Supercooling on the Lunar Surface: A Review of Analogue Information

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Supercooling on the lunar surface: a review of analogue information

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[Plate 1]

The crystallization of the principal constituent minerals, olivine, pyroxene and plagioclase, in dendritic or skeletal forms, is much more characteristic of lunar than of terrestrial igneous rocks. This type of crystallization is found in lunar rocks of such varied composition as olivine-normative mare basalt (12009) and spinel troctolite (62295). Olivine and pyroxene often occur as skeletal phenocrysts and the stage at which they crystallized is of crucial significance to interpretations of the genesis and cooling history of the porphyritic lavas. Furthermore, there is a widespread occurrence of glass and of immature, radiate crystallization, particularly of highly zoned pyroxenes and zoned plagioclase. Most of these characteristics are a response to a range of supercooling and rapid crystal-growth conditions that are typically lunar. The research value of direct comparison with terrestrial analogues is severely restricted, and the value of controlled cooling-rate experiments, with melts of appropriate compositions, is correspondingly enhanced. This need for information on the rapid consolidation of the lavas extruded on the Moon, and of impact liquids, has stimulated investigations of the phase petrology of supercooled melts. The evidence adduced from these analogue approaches is reviewed. Recently published research results based on this evidence have provided new guide-lines to interpreting crystallization on the lunar surface.

1. INTRODUCTION

Evidence for a lack of approach to crystal-liquid equilibrium during crystallization is characteristic of the cooling and consolidation of many lunar mare basalt magmas. Experiments designed to establish successive stages of crystallization *at equilibrium* have therefore a restricted value. It is to a range in non-equilibrium, supercooling conditions that one can attribute the sizes, shapes and textural relations of the mineral phases which crystallized metastably from such magmas.

Terrestrial igneous rocks with textures attributable to supercooling can be correlated with geological, particularly field, relationships and this is rarely possible with lunar lavas. During the earlier investigations of mare basalts, information was therefore sought from terrestrial analogues. Detailed petrographic study of these analogues, with specific reference to immature crystal morphologies and to porphyritic and other textural relationships, advanced our understanding of the conditions governing the cooling of mare basalts only to a minor degree. Perhaps more importantly, it exposed our ignorance of the effects of supercooling almost as much with relation to terrestrial as to extraterrestrial magmas.

If a truly significant advancement were to be achieved, it became imperative to subject material of appropriate mare basalt chemistry to simulative experimentation. Differences in cooling rates and degrees of supercooling would have to be controlled and evaluated accurately, and the effects of these differences, on crystal morphologies, textures and chemical zoning in the mineral phases, systematized. The information obtained experimentally could then be applied analogously to elucidating the cooling history of natural lunar samples. Results of experimental investigations of this kind, and deductions from them, have been published by a group at the Johnson Space Center in Houston. This group has determined the cooling and crystallization histories of many mare basalt samples.

The object of this review is to trace the development of analogue research, terrestrial and experimental, and to demonstrate how experimental modelling can simulate the cooling and consolidation of lunar lavas. We draw heavily on the work of the Houston group, of which the first author was a member.

2. Review of literature

Drever & Johnston (1957, 1958, 1967) attributed the immature crystal morphologies of olivines that commonly develop in picritic minor intrusions of Tertiary age, in Scotland and west Greenland, to supercooling and rapid growth. They also attributed to rapid growth the development of very large skeletal olivines in the classic harrisite on the Isle of Rhum in Scotland (Drever & Johnston 1972; Drever *et al.* 1972), previously investigated by Harker (1908), Brown (1956) and Wadsworth (1961). The range in olivine morphologies in harrisite was later described in more detail by Donaldson (1974) who compared them with those in the ultrabasic Archean 'spinifex' lavas also known as komatiite. Skeletal olivines in submarine lavas have been studied by Bryan (1972).

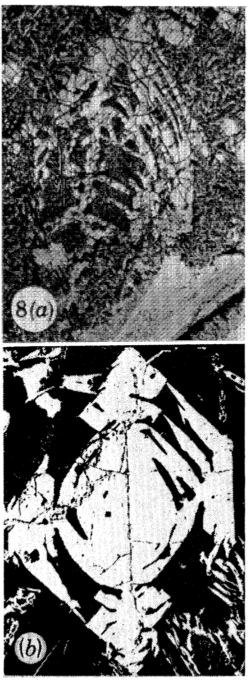
Among lunar samples, the analogue nearest to such terrestrial rocks with skeletal olivines is the vitrophyric mare basalt 12009 (figure 1, plate 1). Although the range of olivine morphologies displayed in thin sections of this sample is greater than in any known specimen of terrestrial rock, all of these morphologies can be matched with reference to the literature cited (figure 8*a*, *b*, plate 1). From such analogical studies it was concluded that forsteritic olivine crystallized in immature forms when rapidly precipitated from magnesia-rich magmas, and that the size range in such olivines is less critical in significance than their skeletal growth (Drever & Johnston 1972; Donaldson 1975*b*).

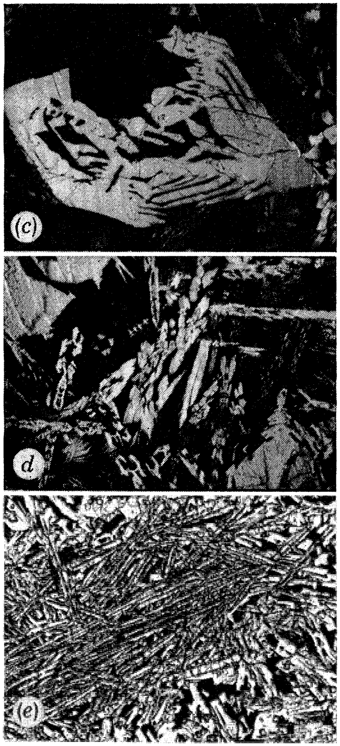
Description of plate 1

Figure 1. Photomicrograph (12009, 6) of a vitrophyric olivine basalt, from the Apollo 12 Mission, with microphenocrysts of forsteritic olivine (white) in a cryptocrystalline groundmass (black). Three stages of olivine crystallization are represented: (1) equant microphenocrysts (with skeletal outgrowths) aggregated in upper right area, (2) skeletal microphenocrysts (lower middle area), (3) microlites (mainly acicular). (Magn. × 15.)

