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LUNAR PLAGIOCLASE: A MINERALOGICAL STUDY

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Lunar plagioclase: A mineralogical study

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Abstract—Mineralogical properties of calcic plagioclase have been analyzed using U-stage, microprobe, x-ray precession cameras, and a 650 kV electron microscope. The orientation of the optical indicatrix in lunar and eucrite anorthites is described with Euler angles. All crystals, except one, show strong *b*- and diffuse *c*-reflections in precession photographs. In 10017, *b*-split-reflections have been found. Dark-field electron micrographs of 14310 anorthite show both large and small *b*-antiphase domains, and an exsolution structure in crystals that display *b*-split reflections in the diffractogram. Diffuseness of *c*-reflections in x-ray photographs and the inability to resolve *c*-domains in electronmicrographs in An 94 anorthite of 14310 indicate relatively rapid cooling of this rock compared to plutonic rocks.

INTRODUCTION

IT WAS THE PURPOSE OF this study to describe the properties of lunar plagioclase and to investigate, by comparison with appropriate terrestrial feldspars, whether the optics and structure of anorthite are indicative of the thermal history of the crystals. Documentation on anorthites is sparse; therefore, lunar rocks provide excellent material to study calcic plagioclase and these new data contribute to a better understanding of this important mineral series.

Techniques used include determination of optical properties on the universal stage, single crystal x-ray photography by the precession method, chemical microprobe analyses, and 650–kV transmission electron microscopy. Procedures are similar to those described by Wenk and Nord (1971). First, a polished thin section was prepared and examined on the petrographic microscope. U-stage measurements were made on several multiply twinned plagioclase crystals (preferentially twinned after albite and albite-Carlsbad laws). Then the chemical composition (Ca, Na, K) was determined on the same spots by microprobe. One crystal was picked either from the thin section or from the rock for x-ray study and later analyzed chemically. Electron microscope samples were prepared from thin sections using the ion thinning technique.

Most of our data were obtained on the only two available thin sections, 14310 (basalt) and 14319 (breccia). Fines were usually not satisfactory for this analysis. Some measurements have been done on small fragments of 10017, 12021, and 14162. The results reported apply only to these few specimens and not to lunar rocks in general.

PETROGRAPHY

Basalt 14310 (Fig. 1a) consists mainly of clear, inclusion-free crystals of calcic plagioclase (An 85–95), clinopyroxene ($2V_\gamma = 12$–20°), orthopyroxene ($2V_\alpha = 72^\circ$),

