References and Notes

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2. E. Roedder, *Amer. Mineral.* **36**, 282 (1951); *Geol. Soc. Amer. Bull.* **64**, 1466, 1554 (abstracts) (1953).
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4. Some of the inclusion types found raised still unanswered questions, owing to the small inclusion size, inclusion rarity, and hence lack of optimum orientation for observation, the necessary prohibition of destructive testing with these sections, and the obvious lack of time. As a result, many of the findings are too tentative to present here, but we believe the evidence for silicate immiscibility is conclusive.
5. During the examination of many of these rocks at the Lunar Receiving Laboratory, the individual thin sections or probe mounts of each rock were identified by the appropriate five-digit rock number followed by a dash and a six-digit section container number (for example, 10072-64-7668). When these sections were released to the principal investigators, NASA replaced these container numbers with new, two-digit section numbers such as 10072, 46). To aid other investigators in checking the specific sections examined, we give the container numbers where section numbers are not currently available, or both when there is ambiguity. We have omitted the "100" of the sample number and the "64" of the container number, and changed the comma to a hyphen to avoid ambiguity in serial listing. For some of these sections, we understand that a complete tabulation of container numbers and their equivalent section numbers cannot be made until the sections are returned to NASA.
6. A few very small secondary inclusions in olivine in samples 03-37 and 20-29 contained only gas, and this gas may be CO_2. Only destructive tests or the discovery of larger inclusions will permit more positive identification. Small amounts of noncondensable gases were found in some of the bubbles in glass fragments from samples 84 and 85, but most bubbles held only a vacuum.
7. All that is known about the identity of the phase at the liquidus is that it is the last portion to dissolve of an opaque phase remaining in the position of the original daughter ilmenite crystal. It could also be the ferropseudobrookite found at the liquidus in one synthetic lunar magma (R. Tuthill and M. Sato, personal communication).
8. Similar but very rapid vacuum heating experiments on minute fragments and spheres of glass from the lunar soil (sample 84) show that the dark glasses, with indices above 1.70, devitrify throughout within a few seconds in the range 1000 to 1100°C, but under these same conditions colorless glasses of index <1.60 may develop only a thin surface film of crystals. Such devitrification experiments may permit placing semiquantitative limits on the cooling history of some lunar materials, as similar devitrification textures are seen in some of the fragments of the breccias and soil, including well-developed chondrule-like features in some former glass spheres.
9. This interstitial occurrence of high-potassium glass and apatite may explain some of the biological growth effects reported for lunar soil. The silica crystals occur as close to olivine as a few hundred micrometers in several rocks, indicating nonequilibrium.
10. As a result of the need for multiple impregnations with epoxy (diluted with toluene) and the use of several epoxy resins with different indices of refraction in the preparation of these sections, there are many examples of apparent immiscibility (for example, filling of inclusion shrinkage bubbles with epoxy where they are cut by the section surface, or filling of the bubbles left in vugs by shrinkage of the previous impregnation), and of real immiscibility (residual globules of one epoxy component in another). These artifacts (and several other types) occur in cracks within grains, between grains, and, most confusingly, in the microvugs where evidence of actual magma immiscibility is most apt to be found.

11. Much of the preliminary work was done at the Manned Spacecraft Center, Houston. We are indebted to the personnel of the Lunar Receiving Laboratory for courtesies extended during this hectic period.

4 January 1970

Petrology of Unshocked Crystalline Rocks and Shock Effects in Lunar Rocks and Minerals

Abstract. *On the basis of rock modes, textures, and mineralogy, unshocked crystalline rocks are classified into a dominant ilmenite-rich suite (subdivided into intersertal, ophitic, and hornfels types) and a subordinate feldspar-rich suite (subdivided into poikilitic and granular types). Weakly to moderately shocked rocks show high strain-rate deformation and solid-state transformation of minerals to glasses; intensely shocked rocks are converted to rock glasses. Data on an unknown calcium-bearing iron metasilicate are presented.*

Evidence of impact metamorphism is widespread in the lunar sample. The fine material and breccias contain abundant small fragments of shocked crystalline rocks and mineral grains and particles of shock-melted rocks; only in the large rock fragments are the shock effects negligible. Moreover, some fragments have a history of multiple impact (for example, fragments of older breccia in younger breccia, and spherules of shock glass coated by different shock glass).