Figure 2. Photomicrograph (15597,18) of a vitrophyric pyroxene basalt, from the Apollo 15 Mission, with microphenocrysts of zoned, hollow clinopyroxenes in a groundmass mainly of glass (black). (Magn. × 6, length of photomicrograph is 20 mm.)

Figure 8. (*a*) Skeletal olivine, with fine radiate crystallization internally of pyroxene and plagioclase, in a picritic basalt sill on Soay in Skye. (Magn. × 11.) (*b*) Skeletal olivine in mare basalt 12009 with olivine microlites and glass. (Magn. × 30.) (*c*) Skeletal olivine crystallized in a melt of chemical composition similar to mare basalt 12009. (Magn. × 60; reproduced from Donaldson 1975*b*.) (*d*) Groundmass crystallization in one part of a thin section of mare basalt, 12009, 6. Crystallites of pyroxene occupying the centre together with a tiny arborescent development near left corner. Bottom right and top left corners are occupied by olivine microphenocrysts, the remaining crystallites are mainly olivine set in dark 'glass'. (Magn. × 50.) (*e*) Aggregate of acicular olivines in spinel-troctolite 62295, 82. Scale: approximately 2 mm across. (*f*) Part of a specimen of ultrabasic komatiite lava from Ontario, Canada. ($\frac{1}{2}$ size.)





FIGURES 1, 2 AND 8. For description see opposite.

(*Facing p.* 208)

The range in textures in samples from the lunar maria have been correlated with a range in the cooling rates responsible for their production (Wood *et al.* 1971; Dowty *et al.* 1974). In mare basalts, a very common groundmass texture often referred to as variolitic, consists of plumose or radiate aggregates of immature and interleaving pyroxene and plagioclase. With reference to terrestrial analogues, this texture can also be attributed to supercooling (Drever *et al.* 1972; Hollister *et al.* 1972; Weigand & Hollister 1973; Dowty *et al.* 1974). But the common occurrence in such mare basalts of pyroxene phenocrysts, also manifestly skeletal and with chemical zoning unique in its range and complexity, led to the denial by the same investigators that a two-stage thermal history could be invoked, even to the extent of asserting that all the pyroxene-phyric basalts crystallized in one stage (e.g. Dowty *et al.* 1974). Others adduced evidence in favour of the more usual interpretation of porphyritic rocks (e.g. Boyd & Smith 1971; Bence & Papike 1972). Texturally, it is only the highly zoned, hollow pyroxene phenocrysts that clearly differentiate these mare basalts from terrestrial pyroxene-phyric lavas.

Morphologies of plagioclase have been investigated by Lofgren (1971, 1974) and some of its textural relations by Drever & Johnston (1972). From Lofgren's work on the morphological responses of plagioclase to crystallization from supercooled feldspar melts, more sophisticated experimentation evolved (Donaldson *et al.* 1975*a*), and was applied to the problem of morphological, textural and chemical responses to supercooling of all principal minerals in mare basalts. This developing experimentation had as its objective (by means of controlling and varying the cooling rates of basaltic melts of appropriate compositions) a precise matching of the products achieved in the laboratory with the range of mare basalts which consolidated on the lunar surface. From comparisons of crystal morphologies, textural relations and zoning trends in the mineral phases, cooling rates could be deduced. Relatively crude attempts to simulate natural skeletal crystallization of olivine (Drever & Johnston 1957; Brett *et al.* 1971) were superseded by this later and still current work (Lofgren *et al.* 1974, 1975*a*, *b*; Usselman *et al.* 1975*a*, *b*; Donaldson *et al.* 1975*b*). Determination of the cooling rates of mare basalt samples has now become of major significance, and other current work with a similar aim to that of the Houston group must also be cited here (Takeda *et al.* 1975 using X-ray diffraction of single crystals; Walker *et al.* 1975*a*, *b*, using experimental petrology; and Taylor *et al.* 1975, using partitioning of Zr between ilmenite and ulvöspinel).

Finally, it is relevant to refer to the occurrence of skeletal olivine in lunar chondrules which have been compared to those in meteorites (Kurat *et al.* 1972). In addition to a barred olivine chondrule (Roedder & Weiblen 1974), the spinel troctolite, 62295, contains distinctive skeletal morphologies of forsteritic olivine, one type being concentrated in a small patch (figure 8*e*, plate 1) and compared by Hodges & Kushiro (1973) to komatiite (figure 8*f*, plate 1). Agrell *et al.* (1973) regard sample 62295 as a crystallized impact melt. The dearth of impact, particularly basaltic, melts of terrestrial origin means that little analogical evidence is available. Melting by an igneous intrusion of the country rock, with or without recrystallization phenomena, has an analogous effect to impact melting, and it is conceivable that the exceptional rock-type at the upper margin of the Gars-bheinn intrusion (Drever *et al.* 1972), in which olivine has crystallized in a manner similar to that in 62295, was generated by fusion of the associated highly metamorphosed basic lavas. Although the field evidence is ambiguous, this rather variable upper-margin contact facies grades outward into the crystallized, and apparently rheomorphosed lavas, and inward into the feldspathic peridotite with feldspar-rich bands. This intrusion is now being more thoroughly explored.

