# LUMINESCENCE PETROGRAPHY OF THE APOLLO-12 ROCKS AND COMPARATIVE FEATURES IN TERRESTRIAL ROCKS AND METEORITES

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## Abstract

The Apollo-12 igneous rocks studied (12018, 21, 39, 65) are basaltic and gabbroic rocks similar to the Tranquility Base specimens although they show striking minor differences. True gabbroic grain size is found in several specimens, and these coarse-grained rocks contain abundant (3.5-4.5%) brilliantly luminescent tridymite laths up to 2 mm in length. In 12039, anhedral plagioclase is found moulded around euhedral tridymite, suggesting an unusual crystallization order. The tridymite also shows a distinctive luminescence effect related to the $\alpha$ - $\beta$ transition. Clinopyroxene, about 50% abundant in the rocks studied, is largely pigeonitic although in some specimens, e.g., 12021, pigeonitic cores are rimmed by augite. Olivine ranges from 0-10% and opaques from 8.5-14%. The luminescent phases are, by volume, plagioclase $\sim$25-35%, tridymite $\ll$1-4.5%, cristobalite $<$1-3.5%, quartz $\ll$1%, and apatite $\lll$1%. Also luminescent are minute regions of glassy residuum which show siliceous and/or potassic composition, and which may contain minute flecks of bright blue luminescing alkali feldspar.

The plagioclase (anorthite and bytownite) luminescence spectra show a minor though definite red-infrared emission band in dull luminescing rims or regions. Brighter yellowish luminescing regions show spectra like those of Apollo-11 plagioclase, and consist of blue and green emission bands only. Plagioclase spectra from eucrite and howardite meteorites also lack the

red-infrared band, but it is strongly developed in all spectra of plagioclase in a suite of twenty-five terrestrial basalts.

Two silica assemblages are found: tridymite-cristobalite and cristobalite-quartz. The first is found in the coarse rocks and the latter appears characteristic of the finer-grained rocks. Several hundred particles of lunar soil were picked by brush from the <1 mm fines and were studied in thin section. About half the particles have an opaque matrix, many with phenocrysts of olivine, pyroxene, or plagioclase. The remainder consist of mineral grains, glass, and lithic fragments. Most of the latter are micro-gabbroic fragments, though anorthosite fragments were also found. Some of the latter consist of many constituent grains and are estimated to contain 90-95% feldspar. Several grains of antiperthite were also found.

Evidences of shock damage are rare in the soil fragments studied, and it appears that these lunar soil materials may have been subjected to less shock damage than the Apollo-11 specimens. Maskelynite showing characteristic luminescence spectral effects was found as well as other plagioclase grains evidencing intermediate luminescence spectral effects previously reported. These effects are rare, however, and most plagioclase grains display normal luminescence spectra. Comparison of the luminescence properties of maskelynite from Shergotty meteorite with those of the lunar maskelynite suggests that the two luminescence aspects of shock damage previously reported are merely stages in the disordering process.

## I. INTRODUCTION

The Apollo 11 crystalline igneous rocks are in many ways analogous to terrestrial basalts, though they show striking differences (L.S.P.E.T. 1969). The eucrite and howardite meteorites, as pointed out by Mason (1970) and others, bear textural and mineralogical similarities to the lunar igneous rocks and micro-breccias respectively. The luminescent phases of the Apollo-11 lunar rocks, mainly plagioclase, showed consistent differences from diverse terrestrial specimens. In order to determine whether these differences also exist in terrestrial and meteoritic analogues of the lunar samples, the following have been examined:* three eucrites (Juvinas, Moore County and Pasamonte), two howardites (Frankfort and Bununu), Shergotty, and a suite of twenty-five terrestrial basalts. This paper presents results of the examination of the Apollo-12 specimens, and comparative features in the meteorites and terrestrial basalts.

## II. GENERAL DESCRIPTION OF THE APOLLO-12 SPECIMENS

Crystalline igneous rocks 12018, 12021, and 12065 were studied in rock chips and thin sections. 12039 was studied in thin section only. The igneous specimens are basaltic and gabbroic rocks similar to the Tranquility Base specimens, although they show minor differences. The two coarse-grained rocks, 12021 and 12039, show similar modal compositions. These are by volume: plagioclase $\sim$34%, clinopyroxene $\sim$50%, opaques (dominantly ilmenite) $\sim$10%, tridymite $\sim$4%, cristobalite $<$1%. Both sections are devoid of olivine and quartz and

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contain coarse tridymite with laths up to two mm. in length. The pyroxene in both rocks appears dominantly pigeonitic though the large phenocrysts in 12021 are strongly zoned to augite on the rims, while the pigeonite of 12039 is largely unzoned. 12021 displays a clearly porphyritic texture with centimeter size pyroxene phenocrysts set in a groundmass of plagioclase, pyroxene, ilmenite, and tridymite. The groundmass has a grain size range from sub-millimeter to a few millimeters. The grain size distribution of 12039 is more uniform and is composed of grains a few mm. in size. Euhedral tridymite laths are present in both rocks, which suggests an unusual crystallization order. Rock 12039 shows it most clearly. Here tridymite and ilmenite are the only clearly euhedral minerals, while the pyroxene and plagioclase are anhedral to subhedral. Anhedral plagioclase is found moulded around euhedral tridymite. The texture suggests early crystallization of tridymite and ilmenite, followed by plagioclase and pyroxene which apparently crystallized together.

The finer grained rocks 12018 and 12065 have somewhat different modal mineralogy from the coarse-grained samples. Both contain olivine though in unequal amounts, $\sim$9.5% in 12018 and $<$1% in 12065. Tridymite is apparently absent in both specimens and the silica phases are cristobalite and quartz. These appear to be residual phases, and the amounts are unequal. Rock 12065 contains 3.5% cristobalite and widely disseminated quartz, aggregating less than 1%. Cristobalite in 12018 is $<$1%, and only one grain of quartz was found in the entire section.

The texture of 12065 is porphyritic with micro-phenocrysts of pigeonitic pyroxene set in a groundmass of pyroxene, plagioclase, ilmenite, and minor olivine. The groundmass shows a quench texture dominated by sub-radial to radial intergrowths of sheaf-like plagioclase and pyroxene. In 23% of the

thin section the intergrowth comprises sheaves of acicular grains intergrown on a fine (micron) scale. The mineral phases cannot be optically resolved, but if one-third of this intergrowth material is apportioned to the pyroxene tally and two-thirds to the plagioclase (as suggested by microprobe estimates), then rock 12065 contains 49% pyroxene and 32% plagioclase compared with 52% pyroxene and 27% plagioclase for 12018. The texture of 12018 is intermediate between the quench texture of 12065 and the texture of the coarse-grained specimens. The rock was apparently also chilled rapidly since there are no well-defined crystal outlines, and no clear order of crystallization, though pyroxene, plagioclase, and olivine were probably early, and ilmenite which shows drop-like anhedral forms was late.

The luminescent phases in the igneous rocks are plagioclase, tridymite, cristobalite, quartz, and sparse apatite. Also luminescent are minute regions of glassy residuum, mainly present in the fine-grained rocks. These show siliceous and/or potassic composition, and contain minute flecks of blue luminescing alkali feldspar. The brightest luminescence is emitted by tridymite, a brilliant blue emission, about ten times more intense than the plagioclase. The cristobalite emission is dull blue, while that of the quartz is pink and/or blue.* Apatite, verified by probe analysis, emits yellow or orange luminescence similar to terrestrial specimens. The plagioclase shows the same compositional range as that in the Apollo-11 igneous rocks, Fig. 1, and displays even stronger luminescence zonation. This is particularly true in the coarse-grained specimens.

