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Luminescence petrography and properties of lunar crystalline rocks and breccias

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Abstract—Calcic plagioclase is the dominant luminescent mineral in crystalline rocks and breccias Spectral analysis shows two broad emission bands centered at 4500 Å and 5590 Å. These blue and green bands are commonly found in terrestrial plagioclase spectra, but a red–infrared band ~7300 Å which is found in terrestrial specimens almost without exception is absent in the spectra of lunar plagioclase.

Shock metamorphism in the breccias is reflected by systematic changes in the plagioclase spectra. It results in spectral shifts of the green peak toward the red, accompanied by intensity reduction at all wavelengths. The effects correlate with degree of shock damage. Maskelynite emits dull red luminescence while less severely altered grains emit yellow or orange luminescence. In some instances shock effects can also produce intensified emission at short wavelengths. These luminescence phenomena give evidence of lattice distortions and disordering on the angstrom scale. They are frequently associated with extinction patterns evidencing disorder on the micron scale.

Luminescence zoning in the crystalline rocks correlates well with normal compositional zoning (An_{75}–An_{95}). Luminescent cristobalite and tridymite are found in crystalline rocks and breccias.

Two types of intergrowth of alkali feldspar with silica phases, possibly quartz, were also found in the breccias. These indicate differentiation, but of uncertain scale.

None of the samples showed any evidence of secondary aqueous mineralization.

1. INTRODUCTION

LUMINESCENCE petrography, the microscopic study of rock luminescence in thin section, is a significant extension of petrographic technique. The luminescence is induced by bombardment with kilovolt electrons in a specialized device. Studies of terrestrial rocks have shown that the method can provide information otherwise unobtainable. For example, aqueous mineralization can frequently be recognized as such by growth banding structures visible only in luminescence (LONG and AGRELL, 1965; SIPPEL and GLOVER, 1965). Generations of mineralization can often be determined where different physico-chemical conditions of formation result in differing luminescence properties. For example, igneous quartz and feldspar are invariably luminescent, but the same minerals, formed by a low-temperature aqueous process, are generally non-luminescent (SMITH and STENSTROM, 1965; SIPPEL, 1968). Delicate details of original structure may be preserved in recrystallized rock by the luminescence distribution, although they are not observable by ordinary microscopy (SMITH and STENSTROM, 1965; SIPPEL and GLOVER, 1965). Radiation damage (SMITH and STENSTROM, 1965) and shock metamorphism (this paper) leave their imprint on the luminescence properties of minerals. Since the luminescence phenomena frequently provide these and other clues to petrogenesis, not otherwise obtainable, it is appropriate to apply the technique to the lunar specimens.

Thus far the approach of luminescence petrography has been purely phenomenological, and interpretation has been aided only by the general theory of luminescence.

The detailed causes of luminescence in specific natural minerals have been little studied, and except for a few examples are unknown. The activators, or defect centers, which theory and experience suggest are responsible, may be present only in parts per million. At these concentrations, natural minerals contain many chemical species. They are also structurally complex. As systems for detailed study they therefore have little attraction, and the main thrust of luminescence research has been directed toward understanding alkali halide and other pure systems. A more complete understanding of luminescence in natural minerals is inevitable and will certainly increase the power of luminescence petrography.

2. Instrumentation and Data Reduction

The luminescence petrography equipment used in this study has been described by Sippel (1965) though several improvements have subsequently been made. The instrument now in use is built around a Zeiss petrographic microscope, and many convenience features have been added. The power supply utilizes the principal of voltage doubling and produces controlled d.c. voltages up to 25 kV. An electromagnetic lens has been incorporated permitting the electron beam to be constricted a factor of ten in diameter, thus producing an intensity increase approaching 100 for the examination of dull luminescing features.

Equipment has been added which permits spectral measurements covering a range of 3700–8200 Å. This consists of a quartz prism monochrometer, E.M.I. 9558Q photomultiplier tube, photometer, and *x–y* plotter. Special apertures make it possible to limit the electron beam to any desired diameter from one centimeter to 40 μ. Sensitivity of the phototube–photometer combination is such that good quality luminescence spectra can be obtained from all but the dullest luminescing specimens using the 40-μ aperture. Therefore, individual mineral grains 40 μ or larger can be excited and their luminescence spectra measured without contamination by light from adjacent minerals. Luminescence zonation in larger grains can also be studied with a 40-μ spatial resolution. The system has been calibrated using standard emission lines from mercury, argon, helium, and neon gas discharge sources. Using narrow slit settings, sharp lines can be measured with resolution as good as 50 Å full width at half maximum (F.W.H.M.). Emission bands in natural minerals are much broader than this, except in rare cases, and settings of 200–300 Å F.W.H.M. can be used with negligible resolution loss. Replication precision is excellent and narrow line positions can be repeated within 25 Å.

The spectra in the figures are reproduced exactly as obtained and should be corrected. The preferred method would be absolute calibration with a thermopile. Deadlines did not permit this. The two main corrections are for the spectral response of the phototube (type S-20) and for the bandwidth of the monochrometer. A theoretical and probably adequate correction factor is $1/(\text{B.W.} \times \text{Q.E.} \times \lambda)$ where B.W. is monochrometer band width, Q.E. is the quantum efficiency of the phototube and λ is the wavelength. For the convenience of the reader, a collection of data and correction factors is shown in Table 1. The correction factors are arbitrarily normalized to unity at 5000 Å. The spectral data presented in this paper will ordinarily require correction only toward the red end of the spectrum.

