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LUNAR SAMPLE ANALYSIS PROGRAM

LUMINESCENCE ANALYSIS OF LUNAR SAMPLES

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"Luminescence of Apollo 14 and Apollo 15 Lunar Samples"

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by

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LUMINESCENCE OF APOLLO 14 AND APOLLO 15 LUNAR SAMPLES

Norman N. Greenman and H. Gerald Gross

ABSTRACT

Luminescence measurements have been made of Apollo 14 lunar samples with far u.v., X-ray, and proton irradiation and of Apollo 15 lunar samples with X-ray irradiation. Preliminary efficiencies with the far u.v. are in the range 10^{-3} to 10^{-2}; efficiencies with X-rays and protons are in the range 10^{-8} to 10^{-6}. The crystalline igneous rocks show higher efficiencies, in general, than the breccias and glasses, and the ratio of intensity of the green to the blue luminescence peak tends to be higher for the crystalline igneous rocks than for the breccias and glasses. Therefore, both the efficiency and the spectral character appear to have a systematic relationship to lithologic type (granitic versus gabbroic versus fragmental) and to geologic history and processes on the moon (shocked versus unshocked or only mildly shocked material).

INTRODUCTION

We have been studying the luminescence of the Apollo lunar samples for the purpose of (1) understanding how the luminescence behavior reflects the origin, history, and environment of the lunar rocks, (2) discovering luminescence characteristics that might aid in geologic mapping and other lunar exploration activities, and (3) evaluating reports of luminescence on the moon based on astronomical observations. We have already reported the results of our studies of the Apollo 11 and Apollo 12 samples (GREENMAN and GROSS, 1970a, 1970b, 1971) and some results from the Apollo 14 sample studies (GREENMAN and GROSS, 1972). In this paper we present additional Apollo 14 and some Apollo 15 sample results.

EXPERIMENTAL PROCEDURE

The experimental arrangements for the various irradiations were described in detail in our previous paper (GREENMAN and GROSS, 1971). In this series of measurements the only major modification was the use of a McPherson 2 m spectrograph as a dispersing instrument in our far u.v. irradiations.

The samples used in the measurements are as follows: Apollo 14: 14003,19 (fines, contingency sample), 14163,30 (fines, bulk sample), 14259,37 (fines, comprehensive sample), 14301,50 (breccia, exterior), 14321,264 (breccia, interior), and 14310,155 (basalt, exterior); Apollo 15: 15015,22 (dark, vesicular, shiny glass from bottom exterior coating), 15015,22,1 (breccia, immediately adjacent to 15015,22), 15015,27 (dark, frothy, dull glass from top exterior coating), and 15085,28 and 15085,30 (both coarse-crystalline gabbro, exterior); terrestrial: granite (California), gabbro (California), and willemite (New Jersey).

DATA ANALYSIS AND RESULTS

Far u.v. irradiation (1100-2200Å)

The terrestrial and lunar samples were first investigated with two vacuum monochromators, one to provide monochromatic excitation from the light source and the second to scan the sample luminescence, but no measurable results were obtained because of the low intensity of the hydrogen discharge light source ($\sim 10^8$ photons/sec). The procedure was then changed to measure the excitation spectrum; that is, the second monochromator was removed, and the variation in total sample luminescence was recorded as the spectrum of the light source was scanned (only luminescence above 3000Å could be sensed because of the detector cutoff). A series of Corning filters was used to study the luminescence spectrally. The most intense radiation in the spectrum of the light source consisted of the group of lines in the band 1200-1400Å and a continuum from about 1800Å into the near u.v.

The excitation spectrum showed (1) two luminescence maxima at excitation wavelengths of about 1370Å and 1700Å in all samples; (2) approximately five smaller bands produced in the interval 1400-1800Å; and (3) the possibility of very narrow bands at about 1230, 1375, 1522, 1569, 1800, 1870, and 1879Å in lunar sample 14310,155, with similar sets for each of the terrestrial samples (Figs. 1-4). Efficiencies determined on the basis of the first maximum at 1370Å are given in Table 1. They are given as ranges because of the uncertainty as to the spectral character of the luminescence.

The major excitation peak at around 1700Å proved to be the most intense in all cases. The light source does not show any significant irradiation intensity in the band 1400-1800Å. Therefore, this peak is produced either

Table 1. Luminescence efficiencies of lunar and terrestrial samples for the excitation band around 1370Å.

Sample	Total band efficiency range (ergs/erg)
Lunar:	
14310,155	3×10^{-2} to 5×10^{-3}
Terrestrial:	
Granite	3×10^{-2} to 5×10^{-3}
Gabbro	5×10^{-3} to 8×10^{-4}
Willemite	4×10^{-1} to 6×10^{-2}

by a lower intensity band around 1600Å, or by higher orders of the extreme u.v.

X-ray irradiation

The results of irradiation with X-rays from a tungsten target at 70 kV, 45 ma, are shown in Figs. 5-8. Distinct to prominent blue (4100-4500Å range) and green (5300-5800Å range) luminescence peaks are present in all samples. A red peak (6400-7200Å range)is distinct in granite but barely discernible, though present, in gabbro and the Apollo 14 samples; it is not evident in the Apollo 15 samples. A faint to distinct near u.v. peak (3300-3600Å range) is present in terrestrial granite and gabbro, in the Apollo 14 samples, and in the Apollo 15 breccia and glass, but is absent in the Apollo 15 gabbro. A small middle u.v. peak (2800-3000Å range) is present in terrestrial granite and gabbro but is absent in all lunar samples with the possible exception of a questionable peak in the 2600-2800Å range in the Apollo 15 samples.

A significant feature of these spectra is that the intensity ratio of the green to the blue peak, with one exception, appears to be related to lithologic type. The ratio is 1 or greater for the crystalline igneous rocks, both terrestrial and lunar, and less than 1 for the breccias and glasses. The exception is one of the two Apollo 15 gabbro samples, 15085,28, the ratio of which is in the breccia and glass range, although its companion sample from the same rock, 15085,30, has a ratio in the igneous range, in conformity with the pattern. Because these two samples are small and the crystals of which they are composed large, this disparity in ratios may be the result of greatly different proportions of luminescent plagioclase to poorly- or non-luminescent pyroxene in the two samples. According to GEAKE, *et al.* (1972), the green peak is caused by Mn^{2+} in Ca^{2+} sites, whereas the blue peak is attributed to strain defects common in silicates. The blue, associated with the silicate nature of plagioclase and pyroxene, might then be expected to vary less in intensity than the green, associated with the more abundent Ca^{2+} sites in plagioclase than in pyroxene. This seems to be the case here because the difference in the intensity of the green peak accounts for the entire difference in ratios between the two samples; the intensity of the blue peak is the same in both. The low ratio for sample 15085,28, therefore, may well be anomalous.

The green-to-blue peak relationships also appear to hold in the luminescence spectra obtained with high energy (100 keV) proton irradiation but not in those obtained with low energy (5 keV) proton irradiation (see below).

Data on the X-ray irradiation are given in Table 2.

Proton irradiation

Two series of proton irradiation measurements were made. One was with protons of 5 keV energy, flux density of 9.3×10^{13} protons/cm^2 sec, and energy flux density of 7.5×10^5 ergs/cm^2 sec; the second was with protons of 100 keV energy, flux density of 7×10^{12} protons/cm^2 sec and energy flux density of 1.1×10^6 ergs/cm^2 sec. The curves for the low energy proton irradiation are shown in Figs. 9-12; those for the high energy in Fig. 13. Both sets are generally similar to the X-ray irradiation results; the chief difference is the tendency for the blue and green peaks in the proton-excited luminescence to broaden and merge into the continuum level. This tendency is more marked with the low than with the high energy protons and makes for some blurring in the latter case and eradication in the former case of the

Table 2. Luminescence data for lunar and terrestrial samples with X-ray irradiation.

