TEXTURE OF CHONDRULES

Hiroko NAGAHARA

Geological Institute, University of Tokyo, 3-1, Hongo 7-chome, Bunkyo-ku, Tokyo 113

Abstract: Textures of chondrules in the unequilibrated ordinary chondrites have been summarized on the basis of the processes of their formation inferred from the results of previous experiments. The chondrules studied are classified by their textures into the following four groups: (1) those formed by complete melting of the precursor materials, (2) those formed by incomplete melting of the precursor materials, (3) "lithic fragments" or "lithic chondrules" formed through low temperature heating of the precursor materials, and (4) complex chondrules formed by accretion of two chondrules or by squeezing out the liquid. Groups (1) and (2) are further classified into different subgroups depending on their texture and constituent minerals. The subgroups in group (1) include barred olivine chondrules, radial pyroxene chondrules, and glassy chondrules. In group (2), the subgroups are porphyritic olivine and pyroxene chondrules, porphyritic olivine chondrules, and porphyritic pyroxene chondrules. The porphyritic olivine and pyroxene chondrules include the following specific types: normal porphyritic olivine and pyroxene ones without relict minerals, chondrules with relict minerals, chondrules which are Ca- and Al-rich, which have been intensively heated, and which are metal-rich. The conditions of formation of these different chondrules have been estimated by comparing them with the experimentally reproduced textures. Group (1) is interpreted to have been heated at above-liquidus temperatures, about 1500°C, and cooled at rates of 10^4–10^2°/hr, with most suitable rates of 10^3°/hr for barred olivine chondrules, and 10^2–1°/hr, with most suitable rates of several tens°/hr for radial pyroxene chondrules. Group (2) was heated at subliquidus temperatures (probably between 1200–1000° and 1500°C, and cooled at various rates, relatively rapidly for porphyritic olivine chondrules and slowly for euhedral tabular pyroxene. Group (3) without spherical form was heated near or below solidus temperatures.

1. Introduction

Recent chemical and petrological studies of individual chondrules in type 3 ordinary and carbonaceous chondrites have revealed that they were formed from pre-existing materials which would have been composed of several different components (*i.e.* GOODING *et al.*, 1980; GROSSMAN and WASSON, 1982, 1983; NAGAHARA, 1981a, 1983; RAMBALDI, 1981; RAMBALDI and WASSON, 1982). The specific origin of chondrules or mechanism(s) of heating the precursors, however, has not been identified.

Chondrules have nearly uniform size, mostly ranging from 0.1 to 2.5 mm in diameter, and show variable chemical compositions and textures. Chemical composition is the most important factor for the estimation of precursor materials and the mechanism of formation. Texture is also an important factor, especially in determining the physical conditions of melting and crystallization, and their mechanism(s) of formation.

Experiments have been performed to reproduce chondrule-like textures to estimate the temperature and cooling rate of their formation (TSUCHIYAMA *et al.*, 1980; TSUCHIYAMA and NAGAHARA, 1981). Major results of the experiments are as follows: 1) texture of chondrules and crystalline phase(s) in them are defined by complex factors, such as bulk chemical composition, heating temperatures, and cooling rate, 2) bulk chemical composition affects the textures and crystalline phases, 3) maximum heating temperature largely affects the texture; barred, radial, and glassy textures were formed from entirely molten liquid, whereas porphyritic texture was easily formed from partially molten precursor materials, 4) cooling rate does not significantly affect the texture, but affects the crystalline phases, 5) cooling rate for producing various textures varies widely between 10^4–1°/hr in the temperature range 1600–1200°C, and cannot be obtained by cooling by radiation in extremely low gas pressure, and 6) according to the experiments by PLANNER and KEIL (1982), porphyritic texture can be also reproduced from an entirely molten state by cooling with a temperature plateau.

Based on the above experimental results, textures of natural chondrules can be interpreted in terms of their formation temperature and cooling rate.

Modal ratios of chondrules with different textures in ordinary chondrites are nearly the same; porphyritic chondrules with 45% porphyritic olivine and pyroxene, 25% porphyritic olivine, and 10% porphyritic pyroxene 10%; barred olivine sometimes with minor amounts of pyroxene 7%, radial pyroxene sometimes with minor amounts of olivine 10%; glassy or cryptocrystalline 2% (GOODING and KEIL, 1981; NAGAHARA, 1983). Within each type, size and amount of crystals are variable, showing various appearances.

In this paper, textures of chondrules in the type 3 ordinary chondrites are described, and conditions for the formation of most of them can be roughly estimated by comparison with the experimental results. The samples observed were ALH-77033 (LL), -77015 (L), -77278 (LL), -77299 (H), and -77304 (L) chondrites from Antarctica, the former two being considered to be paired with ALH-77011 (MCKINLEY *et al.*, 1981). Photographs shown here are all in ALH-77015 chondrites.

