give strong "a" reflections ($h + k$ even, l even) and weak, but fairly sharp, "b" reflections ($h + k$ odd, l odd), an indication that these feldspars have $c \approx 14$ Å and space group $I\bar{1}$. Crystals from type A rocks (10071, 10072) show only "a" reflections, indicating $c \approx 7$ Å and space group $C\bar{1}$. All of the plagioclase crystals examined were twinned on the albite law. In every case the cell parameters determined from single-crystal measurements were indistinguishable from those given by the powder-diffraction refinements of bulk plagioclase samples from the corresponding rocks (Table 1). The crystals examined can therefore be considered representative of the plagioclases in these rocks.

Table 1. Crystallographic data and estimated compositions for eight Apollo 11 plagioclases.

Rock and chip No.	03, 38	50, 32	47, 27	20, 41	57, 36	72, 33	71, 29	49, 22
Rock type	B	B	B	A	A	A	A	A
Space group	$I\bar{1}$	$I\bar{1}$	$I\bar{1}$			$C\bar{1}$	$C\bar{1}$	
Cell parameters								
a (Å)	8.192	8.178	8.187	8.167	8.174	8.178	8.175	8.176
Standard error	0.003	0.002	0.003	0.003	0.003	0.002	0.003	0.002
b (Å)	12.892	12.872	12.882	12.861	12.876	12.871	12.860	12.864
Standard error	0.003	0.002	0.003	0.003	0.003	0.003	0.004	0.003
c (Å)	7.093*	7.092*	7.098*	7.093	7.096	7.097	7.095	7.096
Standard error	0.002*	0.001*	0.001*	0.001	0.002	0.002	0.002	0.001
α (°)	93.24	93.28	93.37	93.46	93.34	93.39	93.25	93.40
Standard error	0.03	0.02	0.03	0.02	0.03	0.03	0.04	0.02
β (°)	116.03	115.95	116.05	115.92	116.06	116.09	116.04	116.07
Standard error	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02
γ (°)	91.02	90.95	90.81	90.54	90.46	90.45	90.41	90.33
Standard error	0.02	0.03	0.03	0.03	0.03	0.03	0.04	0.03
Cell volume (Å^3)	671.3*	669.5*	670.7*	668.3	669.3	669.3	668.6	668.8
Standard error	0.2	0.2	0.2	0.3	0.2	0.2	0.3	0.2
Number of lines refined	24	31	22	22	30	31	24	25
Standard error, °2θ, CuKα_1	0.019	0.018	0.016	0.017	0.023	0.022	0.023	0.016
Estimated chemical composition (weight percent An)	85	83	81	78	75	75	74	73
Calculated $\Delta 2\theta$, (131)–($1\bar{3}1$), °2θ, CuKα_1	2.22	2.20	2.18	2.09	2.00	2.01	1.92	1.97
Γ, °2θ, CuKα_1 (*6*)	1.37	1.35	1.28	1.11	0.94	0.95	0.79	0.85
B, °2θ, CuKα_1 (*6*)	0.77	0.74	0.78	0.74	0.81	0.82	0.82	0.82

* True value is twice the tabular value for space group $I\bar{1}$.

Table 2. Crystallographic data for seven Apollo 11 ilmenites.

Rock and chip No.	03, 38	50, 32	47, 27	20, 41	72, 33	71, 29	49, 22
Cell parameters							
a (Å)	5.088	5.087	5.088	5.086	5.086	5.087	5.088
Standard error	0.001	0.001	0.001	0.001	0.001	0.001	0.001
c (Å)	14.085	14.081	14.085	14.070	14.068	14.068	14.079
Standard error	0.007	0.002	0.002	0.004	0.005	0.008	0.005
Cell volume (Å^3)	315.8	315.6	315.8	315.2	315.2	315.2	315.6
Standard error	0.1	0.1	0.1	0.1	0.1	0.2	0.1
Number of lines refined	8	9	10	9	7	7	8
Standard error, °2θ, CuKα_1	0.019	0.013	0.009	0.018	0.012	0.021	0.012

Powdered bytownite was combined with an internal standard (either CaF_2, $a = 5.4620$ Å, or BaF_2, $a = 6.1971$ Å), and each diffraction pattern was recorded once with CuKα radiation on a diffractometer run continuously from 60° to 13° 2θ. The diffractometer output was collected for successive intervals of 0.005° 2θ and recorded on paper tape as counts per 0.005° 2θ. The position of each diffracted line was reduced from the raw data by a computer program (*1*). The cell parameters given in Table 1 were then obtained by least-squares methods (*2*). Lines affected by ilmenite or clinopyroxene interference were deleted.

For seven samples the cell parameters of ilmenite were refined (Table 2) and were found to be close to those of pure $FeTiO_3$ (*3*), which suggests that these rocks crystallized under reducing conditions (*4*). Good values for the cell parameters of the clinopyroxenes could not be obtained because the diffraction lines were broad. Some zoned bytownite crystals were observed optically in thin sections, but the diffraction lines for each sample were sharp, showing that the proportion of each sample that differs from the bulk is very small. The standard errors listed in Tables 1 and 2 reflect the internal consistency of line positions from one particular pattern of each sample; experience (*5*) indicates that the precision of such cell-parameter determinations is at least twice the stated standard errors. Plagioclase patterns from type C breccias (10021, 10048, 10061, 10073) and type D dust (10084) show peaks that are too broad and weak for refinement.