Sample	Peak Wavelength (Å)	Bandwidth* (Å)	Total band efficiency (ergs/erg)
Lunar			
14301,50	3330, 4420, 5500, 6600	500, 880, 880, 480	7×10^{-7}
14321,264	3340, 4340, 5490, 6620	470, 880, 810, 440	9×10^{-7}
14310,155	3330, 4350, 5530, 6680	400, 890, 780, 580	3×10^{-6}
15015,22	(∿3500?), 4480, 5550	1140, 1100	3×10^{-8}
15015,22,1	(∿3300), 4340, 5590	690, 1100	2×10^{-7}
15015,27	(∿3300), 4380, 5640	790, 970	7×10^{-8}
15085,28	4450, 5380	830, 1280	6×10^{-7}
15085,30	4450, 5570	900, 780	1×10^{-6}
Terrestrial			
Granite	3410, 4230, 5760, 7180	580, 810, 610, 1220	2×10^{-5}
Gabbro	3370, 4260, 5690, 6470	480, 850, 820, 740	3×10^{-6}
Willemite	3540, 4160, 5330	410, 460, 420	2×10^{-3}

*Full width at half maximum.

green-to-blue peak ratio relationships mentioned in the preceding section. Table 3 summarizes the luminescence data for the proton irradiation.

In the irradiation with protons of 5 keV energy the samples displayed a luminescence intensity decline over a time interval of the order of minutes. In our earlier studies we found that, in the 1000-4000Å luminescence band with 100 keV proton irradiation, an Apollo 11 breccia (10048,36) showed a lower initial intensity and a lower rate of intensity decline than an Apollo 11 (10044,53) and two Apollo 12 (12002,114; 12020,55) crystalline igneous rocks (Fig. 14). All three Apollo 14 rocks, however, had lower decline rates than the Apollo 11 and 12 samples, and the crystalline rock rate was somewhat lower than the rates for the fragmental rocks. In part, this may be due to the fact that the two sets of data are not directly comparable. The rates for the Apollo 11 and Apollo 12 samples were calculated from 100 keV proton data on peaks in the middle and near u.v. whereas those of the Apollo 14 samples were calculated from 5 keV proton data on peaks and portions of the band in the visible wavelengths. Also, because of the time durations of the respective runs, the middle and near u.v. data points could be taken at about three minute intervals, whereas the data points in the visible band had to be taken at about seven minute intervals. It is also possible that the decline characteristics of the u.v. luminescence may yield better diagnostic information than those of the visible. NASH and GREER (1970) have reported luminescence decline characteristics associated with lunar rock type and exposure history, and SIPPEL and SPENCER (1970) have reported what are probably related features, intensity and spectral differences in luminescence between shocked and unshocked feldspars. These decline characteristics with proton excitation, therefore, appear to contain important information on the geologic history of lunar rocks.

Table 3. Luminescence data for lunar and terrestrial samples with proton irradiation.

Sample	Peak wavelength (Å)	Bandwidth* (Å)	Total band efficiency (ergs/erg)
Low Energy (5 keV)			
Lunar:			
14301,50	4730, 5510 declining to broad band	2250	1×10^{-6}
14321,264	5300 (broad)	2270	1×10^{-6}
14310,155	5230	1990	1×10^{-6}
Terrestrial:			
Gabbro	4720	1620	5×10^{-6}
High Energy (100 keV)			
Lunar:			
14301,50	4590, 5450	1210, 1620	6×10^{-7}
14321,264	4380, 5520	760, 1280	2×10^{-6}
14310,155	4340, 5480	760, 1070	3×10^{-6}
Terrestrial:			
Granite	5620	2600	1×10^{-6}
Gabbro	4660, 5380	970, 2520	5×10^{-6}

*Full width at half maximum.

DISCUSSION

The luminescence characteristics of the Apollo samples and of the terrestrial comparison samples appear to contain information both as to lithologic type (granitic versus gabbroic) and as to geologic history and processes (unshocked or mildly shocked lunar igneous versus more strongly shocked lunar breccia). Despite some overlap of Apollo 14 and Apollo 15 samples, the efficiencies within each group tend to be higher for the igneous rocks than for the breccias and glasses; moreover, all, in general, tend to be comparable to that of terrestrial gabbro and less than that of terrestrial granite. This is in accord with previous studies (GREENMAN et al., 1965; GREENMAN and MILTON, 1968; NASH, 1966), which have shown granitic rocks to have higher efficiencies than gabbroic ones, so that lunar rocks of more sialic character can be expected to show corresponding relationships. The lower efficiency of the lunar breccia as compared to that of the lunar igneous rock of comparable chemical composition is probably a reflection of shock degeneration of the luminescence (SIPPEL and SPENCER, 1970) and probably also of an admixture of poorly-luminescent glass.

The ratio of the green to the blue luminescence peak also appears to contain both lithologic and geologic process information. The higher ratio in granite than in gabbro and the relationships discussed above between the two Apollo 15 igneous samples 15085,28 and 15085,30 suggest that this ratio reflects lithologic differences. The higher values of the lunar igneous rocks as compared with those of the breccias and glasses, as in the case of the efficiency comparison, may result from greater shock degeneration of the green than of the blue peak and possibly also, in the breccias, an admixture of glass.

All the lunar sample efficiencies we have measured to date, with one exception, are low and, therefore, cannot account for the astronomical observations of luminescence on the moon. The exception, the efficiencies reported here for far u.v. irradiation, are high, but these are preliminary values and require further verification. The solar energy in these far u.v. wavelengths, however, is low enough so that even if these efficiencies are confirmed they still could not account for the reported observations.

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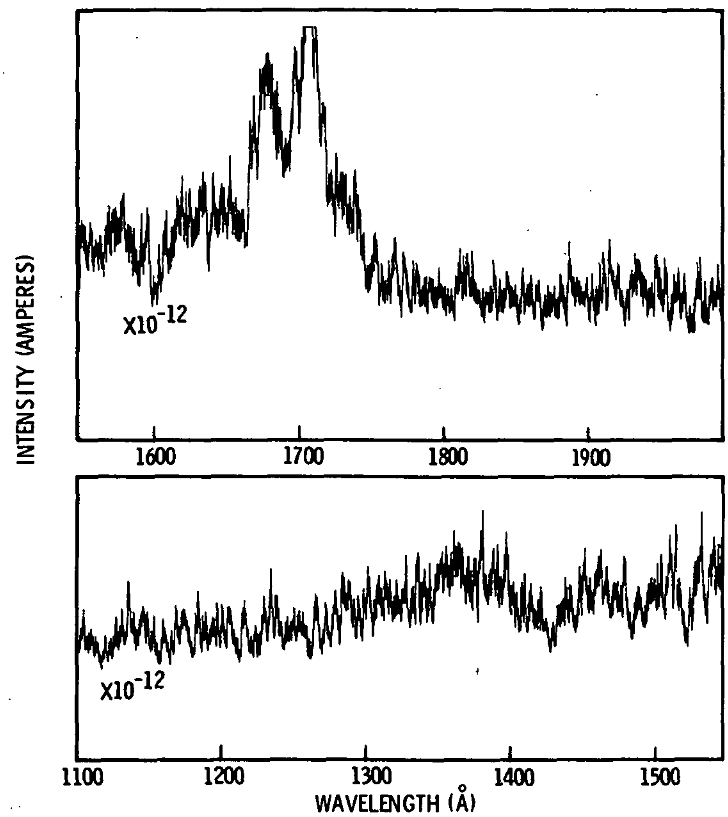

Figure 1. Luminescence of Apollo 14 sample 14310,155 with scanned far u.v. (1100–2200Å) irradiation.