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* This pink and blue luminescing mineral was incorrectly identified as tridymite in the Apollo-11 rocks (Sippel and Spencer 1970). It has now been definitely identified as quartz.

As in the Apollo-11 rocks, major element composition correlates with luminescence zonation. The more calcic regions emit a yellowish luminescence grading to duller shades in less calcic rims or regions. These latter regions in the coarse rocks have a definite reddish tinge, and spectral measurements reveal a minor though definite red-infrared emission band. In this aspect the Apollo-12 specimens are distinctly different from those of Apollo-11.

Over 100 years ago, Grailich (1858) discovered that luminescent emissions from optically anisotropic minerals may be polarized on emission. He further showed that the plane of polarization is oriented in a definite way relative to the crystallographic axes. Later Sohnke (1896) studied a number of doubly refracting luminescent crystals, and established that they all emit completely or partially polarized light. The same is true of all the luminescent phases in the lunar rocks. Feofilov (1961) has detailed this early chronology, and he states:

> "The reason for the polarization of the luminescence of optically anisotropic crystals is rather obvious and the phenomenon admits of a simple classical interpretation, based on the oscillator model. Anisotropic luminescing centers represented by linear or circular oscillators have very definite directions and either completely or partially orient themselves in the strong internal crystal fields."

In the case of lunar cristobalite and tridymite, the orientation is not only partial but slight, so the light is feebly polarized. The effect is stronger in plagioclase, quartz, and apatite, though none emit light approaching 100% polarization. Because polarized luminescence is emitted anisotropically, intensity variations are observed from grain to grain of a specimen depending on their orientations. Minimum intensity is obtained when one examines a grain oriented so that the emitting oscillator axes are parallel with the

direction of observation. It is for this reason that twinning can frequently be observed in the luminescence of feldspars, even though no nicol prism is in the system. The lunar plagioclase and quartz display multiple emission bands, and in such cases the oscillators associated with the separate bands may be oriented in different crystallographic directions, and to different degrees. This produces color effects which are analogous to the intensity effects just described. Although intrinsically interesting, these polarization effects are not unique, and have been seen in many and diverse terrestrial rocks.

The Apollo-12 igneous rocks, like those from Apollo-11, show no evidence of aqueous phases, nor any evidence of secondary hydrothermal alteration. Evidence of shock damage is lacking in the igneous rocks. A surface of rock 12018 exposed at the top of the regolith was examined in a solid sample luminescence device. No definite effects resulting from radiation damage could be identified.

Several hundred particles of lunar soil were picked by brush from the < 1 mm. fines, and were studied in thin section. About half these particles have a dominant opaque matrix, like some terrestrial basalts. Many carry sparse phenocrysts of olivine, plagioclase, or pyroxene. The remainder consists of lithic fragments lacking the dominant opaque matrix, individual mineral grains, and glass spheres, shards, and grains. The lithic fragments are largely basaltic and micro-gabbroic although anorthosite fragments were also found. Some of the latter consist of many constituent grains and are estimated to contain 90-95% feldspar. In soil sample 12001 several grains of anti-perthite were found. The grains are $\sim 500\mu$ in size and bright blue luminescing blebs of potash feldspar with dimensions of 10 to 40 microns are randomly distributed in the duller luminescing plagioclase. Microprobe analysis gives the following data:

| | | | | |
|---|---|---|---|---|
| Plagioclase | $Ab_{32.8}An_{66.7}Or_{0.5}$ | MIN=$1\times10^{-4}$ | FTEST=4.01 | TOTAL=101.9 |
| Potassium Feldspar | $Ab_{20.9}An_{1.4}Or_{77.7}$ | MIN=$2\times10^{-6}$ | FTEST=4.03 | TOTAL=100.1 |

These grains like the anorthosite grains are probably unrelated to the dominant rock types of the area, and may well derive from a distant source. Also present are grains which consist of fibrous intergrowths (on a micron scale) of plagioclase and a mafic phase, probably pyroxene. Some of these grains appear like spherulitic fragments. They are present in all the lunar soils studied, and were also found in the Apollo-11 breccias. These grains are luminescent, and exhibit a typical plagioclase spectrum. Microprobe scans at right angles to the fiber axes showed inverse variation of magnesium and aluminum. The character of these scans shows that individual fibers are too small in diameter to be completely resolved by the microprobe beam. These grains are interpreted to be fragments of a fine quench texture intergrowth similar to that found in rock 12065. Although the statistics are poor, it appears that the plagioclase of the lunar soils may have a wider compositional range than the igneous rocks, Fig. 1. Some grains also contain appreciable amounts of fine-grained and scattered potassium feldspar, and some are much richer in apatite than any of the igneous rocks examined to date. Although evidences of shock damage are found in the lunar soil fragments, the general impression is that the soils examined have been subjected to much less shock damage than the breccias from Apollo-11.

## III. THE LUNAR PLAGIOCLASE LUMINESCENCE, AND COMPARISONS WITH METEORITES AND TERRESTRIAL BASALTS

Experience with a considerable range of terrestrial feldspar specimens has shown that, with very few exceptions, their luminescence consists of three broad emission bands (Sippel and Spencer 1970). In a given feldspar spectrum one, two, or all three of the bands may be present. Over a wide range of

samples each of the three bands shows some variability in peak position. The three bands with their most probable positions, extreme ranges, and estimated bandwidths full width at half maximum (F.W.H.M.) are as follows:

| | PEAK POSITION (ANGSTROMS) | BANDWIDTH ANGSTROMS (F.W.H.M.) |
|---|---|---|
| BLUE BAND | $4500^{+160}_{-200}$ | 1750 |
| GREEN BAND | $5590^{+160}_{-65}$ | 900 |
| RED BAND | $7300 \pm 200$ | 1250 |

Although the red band shows a considerable variability in peak position, it is interpreted as a single luminescence center because the variability is not random, but correlates with composition. Pure albite specimens display peak positions in the vicinity of 7500 Å, while potassium feldspar or anorthite peaks are in the vicinity of 7100 Å. Intermediate peak positions are shown by intermediate compositions of either plagioclase or alkali feldspar, and correlate reasonably well with the percent of albite.

The peak variability in the blue band, and the minor variability in the green peak position, do not correlate with major element composition, but may be related to degree of order in the feldspar lattice. They also probably represent single luminescence centers. The green band is absent in spectra of alkali feldspar, and the usual spectrum consists of a dominant blue and a minor red band. In some alkali feldspars, the red band is completely missing, and in rare specimens the red band dominates almost completely and the blue is essentially nil. In terrestrial plagioclase, all three bands are usually present, although the relative intensities may vary widely, e.g., compare A and B of Fig. 2. The blue emission band is shown by many silicates other than feldspar, and a similar blue emission is shown by glass and fused silica.

Rapidly solidified fused silica shows elaborate feathery patterns of blue luminescence, which almost certainly do not reflect trace element chemistry. In fused silica the blue luminescence can also be intensified by electron bombardment. All this suggests that the blue luminescence may originate in a defect center rather than from activator ions. The blue luminescence cannot be intrinsic, since authigenic feldspars of good purity are apparently always non-luminescent. The green and red bands, on the other hand, probably do result from activator ions, though preliminary experiments have not thus far resulted in their identification.

The luminescent emissions from all types of terrestrial feldspars, with the exception of sanidine and adularia, are polarized to some degree, though the strength of polarization seems to vary among specimens of the same feldspar type. In the case of plagioclase, the three emission bands are partially polarized, and it appears generally true that the green band is most strongly polarized. Its degree of polarization approaches 100% in some specimens. The red and blue bands are less strongly polarized, and data are insufficient to state which is usually the stronger. In any case, the polarization varies with wavelength, and this produces distinct color variations as the upper nicol prism of the microscope is rotated.