3. Textures and crystal morphologies as cooling indicators

(*a*) *Porphyritic*

When minerals of an early crystallizing phase in an igneous rock occur in a much larger size than those in the groundmass it is possible that they have moved in the residual liquid, either up or down, or in random directions in response to turbulence, or have become associated in aggregates by synneusis. The petrogenetic implications of these possible movements justify here a short diversion. That a porphyritic rock cannot with certainty be held to represent a liquid of its own bulk chemical composition is normally incontrovertible. Movement of crystals relative to the residual liquid will depend on the viscosity of this liquid, on crystal size and on the relative specific gravities of the crystal and liquid. Early-formed crystals of a specific gravity lower than that of a residual mare basalt liquid would move upward more slowly than on earth owing to the much lower lunar gravity but more rapidly due to the lower viscosity. The lower viscosity would also favour downward settling of relatively heavy minerals. Lunar gravity is approximately 1/6 that of the Earth, and the viscosity of mare basalt magma is approximately $\frac{1}{10}$–$\frac{1}{20}$ that of a terrestrial tholeiite. Hence a crystal of a given size will move 1.6–3 times faster in a lunar basaltic magma than in a terrestrial tholeiite. Even so, any movement of skeletal olivine microphenocrysts following eruption, in the vitrophyric mare basalts, would be on a negligible scale owing to their rapid cooling and consolidation. This does not apply to skeletal phenocrysts in coarser grained rocks.

The size of skeletal or hollow pyroxene phenocrysts relative to groundmass crystals is very variable in the range of mare basalt samples collected by the Apollo missions. One of the more extreme discordances in size (Weigand & Hollister 1973) is in pyroxene-phyric, quartz-normative basalt sample 15597 (figure 2, plate 1), some thin sections of which have a megacryst attributed by Weigand & Hollister to growth in a restricted region of lower nucleation density. They inferred that this basalt cooled on the lunar surface from a totally molten magma. That the two generations of pyroxene in the pyroxene-phyric basalts can be derived experimentally from a melt of quartz-normative basalt by monotonic cooling (Lofgren *et al.* 1974) has further validated this one-stage cooling hypothesis as applicable to many of the pyroxene-phyric lunar lavas. It is stressed that the phenocrysts in these experiments did not grow at the liquidus temperature of the melt, but rather under non-equilibrium supercooling conditions of 10–30 °C.

(*b*) *Glomeroporphyritic*

The aggregation of phenocrysts or microphenocrysts by synneusis (Vance 1969), is well illustrated by some of the microphenocrysts in sample 12009 (Donaldson *et al.* 1975*b*), and it is the more solid, less obviously skeletal, crystals which demonstrate this phenomenon (figure 1). The optical orientations of most of the olivines in these aggregates appears to be random (Butler 1970; Drever & Johnston 1972). If developed as phenocrysts or microphenocrysts at an early stage in the thermal history of a magma (Donaldson *et al.* 1975*b*), skeletal crystals of olivine can also aggregate (figure 3). The writers have no information on any lunar basalts in which there is an aggregation of pyroxene phenocrysts and the uniform distribution of pyroxenes in 15597 (figure 2) can be contrasted with the uneven distribution of olivine in 12009 (figure 1).

(*c*) *Groundmass*

Crystallization in the groundmass of 12009 is characterized by bladed and acicular skeletons of olivine (figure 1), referred to as type III in supercooling experiments (Donaldson *et al.* 1975*b*). The crystallization of dendritic pyroxenes in this rock (Lofgren 1971) occurs so sporadically (figure 8*d*, plate 1) that it could be ascribed, as is the crystallization in some of the orange glass spherules (Haggerty 1974), to devitrification rather than crystallization from a liquid. On the other hand, experimental evidence (Donaldson *et al.* 1975*b*) indicates that the groundmass variation is due to a slower cooling rate (< 80 °C/h) in the portion containing pyroxene and that such a variable cooling rate may imply liquid movements even when crystallization was far advanced. The sporadic pyroxenes in the glassy groundmass of the pyroxene-phyric mare basalt 15597 have been cursorily attributed to nucleation and growth before 'final quenching of the magma' (Weigand & Hollister 1973). Analogous examples of dendritic pyroxene from a terrestrial rock are well illustrated by Gansser (1950).

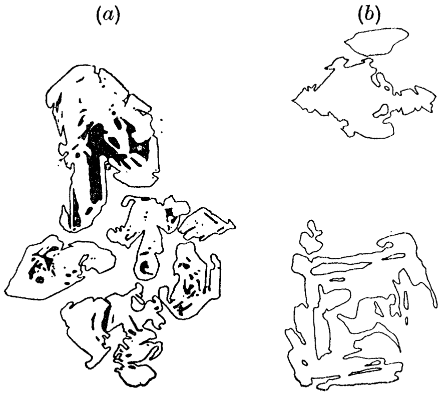


FIGURE 3

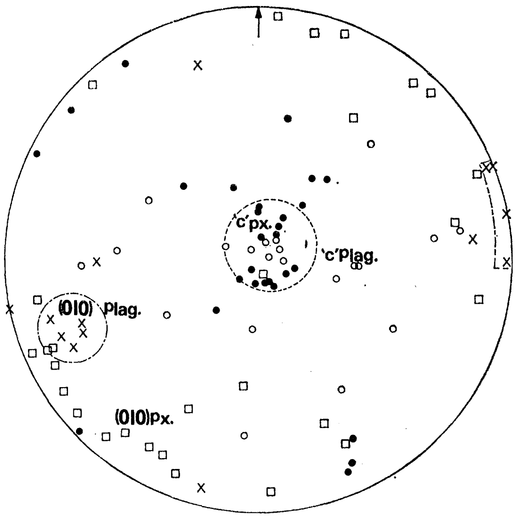


FIGURE 4

FIGURE 3. (*a*) Cluster of five olivines in the centre of an attenuated part of Dyke 5, Coire Lagan, Cuillins, Skye. Drawn with each olivine slightly separated from the cluster. Black indicates very fine-grained groundmass enclosed in the olivine. (Magn. × 10; reproduced from Drever & Johnston, 1958, text-fig. 12.) (*b*) Two skeletal olivines drawn from a photomicrograph of a thin section of an Apollo 12 mare basalt (12002, 167). Both have uniform extinction under crossed polars. (Magn. × 20; see page 210 in text.)

FIGURE 4. Equal area projection (upper hemisphere) of the 'c' axes and (010) planes of clinopyroxene and plagioclase forming a radiate group in an Apollo 12 mare basalt (12021, 3).