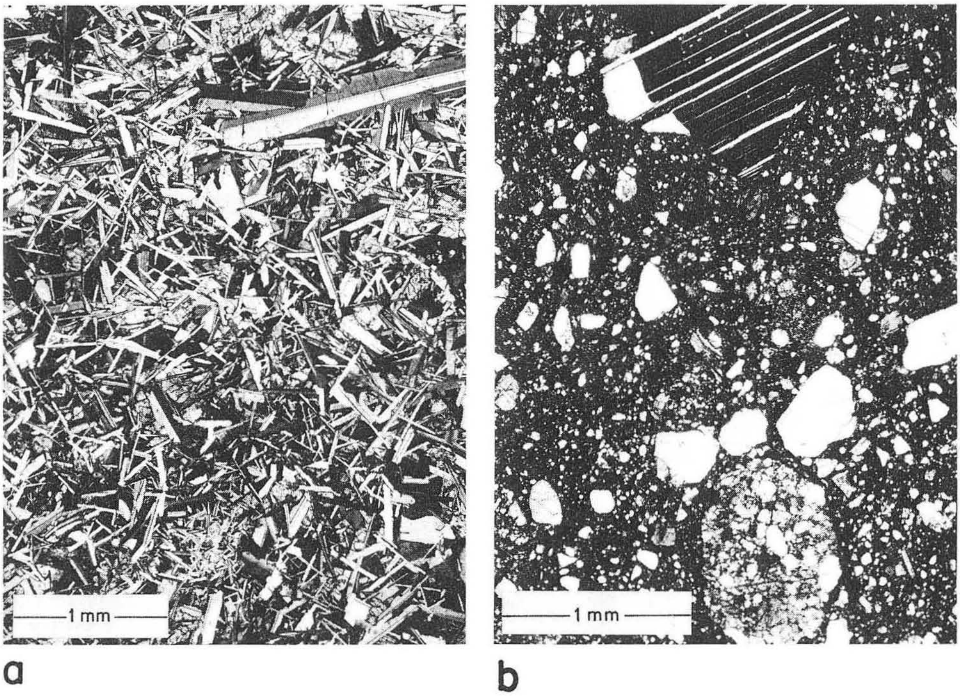


Fig. 1. (a) Photomicrograph of subophitic basalt 14310. Crossed nicols. Notice the range in grain size of plagioclase, and the areas with extremely fine-grained anorthite needles. (b) Photomicrograph of breccia 14319. Crossed nicols. Notice a large anorthite crystal and a breccia fragment.

and opaque minerals. The texture is subophitic. Plagioclase ranges greatly in size. The largest crystals in the thin section are 2 mm long, but most of them range between 0.3 and 0.5 mm. Chemical analysis indicates that there are two groups of plagioclase present; these, however, are not apparent by grain size, shape, or texture. An average of microprobe analyses on many crystals gives a composition An 86.9, Or 1.44 for one group and An 94.0, Or 0.42 for the other. Of special interest is the large difference in potassium. These two groups are quite distinct, without intermediate compositions. No zoning has been found except for one very large crystal, which shows a thin rim of the potassium-rich phase; therefore, this An-poor and Or-rich plagioclase may be younger than the other crystals. There are small areas of very fine-grained plagioclase needles chemically indistinguishable from the Or-poor, large ones that show polysynthetic twinning. These "clots" have almost no interstitial pyroxene. Twin laws identified on the U-stage are albite, Carlsbad, albite-Carlsbad (common), pericline (less common), Baveno-r (one crystal only). Cruciform intergrowth is quite common. Attention has been given to the commonly occuring pseudotwins and peculiar intergrowths.

In one group of crystals, the plane between two intergrown crystals looks like a "composition plane" of a twin (Fig. 2a). The two indicatrices are related by a single rotation as in a regular twin, but neither axis nor composition plane is a rational direction. The composition plane is in the vicinity but distinctly different from $(0\bar{2}1)$ (Fig. 2b). These "irrational" intergrowths are not uncommon in lunar and meteoritic plagioclase (Ulbrich, 1971; Wenk and Nord, 1971).

In another case (Fig. 2c), three crystals are intergrown. Crystal 1–2 is a regular albite-Carlsbad twin with (010) as composition plane; 2–3 is a pericline twin, whose composition plane should be the rhombic section which is close to (001) for anorthite. The actual plane of intergrowth in these crystals is a rough surface close to (010) (Fig. 2d).