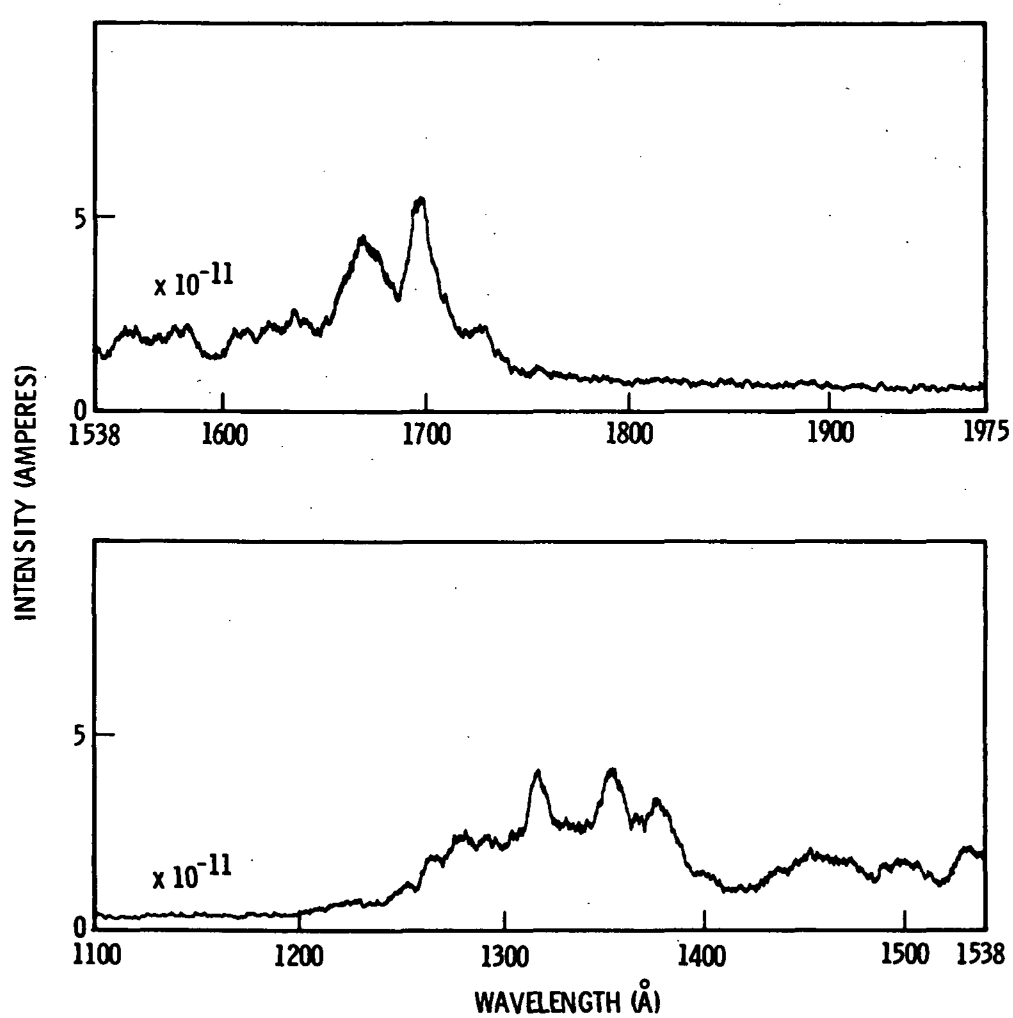

Figure 2. Luminescence of granite with scanned far u.v. (1100–2200Å) irradiation.

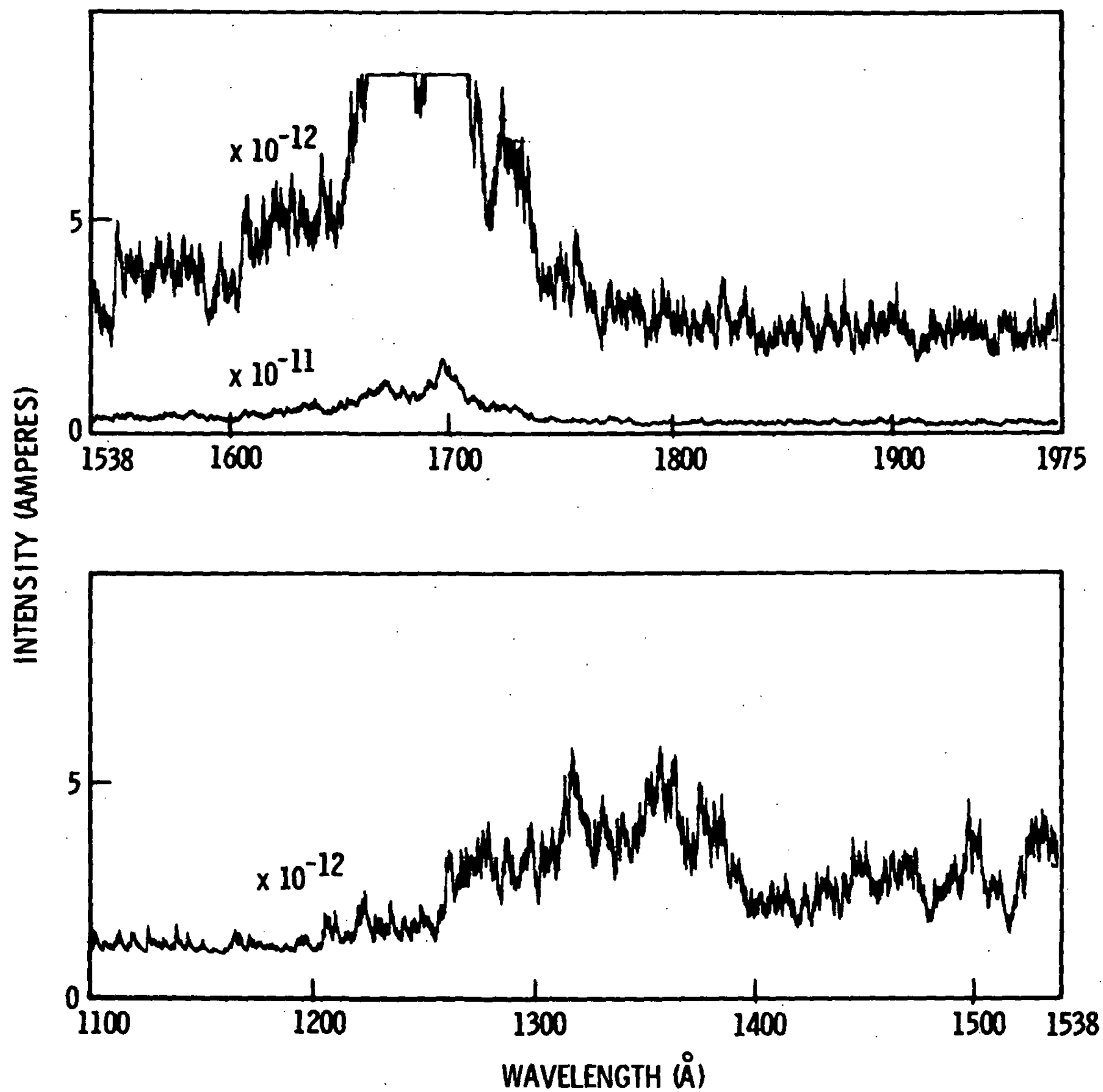

Figure 3. Luminescence of gabbro with scanned far u.v. (1100–2200Å) irradiation.