In order to study the effects of shock in the returned lunar samples, it is necessary to know in detail the rock textures and mineralogic variations characteristic of the unshocked crystalline rocks. On the basis of rock modes, mineralogy, and textures, we have classified these rocks into two suites: a dominant ilmenite-rich suite and a subordinate feldspar-rich suite. All the large samples and the bulk of the smaller rock fragments and mineral grains in the fines and breccias are from the ilmenite-rich suite; rocks of the feldspar-rich suite are found only as small fragments in the fines and breccias.

In the ilmenite-rich rocks, the major mineral constituents are clinopyroxene, calcic plagioclase, and ilmenite. Olivine is a common minor constituent, and cristobalite, troilite, and native iron are accessory and trace constituents of nearly all rocks. Interstitial glass is present in many rocks. The rocks are dominantly volcanic; both the presence of vesicles and vugs in all large samples and the rock textures suggest that they crystallized from magmas at or near the lunar surface (*1*).

Most of the ilmenite-rich rocks have one of three types of texture: (i) intersertal, (ii) ophitic-subophitic, and (iii) hornfels (*2*).

Intersertal rocks (Fig. 1A) have abundant interstitial glass that contains skeletal plagioclase grains, fine myrmekitic intergrowth of plagioclase and glass, and minute grains of pyroxene. Olivine forms sparse phenocrysts marginally reacted to clinopyroxene or small rounded cores in pyroxene grains. Ilmenite grains are subhedral. Clinopyroxene grains tend to be subhedral, but locally they form subophitic patches partly enclosing ilmenite. Patches of micrographic intergrowth of pyroxene and plagioclase fill some interstices. Grain size is typically fine and ranges from about 0.05 to 0.2 mm.

Ophitic rocks (Fig. 1B) are characterized by ophitic to subophitic intergrowth of clinopyroxene and plagioclase; plagioclase forms subhedral laths, and pyroxene is anhedral and partly encloses plagioclase. Olivine occurs as phenocrysts or as partly resorbed cores in pyroxene grains, and the pyroxene grains may be pigeonitic or contain cores of pigeonite. Interstitial myrmekitic intergrowth of plagioclase with glass is common. Grain size is highly variable and ranges from about 0.05 to 1 mm.

Hornfels (Fig. 1C) are characterized by reduced size of pyroxene and ilmenite grains and growth of coarse poikiloblastic grains of plagioclase. The ilmenite grains are equant rather than bladed; the pyroxene grains are equant and subhedral, or rounded, or form a mosaic of minute grains. The rocks may be highly inequigranular; ilmenite and pyroxene range from about 0.02 to 0.15 mm, and poikiloblastic plagioclase may be up to 3 mm across. Locally, primary rock texture is preserved in relict patches.

In nearly all the ilmenite-rich rocks, troilite (containing minute droplets of native iron) forms irregular patches or globules between grains. Minor cristobalite (locally intergrown with tridymite) fills interstices. In the unmetamorphosed rocks, pyroxene shows feathery, patchy, banded, hourglass, or polygonal extinction and color variation, and these features tend to disappear with increasing degree of thermal metamorphism. Apatite occurs as euhedral inclusions in, or myrmekitically intergrown with, pyroxene. Rutile and chrome-titanium spinel are trace and accessory constituents, occurring both as exsolution lamellae in ilmenite and as single grains in the rocks.

