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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15 November 1971

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 feldspathic rocks and may have a relatively deep-seated origin.

This report presents a petrographic description of anorthosite 15415 and a discussion of its history, based on detailed optical and electron microprobe studies of thin section 15415,15 and on optical examination of thin sections 15415,17; 15415,19; 15415,21; 15415,29; and 15415,30. The geologic setting of the rock and additional hand-specimen and petrographic descriptions are given by Wilshire *et al.* (*2*), and detailed studies of individual mineral constituents are given by Stewart *et al.* (*3*).

Anorthosite 15415 consists almost entirely of anorthite, with accessory diopsidic augite and traces of hypersthene, ilmenite, and a silica mineral. An examination of the hand specimen shows that the plagioclase is highly inequigranular, with the largest grains up to 3 cm across and the smallest below the limit of resolution of the unaided eye (*4*). The plagioclase content is well over 95 percent and may be greater than 99 percent (*2,4*), but the textural heterogeneity precludes determination of an accurate mode from a single subsample. The structures apparent in the hand specimen are sets of pervasive fractures and local zones of intense granulation.

As can be seen in thin section, the largest grains of plagioclase are anhedral and form a medium- to coarse-grained granular mosaic. Plagioclase grains of intermediate size [from 1.3 to 0.1 mm (*4*)] form polygons with plane or smoothly curving boundaries. These polygons occur in patches within and between, and in bands cutting through, the larger grains (Fig. 1a). Both the large mosaic and intermediate-sized polygonal grains appear unzoned and contain relatively broad throughgoing twins. The twin laws are pericline and albite; in the nine grains studied with Universal stage methods using a petrographic microscope in 15415,15, eight had pericline and one had albite twinning. The grains of both textural types are cut by pervasive, closely spaced shear fractures and contain abundant intragranular deformation features. Many of the shears are healed, and some are marked by small patches and thin bands of minute recrystallized grains. The thin sections also show widely spaced patches and streaks of intensely granulated minerals (Fig. 1b), generally near their edges, and these cataclastic zones show no evidence of subsequent annealing.

The intragranular deformation features exhibited by plagioclase are (i) extinction variation and (ii) mechanical twinning. The variations in extinction position are slight and range from smoothly undulatory to patchy. The lamellae of mechanical twins are abundant; they are lenticular and are generally much finer and more closely spaced than the twins described above. They tend to be strongly localized and related to shear fractures or bending of the surrounding grain (Fig. 1c). In the acute angles between some intersecting shears plagioclase is intensely twinned (Fig. 1d), and along a few shears thin slivers of feldspar are in twin orientation relative to the surrounding grain. Nearly all the mechanical twins in 15415,15 studied with Universal stage are albite or pericline, and the two types are commonly closely associated (Fig. 1c). These twins appear to be identical in nearly all characteristics to mechani-