Table 1. Data for correction of spectra

λ(Å)	B.W.	Q.E.	Corr. factor
3700	2·5	20	2·35
4000	3·2	20	1·70
4500	4·6	19	1·11
5000	5·8	15	1·0
5500	7	10·5	1·08
6000	8·3	7·5	1·16
6500	9·1	4·5	1·64
7000	10	2·5	2·48
7500	10·5	1·2	4·61
8000	11	0·6	8·24

The microprobe analyses of feldspar reported in this paper were all made with an Applied Research Laboratory A.M.X. microprobe. In the analysis of feldspar five elements are measured: Al, Si, K, Ca and Na. Oxygen concentration is assigned on the assumption of stoichiometry. Atomic number and absorption corrections for each of the five elements follow standard proceedures, but are built into a specialized feldspar analysis computer program of our own design. Corrections are applied in three iterations and the resulting corrected concentrations are fitted by least squares to a linear combination of the three end members, albite, anorthite and potassium feldspar (Ab, An, Or). The procedure provides the molecular percentage of each end member. In addition, several parameters are computed by which the true stoichiometry of the feldspar and the quality of the data may be judged. These are FTEST, MIN and TOTAL. FTEST is the sum of aluminum and silicon atoms divided by the sum of potassium, sodium and calcium atoms, and should equal 4·0 for any ordinary feldspar. MIN is the sum of the squares of the deviations of the corrected elemental concentrations from those implied by the least squares determined molecular composition. TOTAL is the sum of the corrected elemental concentrations. All feldspar analyses reported here have TOTAL $= 1{\cdot}0 \pm 0{\cdot}03$, FTEST $= 4{\cdot}0 \pm 0{\cdot}25$ and MIN $< 3{\cdot}0 \times 10^{-4}$, although most of the data are considerably better in all three respects. MIN values of 10^{-5} are most common and 10^{-6} or 10^{-7} are not rare. Seventy per cent of all analyses reported total 100 per cent within ±1 per cent.

3. LUNAR ROCKS—LUMINESCENCE PETROGRAPHY AND GENERAL DESCRIPTION

The crystalline igneous rocks studied (10020 and 10045) are intermediate between types A and B in grain size (LSPET 1969). The specimens are much alike and both contain cristobalite and olivine. Their texture is sub-ophitic. The dominant luminescent mineral is calcic plagioclase ~25 per cent abundant. Its luminescence is blue to yellowish blue. Cristobalite ~1 per cent abundant emits blue luminescence and like terrestrial quartz its luminescence color changes with extended electron bombardment. SMITH and STENSTROM (1965) first reported the effect in quartz, describing it as a shift in the emission color from blue toward red under electron bombardment. Our spectral measurements show that terrestrial quartz usually has two broad emission bands, one peaking at about 4500 Å and one at about 6650 Å. Upon first bombardment of a fresh specimen the blue band is usually dominant, but under extended electron bombardment the intensity of the blue band decreases and the intensity of the red band increases, finally reaching a saturation value. Increases of a factor of 10 for the intensity of the red band have been observed, accompanied by a factor of three decrease in the blue band. These changes occurred during a 45-min bombardment so that the visual effect is a gradual but definite shift from blue to red emission. Increasing the intensity of bombardment accelerates the rate not the kind of change. The effects are permanent, at least on a time scale of a few months. The lunar cristobalite appears to show the same effect. Tridymite $\leqslant 1$ per cent abundant is disseminated throughout the crystalline rock as pink luminescing 10–50 μ crystals, and is often closely associated with cristobalite or plagioclase. Pyroxene $\sim$45%, olivine $\sim$5%, opaque phases $\sim$22% abundant and several unidentified iron bearing trace minerals are non-luminescent. The same is invariably true of terrestrial mafic minerals that contain more than a few per cent iron. Apatite and zircon, although common and brightly luminescent in terrestrial basalts, 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 plagioclase crystals show dull luminescence only, like the rims of larger laths. Some intensity variation always results from the fact that the luminescence from plagioclase is partially polarized, and is therefore anisotropically emitted. Variations in crystallographic orientation from grain to grain thus result in modest intensity variations. The lunar plagioclase, however, has a greater range of intensity than can be explained in this way, and microprobe analysis shows that the zoning of luminescence correlates with normal compositional zoning. The brightest luminescing central regions are calcium rich ($\sim$An$_{89-95}$) grading to An$_{75}$ in the dullest rims or grains. This suggests preferential partitioning of activator ions in the crystalline phase so that they become impoverished in the melt as crystallization proceeds.

Luminescence petrography of the crystalline rocks shows no evidence of complex or inverted zoning, nor any evidence of secondary hydrothermal or aqueous mineralization. All factors point to formation of the crystalline rocks by simple freezing of a basaltic melt, in which turbulence was slight and water played a negligible role.