Tables 1 and 2 present mineral proportions and compositions of the major silicate minerals from typical ilmenite-rich rocks. These minerals are relatively homogeneous in the intersertal and fine-grained ophitic rocks and relatively heterogeneous in the hornfels and the coarse-grained ophitic rock. Compositions of interstitial material have also been investigated. Interstitial glass is potassium-rich: semiquantitative microprobe analyses of three spots in glass in the intersertal rock indicate minimum K_2O contents of 6.0, 6.6, and 5.4 percent. Plagioclase that forms skeletal grains in interstitial glass or is myrmekitically intergrown with glass is relatively enriched in sodium; semiquantitative microprobe analyses suggest compositions of about 70 to 73 percent anorthite.

The feldspar-rich rocks have characteristic modal compositions, mineralogy, grain sizes, and textures much different from those of the ilmenite-rich rocks. The essential minerals are calcic plagioclase, clinopyroxene, and olivine. Modes of two specimens are presented in Table 1; content of plagioclase is much higher and content of opaque and oxide minerals is much lower than in ilmenite-rich rocks. Grain size is typically very fine; the maximum we have observed in our samples is 0.15 mm.

Most of the undeformed feldspar-rich rocks are of two textural types: (i) poikilitic and (ii) granular. In poikilitic rocks (Fig. 1D), pyroxene is poikilitic and interstitial, plagioclase grains have euhedral shapes bordering pyroxene, and olivine forms either equant rounded grains enclosed by pyroxene or poikilitic interstitial grains between and enclosing plagioclase grains. Textures are similar to those of terrestrial cumulates (*3*), and at least one of us (E.D.J.) considers some of these rocks to be the product of crystal accumulation. In granular rocks (Fig. 1E), plagioclase forms a mosaic of lath-shaped grains that commonly define a rough foliation, and olivine and pyroxene occur as small equant rounded grains along boundaries between the plagioclase laths.

Table 1. Rock modes.

Minerals	Ilmenite-rich rocks				Feldspar-rich rocks	
	Intersertal	Fine-grained ophitic	Coarse-grained ophitic	Hornfels	Poikilitic	Granular
Olivine		7	0.5		6	} 19
Clinopyroxene	53	39	48.5	48	7	
Plagioclase	23.5	32	36	27	86.5	80.5
Cristobalite	2	4	0.5	1.5		
Myrmekite	3	6		2		
Glass	4.5			6.5		
Ilmenite and spinel	13	11	14	14	} 0.5	} 0.5
Sulfides and native iron	1	1	0.5	1		
Similar to:	10072	10020	10047	10017		

Table 2 presents compositions of the major silicate minerals of the poikilitic rock shown in Fig. 1D. In this specimen and in the three other feldspar-rich rocks that were analyzed, olivine and pyroxene are richer in magnesium and plagioclase is richer in calcium than in any of the ilmenite-rich rocks studied. The oxide minerals we have identified with the microprobe (*4*) are ilmenite, rutile, chrome spinel, and magnesian ferropseudobrookite, and the proportion of ilmenite relative to other oxides is much lower than in the ilmenite-rich rocks.

Two types of shocked material are common in the breccias and fine material of the returned lunar sample and may be classified (*5*) as follows: (i) Weakly to moderately shocked. Minerals show high strain-rate de-

Table 2. Electron microprobe analyses of silicate minerals (percent by weight).

