Intergrowths in Lunar and Terrestrial Anorthosites with Implications for Lunar Differentiation

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Abstract

Pyroxenes, ilmenite, and a silica mineral occur as inclusions in and at grain boundaries of plagioclase in some lunar anorthosites. These textures are consistent with exsolution from high-temperature plagioclase containing Fe,Mg,Ti, and excess Si. Laboratory data on partitioning of Fe and Mg show that the parent liquid would have mg ($=$ atomic Mg/ (Mg+Fe)) $\sim$ 0.4 if the pyroxenes crystallized directly from the liquid, and $\sim$ 0.7-0.8 if they exsolved from the plagioclase. The latter is reasonable for derivation of a feldspar-rich crust during primary differentiation of the Moon whereas the former is too poor in Mg. Inclusions of amphibole in calcic plagioclase of terrestrial Archean anorthosites are also attributed to exsolution, but under hydrous conditions.

Introduction

Plagioclase-rich rocks, including anorthosite in the strict sense, are now generally considered to dominate the lunar crust (*e.g.,* Adler *et al,* 1973; Prinz, Dowty, and Keil, 1973a; Taylor *et al,* 1973). Seismic data are consistent with a mantle below the lunar crust (*e.g.,* Toksöz *et al,* 1973), but the chemical nature of the proposed mantle is controversial. Models for developing a crust and mantle by primary differentiation of the Moon (*e.g.,* Smith *et al,* 1970; Wood *et al,* 1970) require testing by detailed evaluation of appropriate crystal-liquid relationships.

Unfortunately most plagioclase-rich rocks ascribed to the lunar crust were altered by impact or thermal metamorphism or both (*e.g.,* James, 1972; Hargraves and Hollister, 1972). Nevertheless several investigators used chemical properties of mafic minerals of plagioclase-rich material to infer chemical relationships during primary crystallization: *e.g.,* Ti and Cr contents of the pyroxenes were used to infer the chemistry of the parental liquid (Taylor, 1972); pyroxenes in the 15415 anorthosite were suggested to be the product of droplets of trapped magma (Hargraves and Hollister, 1972); inclusions of high-Mg ilmenite and diopside in a fragment of anorthosite were proposed as a sample of primitive lunar crust (Powell and Weiblen, 1972); and mafic fragments were regarded as primary but modified by unmixing at low temperature (Stewart *et al,* 1972).

We now argue that the mafic phases of at least some lunar anorthosites result at least partly from exsolution, and demonstrate the consequences for the mg value of the hypothetical parent liquid.

Mineralogical Features of Lunar Anorthosites

Table 1 summarizes the mineralogy of the four largest and best documented lunar anorthosites. Descriptions and major-element analyses were reported as follows: 15415 (James, 1972; Hargraves and Hollister, 1972; Stewart *et al,* 1972; Steele and Smith, 1971); 61016 and 67075 (Steele and Smith, 1973a); 15362 (Dowty, Keil, and Prinz, 1972). New data were obtained for 15415, 61016, and 67075.

All four anorthosites, as well as nearly all plagioclase-rich rocks usually attributed to the highlands, contain high-Ca plagioclase ($>$An 95) with contents of minor elements (Fe $<$ 0.2 wt percent; Mg $<$ 0.1 wt percent; K $<$ 0.1 wt percent) lower than those from the plagioclases of Fe,Ti-rich (mare) basalts (Steele and Smith, 1973b; Smith, 1971). The plagioclases show a range of textures consistent with different degrees of mechanical deformation and solid-state recrystallization.

The pyroxenes of 15415 (James, 1972, and others) occur (a) as equant inclusions in plagioclase, (b) as polygonal grains interstitial to plagioclase grains, (c) as septa between plagioclase grains,

TABLE 1. Summary of Mineralogy of Four Anorthosites

	plagioclase	low-Ca pyroxene	high-Ca pyroxene	other
15415	An 96–99 (97–99)	En 57 Fs 40 Wo 3 (tr.)	En 40 Fs 16 Wo 44 (~ 2)	phosphate? olivine? spinel
61016	An 95–97 (99)	En 58 Fs 40 Wo 2 (~.5)	En 41 Fs 15 Wo 44 (~.5)	–
15362	An 96.7±0.6 (97–98)	En 56.4 Fs 40.7 Wo 2.9 (~0.5)	En 39 Fs 18.2 Wo 42.6 (~1.5)	chromite, troilite
67075	An 95–98 (99)	En 45–65 Fs 35–55 Wo 5 (tr.)	En 33 Fs 25 Wo 42 (~1.0)	–