The breccias studied (10019, 10060, 10065) consist of fragments of minerals, rocks, and several types of glass (LSPET, 1969). Lithic fragments are abundant. (In one thin section of sample #60 there are about fifty in the size range 0·2–2 mm.) Constituent grain sizes of lithic fragments vary from a few microns in aphanitic clasts to 1 mm phenocrysts in porphyritic fragments but most fall between 0·02–0·2 mm. Monomineralic fragments range from 0·01 to 0·6 mm. The lithic fragments, some of which are well rounded, are generally basaltic. Fragments of rocks apparently identical to the crystalline igneous specimens are common, but the lithic fragments in the breccias 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. Some carry xenomorphic plagioclase. The modal compositions are also more variable. Plagioclase is dominant in some fragments, and opaques are essentially nil. Some appear to be breccia fragments, but are composed mainly of plagioclase, with opaques and mafics constituting only about 10 per cent. Finally some contain plagioclase as sodic as Ab$_{44}$.

The dominant luminescent phase, both in lithic fragments and mineral grains, is calcic plagioclase, and most is similar in composition to plagioclase in the crystalline rocks, Fig. 1. The luminescence of many plagioclase grains in the breccias is similar to that in the crystalline rocks, although some show anomalous orange luminescence. The significance of this will be discussed in a later section. Luminescent tridymite and cristobalite are also present and show properties identical to those evident in the crystalline rocks. Apatite and zircon are apparently absent.

Alkali feldspar–silica intergrowths of two distinct types were found in the breccias. The first type, Fig. 2A, contains a silica phase that displays pink luminescence similar to the tridymite. The feldspar has composition Ab 28, An 0, Or 72 and FTEST = 3·76, MIN = 3×10^{-5}, TOTAL = 100·9. This feldspar emits a pure blue luminescence frequently found in terrestrial sanidine. The birefringence is lower than normal, probably the result of shock damage. It is not possible to identify the silica phase with certainty, but because of its luminescence properties it may be tridymite. Several grains, of this type, were found in the breccias. The second type of intergrowth, Fig. 2B, has a dull blue luminescent or non-luminescent silica phase, possibly quartz. The feldspar shows a whitish-blue luminescence like that frequently seen in terrestrial microcline or orthoclase. Composition from microprobe analysis is Ab 15, An 0, Or 85 with FTEST = 4·16, MIN = 2×10^{-4} and TOTAL = 100·1. Both phases show no apparent birefringence, but observations with the universal stage verify that both phases have definite though reduced birefringence. Only one grain of this type could be found in three thin sections of breccia. Because such intergrowths are

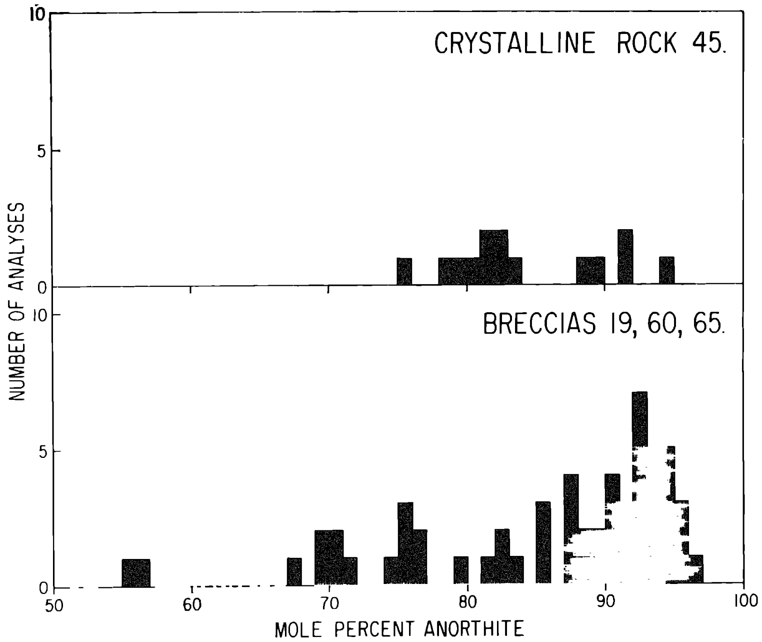

Fig. 1. Summary of data from microprobe analysis of calcic plagioclase. Selection was not strictly random. The crystalline rock specimens range fron An_{89} to An_{95} in bright luminescing regions grading to An_{75} in dull rims or grains. The low values An_{56} in breccias were found in unzoned plagioclase in a lithic fragment. Dominant range of compositions is very similar in crystalline rocks and breccias.

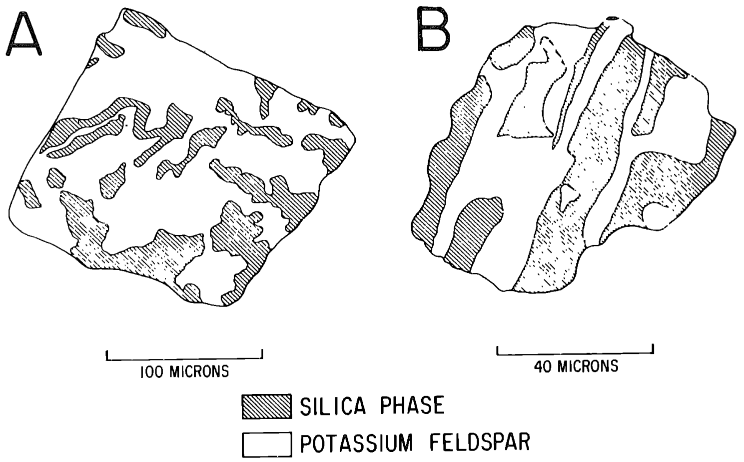

Fig. 2. Two types of intergrowth between potash feldspar and silica phases possibly quartz. (A) shows pink luminescing silica and (B) shows dully luminescent silica. See text Section 3 for more details.

common in terrestrial acidic rocks, it is tempting to speculate that acidic rock bodies exist on the moon. The suggestion is, however, tenuous for although such intergrowths indicate differentiation, they say nothing about the scale of differentation.

