X-644-69-550
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NASA TM X? 63916

CRYSTALLINE ROCKS FROM MARE TRANQUILLITATIS: PRELIMINARY PETROLOGIC INFERENCES

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DECEMBER 1969

GSFC

GODDARD SPACE FLIGHT CENTER
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ABSTRACT

This paper reports preliminary petrographic studies of two crystalline rock samples returned from the Apollo 11 mission to Mare Tranquillitatis, and presents a discussion of their petrologic implications. Sample 10017 is a fine-grained vesicular Type A rock with the following volumetric composition: clinopyroxene, 49.7%; plagioclase, 18.0%; ilmenite and other opaques, 23.9%; interstitial material, 8.3%; and traces of an unidentified mineral. Sample 10047 is a coarser-grained non-vesicular holocrystalline Type B rock with the following composition: clinopyroxene, 49.9%; plagioclase, 32.5%; ilmenite and other opaques, 15.2%; cristobalite, 2.5%. Neither sample showed any evidence of shock. The samples appear representative of the Apollo 11 samples in general and at least locally of the Mare Tranquillitatis bedrock. The crystalline rocks are deduced to be true igneous rock, formed from internally-generated magma, rather than impact melts. The magma is believed to have been primary, and very hot, dry, and fluid by terrestrial standards. The rocks chemically resemble titanium-rich pyroxene gabbros from the Adirondack anorthosite complex. Their petrology implies that the interior of the Moon went through a high-temperature stage (1300° to 1500° C) very early in its history.

INTRODUCTION

The crystalline rocks collected at the Tranquillity Base landing site by the Apollo 11 crew can reasonably be assumed to represent the local bedrock of Mare Tranquillitatis, although not taken from outcrops, because of their general similarity to each other, to the breccias, and to the Surveyor V analysis from a site 25 kilometers northwest of Tranquillity Base. Thin sections of two crystalline rock samples, 10017 (Type A) and 10047 (Type B), have been examined with the petrographic microscope in connection with other investigations (Adler, et al., in press; Short, in press). This paper presents brief descriptions of these sections and a discussion of their petrologic implications.

ACKNOWLEDGEMENTS

Sample 10017 was allocated to Dr. Isidore Adler, Goddard Space Flight Center, for electron microprobe analysis, and sample 10047 to Dr. Nicholas Short, also of Goddard Space Flight Center, for study of shock metamorphism. I am indebted to them for the opportunity to study the samples and for much helpful discussion. I have also benefited greatly from discussion of the petrology with Drs. John Philpotts, Louis Walter, Bevan French, and Billy Glass. It is a pleasure to acknowledge the excellent field work of the Apollo 11 astronauts, Neil Armstrong and Edwin Aldrin, and the analytical work of the Lunar Sample Preliminary Examination Team.

PETROGRAPHIC DESCRIPTIONS

Because both these samples were needed for other investigations, it was not possible to do many standard petrographic studies, such as universal stage determination of feldspar compositions. In addition, only one thin section of each sample was available. Therefore, the following descriptions are only a petrographic reconnaissance.

Sample 10017

Texture

According to data from the Lunar Receiving Laboratory, this sample was from a fine-grained vesicular crystalline rock. In thin section, it appears to be almost entirely crystalline and fine-grained, with all measurable crystals under 1 mm in the longest dimension and most 0.1 to 0.5 mm in the longest dimensions. The main phases are pyroxene, occurring as a partly continuous matrix and as isolated grains, plagioclase, occurring as subhedral laths, ilmenite occurring as plates, and a largely amorphous interstitial phase (Unknown A in the mode). The texture can be classed as hypautomorphic-granular and sub-ophitic. A few vesicles were found in the thin section, making up about 10% of the volume; all were unlined. The crystals appear to be randomly oriented.

No shock features were found in the section. In particular, there were no planar features or undulatory extinction in the plagioclase, and few irregular fractures. Pyroxene showed no unusual fracturing, and even the normal cleavage was poorly developed. There were no thetomorphic glasses; the isotropic interstitial phase is almost certainly not a shock-formed glass in view of the apparent absence of lower grades of shock metamorphism. This evidence does not rule out shock, but indicates that shock pressures could not have been greater than about 100 kb.

