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LUMINESCENCE PETROGRAPHY OF LUNAR SAMPLES

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ABSTRACT

Light-colored metaclastic rock fragments, mainly anorthositic breccias, are dominant in the lithic clasts of rock 14321 and constitute about 25% of the Apollo-14 soils. Concentration of anorthositic breccias is less in the Apollo-15 soils, but is higher in the Front samples ~10% than in the Mare ~2.5% or the Rille samples ~0%. The Rille edge soils are extremely rich in basalt fragments ~33%. The Apollo-15 soils are also very rich in green glasses. True anorthosites in the Hadley region were found only at the St. George Crater site, a Front location. Varying degrees of metamorphism were found in the anorthositic fragments, and luminescence zonations give independent evidence of metamorphism. Compositional zoning is found and verifies the interpretation of the luminescence observations. However, in the true anorthosites ~An(97) compositional zoning is slight or nil. Rock 14321 gives evidence of having been subjected to modest annealing (post-lithification), but the light metaclastic fragments were metamorphosed before incorporation into the rock. It is shown that reaction rimming on plagioclase (an evidence of post-lithification annealing) results in mosaicism and preferentially affects grains evidencing microscopic disorder resulting from shock damage. The mechanism involves alkali ion diffusion and associated recrystallization into diversely oriented mosaic domains. The spectral analysis of luminescence in plagioclase shows results very similar to those reported for Apollo-12. A red-infrared emission band is present in a small fraction of plagioclase grains, but is weak by terrestrial norms. Samples from trench bottoms, and one which was collected from beneath a large boulder, were studied and compared with surface samples. No differences attributable to radiation effects were found. However, large variations in soil composition were found indicating marked layering in the Apollo-15 soils. It is shown that gradual zonation of luminescence (previously reported) results from zonation of ferrous iron. Data given here also raise serious doubt that Mn^{++} is the activator ion producing the green plagioclase emission band.

I. INTRODUCTION

As originally signed, Contract NAS 9-11610 provided for Luminescence Petrography of Lunar Samples, comparative study of terrestrial and meteoritic specimens and auxiliary experiments to determine fundamentals of the luminescence mechanism. The cost estimate was $58,200. In early 1971 Dr. Sippel, the principal investigator for Contract NAS 9-11610, also became involved in a project involving the vital interests of the Mobil Oil Corporation, and by mid-year the demands on his time became so great that adjustment of the NASA commitment was required. Accordingly, the contract was amended on August 30, 1971. Comparative studies and auxiliary experiments were dropped from the work statement and the cost estimate reduced to $32,000. This sum was to cover luminescence petrography of lunar samples only.

Time pressures did not abate in the latter part of the year as expected, and it became clear that even this reduced amount of work could not be completed. Dr. Sippel consulted with Mr. John W. Harris of MSC by telephone concerning the necessity for further amendment of the contract. Mr. Harris felt the best procedure would be to simply continue to the end of the contract doing as much work as possible, and to provide a final report. Through January 31 we have incurred costs of $11,856 which have been billed. We present here an account of the work which we have done under the contract. Studies were performed on two rocks and two soil samples from the Apollo-14 flight, and one rock and eight soil samples from Apollo-15.

II. LUNAR ROCKS

Rock Sample 14310

This specimen, thought to have been collected just east of Triplet Crater at Station G, is a fine-grained basalt of intergranular to intersertal texture. Dominant minerals are: plagioclase which occurs in euhedral laths mostly 0.3 to 0.5 mm in size, and clinopyroxene mostly in the same size range with a few grains longer than 1 mm. The pyroxene is anhedral and is dominantly pigeonitic. Plagioclase and pyroxene constitute about 95% of the rock. Of the two, plagioclase dominates in amount, in the ratio 3 to 2. The remaining 5% consists of finely disseminated blebs of anhedral opaque minerals ~2%, potassium feldspar ~1.5%, and porosity ~2%. The amount of mesostasis is very slight.

Also present in the thin section studied was a spherulitic appearing inclusion about 1 mm in diameter. This is no doubt one of the features referred to by the preliminary examination team as "scattered small cognate inclusions that are finer grained than the body of the rock." This spherulitic appearing feature has a central core of fine grain size consisting mainly of plagioclase and grading to coarser plagioclase laths growing radially from the central core. These radial outer rim plagioclase laths are about the same size as plagioclase in the bulk of the rock.