The 'variolitic' type of groundmass is rarer in terrestrial than in lunar basalts. More discriminate terms that have been suggested for this texture are 'radiate' and 'intrafasciculate' (Drever & Johnston 1972; Drever *et al.* 1972). The optical orientation of the radiate pyroxene and plagioclase, plotted stereographically, provides a means of comparing this type of texture in lunar samples with terrestrial analogues. Such comparisons were made by Drever *et al.* (1973) who concluded that these radiate aggregates represented random sections through cones of thinly tabular pyroxene and plagioclase fibres. They attributed the texture to rapid cotectic crystallization. An example from lunar basalt 12021 is plotted stereographically in figure 4. These radiate textures have been faithfully simulated in supercooling and controlled cooling rate experiments (Lofgren *et al.* 1974). Radiate crystallization of pyroxene alone (Hollister *et al.* 1971; Drever *et al.* 1973) and of plagioclase alone (Gancarz *et al.* 1972) can also be attributed to supercooling.

Ophitic, subophitic and intersertal textures, which are prevalent in terrestrial basalts and dolerites, also characterize many lunar basaltic samples. Since ophitic and subophitic textures are commonly referred to as evidence of cotectic precipitation it is desirable that the advantages of microprobe analyses of compositional changes, due to zoning in the phases represented, should be correlated with the degree of intergrowth achieved by these phases. This correlation is illustrated in figure 5. Two zoned clinopyroxenes, (I) and (II), in a single thin section (15058, 127) of a mare basalt were selected, (I) being in subophitic relation to the plagioclase and (II) being in ophitic relation. The compositional area indicated by the oblique shading is interpreted as closely corresponding to the cotectic crystallization of plagioclase with ferriferous augite.

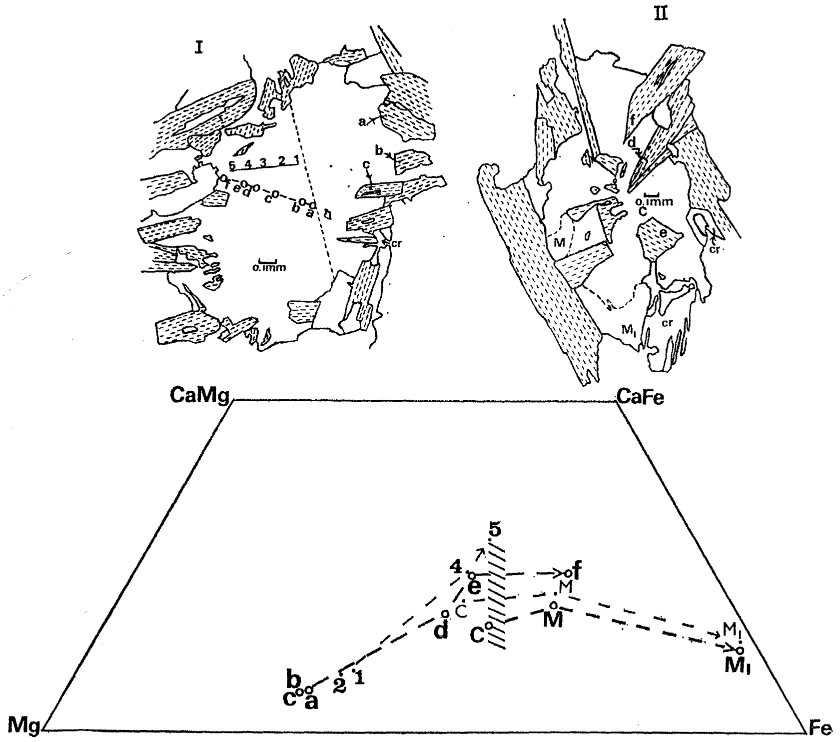


FIGURE 5. Sketches (from photomicrographs) of two examples, in a thin section (15058, 127) of an Apollo 15 mare basalt, of the textural relationships of zoned clinopyroxenes (white, subophitic and twinned in I; white, ophitic in II) and zoned plagioclase (dashed). The numbers or letters (C, M, M_1 refer to pyroxene II) correspond approximately with microprobe analyses in the positions shown in these sketches; arrows indicate in the quadrilateral the inferred directions of crystal growth; cr-cristobalite, opaques omitted. In pyroxene II the position of the second three determinations only approximately coincided with the first three but are given the same lettering (C, M, M_1). The area hachured is the approximation to the pyroxene composition at the time when plagioclase began to crystallize, inferred from the textural relations. Two independent series of microprobe analyses on these pyroxenes were made as a check on accuracy.

4. Cooling models

Glass represents incontrovertible evidence of the supercooling with which this review is concerned. In the following interpretative outline of lava cooling rates on the lunar surface, it is therefore appropriate to refer first to the glassy material, so prevalent on the lunar surface as a whole, which constitutes part of the groundmass in the few vitrophyric lavas such as 12008, 12009 and 15597.

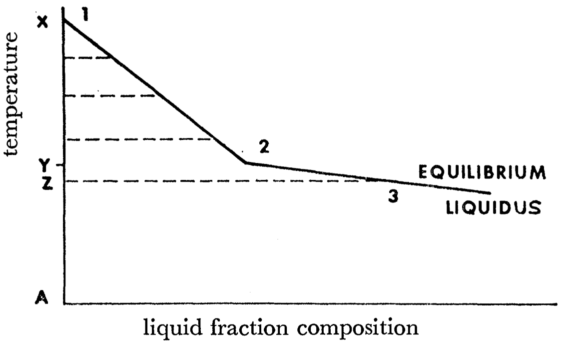


Figure 6

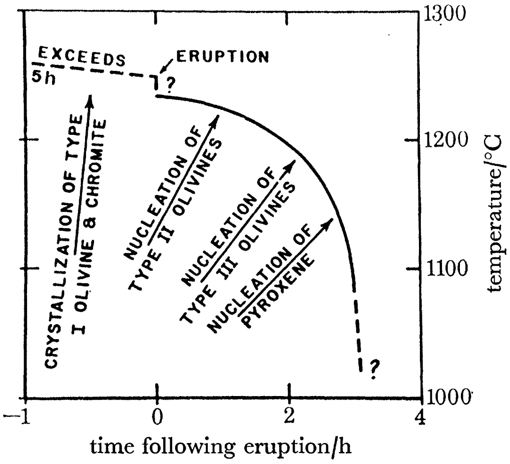


Figure 7

Figure 6. Graphical representation of the effect of a change in slope of the liquidus (melt of composition A) on supersaturation, one phase crystallizing between 1 and 2 and two phases between 2 and 3. Supersaturation (proportional to the length of the hachures) suddenly increasing at temperature Y would result in a sudden increase in crystal growth rate. The small degree of supercooling from Y to Z would result in a relatively large increase in supersaturation.