Oxides	Ilmenite-rich						Feldspar-rich poikilitic (10084, 12-61)
	Intersertal (10084, 12-12)	Fine-grained ophitic (10084, 12-2)	Coarse-grained ophitic (10029)*		Hornfels (10084,12-27)*		
			Olivine				
SiO_2		35.6	31.6	29.8			37.4
FeO	None	29.4	44.4	55.4	None		25.2
MgO		33.9	19.6	11.1			37.2
CaO		0.33	0.34	0.44			0.06
MnO		0.28	0.54	0.53			0.18
Total		99.51	96.48	97.27			100.04
Fo		66.7	44.0	26.3			72.5
			Clinopyroxene				
SiO_2	45.2	45.1	49.1	46.2	47.5	49.9	51.4
TiO_2	4.96	4.43	1.55	1.66	1.53	2.22	1.58
Al_2O_3	5.24	3.81	1.49	0.83	1.57	2.34	1.64
FeO	10.24	15.2	15.3	32.3	19.6	11.71	8.40
MgO	12.93	10.53	14.6	6.51	10.54	16.4	17.8
CaO	20.5	19.0	16.3	11.38	17.5	17.6	19.0
MnO	0.17	0.30	0.30	0.59	0.28	0.18	0.09
Total	99.24	98.37	98.64	99.47	98.52	100.35	99.91
Ca	44.1	41.7	33.6	24.9	36.9	35.5	37.7
Mg	38.7	32.2	41.8	19.9	30.9	46.0	49.2
Fe	17.2	26.1	24.6	55.2	32.2	18.5	13.1
			Plagioclase				
SiO_2	50.9	44.4	44.2	47.7	47.9	51.3	43.8
Al_2O_3	28.5	34.1	34.7	31.6	31.8	29.5	34.8
Fe_2O_3	1.14	N.D.	N.D.	N.D.	0.59	1.37	0.17
CaO	14.4	18.2	18.6	15.6	16.4	14.2	18.8
Na_2O	2.51	0.89	0.81	2.62	1.79	2.61	0.71
K_2O	0.24	0.05	0.05	0.18	0.19	0.60	0.07
Total	97.69	97.64	98.36	97.70	98.67	99.58	98.35
An	74.9	91.6	92.4	75.9	83.5	75.0	93.6

* Different grains from the same rock. N.D. not determined.

Table 3. Selected electron microprobe analyses of mineral and rock glasses. Indices of refraction were determined by interference microscopy.

Component	Anorthite A-1	Feldspathic A-6	? A-10	Olivine-rich B-6	Titaniferous B-14	Titaniferous C-1	Titaniferous C-9
SiO_2	45.4	46.0	51.0	43.5	41.2	40.1	41.1
TiO_2	0.1	0.4	2.0	0.4	5.0	6.5	9.2
Al_2O_3	34.5	24.6	12.1	6.9	16.9	13.6	10.3
Total Fe as FeO	0.3	5.9	14.4	22.1	12.1	15.0	18.9
MgO	0.2	8.0	8.5	17.4	8.8	7.6	6.8
CaO	19.0	15.1	9.9	8.4	13.3	11.9	10.5
Na_2O	0.8	0.2	0.2	0.2	0.1	0.1	0.5
K_2O	0.1	0.1	0.3	0.1	0.1	0.1	0.2
MnO		0.1	0.2	0.3	0.2	0.2	0.3
Total	100.4	100.4	98.6	99.3	97.7	95.1	97.8
Index of refraction							
	1.5701	1.5942	1.6164	1.6534	1.6500	1.6705	1.7001

formation features and solid-state transformation to glasses [thetomorphic glasses (*5*)]. (ii) Intensely shocked. Rocks are melted by shock and form glasses that contain inclusions of shocked minerals and minute spherules of meteoritic nickel-iron. Rocks that show intermediate degrees of shock metamorphism are rare.

Most weakly shocked feldspar-rich rocks are intensely granulated and brecciated. The samples consist of angular fragments of feldspar-rich rock, plagioclase, olivine, and pyroxene in a finely granulated matrix of the same minerals; many of the larger fragments are strongly sheared and deformed. In most of the specimens there is little conclusive evidence that the brecciation is shock induced, but a few show features diagnostic of shock [planar features (*5*) in plagioclase, fine lamellar twinning parallel to (001) in clinopyroxene (*6*)]. Moderately and strongly shocked feldspar-rich rocks are rare.