Examination of this specimen in the luminescence microscope reveals that in the bulk of the rock there are only two luminescent phases, plagioclase and a minor blue luminescing residuum phase which appears in luminescence like the glassy potassium rich residuum formerly described in Mare basalts. However, the material proved to be invariably birefringent, and in fact is all potassium feldspar. Probe analysis (5-element, least-square fitted) on twelve grains of this material scattered through the thin section all showed acceptable potassium feldspar stoichiometry. The results appear bimodal, five of the analyses falling in the range OR(77.5) to OR(81) and seven falling in the range OR(84) to OR(86.3). The grains are mostly anhedral and vary from less than 10μ to 200μ in size, but most fall in the range 10-100μ. An adequate uniaxial (or very small 2V) interference figure was obtained from one of the intermediate sized grains, suggesting that the mineral is sanidine. This is consistent with the fact that all the grains showed essentially nil luminescence polarization. The spectrum was measured and is identical with lunar potassium feldspar luminescence spectra previously described (Sippel, 1971). Among its other unique features, this rock lacks all three of the siliceous residuum minerals quartz, tridymite, and cristobalite found in various combinations or separately in Apollo-11 and 12 Mare basalts.

The spherulitic feature shows a brilliantly luminescing central core of about 0.6 mm diameter closely circular, and abruptly differentiated from the outer radially arranged plagioclase grains which show the same intensity and color of luminescence as the plagioclase in the rest of the rock. About 70% of the central core consists of small plagioclase grains, some equant $\sim$20μ or less in size grading to acicular shapes ranging up to $\sim$10 x 50μ or a maximum of 10 x 100μ. These small plagioclase grains emit a blue luminescence which is undoubtedly several orders of magnitude more intense than the

plagioclase in the rest of the rock. Spectral measurements of the spherulitic core show a spectrum in which the blue emission band is dominant, and where the green plagioclase band is barely detectable. On the other hand, five spectra measured on diverse grains of plagioclase in the main part of the rock showed the blue and green peaks (Sippel and Spencer, 1970) more equally developed. In one of the five spectra, a minimal red-infrared peak was apparent, though no more intense than some described in Apollo-12 rocks (Sippel, 1971). In the other four, the red-infrared peak was very weak or nil. The brilliantly luminescing spherulite core plagioclase crystals are set subradially in a matrix which is much less intense in luminescence. Probe analysis shows that these brilliantly luminescing grains have stoichiometric plagioclase composition and are very calcic An(97). The plagioclase of the bulk of the rock on the other hand is about An(90). Six of nine grains analyzed by probe yielded An(90 $\pm$ 1.5) and the other three were lower, the least of these being An(75). Probe analyses were also made on the outer rim of the spherulite where plagioclase laths about the same size as those in the bulk of the rock extend radially from the spherulite core. It was found that the proximal parts of these laths show $\sim$An(92) while the distal parts gave An(90). This gradation toward more sodic plagioclase from the center to the outer periphery of the spherulite is no artifact of the analyses but is reflected by the raw sodium count rate data.

The spherulite appears somewhat different in an ordinary petrographic microscope than does its luminescence image. The petrographic scope shows what appears to be small blebs of reddish brown glass distributed with the plagioclase in the central core. There are several erratic fractures in the central core which extend a small way into the coarser plagioclase of the rim. In crossed nicols the central core shows very wavy extinction but the grain size appears larger than the luminescence image would suggest. A careful comparison of the two suggests that the small brilliantly luminescing plagioclase grains are set in plagioclase of much dimmer luminescence, and that several bright luminescing grains may be present in a grain which though very wavy appears as one in the petrographic scope. Probe analysis of some dull luminescing plagioclase in the central core gave An(76), but stoichiometry was not acceptable, probably because resolution is not adequate to analyze the small dim luminescing regions.

There can be little doubt that this spherulitic inclusion is a crystallization center. It is quite possible that crystallization was initiated by the addition of a xenocryst to the melt. In this sense the inclusion may not be cognate.

Compositionally, the rock is very far from a Mare basalt and is much more akin to the norite-anorthosite type of material. Similar types of basalts may prove to be important rock types of the highlands.