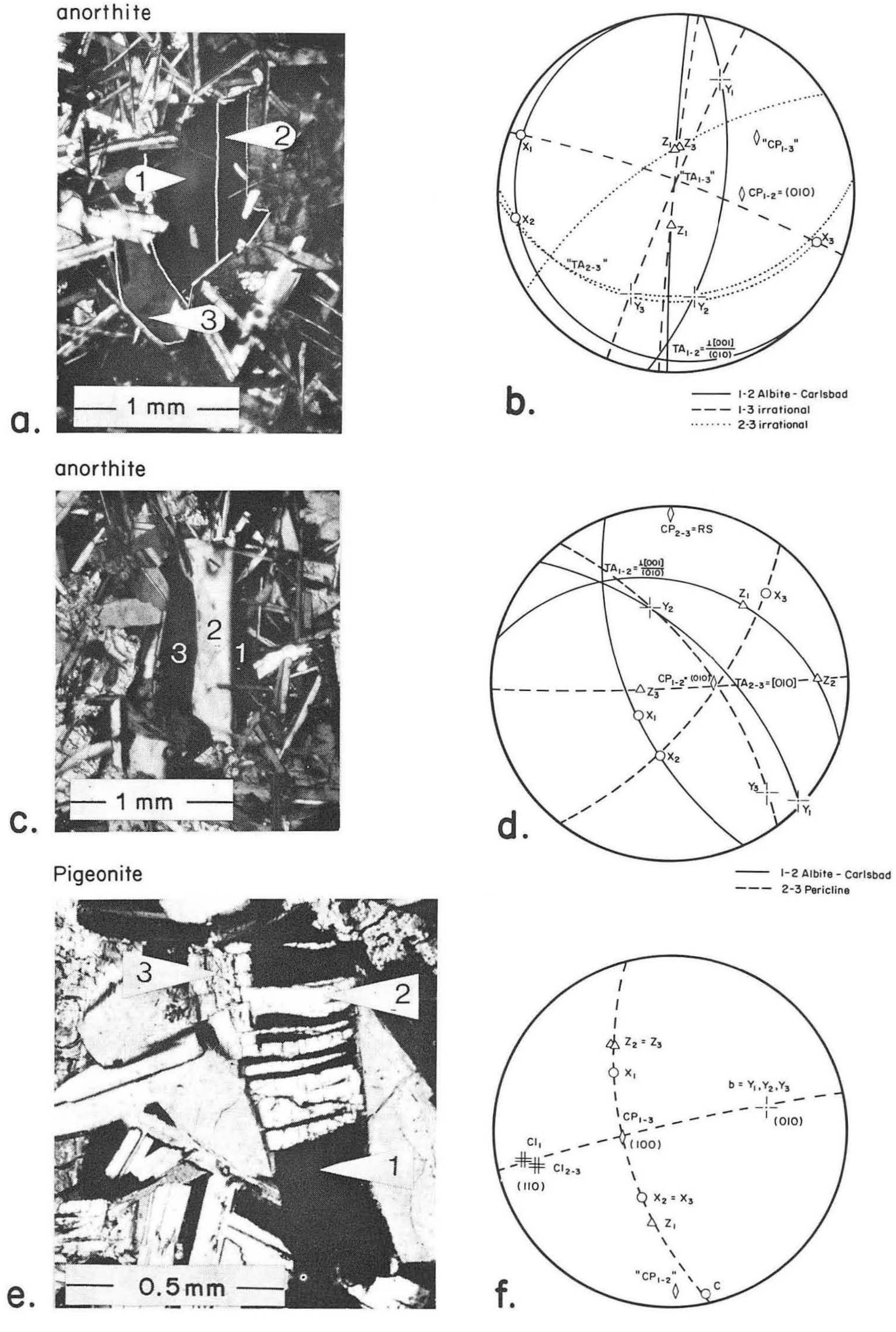
Pyroxenes have not been studied in detail. Routine checks showed that clinopyroxenes with small $2V_\gamma$ (12–22°) twinned on (100) are common. No exsolution lamellae were seen in the petrographic microscope. Orthopyroxene (hypersthene) is less common and frequently mantled by pigeonite. A similar type of intergrowth as described for plagioclase (Figs. 2c, d) has been found in pyroxene. Fig. 2e is an example of polysynthetically twinned pigeonite (1–2) ([010] common axis = Y), yet the composition plane 1–2 is not (100) but an irrational and slightly curved surface (C.P. 1–2, Fig. 2f). This twinned crystal is partly rimmed by another clinopyroxene (3), which appears to be more iron-rich, because it has the same optical orientation as 2 ($X_2 = X_3$, $Y_2 = Y_3$, and $Z_2 = Z_3$), but has a higher birefringence and higher $2V_\gamma$.

A fragment from 14162 coarse fines has properties very similar to that of 14310 basalt. Textures are identical and two groups of plagioclase are present. We assume that it is a fragment of the same rock.

A large number of plagioclase fragments appear in 14319 breccia (Fig. 1b). Plagioclase is heterogeneous: many crystals are twinned, some are undeformed, some are fractured, some have patchy extinction and bent lamellae. One crystal of plagioclase shows very thin platelets of an opaque mineral on (010). Other components of the breccia are ortho- and clinopyroxene with exsolution and twin lamellae, perovskite, and an unidentified small fragment of a yellow biaxial positive crystal. Apart from crystal fragments, the breccia contains many lithic fragments. Euler angles of plagioclase have been determined in anorthositic and gabbroic fragments. A basalt fragment appears to be closely related to basalt 14310. In the breccia there also are fragments of an older breccia. Brown glass inclusions show beginning crystallization. Noteworthy are spherical aggregates of pyroxene with radial crystallites, resembling meteoritic chondrules. Many lithic and crystallite fragments in the breccia are rounded; others, however, have sharp corners.