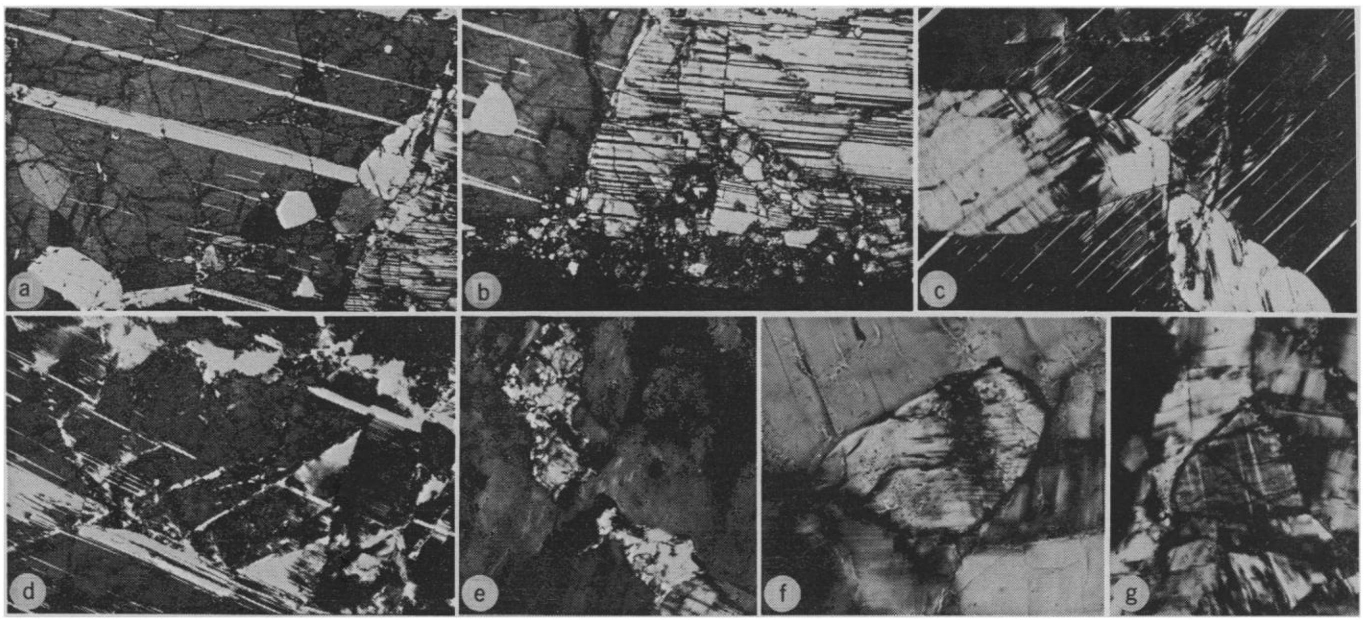

Fig. 1. Textures of 15415. All the photomicrographs were taken in light passed through crossed polars. The photograph in (f) is of 15415,17; all the others are of 15415,15. (a) Margin of a large mosaic grain of plagioclase that contains throughgoing pericline twins. The grain is cut by a curving band of intermediate-sized polygons of plagioclase (from right center to bottom left to top left). The adjacent large grain at the right shows abundant fine mechanical twins, and all grains are pervasively fractured. The width of the field of view is 2.2 mm. (b) Patch of granulated, unrecrystallized plagioclase (bottom) at the broken edges of two large mosaic grains. The width of the field of view is 0.88 mm. (c) Plagioclase polygon (left center) containing lamellae of albite and pericline mechanical twins (trending northeast to southwest and northwest to southeast, respectively). The right end of the grain abuts a healed shear (trending north to south) and is related to the untwinned left end by albite twin glide. The width of the field of view is 0.7 mm. (d) Large mosaic grain of plagioclase, containing pericline twinning related to sets of intersecting healed shears. Untwinned parts of the grain are gray and twinned parts are white. The width of the field of view is 0.7 mm. (e) Recrystallized aggregates of pyroxene, within plagioclase. The width of the field of view is 0.2 mm. (f) Fine probable twin lamellae (trending east to west) in augite, related to kink band (dark gray, trending north to south). The lamellae are parallel to (100). The width of the field of view is 0.17 mm. (g) Twin lamellae (trending north-northwest to south-southeast) in augite. The lamellae are 1 to 2 μm thick and are parallel to (001). The grain was analyzed with a microprobe at intervals of 1 μm along a traverse perpendicular to the lamellae, and no trace of variation in CaO content was detected. The width of the field of view is 0.14 mm.