The breccias also contain much glass of diverse types. Spheres, shards, grains, glass bound mineral fragments and partially vitrified lithic fragments are present. Most of this glass is iron rich and non-luminescent.

There are, however, numerous isotropic or weakly birefringent grains that show dull reddish luminescence. Microprobe analysis shows these grains to possess stoichiometric plagioclase composition. Many of them are stoichiometric to a high degree. One, for example, shows composition $\mathrm{Ab}_{8\cdot3}$, $\mathrm{An}_{90\cdot7}$, $\mathrm{Or}_{0\cdot9}$ with MIN = 4×10^{-6}, FTEST = 4·02 and TOTAL = 99·7 per cent. We interpret these to be maskelynite, plagioclase disordered by shock waves. Apparently the luminescence is strongly altered in the process. This and the extraordinary extinction patterns which many breccia grains display will be discussed further in a later section.

4. SPECTRA OF TERRESTRIAL FELDSPAR

In order to provide a framework for comparison with the spectral properties of lunar feldspar luminescence, it is necessary to briefly summarize the luminescence properties of terrestrial feldspar. A considerable body of experience has been accumulated but has not yet been published. Results from a diverse group of 47 terrestrial feldspar samples will be summarized, though this is by no means the limit of our experience. The 47 samples* were selected because concurrent microprobe analyses are available. Feldspars from diverse localities and various rock types show a wide range of luminescence colors although the spectra of such specimens are surprisingly regular. Virtually all of the varied color effects can be understood in terms of the presence of, and the relative intensities of, three broad peaks which are characteristic

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* This suite consists of mineral collection feldspars from 8 states and 5 foreign countries. Also included were granites, pegmatites, charnockite, troctolite and diallage gabbro.

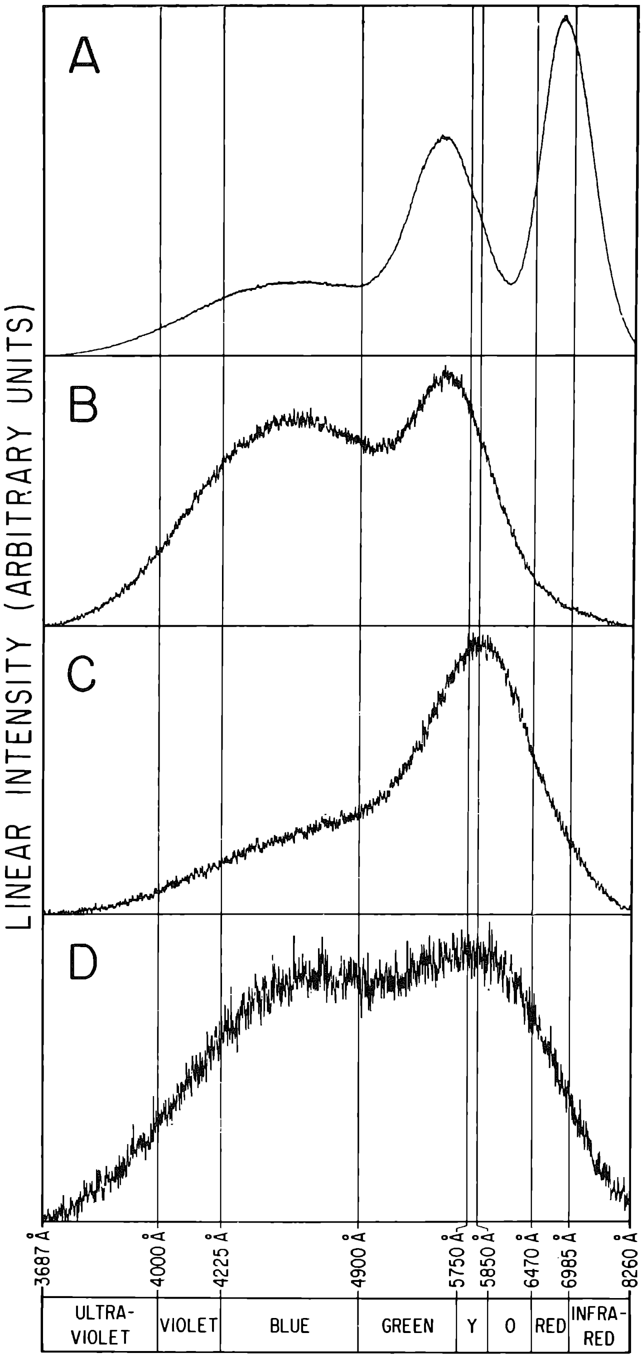

Fig. 3. Spectra for comparison. (A) Terrestrial plagioclase An_{85}. (B) Lunar crystalline rock plagioclase. Note absence of red–infrared peak. (C) Plagioclase grain from lunar breccia showing intermediate degree of shock damage. Note shift and broadening of the green plagioclase peak. The luminescence of this specimen appears orange. (D) maskelynite grain: Note non-linear abcissa. (Spectra should be corrected as discussed in Section 2 of the text.)

