and has been produced experimentally at low strain rates (*5*). Nevertheless, the evidence strongly suggests that the multiple basal-plane twinning observed in clinopyroxene fragments in Apollo 11 material is the result of shock.

Although some of the olivine fragments in the microbreccia and fines show irregular microfracturing and undulatory extinction, only a few grains were found that showed any development of planar or lamellar features considered to be indicative of shock. One olivine from a crystalline igneous rock fragment in the fines showed in the electron microscope (Fig. 3) the incipient development of lattice-controlled discontinuities of the type that are highly developed in particulate olivine samples experimentally shock loaded at about 200 kb (*6*). Such planar features, interpreted as microfractures, constitute excellent evidence of shock-wave damage. Several olivine grains were observed to contain one set of optically resolvable thin lamellae, which appear to be similar to those described in olivine from shocked basalt [fig. 8D in (*4*)]; another olivine grain in a microbreccia (10061) showed some recrystallization (development of tiny new grains) similar to the well-developed recrystallization effects in dunite experimentally shock loaded to 1 Mb (*7*).

In a thin section of microbreccia (10060,20) are three grains of a colorless untwinned mineral with a low birefringence of section which show several close-spaced sets of planar features that resemble those observed in shocked quartz (*8*) and shocked plagioclase (*9*). These grains show no cleavage and are biaxial positive with $2V$ in the range 25° to 32°. They are either shocked and strained quartz or shocked plagioclase in which the optical indicatrix has been changed markedly, or, possibly, shocked clinopyroxene. Chao (*2*, p. 146) has reported that shocked quartz may be biaxial positive with an optic angle as high as 28°, and Bunch (*10*, p. 425) has found that shocked labradorite may have an optic angle as much as 20 percent smaller than its unshocked compositional equivalent. Evidently these grains should be checked with the electron microprobe, inasmuch as the possible occurrence of quartz could have significant petrological implications.

Each of two magnetic particles from the fines was found to contain an angular grain of metallic iron containing about 5 percent nickel as revealed by the electron microprobe. The grains are probably kamacite fragments from a metallic meteorite. When etched with Nital, one grain developed what appear to be Neumann bands typical of lightly shocked iron meteorites [fig. 3a in (*11*)]; the other shows an exceedingly fine microstructure near the resolution limit of the light microscope which may represent the $\alpha \rightleftarrows \varepsilon$ transformation as recorded in meteorites shocked between 100 and 200 kb [fig. 3b in (*11*)]. Electron micrographs of the latter show a fine granular structure with a tendency toward a "woven cloth" appearance.

Shock-induced thermal effects are manifested in the microbreccia and fines by spherules and angular fragments of glass of variable composition. In addition, many of the spherules and angular fragments show the development of quench crystals, which are typically skeletal or dendritic and are enclosed in a matrix of glass or devitrified glass. Finally, less common are fragments of partly melted pyroxene and plagioclase enclosed in brown and colorless vesiculated glass, respectively.

Although the crystalline igneous rocks show little or no effect of shock, selected mineral fragments in the microbreccia and fines show shock-induced structural damage and shock-induced thermal effects. These phenomena suggest that the Apollo 11 rocks were subjected to relatively weak to moderate shocks with associated peak pressures of the order of 100 to 200 kb.

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Cathodoluminescence Properties of Lunar Rocks

Abstract. *Calcic plagioclase is the dominant luminescent mineral in crystalline rocks and breccias. Minor amounts of cristobalite and tridymite are also luminescent, as are trace grains of potassium feldspar. Two types of intergrowths of potassium feldspar with a silica phase, possibly quartz, were found in the breccias. Luminescence spectra of plagioclase show significant similarities to, and differences from, spectra of terrestrial plagioclase. Shock damage in the breccias is reflected in systematic changes in the plagioclase spectra, thus giving evidence of disordering on the angstrom scale. Associated extinction patterns seen between crossed Nicol prisms give evidence of disordering on the micrometer scale.*

Luminescence petrography, the microscopic study of rock luminescence in thin section, is a significant extension of petrographic technique. Studies of terrestrial rocks have shown that this technique can provide information unobtainable by any other method (*1*). By means of auxiliary equipment one can measure the spectra of luminescing regions as small as 40 μm in diameter. Such measurements are important in the work reported here.