Composition

Clinopyroxene:

This mineral occurs as interlocking crystals making up a largely continuous matrix and as isolated short, stubby crystals. The crystals are essentially colorless or slightly brownish, with no pleochroism. As seen with crossed Nicols, there is no distinct zoning. There were no reaction rims nor evidence of alteration. The extinction angle ($Z \wedge c$) was about 45°, suggesting augite.

Plagioclase:

Plagioclase occurs as anhedral to subhedral laths. Twinning is not well-developed, but almost all crystals have albite twins and some another set at high angles to the albite twin plane. Extinction angles indicated a composition at least as calcic as An_{60}, but since only a few crystals were oriented suitably for measurement from the 010 plane, this must be considered a minimum figure. There was no visible zoning. All plagioclase appears completely unaltered, with no evidence of minerals such as sericite.

Opaque Minerals:

Although not identifiable in transmitted light, the opaque minerals are known from electron microprobe analysis (Adler, et al., in press) to be largely ilmenite, with troilite, cohenite, and metallic iron.

Unknown A:

This is a brownish interstitial phase, largely isotropic, containing clusters of small grains (possibly apatite).

Unknown B:

This is a clear, colorless mineral, birefringent with parallel extinction, occurring as small, needle-like crystals.

Mode:

A point-count modal analysis was made with the modified Leitz mechanical stage according to the methods of Chayes (1956). Measurement area was about 200 mm^2, and the IC number, measured on pyroxene, plagioclase, and ilmenite, over 700. Traverses were made east-west and north-south at two-click intervals. Vesicles were not counted.

Table 1
Modal Composition of Sample 10017

	Pyroxene	Plagioclase	Opaques	Unknown A	Unknown B	Total
E-W	211	69	100	31	0	412
N-S	194	78	94	37	0	404
	405	147	194	68	0	816 points
Vol. % (corr. for vesicles)	49.7	18.0	23.9	8.3	0.0	99.9

Sample 10047

Texture

This thin section (Fig. 1) is holocrystalline and equigranular, with an average grain size between 1 and 2 mm. The phases identified are pyroxene occurring as a discontinuous matrix and as discrete grains, plagioclase occurring as laths, ilmenite and other opaque minerals occurring as plates, and cristobalite occurring interstitially. The texture can be classed as fine to medium-grained, hypautomorphic-granular, and ophitic. There are no vesicles in the section. Crystals appear to be randomly oriented.

The shock features listed in the previous section were looked for but not found. The cristobalite was examined closely because of the well-known sensitivity of quartz to shock, but looked normal. It appears that this sample, like 10017, has not been subjected to shock at pressures over about 100 kb, if at all.

Composition

Clinopyroxene:

Clinopyroxene forms a matrix enclosing plagioclase laths and as discrete anhedral crystals. It has well-developed cleavage, and is colorless or light brown with slight pleochroism in some grains. The extinction angle ($Z \wedge c$) is about 47°, and 2V estimated at about 30° from the interference figure. Although undulatory extinction is common, there is no distinct concentric zoning and no reaction rims or alteration.

Plagioclase:

Plagioclase occurs as anhedral to subhedral laths interlocked with and surrounded by pyroxene. Crystals show albite, combined Carlsbad-albite, and possibly pericline twinning. Extinction angles measured from the 010 plane indicate an anorthite content of at least An_{63} , but only a few crystals were oriented suitably for measurements. The plagioclase is apparently unzoned and unaltered.

Opaque minerals:

The chief opaque mineral is assumed to be ilmenite; no others could be identified in transmitted light.

Cristobalite:

Cristobalite occurs as interstitial material between plagioclase crystals, and is recognizable by low relief and curved fracture. It is apparently a late-stage product.

Mode:

The total measurement area of the slide was about 80 mm^2 , and the IC number, measured on pyroxene, plagioclase, and ilmenite, about 120. An extra traverse was made to compensate for the small measurement area in some degree.