of terrestrial feldspar spectra. Figure 3A shows a spectrum of terrestrial plagioclase where all three peaks are well developed. Relative intensity of the three peaks varies widely among specimens. This accounts for the variable color, and suggests that three distinct luminescence centers are involved.

Of the 47 feldspar specimens, microprobe analysis shows 20 of them to be alkali feldspar, 20 plagioclase, 6 approximately albite, and one of mixed calcic-alkali composition. The green peak (~5590 Å) does not appear in the spectra of alkali feldspar, but is present in each of the sixteen plagioclase spectra where mole per cent anorthite exceeds 11 per cent. It probably results from a divalent activator ion substituting for calcium in the plagioclase structure. The position of the green peak is not sensitive to composition within the plagioclase series and spectrum corrections do not result in any appreciable change in the peak position. The blue peak (~4500 Å) shows some variability from specimen to specimen in peak position and in shape. This variability does not correlate with composition, and its cause is 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 red–infrared peak (~6850 Å) in the uncorrected spectrum shown in Fig. 3A falls in the region where correction is important. The peak actually occurs at about 7050 Å when corrected. The red–infrared peak is modestly sensitive to composition. It shows a range of about 400 Å and its position correlates roughly with mole per cent 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 band 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–infrared peak is clearly present. The mean position is about 7300 Å corrected.

5. COMPARISON OF LUNAR AND TERRESTRIAL FELDSPAR SPECTRA

A typical spectrum of plagioclase from the lunar crystalline rock is shown in Fig. 3B. The blue and green peaks are present, but the red–infrared peak is entirely missing. The spectra of more than one hundred 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. This is anomalous because in our suite of terrestrial rocks all 20 plagioclase specimens show a red–infrared peak. In a further test performed since the first lunar science conference, spectra of feldspar were measured in an additional suite of 11 terrestrial basalts.* All spectra show a well defined red–infrared peak.

The luminescence spectra of the plagioclase of rocks from Tranquillity Base thus appear to be, at the least, unusual. The full significance of this observation cannot be adduced, because a detailed understanding of the luminescence center involved is lacking. Certainly it must relate to the unique chemical composition of the lunar magma. Apparently an activator was lacking in the environment of crystallization.

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* This group consisted of continental basalts and diabases from New York, Nicaragua, Oklahoma, Ethiopia and Washington. Eocene, Miocene, Quaternary, and Precambrian ages were represented.

On the other hand, the activator appears to be ubiquitous in diverse terrestrial environments. One cannot help but wonder whether water may not in some way be the missing substance. Speculation is pointless until additional information is obtained.

As already mentioned, maskelynite grains in the breccias emit a dull reddish luminescence. Examination of the spectra of such specimens (Fig. 3D)* suggests that this results from shifting and broadening of the green plagioclase peak. This is strengthened by the fact that luminescence spectra of birefringent plagioclase in the breccia provide examples of intermediate degrees of shift and broadening. The spectrum of one such grain which emits orange luminescence is given in Fig. 3C.†

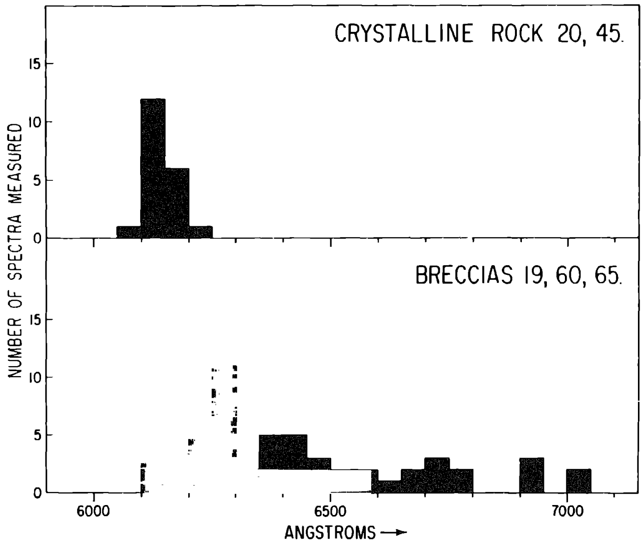

Fig. 4. Distribution of upper half intensity points of plagioclase spectra (computed from uncorrected spectra. Correction will materially enhance the effect shown here).