These are the regularities; there are anomalies also. For example, additional emission bands have been seen which peak at about 4075 Å and at 4950 Å but these are rare. It is not the existence of anomalies that is extraordinary, but their rarity.

With regard to polarization properties, the lunar plagioclase seems to fail easily within terrestrial norms. It is possible that detailed study of the orientation distribution of the various emission band oscillators in

terrestrial and lunar plagioclase would reveal significant differences. This would require a great deal of universal stage work, and has not been attempted. In terms of visual observation, the polarization of lunar plagioclase luminescence appears "normal" in terms of terrestrial experience.

One of the unique aspects of the Apollo-11 specimens was their total lack of the red-infrared emission band (Sippel and Spencer 1970). The plagioclase of six eucrite and howardite meteorites was also found to lack the red-infrared emission band. Figure 3 shows how closely analogous the spectra of meteoritic and lunar plagioclase can be. On the other hand, plagioclase from a suite of twenty-five terrestrial basalts showed a well-developed red-infrared band without exception. In many of the spectra of Apollo-12 plagioclase grains there is a minimal though definite red-infrared emission band. It is better developed in the coarse rocks, and is more easily seen in grains where the luminescence is zoned to dull rims or regions. In brighter yellowish luminescing cores or regions it may be undetectable. It can be detected, however, in some spectra of both fine rocks and in many lunar soil fragments. Figure 2 shows the spectrum of a grain from one of the coarse rocks compared with spectra of plagioclase from two of the terrestrial basalts. The red-infrared band in the lunar plagioclase is small, but definitely present.

Clearly a quantitative comparison is desirable. Since the spectra consist of the three emission bands, an individual spectrum could be simply summarized by stating the intensity of the three bands. On the other hand, normalized data can be more easily compared, and for this purpose the percent of the total energy radiated by each emission band provides a convenient summary. If the raw spectra are multiplied by the correction factor $\frac{1}{B.W. \times Q.E. \times \lambda}$ (Sippel and Spencer 1970), the corrected spectra give energy radiated per unit wavelength.

If then the corrected spectra are deconvolved to obtain an estimate of the separate band intensities and emission bandwidths, the product of these two quantities gives a number proportional to the energy radiated in each emission band. This procedure was followed on a group of spectra sufficiently large to provide estimates for the bandwidths of the emissions, and correction factors to convert raw spectral peak height into corrected peak height. Then each raw spectrum was roughly deconvolved to obtain apparent band intensities. These were multiplied by the correction factors to obtain corrected band intensities. Because the corrections are large and rapidly changing in the red end of the spectrum, corrections were determined at 7100 and 7500 Å, and an interpolated value was used depending on the position of the red peak in the raw spectrum.

The red band is greatly augmented in the correction process. For example, in Fig. 2A the spectrum is described by blue 7%, green 7%, and red 86%, B(7)G(7) R(86). In Fig. 2B the spectrum is described by B(50)G(9)R(41). In Fig. 2C, even though the red emission appears very weak, it constitutes 16% of the total. The numbers are B(64)G(20)R(16). In Fig. 3, although the two spectra appear quite similar, the Moore County meteorite spectrum is concave throughout the red peak region, and the spectrum is characterized by B(60)G(40)R(0). The Apollo-12 spectrum, on the other hand, shows a definite flattening in the same region and yields B(62)G(31)R(7). For even smaller relative amounts of red-infrared emission, estimation becomes increasingly difficult, and an R(0) estimate must be considered to be zero plus a few percent uncertainty.

The spectra of plagioclase in the meteorites, terrestrial basalts, and lunar specimens are summarized and compared in Fig. 4. Table 1 gives identification data on the basalts, and Table 2 gives results of probe analyses on the meteorites. The lunar sample plots include unshocked plagioclase spectra from

igneous rocks and breccias (Apollo-11) and plagioclase spectra from igneous rocks and lunar soils (Apollo-12). The lunar rock plots do not include all the spectra measured, but care was taken to include the extreme values. The plots show the degree of variation in the spectra of each rock type, but the most interesting point is the extreme separation between the field of the terrestrial basalts on the one hand, and that of the meteorites and lunar rocks on the other. Thus, the distinction remarked before (Sippel and Spencer 1970) between lunar rock plagioclase and diverse terrestrial specimens holds up for the rock type which is the closest terrestrial analogue of the lunar rocks. This is true, even though the terrestrial suite includes basalts of widely diverse geography, magma type and age. No less interesting is the close similarity of the fields of meteorites and lunar rocks.

The fact that a vertical line from the apex of the triangles to the base separates the terrestrial from the non-terrestrial plagioclase spectra, largely results from the relative lack of the red-infrared emission band in the lunar rocks and meteorites. The significance of this phenomenon will only become clear when we determine the nature of the red-infrared luminescence center. If it is activated by an OH group, for example, it will be of considerable significance. On the other hand, if it merely reflects the depletion of a trace element, in the lunar rocks, which we already know to be depleted from the trace element analyses, the significance will be slight. In this connection, the extensive chemical analyses which have been performed on the lunar samples can give us a clue to the identity of possible activator ions. Elements which are depleted in the lunar specimens, relative to terrestrial basalts, comprise a list of at least a dozen (Ganapathy, et al. 1970). Many of these are also known luminescence activators. To account for the luminescence

data, the proposed activator must be present in terrestrial basalts in sufficient amount to account for the red-infrared emission. Although a few parts per million are found adequate to produce bright luminescence in synthetic phosphors, a level of 50-100 ppm would probably be required in natural plagioclase. Using the data of Taylor (1964) we find that most elements in the list are not present in terrestrial basalts in sufficient quantity. Only copper and zinc (both present to $\sim$100 ppm) are likely candidates. Both are known activators.

## IV. THE SILICA PHASES AND POTASSIUM FELDSPAR

The silica phases of the lunar rocks are tridymite, cristobalite, and quartz. In the coarse-grained rocks (12021 and 12039), quartz is absent and the silica assemblage is tridymite-cristobalite. In the finer grained rocks (12018, 12065, 10020, and 10045), tridymite appears to be absent, and the assemblage is cristobalite-quartz. The tridymite of the coarse-grained rocks is brilliantly luminescent, about ten times as intense as the plagioclase. Figure 5A is a spectrum of one of these brightly luminescing tridymite laths. The spectrum consists of a single broad band peaking at 4550 Å corrected. The tridymite luminescence increases in intensity as the electron beam energy and/or current is raised. This continues to a certain level, then there is an abrupt change in the luminescence. There is extinction of the brilliant luminescence in a sudden sweep throughout the grain. If the electron beam is abruptly reduced, the brilliant luminescence returns. The cycle may be repeated several times, with care, but after a few times there will be regions of the grain which do not recover, and with prolonged heavy bombardment the brilliant luminescence is irreversibly extinguished, and will not reappear even after waiting times up to a month. The luminescence is not completely destroyed in the process,

and after extinction of the brilliant luminescence there still remains a dull bluish emission. Spectral measurements show that it is about 30% as intense as the original. It also shows a single blue band spectrum very similar to Fig. 5A, but the peak intensity has been shifted about 100 Å toward longer wavelengths. Apparently the electron beam is intense enough to heat the bombarded region of the specimen above the $\alpha$- $\beta$ transition temperature at about 117°C., and in repeated passes through the $\alpha$- $\beta$ transition the luminescence centers are "permanently" altered. In thin section, none of the other lunar minerals can be brought to high enough temperature to show quenching of the luminescence, but using a solid sample luminescence device small crystals can be heated to incandescence by the electron beam. In this device small crystals can be very rapidly heated and cooled. Thermal quenching of plagioclase luminescence occurs well below incandescence and one can readily quench and recover the plagioclase luminescence several hundred times with no evidence of permanent change. Another question which occurs is whether the "permanent" change in luminescence indicates metastable formation of the $\beta$ phase. To test this, a grain showing a good biaxial optic axis figure was located with the conoscopic microscope. It was then placed in the luminescence device and bombarded to produce the irreversible change. When the grain was relocated in the conoscope, a biaxial positive figure was again observed, ruling out a metastable $\beta$ tridymite phase. Whatever the cause of the phenomenon, it is useful in petrography, not only for identifying scattered tridymite, but for distinguishing minute flecks of alkali feldspar intergrown with tridymite. One merely increases the electron beam and extinguishes the brilliant tridymite luminescence. Then minute flecks of potassium feldspar stand out clearly against the dully luminescing tridymite. Such feldspar flecks are sparse and minor in the coarse lunar rocks.