Figure 7. Graphical synopsis of the experimentally determined successive stages in the nucleation of the distinctive olivine morphologies represented in 12009 (types II and III: see figure 1) correlated with the experimentally evaluated increasing cooling rate curve. The evaluated slower cooling rate required to reproduce type I olivine (plus chromite) is held to indicate pre-eruption crystallization (Donaldson *et al.* 1975).

In his investigation of the Apollo 17 orange glass, Haggerty (1974) has reviewed other work on the generation and devitrification of lunar glasses. Since the sporadic crystallization in the orange glass appears to have occurred after the glass spherules had become rigid it is regarded as due to devitrification. On the other hand, the nucleation and sporadic crystallization of pyroxene crystallites in the glassy groundmass of the vitrophyric mare basalt 12009 is attributed to nucleation during the optimum cooling rate of the *liquid* (Donaldson *et al.* 1975*b*). Furthermore, according to Weigand & Hollister (1973), the composition of ferropyroxene crystallites in the groundmass of quartz-normative mare basalt 15597: 'is nearly identical to that of the ferroaugite edge of the augite (phenocrysts) rims which suggests that pyroxene nucleation, as well as growth, continued until final quenching of the magma'. Since solidification at the final stage of very rapid cooling may have been virtually instantaneous, a distinction between pre-consolidation and post-consolidation (devitrification) crystallization may be purely academic.

Experimental evaluations of cooling rates and supercooling of basaltic lavas have been largely confined to melts of mare basalt compositions, exceptions being the work of Gibb (1974) on the nucleation and crystallization of plagioclase, over a range of supercooling values, in a sample of Columbia River basalts, and that of Lofgren & Donaldson (1975) on an oceanic tholeiite from the Deep Sea Drilling Project. Donaldson (1975*a*) has also calculated the diffusion coefficients of melt components and the growth rate of olivine in oceanic tholeiite. Significant advancements in understanding cooling conditions in basaltic lavas stem from the experimental work of Lofgren *et al.* (1974, 1975*a*, *b*) on quartz-normative lunar basalts (of which 15597 is an example) followed later by that of Donaldson *et al.* (1975*b*) on 12009 and olivine-normative mare basalts, and of Usselman *et al.* (1975*a*, *b*) on high-titanium mare basalts.

In their experiments, Lofgren and his co-workers (1974) crystallized a synthetic quartz-normative basalt at linear cooling rates ranging from 1250 °C/h to 1 °C/h, the development of porphyritic textures being restricted to rates less than 60 °C/h. The increase in nucleation density, responsible for the groundmass crystallization, is attributed to a sudden increase in pyroxene supersaturation as the liquidus slope abruptly decreases (figure 6) when co-precipitation with plagioclase commences (Wyllie 1963). Analogous zoning in pyroxenes and other non-eqilibrium characteristics of such lunar basalts are reproduced during cooling. Furthermore, a systematic relationship is established between different cooling rates and a range of different textures and crystal morphologies. In six Apollo 15 mare basalts, including 15597, the crystal morphologies and zoning trends of the pyroxene phenocrysts have their analogues in the phenocrysts grown experimentally at cooling rates between 1.2 °C/h and 30 °C/h. It is estimated that mare basalt 15499 supercooled 30 °C before pyroxene nucleated. Following this work, further analogical evaluations of the cooling rates of samples of individual Apollo 15 quartz-normative basalts were undertaken (Lofgren *et al.* 1975*a*, *b*). In the case of the majority of these basalts it is deduced that the phenocrysts grew at slightly slower cooling rates than the groundmass crystals and that the cooling rate has been of the continuously increasing, one-stage type. Since the skeletal morphologies of the phenocrysts indicate rapid growth and supercooling not less than 30 °C (Lofgren *et al.* 1974), it is still maintained that they crystallized on the lunar surface. By varying the oxygen fugacity during experimental crystallization, similar phenocryst morphologies, but different groundmass textures, are achieved; and it is suggested that this variation might explain some of the differences in the deduced cooling rates for phenocrysts and groundmass. Were these differences, in the deduced cooling rates for phenocrysts and groundmass, to be attributed to different sampling positions within a single lava flow, or from two flows of similar thickness, the discrepancies could be explained by variation in oxygen fugacity, in temperature of nucleation, or by invoking some crystal settling. The samples were collected at distances up to 4 km apart.

Similar analogue experiments, at controlled cooling rates and oxygen fugacities, have been undertaken to elucidate the cooling history of high-titanium mare basalts (Usselman *et al.* 1975*a*, *b*). The low-alumina, high-titanium basalt crystallized with an intersertal texture, and the high-alumina high-titanium basalt with ophitic texture at rates less than 5 °C/h. (Faster cooling rates yield an intersertal texture in the high-alumina composition.) Zoning in the pyroxene of the high-alumina basalts is also reproduced. The deduced cooling rates for groundmass crystallization provide information on the thickness of the flows from which the lunar samples were derived.

