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Silicate Luminescence and Remote Compositional Mapping

Exploration for resources on the Moon will require, as it does on Earth, geologic maps of large areas of the surface. These can best be provided by remote sensing techniques from lunar orbiters. Almost two decades ago, when Link proposed that luminescence exists on the Moon, the possibility arose that this property could be the basis for such a technique, both for mapping the country rocks and for localizing the more rare mineralized zones. To evaluate this possibility, luminescence intensities of the common igneous rock-forming minerals (to represent likely lunar country rock constituents) were measured with proton, electron, and X-ray excitation. The feldspars showed the highest intensities, and quartz, the next highest; intensities of the ferromagnesian minerals (mica, amphibole, pyroxene, and olivine) were very low, for the most part. This order of intensity was the same with all three excitation types. These results indicate that lunar acidic, basic, and ultrabasic rocks could be distinguished from one another on the basis of luminescence intensity. To represent possible lunar resource materials, volcanic, hydrothermal, and pneumatolytic minerals that may exist on the Moon, many of which contain water or OH groups in the lattice, will be measured in continuation studies now in progress. These studies will also include the measurement of luminescence spectra, grain size, temperature, and radiation damage effects and the use of ultraviolet radiation as an excitation source.

INTRODUCTION

The exploitation of lunar resources is one of the prime practical objectives of the Nation's space program. Water will head the list of resources to be located because of its importance for life support and for supplying hydrogen and oxygen for rocket fuel, but iron and metals generally, sulfur, and other useful materials will also have high priority. If experience on Earth is any guide, an exploitable deposit of a given resource will probably be associated with specific rock types and/or specific geologic environments such as volcanic terrains, areas of intrusives, and faulted and fractured zones. Exploration will therefore be best pursued as on Earth by first mapping the lithologic composition and other geologic features over large areas of the Moon and then by exploring intensively the areas shown by the mapping to have most promise. The compositional information derived in the early manned landing missions from
limited areal reconnaissance by the astronau
and from the returned samples will not ful
these needs because it will represent only a f
sampled points from a surface as large as o
fourth the land area of the Earth. Rem
sensing techniques from lunar orbiters w
therefore play an indispensable role in the sea
for lunar resources, both in mapping the surf
composition over large areas and in selecti
promising localities for on-the-ground explo
tion.

The possibility of using luminescence me
surement and analysis as a suitable techniq
for remote compositional mapping arose wh
Link (ref. 1) first proposed the existence
luminescence on the lunar surface to explain t
excess of light he observed in the penum
during many lunar eclipses. Its existence w
later confirmed by Kozyrev (ref. 2), Dub
(ref. 3), Grainger (ref. 4), and Spinrad (ref.
by means of the sensitive line-depth techniq
in which the depths of corresponding Fraunho

lines in the solar and lunar spectra are compared. We are making laboratory measurements of terrestrial rocks and minerals likely to occur on the Moon to test whether they display distinctive luminescence characteristics upon which a remote sensing system can be based and, if they do, to gather the information needed to interpret the remote sensing data. Two groups of samples are required in these measurements—one to represent the common rock types that may be present over most of the lunar surface, and the other to represent the more rare mineralized zones where the resources are likely to be concentrated. In this paper we report some results of our studies with the first group to answer, in particular, the question of whether the common lunar rock types can be distinguished on the basis of their luminescence intensity.

EXPERIMENTAL ARRANGEMENT

Luminescence was excited with protons, X-rays, and electrons. (Ultraviolet excitation, the most important source in the natural radiation environment of the Moon, was not used in these first measurements because more complex instrumentation would have been required to eliminate the interfering background of visible light present in ultraviolet lamps; it is being used in our later studies.) Total luminescence intensity was measured with all three types; measurements of luminescence spectra with proton excitation were also made.