Cristobalite exhibits a spectrum identical to the bright luminescing tridymite, Fig. 5A, but is a much duller emission. There are variations, and some grains are moderately bright, although much duller than the brilliant tridymite. In the coarse rocks, cristobalite is frequently intergrown with tridymite. In the fine-grained rocks it is frequently intergrown with small flecks of potassium feldspar or glassy mesostasis. The cristobalite is stable in the luminescence microscope, but when intensely bombarded in the microprobe, develops red-emitting luminescence centers as previously described (Sippel and Spencer 1970).

Quartz is absent in the coarse-grained rocks, but is widely though sparsely (in 12018 it is very sparse) distributed in the finer-grained rocks of both Apollo-11 and 12. It occurs as 10-50 micron, usually anhedral, crystals and could be easily overlooked if it were not for its pink and bluish luminescence. It exhibits a very marked color change when examined through a rotating nicol prism. As the upper nicol of the microscope is rotated, the color changes distinctly from red to blue. Maximum red or blue colors are obtained when the vibration direction of the upper nicol prism is parallel to a principal vibration direction of the crystal. That is, the maximum red and blue colors are obtained at normal extinction positions. The spectrum has been measured using a micro aperture collimator, and is shown in Fig. 5B. It consists of a blue and an orange-red band which peak at 4300 Å and 6500 Å corrected. The spectrum is virtually identical with spectra of terrestrial quartz which had been previously obtained. Using a monocular tube with bertrand lens and aperture, the uniaxial positive interference figure of these minute crystals has been verified, and probe analysis shows them to consist essentially of silica. Because of the simplicity of the uniaxial system, it is easy to establish the orientation

of the oscillators responsible for the red and blue emissions, without recourse to the universal stage. The blue oscillators are aligned with the c-axis, and the red emission is unpolarized. The polarization effects in the lunar quartz are similar in kind, but apparently stronger than in most terrestrial quartz.

The potassium feldspar of the lunar rocks, whether in lunar soils, breccias, or as minute residual grains in the igneous rocks, all exhibit luminescence spectra virtually identical to the tridymite spectrum, Fig. 5A. Many terrestrial specimens show a similar spectrum although often in terrestrial specimens there is an observable red-infrared band also. Figure 5C shows the spectrum of a terrestrial orthoclase in which the red-infrared band constitutes 58% of the total emission. In many terrestrial specimens the red-infrared band is less well developed, frequently constituting only 5-20% of the total emission. In a significant percent of cases, it is entirely missing, resulting in a spectrum like Fig. 5A.

## V. SHOCK EFFECTS, LUNAR SOILS AND METEORITES

As previously reported (Sippel and Spencer 1970), shock damage in plagioclase of the Apollo-11 breccias has produced distinctive changes in their luminescence spectra. Lunar maskelynite most often shows a broad structureless spectrum extending from ultraviolet to infrared. The intensity is reduced at all wavelengths compared to plagioclase of normal birefringence, and the green emission band is broadened and shifted toward longer wavelengths. The luminescence appearance is dull red. Birefringence is nil or nearly so, and not surprisingly the polarization of plagioclase luminescence is also destroyed. More rarely, lunar maskelynite shows a definitely blue luminescence, and spectral measurements show that the red end of the spectrum is severely depressed compared to the blue. Both aspects of shock damage were found in adjacent regions

of a single grain. Largely because of this, our initial assumption was that two distinct effects were involved (Sippel and Spencer 1970).

Maskelynite of Shergotty meteorite has been known to bear some relation to the mineral plagioclase for almost a hundred years (Tschermak 1872). It was, however, only following the work of Milton and De Carli (1963) that its origin as resulting from shock damage of plagioclase has become clear. Duke (1968) calls the Shergotty meteorite the "type occurrence of maskelynite." When we compare maskelynite of the lunar specimens with maskelynite of the Shergotty meteorite, we find that the luminescence of the latter changes slowly under electron bombardment. Upon first examination of a fresh grain we obtain dull red luminescence and a spectrum very much like that reported for the lunar maskelynite (Sippel and Spencer 1970, Fig. 3D). After a few minutes' bombardment, the spectrum is as shown in Fig. 6, where it is compared with a maskelynite grain from the lunar rocks. After forty-five minutes of continuous bombardment in the luminescence device, the Shergotty maskelynite spectrum approaches that of a blue enhanced spectrum (Sippel and Spencer 1970, Fig. 6B). The changes result mainly from degradation of the red end of the spectrum, the blue end showing only slight decrease in intensity after forty-five minutes of bombardment. Thus, the luminescence of the Shergotty maskelynite passes from one aspect of shock damage to the other with protracted bombardment. This is anomalous compared to experience with the lunar maskelynite and with maskelynite from the Manicouagan impact structure. In these specimens, the spectra are stable and show no change with protracted bombardment.

It is interesting that Bunch and Cohen (1968) also found Shergotty to be anomalous in its annealing behavior, compared with diverse terrestrial maskelynite samples. These authors state:

> "The terrestrial samples behave metastably at temperatures below 700°C., but revert rapidly to the crystalline form on heating at 800-1000°C. Shergotty maskelynite behaves in the opposite manner, tending toward the properties of fused plagioclase on even gentle heating at 450°C."

If the same trend occurs under electron bombardment as occurs in gentle heating, then the blue enhanced spectra may arise from fused plagioclase and the reddish spectrum may result from a less severely disordered structure. In any case, since the Shergotty maskelynite luminescence spectrum can be altered from one form to the other by electron bombardment, it appears that we are seeing two stages of the same fundamental process rather than two distinct effects. In addition to the maskelynite, the Apollo-11 breccias also contain much plagioclase which has suffered intermediate degrees of disordering due to shock damage, and these grains show characteristic luminescence spectra which are also intermediate between normal plagioclase and maskelynite. These intermediate changes result from a shift of the green emission band towards longer wavelengths, accompanied by broadening of the band and reduction of the luminescence polarization. There can be little doubt of the correctness of the interpretation of these luminescence properties as resulting from the shock damage mechanism in the lunar rocks. On the other hand, one must be aware that these phenomena may be necessary, but by no means have they been proven to be sufficient, evidences of shock damage.

With regard to the Apollo-12 specimens, there is no evidence of shock damage in the igneous rock sections studied, and the lunar soils appear to have suffered much less shock damage than the Apollo-11 breccias. Maskelynite was found, though it is sparse, and likewise present but sparse are evidences of intermediate spectral shifts resulting from shock. Most of the plagioclase examined is identical in its luminescence properties to the igneous rock plagioclase.

Glass is not rare in the lunar soils; spheres and ellipsoids, shards and grains were found as well as many lithic fragments which were partly vitreous, but the glass does appear less abundant than in the Apollo-11 samples. Grains of glass were found with many plagioclase microlites strongly oriented parallel to flow structures visible in the glass. This suggests considerable flow, and perhaps some of the glass has originated by melting processes other than shock.