One may verify that something extraordinary is affecting the spectra of plagioclase in the breccias by the following comparisons. Average peak positions for the longer wavelength band were calculated for 16 samples of terrestrial plagioclase, for 21 plagioclase grains from the lunar crystalline igneous rock and for 48 plagioclase grains from lunar breccias. The average values and extremes are:

$$5590 \begin{matrix} +120 \\ -65 \end{matrix} \text{Å} \qquad 5590 \begin{matrix} +160 \\ -65 \end{matrix} \text{Å} \qquad 5735 \begin{matrix} +495 \\ -230 \end{matrix} \text{Å}.$$

Notice not only the extraordinary average value for the breccias but also the increased range which just permits overlap. To give a better idea of the range of effects involved, we may take advantage of the absence of the red–infrared peak and plot the distribution of upper half power points for the crystalline rocks and breccias, Fig. 4. It forcefully demonstrates that a continuous range of effects is involved, and provides a stark contrast between the two rock types. Actually the contrast between

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* Correction of this spectrum results in elevation of the red end and shows the peak actually to fall close to the red. The shift involved on correction amounts to about 500 Å, from the apparent 5810 Å to a corrected 6310 Å.

† Correction here moves the peak from 5850 Å to 6140 Å to the center of the orange.

the rock types and the magnitude of the shifts in the breccias would be considerably increased if the upper half power points were computed from corrected spectra. The breccia plagioclase is characterized by a continuous range of spectral shifts where the maximum shift is shown by maskelynite.

6. SIGNIFICANCE OF THE SPECTRAL SHIFTS—IMPACT METAMORPHISM

We interpret the spectral shifts in breccia plagioclase to reflect a continuous range of impact metamorphism. The degree of shock damage is no doubt related in a general way to the magnitude of spectral shifts, because the greatest shifts are found in isotropized plagioclase, and unshifted spectra are associated with plagioclase of normal birefringence. Intermediate shifts are commonly associated with other evidences of shock damage, particularly mosaic extinction patterns in larger grains. The breccia samples studied show very few of the classical lamellar and planar features diagnostic of shock damage (CHAO, 1967; BUNCH *et al.*, 1968). SHORT (1966a) found very few of these features in experimentally shock lithified sand. This he attributed to insufficient shock loading, but perhaps these features are formed less readily in disaggregated material.

The most plentiful, and probably the next best evidence of shock damage, after the maskelynite, are grains having mosaic extinction. These extraordinary features have been described in the literature, and attributed to shock damage (DACHILLE *et al.*, 1964; SHORT, 1966). Apparently the crystal lattice has been reorganized into smaller mosaic regions without destroying the original morphology. Birefringence is apparently reduced in the mosaic blocks, although this is difficult to assess in some cases. Internal fragmentation, the expression of QUADE and BUNCH (1970), seems an apt description. These same authors have produced similar features by experimental shock loading, and assert that the size of the mosaic blocks is indicative of the degree of shock loading. There is, therefore, no doubt that shock damage can and does produce such features. Whether any other mechanisms can produce them is less clear. For example, it is possible that devitrification may account for some of the textures seen in the breccias. One grain having mosaic texture is non-stoichiometric but of approximate plagioclase composition with about 5 wt.% magnesium, which the microprobe indicates is uniformly distributed. It is significant that breccia plagioclase grains which show mosaic extinction invariably also show spectral shifts. Many of these appear yellow or orange in luminescence. Figure 3C is the spectrum of a grain showing mosaic extinction. Spectral shifts are also evident in many grains showing no mosaic texture. Occasional small grains emit in the orange, and have the luminescence appearance of terrestrial apatite.

Grains were found showing both birefringence and normal plagioclase luminescence on one end, and isotropism and dull red luminescence on the other. Spectra measured at opposite ends of such a grain about 125 μ long is given in Fig. 5. The spectra were taken under identical conditions so the relative intensities are significant, although the brighter luminescing portion has no doubt suffered intensity reduction also. We see that there is a general reduction of luminescence intensity at all wavelengths. The green peak of the birefringent part of the grain has undergone a considerable shift also. There is a compositional difference between the ends of this grain. The isotropic end shows very good plagioclase stoichiometry and about 91 per cent anorthite. The birefringent end shows about 86 per cent anorthite and considerably poorer stoichiometry. Perhaps chemical zonation has affected the shock resistance of the two portions of this grain. The whole question of whether shock damage can alter the chemistry of grains or whether minor chemical variations can affect shock shock resistance is much too tedious a question to be answered at this early date.

Our interpretation of peak shifts, peak broadening and decrease of luminescence intensity with lattice disordering resulting from shock is consistent with the general theory of solids. Luminescence spectra depend in part on the nature of the luminescence centers but also on the nature of the solid containing them, because excited states are displaced in energy by the crystal field of the solid. Distortions or disorder in the crystal lattice results in crystal field perturbations. Local variations in the crystal field results in an altered or broadened distribution of excited state energies. This would reasonably be expected to lead to shifts and broadening of the emission bands. Non-radiative transitions would also tend to become more probable as order decreases, accounting for the general intensity reduction.