Figure 1 shows the experimental arrangement for the measurements with proton excitation. A Texas nuclear neutron generator was used to provide a 2.5-centimeter-diameter beam of 20 keV protons with a flux of 10^{12} protons $cm^{-2} sec^{-1}$ for the total intensity measurements. The light was detected by an RCA 931A photomultiplier (3000- to 7000-ampere response, 4000-ampere peak) placed at the sample chamber window directly above the sample. For the spectral measurements, the entrance slit of a Gaertner quartz-prism monochromator was placed at the sample chamber window, as shown in the figure, and the detector at the exit

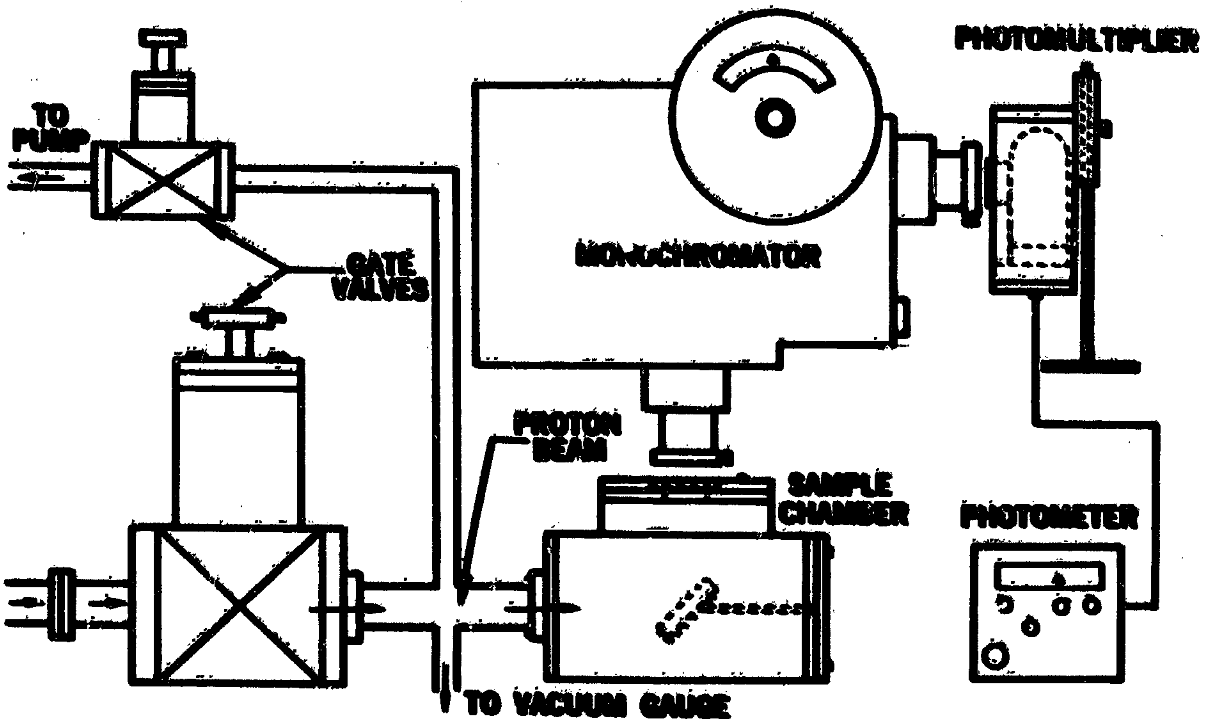

FIGURE 1.—Luminescence measurement apparatus for proton excitation.

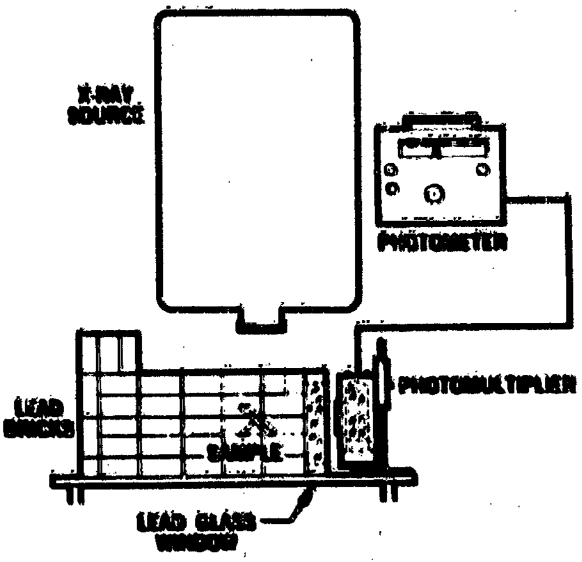

FIGURE 2.—Luminescence measurement apparatus for X-ray excitation.