Table 2
Modal Composition of Sample 10047

	Pyroxene	Plagioclase	Opaques	Cristobalite	Total
E-W	110	82	42	4	236
N-S	108	69	31	10	218
E-W	127	74	32	3	238
	345	225	105	17	692 points
Vol. %	49.9	32.5	15.2	2.5	100.1

PETROLOGY OF THE CRYSTALLINE ROCKS

Before discussing the petrologic implications of these samples, it is necessary to consider the question of how representative they are, first, of the material returned by the Apollo 11 crew and, second, of Mare Tranquillitatis in general. With respect to the first, it appears that the chemical composition of these two samples would clearly fall in the range of 12 analyses reported by the Preliminary Examination Team (Science, Sept. 19, 1969) for all five categories of material (Type A and B crystalline rocks, breccias, fines, and biological sample). The high ilmenite content, for example, shows that samples 10017 and 10047 share the high titanium content of the other samples. The mineralogical compositions appear similar to those reported by the PET for other crystalline rocks, but there are some possibly significant differences. Several other samples contain a few percent olivine (compositions between Fo_{65} and Fo_{75}). Plagioclase compositions reported by the PET are more calcic than the figures presented here: An_{70} to An_{90}. Some clinopyroxene (augite-pigeonite series) crystals are described as strongly zoned. It seems evident that there is considerable variation in composition among the Apollo 11 crystalline rocks, but not enough to prevent some general conclusions about their petrology being reached if this variation is kept in mind. These conclusions are the following.

1. The most important petrologic inference that can be drawn is that the Tranquillity Base crystalline rocks are true igneous rocks formed from internally-generated magmas, rather than crystallized impact melts from the supposed impacts that formed the mare basins, as proposed by Urey (1962) and others. This conclusion does not preclude localization of lava flows by major impacts, but means that the magma was at most only released, not formed, by impact. Evidence for this conclusion includes the following.

(a) The gross field relations of the Tranquillitatis lavas strongly contradict an impact origin for them. Impact melts in terrestrial structures, such as those described by Dence (1968), occupy a small zone near the bottom of the crater-filling breccias (although of course small amounts may be thrown out as at Meteor Crater). However, Mare Tranquillitatis obviously does not occupy a crater-like basin, and the lavas can not be ascribed to Mare Serenitatis because that would require that much more melt be produced by the Serenitatis impact than the apparent volume of the excavated basin. Even if this problem is circumvented by calling on isostatic adjustment to flatten an originally deeper basin, it does not answer the question of why the impact produced so much more melt than breccia, in complete contradiction to terrestrial craters of all sizes. Both difficulties, and the absence of a mascon, tend to rule out a buried basin under Mare Tranquillitatis.

(b) The Tranquillity Base crystalline rocks, at least those classed as Type A (which are petrographically similar to the Type B rocks), must have crystallized near or at the surface, judging from their vesicularity and fine grain. But as just pointed out, all suspected terrestrial structures ascribed to impact have the impact melt, if any, near the bottom of the crater. The Sudbury structure, which is the closest known analogue to the circular maria (Lowman, 1962), was apparently filled with breccia, now mapped as Onaping tuff (French, 1967), rather than impact melt; the impact melt as Sudbury, if any, is so deeply buried, and is such a minor fraction of the basin volume, that it has not yet been found (French, 1969).

(c) All known or suspected terrestrial impact melts are heterogeneous mixtures of glass, minerals, and rock fragments, frequently with clear evidence of shock such as thetomorphs, planar features, and disassociated refractory minerals (Fig. 2). Even devitritrified impact melts can be recognized by these characteristics (French, 1967, 1969). The Tranquillity Base A and B rocks, in contrast, are almost entirely crystalline, have normal igneous textures, and show no evidence of shock. (This description does not of course apply to the breccias (Type C); but these contain fragments of crystalline rock, and have clearly been formed by minor post-mare surficial impacts.)

(d) The minerals of the Type A and B rocks form a familiar petrographic association: calcic plagioclase, magnesian olivine, and calcium-magnesium clinopyroxene. This association can be explained by known petrologic principles, as will be shown, but there is no good reason why an impact melt should show it, barring the chance of a major impact on a target area of the same composition (which would raise the problem of how it was formed).