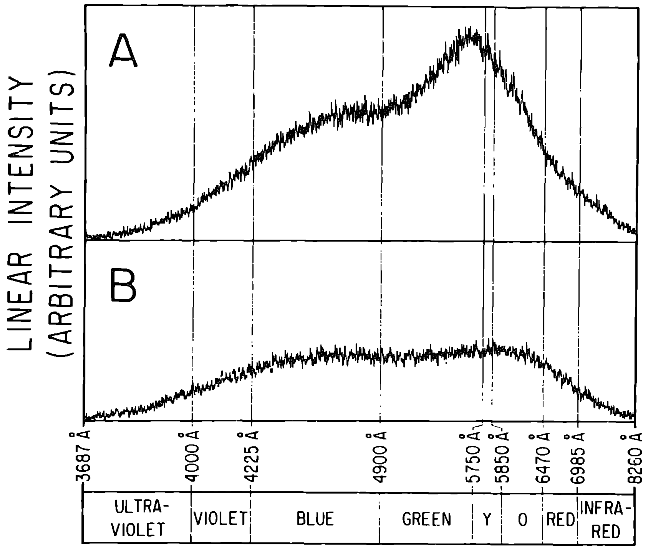

Fig. 5. Spectra measured from two sections of a single grain of shocked plagioclase. (A) Birefringent part (B) Isotropized part.

Shifts as large as those documented here must reflect large changes in the crystal field of feldspar, and must reflect significant distortions and disordering of the crystal lattice on the unit cell scale. Therefore, the luminescence shifts show that disordering on the angstrom scale is associated with disordering on the micron scale as shown by mosaic textures. The relations between birefringence, mosaic block size and luminescence spectral shifts have not been studied in sufficient detail to arrive at reliable generalizations.

A reasonable question which arises is whether an alternative mechanism might not produce the lattice disorder resulting in spectral shifts. The only apparent alternative is radiation damage and this seems unlikely on a number of grounds.

Known radiation damage effects such as the development of red emitting luminescence centers in cristobalite, and the extinction of feldspar luminescence, are not seen. Also the association of the spectral shifts with internal fragmentation and maskelynite seems to greatly favor the shock damage mechanism.

7. Another Evidence of Impact—Blue Enhancement

Evidence for spectral shifts and associated intensity reduction resulting from shock damage is widespread in the breccias. In addition, some grains show bright luminescence in the blue end and reduced intensity in the red end of the spectrum. One rounded grain of about 400 μ shows both types of shock effect. One part of the grain emits the characteristic dull red luminescence of heavily shocked plagioclase. Its spectrum approaches maskelynite although it shows definite but reduced birefringence. The other part of the grain has very low birefringence, about 0·0015, and emits an anomalous blue luminescence, Fig. 6. The two regions are separated by a complex boundary. The red luminescing region penetrates the blue luminescing region in several dendritic branches. With luminescence one can see that secondary branches have rounded bleb-like shapes. The boundary, though complex, is perfectly sharp with no graded transition zone from the red to the blue regions. Microprobe analysis shows the following:

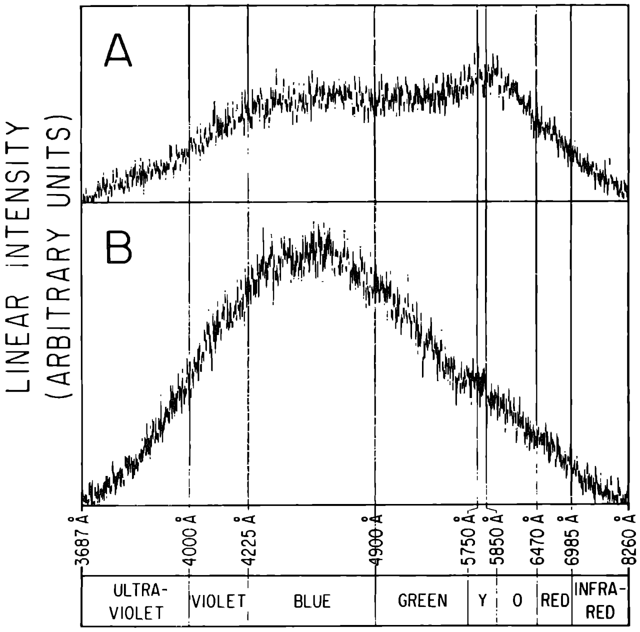

Fig. 6. Spectra measured from two sections of a single grain of shocked plagioclase. (A) Spectrum similar to maskelynite. (B) Unusual blue enhanced spectrum. The two regions are separated by a complex boundary (for other details see Section 7 of text).

Red end	$An_{92\cdot 8}$	$MIN = 2 \times 10^{-7}$	FTEST = 4·18	TOTAL = 99·6
Blue end	$An_{93\cdot 9}$	$MIN = 2 \times 10^{-7}$	FTEST = 4·09	TOTAL = 99·1.

Apparently here are two distinct aspects of shock damage in one grain of plagioclase.

Other examples of relative blue enhancement were found. One small composite grain consists of two regions, one heavily shocked plagioclase, and the other a silica phase. The plagioclase emits the usual dull red luminescence. The silica phase emits an anomalously bright blue luminescence. Similar effects have been seen in shocked quartz from a graded suite of shock damaged specimens.* This may indicate the production of blue emitting luminescence centers by shock damage.

A similar phenomenon has been observed in shocked anorthosite from the Manicouagan impact structure† in Canada. In this specimen spectra were measured from adjacent birefringent and isotropic lamellae. These spectra are shown in Fig. 7.