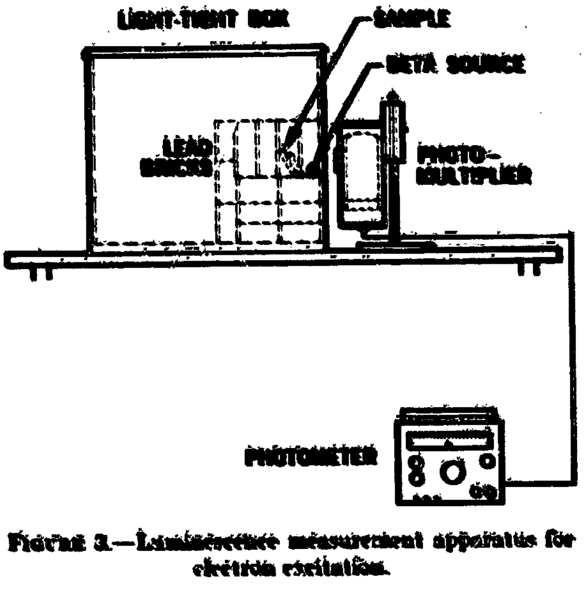

FIGURE 3.—Luminescence measurement apparatus for electron excitation.

slit was an RCA 1P28 photomultiplier (2000- to 7000-angstrom response, 3500-angstrom peak) designed to give better sensitivity at the short-wavelength end of the range. For these measurements the proton energy was increased to 150 keV and the flux to 8×10^{12} protons cm^{-2} sec^{-1}.

The experimental arrangement for the measurements with X-ray excitation is shown in figure 2. The X-rays were from a tungsten target, and the tube was operated at 200 kilovolts and 4.0 milliamperes. A lead-glass window was used to shield the RCA 931A photomultiplier from scattered X-rays. Transmission measurements of the lead glass showed that it cut out some of the blue end of the spectrum, but this introduced no serious error in the relative luminescence intensities because the mineral spectral peaks, except in the case of the low-intensity mineral hornblende, are in the region of high transmission of the glass.

Figure 3 shows the experimental arrangement for the measurements with electron excitation. The electrons were obtained from the beta decay of ^{90}Sr which provided electrons of up to 2.3 MeV energy with a flux, in this configuration, of about 10^9 electrons cm^{-2} sec^{-1}. The RCA 931A photomultiplier was the light detector here, also.

SAMPLES

Even before the Surveyor landings, the evidence of the meteorites and other considerations suggested that the lunar rocks were probably silicates and probably most closely resembled terrestrial igneous rocks. The results of the Surveyor alpha-scattering experiments are in remarkable agreement with this; they give chemical compositions very close to those of terrestrial basalt and gabbro (refs. 6 and 7). Therefore, the common igneous rock-forming minerals were chosen to represent the rock types likely to be most abundant on the lunar surface for this first study. Minerals were chosen because they are more restricted in composition and structure than are rocks and, as a result, can be expected to give a more nearly uniform response. Rocks, by definition, are aggregates of minerals, and their luminescence characteristics can be deduced from the characteristics of their constituent minerals. Single crystals or coarsely crystalline aggregates were measured.

With mineral data, luminescence intensity calculations can be made for any rock in the differentiation series. The extent to which differentiation may have occurred on the Moon is unknown. The one published Surveyor VII chemical analysis from a lunar continental area is not greatly different from the maria analyses of Surveyors V and VI (ref. 8), which suggests that differentiation, if it occurred at all, may be much less advanced than it is on Earth. However, the data are too few to be conclusive, so that in this study the entire range from granitic to ultrabasic was considered.

No meteorite samples were measured, but since the average meteorite composition is approximated very closely by one part iron, which is not luminescent, to three parts peridotite, the luminescence characteristics of meteorites can be deduced from the mineral data. The Surveyor V, VI, and VII magnet experiments indicated that little or no material of chondritic or iron meteorite composition was present at the landing sites (refs. 9 to 11), but, again, these few data do not eliminate the possibility that such material exists elsewhere on the Moon. In fact, any local accumulations of iron or iron-rich meteorites would constitute important resources; therefore, meteorites were considered in this study.