Of the meteorites examined, other than Shergotty, Moore County showed no evidence of shock damage, and Frankfort, though it shows textural similarities to lunar breccias, showed slight evidence of shock damage. Juvinas and Pasamonte showed definite spectral shifts in the luminescence of plagioclase which probably result from shock damage. The degree of spectral shift varies from grain to grain. In Pasamonte, blocky and wispy regions of individual grains show variations in the degree of spectral shift. Bununu, like Frankfort, is a howardite, and as Mason (1970) showed, these meteorites bear a strong textural similarity to lunar breccias. In the case of Bununu, the resemblance is extraordinary and includes much evidence of shock damage including mosaicism, luminescence spectral shifts, and some planar features. The only apparent dissimilarities are the lack of maskelynite and a lower content of opaque minerals. Whether such meteorites could have derived from the moon will become clearer as more lunar samples become available for study. Meanwhile, there can be little doubt that they derive from a similar environment, that is, from the surface of an atmosphereless body.

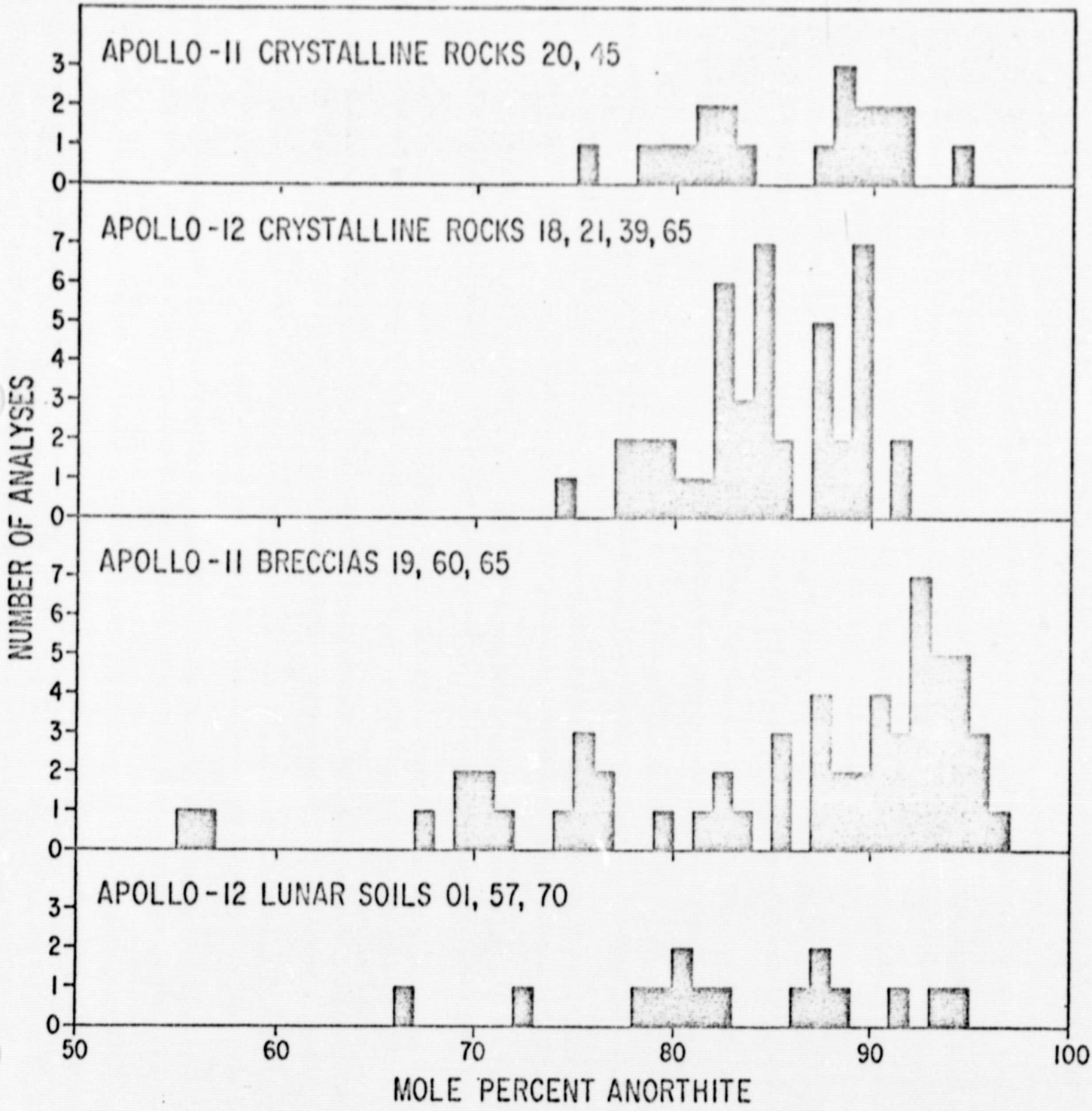


Fig. 1. Summary of all microprobe analyses of lunar plagioclase. Selection of grains to be analyzed was not strictly random, but was guided by the luminescence observations. In the igneous rocks the most calcic compositions were found in brightly luminescing cores or regions, while duller luminescing regions yield the less calcic compositions.