Ilmenite-rich rocks show somewhat different shock effects. In weakly shocked rocks, texture is generally preserved and intense shear and brecciation are uncommon. Grains of all minerals are strongly fractured and cleaved (Fig. 1F). Pyroxene shows fine lamellar mechanical twinning (*7*), and ilmenite shows fine lamellae that may be mechanical twins. Olivine shows weak extinction variation and faint possible deformation lamellae. In some samples, pyroxene has poorly defined kink bands, and some plagioclase shows lamellar mechanical twinning. In slightly more shocked rocks, in plagioclase, planar features appear and become abundant, birefringence and indices of refraction decrease, and the plagioclase is converted in patches to thetomorphic glass (Fig. 1G). Rock texture, however, is perfectly preserved. In moderately shocked rocks (Fig. 1H), plagioclase is wholly converted to glass. The grains retain their gross lath shapes, but in some rocks they are slightly bent and show internal streaks of varying indices of refraction that suggest small-scale flow. Pyroxene is finely granulated, and the frequency of twinning appears less than in weakly shocked rocks. Ilmenite shows more abundant and more closely spaced fractures than in weakly shocked rocks.

The particles of glass found in the fines and breccias can be classified into mineral glasses or rock glasses depending on their chemical compositions (Table 3). The mineral glasses are clearly formed by shock, as thermal melting is fractional and should not produce glass of the composition of single minerals. The rock glasses are also shock-melted, for they contain nickel-iron spherules, shocked mineral fragments, and flow bands, and they are highly heterogeneous.

At present, the only mineral glass we have identified is of plagioclase composition. It occurs mostly in colorless angular chips or cleavage fragments and only rarely in spherules. Where recrystallized, the fragments are white in color, transparent to opaque.

Fragments of a single clear glass chip of thetomorphic plagioclase (92 percent anorthite) were annealed for 2 to 24 hours in air or in evacuated capsules at 850°, 875°, 900°, and 950°C and were air quenched to study variation of its optical and crystalline properties. Annealing at 850° for 2 hours reduced the index of refraction from 1.5688 to 1.5674 ± .0002, an indication that this anorthite glass is a dense glass with a high pressure history (*8*). The same glass recrystallized into a spherulitic to mosaic mat of anorthite crystals after heating at 900°C for 2 hours; at 875°C, recrystallization did not take place after 8 hours but occurred after 24 hours. Heating in air and in evacuated capsules produced no distinguishable differences. These crude experiments produced recrystallized plagioclase glass with textures similar to those in many fragments in the fines and breccias.

Rock glasses occur as angular fragments, spherules, oblate spheroids, dumbbells, and teardrops and also as spatter on surfaces of fragments and vesicular rinds wrapped around small fragments. Their colors are pale green, yellow, orange, brown, garnet red, and black.

The indices of refraction of the plagioclase mineral glass and rock glasses correlate well with their chemical compositions (Table 3). Indices vary directly with iron and titanium content (reflecting the amount of normative ilmenite

Fig. 1. Textures of unshocked and shocked crystalline rocks. Scale in each is 0.3 mm. (A) Photomicrograph of intersertal ilmenite-rich rock in plane light. Interstices between pyroxene and ilmenite grains are filled by glass (gray, granular appearing) that contains skeletal plagioclase grains (left center, top left). (B) Photomicrograph of fine-grained ophitic ilmenite-rich rock in plane light. Olivine (right center) forms phenocrysts, and subhedral plagioclase (clear) is enclosed by ophitic clinopyroxene. (C) Photomicrograph of hornfels ilmenite-rich rock in light passed through crossed Nicol prisms. Fine pyroxene and ilmenite grains are enclosed by coarse poikiloblastic plagioclase. (D) Photomicrograph of poikilitic feldspar-rich rock in plane light. Pyroxene (left, top center) and olivine (bottom right) are interstitial and poikilitic and enclose subhedral plagioclase grains (clear). (E) Photomicrograph of granular feldspar-rich rock taken in light passed through crossed Nicol prisms. Pyroxene and olivine form small grains along boundaries between plagioclase laths. (F) Photomicrograph of weakly shocked ilmenite-rich rock taken in light passed through crossed Nicol prisms. Plagioclase (right center) and pyroxene (left) are strongly fractured, and pyroxene (center) shows fine lamellar twinning parallel to (001) (bottom center) and (100) (top center). (G) Photomicrograph of plagioclase grain (center) partly converted to thetomorphic glass, taken in light passed through crossed Nicol prisms (rotated slightly from perpendicular). The birefringent parts of the grain show planar features (left center). (H) Photomicrograph of moderately shocked ilmenite-rich rock in plane light. Ilmenite (center) and pyroxene (bottom right) are intensely fractured, and laths of plagioclase glass (right center, left) are slightly bent.