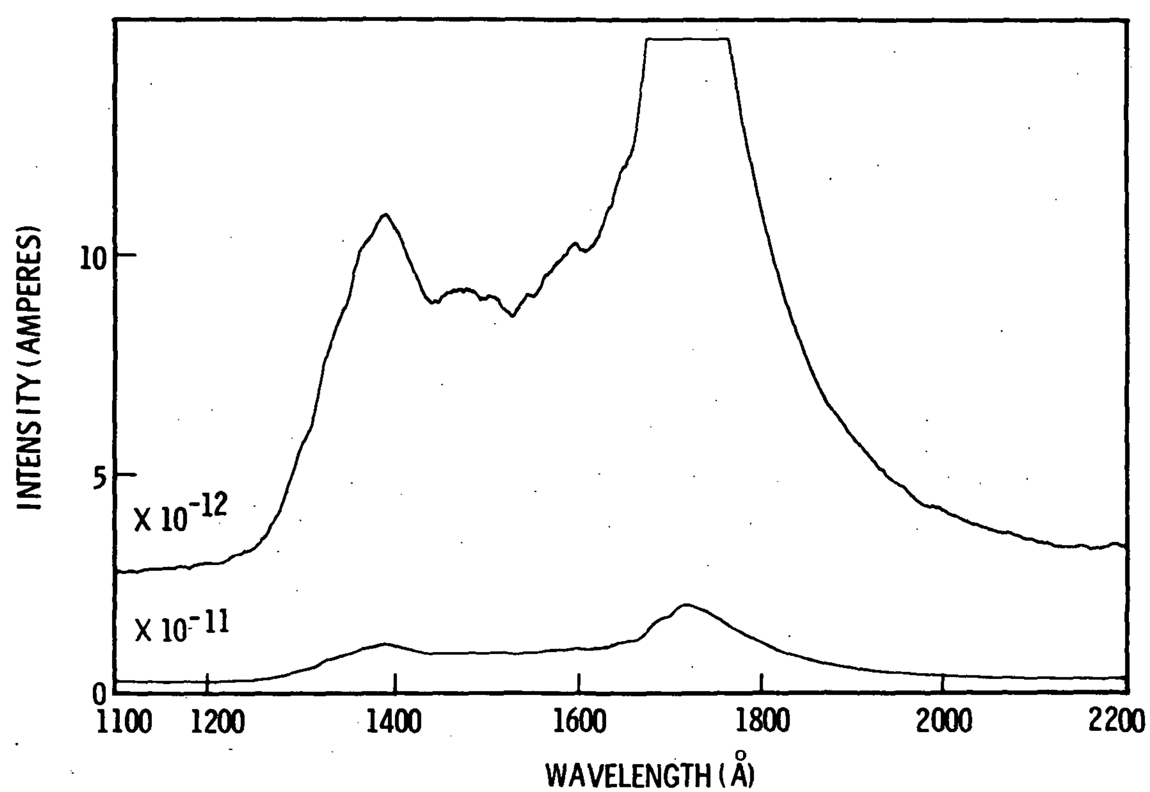

Figure 4. Luminescence of willemite with scanned far u.v. (1100–2200Å) irradiation.

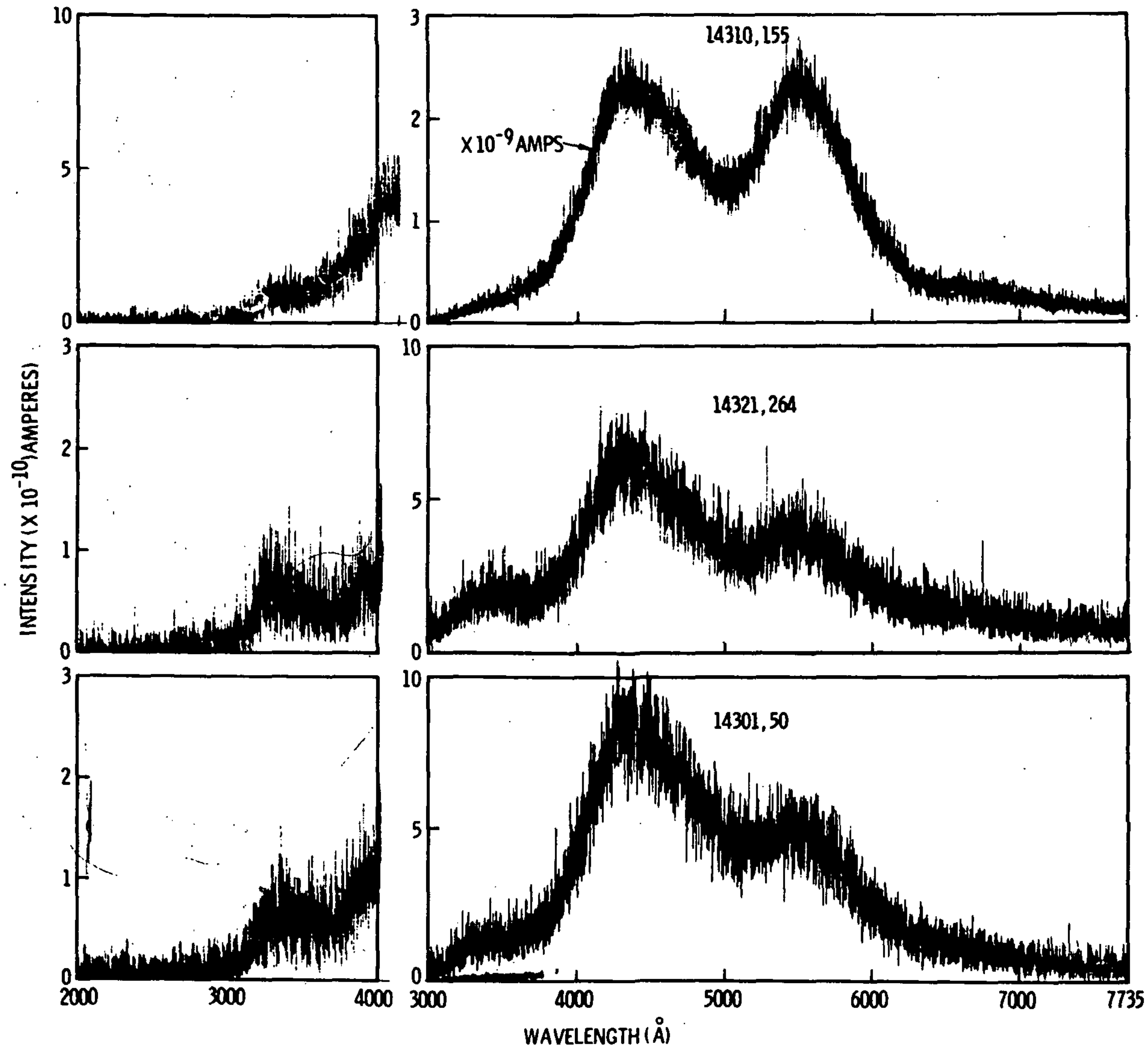

Figure 5. Luminescence of Apollo 14 samples with soft X-ray (0.2–8Å) irradiation.