(e) Although perhaps not directly applicable to Mare Tranquillitatis, it has been pointed out by Shoemaker and Hackman (1962) and Baldwin (1963) that the mare material of Mare Imbrium must have been erupted a significant time after the formation of the Imbrium basin, as demonstrated by the existence of post-basin pre-mare craters such as Archimedes. This strongly implies that the mare lavas were at most localized by the supposed basin-forming impact, and could not be melts produced directly by impact. This argument applies to Mare Tranquillitatis by association.

2. A second petrologic inference - depending on the correctness of the first - is that the magma from which the Tranquillity Base crystalline rocks

formed was a primary magma, rather than one formed by differentiation of a parent magma or assimilation of solid material. Evidence for this follows.

(a) Mare material has evidently been produced in large volumes and at many times in the Moon's history, and repeatedly erupted over large areas. Such characteristics are generally considered to indicate the primary nature of a magma by such authorities as Bowen (1947) and Turner and Verhoogen (1960). Furthermore, the general similarity of the Tranquillity Base rocks to basalt, universally considered primary, indicates a primary nature for them as well. Finally, the occurrence of mare material as widespread flows, rather than as minor intrusive segregations, apophyses, or dikes, indicates it to be a primary magma rather than a product of magmatic differentiation.

(b) The mineralogic association is perhaps the strongest single indicator of the primary nature of the Tranquillitatis magma. As shown by many laboratory and field investigations, in particular the monumental study of the Skaergaard intrusion (Wager and Brown, 1967), the silicate minerals of a differentiating basaltic magma change composition systematically if equilibrium or approximate equilibrium is maintained. Plagioclase feldspars become more sodic (Bowen, 1913); olivines become more iron-rich (i.e., more fayalitic) (Bowen and Schairer, 19[illegible]); and pyroxenes change from calcium and magnesium-calcium end members (diopside and enstatite) toward the iron-bearing pyroxenes (Hess, 1941). As has been shown, the silicate minerals of the Tranquillity Base rocks are calcic plagioclase, magnesian olivine, and calcium-magnesium clinopyroxene, all typical of the beginning of magmatic crystallization rather than its end. Although some allowance must be made for a possibly unusual source material or parent magma, such as one extremely low in sodium (which would limit the reaction to albite-rich plagioclase), it seems clear that the simplest explanation for the observed mineralogy is the primary nature of the magma.

(c) Igneous rocks formed by magmatic differentiation frequently show evidence of early crystallization in the form of phenocrysts, such as calcic plagioclase, which are commonly zoned or rimmed with reaction products. There are apparently no phenocrysts in the Tranquillity Base rocks, and it seems unlikely that this can be due to extremely effective crystal settling because of the probably high density of the parent liquid. (Feldspar crystals would in fact probably float.) A related petrographic characteristic of late-stage differentiates is the presence of hydrothermal alteration products such as sericite and clay minerals, chlorite, hornblende, iddingsite, biotite, zeolites, and similar minerals. None of these have been reported from the Tranquillity Base rocks; the interstitial material (Unknown A) of sample 10017 may be a granophyric residuum representing the limit of magmatic differentiation.

3. The magma from which the crystalline Tranquillity Base rocks were formed was unusually hot, dry, and fluid by terrestrial standards.

(a) A high temperature - probably around 1300° C - is indicated by the bulk minerological composition. Taken alone, the feldspars and olivine compositions would indicate temperatures well over 1400° C, but the melt was of course a multi-component system, probably of near-eutectic composition judging from the almost simultaneous crystallization of the silicates. A possibly comparable composition is the diopside-forsterite-anorthite system (dry, 1 atm) investigated by Osborn and Tait (1952); this has a ternary eutectic at 1270° C at which diopside, anorthite, and forsterite crystallize simultaneously. This system obviously gives only a rough idea of the crystallization temperature of the Tranquillity magma; probably the most direct approach would be simply experimental melting of the natural samples or a comparable synthetic mixture.

(b) The low water content of the magma is indicated by the absence of OH-bearing primary minerals and of hydrothermal alteration products. In terrestrial basalts, water is accounted for by, for example, hornblende, biotite, and glass, which are scarce or absent from the Apollo 11 samples. Low oxygen fugacity, indicated by electron microprobe analyses showing metallic iron and cohenite (Adler, et al.), also implies low water content. If verified, this conclusion will permit application of many classic petrologic studies done in the dry way to the Moon.