Crystalline rocks. The crystalline igneous rocks studied (samples 10020 and 10045) are intermediate in grain size between rocks of types A and B (*2*). Both specimens are similar and contain cristobalite and olivine. The dominant luminescent mineral is calcic plagioclase which has an abundance of $\approx$ 25 percent. Its luminescence is blue to yellowish-blue. Cristobalite ($\approx$ 1 percent abundance) emits blue luminescence and, like terrestrial quartz, shows development of red-emitting luminescence centers under electron bombardment. Tridymite ($\ll$1 percent abundance) is disseminated throughout as pink luminescing crystals 10 to 50 μm in diameter and is often closely associated with plagioclase. Pyroxene ($\approx$ 45 percent abundance), olivine ($\approx$ 5 percent abundance), and several unidentified iron-bearing trace minerals are nonluminescent, as are terrestrial mafic minerals containing more than a few percent iron. Apatite and zircon, although brightly luminescent in terrestrial rocks, were not found.

The plagioclase luminescence shows a range of intensity and color. Central regions of many laths are more yellow and more intensely luminescent than peripheral regions. Some small plagio-

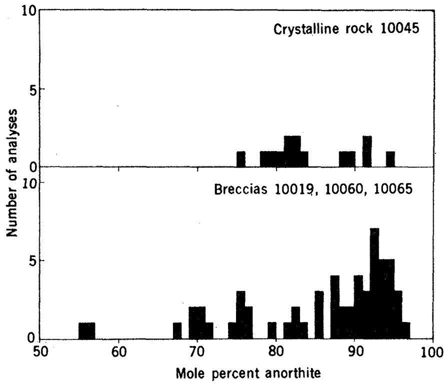

Fig. 1. Summary of data from microprobe analysis of calcic plagioclase. Selection was not strictly random. The crystalline rock specimens range from An_{89} to An_{97} in bright luminescing regions, grading to An_{75} in dull rims or grains. The low values of anorthite (An_{56}) in breccias were found in lithic fragments. The dominant range of compositions is very similar in crystalline rocks and breccias.

clase crystals show dull luminescence only, like the rims of larger laths. Microprobe analysis shows that the zoning of luminescence correlates with normal compositional zoning. The brightest luminescing central regions are calcium-rich [$\approx An_{95}$ (95 mole percent anorthite)], and the amount of Ca diminishes to An_{75} in the dullest rims or grains (Fig. 1). This suggests preferential partitioning of activator ions in the crystalline phase so that they become impoverished in the melt as crystallization proceeds.

Terrestrial feldspar specimens from diverse localities show a wide range of luminescence color, although the spectra of such specimens show a surprising degree of regularity. Virtually all of the varied color effects are the result of the presence or absence of, and the relative intensities of, three broad peaks which are characteristic of the spectra of terrestrial feldspar. The luminescence spectrum of a terrestrial plagioclase An_{85}, where all three peaks are well developed, is shown in Fig. 2A. To facilitate comparisons with lunar specimens, experience with a suite of terrestrial feldspars will be briefly summarized.

Luminescence spectra of 47 diverse terrestrial feldspars were measured. Composition as determined by microprobe analysis shows 20 of them to be alkali feldspar, 20 to be plagioclase, and 6 to be approximately albite; one of them has mixed composition (calcic alkali). The relative intensity of the three peaks varies widely among specimens and suggests that three distinct luminescence centers are involved. The green peak ($\approx$ 5590 Å) does not appear in the spectra of alkali feldspar but is present in the 16 plagioclase spectra where anorthite exceeds 11 mole percent. It probably results from a divalent activator ion proxying for calcium in the plagioclase structure. The position of the green peak is not sensitive to composition within the plagioclase series. The blue peak ($\approx$ 4500 Å) shows some variability in position and shape. Neither feature correlates with composition, and the causes are unknown. In some cases more than one luminescence center may be involved in the blue emission. In any case, a definite blue emission band is found in 45 of the 47 specimens. The two exceptions are both alkali feldspar. The position of the red-infrared peak ($\approx$ 7100 Å) is somewhat sensitive to composition. It shows a range of about 300 Å and correlates roughly with the mole percent albite without regard to whether the feldspar is calcic or potassic. The red-infrared peak of alkali feldspar is usually less intense than that of plagioclase. Potassium-rich specimens usually exhibit a broad blue peak and a small but definitely observable red-infrared peak. In three cases alkali feldspar shows no red-infrared peak at all. In the other 44 specimens the red peak is clearly present.