Rock Sample 14321

This specimen was collected at the south rim of Cone Crater at Station C1. It is a breccia of great complexity. About 20% of the thin section studied consists of a fragment of a breccia clast having quite a dark matrix. The remaining 80% has a somewhat lighter matrix and encloses the dark matrix clast on two sides. The boundary between the two is gently curved. Apparently the dark matrix clast is contained within the lighter matrix material. Within the darker clast there are other breccia clasts, so we have three generations of breccia within breccia within breccia. This is within a piece of rock about 1 cm long. Greater numbers of breccia generations have been reported by the LSPET in rock 14321. The boundary between the dark and lighter matrices is clearly seen at low magnification, though the lighter matrix is also quite dark. At high magnification the boundary becomes more subtle. The chief distinction between the two appears to be the higher feldspar concentration of the lighter matrix. This is particularly evident using luminescence examination.

Reaction rims on monomineralic plagioclase grains, and halos (evident only using luminescence observation) which surround several small epoxy filled void spaces suggest that the rock has been annealed. However, glass clasts present in the rock are not 100% devitrified, suggesting that the annealing has been moderate. On the other hand, there are light-colored compound clasts which have apparently been subjected to considerable metamorphism, some having partly hornfelsic textures. These facts together with the multiple brecciation suggest a complex history for rock 14321.

Simple mineral clasts are abundant in the rock, and in a small percentage of plagioclase grains the above-mentioned rimming is evident. In one excellent example, a grain of plagioclase about 0.3 x 0.6 mm in size, the rim is continuous about the entire grain and ranges from 20 to 40μ thick. The rim

is not evident in plane polarized light, but in crossed nicols one can see that the rim has a mosaic texture. The rim material emits a bright blue luminescence, while the core is dull reddish luminescing. The luminescence provides additional information. It shows that there are other grains in this thin section where the rimming has proceeded to varying degrees. In each case the same mosaicism and identical appearing luminescence are evident. In one small grain ~0.1 mm in size the rim is thicker than the core, and only a small central region is unaffected. In fact, there are grains of 0.4 mm diameter which are completely mosaicised and show the identical bright blue luminescence. On the other hand, some grains show only a very thin rim 5-10μ thick, and the great majority of plagioclase grains show no rim at all.

These rims have been interpreted as reaction rims involving in-situ reaction with the breccia matrix and have been cited as evidence of annealing (Warner, 1972 and others). The enormous variation in the degree of rimming is bothersome in this regard and careful probe work was employed to try to define the nature of the reaction. The 0.3 x 0.6 mm grain was carefully analyzed in the core and rim, and 5-element least-square fitted results gave:

Core - - Ab(7.05) An(88.5) OR(4.46)
Rim hit #1 Ab(9.42) An(88.8) OR(1.78)
Rim hit #2 Ab(8.32) An(89.84) OR(1.84)

The reaction seems to involve slight changes in sodium and potassium, the rim being slightly enriched in sodium and depleted in potassium relative to the core. Other major elements are not changed within the accuracy of the measurements. Microprobe wavelength scans were performed to see if any trace element differences could be found. The only element showing any difference was iron and again the effect was very slight. The rim was found to contain 0.2% Fe and the core 0.06%. Probe analyses on nine grains of plagioclase which showed no rimming gave compositions from An(79) to An(93.5) with several grains of closely the same composition as the rimmed grain, though the most potassic of the nine showed only OR(2.79) and the majority were less than OR(2).

Spectral measurements of the core showed a pronounced spectral shift and broadening reflecting a microscopically disordered structure which is attributed to shock damage (Sippel and Spencer, 1970). Spectral measurements of the nine unrimmed grains showed normal unshocked plagioclase spectra. The

reaction rimming mechanism thus apparently involves diffusion of cations, mainly alkali cations, together with local reorganization of the mineral. The iron enrichment very possibly predated the rim formation. (See discussion of iron-rich rimming in discussion of rock 15555.) The diffusion would be expected to proceed much more readily in shock disordered plagioclase, accounting for the wide variability in rimming. The solid diffusion mechanism may well result in incorporation of defect centers which could account for the increased blue emission of the rim material. A variety of evidence has suggested that the blue emission in plagioclase results from defect centers (Sippel, 1971; Geake et al, 1971). The mosaicism evident in crossed nicols must result from a reordering of the lattice which accompanies the process and results in a degree of recrystallization in which the single crystal is reordered into variously aligned crystal domains. No doubt the microscopic deformation and disorder is removed in the process. This in itself would produce a considerable intensity increase in the luminescence. Thus, mosaicism can reflect a secondary annealing recrystallization mechanism by which evidence of shock damage on the unit cell scale is removed, in addition to resulting directly from shock damage disordering as previously reported (Sippel and Spencer, 1970). Luminescence can readily distinguish the two. In any case, shock damage appears as the root cause of mosaicism whether through direct disordering or through annealing recrystallization.