Sample 12021 is a basalt of ophitic texture. Some of the large plagioclase crystals are skeletal with pyroxene and opaque inclusions.

Calcic plagioclase from terrestrial rocks and from eucrite meteorites with similar mineralogical composition has been analyzed and compared with the lunar crystals. Some results on meteoritic plagioclase are included here, because, to our knowledge, this paper gives the first description of optical properties of plagioclase in such meteorites. The eucrites are composed of calcic plagioclase, and pigeonite with exsolution lamellae of subcalcic augite to augite. Cachari (Argentina) is brecciated, Serra de Magè (Brazil) shows a beautiful equigranular texture, Ibitira (Brazil) has


anorthite
1
2
3
1 mm
a.
Y_1
X_1
Z_1
Z_3
"CP_{1-3}"
"TA_{1-3}"
CP_{1-2} = (010)
X_2
Z_1
X_3
"TA_{2-3}"
Y_3
Y_2
$TA_{1-2}=\frac{\perp[001]}{(010)}$
b.
1-2 Albite - Carlsbad
1-3 irrational
2-3 irrational
anorthite
3
2
1
1 mm
c.
CP_{2-3}=RS
$TA_{1-2}=\frac{\perp[001]}{(010)}$
Z_1
X_3
Y_2
CP_{1-2}= (010)
TA_{2-3}= [010]
Z_2
Z_3
X_1
X_2
Y_3
Y_1
d.
1-2 Albite - Carlsbad
2-3 Pericline
Pigeonite
3
2
1
0.5 mm
e.
$Z_2 = Z_3$
X_1
b = Y_1, Y_2, Y_3
CP_{1-3}
(010)
(100)
CI_1
CI_{2-3}
(110)
$X_2 = X_3$
Z_1
"CP_{1-2}"
c
f.

few large crystals and a ground mass of fine annealed grains with polygonal outlines. Plagioclase in all of them is twinned after the albite, albite-Carlsbad, Carlsbad, and pericline laws (Ulbrich, 1971).

U-Stage Analysis of Plagioclase

Euler angles are used to describe the orientation of the optical indicatrix in the crystal. Euler I angles (Θ, Ψ, and Φ) have been derived from measurements of the albite composition plane (010) and the albite-Carlsbad twin axis $\perp$[001] in (010), and in some cases, from the cleavage (001). The results are listed in Table 1. In order to evaluate the use of the orientation of the indicatrix as an indicator for the thermal history, we plot the angles Φ and Ψ, which show the largest variation in calcic plagioclase, as a function of the anorthite content (Fig. 3). For reference we also plot all data on calcic plagioclase found in the literature and add new measurements. This gives a better measure of the significance of an interpretation than if we compare the new data points with averaged determinative curves (Burri *et al.*, 1967). Above An 75 there are no longer two distinct curves for plutonic and volcanic plagioclase; there is, instead, a diffuse band of scattering points. To make any statement about the thermal history of the rock, a statistical number of high-precision measurements is necessary. It is difficult also to predict the chemical composition in this range of the plagioclase series with accuracy greater than ±5 to 10% An. The scatter in the data is larger than the accuracy of the measurements and we expect that in addition to the chemical composition and the thermal history, submicroscopic features such as twins and domains may account for it. Looking at all anorthites, Φ and Ψ appear to be slightly larger for plutonic than for volcanic feldspars, and the rather large angles in lunar and meteoritic plagioclase agree with plutonic optics (Wenk and Nord, 1971; Ulbrich, 1971; E. Wenk *et al.*, 1972). As has been shown by E. Wenk *et al.* (1972), in $\Phi\Psi$ plots our data scatter in the same field as theirs. The $\Phi\Psi$ plots also indicate that lunar plagioclase may have slightly different optical properties than terrestrial ones. To prove this, very pure anorthites have to be studied.