Since the vitrophyric mare basalt 12009 has been regarded as one of the lunar samples most critical in studies of magma generation and fractionation trends, the application of analogue cooling rate experimentation to melts of similar chemical composition is correspondingly important. A crucial problem is the apparent multi-stage nucleation of olivine. Recently completed results (Donaldson *et al.* 1975*b*) are summarized in figure 7. The exceptional range in olivine morphologies (figure 1) and compositions is reproduced and equated with differing nucleation temperatures and cooling rates (figure 7 and figures 8*b*, *c*, plate 1), the reproduction, principally of the most magnesian non-skeletal equant olivines (Stage I), having been achieved at a cooling rate significantly lower than the cooling rate equated with the ensuing nucleation (Stage II). It is suggested that this may indicate that approximately 5% of the olivine, non-skeletal and skeletal, crystallized prior to extrusion of the lava. Evidence that olivine phenocrysts in some Apollo 17 vitrophyric basalts grew during cooling at less than 2 °C/h, whereas the groundmass may have cooled at 200 °C/h, also suggests that crystallization of these phenocrysts antedated extrusion (Usselman *et al.* 1975*a*, *b*).

Linear cooling rate experiments were also employed in a re-investigation of the cooling history of olivine-rich basalt 12002 (Walker *et al.* 1975*a*, *b*). At all rates between 0.5 °C/h and 2000 °C/h olivine crystallizes as phenocrysts and, at all experimental rates olivine core chemistry, unlike olivine nucleation density, shows little change. Nucleation temperatures of all phases were found, as with Gibb (1974), to be suppressed by increasing cooling rate, and nucleation in the groundmass of melts of the composition of 12002 is thus retarded at relatively high cooling rates. Since the natural basalt has a higher degree of crystallinity than that achieved at the slowest employed cooling rate of 0.5 °C/h, the cooling rate of this basalt must therefore have decreased after eruption, and it is calculated that this rock represents a lunar sample from about 2 m below the lava surface. It is established that the porphyritic texture in sample 12002 apparently forms during continuous *decrease* in cooling rate (contrast two-stage models for the origin of porphyritic texture). Apart from confirming the same, systematic changes in olivine morphologies with increasing cooling rate (Donaldson *et al.* 1975*b*), the results from this experimental work at Harvard University (Walker *et al.* 1975*a*, *b*) support the contention (Walker *et al.* 1975*a*, *b*; O'Hara *et al.* 1975) that the liquidus olivines in a lava flow of this composition would readily settle. Should this be true, other basaltic types could be generated in such a flow by fractionation of non-equilibrium crystals on the lunar surface.

According to the evidence from the experimental work of Walker *et al.* (1975*a*, *b*), skeletal olivines can crystallize in 12002 even at cooling rates less than 50 °C/h. The skeletal olivines from basalt 12002, drawn by one of the authors of this review (figure 3*b*), are relatively rare, compared with the non-skeletal crystals, and could have been precipitated at a cooling rate of this order. That olivines would tend to move from their position of nucleation in a magma of such high liquidity is not contested. But the direct textural evidence of such olivine movement is negligible, the only observable aggregation being that in 12009 (figure 1) to which reference has already been made. Yet in rocks derived from liquids that have cooled more slowly, and thus maintained a high liquidity longer, it would be reasonable to predict more direct evidence of olivine movement. Furthermore, no sample of a complementary cumulate relatively enriched in olivine (in a mare basalt groundmass) has been discovered on the Moon. A rock of this kind would have been distinctive enough to be easily identified by the astronauts. Some small olivine-rich gabbroic fragments might possibly represent this elusive cumulate fraction (Wood *et al.* 1971).

With specific reference to the crystallography and chemistry of pyroxenes, the relative cooling rates of Apollo 12 and Apollo 15 mare basalts were investigated by Takeda *et al.* (1975). New data on the exceptionally large pyroxene phenocrysts in mare basalt 15495, when compared with published data on smaller pyroxenes in other mare basalts, suggest that relatively large size does not imply a slower cooling rate. Another inference from the pyroxene data is that rapidly cooled rocks may be more abundant at the Apollo 15 site than at the Apollo 12 site.

This briefly reviewed experimental work on cooling rates of lunar lavas, supported by earlier petrographic information, represents a substantial advancement in our knowledge of the Moon. Much has been learnt from the random samples gathered and returned to Earth under the uniquely formidable circumstances of the Apollo missions. When the new research methods, devised for the Moon, are applied to terrestrial problems they should be even more fruitful.

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Harald Drever died suddenly in October 1975. He is mourned by his friends in lunar science.

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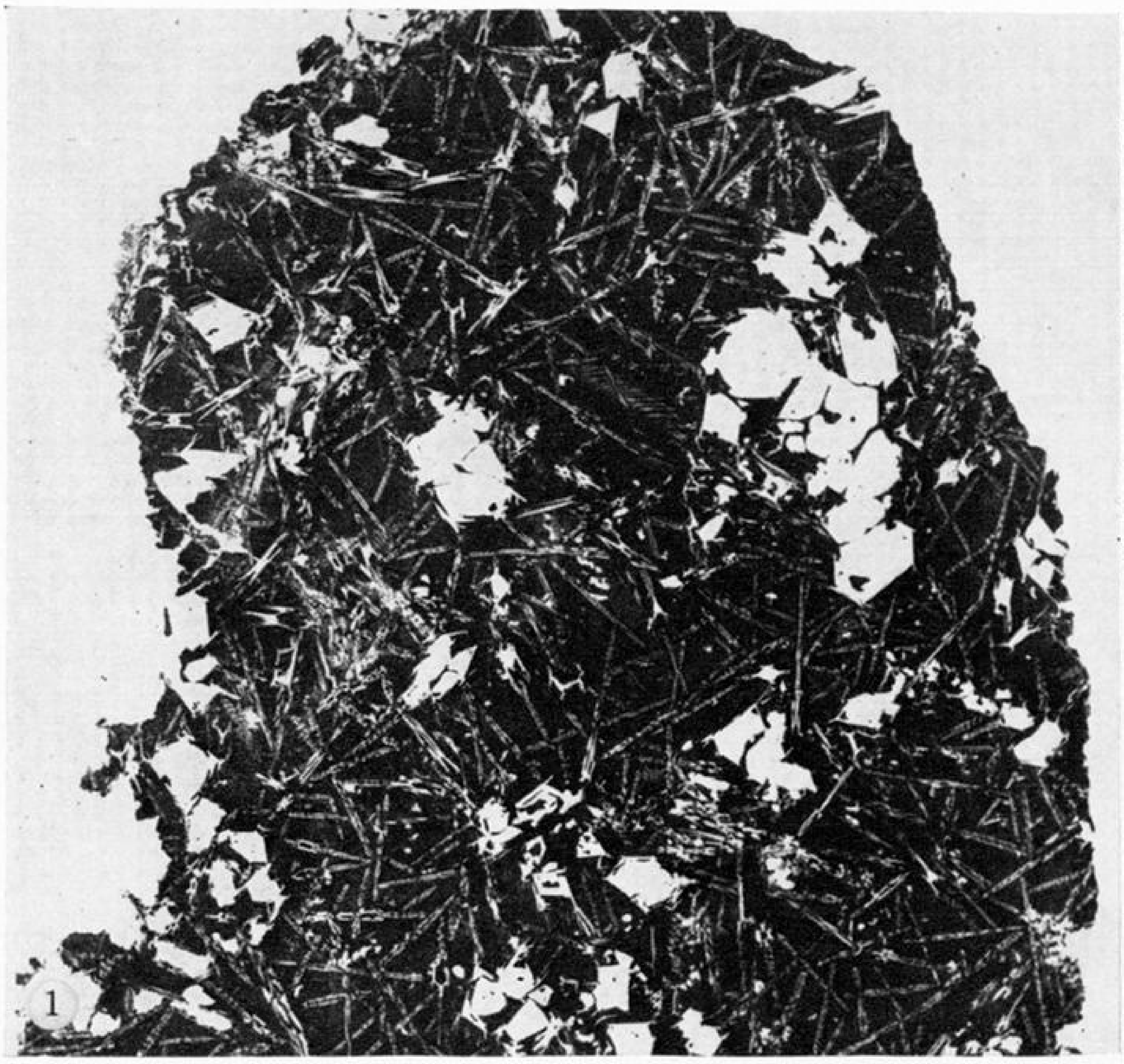