Mosaic grains are present in moderate number in rock 14321, but other evidences of shock are few. One basalt fragment is severely shocked, and a large clast of plagioclase ~1 mm in size has been partially shock melted. The glassy part now largely devitrified embays the unmelted part which shows birefringence and twinning. This birefringent part, however, shows a definite luminescence spectral shift resulting from shock damage. The composition of this grain is Labradorite An(63). All other feldspar analyses of features in this rock, some forty analyses in all, fall between An(73) and An(93.5).

Among the larger lithic clasts light-colored clasts predominate and they all show breccia or cataclastic textures. They also show varying degrees of recrystallization. These are no doubt related to the anorthosite-norite clan described by Marvin et al (1971). One of these, a subrounded grain ~ 1 x 2 mm, is apparently noritic. The pyroxene which aggregates about half the particle shows birefringence only about equal to the plagioclase,

and all the larger grains show parallel extinction. Plagioclase constitutes about one-half of the clast and three probe hits at different spots in the plagioclase gave An(86.1) to An(91.4). It has breccia texture, characterized by great variation in grain sizes, a tight interlocking matrix, probably recrystallized, but it lacks the hornfelsic texture which is evident in several more strongly metamorphosed clasts. In the clasts which show varying degrees of hornfelsic texture there is clear corroborative evidence of grain growth in the luminescence distribution. One angular clast about 1 x 2 mm shows breccia texture with great variation in grain size. Clinopyroxenes and sizable opaques are evident. Plagioclase constitutes about 70% of the clast. Incipient polygonal grain growth is evident in the smaller grains while larger grains are irregular in shape. Luminescence shows that the smaller grains all emit a gray-blue luminescence which is very uniform in color and intensity from grain to grain and point to point in the majority of the clast. However, in a large grain of plagioclase approximately 0.2 x 0.3 mm, one can see a relict grain which now constitutes the core of the present grain. The core is about 0.1 x 0.15 mm and its periphery shows a diffuse blue rim ~10-20μ in width. In fact, the rounded core appears as two grains but close inspection shows that the original core was apparently fractured into two parts and the diffuse blue rimming has formed along the fracture as well as around the periphery. Outside this, one finds a second rim of plagioclase which is up to 70μ thick and extends to the edges of the present grain. It emits a gray-blue luminescence which just matches the luminescence of most of the rest of the clast. Probe analysis shows that the core of this grain consists of An(91.8) while the gray-blue rim shows An(83). The same phenomenon is seen in another large grain in this clast. These phenomena are invisible using ordinary petrography. Hornfelsic texture and luminescence zoning reflecting grain growth is best shown by a small clast about 0.25 x 0.5 mm in size. Again the polygonal grains show gray-blue luminescence while zoning resulting from grain growth is confined to the larger grains. In this grain the largest central core has An (93.3) and the gray-blue luminescing rim shows An(89.7). In yet another light-colored clast one rather small grain shows a rounded blue luminescing core.

Clearly these light-colored clasts have been subjected to rather extensive metamorphism. In an aqueous system such effects might be accomplished at modest conditions, but in the lunar environment where solid-state processes

must be relied on, high temperatures undoubtedly are required.

It is evident that the metamorphism of these light clasts did not occur in the present rock. They may well be fragments of Imbrium ejecta but the multiple brecciation in this rock suggests that such material has been mixed, comminuted, and lithified numerous times, and that since the final event which produced rock 14321 it has been subjected only to modest annealing.