RESULTS

The relative luminescence intensities of the measured samples are shown in table 1, with the value for smoky quartz, set at 100, taken as the standard. With a few exceptions the results for the three types of excitation are in generally good agreement. The highest intensities are shown by the potassium feldspars and the sodic members of the plagioclase feldspars (albite and oligoclase). Next in intensity are quartz and the calcic plagioclases (labradorite and bytownite). The ferromagnesian minerals (mica and all those listed below it in the table) show very low intensities. Nash, in his experiments with proton excitation, also found quartz and the feldspars to exceed the ferromagnesians in luminescence intensity, although he found the quartz intensity to be higher than that of feldspar (ref. 12).

Quartz and feldspar make up the bulk of most of the common igneous rocks, so that, on the basis of both abundance and intensity, these minerals clearly dominate the luminescence response of the igneous rocks. The higher intensity members—quartz, potassium feldspar, and sodic plagioclase—occur typically in the acid, or granitic, rocks; the basic, or gabbroic, rocks typically contain the lower intensity calcic plagioclase and little or no quartz. These two rock types, therefore, can be expected to differ significantly in luminescence intensity. Figure 4 summarizes these relations.

The luminescence intensities of the igneous rocks can be estimated in greater detail by applying the data in table 1 to the known or calculated mineral compositions of the various rocks in the differentiation series. Listed in table 2 are average chemical compositions of these rocks. Granite and basalt are the acidic and basic members, respectively. Diorite and the average igneous represent intermediate members, and peridotite the ultrabasic. The stony component that makes up about three-fourths of the average meteorite is very close in composition to peridotite. With these data and the known chemical compositions of the minerals, the mineral composition was calculated for each rock. The results are shown in table 3; they clearly indicate the decrease in quartz and potassium feldspar and the increase in plagioclase (except in the ultrabasic rocks) and ferromagnesians in going from granite to peridotite. Though not shown in the table, the increase in plagioclase also involves a progressive change from dominantly sodic composition at the granite end of the range to dominantly calcic composition at the basalt and peridotite end. Finally, for each rock the mineral proportions were multiplied by the relative luminescence intensity of the corresponding minerals from table 1 and the results were added to give the numbers shown in table 4; these are the estimated relative luminescence intensities of the various igneous rocks, including meteorites, that would be measured with proton, X-ray, and electron excitation.

For all three excitation types, the data of table 4 show a maximum intensity for granite and a progressive decrease to a minimum intensity at the ultrabasic end of the differentiation series. Moreover, over the granite-peridotite range there is no overlap between rocks of the intensity values for the three excitation types, except in the case of diorite and basalt which, in any event, are close together in the differentiation series. Applied to

TABLE 1.—*Relative Luminescence Intensity of the Common Igneous Rock-Forming Minerals With Various Types of Excitation*

[Value for smoky quartz, 100, taken as standard]

Mineral	Intensity with excitation by—		
	Proton	X-ray	Electron
Quartz:			
Milky	57	54	250
Rose	40	43	120
Smoky	100	100	100
K-feldspar:			
Orthoclase	350	270	200
Microcline	720	650	410
Plagioclase feldspar:			
Albite	450	200	400
Oligoclase	320	590	730
Labradorite	35	19	21
Bytownite	74	260	92
Mica:			
Muscovite	1.8	0	2.8
Biotite	.4	0	.5
Amphibole: Hornblende	.1	0	1.6
Pyroxene:			
Enstatite	3.2	5	13
Diopside	.5	57	47
Hypersthene	1.4	0	1.5
Hedenbergite	.1	15	3.6
Augite	2.8	1.4	6.3
Olivine:			
Olivine I (Arizona)	5.5	0	15
Olivine II (North Carolina)	.6	0	17