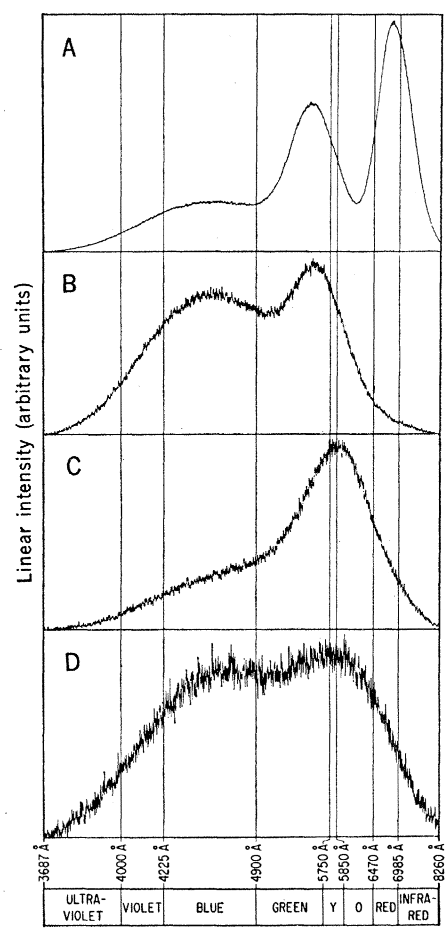

Fig. 2. Raw spectra for comparison. (A) Terrestrial plagioclase An_{85}. (B) Lunar crystalline rock plagioclase. The red-infrared peak is absent. (C) Plagioclase grain from lunar breccia showing intermediate degree of shock damage. The green plagioclase peak is shifted and broadened. The luminescence of this specimen appears orange. (D) Maskelynite grain; note the nonlinear abscissa. Correction of the spectra for phototube spectral response and for monochromator resolution will increase the shifts evident in C and D.

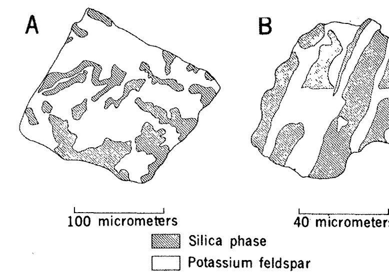

Fig. 3. Two types of intergrowth between potash feldspar and silica phases, possibly quartz. (A) Pink luminescing silica; (B) dully luminescent silica.

A typical spectrum of plagioclase from lunar crystalline rock is shown in Fig. 2B. The blue and green peaks are present, but the red-infrared peak is missing. The spectra of over 100 grains of plagioclase have been measured in lunar crystalline rocks and breccias, and no evidence of a red-infrared peak was found in any of them. The reason is not known.

Luminescence petrography of the crystalline rocks showed no evidence of complex or inverted zoning, nor was there any evidence of secondary hydrothermal or aqueous mineralization.

Breccias. Breccias studied (samples 10019, 10060, 10065) consist of fragments of minerals, rocks, and glass of several types (*2*). Lithic fragments are abundant. In sample 10060 we identified 50 fragments between 0.2 and 2 mm in size. Constituent grain sizes of lithic fragments vary from a few micrometers in aphanitic clasts to 1-mm phenocrysts, but most fall between 0.02 and 0.2 mm. Monomineralic fragments are less than 0.6 mm in size and cover a range of 0.01 to 0.6 mm. The lithic fragments, some of which are well rounded, are generally basaltic. Fragments recognizable as clasts of lunar crystalline igneous rocks are common, but the lithic fragments appear to encompass a somewhat wider range of basaltic rock types than the crystalline specimens available for study. For example, some are porphyritic and others have felty textures. In some the plagioclase is anhedral. The modal composition is also more variable than in the crystalline rocks. Plagioclase is dominant in some fragments, and opaques are rare. Some clasts appear to be breccia fragments but are composed mainly of plagioclase, whereas opaques and mafic minerals constitute only about 10 percent. Some fragments contain plagioclase as sodic as Ab_{44}.

The dominant luminescent phase both in lithic fragments and mineral grains is calcic plagioclase, and most fragments are similar in composition to plagioclase in the crystalline rocks (Fig. 1). Luminescent tridymite and cristobalite are also present, whereas luminescent apatite and zircon are not.

The crystalline igneous rocks and closely associated rock types are probably the source of most of the clastic and glassy fragments found in the breccias. However, the breccias may also contain grains or fragments from a distant source. Considerable effort was expended in a search for alkali feldspar.