Rock Sample 15555

This specimen collected twelve meters north of the rim of Hadley Rille at Station 9a is a basalt of hypidiomorphic texture. It contains about 50% clinopyroxene largely anhedral, and about 30% anhedral plagioclase up to 2 mm in size. The plagioclase has a poikilitic texture enclosing small grains of clinopyroxene and subhedral to euhedral grains of olivine ~0.3 mm in size. The plagioclase, however, is generally interstitial to the bulk of the clinopyroxene grains which range up to 2 mm in size. Olivine, aggregating perhaps 10% of the total rock, is found not only as poikilitic inclusions in plagioclase, but also as interstitial grains. Opaques are mostly anhedral and constitute only about 1% of the rock. Scattered patches of cristobalite up to 300μ in size aggregate less than 1% and except for a slight amount of mesostasis the remainder is void space. A considerable part of the void space may result from plucking of grains because the thin section is thinner than standard and there is a great deal of fracturing which is interpreted as an artifact of thin section preparation.

Luminescent phases are plagioclase, cristobalite, and a trace amount of apatite which emits orange luminescence. The appearance of the cristobalite luminescence and its spectrum are as previously described (Sippel, 1971). Some grains of plagioclase emit a bluish yellow luminescence which is uniform over the grain, but in many other grains a considerable zonation is evident, the luminescence grading from bluish yellow in the center to duller reddish appearing tones at the edges of grains.

Spectral analyses reveal that in all these regions the luminescence consists of a blue and a green emission band as previously described (Sippel and Spencer, 1970). Probe analysis shows that the zonation as before (Sippel and Spencer, 1970; Sippel, 1971) is correlated with composition. The mean composition of plagioclase in this rock is about An(84.5), but in the very brightest luminescing grains this rises to about An(87), and in the dullest

luminescing rims is about An(76).

It has been suggested on the basis of doping experiments (Geake et al, 1971) that the green emission band of plagioclase is activated by Mn^{++} substituting for calcium in the plagioclase structure. To test this hypothesis a grain was found which showed a continuous zonation to quite dull luminescence approaching the rim. Spectra were measured using a micro-aperture collimator in the bright and dull parts of the grain. It was found that the brighter luminescing part of the grain showed a 56% more intense green emission band than the dull rim. However, the blue band was 60% more intense in the brighter zone. In fact, the entire spectrum in the brighter luminescing zone was about 60% more intense at all wavelengths from ultraviolet to infrared. This suggests that the brightness difference results from variations in amount of a quenching element rather than the density of luminescence centers.

Probe analyses were carried out in several grains for feldspar composition, iron, and manganese with the following results.

Grain	Description of Lum.	% Anorthite	% Iron	% Mn
1	Very Dull	76.29	.65	.01
2	Brighter	82.44	.35	.011
2	Brightest	86.65	.26	.002
3	Dull	76.26	.54	.01
3	Brighter	79.40	.41	.002

It is apparent that % Anorthite correlates directly and iron concentration inversely with intensity of luminescence. Since ferrous iron is the single most important quenching element known, and since iron is largely in the ferrous state (Hafner et al, 1971), it is reasonable that the zoning observed here should result from variations in iron concentration. In this rock, late crystallizing plagioclase is enriched in iron. The whole picture is verified by the fact that cristobalite seems to be associated with the very dull luminescing parts of the plagioclase virtually without exception. Note that Quaide (1972) shows a similar trend for rock 14053. I believe that iron zonation probably accounts for most of the gradual luminescence zonation reported in Apollo-11 and 12 rocks also (Sippel and Spencer, 1970; Sippel, 1971).

The data, however, raise serious doubts about the role of Mn^{++} in

activating the green emission band for two reasons. First, the manganese is contratrend, being depleted a factor of five in the brightest luminescing region over its concentration in the dullest luminescing regions. Under the circumstances, we would expect it to be about equal in the two regions. Secondly, and perhaps more importantly, the absolute amount in the brightest luminescing region is only 20 ppm, an amount which is almost certainly too small to account for bright luminescence in a natural mineral, particularly one containing about 130 times as much ferrous iron.

Rock 15555, despite its unprecedented size, does not appear to be otherwise unique, and despite its low opaque content seems acceptable as a Mare type basalt.

III. SOIL SAMPLES

Grain mount thin sections were made from hand-picked grains from two soil samples from Apollo-14 and eight soil samples from Apollo-15. Sixteen excellent doubly polished grain mount thin sections were prepared from Apollo-15 soils. Four thin sections were prepared from Apollo-14 soils, but we ran into trouble with these four sections. Our epoxy had deteriorated, and the sections began to detach in preparation. In order to save the sections, we mounted new slides on the top face and ground off the old slides. We did save the sections but they are not equal in quality to the Apollo-15 slides which we will describe first.