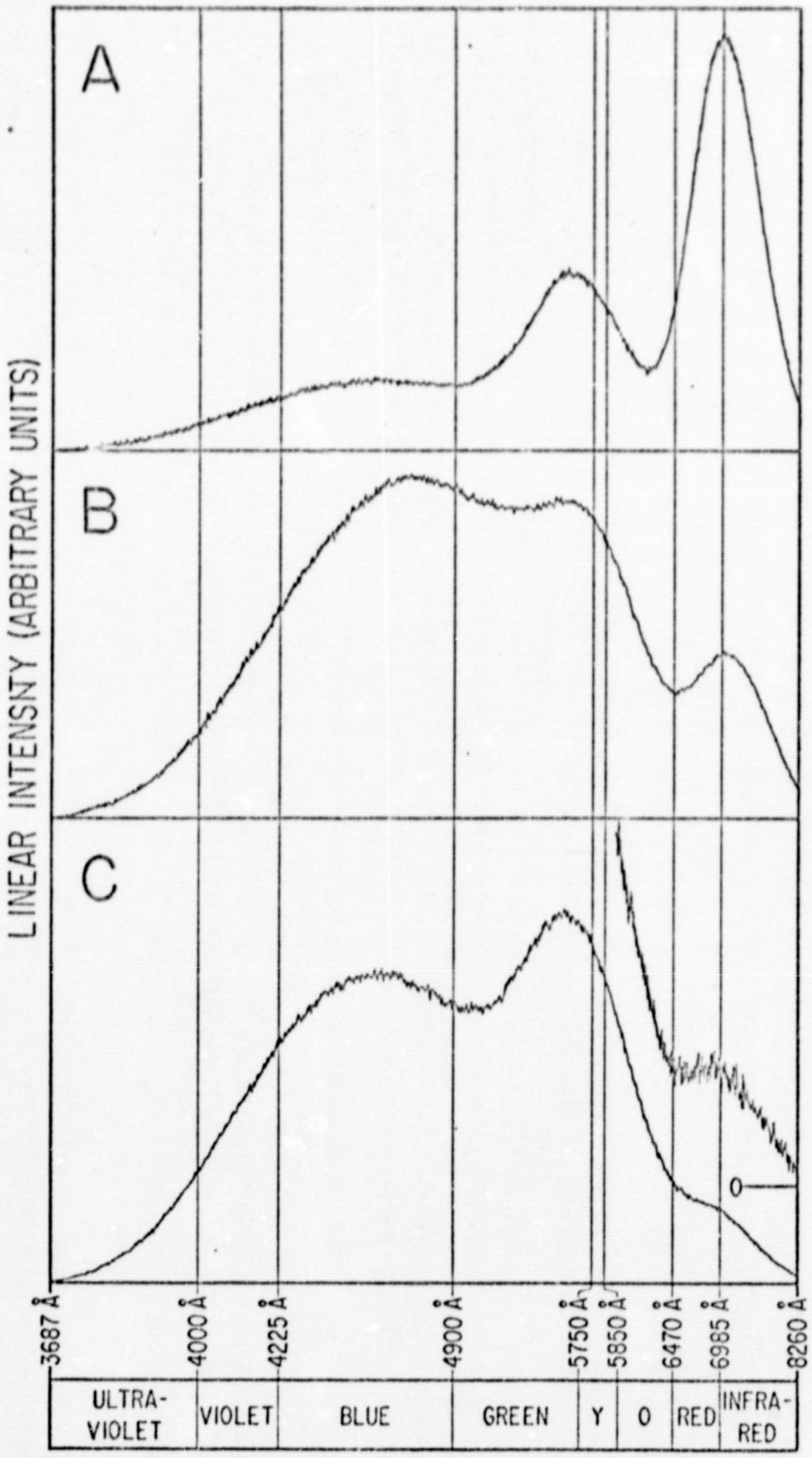


Fig. 2. Luminescence spectra of plagioclase for comparison. (A) Basalt NMNH 108982/AG-4 Southern Agrihan, Pacific Ocean. (B) Basalt NMNH 112383 Pacific Ocean 44° 10' N 130° 25' W water depth 2435-2560 M. (C) Lunar rock 12039. In (C) the inserted partial spectrum was taken with a narrow spectrometer slit setting for ultimate resolution. Note non-linear abcissa. This and all other spectra in this paper should be interpreted with consideration of the correction procedures described in Sippel and Spencer (1970 section 2 of text).

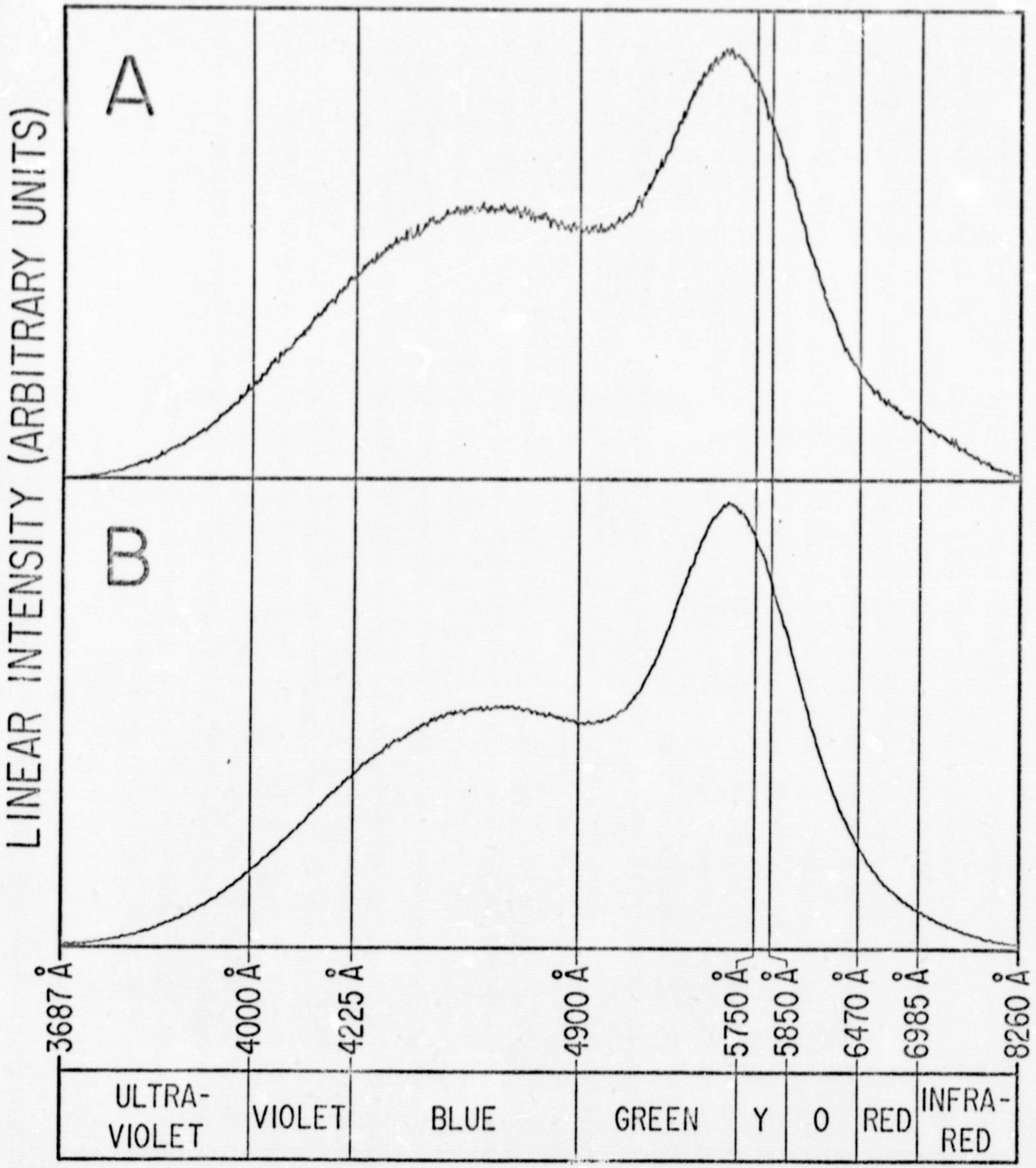


Fig. 3. Luminescence spectra of plagioclase for comparison. (A) Lunar rock 12039. (B) Moore County meteorite. The spectra are similar though the lunar specimen exhibits 7% red-infrared emission, after correction, while Moore County meteorite shows none.