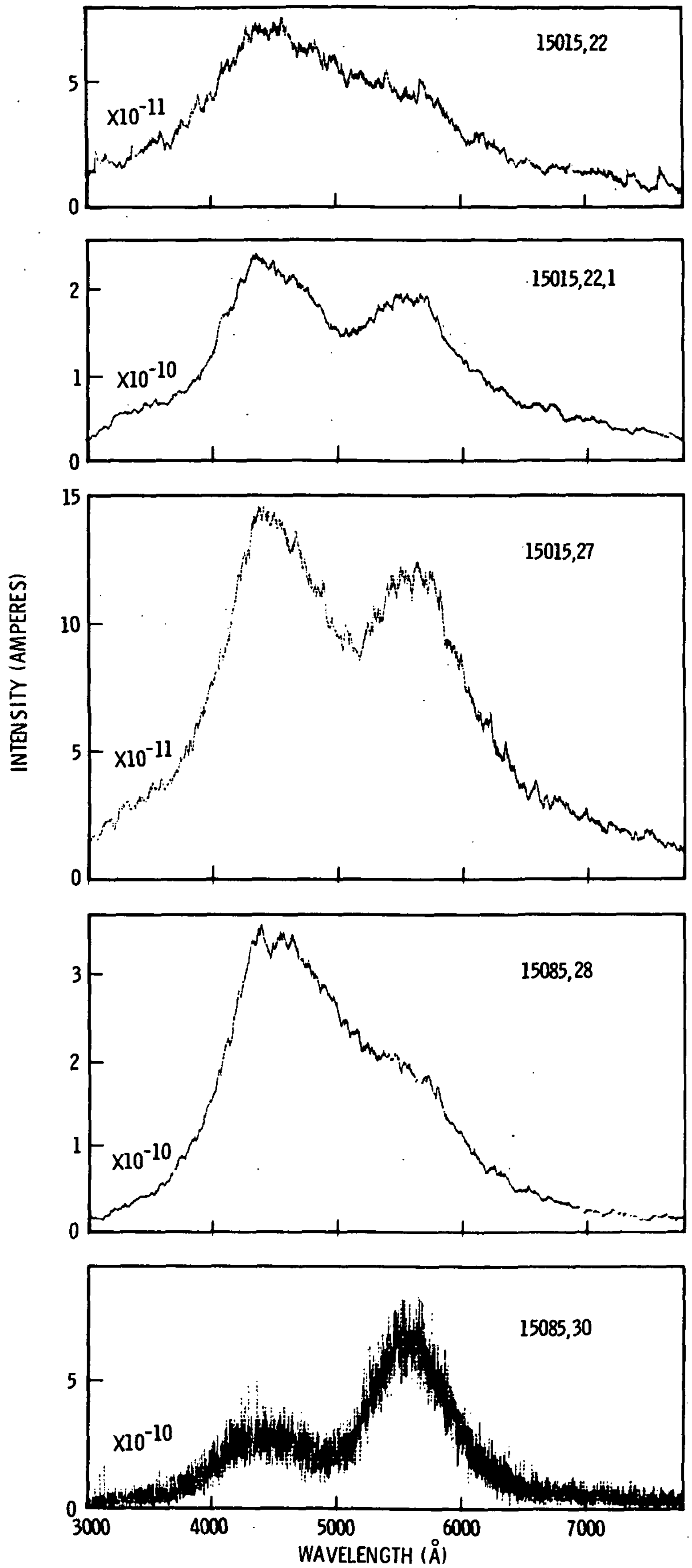

Figure 6. Visible-wavelength luminescence of Apollo 15 samples with soft X-ray (0.2–8Å) irradiation.

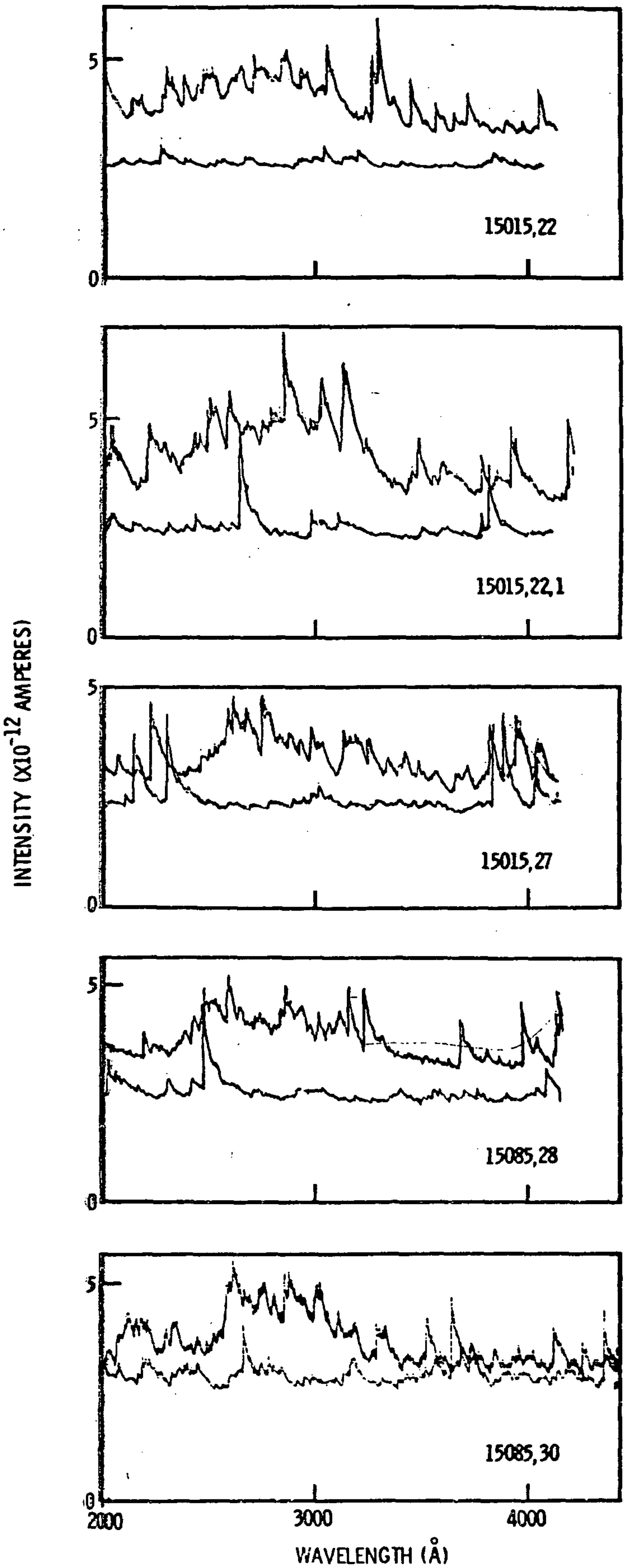

Figure 7. Possible u.v. luminescence of Apollo 15 samples with soft X-ray (0.2–8Å) irradiation. Upper curve, signal from sample; lower curve, dark current.

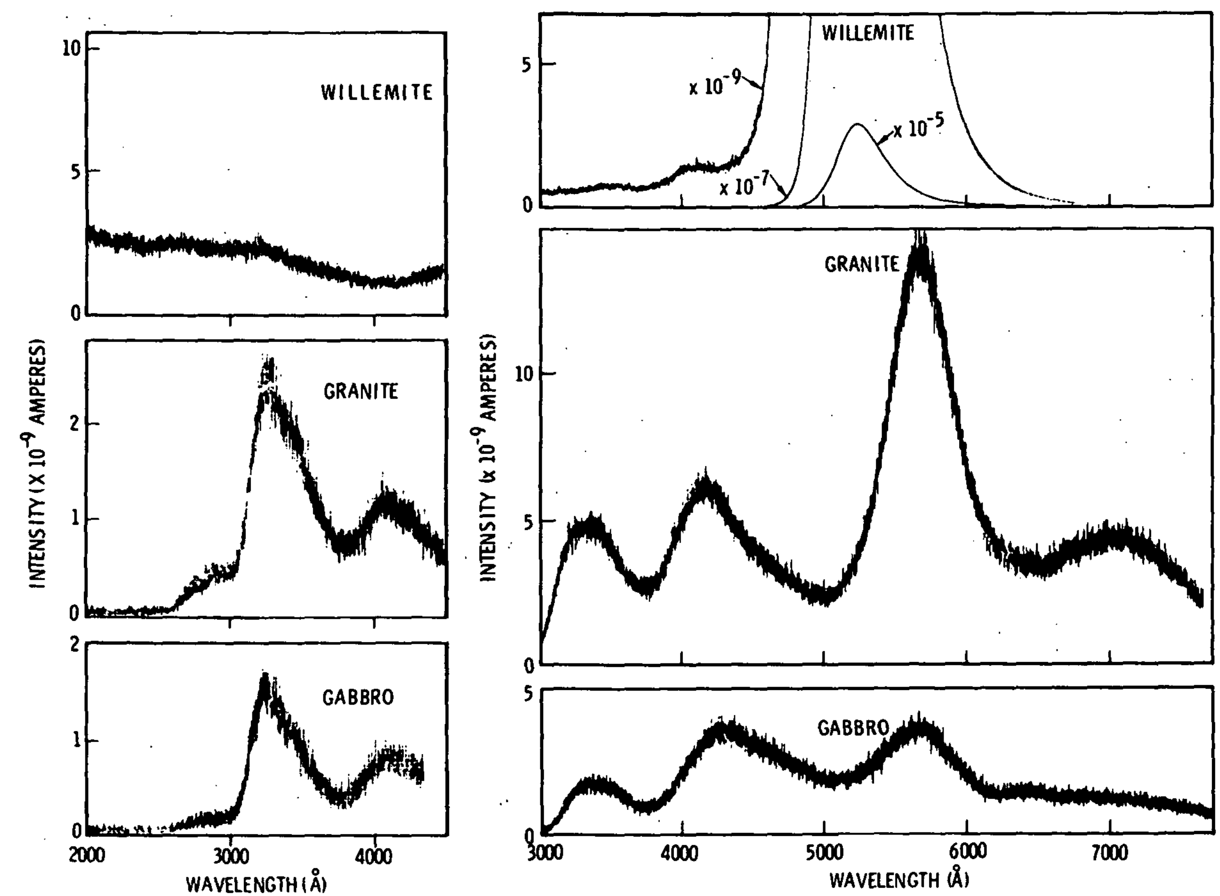

Figure 8. Luminescence of terrestrial mineral and rocks with soft X-ray (0.2–8Å) irradiation.