Apollo-15 Soils

Soils studied were 15261, 15271, 15041, 15031, 15231, 15071, 15081, and 15531. This included samples from the Apennine Front, both at Station 6 (samples 15271 and 15261) and at Station 2 (sample 15231) near St. George Crater. Hadley Rille was represented by sample 15531 collected at Station 9a. Two samples (15031 and 15041) are from Station 8 at the AISEP site and two from Station 1 at Elbow Crater (15071 and 15081). Several samples were from somewhat protected locations to see if comparisons with surface samples revealed any luminescence effects attributable to radiation. Samples 15261 and 15031 were collected from trench bottoms, and 15231 from under a large boulder.

Larger grains from these samples were picked by brush under the microscope, then mounted in regular lattice arrays in a thin layer of epoxy on the bottom of plastic molds. Glassy grains evidencing a regular geometric shape were rejected at this time and a separate search was later conducted for these

grains in four of the samples. After the epoxy film had hardened, the molds were filled with epoxy. When hard, the epoxy blocks were removed from the molds and flattened and polished on the lap until flat sections of the grains were exposed at the surface. At this stage the grains were subjected to a first examination and description. Then polished thin sections were prepared and the grains were examined in the petrographic microscope comparing with the prior description. Finally, in a third examination all grains were studied in the luminescence microscope.

Virtually all of the 660 grains examined fell in the size range 0.3 mm to 0.8 mm and could be classified under a small number of headings (Table 1). Glassy grains which contained appreciable mineral debris were classed as agglutinates. Vesicles were usually evident in these grains. In fact, they commonly ranged from vesicular to scoriaceous. Breccias were classed under two headings. First, anorthositic breccias were those grains which satisfied the following three criteria:

(1) Breccia texture
(2) Feldspar content >50%
(3) Light color

The last was judged from the appearance of the grains in the epoxy block, and the feldspar content was estimated using luminescence observation. The break point at 50% was greatly exceeded by most grains accepted as anorthositic breccias. The great majority were >70% feldspar. Grains evidencing a breccia texture which failed either of the other two criteria were simply classed as breccias. Basalt fragments were not broken down as to textural or compositional type. Glasses and devitrified glasses were lumped together. Green, yellow, amber, and brown glasses were present. Grains classed as anorthosites all contained >90% plagioclase and were polycrystalline containing numerous grains. Only six grains were found and these were all at the St. George Crater site. Two of the six had been cataclastically deformed. The remaining four showed the mosaic and polygonal grain texture which has been described in rock 15415 (LSPET 1972). Fractures are absent, however. These four clasts consist of extremely calcic plagioclase An(94.1)-An(97.8).

The most interesting features revealed by luminescence were found in the true anorthosite. Once again the luminescence reveals details of the

metamorphism which this material has undergone. Some of the polygonal grains reveal cores, and grain growth is also evident in grains which do not show polygonal form. These phenomena are still being investigated as this is written, but it appears thus far that much less compositional zoning is evident in the true anorthosite recrystallization than was evident in the anorthositic breccias of rock 14321. Some grains which appear to be mosaic grains also show diffuse features related to the metamorphism. It is apparent that these phenomena are of considerable significance and will be reported in greater detail in a planned publication. Some of these phenomena were not even discovered until after the expiration of the current contract.

The agglutinates generally contain non-luminescing glass, and the plagioclase in them often shows evidence of shock damage.

A complete range of devitrification was seen in the yellow glasses from incipient to total. The glass is invariably non-luminescent, but the devitrified parts emit a dull luminescence. Devitrification apparently proceeds by exsolution of extremely fine fibrous intergrowths of plagioclase and mafic minerals, probably mainly pyroxene. These form interesting linear and radial patterns. The intergrowth plagioclase is apparently prevented by the close association of intergrown mafic phase, and by the constraints of the devitrification process, from achieving a completely regular plagioclase lattice. The plagioclase structure is apparently distorted and disordered to a considerable degree because the luminescence spectra show a shifted broadened less intense spectrum like those we have previously reported as resulting from shock damage (Sippel and Spencer, 1971). It is important to realize that these spectral effects reflect distortions and disorder on the unit cell scale in the mineral. Ascribing a cause for the disorder, i.e., shock damage devitrification or what not, is another level of inference. However, I still believe that everything we have inferred to date is correct. Hindered growth as in devitrification, shock damage, and radiation damage appear to be the only possible causes. Devitrification could not account for the effect in large plagioclase crystals, and radiation damage is very unlikely on a number of grounds. This is strengthened by the fact that no effects attributable to radiation damage could be detected in these soils, and no differences attributable to radiation could be detected between the exposed surface and the protected samples. The latter is based on careful visual examination and

spectral measurements. Thirty-five spectra were measured, and perhaps a hundred more surveyed but not recorded.