2. Chondrules Formed Through Complete Melting of the Precursor Materials

2.1. *Barred olivine chondrules*

Barred olivine (BO) chondrules are spherical and composed of olivine bars and glassy or devitrified groundmass. Sometimes a thick olivine shell encloses the chondrule (Fig. 1a), though the mechanism of shell formation is not known. The width of olivine bars varies mostly from 10 to 100 μm (Figs. 1b and 1c). Experimental results show that barred olivine texture is formed from an entirely molten liquid and that the width of the olivine bars increases with decrease in cooling rate. It is formed at cooling rates of 10^4–10^2 °/hr, with most suitable rates of 10^3 °/hr in order.

Rare BO chondrule composed of two parts with different barred widths is present (Fig. 1d). Olivine bars form several bundles (Figs. 1e and 1f) with various widths; these chondrules should be called "radial olivine" chondrules, because of different crystallographic orientations of olivine fibers.

Groundmass of BO chondrules is mostly glassy or devitrified (Figs. 1b and 1c), but

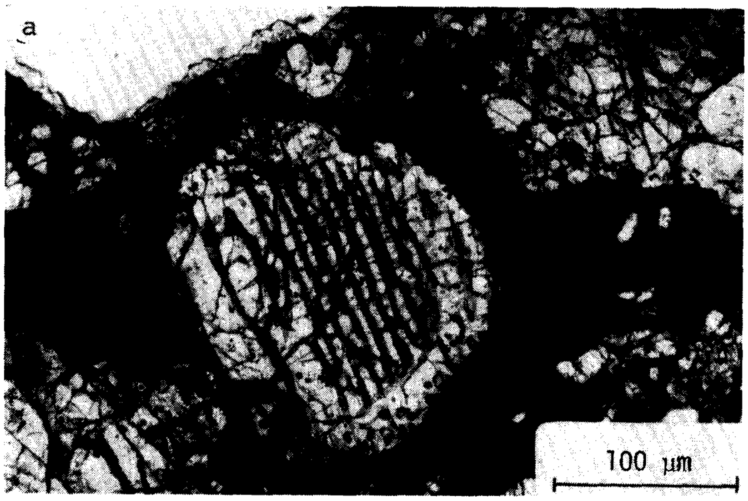


Fig. 1a. Barred olivine (BO) chondrule with olivine shell. BO chondrule would have been once entirely molten and cooled relatively rapidly (faster than 10^{3}°/hr). Transmitted, plane polarized light.

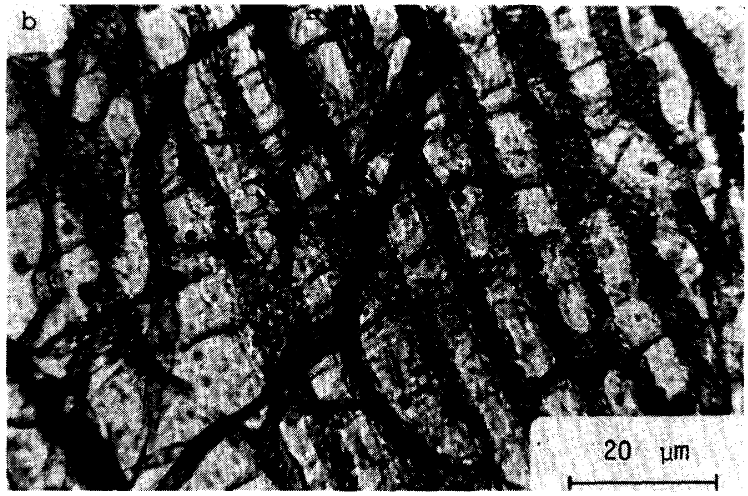


Fig. 1b. Enlarged view of olivine bars of Fig. 1a. The width of olivine bars becomes wider with decrease of cooling rate. Width of olivine bars of this chondrule is about the average of natural ones. It resembles the experimentally produced one (Fig. 5e of TSUCHIYAMA et al., 1980), which was cooled at a rate of several thousands °/hr. Transmitted, plane polarized light.

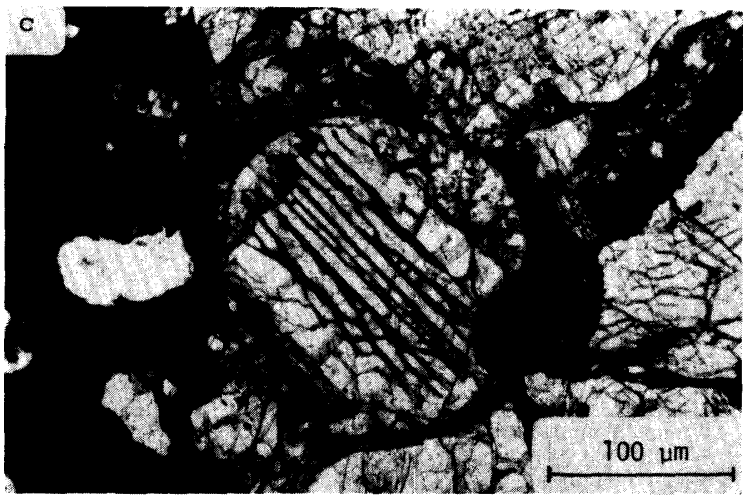


Fig. 1c. BO chondrule with clear glassy groundmass. Olivine bars in this chondrule are slightly wider than those in Fig. 1a and 1b. This chondrule would have once entirely molten and cooled at several thousands °/hr at high temperatures. Transmitted, plane polarized light.