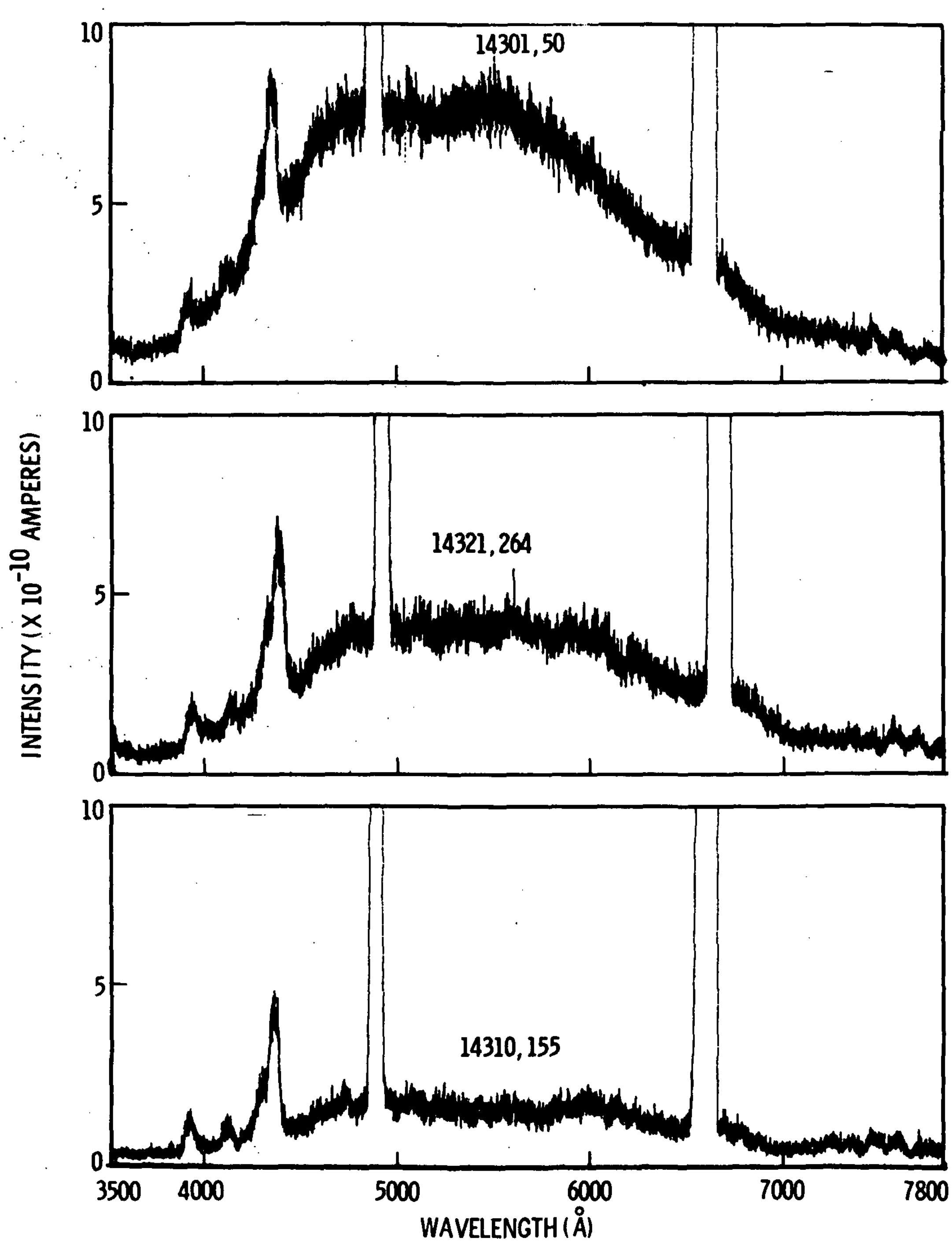

Figure 9. Visible-wavelength luminescence of Apollo 14 samples with proton (5 keV) irradiation.

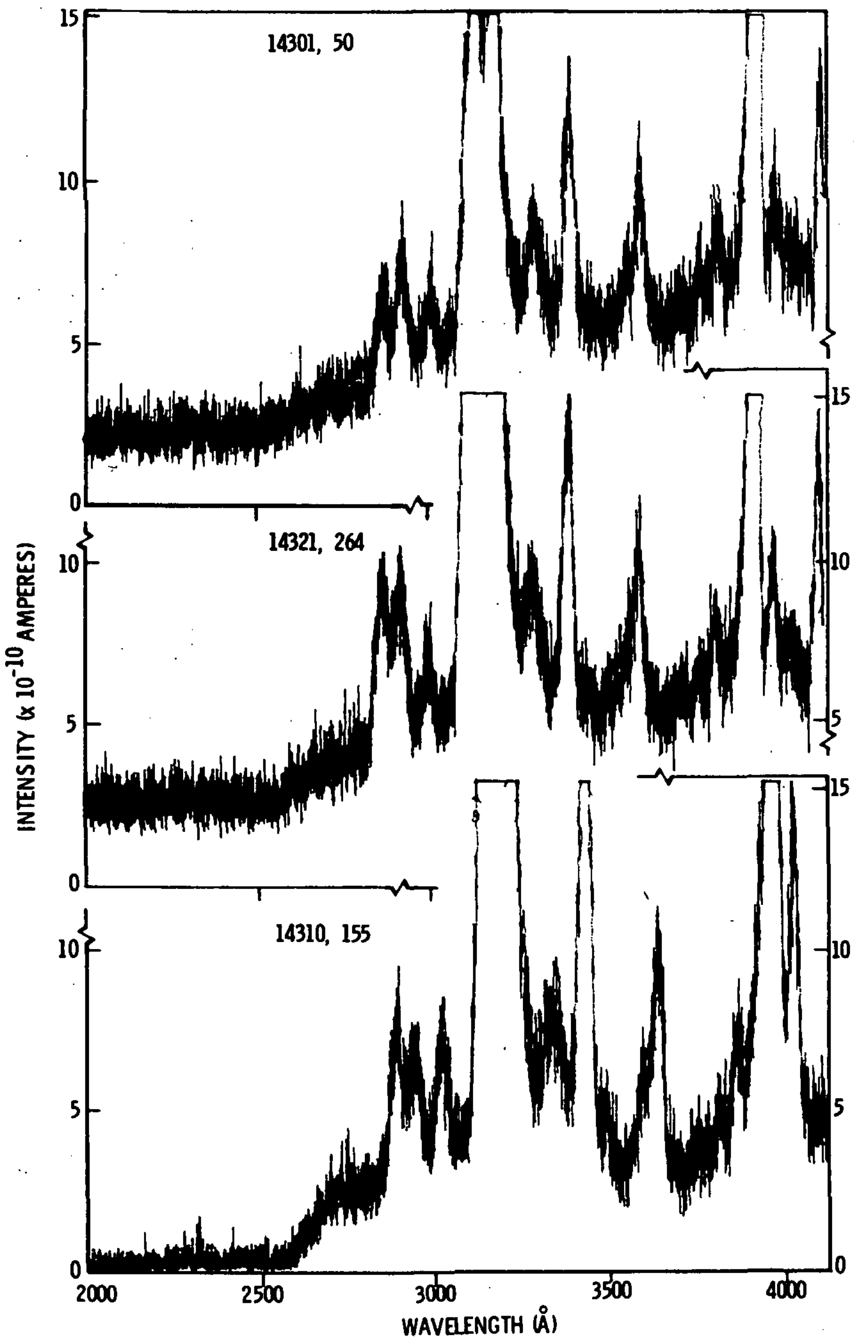

Figure 10. U.V. luminescence of Apollo 14 samples with proton (5 keV) irradiation.