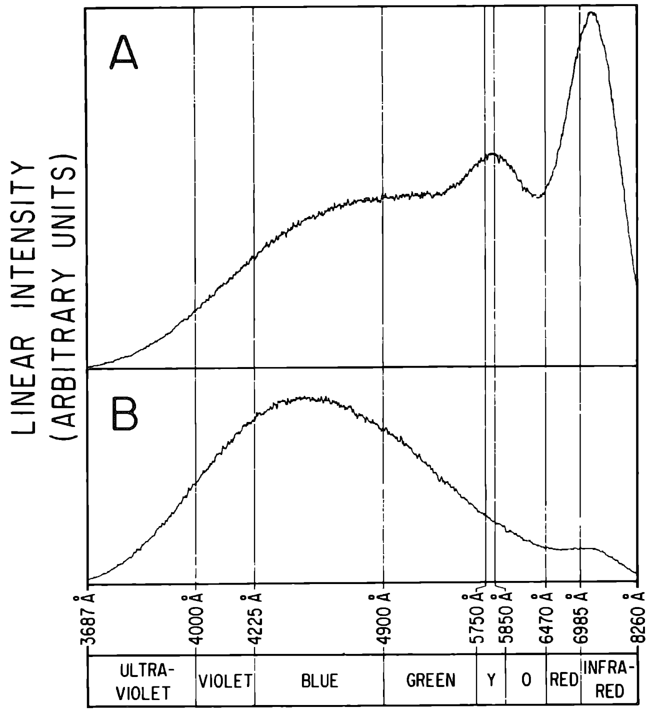

Fig. 7. Example of blue enhanced spectrum from shocked terrestrial specimen. Spectra measured from adjacent birefringent and isotropized lamellae in anorthosite from Manicouagan impact structure, Canada. (A) Birefringent lamella (B) Isotropized lamella.

Note the severely reduced intensity in the red end of the spectrum and the enhanced emission in the ultraviolet, violet, and blue. It is still uncertain whether we are seeing production of luminescence centers by shock damage. It is also possible that a unique type of lattice deformation may produce shifts resulting in the blue enhanced spectral distributions.

8. Discussion

Petrography, microprobe data and bulk chemistry all suggest that a substantial percentage of the clastic and glassy fragments found in the breccias derive from the crystalline igneous rocks and closely associated rock types. This and the conclusive

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* N. M. Short supplied these specimens showing graded shock from the Sedan nuclear explosion of July, 1962.

† The authors wish to express thanks to T. E. Bunch for supplying these specimens.

evidence of widespread shock metamorphism in the breccias and its absence in the crystalline rocks seem to support the process postulated by SHORT (1966a): the initial comminution of consolidated rocks by meteorite impact and subsequent shock lithification of the rubble so produced. Data of others now suggest that the breccias are more complex than this, and the results of geochronology raise difficult questions about the whole picture. Nature is always more interesting than our preconceptions.

With regard to the results reported in this paper, it is interesting that the lunar feldspars appear to have somewhat different luminescence spectra than their terrestrial equivalents. The absence of the red–infrared peak in the lunar plagioclase, the spectral shifts and possible production of luminescence centers from shock damage are all new phenomena. We are mindful that a more complete investigation is required, and that many implications of these phenomena remain to be explored.

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REFERENCES

BUNCH T. E., COHEN A. J. and DENCE M. R. (1968) Shock-induced structural disorder in plagioclase and quartz. In *Shock Metamorphism of Natural Materials*, (editors B. M. French and N. M. Short), Part 7, pp. 509–518. Mono Books.

CHAO E. T. C. (1967) Impact metamorphism. In *Researches in Geochemistry*, (editor P. H. Abelson), Vol. 2, pp. 204–233. John Wiley.

DACHILLE F., FAUTH J. and VAND V. (1964) Mechanical deformation of shocked quartz grains as determined by optic axis measurements. *Program Geological Society of America*, Annual Meeting, Miami Beach, (Abs.).

LONG J. V. P. and AGRELL S. O. (1965) The cathodo-luminescence of minerals in thin section. *Mineralog. Mag.* **34**, 318–326.

LSPET (LUNAR SAMPLE PRELIMINARY EXAMINATION TEAM, 1969) Preliminary examination of lunar samples from Apollo 11. *Science* **165**, 1211–1227.

QUADE W. and BUNCH T. E. (1970) Impact metamorphism of lunar surface materials at Tranquillity Base. *Geochim. Cosmochim. Acta*, Supplement I.

SHORT N. M. (1966a) Shock-lithification of unconsolidated rock materials. *Science* **154**, 382–384.

SHORT N. M. (1966b) Effects of shock pressures from a nuclear explosion on mechanical and optical properties of granodiorite. *J. Geophys. Res.* **71**, 1195–1215.

SIPPEL R. F. and GLOVER E. D. (1965) Structures in carbonate rocks made visible by luminescence petrography. *Science* **150**, 1283–1287.

SIPPEL R. F. (1965) Simple device for luminescence petrography. *Rev. Sci. Instrum.* **36**, 1556–1558.

SIPPEL R. F. (1968) Sandstone petrology, evidence from luminescence petrography. *J. Sediment. Petrol.* **38**, 530–554.

SMITH J. V. and STENSTROM R. C. (1965) Electron-excited luminescence as a petrologic tool. *J. Geol.* **73**, 627–635.