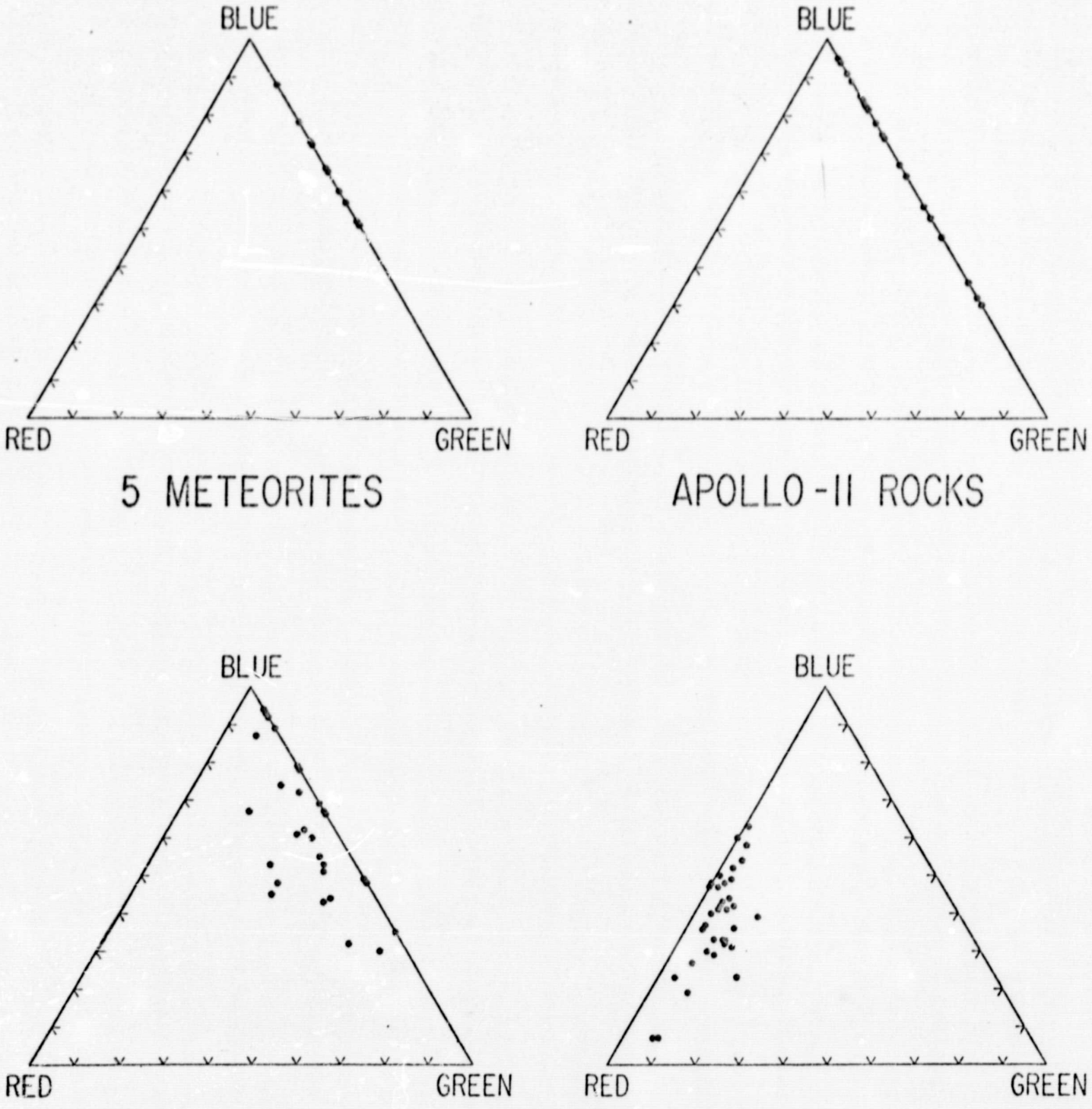


Fig. 4. Plots of the percent of total energy radiated in the blue, green, and red-infrared emission bands for diverse specimens of plagioclase. Note that a vertical line separates the terrestrial from the non-terrestrial specimens.

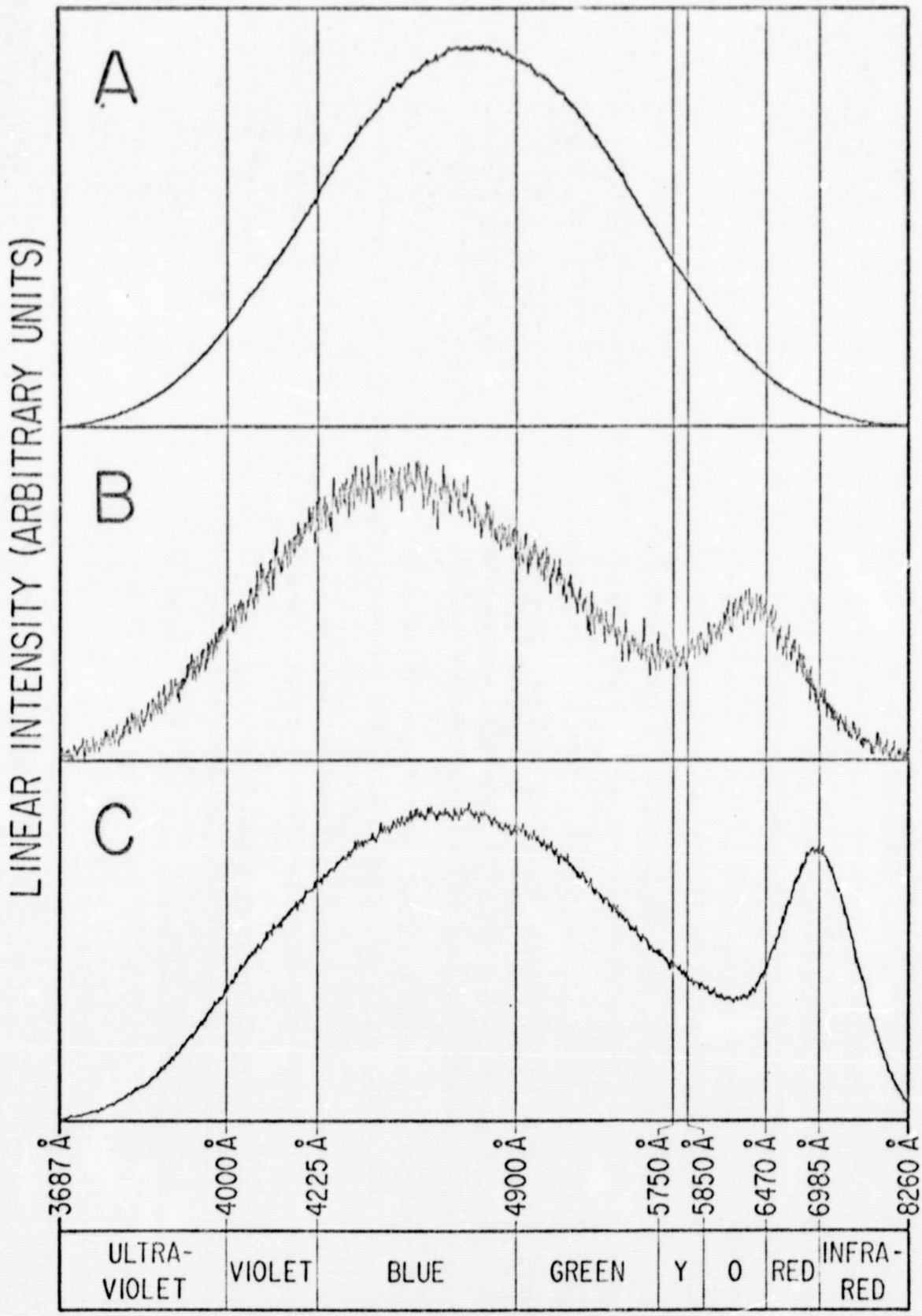


Fig. 5. Luminescence spectra for comparison. (A) Lunar tridymite. (B) Lunar quartz. (C) Terrestrial orthoclase. The tridymite spectrum is virtually identical to spectra of cristobalite and potassium feldspar in the lunar rock samples, while spectra of terrestrial potassium feldspars frequently show a red-infrared emission band as in (C).