(c) Very low viscosity of the magma is indicated petrographically by the high degree of crystallinity. Iron-rich melts are typically extremely fluid and hard to quench, so that the chemical composition of the Tranquillity Base rocks is consistent with low viscosity. On a larger scale, the general topography of the maria - in particular the flatness and scarcity of flow fronts - has been recognized for several years as implying a very fluid melt. Two explanations have been proposed for this apparent fluidity: formation from rhyolitic ash flows (O'Keefe and Cameron, 1962; Lowman, 1963), or from very hot ultrabasic magmas (Baldwin, 1963). Although the Tranquillity Base rocks are definitely not typical ultrabasics such as peridotites or dunites, it is obvious that Baldwin's explanation was close to the truth.

TERRESTRIAL ANALOGUES

Before discussing the question of whether the Mare Tranquillitatis crystalline rocks have any terrestrial counterparts, it will be helpful to classify them petrographically. Being nearly holocrystalline, they can be fitted into Johannsen's (1939) mode-based system: by dark mineral content, into Class 3; by the anorthite content of plagioclase into Order 2; by the low quartz (or cristobalite) content and absence of potassium feldspar into Family 12; in aggregate, 3312E ("E" referring to extrusive occurrence). If the deduction presented here that the magma was undifferentiated is correct, they would be also labeled aschistic. The monoclinic nature of the pyroxene, with the other characteristics, indicates a designation of samples 10017 and 10045 as melabasalt (3312E).

The foregoing is not simply an exercise in formal petrography, for it gives us some idea where to look for terrestrial analogues of the Tranquillity Base rocks. Among the several other members of this petrographic niche listed by Johannsen (Vol. III) is an "ilmenite-norite" from Soggendal, Norway (p. 331, Table 100, #11). Although there is not enough information given by Johannsen to compare this rock with those from Apollo 11, it suggests their possible relation to comparable rocks in North America, in particular to the titaniferous basic rocks associated with anorthosites of the Adirondack Mountains. Examination of the standard reference on Adirondack igneous rocks by Buddington (1939) reveals two analyses of rocks that are significantly similar to the Tranquillity Base samples discussed here: a sphene gabbro pegmatite and a pyroxene gabbro. (After the foregoing similarity had been found, it was learned that Olsen (1969) had made an identical comparison between these two analyses and the analysis reported by Turkevich, et al. (1969) from Surveyor V on Mare Tranquillitatis.) Since there are no extrusive equivalents of pegmatites, one of these analyses is not directly comparable to the volcanic rocks of Tranquillity Base, but the pyroxene gabbro (Analysis 27, Table 7, p. 36) is. As described by Buddington, this rock is from the pyroxene gabbro facies of coarse-grained gabbroic anorthosite, one mile SSW of Brown Point (New York). The analyzed sample has a gneissic structure and granoblastic texture with some plagioclase and pyroxene porphyryoclasts. The approximate modal composition is plagioclase (An_{48}) 40%, augite 30%, hypersthene 12%, ilmenite 15%, orthoclase 2%, apatite 1/2%, with traces of biotite, quartz, and pyrite. In Table 3, this rock is compared with the average composition of all Tranquillity Base samples and with the average compositions of terrestrial basalts. The chemical similarity between Buddington's sample and the Apollo 11 rocks is apparent, although there are major differences in texture and mineralogy due to the different conditions under which the terrestrial and lunar rocks formed.

It thus appears that, although the Apollo 11 samples are significantly different in bulk composition from terrestrial basalts, they do have normal though

Table 3
Chemical Compositions of Tranquillity Base Samples, Terrestrial Basalts, and a Pyroxene Gabbro

	Pyroxene[1] Gabbro	Tranquillity[2] Base	Pacific[3] Olivine Basalt	Average Tholeiitic[4] Basalt
SiO_2	45.25	41.1	47.0	51.0
Al_2O_3	11.84	11.2	15.1	15.6
TiO_2	6.88	9.6	3.0	1.4
FeO	14.12	18.1	8.1	9.8
Fe_2O_3	1.59	n.d.	3.7	1.1
MgO	6.42	8.0	7.9	7.0
CaO	10.23	10.4	10.9	10.5
Na_2O	2.14	0.51	2.7	2.2
K_2O	0.47	0.14	1.0	1.0
MnO	0.23	0.36	0.2	0.2
Cr_2O_3	n.d.	0.55	n.d.	n.d.
ZrO_2	n.d.	0.12	n.d.	n.d.
NiO	n.d.	0.03	n.d.	n.d.
Total	99.76	100.0	99.9	100.0