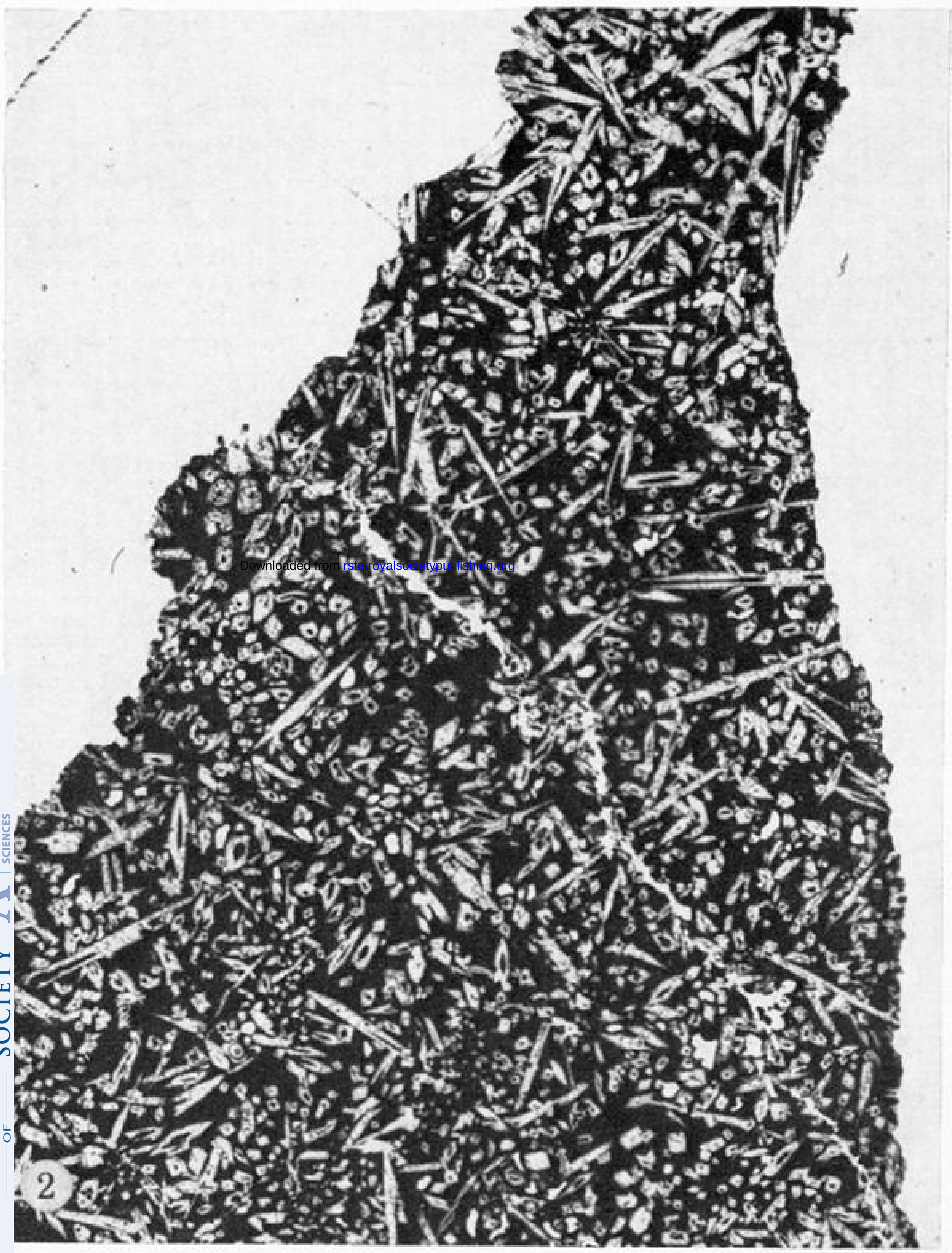

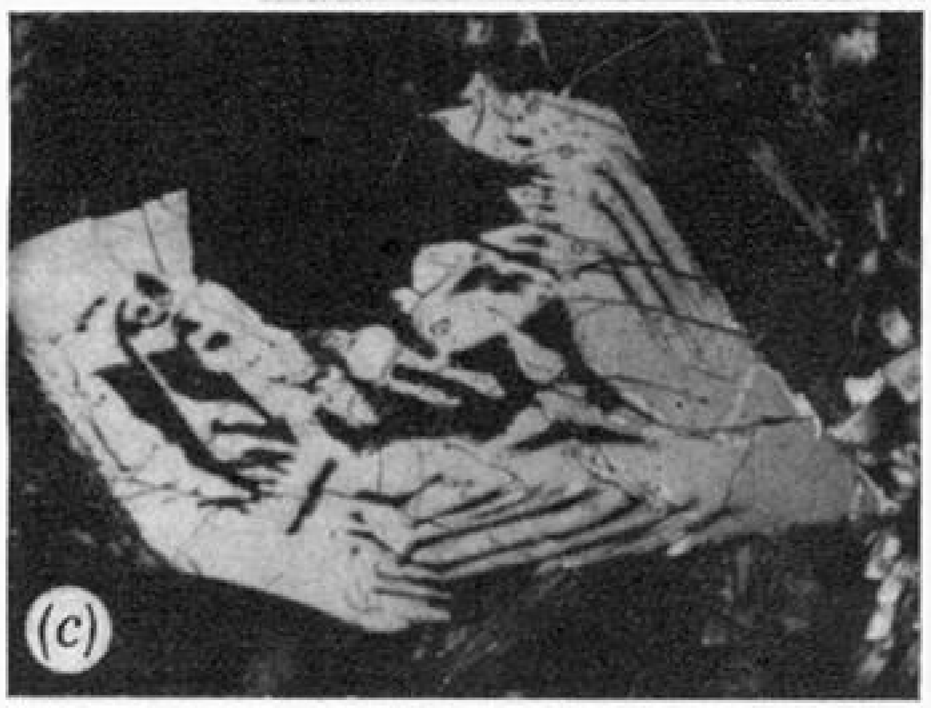

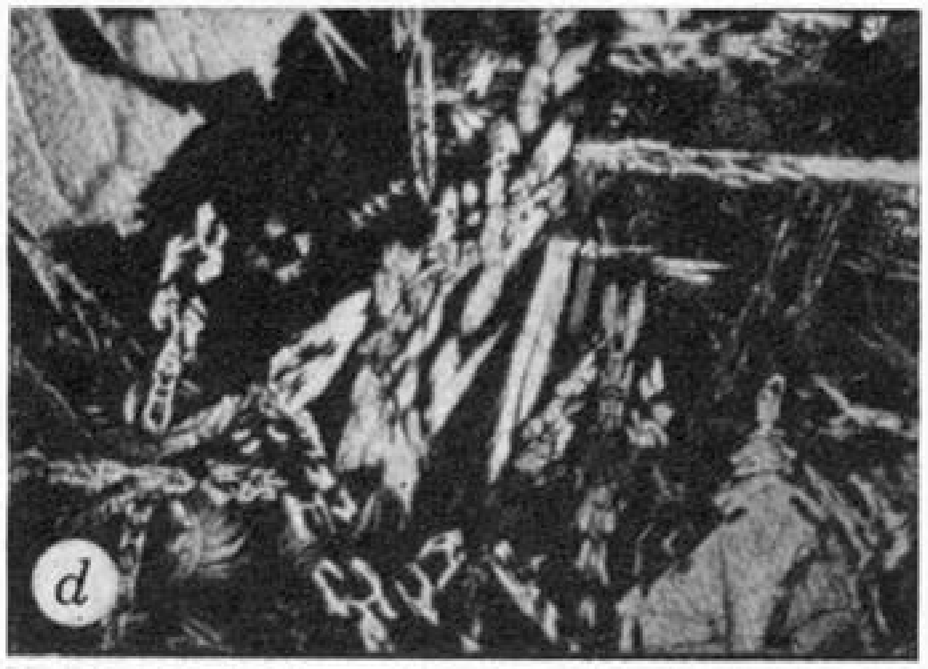