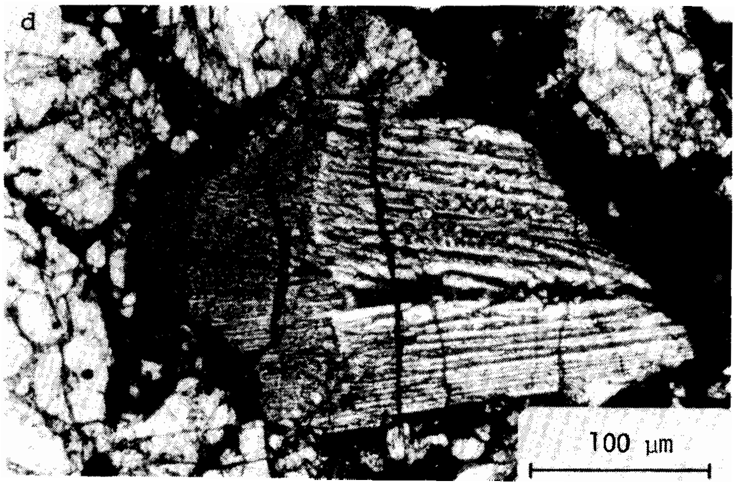


Fig. 1d. BO chondrule composed of two parts with different barred olivine widths. The origin of this texture is not known. Radial pyroxene texture with two different widths was experimentally formed at a cooling rate of 5°/hr from an entirely molten state. Transmitted, plane polarized light.

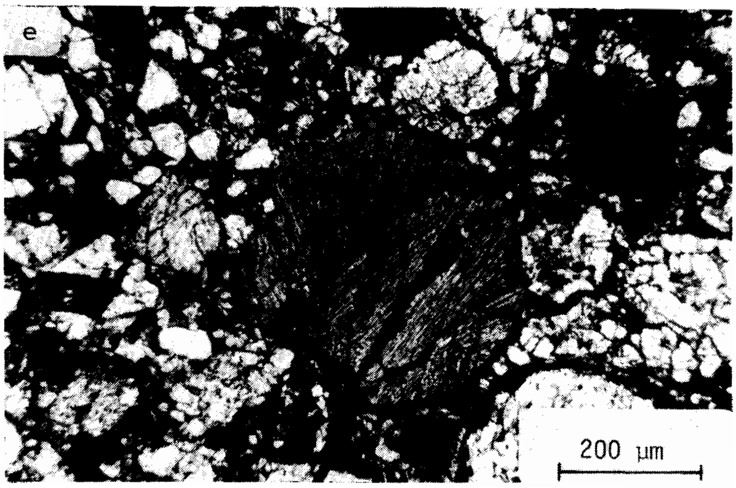


Fig. 1e. BO chondrule made up of several bundles of narrow olivine bars. This is interpreted to have cooled more rapidly than those in Figs. 1a and 1c. This should be called a "radial olivine" chondrule. It resembles the experimentally produced one (Fig. 6 of TSUCHIYAMA et al., 1980), and the cooling rate is estimated to be about several thousands °/hr. Transmitted, plane polarized light.

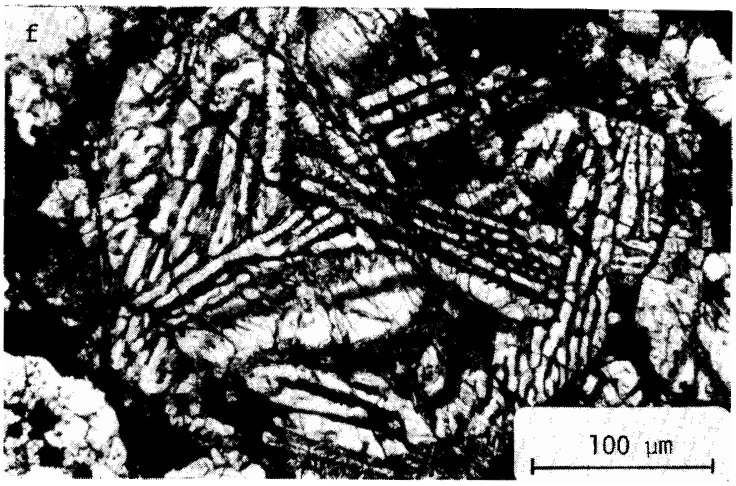


Fig. 1f. BO chondrule composed of many bundles of olivine bars which are wider than those in Fig. 1e. It would have cooled at rates nearly the same as those for chondrules in Figs. 1a and 1c, though the nucleation was different. Transmitted, plane polarized light.