Fig. 2. Unusual twins in lunar basalt 14310. Photomicrographs and stereographic projection in upper hemisphere are in the same orientation. (a), (b): anorthite showing irrational intergrowth between crystals 1 and 3. The pseudocomposition plane, CP 1–3, is close to but different from $(0\bar{2}1)$. The "twin axis" 1–3 is also irrational. Crystals 1 and 2 are in albite-Carlsbad relation. (c), (d): anorthite with albite-Carlsbad (1–2) and pericline twin (2–3). The 2–3 composition plane (rhombic section) should be close to (001). The actual plane of intergrowth is close to (010). (e), (f): Polysynthetically twinned pigeonite (1–2). The common axis between 1 and 2 is [010] = Y. The plane of intergrowth (C.P. 1–2) is not the theoretical composition plane (100), but an irrational surface. The twinned crystal is rimmed by another clinopyroxene, which is in the same optical orientation as 2 but has higher $2V_{\gamma}$ (3).

Table 1. Euler I angles and chemical composition of plagioclase from lunar rocks and eucrite meteorites. The accuracy of Euler angles is ±1/2°.

Lunar Rocks	Twin laws	$2V_\alpha$	Φ	Ψ	Θ	An	Or	Ab
12021, 118C basalt fragment	Ab, Ca Ab-Ca; Pe	77°	$25\frac{1}{4}$	-6	36	92.9	0.34	6.7_4
14310, 23 & 95 plagioclase-pyroxene basalt	Ab, Ca Ab-Ca	—	$25\frac{1}{2}$	-2	38	85.3_0	1.72	12.9_8
	Pe (rare)	—	25	-4	38	87.6_9	1.22	11.0_9
	Baveno-r (only one)	81°	$23\frac{3}{4}$	$-5\frac{1}{2}$	38	87.6_0	1.38	11.0_2
		77°	22	$-5\frac{1}{2}$	37	93.0_9	0.48	6.4_3
		78°	24	-6	34	94.3_3	0.39	5.2_8
		—	$23\frac{1}{2}$	-6	38	93.4_1	0.45	6.1_4
14319, 6 Breccia	Ab, Ca							
(A) plag.-pyr. aggr. (anor.)	Ab-Ca	79°	$22\frac{3}{4}$	-4	38	93.8_9	0.37	5.7_4
	Pe	78	$21\frac{1}{2}$	-7	37	94.6_1	0.54	4.8_5
(B) plag.-pyr. aggr. (gab.)	Ab, Ca Ab-Ca, Pe	—	20	-6	37	92.6_9	0.63	6.6_8
(C) plag. aggregate	Ab, Ca Ab-Ca	—	26	-1	34	84.2_3	1.56	14.2_1
(D) plag. frag.	Ab	—	23	-8	41	96.7_0	0.39	2.9_1
14162, 13 coarse fines	Ab, Ca Ab-Ca	—	23	$-6\frac{1}{2}$	38	93.5_6	0.44	6.0_0
plag.-pyrox. in the fines	Pe (rare)	—	17	-10	$37\frac{1}{2}$	93.7_2	0.31	5.9_6
Eucrite Meteorites								
Serra de Magè	Ab, Pe	—	20	$-8\frac{1}{4}$	$37\frac{1}{2}$	94.8_3	0.09	5.0_8
	Ca, Ab-Ca	77°	23	-6	38	95.3_7	0.04	4.5_9
Ibitira	Ab-Ca,	81°	$22\frac{3}{4}$	-6	37	95.3_0	0.21	4.4_9
Cachari	Ab, Ca, Pe	—	28	-6	42	88.2_9	0.45	11.2_5

Ab: Albite; Ca: Carlsbad; Pe: Pericline.