1. From Buddington (1939, Table 7, Analysis 27); analysis included 0.14% H_2O+ and 0.03 H_2O- to give total of 99.76. Analyst, R. B. Ellestad.
2. From "Preliminary Examination of Lunar Samples from Apollo 11," Science, 165, 1211, 19 Sept. 1969; figures are average of 12 analyses (Table 1), including 4 Type A and 4 Type B rocks, 2 breccias, 1 fine material, and 1 Bio-Pool sample.
3. From Poldervaart (1955); average Pacific olivine basalt (water free). Data included 0.3% P_2O_5.
4. From Poldervaart (1955); average tholeiite (water free). Data included 0.2% P_2O_5.

Note: "n.d." means not determined or not listed.

uncommon terrestrial analogues in the basaltic rocks associated with anorthosite complexes. The origin of the anorthosites is still a geologic problem, and it seems possible that, if the similarity suggested here is confirmed, the lunar rocks may throw some light on the anorthosites. Discovery of lunar anorthosites would of course be of more direct help.

IMPLICATIONS FOR THE EVOLUTION OF THE MOON

To discuss the evolution of a planetary body on the basis of two thin sections may seem presumptuous. However, if studied in light of the outstanding work of the Preliminary Examination Team on other samples and the great amount of previous theoretical investigation of lunar petrology, a few general conclusions can be tentatively suggested with some justification.

The first of these is that, if the Tranquillitatis lavas are of internal origin, as suggested here, the Moon must have reached high internal temperatures in the first few hundred million years of its history (assuming the Tranquillity Base rocks to be over 4 billion years old). These temperatures were probably on the order of 1300 to 1500° as a minimum, assuming the magmas to have been formed by partial melting of iron-magnesium silicates (Fig. 3). Higher temperatures are definitely not ruled out, although if the interior of the Moon became much hotter than 1500° C, total melting, at least locally, would have occurred.

A second general conclusion is that, if the Tranquillitatis magma was primary, any peculiarities of composition (such as high titanium content) must be due to the nature of magma generation in the Moon or to the bulk composition of the source region of the magma, rather than to differentiation or other magmatic process. This may be important in studying the implications of the high titanium and low alkali contents of the Mare Tranquillitatis samples. For example, it might be speculated that the source region of the magma was already low in alkalis, before the magma was formed, as a result of pre-mare differentiation to form the lunar highland crust. This is obviously but one of many possible explanations.

SUMMARY AND CONCLUSIONS

The petrographic results reported here, taken with other analyses of Apollo 11 samples and with the Surveyor V results, indicate that Mare Tranquillitatis is an immense lava flow or series of flows mantled with a layer of fragmental debris. The lavas appear to have been primary magma that came from deep within the Moon without major modification by magmatic differentiation or assimilation. The magma may have erupted through impact-formed fractures, but is essentially of internal origin, formed by partial or even complete melting of part of the Moon's interior.

The Tranquillity Base crystalline rocks have major chemical differences from basic terrestrial rocks, but nevertheless they do have terrestrial analogues in the titanium-rich gabbros associated with Precambrian anorthosite complexes. If they were indeed formed by solidification of essentially unmodified primary magma, their peculiar chemistry reflects the nature of magma-generating processes or the composition of the source region, and probably both, rather than unusual magmatic differentiation.

The apparently great age of the Apollo 11 crystalline rocks implies, if the foregoing deductions are correct, that the Moon's very early history was marked by high internal temperatures, and that much of its geologic evolution was accomplished in a few hundred million years.