Compositions in mol.% (An $CaAl_2Si_2O_8$, En $MgSiO_3$, Fs $FeSiO_3$, Wo $CaSiO_3$); electron microprobe analyses. Volume percentage given in parentheses (tr=trace). See Stewart et al (1972) for detailed analyses of 15415 pyroxenes. Description of 61016 applies to light portion: some samples show devitrified glass. Description of 67075 applies to large microanorthosite clasts (~ 1mm) in polymict breccia. All four have traces of ilmenite and a silica phase.

and (d) with plagioclase grains in fine-grained mosaics. Electron microscopy of 15415 plagioclase showed tiny pyroxene grains lying in plagioclase twin boundaries (Lally et al, 1972). We observed several grains of 15415 plagioclase which contained pyroxene inclusions with parallel optical extinction. Hargraves and Hollister (1972) specifically mentioned that this was not observed in their sample of 15415 anorthosite, although they mentioned "partly oriented" grains. However, the anorthosites are quite heterogeneous because of variable degrees of shock metamorphism and solid-state annealing. The pyroxenes in the anorthosites are dominantly augite (Table 1), some with exsolution lamellae of low-Ca pyroxene (both pigeonite and hypersthene; Stewart et al, 1972): rare discrete grains of orthopyroxene occur. These textural data are also consistent with different degrees of mechanical deformation and solid-state recrystallization, and show features typical of nucleation at grain boundaries and internal imperfections.

Figure 1 shows that the Ca,Mg,Fe contents of most pyroxenes fall into two narrow ranges, separated widely across the pyroxene composition gap. Stewart et al (1972) gave many details of 15415 pyroxenes, including electron microprobe analyses and X-ray data of rare sub-calcic augite and pigeonite. Apart from these rare pyroxenes which might result from foreign regolith, all the pyroxenes
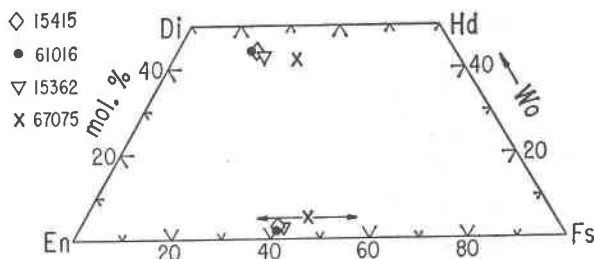

FIG. 1. Pyroxene analyses from Table 1 plotted on En–Fs–Wo ternary diagram.

in Figure 1, except for the 67075 specimens, have compositions and X-ray characteristics (exsolution) consistent with solid-state recrystallization. The mean distribution coefficient [(Fe/Mg) augite/(Fe/Mg) low-Ca pyroxene] is 0.55, almost identical with the mean value 0.54 found by Kretz (1963) for coexisting pyroxenes in terrestrial metamorphic rocks, and quite different from the mean value 0.73 for those from terrestrial igneous rocks. Particularly important is the observation that the compositions are the same for pyroxenes enclosed entirely within plagioclase and those interstitial to plagioclase. Minor elements (Al,Cr,Mn) fall in the ranges found for pyroxenes from lunar breccias (e.g., Stewart et al, 1972). The range of pyroxene compositions is greater for the anorthosite clasts of 67075; these clasts have polygonal plagioclase grains with no textural evidence of shock.

A silica mineral was seen in all four anorthosites, and also in other samples (Taylor, 1972). James (1972) noted three occurrences in 15415 anorthosites: (a) rounded inclusions in plagioclase, (b) thin septa between plagioclase grains, and (c) anhedral grains intergrown with pyroxene. We saw similar occurrences in 61016 and 67075 anorthosites (Fig. 2). Some silica inclusions are isolated from other inclusions, while others occur as composites with pyroxene or ilmenite inclusions.