present) and inversely with aluminum content (reflecting the amount of plagioclase present). Among the samples studied, there is a tendency of indices of rock glasses to cluster around $N = 1.59$ (rich in plagioclase) and $N = 1.66$ (rich in normative ilmenite). This grouping may indicate that these glasses correspond to the two suites of rocks described earlier.

There is also a general correlation between color and the index of refraction or composition of the glasses. Feldspar-rich glasses range from colorless to pale green to green. Glasses of intermediate composition are gray-green or yellow, and glasses high in iron and titanium are brown to garnet red.

Many rock glasses show recrystallization or devitrification textures. They range from textures typical of annealing to textures typical of igneous crystallization in a melt. Features indicating that these glasses were originally of impact origin are inclusions of shocked or recrystallized shocked minerals and meteoritic nickel-iron spherules.

An unknown transparent yellow mineral from sample 10047 has been identified. It is a calcium-bearing iron metasilicate isostructural with pyroxmangite (*9*). Electron microprobe analysis: 46.8 percent SiO_2, 0.5 percent TiO_2, 0.3 percent Al_2O_3, 44.6 percent FeO, 0.8 percent MgO, 6.0 percent CaO, trace Na_2O, and 0.8 percent MnO. Chemical formula: $(Fe_{.81}Ca_{.14}Mg_{.03}Mn_{.02})(Si_{.98}Ti_{.01}Al_{.01})O_3$. This mineral is biaxial positive with optical constants α = 1.753–1.756, β = 1.755–1.758, γ = 1.766–1.767, birefringence 0.013–0.011, $2V$ = 35–40°. It is triclinic, space group $P\bar{1}$, with $a = 6.623 \pm .001$ Å, $b = 7.543 \pm .002$ Å, $c = 17.354 \pm .006$ Å, $\alpha = 114.34 \pm .02°$, $\beta = 82.72 \pm .02°$, $\gamma = 94.51 \pm .02°$, $Z = 14$. Strong lines of yellow mineral are: *d* 2.934, *hkl* (014), intensity 100; 3.09 (021) 35; 4.68 (110) 35; 6.56 (100) 25; and 2.672 $(0\bar{2}6)$ 25. Calculated specific gravity is 3.82 (x-ray), 3.80 (Gladstone-Dale). The measured specific gravity (flotation technique) is 3.76.