LATTICE CONSTANTS AND STRUCTURE

Lattice constants were measured on x-ray precession photographs, which were used to determine the structural state from the presence and diffuseness of indicative *b*- and *c*-reflections. The lattice parameters along with other structural information for four crystals are listed in Table 2. The variations are within the standard deviation and no conclusions can be drawn. Except for crystals from 10017, all analyzed crystals showed a transitional anorthite structure with strong *b*-reflections and diffuse *c*-reflections streaking parallel to b^* in 0kl sections. As has been pointed out by Gay (1953), Gay and Taylor (1953), and Laves and Goldsmith (1954a, b), the diffuseness of *c*-reflections is a function of the chemical composition and of the thermal history. Comparing lunar crystals with terrestrial and eucrite anorthites *of*

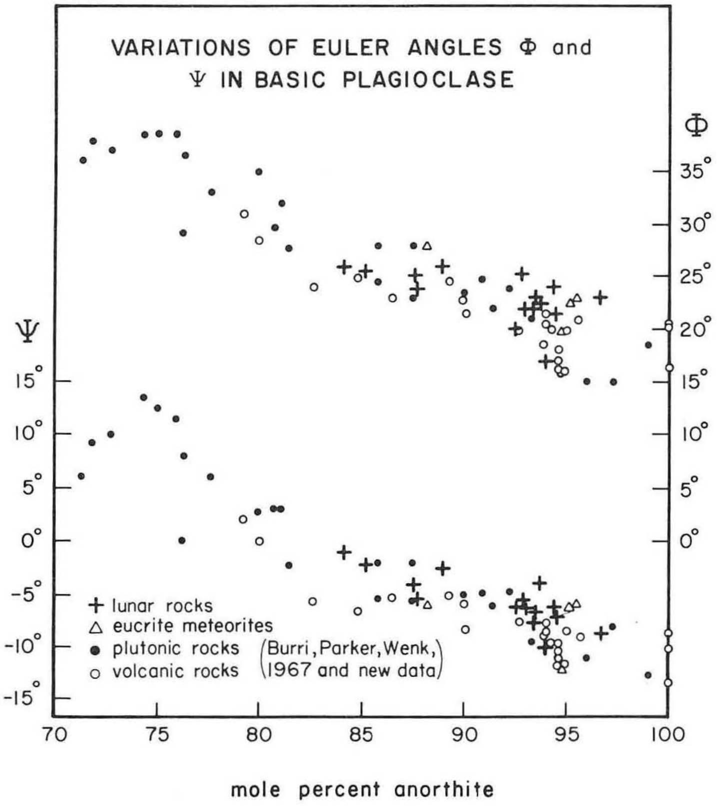


Fig. 3. Variation of Euler angles Φ and Ψ as a function of chemistry in anorthites. Data from the literature and new measurements.

Table 2. X-ray data of anorthites from precession photographs.

Sample	*a*	*b* (Å)[1]	*c*	α	β (degrees)[2]	γ	Structure	An	Or	Ab
10017 (A)	8.19	12.87	14.18	93.1	116.1	90.9	*b* weak			
10017 (B)							*e* (*b*-split) and *b*			
12021 (A)	8.18	12.87	14.18	93.3	115.9	90.9	*b* sharp, strong *c* diffuse, streaks along *b**	92.0_6	0.42	7.5_2
12021 (B)							*b* sharp, strong *c* diffuse, streaks along *b**			
12021 (C)							*b* sharp, strong *c* diffuse, streaks along *b**			
14310	8.18	12.87	14.19	93.3	116.2	91.0	*b* sharp, strong *c* diffuse, streaks along *b**	93.4_4	0.16	6.4_0
Serra de Magè eucrite	8.19	12.9	14.18	92.9	116.1	91.4	*b* sharp, weak *c* sharp, strong	95.5_7	0.05	4.3_9

[1]error ± 0.01 Å [2]error ± 0.1°

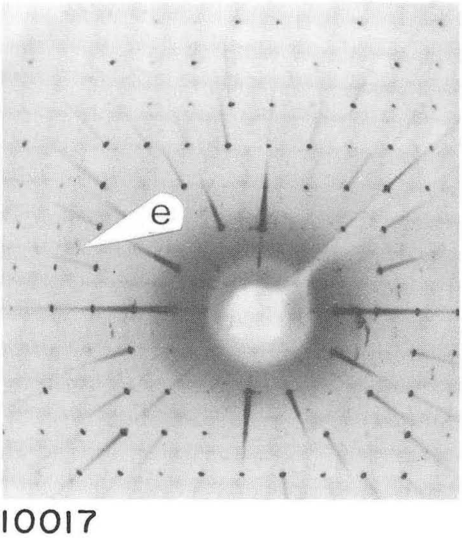


Fig. 4. X-ray single-crystal precession photograph (0kl). (Mo-radiation, Zr filter) of a plagioclase crystal in rock 10017. Notice asymmetric *e*-reflections and sharp *b*-reflections in the same crystal.