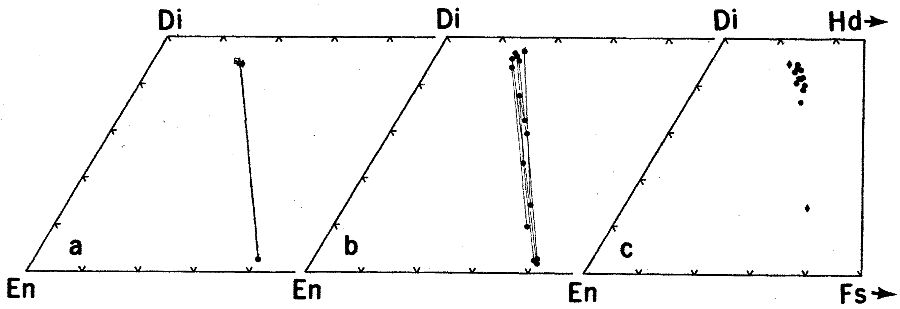

Fig. 2. Wo:En:Fs ratios of pyroxenes in 15415,15. The tie lines connect the compositions of coexisting pyroxenes. (a) Compositions of included and interstitial grains; (filled diamond) average of analyses of six inclusions in plagioclase; (open square) average of analyses of nine polygons at plagioclase grain boundaries; (open triangle) septum between large plagioclase grains; (filled circles) composite grain of orthopyroxene and augite (see text for description). (b) Compositions of points in recrystallized aggregates. (c) Compositions of points in an interstitial polygonal grain containing fine exsolution lamellae; (filled circles) unrecrystallized areas with lamellae; (filled diamonds) recrystallized partial rim.

cal twins produced in static deformation experiments in terrestrial plagioclase (*5*). [One grain was observed in 15415,15 that contains a few small patches of twin lamellae of two types other than albite or pericline. Composition planes of these twins are within 10° of (100) and (001), respectively, but do not appear to be exactly on these planes. The precise composition planes and twin laws could not be determined because of extinction variations in the host and the extreme thinness of the lamellae.]

The pyroxenes have various modes of occurrence. Diopsidic augite forms (i) equant inclusions in plagioclase; (ii) polygons along grain boundaries between large plagioclase grains; (iii) polygons intergrown with polygonal plagioclase in patches interstitial to, and bands cutting through, large plagioclase grains; and (iv) thin septa between large plagioclase grains. In 15415,15 most of the included grains are between 0.015 and 0.035 mm, and most of the polygonal grains are between 0.035 and 0.2 mm. Many of the augites contain abundant fine exsolution lamellae of low-calcium pyroxene along (001), (100), or both; x-ray studies (*3*) show that the former are of pigeonite and the latter are of orthopyroxene. Orthopyroxene also forms rare discrete grains, generally about 0.03 mm across. The largest such grain in 15415,15 is part of a composite polygon that consists of orthopyroxene at one end and augite at the other, and the boundary between the two minerals is plane and parallel to (100) of both; the augite contains a single broad exsolution lamella of orthopyroxene, also parallel to (100).

Locally, pyroxenes form recrystallized aggregates that consist of minute discrete grains of both diopsidic augite and orthopyroxene. These aggregates occur as partial rims on unrecrystallized grains, replace polygonal grains (Fig. 1e), and form minute septa along boundaries between plagioclase polygons. Such recrystallization is more common in grains that are interstitial to or intergrown with plagioclase than in grains that are completely included within the feldspar.

The diopsidic augite shows the same types of intragranular deformation—extinction variation and mechanical twinning—as the anorthite, but these features are not as abundantly developed as in the plagioclase. Unfortunately, at present it is not possible to estimate the frequency of twinning in the pyroxene or the relative frequency of twins of differing orientations, because of the difficulty of distinguishing fine twin lamellae from fine exsolution lamellae. Sparse grains show lamellae that are likely twins because they are related to bending or kinking (Fig. 1f). Others show broader, more widely spaced lamellae that differ in extinction position from the host (Fig. 1g); that these are twins is indicated by microprobe analysis (see the legend for Fig. 1g). In the grain shown in Fig. 1f the lamellae are parallel to (100), and in the grain shown in Fig. 1g they are parallel to (001).