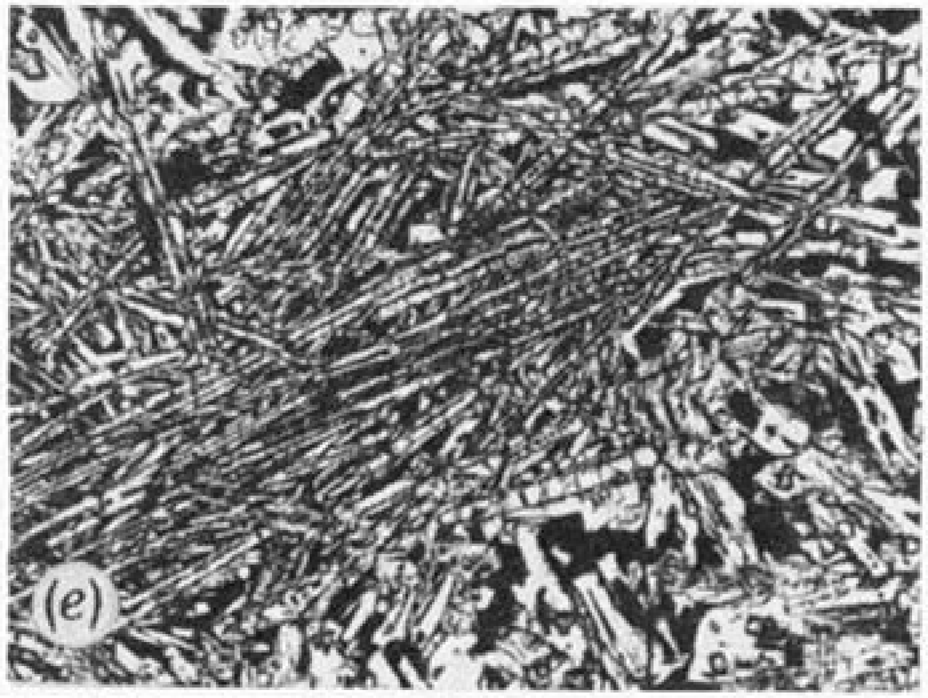

FIGURES 1, 2 AND 8. For description see opposite.