Plagioclase ranged from clear single crystals showing sharp extinction and often twinning, to shattered and cataclastically deformed textures. Some but not all of the latter showed disordering on the unit cell scale as interpreted from luminescence spectral shifts. Some damaged plagioclase grains when examined by luminescence showed complex healed fractures up to 20μ wide. This sort of healing is readily accomplished in terrestrial rocks at low temperatures through the agency of aqueous solutions. In the lunar environment, such effects again point to high temperature solid-state processes. There is little doubt that such processes would result in removing the Angstrom scale disorder which produces the luminescence spectral shifts. The overwhelming number of grains surveyed show normal plagioclase luminescence with no evidence of disordering from shock or other causes. This is particularly true of the Rille samples where the basalt fragments largely appear fresh and unshocked. Spectra of the Apollo-14 and 15 plagioclase all show nil or minor red-infrared emission similar to that reported for the Apollo-12 specimens.

Many of the grains described as anorthositic breccias show evidence in luminescence of metamorphism. Many also show phosphatic phases (apatite-whitlockite) which luminesce orange to red in color. Large whitlockite grains described by others were not found. The phosphatic phases seen are all small grains. No doubt the anorthositic breccias described encompass the anorthosite and norite fragments described by Marvin and others (Marvin et al, 1971) and probably the gray mottled fragments described by Anderson and Smith (1971) though time pressures prevented a further breakdown.

Several things may be seen by the breakdown as shown in Table I. First, the three Front samples show the highest concentration of anorthositic breccias though the percentages are not really striking. Anorthosites are found only at the St. George Crater site, a Front specimen. The Rille sample shows a preponderance of basalt and mafic mineral fragments. Plagioclase is also quite rich at the front locations, though the Elbow Crater samples are also quite high.

If we define a felsic index as

$$100 \times \frac{\Sigma \text{ Anorthosites} + \text{Anorthositic Breccia} + \text{Plagioclase}}{\Sigma \text{ Basalts} + \text{Olivine} + \text{Pyroxene}}$$

we find the following breakdown:

Sample	Station	Location	Description	Felsic Index
15261	6	Front	Bottom of Trench	86
15271	6	Front	Surface	150
15231	2	Front (St. George)	Surface	114
15071	1	Elbow Crater	Surface	21
15081	1	Elbow Crater	Surface	32
15031	8	AISEP Site	Bottom of Trench	33
15041	8	AISEP Site	Surface	7.4
15531	9a	Rille Edge	Surface	3.5

The felsic index rises to the vicinity of 100 or more at the Front locations, attains intermediate values <40 at the AISEP and Elbow Crater locations, and attains the value 3.5 at the Rille location. Although the astronauts described the trench walls as uniform in color, note the large variations in the index at trench bottoms and tops. This large change no doubt reflects real layering.

Apollo-14 Samples

Table II gives the breakdown of components found in the Apollo-14 soil samples. The 14163 thin section was quite thick, and this data is less accurate than 14003. However, both specimens show an enormous anorthositic breccia content and if we compute a felsic index as before it gives

14003	-	670
14163	-	348

This reflects the high anorthositic breccia content and the low concentration of basalt and mafic mineral fragments.

Glasses Showing Regular Forms

A second pick-through of four of the Apollo-15 samples and the two Apollo-14 specimens was made to pick out glassy particles which displayed regular geometric shapes (spheres, rods, etc.). Results are shown in Table III. Many of the grains listed as opaque were so listed because surface coatings or etching of the surface precluded their identification in solid form. The great majority of grains fell in the 0.1 - 0.3 mm size range. Analyses were

planned, but time did not permit, and the data are shown here mainly to show that the green glasses which were quite rare in Apollo-14 samples (Marvin et al, 1972) are very common in Apollo-15 samples.