Ilmenite occurs as discrete grains both within plagioclase and associated with interstitial pyroxene grains in all four anorthosites. The Mg/Fe distribution between ilmenite and low-Ca pyroxene is consistent with an equilibration temperature of 650–800°C (Anderson et al, 1972).
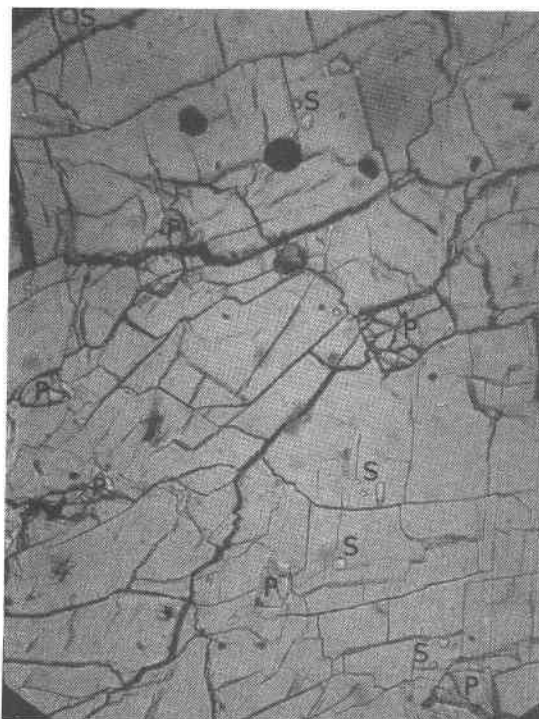
Origin of the Minor Phases

Weill et al (1970) and others noted that plagioclase from lunar Fe,Ti-rich basalts is chemically anomalous in that (3 Al − Si)/(Al + Si) does not equal Ca/(Ca + Na + K) as in the ideal (Ca,Na,K)(Al,Si)$_4$O$_8$ formula. The available elec-

tron microprobe analyses are consistent (Wenk and Wilde, 1973) with several possible substitutions including the $Ca(Fe,Mg)Si_3O_8$ unit with (Fe,Mg) atoms in tetrahedral sites. We now ask whether plagioclase from lunar anorthosites could have crystallized initially at solidus temperatures with substantial substitution of the above and other units, followed by solid-state recrystallization to yield a mixture of $Ca(Fe,Mg)Si_2O_6$ (pyroxene), SiO_2 (silica mineral) and ilmenite. In Fe,Ti-rich lunar basalts, the plagioclase contains up to 1 wt percent Fe, 0.4 wt percent Mg and perhaps 0.1 wt percent Ti (*e.g.,* Smith, 1971; Crawford, 1973), thereby showing that substantial substitution can occur at solidus temperature. Plagioclases from terrestrial volcanic rocks contain similar amounts of Fe and Mg (reviewed by Smith, 1974). Plagioclases synthesized in the presence of liquid from lunar and terrestrial basaltic compositions contain 0.1–0.6 MgO and 0.3–1.0 wt percent FeO (Tables 2 and 3). These amounts of Fe and Mg are quite sufficient to yield the pyroxenes now found in the anorthosites of Table 1 (*e.g.,* for the simple equation $Ca(Fe,Mg)Si_3O_8 \rightarrow Ca(Fe,Mg)Si_2O_6 + SiO_2$, loss of 0.4 wt percent Fe and 0.2 wt percent Mg would yield ~ 2 volume percent pyroxene). This simple model implies that the atomic volumes of pyroxene and silica mineral should be equal, whereas the silica mineral is probably less abundant than the pyroxene (Table 1). Actually Wenk and Wilde (1973) concluded that several substitution mechanisms occur. Furthermore, the substitution of Ti in the plagioclase (a potential source with Fe for the ilmenite) and of other minor elements including Mn causes further complications.

Whatever the details of the substitution and exsolution mechanisms, we question whether the anorthosites in Table 1 contained any primary mafic phases, and now go on to consider petrogenetic implications of the Fe and Mg content of the anorthosites.