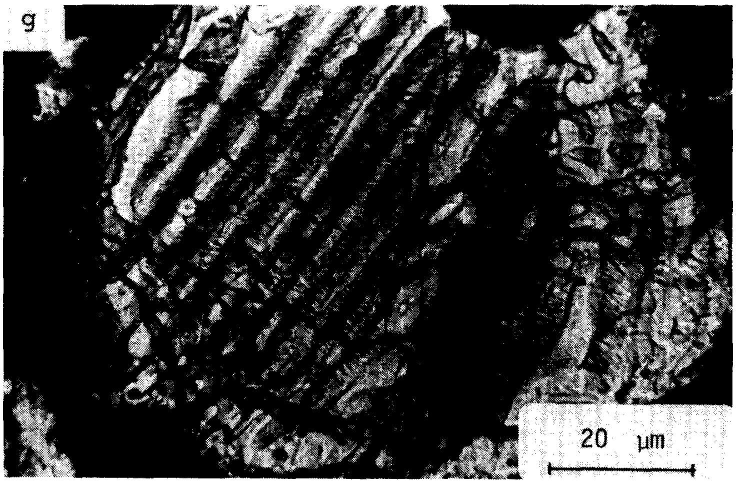


Fig. 1g. BO chondrule of which groundmass consists of slender pyroxene and glass. It would depend on the cooling rate at lower temperature and chemical composition whether the groundmass is crystalline or glassy. Transmitted, plane polarized light.

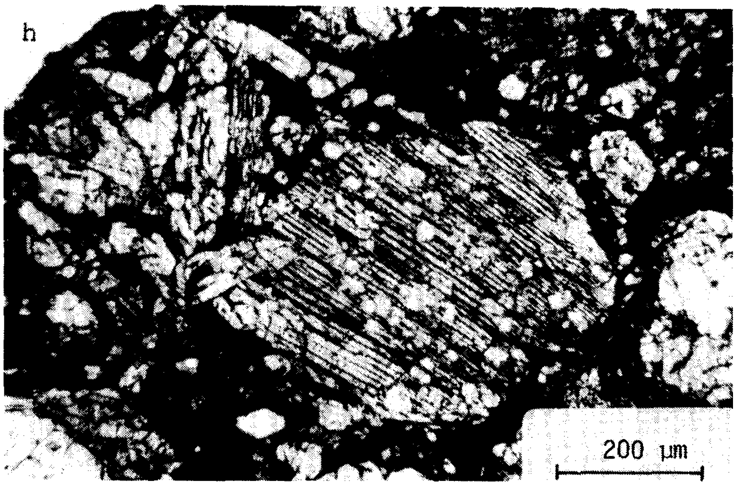


Fig. 1h. BO(P) chondrule of which olivine partly reacted with the residual liquid to form pyroxene. This chondrule would have been cooled rapidly at high temperature and slowly enough to have reacted with liquid at lower temperatures. The reaction relation between olivine and liquid is observed only in such BO(P) chondrules and it is not found in porphyritic chondrules. Transmitted, plane polarized light.

Fig. 1i. Enlarged view of the olivine bars and pyroxene in Fig. 1h. Pyroxene grows where olivine became slender; that is, the relation of resorption of olivine by pyroxene is observed. Olivine bars contain many blebs of trapped liquid which indicates rapid cooling at crystallization of olivine. It is often observed in the natural chondurles (e.g. IKEDA, 1980), though it is not found in the synthetic ones. Transmitted, plane polarized light.

in some places slender pyroxene is present (Fig. 1g). Further, olivine reacted with the residual liquid to form pyroxene (Figs. 1h and 1i), indicating relatively slow cooling rates at subliquidus temperatures.

The bulk chemical compositions of BO chondrules are rich in MgO and poor in SiO_2 and FeO. About half of BO chondrules are more enriched in Al_2O_3 (up to 8 wt %) and CaO (up to 6 wt%) than other textural types of chondrules (0.5–4, 0.5–3 wt%, respectively) (NAGAHARA, 1981b).

2.2. *Radial pyroxene chondrule*

Radial pyroxene (RP) chondrules show rounded shape and are composed of fibrous pyroxene and glassy groundmass. The amount of groundmass is much less than that in the BO chondrules. The width of pyroxene fibers varies from 1 to several tens of micron meters (Figs. 2a and 2b).

Experimental results show that radial pyroxene texture is formed from an entirely molten liquid which is rich in pyroxene component and that the width of pyroxene fibers increases with decrease of cooling rate. It is formed at a cooling rate of 10^2–1°/hr, with most suitable rates of several tens of °/hr.

Euhedral to subhedral olivine grains are sometimes present in RP chondrules (Fig. 2c). It is not known whether the olivine crystals are relict or were crystallized from liquid before pyroxene fibers. The presence of olivine crystals indicates that pyroxene did not crystallize under an extremely supercooled condition, which would be different from the case for BO chondrules. However, pyroxene fibers contain much trapped liquid (Fig. 2d) indicating relatively rapid cooling during crystallization of pyroxene. Pyroxene fibers are often extremely narrow and may be too small to be resolved under the microscope (Fig. 2e).