the same chemical composition, the structure of lunar plagioclase is similar to that of plagioclase from volcanic rocks. All comparative metamorphic, plutonic and meteoritic feldspars that have been studied by the authors show much stronger and sharper *c*-reflections (Wenk and Nord, 1971; Müller *et al.*, 1972). Of special interest is a crystal from 10017 that shows *e*(*b*-split)-reflections and sharp *b*-reflections in the same crystal (Fig. 4). Similar patterns have been observed by Jagodzinski and Korekawa (1972) in terrestrial An 70–77 plagioclase and have been interpreted as exsolution of an An 65 and an An 80 end member. We did not find that lunar plagioclase is "intimately twinned" on a submicroscopic scale according to the albite-Carlsbad law (Czank *et al.*, 1972). The x-ray patterns of 14310 plagioclase and other crystals analyzed indicate perfect single crystals.

Electron Microscopy

High voltage (650 kV) transmission electron microscopy of plagioclase was done on specimens from 14310. Isolated submicroscopic twin lamellae were observed (Fig. 5a). They commonly occur singly or as two to three parallel lamellae, approximately 1 micron wide, with a few lamellae as small as 0.2 microns. Twin laws identified were albite and Baveno-r. It is not known what influence these submicroscopic twins have on the U-stage determined orientation of the indicatrix. Possibly they account for the difficulty in obtaining perfect extinction in the optical measurements. Selected-area electron diffraction patterns showed sharp *a*- and *b*-, diffuse *c*-, and very weak, diffuse *d*-reflections. The *c*- and *d*-reflections were streaked in