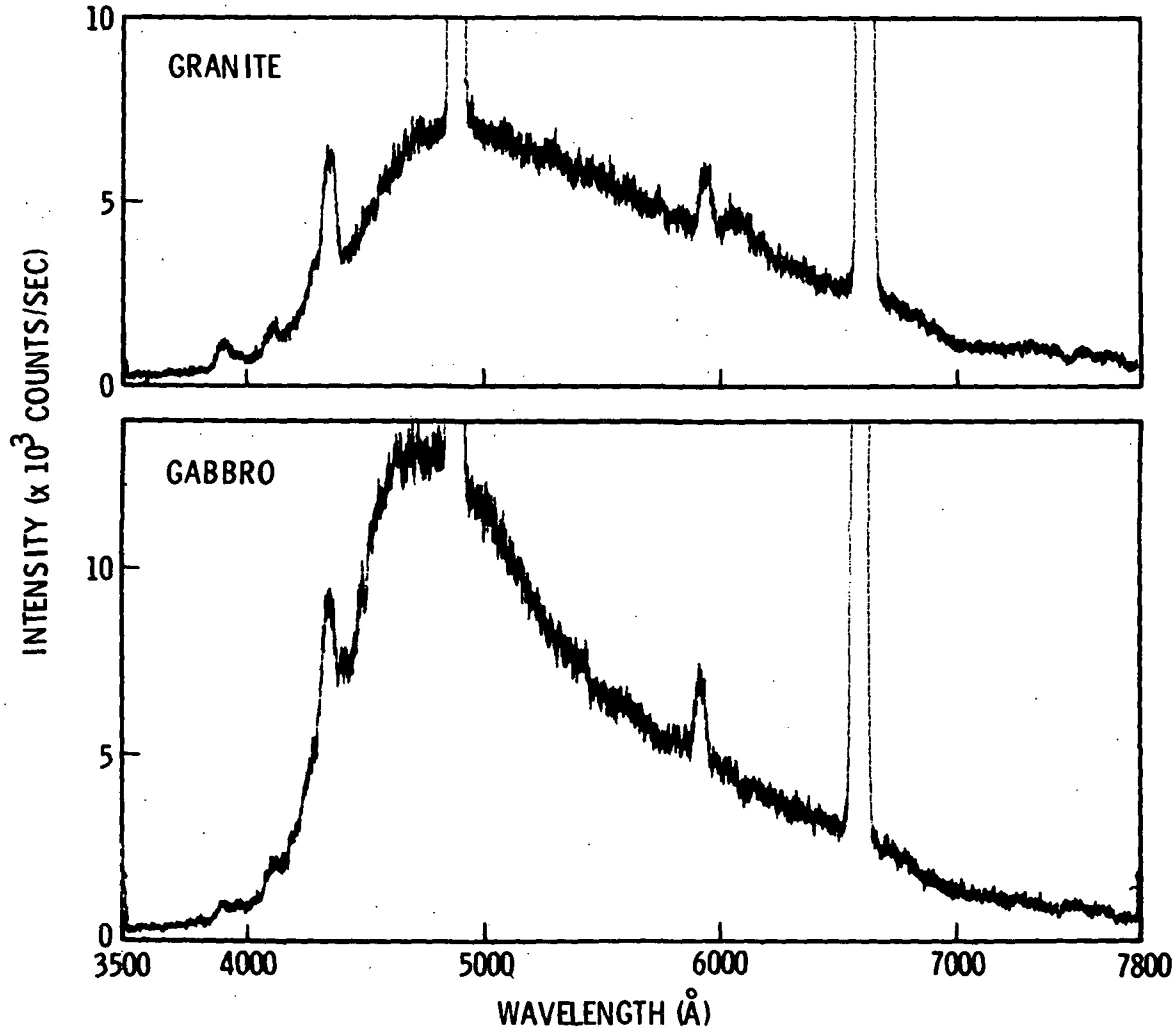

Figure 11. Visible-wavelength luminescence of terrestrial rocks with proton (5 keV) irradiation.

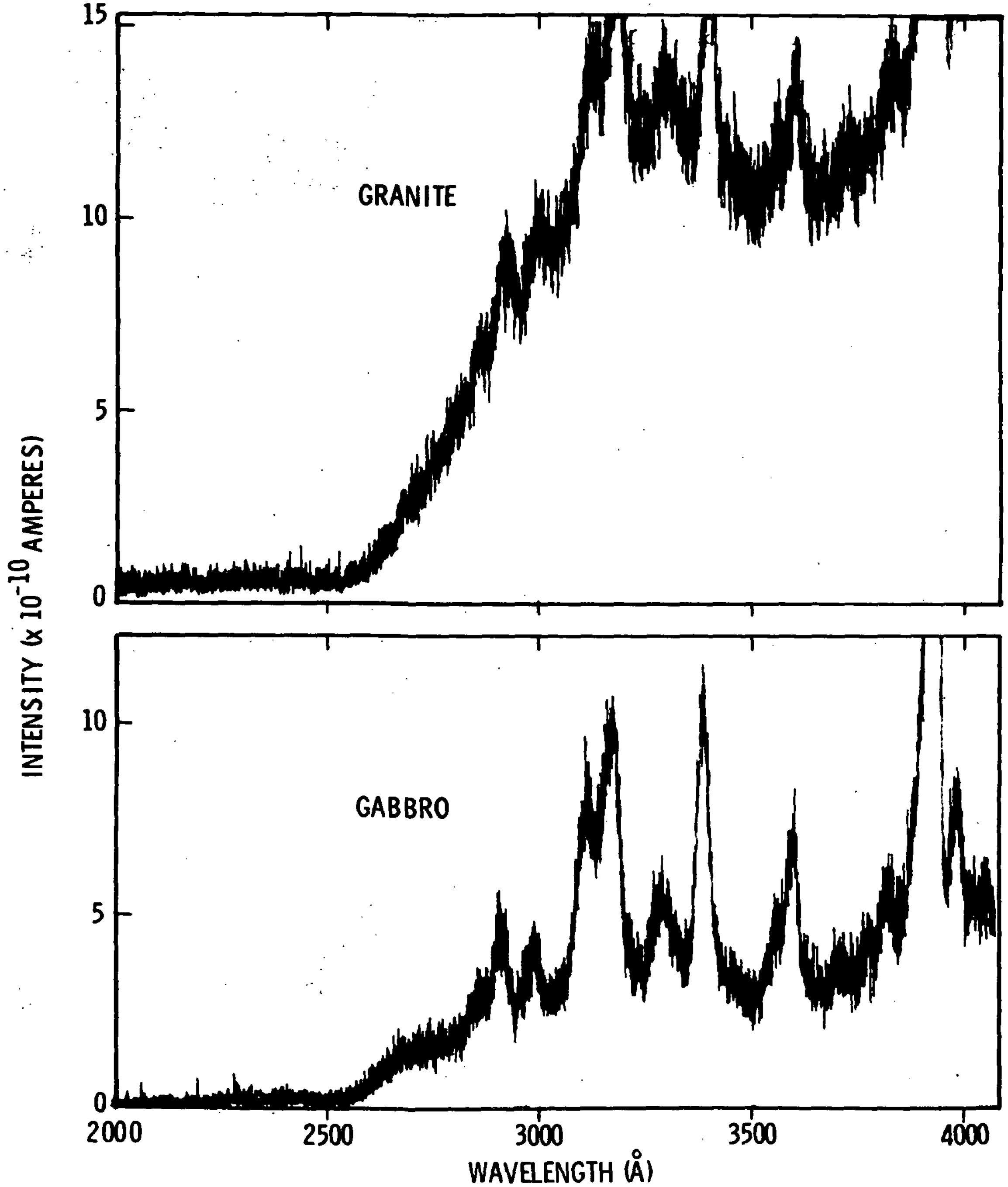

Figure 12. U.V. luminescence of terrestrial rocks with proton (5 keV) irradiation