Implications for the Parent Magma

The partition of Mg and Fe between basaltic magma and olivine plus pyroxene provides an im-

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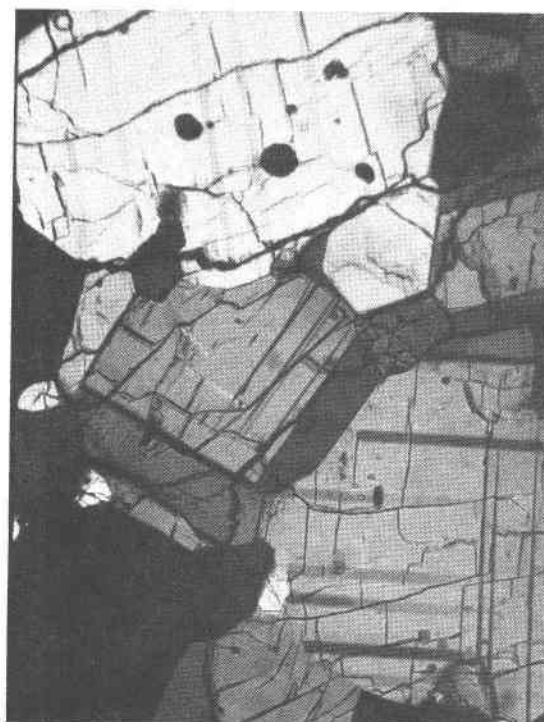
b

Fig. 2. Photomicrographs of inclusions in plagioclase from anorthosite 67075: (**a**) plane-polarized light, (**b**) crossed polars; 2 mm across. The inclusions are: ilmenite (round, dark), pyroxene (gray, polygonal, marked by P), and silica mineral (small, light, marked by S). Note polygonal nature of plagioclase grains. The bands are twin lamellae.

TABLE 2. Mg and Fe Distribution between Plagioclase and Glass in Laboratory Syntheses Using 14310 Basalt

plagioclase composition			glass composition			synthesis conditions
FeO wt %	MgO wt %	mg atomic	FeO wt %	MgO wt %	mg atomic	
0.72	0.23	0.36	10.82	7.46	0.55	1189°C, 1bar, Fe/FeO buffer
0.32	0.30	0.62	5.21	9.27	0.76	1290°C, 5kb, Fe capsule
0.43	0.25	0.51	8.04	7.83	0.63	1300°C, 15kb, Pt capsule

From Ford et al (1972)

portant clue to crystal-liquid differentiation models (see Steele and Smith, 1973a, for a summary of available data).

Assume first that the pyroxenes of the anorthosites crystallized from the parent liquid. The dashed curve in Figure 3 shows the average relation between mg of pyroxene and mg of coexisting liquid for laboratory syntheses using lunar basaltic compositions (see Steele and Smith, 1973a, for derivation of original diagram). From the pyroxene compositions in Figure 1, the predicted mg for the parent basaltic liquid would be ~ 0.4. The individual compositions for augite and low-Ca pyroxene are shown, but at solidus temperature they would be represented by a single pyroxene with bulk composition much closer to the augite composition than that of the other pyroxene (mg ~ 0.67).

Now assume that the pyroxenes exsolved from the plagioclase, and that mg depends on plagioclase-liquid relations. The continuous curve in Figure 3 fits the three data points for coexisting plagioclase and glass (Table 2). In contrast to pyroxene, plagioclase has a lower mg value than the coexisting basaltic liquid. The primary plagioclase would have

mg near 0.67 (the observed pyroxene mg value in anorthosites) if the Mg and Fe came solely from the exsolved pyroxenes. The actual value, of course, would depend on the amounts of the other exsolved minerals and the amount of Mg and Fe retained in the plagioclase. From the experimental distribution curve (Fig. 3), the parent liquid should have mg near 0.8. Another estimate of the mg of the parental liquid can be obtained from data on coexisting synthetic plagioclase and either pyroxene or olivine (Table 3), which are plotted on Figure 4. Note that all the mineral analyses (as also in Table 2) were obtained by electron microprobe analysis, and that the accuracy for FeO and MgO of the plagioclase is low for most data. Nevertheless the data in Figure 4 show that mg is consistently lower in the plagioclase than in the coexisting pyroxene or olivine. Considering just the data for coexisting plagioclase and clinopyroxene, the ratio $(Fe/Mg)_{plag}/(Fe/Mg)_{cpx}$ averages near 4 with a range from ~ 2.5 to ~ 6. Obviously the data permit only a semi-quantitative interpretation. The dashed lines convert the mean mg value for the supposed primary plagioclase to ~ 0.89 for a hypothetical coexisting pyroxene. Returning to Figure 3, the dashed line at a mg of 0.89 for the silicate yields an estimate of ~ 0.7 for mg of the supposed parent liquid. The difference between the mg estimates of ~ 0.8 and ~ 0.7 for the parent liquid by the two methods arises merely from uncertainty in the experimental data, and the former might be preferred.