Other trace constituents observed in the thin sections (*6*) are ilmenite and a silica mineral (low index of refraction, thus either tridymite or cristobalite). Most of the ilmenite occurs within pyroxene grains, generally near their margins, forming sparse equant or elongate inclusions (up to about 0.008 mm across in 15415,15). Many other pyroxene grains contain numerous minute oriented plates of an oxide mineral too fine to be identified with a microprobe, and these may be ilmenite as well, or possibly ulvöspinel. The silica mineral forms (i) rounded inclusions in plagioclase (up to 0.06 mm across; the larger of these are mosaics of weakly birefringent grains); (ii) thin septa bounding plagioclase grains; and (iii) minute anhedral grains intergrown with pyroxene in recrystallized aggregates. Traces of apatite and olivine were tentatively identified by Wilshire *et al.* (*2*); neither mineral was found in this study.

The mineral compositions in 15415,15, determined with an electron microprobe (*7*), appear to be nearly homogeneous within the limits of analytical error. All the textural variants of plagioclase were analyzed—centers and edges of large mosaic grains and of intermediate-sized polygons, twin lamellae, recrystallized patches—and all analyses are 96.6 ± 1.2 molecule percent anorthite ($An_{96.6 \pm 1.2}$) [in good agreement with data presented by Stewart *et al.* (*3*)]. In addition, grains of all textural types of pyroxene were analyzed (Fig. 2), and again compositions do not appear to vary with texture. The diopsidic augite averages about $Wo_{44.5}En_{40}Fs_{15.5}$, and the largest discrete grain of orthopyroxene is about $Wo_3En_{57}Fs_{40}$ (Fig. 2a). The minute grains of diopsidic augite and orthopyroxene in recrystallized aggregates appear to be of the same compositions as the larger discrete grains of these minerals (Fig. 2b); points on Fig. 2b that indicate intermediate compositions are most likely analyses of mixtures of the two finely intergrown phases. In some of the larger augite grains, compositional variations due to exsolution of low-calcium pyroxene can be detected with the microprobe (Fig. 2c). The silica mineral appears to be nearly pure SiO_2; no significant contents of Na_2O, K_2O, Al_2O_3, or CaO were detected with the microprobe.

Fine fragmental material that was apparently clinging to the surface of the rock chip is preserved along the edges of some of the thin sections. The fragments observed are of pale brown vesicular glass, devitrified glass, plagioclase, and pyroxene (including one grain of ferroaugite, about $Wo_{29}En_{24}Fs_{47}$, in 15415,15). Some of this material may be derived from the anorthosite itself and some, or all, of it may be extraneous. No attempt has been made to determine the source of these fragments.

The data presented here indicate that anorthosite 15415 has had a complex history of repeated episodes of deformation and recrystallization. Following is a tentative outline of events in the history of the rock, in chronological order; the true rock history may have been more complex than described here, but was certainly no less complex.

1) At the earliest stage that can be discerned by petrographic observations, the parent rock of 15415 was a coarse mosaic of plagioclase grains. This type of texture can be the product of postcumulus overgrowth in a cumulate of igneous plagioclase or the result of solid-state recrystallization, and the texture in itself indicates little about the ultimate origin of the rock. However, the presence of dominant pericline twinning in the plagioclase suggests that a metamorphic origin for the texture may be most likely: (i) under terrestrial conditions pericline twinning rarely is preponderant in igneous rocks, but commonly is in metamorphic rocks (*8*); (ii) in lunar basalts albite, Carlsbad, and complex Carlsbad-albite twins are more common than pericline twins (*9*); and (iii) pericline twins are also dominant in the polygonal grains in 15415 that clearly are of metamorphic origin (see below).

2) The parent rock was deformed and was subsequently recrystallized. The preexisting coarse mosaic of grains and the twins within these grains were preserved through deformation and recrystallization; the recrystallization produced, superimposed on this mosaic, a network of interstitial patches and crosscutting bands of intermediate-sized polygonal grains. The resulting textures are very similar to those of terrestrial granulites. The annealing appears to have been intense, and characteristics of the rock that may have been produced by this event are (i) extreme homogeneity of mineral compositions; (ii) complete ordering of the structure of the anorthite, as observed by Stewart *et al.* (*3*); (iii) formation of pericline and albite twins in polygonal plagioclase; and (iv) formation of sparse discrete grains of orthopyroxene by extensive unmixing of preexisting augitic pyroxene (suggested by the relationships observed in the composite augite-orthopyroxene grain described above). The occurrence of an episode of deformation prior to recrystallization is inferred from the observation that polygonized bands cut through the interiors of the large plagioclase grains and thus probably formed by annealing along shear fractures. However, nearly all the effects of the deformation were erased during recrystallization, and a study of the textures of large cross sections of the rock would be necessary to delineate the nature and distribution of features related to this deformation. Causes of the deformation and annealing cannot be evaluated at present.