Two distinct types of alkali feldspar were found. Both consist of intergrowths on a fine scale between potassium feldspar and a silica phase, possibly quartz (Fig. 3). Careful microprobe analysis indicated that the potassium feldspar composition in each type was stoichiometric. One type (Fig. 3A) has pink luminescing silica similar in color to that of the tridymite of the crystalline rocks. Several grains of this type were found. The second type (Fig. 3B) has a nonluminescent or a dully luminescent silica phase, and only one such grain was found in three thin sections of breccia. Both show spectra typical of potassium feldspar. Because such intergrowths are common in terrestrial acidic rocks, it is tempting to speculate that similar rocks exist on the moon. The argument is equivocal at best, however, because such intergrowths do point to differentiation but say nothing about the scale.

Numerous isotropic or weakly birefringent grains of stoichiometric plagioclase composition were found in the breccia. Most show dull reddish luminescence. We interpret these to be maskelynite, that is, plagioclase disordered by shock waves. Single grains showing both birefringence and normal plagioclase luminescence on one end, and isotropism and dull reddish luminescence on the other, were found. The reddish luminescence results from both shifting of the green peak toward longer wavelengths and broadening of the peak. This results in increased relative red emission (Fig. 2D). Intermediate degrees of disordering are reflected in

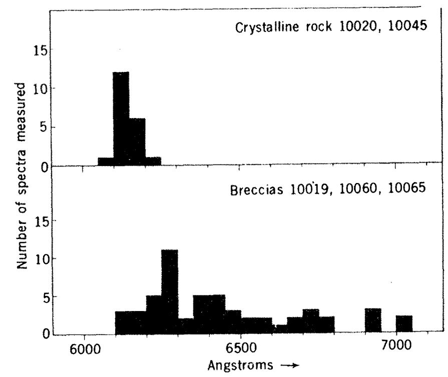

Fig. 4. Distribution of upper half intensity points of plagioclase spectra. Maxima were taken from the green to the yellow peak.

the luminescence spectra. Something extraordinary is affecting the spectra of plagioclase in the breccias, as can be readily seen from the following comparisons. Average positions of the green peaks were calculated for 16 samples of terrestrial plagioclase, 21 plagioclase grains from the lunar crystalline igneous rocks, and 48 plagioclase grains from lunar breccias. The average values and extremes are: 5590^{+120}_{-65} Å, 5590^{+160}_{-65} Å, and 5735^{+495}_{-230} Å. Notice not only the extraordinary average value for the breccias but also the increased breccias which just permits overlap. Both shifts and broadening can be reflected by plotting the upper half intensity position (Fig. 4). This graphically shows that a continuous range of effects is involved in plagioclase from the breccia, a result in stark contrast with the plagioclase of the crystalline rocks. Correction of the raw spectra will enhance the result. Grains that show intermediate degrees of disordering (Fig. 2C) may appear yellow or orange in luminescence and frequently show mosaic extinction patterns when viewed between crossed Nicol prisms. Similar phenomena have been reported in shock-damaged specimens, but such features in and of themselves might not be sufficient evidence to support the interpretation of shock damage (*3*). Strangely, the breccia specimens studied show very little of the fracturing and lamellar and planar features diagnostic of shock damage (*4*). This same observation was made by Short for experimentally shock-lithified sand (*5*). The association of evidence of disordering on the micrometer scale, as shown by the mosaic extinction patterns, and evidence for disordering on the angstrom scale, as shown by luminescence, strengthens our conclusion that these features result from shock damage.

Our interpretation of peak shifts, peak broadening, and decrease of luminescence intensity with lattice disordering is consistent with the general theory of solids. Luminescence spectra depend in part on the nature of the luminescence center but also on the nature of the solid because excited states are displaced in energy by the crystal field of the solid. Disorder in the crystal lattice results in crystal field perturbations. Local variations in the crystal field result in an altered or broadened distribution of excited-state energies. Anisotropic distortions in the crystal field might produce peak shifts, whereas isotropic disordering would certainly lead to broadened emission bands. Nonradiative transitions would also tend to become more probable as order decreases.

In addition to the above process, for which evidence is ubiquitous, some grains suggest the production of luminescence centers by shock damage. These show enhanced luminescence in the blue end, and reduced intensity in the red end, of the spectrum. Enhancement of luminescence in the blue end of the spectrum has also been observed in shocked anorthosite from Manicouagan, Canada (*6*), and has been qualitatively observed in quartz in a graded suite of shock-damaged specimens (*7*).

On the whole, the breccias seem to attest to the actuality of the process postulated by Short: the initial comminution of consolidated rocks by meteorite impacts and subsequent shock lithification of the rubble so produced (*5*). In contrast, the crystalline igneous rocks studied showed no evidence of shock damage.

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