Plotted below the base of Figure 3 are the ranges

TABLE 3. Mg and Fe Distribution between Olivine, Pyroxene, Plagioclase, and Bulk Composition in Laboratory Syntheses

label	bulk composition			plag. composition			ferromagnesian composition				run conditions
	FeO wt %	MgO wt %	mg atomic	FeO wt %	MgO wt %	mg atomic	type	FeO wt %	MgO wt %	mg atomic	
T87	9.07	9.17	0.64	0.8	0.4	0.47	cpx	9.5	18.0	0.77	dry, 10kb, 1225°C
59P13	13.58	6.70	0.47	0.28	0.05	0.24	ol	33.2	30.7	0.62	dry, 8kb, 1150°C
							cpx	14.3	16.5	0.67	
14310	8.2	7.6	0.62	0.5	0.3	0.52					dry, 1 atm, 1320°C
				1.0	0.6	0.52					dry, 5kb, 1280°C
				1.0	0.5	0.47	opx	9.4	28.4	0.84	dry, 5kb, 1260°C
KREEP	11.1	8.3	0.57	0.8	0.5	0.53					dry, 1 atm, 1215°C
				0.8	0.4	0.47	cpx*	11.7	25.0	0.79	dry, 5kb, 1220°C
				0.7	0.6	0.60	cpx†	10.5	22.1	0.79	dry, 7kb, 1240°C
A	15.12	12.72	0.60	0.64	0.34	0.49	cpx	9.1	14.9	0.74	dry, vacuo, 1110°C
							ol	29.8	32.2	0.66	

T87 olivine tholeiite (Kushiro and Thompson, 1972); 59P13 olivine tholeiite (Thompson, 1972); 14310 basalt and KREEP-type composition (Green et al, 1972); A artificial mix $Wo_{25}Fs_{30}En_{45}$ with 10% $CaAl_2TiO_6$ (Akella and Boyd, 1972). For T87 and 59P13, FeO and Fe_2O_3 combined as FeO. *mean of 2 analyses. † interpolated. Data from Akella and Boyd (1973, Table 2) not listed because of unreasonably high MgO and FeO in plagioclase.
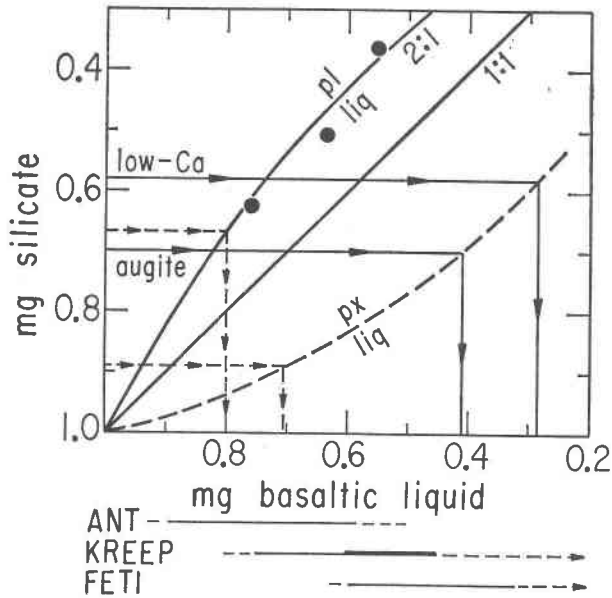
FIG. 3. Relation of mg for coexisting basaltic liquid and plagioclase or pyroxene. The dashed curve is the approximate mean of experimental data, and the data below the diagram summarize the ranges of mg for three types of lunar rocks (see Steele and Smith, 1973a, for details). The dots show coexisting plagioclase and liquid from synthetic charges of 14310 basalt (Table 2), and the curve shows $(Fe/Mg)_{plag}/(Fe/Mg)_{liq} = 2.0$ as an approximate fit to these three points.