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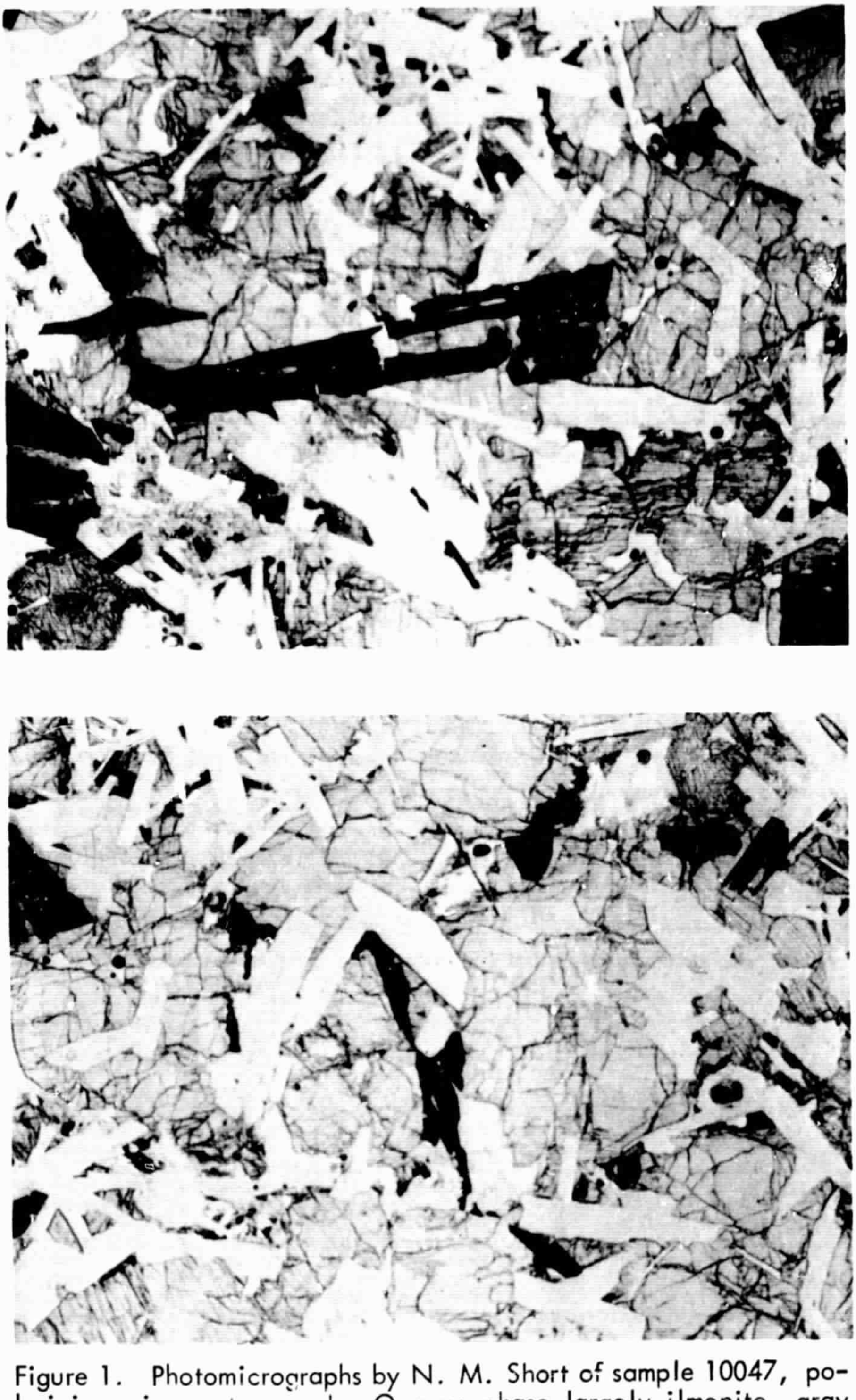

Figure 1. Photomicrographs by N. M. Short of sample 10047, polarizing prisms not crossed. Opaque phase largely ilmenite, gray phase clinopyroxene, white phase plagioclase. Sample 10017 has similar texture and composition but is finer-grained.

Figure 2. Photomicrograph by B. M. French showing partly crystalline impact melt from Tenoumer crater in Mauritania. Polarizing prisms not crossed; width of field about 1 mm. Large fragment is quartz; note planar features indicating shock. Fine-grained groundmass consists of feldspar laths, pyroxene, and interstitial glass.