Corresponding cell parameters for the eight crystalline samples range only 4 to 11 times the associated standard errors, except for the values of the angle γ, which have a range about 23 times the associated standard errors. The separa-

tion in degrees 2θ of the 131 and $1\bar{3}1$ lines depends strongly on the value of γ, and varies by 0.3° 2θ for CuKα radiation in the samples studied. When the compositions of the feldspars in Table 1 are known independently, the 131-$1\bar{3}1$ separations given in Table 1 can be calibrated and may then prove useful in estimating feldspar compositions in other similar samples.

The cell parameters of calcic plagioclases vary slightly with change of composition and with Al/Si order. From investigations utilizing methods based on the indices of refraction (*6*) and on cell parameters and line positions (*7*) of terrestrial plagioclases, it appears that the lunar plagioclases in type B rocks are from 5 to 10 percent by weight more calcic than those in type A rocks, but that within each rock type the plagioclase composition varies relatively little. The lunar plagioclases do not differ in any obvious ways from terrestrial plagioclases that are chemically equivalent. If the compositional estimates in Table 1 are accurate, values of the parameters Γ and B (*7*) suggest that the plagioclases in type B rocks probably have relatively high Al/Si disorder compared to those in terrestrial intrusive igneous rocks.

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Petrology of a Fine-Grained Igneous Rock from the Sea of Tranquillity

Abstract. *All phases in a thin section of sample 10022 have been analyzed by electron microprobe. Augite grains show strong iron enrichment in the outer 15 to 20 microns. Pigeonite cores occur within augite grains. The plagioclase has an anorthite content of between 73 and 81 mole percent and is high in Si and low in Al compared to stoichiometric feldspar. Residual phases include microcrystalline Fe-rich "pyroxene," plagioclase, K-rich alkali feldspar, silica, and rare areas rich in P and Zr with concentrations of Ba, Y, and rare earth elements. The density, viscosity, and crystallization history of the lava of sample 10022 are discussed.*

Results reported here are based primarily upon electron probe microanalyses (*1*) of a fine-grained vesicular igneous rock, NASA sample 10022,28. Phase designations are based principally on chemical composition and do not imply direct knowledge of structure. The rock has an igneous texture, and our interpretations assume that it crystallized from a melt. Average compositions of analyzed phases are presented in Tables 1 and 2. Volume percentages of the major phases have also been determined on the basis of 2000 random point identifications in transmitted and reflected light microscopy.

Skeletal ilmenite crystals up to several hundred microns long are distributed evenly throughout the section, some having delicate branches less than 10 μm wide. Euhedral ilmenite grains are enclosed in some augites; this suggests that ilmenite crystallized first. In section some ilmenite grains have rounded cavities filled with fine crystals of the other phases. The ilmenite exhibits no zoning or exsolution that can be resolved with the probe. Plagioclase crystals are often hollow and appear tubular in thin section, a habit characteristic of relatively rapid growth. The "tubes" are filled with an assortment of pyroxene, ilmenite, additional plagioclase, and residual phases. Plagioclase crystals occasionally transect the outer rims of augite. Many plagioclases grade into microcrystalline or glassy material of quartzofeldspathic composition. Figure 1a (detail) shows the range of composition in 19 plagioclase grains. There is not much systematic zoning of individual grains. In the average plagioclase of Table 2 Si $-$ (Na $+$ K) $=$ 2.10 and Al $-$ (Ca $+$ Fe $+$ Mg) $=$ 0.82 (based on eight oxygens), whereas these parameters are 2.00 and 1.00, respectively, in stoichiometric feldspars. Excess Si and a deficiency of Al have also been detected in terrestrial feldspars (*2*). The Ti and Fe (assumed to be Fe^{2+}) content is higher in the average lunar plagioclase of rock 10022 than in most terrestrial plagioclases.

Clinopyroxene is the most abundant phase and occurs in approximately equant grains up to several hundred microns in diameter. Most grains are composite, containing cores of pigeonite (10 to 100 μm) surrounded by augite. Pigeonite compositions (Fig. 1b) cluster close to the area where terrestrial pyroxene trends show inversion from orthopyroxene to pigeonite. There is a sharp composition break between the pigeonite and augite (Fig. 1, b and c). In contrast to the lack of zoning in the pigeonite, there is a continuous increase of Ca relative to Mg in the main body of the augite, followed by a sharp increase of Fe and a decrease of Mg and Ca in the outer 20 μm. The minor elements Ti, Al, and Cr are enriched in augite relative to pigeonite whereas Mn shows a reversed distribution. Titanium, Al, and Cr decrease in the augite rims whereas Mn increases. The smooth composition trends in the main body of the augites are similar to trends observed in plutonic terrestrial pyroxenes and may reflect growth from an ample liquid reservoir under near equilibrium conditions, whereas the abrupt zoning of the rims may be due to rapid changes of local residual liquid composition. Some augite rims appear to grade into material of Fe-rich pyroxene composition associated with other residual phases. The profile labeled *ar-rp* (Fig. 1b) extends from an augite rim into such a residual phase area. X-ray area scans across pigeonite-augite boundaries often reveal irregular borders suggestive of resorption of pigeonite and compatible with a peritectic reaction between pigeonite, augite, and liquid. Several grains of olivine (10 to 20 μm) are included in augite crystals. It seems likely that minor olivine crystallized before augite. Troilite is present as small interstitial blebs 5 to 30 μm in diameter. Its composition is close to that of stoichiometric FeS, and it has a lower content of Ti than some chondritic troilites have, in spite of the high Ti content of the rock. This may be related to conditions that contribute to a greater amount of oxidation or to