of mg for the three major types of lunar rocks so far described: the anorthositic-noritic-troctolitic group; the ones rich in K, REE and P; and the Fe,Ti-rich (mare) basalts. The value of 0.4 for the model in which the anorthositic pyroxenes grew directly from a liquid is consistent with that liquid yielding the FETI basalts, or just possibly the least magnesian of the KREEP group. The value of 0.8–0.7 for the exsolution model is consistent with the parent liquid yielding ANT rocks or just possibly the more magnesian of the KREEP group. Space forbids detailed evaluation of the complex chemical data in the lunar literature, but the exsolution model is much easier to reconcile with these data. In a supposed primary differentiation of the Moon, a liquid with mg near 0.75 would yield pyroxenes and olivines with mg near 0.9, which is consistent with many observations of single grains, small clasts and a few larger rock samples from the Moon (*e.g.,* Steele and Smith, 1972; Anderson, 1973; Prinz *et al,* 1973b; Brown *et al,* 1973). A detailed listing of such samples is being prepared. In spite of the uncertainties in the experimental partition coefficients, the simplest ex-

planation of the present data is that the anorthosites of Table 1 crystallized entirely, or almost entirely, as plagioclase from a liquid with mg near 0.8–0.7, and that the other minerals developed principally or entirely by exsolution. Of course, the pyroxenes or olivines from anorthosites with more than several percent ferromagnesian minerals probably result at least in part from primary phases, but even these relatively mafic anorthosites should have mg values biased by plagioclase exsolution. The mg values of lunar noritic and troctolitic rocks tend to lie in the range of 0.7–0.9, which encloses the value deduced here for the plagioclase-rich anorthosites.

Terrestrial Anorthosites

There are innumerable observations of inclusions in plagioclase of terrestrial anorthosites. Two examples are the occurrence of opaque minerals in anorthosites from Morin, Quebec (Anderson, 1966) and E. Greenland (Bridgwater and Harry, 1968). Antiperthites with K-feldspar occurring as precipitates on twin lamellae and other imperfections (*e.g.,* Carstens, 1967) are common. We now mention the occurrence of needles of amphibole in anorthosites from two Archean complexes interpreted as the product of metamorphism of layered igneous bodies.