IV. CONCLUSIONS

The high percentage of anorthositic breccia fragments at the Fra Mauro site both in the soils and as clasts in the breccias suggests that the Imbrium event did contribute a great deal of such material to the area. The varying degrees of metamorphism which the light metaclastic fragments have suffered is also suggestive. One cannot really tell where this metamorphism occurred, but clearly severe conditions must have been involved. It is reasonable that an event of the scale of the Imbrium impact could provide such conditions in a thick ejecta blanket, or that these fragments could have been excavated in the impact from depths in the pre-Imbrium crust where severe conditions could have prevailed. The latter would suggest a brecciated pre-Imbrium crust. This cannot be disproved from the data, but it seems more likely that the brecciation occurred in the Imbrium event followed by metamorphism in the resulting ejecta blanket. Although rock 14321 gives evidence of annealing recrystallization, it could not have formed in such an event. The annealing recrystallization is much too low grade a phenomenon involving mainly alkali ion mobility and partial devitrification of glass. Metamorphic conditions would also certainly remove shock-induced disorder on the unit cell scale. Yet the luminescence shows it is present and predated the annealing recrystallization episode (i.e., shocked cores of rimmed grains).

The complex multiple brecciation shown by the Fra Mauro breccias suggests that several generations of comminution, mixing, and relithification resulted in mixing of light metaclastic fragments and possibly other entities contributed by the Imbrium event, with Mare material ultimately resulting in the lithification of rock 14321 probably in an impact of modest scale. The rock then suffered a modest annealing recrystallization, and was probably excavated to the lunar surface by the Cone Crater impact.

The suggestion (Wood et al, 1970) that the moon early had a differentiated anorthositic crust is rapidly taking on the force of reality as data and samples become increasingly available. The data presented here from Apollo-14 samples is certainly consistent with this model. When we come to Apollo-15 specimens, once again the facts seem to fall in line with the

suggestion. The soil samples show increasing felsic nature in the vicinity of the Front. The fact that most of this material is brecciated shows that none of this material is the actual primordial anorthositic crust, though such may well exist in the highlands. The fact that true anorthosite was found only at the St. George site indicates that there is considerable depth variation in the nature of the anorthositic rocks, though the anorthosites are definitely metamorphic in origin and are also not examples of primordial anorthositic crust.

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TABLE I

PERCENTAGE OF COMPONENTS APOLLO-15 SOIL

	Front Samples			Mare Samples				Rille Samples
Sample No.	15261*	15271	15231	15041	15031*	15071	15081	15531
Location			St. Geo.	AISEP	AISEP	Elbow	Elbow	Rille Margin
Agglutinates	36	29	31	34	18	17	30	15
Breccia	16	32	23	31	36	9.5	14	7.0
Anorthositic Breccia	6.5	9.5	5.1	1.5	2.7	3.6	2.8	0
Basalt	12	8.2	5.9	11	8.1	14	21	33
Plagioclase	5.2	8.2	10	0	4.1	8.3	9.9	2.3
Glass & Devitrified Glass	16	9.4	8.5	14	19	9.5	5.6	10
Pyroxene	3.9	2.4	7.6	6.2	8.1	33	13	24
Olivine	5.2	1.2	4.2	3.1	4.1	4.8	4.2	8.1
Anorthosite	0	0	5.1	0	0	0	0	0
Total Particles	77	85	118	65	74	84	71	86

* These samples were collected from soil mechanics trench bottoms.

TABLE II

PERCENTAGE OF COMPONENTS APOLLO-14 SOIL

Sample No.	14003	14163
Agglutinates	29	39
Breccia	21	22
Anorthositic Breccia	29	22
Basalt	3.6	5.1
Plagioclase	5.3	1.7
Glass & Devitrified Glass	11	8.5
Pyroxene	1.8	1.7
Olivine	0	0
Anorthosite	1.8	0
Total Particles	56	59

TABLE III

GLASSES OF REGULAR GEOMETRIC SHAPE
IN SOME APOLLO-14 & 15 SOILS (PERCENTAGE)

Sample	14003	14163	15071	15081	15231	15531
Green	6.7	0	36.8	21.4	41.5	16.7
Yellow	6.7	7.7	5.2	21.4	12.2	4.5
Amber	6.7	7.7	15.8	7.1	19.5	7.6
Brown	13.3	7.7	5.2	28.6	7.3	6.1
Opaque	66.7	77	36.8	21.4	19.5	65.2
Total Particles	15	13	19	28	41	66

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