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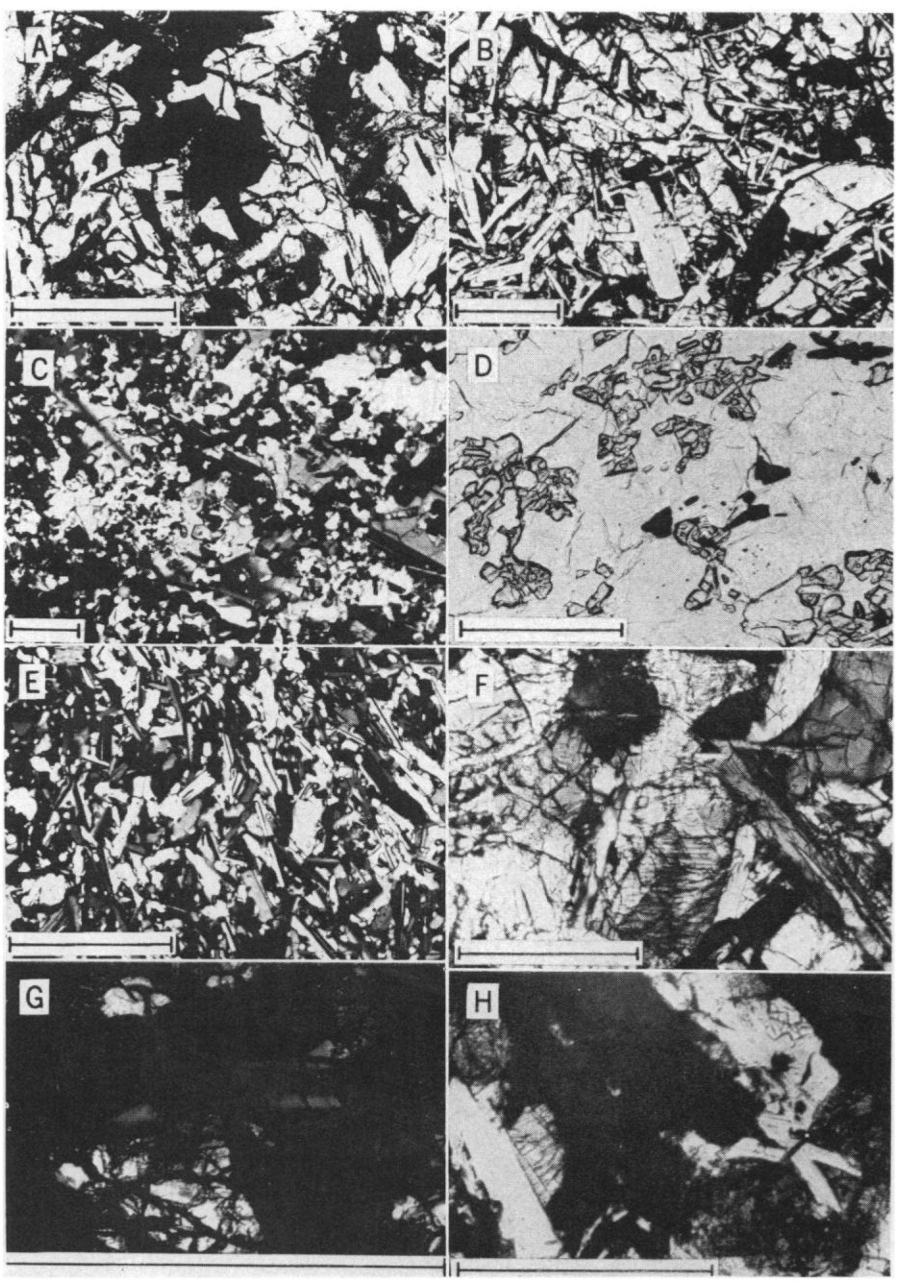

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4. Electron microprobe analyses of grains of these oxides in the sample shown in Fig. 1D follow:

	Ilmenite	Rutile	Chrome spinel	Magnesian ferro-pseudo brookite
TiO_2	55.8	98.7	3.89	72.0
Al_2O_3	0.11	0.26	14.1	0.97
Cr_2O_3	0.33	0.27	51.5	1.26
FeO	31.4	0.00	20.8	11.3
MgO	10.6	0.10	9.09	11.1
MnO	0.24	0.00	0.20	0.01
Total	98.48	99.33	99.58	96.64

5. This qualitative classification of degree of shock is based on diagnostic criteria of shock or impact metamorphism established from studies of terrestrial shocked materials [E. C. T. Chao, in *Researches in Geochemistry*, P. H. Abelson, Ed. (Wiley, New York, 1967), vol. 2, p. 204; E. C. T. Chao, *Science* 156, 192 (1967); E. C. T. Chao, in *Shock Metamorphism of Natural Materials*, B. M. French and N. M. Short, Eds. (Mono Book, Baltimore, 1968), p. 135.
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10. The petrographic and electron microprobe data were obtained primarily from polished thin sections of materials from the allocated 1-mm to 1-cm chips (10084,12). We thank N. G. Benjamin for preparing these polished thin sections. We also thank George Desborough for electron microprobe analyses of the glasses. Work was supported by NASA contract T-75412.

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