The bulk chemical composition of RP chondrules is more enriched in SiO_2 than BO chondrules, indicating that the precursor materials of RP chondrules melted thoroughly at lower temperatures than BO chondrules.

2.3. *Glassy chondrules*

Glassy (GL) chondrules show spherical shapes and are composed entirely of glass which is usually devitrified. Some GL chondrules show a zoned texture (Fig. 2f), of which two parts have slightly different chemical compositions.

The bulk chemical composition of GL chondrules is rich in SiO_2 and FeO, indicating that they have lower liquidus temperatures than chondrules of other textural types. The precursor materials with low liquidus temperatures easily melt completely, and therefore the GL chondrules may not be the result of intensive heating and extremely large cooling rates.

3. Chondrules Formed Through Incomplete Melting of the Precursor Materials

3.1. *Porphyritic olivine and pyroxene chondrules*

Porphyritic olivine and pyroxene (POP) chondrules are composed of olivine and pyroxene phenocrysts and groundmass, and usually show spherical shapes. The mode of occurrence of olivine and pyroxene varies; namely, chondrules with euhedral

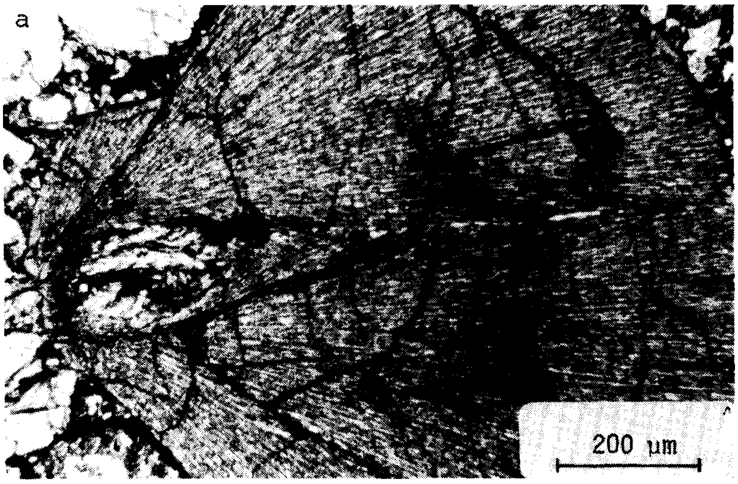


Fig. 2a. Radial pyroxene (RP) chondrule. Residual liquid was trapped near the nucleation site. This chondrule would have been entirely molten and cooled relatively slowly, probably at about 100°/hr. Transmitted, plane polarized light.

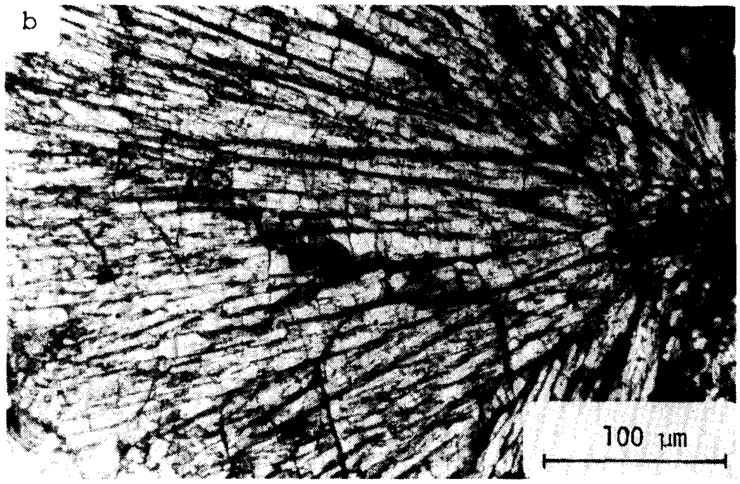


Fig. 2b. RP chondrule in which pyroxene fibers are wider than those in Fig. 2a. This would have been cooled more slowly than the former, probably at a rate less than several tens °/hr. Transmitted, plane polarized light.

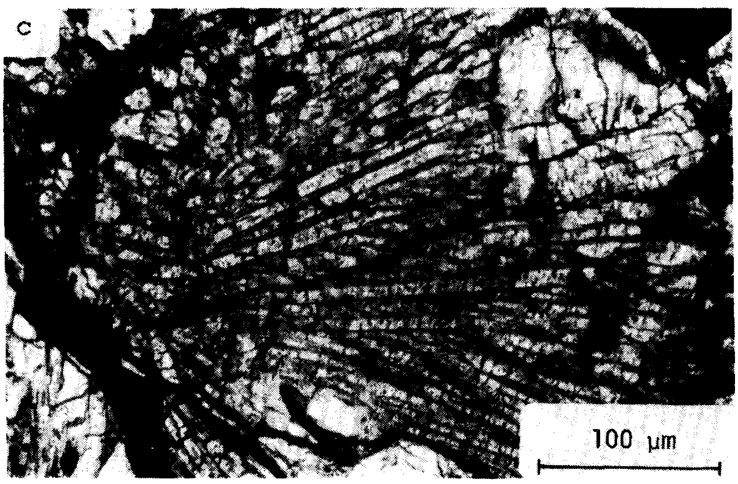


Fig. 2c. RP(O) chondrule which contains radial pyroxene and subhedral olivine grains (upper right and lowest middle). Olivine and pyroxene are not in reaction relation. It is not known whether the olivine grains are relict or crystallized before pyroxene fibers. This relation indicates that contrary to the barred olivine texture, radial pyroxene texture was not formed under an extremely undercooled condition, that is, it cooled relatively slowly. This is consistent with the experimental result that radial pyroxene texture was formed at cooling rates much less than those for barred olivine texture. Transmitted, plane polarized light.