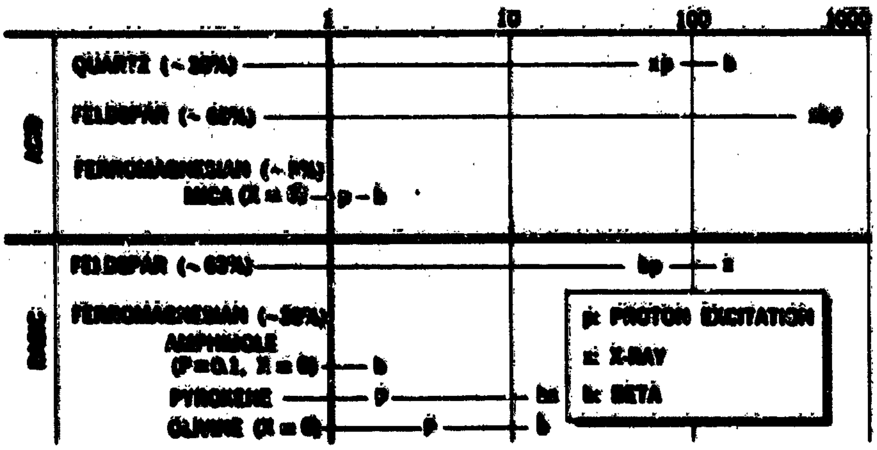

FIGURE 4.—Relative luminescence intensity of acid and basic igneous rock minerals.

TABLE 2.—*Chemical Composition of Possible Lunar Rocks*

Oxide	Amount, percent, in—					
	Granite [a]	Average igneous rocks [b]	Diorite [c]	Basalt [d]	Peridotite [e]	Meteorite [f]
SiO_2	71.0	59.4	55.5	49.1	42.0	36.3
Al_2O_3	14.5	15.4	17.0	15.7	4.7	2.0
Fe_2O_3	1.5	6.4	2.7	5.4	8.1	.1
FeO	1.1		4.8	6.4	5.6	13.0
MgO	.9	3.5	4.4	6.2	28.5	19.7
CaO	2.0	5.1	7.3	9.0	3.4	2.5
Na_2O	3.5	3.8	3.6	3.1	.8	.8
K_2O	4.1	3.1	2.4	1.5	.2	.2
Others	1.3	3.3	2.3	3.6	6.8	2.3
Total	100.0	100.0	100.0	100.0	100.1	76.9
Iron meteorite						23.0
Total						99.9

[a] From work of Tschirwinsky, cited in ref. 13.
[b] From work of Goldschmidt, cited in ref. 13.
[c] From work of Rosenbusch-Osann, cited in ref. 13.
[d] From work of Daly, cited in ref. 13.
[e] From work of Pirsson and Knopf, ref. 13.
[f] From work of Daly, cited in ref. 14; Watson, cited in ref. 15; and Mason, ref. 16.

TABLE 3.—*Mineral Composition of Possible Lunar Rocks*

	Amount, percent, in—					
	Granite	Average igneous	Diorite	Basalt	Peridotite	Meteorite
Quartz	32	13	6			
K-feldspar	23	19	15	10	1	1
Plagioclase	38	42	47	54	17	11
Mica	4					
Amphibole		21	20			
Pyroxene:						
Enstatite		3	6	7	22	17
Other		2	6	13	12	10
Olivine				13	42	38
Accessories	3	1	1	4	6	
Total	100	101	101	101	100	77
Iron meteorite						23
Total						100

TABLE 4.—*Estimated Relative Luminescence Intensity of Possible Lunar Rocks*

Rock	Intensity with excitation by—		
	Proton	X-ray	Electron
Granite	300	280	350
Average igneous	210	210	220
Diorite	120	140	80
Basalt	91	180	60
Peridotite	10	31	24
Meteorite	15	22	10

remote sensing, these results indicate that lunar counterparts of the rocks listed in the table should be distinguishable on the basis of luminescence response. At the very least, it should be possible to map lithologic differences over large areas. The particular rock types could then be identified by the use of spectral data in addition to intensity data and by calibration of the detected signal with the samples returned by the Apollo manned landing missions.

The meteorite and peridotite values in table 4 also represent a case of overlap, but this, it should be recalled, applies to the average meteorite composition, which contains about one part in four of iron. In any particular instance, an area of the Moon covered by iron meteorites only, a most favorable resource locality, would show almost zero luminescence. Chondritic stony meteorites, on the other hand, would be expected to have a luminescence intensity indistinguishable from that of peridotite, whereas the basaltic achondrites could probably not be distinguished from basalt on the basis of intensity.