Figure 5 shows photomicrographs of two adjacent regions of a thin section of anorthosite from the Fiskenaesset Intrusion, W. Greenland (Windley *et al,* 1973; Windley and Smith, 1974). In (a), the center of a large bytownite megacryst is crowded with hornblende prisms in many different orientations, and with no preference for location in twin bound-
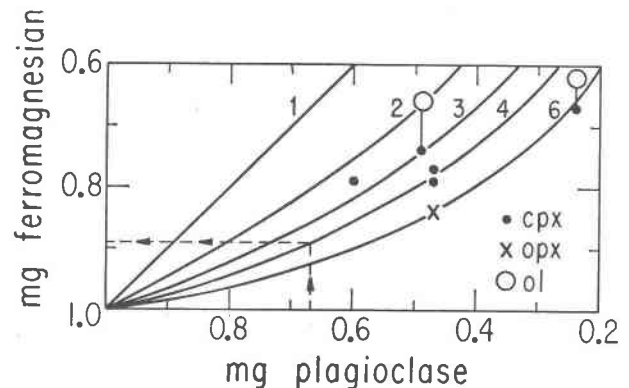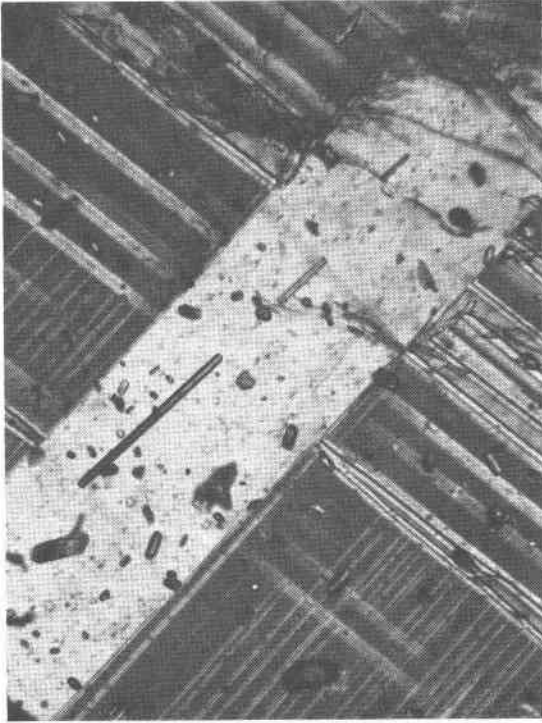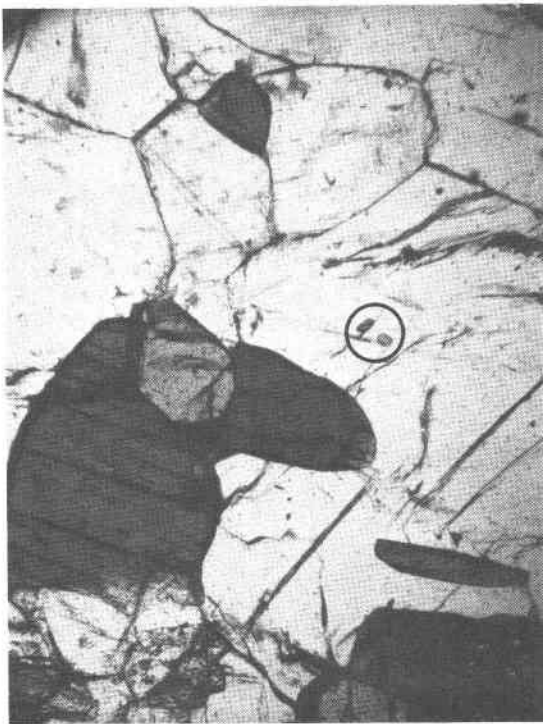

FIG. 4. Relation of mg for coexisting plagioclase and ferromagnesian minerals synthesized from basaltic compositions (Table 3). The reference curves are isopleths for $(Mg/Fe)_{plag}/(Mg/Fe)_{ferromagnesian}$.

a

b

aries. In (b), a nearby region of the same thin section shows plagioclase grains about 1 mm across with polygonal outlines. Only two small amphibole inclusions are visible. Large amphibole grains lying in a band which extends throughout the whole hand specimen are visible, together with a grain interstitial to plagioclase grains at the top center. Detailed study of the texture of this and other specimens suggests that anorthosites formed from igneous megacrysts of plagioclases with varying amounts of primary ferro-magnesian minerals (not necessarily hornblende). Subsequent metamorphism resulted in solid-state annealing and recrystallization of which Figure 5 shows two intermediate stages. Ultimately a uniform polygonal texture was produced in some specimens with no amphibole inclusions in the plagioclase.

Similar observations of textural changes, plus major metasomatic alteration of the plagioclase to more sodic compositions, were observed in the Limpopo Complex of South East Africa (Hor *et al*, in preparation).

Conclusion

Calcic plagioclase from both lunar and terrestrial high-Ca anorthosites shows textural evidence of exsolution. Under the anhydrous conditions on the Moon, the Mg and Fe exsolve principally as pyroxene, whereas under the hydrous conditions on Earth the ultimate product is amphibole, though pyroxene might have been a precursor. For the lunar anorthosites, *mg* of the parent magma should be near 0.8–0.7 rather than 0.4 deduced on the assumption that the pyroxene is primary. Detailed study of the trace elements, including Ti, Cr and Mn, is desirable: perhaps ion microprobe techniques will prove suitable.

Acknowledgments

FIG. 5. Photomicrographs of anorthosite from Fiskenaes-set Intrusion, W. Greenland. Each area is 2 mm across, and the two regions are separated by 1 cm. (a) shows the center part of a megacryst of plagioclase with albite and pericline twinning and many inclusions of amphibole. (b) shows a region with polygonal plagioclase essentially free of amphibole except for two circled inclusions just NE of center. All the dark grains are amphibole, but the tone changes because of pleochroism. (a) in crossed polars, (b) in plane polarized light. Specimen 84426 of B. F. Windley, University of Leicester.

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