3) The parent rock was pervasively deformed on a fairly fine scale. Much closely spaced shear fracturing and associated fine mechanical twinning formed during this event. Unfortunately, it is not possible with the available data to establish whether the deformation was tectonic or related to impact. The nature of the twinning in plagioclase is not diagnostic of its origin; similar twinning is observed in tectonically deformed terrestrial rocks (*10*), naturally shocked lunar and terrestrial plagioclase (*11*), and experimentally shocked (*12*) and statically deformed (*5*) terrestrial plagioclase. In contrast, the nature of twinning in augite is diagnostic of origin—in tectonically deformed rocks augite twins more readily on (100) (*13*), and in rocks deformed by shock, on (001) (*14*)—but a detailed study to determine the relative proportions of the two types of twins is beyond the scope of the present work.

4) The parent rock was annealed, although not as profoundly as in the last prior annealing. Shear fractures healed, and granulated streaks recrystallized to form mosaics of minute interlocking grains. Other characteristics of the texture that may have been produced by this event are (i) recrystallized aggregates of pyroxene and silica; and (ii) fine exsolution in augite. These features appear superimposed upon textures produced in the earlier, more intense annealing, such as polygonal grain outlines. It is not possible to determine, on the basis of texture alone, the length of time that elapsed between annealing and the preceding deformation or the cause of the annealing.

5) The parent rock was cataclastically deformed. This event produced widely spaced bands and patches of crushed rock. Minor mechanical twinning in plagioclase appears to have formed at this time, but in general most twinning is associated with the healed shears formed during the prior deformation. There is no evidence for any subsequent recrystallization.

6) The anorthosite underwent one or more periods of shattering and fragmentation. This episode (or these episodes) produced pervasive fracturing. From the geologic occurrence of the rock, Wilshire *et al.* (*2*) infer at least two, possibly three, such events. One of these is fragmentation associated with separation of the anorthosite from its parent rock body; this event may be represented in sample 15415 solely by fracturing or, alternatively, by the episode of unannealed cataclastic deformation. The separation of 15415 from its parent body, and subsequent shattering events, were almost certainly related to impact processes.

In conclusion, it appears that anorthosite 15415 is a fragment of a complex polymetamorphic rock. The multiple events of deformation and recrystallization it has undergone have likely affected its gas retention age, which is nonetheless greater than 4×10^9 years (*15*). Clearly, the geologic source region from which the rock was derived—whether highlands, primitive lunar crust, or not—was far from static during early lunar history. It is not yet possible to establish whether the deformation episodes were all related to impacts, or whether they might have been tectonic and related to internal lunar processes. However, it is evident that solid-state recrystallization and high-grade metamorphism were important processes in the "crust" of the moon during its early history.

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Apollo 15 Geochemical X-ray Fluorescence Experiment: Preliminary Report

Abstract. *Although only part of the information from the x-ray fluorescence geochemical experiment has been analyzed, it is clear that the experiment was highly successful. Significant compositional differences among and possibly within the maria and highlands have been detected. When viewed in the light of analyzed lunar rocks and soil samples, and the data from other lunar orbital experiments (in particular, the Apollo 15 gamma-ray spectroscopy experiment), the results indicate the existence of a differential lunar highland crust, probably feldspathic. This crust appears to be related to the plagioclase-rich materials previously found in the samples from Apollo 11, Apollo 12, Apollo 14, Apollo 15, and Luna 16.*

The recent Apollo 15 mission included a large complement of orbital experiments, of which three were components of an integrated geochemistry experiment. These three experiments, involving gamma-ray, x-ray, and alpha particle spectrometers, were included to obtain a geochemical map of the moon along the projected paths swept out by the orbiting spacecraft.