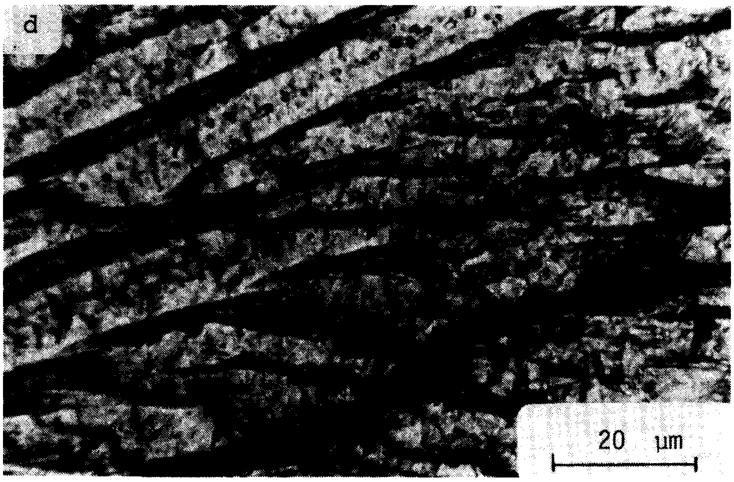


Fig. 2d. Enlarged view of radiating pyroxene. Pyroxene contains many blebs of trapped liquid indicating relatively rapid cooling at high temperatures. Unlike the olivine bars in the BO chondrules, pyroxene bars in RP chondrules are not in the same optical orientation and often do not continue from one end to the opposite end of the chondrule. Transmitted, plane polarized light.

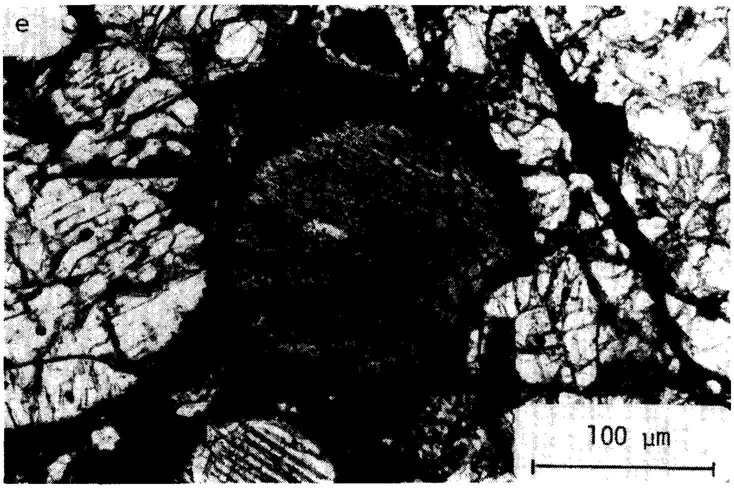


Fig. 2e. RP chondrule in which pyroxene fibers are too narrow to be distinguished separately. It would have cooled more rapidly than other RP chondrules in Figs. 2a–2c. Transmitted, plane polarized light.

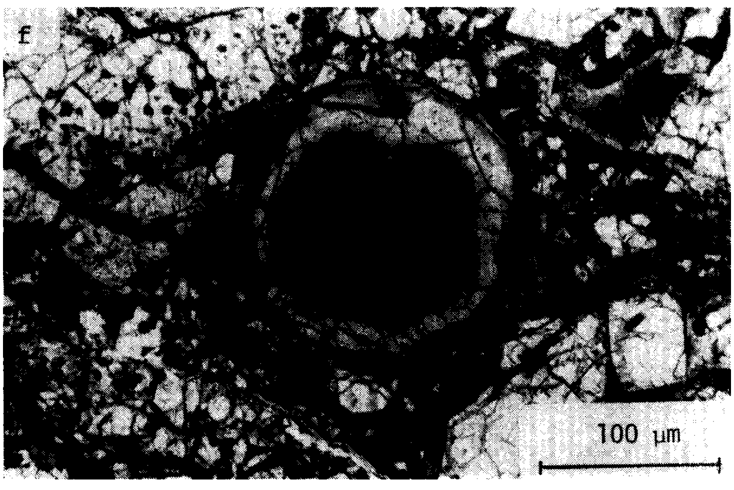


Fig. 2f. Glassy (GL) chondrule with zoned texture. The interior is glassy and the exterior is microcrystalline. The interior is more enriched in Si, Fe and Ca than the exterior. DODD (1978) reported a similar chondrule in the Manych chondrite. This would have been once entirely molten and cooled rapidly (more than 10^3 °/hr). Transmitted, plane polarized light.