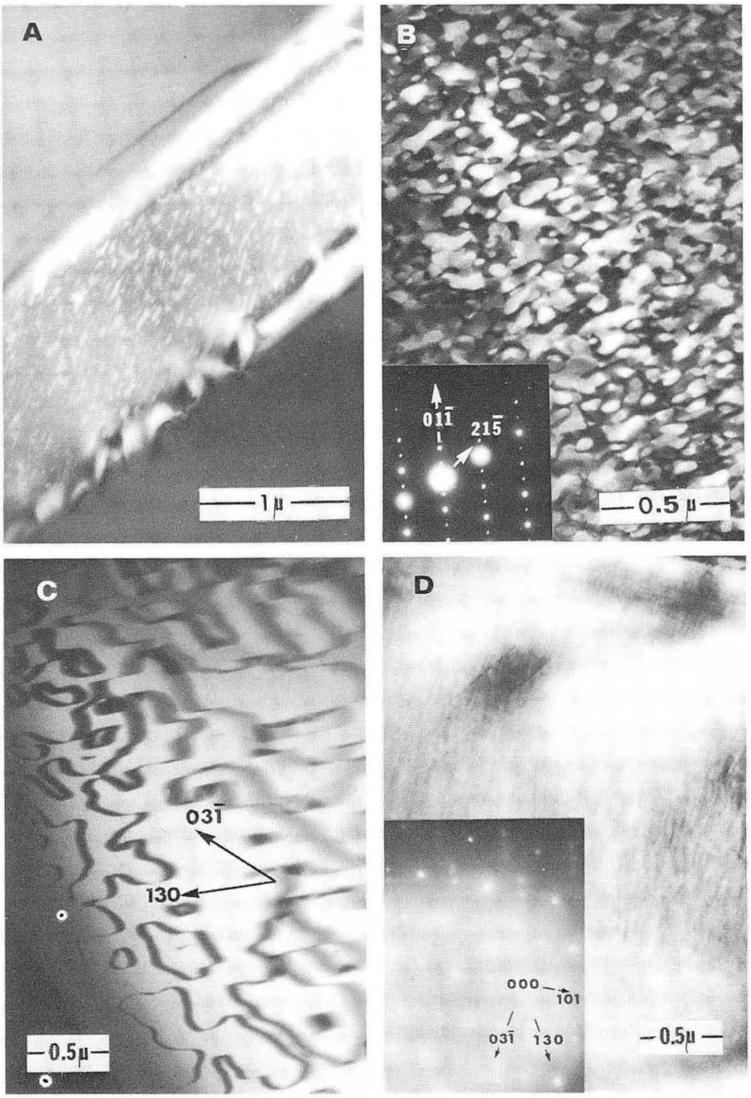


Fig. 5. High voltage (650 kV) transmission electron micrographs of plagioclase from 14310. (a) Baveno-r twin lamellae with *b*-antiphase-domain boundaries in contrast. Dark-field image with $\vec{g} = 011$ as the operating beam. (b) Small *b*-antiphase domains. Dark-field image with $\vec{g} = 31\bar{5}$. The selected area electron diffraction pattern is inserted. (c) Boundaries of *b*-antiphase domains. Dark-field image with $\vec{g} = 03\bar{1}$. Note the larger domain size compared to (b). (d) Cross-hatched structures. Dark-field image with $\vec{g} = 130$. The corresponding selected area diffraction pattern (insert) displays "*b*-split" reflections. Different part of the same crystal as in (c). Note radiation tracks.

directions perpendicular to about $(2\bar{3}\bar{1})$ in a diffractogram normal to [211]. This agrees with x-ray studies by Ribbe and Colville (1968) and electron diffraction results by Appleman *et al.* (1971). Dark-field images using *b*-reflections revealed smoothly curved antiphase-domain boundaries (Figs. 5a, b and c). Most of these *b*-antiphase domains were 500–1000 Å wide (Fig. 5b) but in some cases larger *b*-domains have been observed in the same specimen (3000–10,000 Å, Fig. 5c; compare also Christie *et al.*, 1971). No *c*-domains could be resolved in dark-field images exposed for as much as two minutes. Of special interest was a crystal with a range of chemical composition, probably similar to the one described in the section on petrography, which had a composition of An 94 in the core and had a rim of An 87 bytownite. This crystal shows in one part very large *b*-domains (Fig. 5c). No *c*-domains could be imaged. The crystal is bordered by a 2.5 micron broad band of a plagioclase phase that displays strong *b*-split reflections and very small *b*-domains in dark-field pictures. In this crystal a cross-hatched structure resembling peristerite was seen (Fig. 5d). The same structure has been observed by Lally *et al.* (1972) and may represent an exsolution in the bytownite composition range (Nissen, 1968; Jagodzinski and Korekawa, 1972). Radiation tracks can be seen in the same picture (Fig. 5d) with a maximum track density of about 2×10^8 cm^{-2}. The presence of *b*-domains and the absence of *c*-domains has been seen in at least 15 of the crystals that were examined. This makes it very probable that many of these anorthites have the far more common An 94–95 composition. The diffraction patterns agree with the x-ray precession photographs of the crystal that had a chemical composition of An 93.4.

Müller *et al.* (1972) found that anorthites (An 95–97) from a metamorphic calc-silicate rock and a eucrite meteorite contained *c*-antiphase-domain boundaries, the domain walls being as much as a few microns apart; whereas an anorthite (An 95) from a volcanic tuff displayed only small *c*-domains of the order of 70 to 100 Å in diameter. In view of these observations, it appears that the fact that no *c*-domains could be imaged in anorthite from rock 14310, which showed more diffuse *c*-reflections than all comparative terrestrial anorthites of similar chemical composition, can be interpreted as an indication for relatively rapid cooling of 14310. This characterization is not in disagreement with the results of other investigators who describe 14310 as having been more slowly cooled than other lunar basalts (e.g. Finger *et al.*, 1972). The distinction suggested by structural variations of anorthite so far is merely between a volcanic and a plutonic/metamorphic geological history. Other lunar igneous rocks may have had a different history than 14310. Large *c*-antiphase domains were observed in the anorthite of 15415 anorthosite (Lally *et al.*, 1972), which indicates that this rock may have formed under plutonic conditions.

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