This report presents some of the preliminary results from the survey of the lunar surface obtained with the x-ray spectrometer. Although measurements of Al/Si and Mg/Si ratios were made, only the Al/Si ratios will be reported here. The Mg/Si ratios are important but more difficult to calculate and will be reported at a later date.

The Apollo x-ray experiment is based on the production of characteristic x-rays due to the interaction of the solar x-rays with the lunar surface. It appears from a number of calculations (*1*) that the typical solar x-ray spectrum is energetically capable of producing measurable amounts of characteristic x-rays from all the abundant elements up to about atomic number $Z = 14$ (Si). Furthermore, during brief periods of more intense solar activity when the solar flux "hardens" (higher fluxes of more energetic x-rays) it should be possible to observe radiation from elements of higher atomic number. Thus the secondary radiation excited from the lunar surface depends on the nature of the solar flux. It can affect not only changes in the fluorescent x-ray intensities but also changes in the relative intensities from the various elements. For example, should the solar spectrum harden, then there would be an enhancement of the intensities from the heavier elements relative to the lighter ones.

The instrument will be described briefly; a more detailed description can be found in documents detailing the Command Service Module (CSM) "J" series mission experiments (*2*). The x-ray detector assembly consisted of three large-area proportional counters with Be windows 0.0025 cm thick. Two of the detectors had large-area x-ray filters (Mg and Al foils) for energy discrimination among the characteristic x-rays of Al, Mg, and Si. A fourth detector was used as a solar monitor. A single collimator assembly was used to define a field of view of the three proportional counters as a single unit. The field of view was ± 30° full width at half maximum in two perpendicular directions. At orbital altitudes of 60 nautical miles (111 km) this field of view covered a sector approximately 60 by 60 nautical miles. The actual surface resolution defined by the collimators was also a function of the spacecraft motion and the time interval for data accumulation. Because the preliminary results in this report are based on 1-minute accumulation periods (the prime data are for 8-second intervals), one must consider each data point as representing a swath on the lunar surface of approximately 60 by 120 nautical miles. An eight-channel pulse height analyzer was used for each of the four detectors to obtain energy information. The filtered counters and the solar monitor covered a fixed energy of from 0.75 to 2.75 kev, whereas the unfiltered detector covered two energy ranges: 0.75 to 2.75 kev and 1.5 to 5.5 kev. The two gain modes of the unfiltered detector were operated alternately by a program built into the x-ray processor. The x-ray experiment was mounted in the Science Instrument Module. The proportional counter of the solar monitor was mounted on the opposite side of the spacecraft to continuously monitor the sun's x-ray flux simultaneously with the surface measurements.

The x-ray experiment was turned on by command module pilot A. Worden some 84 hours after the start of the mission, during the third revolution around the moon. About 100 hours of data were taken of the illuminated portion of the lunar surface during 84 revolutions. Lunar backside data were recorded on magnetic tape and telemetered while the spacecraft was on the forward side. The region covered ranged from about 150°E to 50°W.

The data have been reduced in a simple manner based on the energy discrimination afforded by the selected x-ray filters. Three simultaneous equations were written and solved by least-squares analysis, a procedure which permits easy estimates of statistical validity. The Al/Si intensity ratios were reduced to concentration ratios by a procedure which was in part theoretical and in part empirical. The theoretical calculations were based on an assumption of a coronal temperature of about 3×10^6 °K. Under these conditions we were able to calculate an x-ray energy distribution consisting of both continuum and characteristic lines which is consistent with our observations by means of the solar monitor of the solar x-ray flux. Using this calculated distribution, various compositions of lunar materials taken from the literature, and known fluorescence yields, we were able to derive a nearly linear relationship between Al/Si intensity ratios and Al/Si concentrations.

Empirically, the analysis of lunar