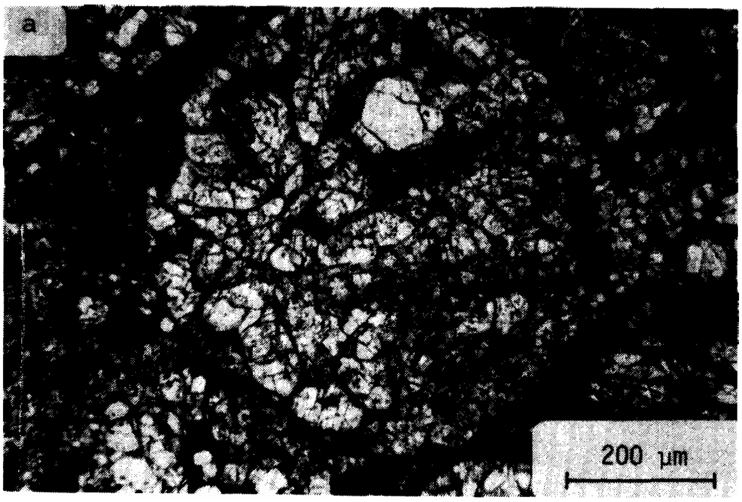


Fig. 3a. Porphyritic olivine and pyroxene (POP) chondrule. Short prismatic low-Ca clinopyroxene (gray) is more abundant than polyhedral olivine (white). Both olivine and pyroxene are euhedral. Transmitted, plane polarized light.

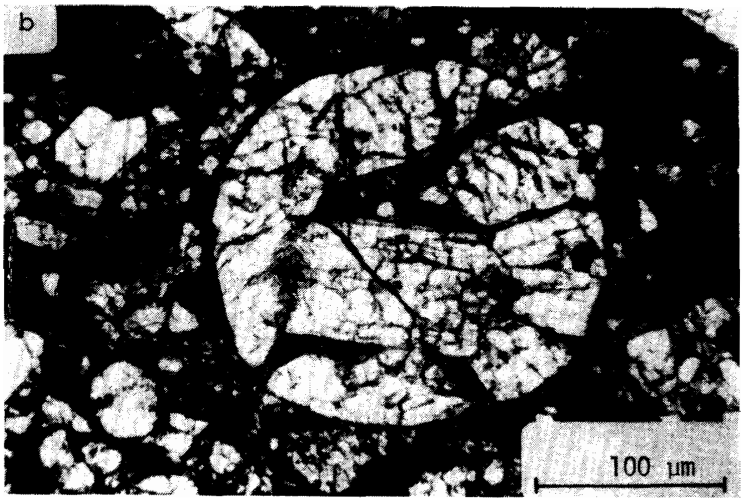


Fig. 3b. POP chondrule with euhedral to subhedral pyroxene and poikilitically enclosed olivine grains. As mentioned in Fig. 4, olivine grains are considered to be relict and pyroxene to have crystallized from a liquid. This chondrule resembles the experimentally produced porphyritic pyroxene texture (Fig. 7 of NAGAHARA, 1983), which shows that pyroxene with such clear euhedral shapes would have been formed at slow cooling rates (less than $10^{2\circ}$/hr). Transmitted, plane polarized light.

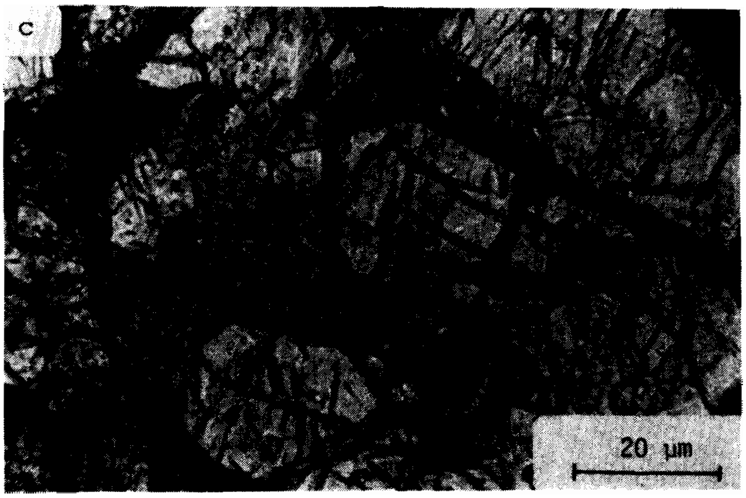


Fig. 3c. POP chondrule with euhedral large olivine phenocrysts and acicular pyroxene in the groundmass. This texture resembles the experimentally reproduced one by PLANNER and KEIL (1982) which was cooled at rates of 300–450°/hr from super-liquidus temperature down to subsolidus temperature with an intermediate temperature plateau below liquidus. Transmitted, plane polarized light.