Some of the luminescence spectra of the minerals measured with proton excitation are shown in figures 5 and 6. The bandwidth of the quartz prism monochromator with the slit widths required was rather wide in the visible wavelengths; therefore, the spectra have been corrected to give values over more narrow intervals. The most outstanding feature is the tendency for the quartz and the feldspar spectral peaks to occur at wavelengths longer than 500 mμ and for the ferromagnesian spectral peaks to occur at wavelengths shorter than 500 mμ. Other spectral differences are apparent, but their significance cannot be evaluated without additional study, especially of numerous samples of each mineral representing various localities, geologic ages, and forms of crystallization, and of the flash and aging effects described by Nash (ref. 12). These additional studies are now in progress.

The measurements of the common igneous rock-forming minerals just described will assist in mapping the country rocks of the Moon and, to the extent that resource deposits are associated with one or another rock type, will assist in selecting areas that should be explored more intensively. We would like also to use remote sensing techniques based on luminescence to detect resource deposits directly. For this purpose we are studying some of the more important pneumatolytic and hydrothermal minerals that may be stable or metastable under lunar-surface conditions. Hydrothermal and pneumatolytic deposits may occur on the Moon if internal processes, such as local volcanism and defluidization, have been active, as seems to be the case according to evidence from lunar orbiter photographs and from studies of lunar transient events. The deposits could occur as surface blankets or as fillings and linings of fissures opened by either impact or internal forces. They will be a prime target for lunar resource exploration both because of the water and other resources contained in the minerals and because the fissure itself, in the case of fissure occurrences, may have been an avenue for rising fluids and may contain bodies of water (or ice) trapped below the surface. The hydrothermal and pneumatolytic minerals included in our studies are the silicates, epidote, serpentine, chlorite, and the zeolites, which contain water or OH groups; sulfur and the sulfates; barite and alunite, which are sources of sulfur; and the carbonates calcite and magnesite, of which calcite, at least in some of its forms, is known to be a strongly luminescent mineral.

Some resource materials are known to be strongly luminescent and could be detected against the relatively much more weak lumi-