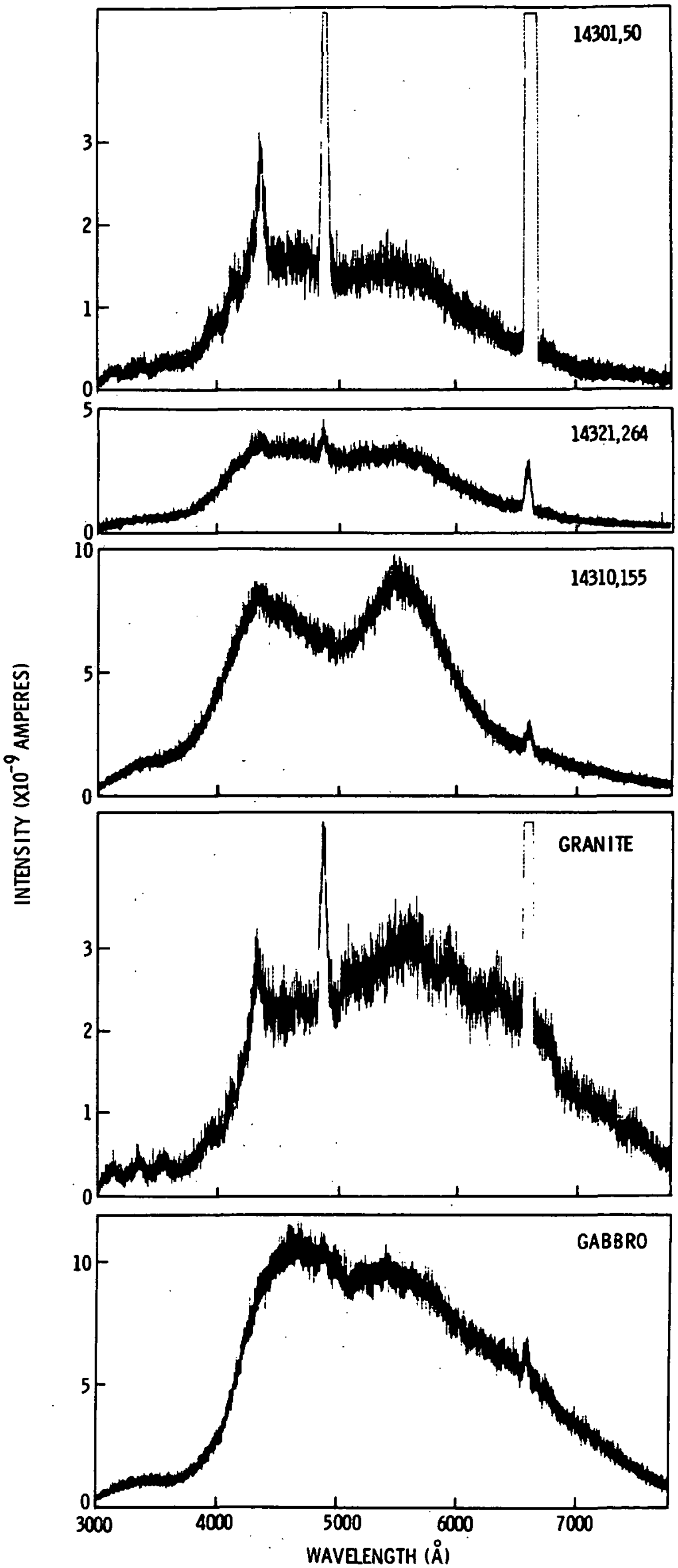

Figure 13. Luminescence of Apollo 14 and terrestrial samples with proton (100 keV) irradiation.

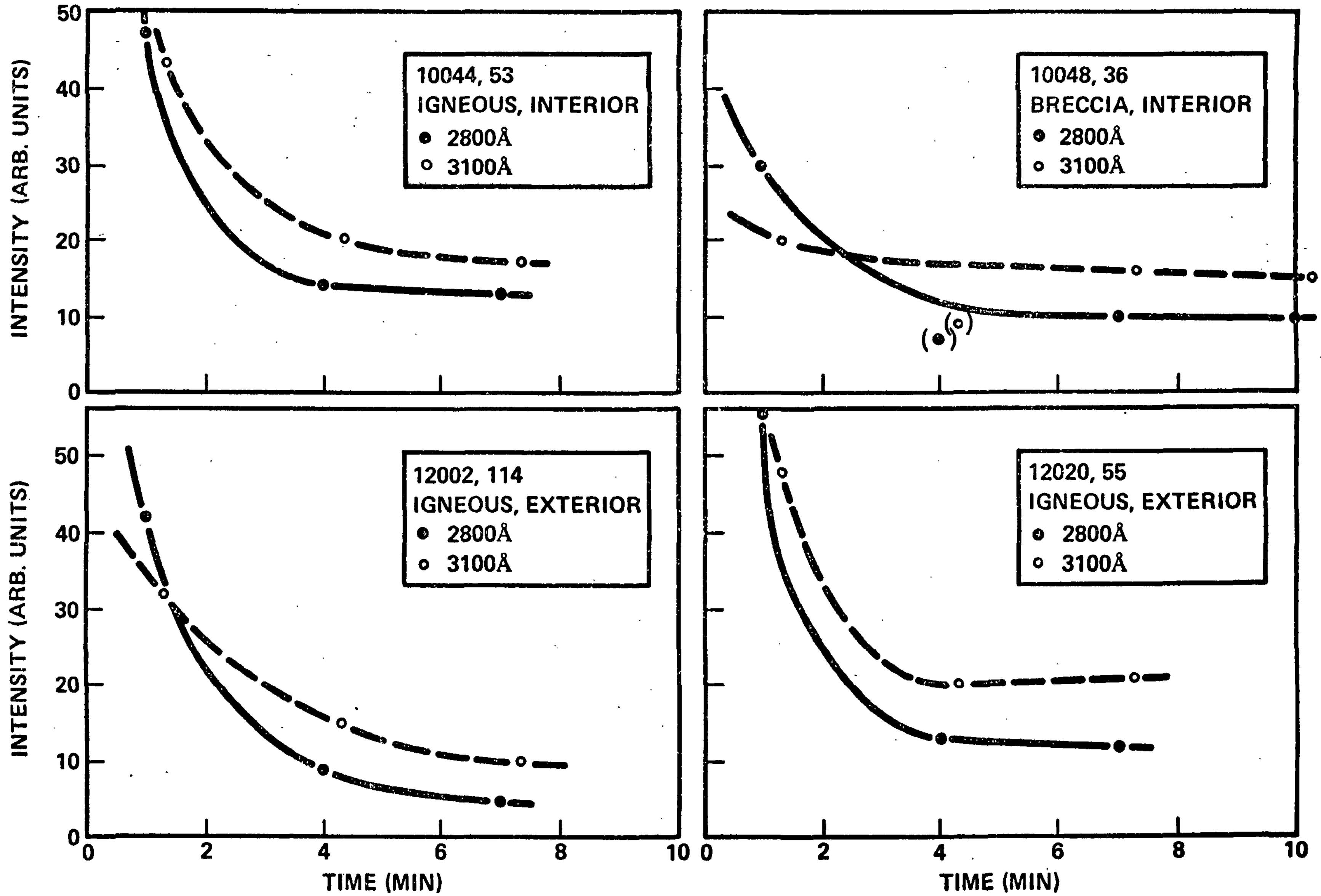

Figure 14. Luminescence intensity decline in Apollo 11 and Apollo 12 samples with irradiation time. Luminescence peaks at 2800Å and 3100Å, irradiation with 100 keV protons.