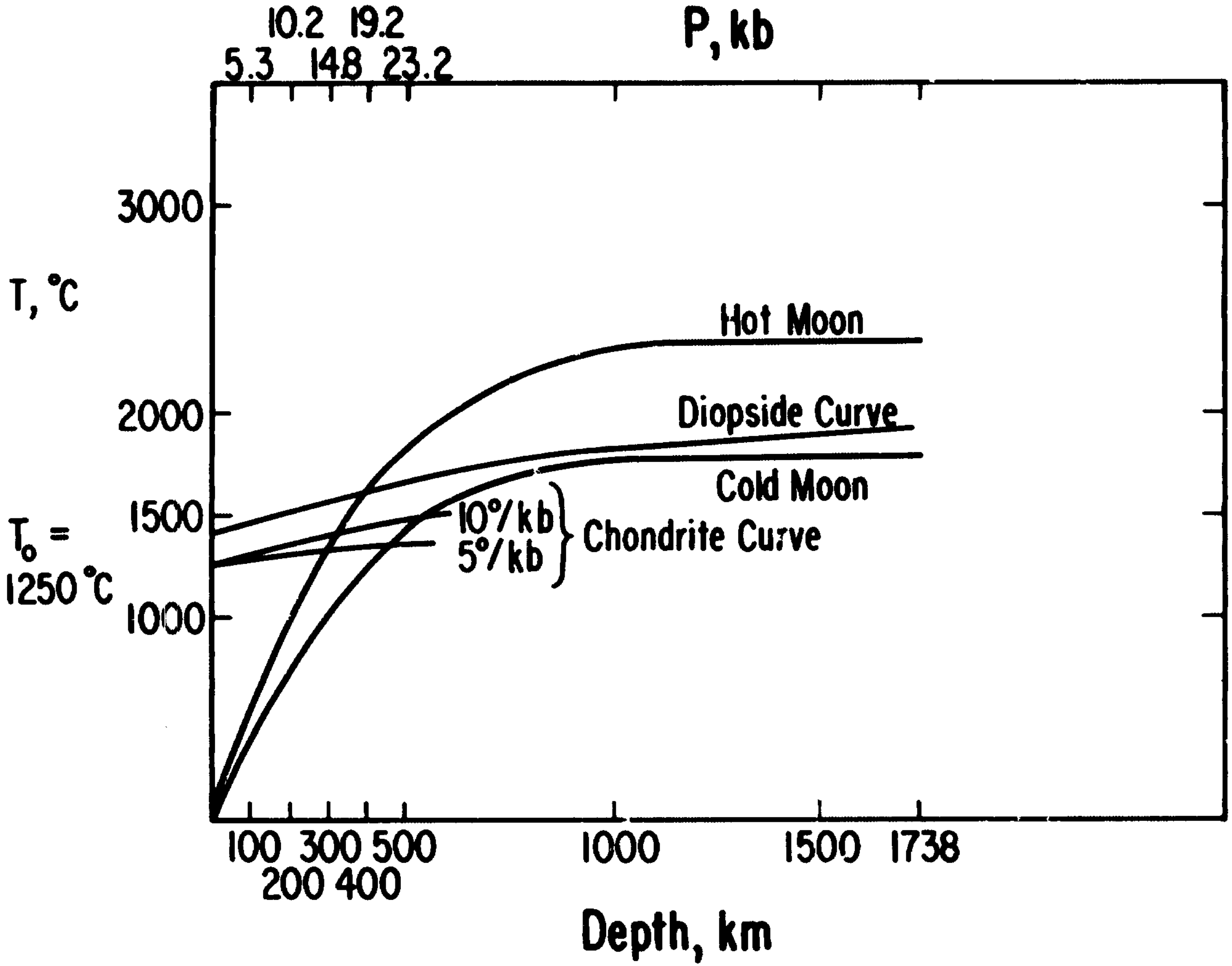

Figure 3. Depth and temperatures of lunar magma generation, from Lowman (1963), assuming chondritic composition and initially "cold" (0°C) and "hot" (600°C) Moon models, as calculated by MacDonald (1959).