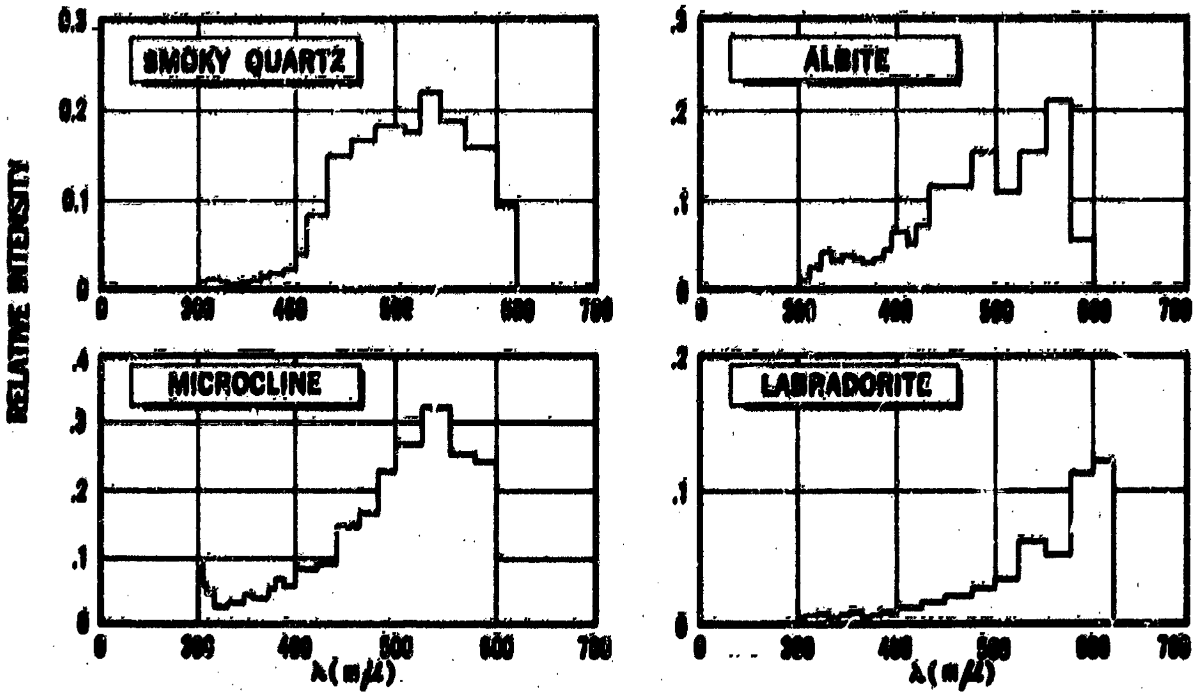

FIGURE 5.—Luminescence spectra of quartz and feldspars with proton excitation.

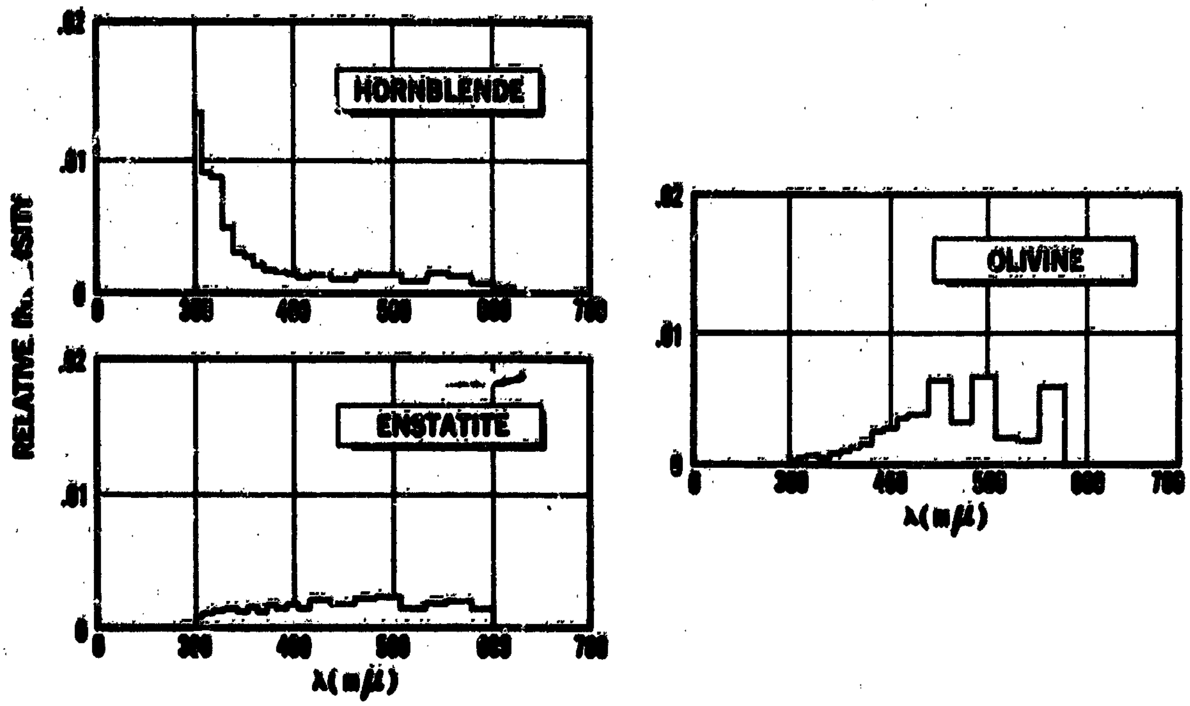

FIGURE 6.—Luminescence spectra of ferromagnesian minerals with proton excitation.

nescence of the common igneous rocks. These include fluorite (CaF_2), scheelite ($CaWO_4$), and kunzite, a type of spodumene ($LiAlSi_2O_6$).

In the studies now in progress, we are also evaluating ultraviolet radiation as an excitation source and studying the effects of grain-size variation, temperature variation, and radiation damage on the luminescence characteristics. The results of these studies are expected to provide a foundation upon which a luminescence remote sensing technique can be built both for general geologic mapping and for the discovery of resource deposits.

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