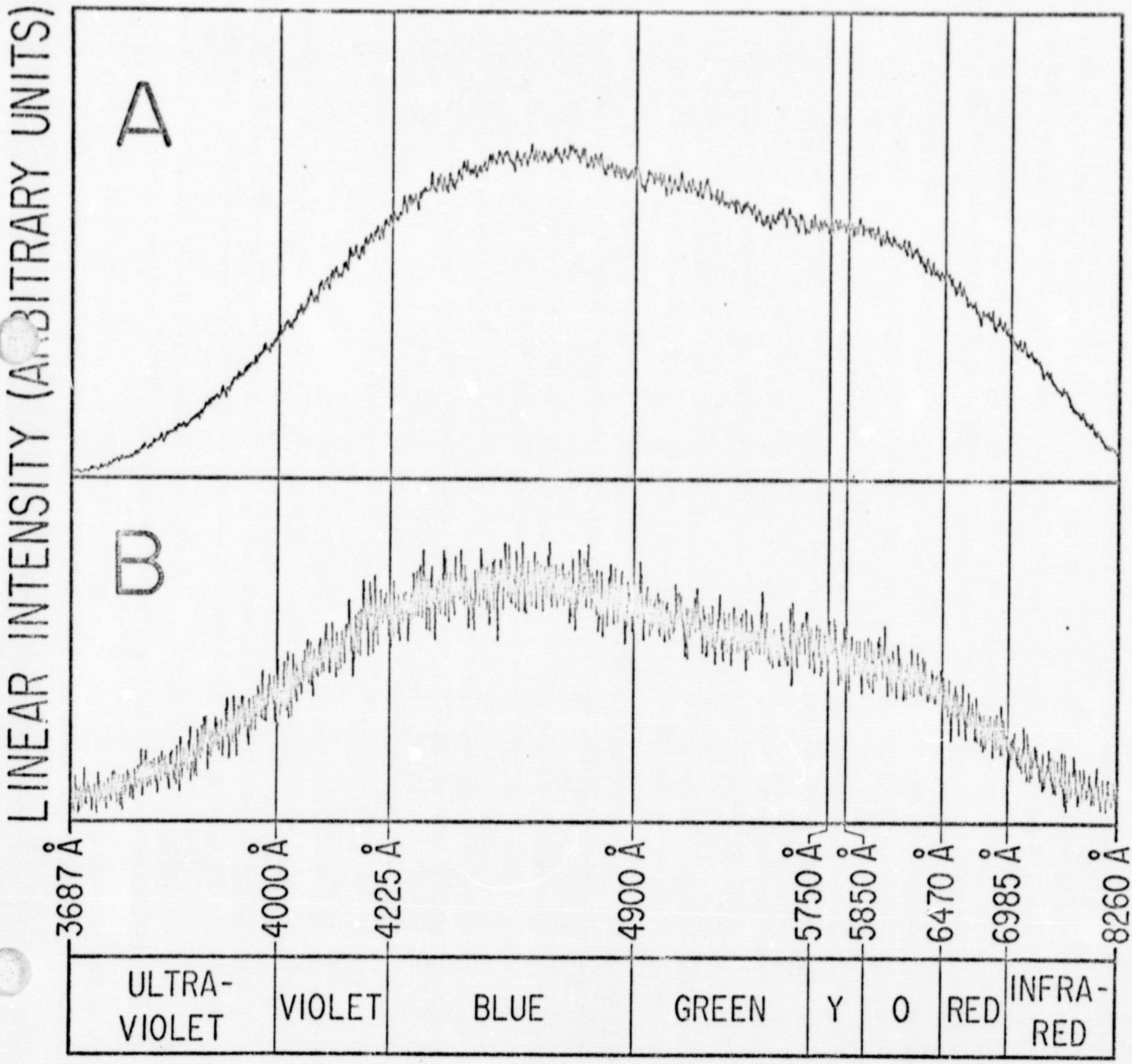


Fig. 6. Luminescence spectra for comparison. (A) Maskelynite from Shergotty meteorite. (B) Lunar maskelynite, Apollo-11 breccia. The Shergotty maskelynite spectrum changes with electron bombardment. The spectrum shown was taken after two minutes of bombardment. For details see text.

TABLE 1

| Description | Location | NMNH No.[Δ] | Plagioclase Composition Ab | An | Or | Age |
|---|---|---|---|---|---|---|
| Basalt (Deccan Trap) | Jiran, Central India | 99677 | 35 | 65 | 0 | Cretaceous[+] |
| Basalt (Deccan Trap) | Panandrao, Cutch, India | 99682 | 47 | 51 | 2 | Cretaceous |
| Basalt | The Dalles, Oregon | 99690 | 45 | 53 | 2 | Miocene |
| Alkali Olivine Basalt | Ardslingnish, Scotland | 109387/37 | 39 | 61 | 0 | |
| Augite Basalt | Southern Agrihan, Mariana Islands, Pacific Ocean | 108982/AG-4 | 7 | 92 | 0 | |
| Basalt | Mid-Atlantic Ridge 45°44'N27°43'W Depth 3370 M | 110028 | 59 | 23 | 18 | Pliocene* |
| Tholeiite Basalt | Kilauea, Hawaii | 110048 | 38 | 61 | 1 | 1961 Flow |
| Olivine Basalt | Moen, Truk Islands | 111032/153 | 24 | 75 | 0 | Miocene |
| Melilite-nepheline Basalt | Tol, Truk Islands | 111034/315 | 57 | 36 | 7 | Miocene* |
| Melilite-nepheline Basalt | Tol, Truk Islands | 111034/316 | 42 | 39 | 19 | Miocene* |
| Olivine Basalt | Fefan, Truk Islands | 111036/118 | 34 | 65 | 1 | Miocene |
| Nepheline Basalt | Uvalde Quad., Texas | 111123/1065 | 61 | 34 | 5 | Cretaceous* |
| Olivine Basalt | Indian Ocean, 5°36'N61°53'E | 111716 | 39 | 48 | 13 | * |
| Basalt | Pacific Ocean 44°10'N130°25'W | 112383 | 33 | 66 | 0 | |
| Basalt | Pacific Ocean 44°25'N129°55'W | 112392 | 36 | 64 | 0 | |
| Basalt | Doña Ana Co., New Mexico | | 26 | 73 | 1 | Quaternary |
| Basalt | Yakima Series, Washington | | 43 | 55 | 2 | Miocene |
| Basalt | Yakima Series, Washington | | 44 | 55 | 1 | Miocene |
| Basalt | Great Corn Island off Nicaragua | | 37 | 62 | 1 | Eocene |
| Diabase | Johnston Co., Oklahoma | | 31 | 69 | 0 | Pre-Cambrian |
| Basalt | Yakima Series, Washington | | 25 | 75 | 0 | Miocene |
| Diabase | Johnston Co., Oklahoma | | 45 | 52 | 3 | Pre-Cambrian |
| Basalt | Ethiopia | | 34 | 65 | 1 | Miocene |
| Diabase | Johnston Co., Oklahoma | | 37 | 62 | 1 | Pre-Cambrian |

TABLE 1 (Cont.)

| Description | Location | NMNH No.△ | Plagioclase Composition Ab | An | Or | Age |
|---|---|---|---|---|---|---|
| Basalt | Yakima Series, Washington | | 35 | 65 | 0 | Miocene |
| Basalt | Washington | | 43 | 55 | 0 | Eocene |

△ National Museum of Natural History identification number.

\+ Larger phenocrysts have anomalous additional peak at 4075 Å; small phenocrysts have "normal" spectra.

* Probe data are not accurate for these samples because of small grain size or alteration. Composition data of these samples must be assumed to constitute crude estimates only.

TABLE 2

| | Plagioclase Composition | | | | | |
|---|---|---|---|---|---|---|
| | Least Calcic Analysis | | | Most Calcic Analysis | | |
| | Ab | An | Or | Ab | An | Or |
| Shergotty | 48.1 | 50.1 | 1.0 | 46.8 | 51.5 | 1.6 |
| Juvinas | 23.3 | 74.6 | 2.1 | 9.4 | 90.0 | 0.6 |
| Moore County | 10.8 | 89.0 | 0.2 | 10.2 | 89.8 | 0.0 |
| Pasamonte | 25.7 | 71.3 | 3.0 | 7.0 | 93.0 | 0.0 |
| Frankfort | 10.7 | 89.4 | 0.0 | 6.6 | 93.4 | 0.0 |
| Bununu | 19.7 | 78.9 | 1.4 | 10.0 | 90.0 | 0.0 |

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