Fig. 3d. POP chondrule composed of euhedral olivine (white) and subhedral to anhedral pyroxene (gray). This would have cooled slowly, though it is not clear whether it was once completely molten nor how fast it cooled. Transmitted, crossed polars.

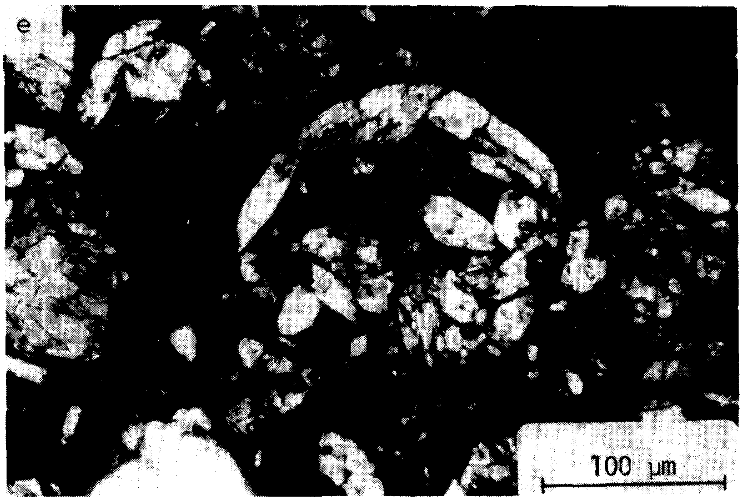


Fig. 3e. POP chondrule with pyroxene crystals grown along the outline of the chondrules. This texture suggests that pyroxene nucleated or grew from an entirely molten state. Transmitted, crossed polars.

Fig. 3f. Porphyritic pyroxene (PP) chondrule. This type of chondrule is rare as compared with other types of porphyritic chondrules. According to experimental results, this would have been cooled slowly, probably less than 10^2 °/hr from either subliquidus or superliquidus temperatures. Transmitted, plane polarized light.

olivine and pyroxene (Fig. 3a), euhedral pyroxene and subhedral to anhedral olivine (Fig. 3b), euhedral olivine and dendritic pyroxene in groundmass (Fig. 3c) and subhedral pyroxene (Fig. 3d).

It is not known whether these chondrules have been once completely molten or not, though poikilitically enclosed olivine in pyroxene phenocrysts may be relict (NAGAHARA, 1983). Experimentally, porphyritic texture was inevitably formed from incompletely molten states; however, the results of PLANNER and KEIL (1982) show the possibility of porphyritic texture from completely molten states through cooling with a temperature plateau. Phenocrysts often grow along the outline of chondrules (Fig. 3e) indicating crystallization of those crystals from liquid. Rare porphyritic pyroxene chondrule is observed (Fig. 3f).

The bulk chemical composition of POP chondrules varies widely, indicating various liquidus temperatures.

3.2. Porphyritic chondrules with relict minerals

Large relict olivine has a dusty appearance (Figs. 4a–4d), and is easily defined. Surrounding the relict olivine, clear olivine overgrows and small euhedral olivine and/or pyroxene grains are present in the outer portion of the chondrules.

In some POP chondrules, euhedral olivine phenocrysts (Figs. 4e and 4f) and some poikilitically enclosed olivine chadacrysts in euhedral pyroxene (Fig. 4g) contain dusty inclusions like those in the large relict olivine grains and are similar in appearance. They are also considered to be relict. These poikilitically enclosed relict olivine grains suggest the possibility that olivine chadacrysts without dusty inclusions are also relict (Fig. 4h). The proportion of POP chondrules with poikilitic texture is about 40–50 % of all chondrules, which means that large amounts of chondrules would not have been completely molten.

The bulk chemical compositions of relic-bearing chondrules are not anomalous and are within the range of porphyritic chondrules, indicating that the presence of relic minerals is due to heating temperature and not due to bulk composition.

3.3. Unusual chondrules

Chemically very rare chondrules with Ca- and Al-rich composition are observed (Fig. 4i). Their bulk chemical compositions are mainly composed of SiO_2, Al_2O_3, MgO and CaO, which is quite different from usual chondrules composed mainly of SiO_2, FeO and MgO. They consist of phenocrysts of spinel (pure $MgAl_2O_4$), small amounts of olivine, and abundant fassaite phenocrysts in the glassy groundmass. Experimental results in the system Di-An (TSUCHIYAMA, private commun.) show that the cooling rate would be 1–100 °/hr, which is consistent with relatively slowly cooled chondrules (NAGAHARA and KUSHIRO, 1982).

Highly crystalline chondrules without liquid (glass) are often observed. Some of them seem to be intensely heated chondrules (Fig. 4j). Others do not show any evidence for chondrule origin. FODOR and KEIL (1975) considered the large clasts with granular poikilitic texture as "lithic fragments". It is difficult to distinguish whether such fragments were chondrules or parts of large bodies; however, those in Fig. 4j present the possibility that at least some of them are severely heated chondrules.

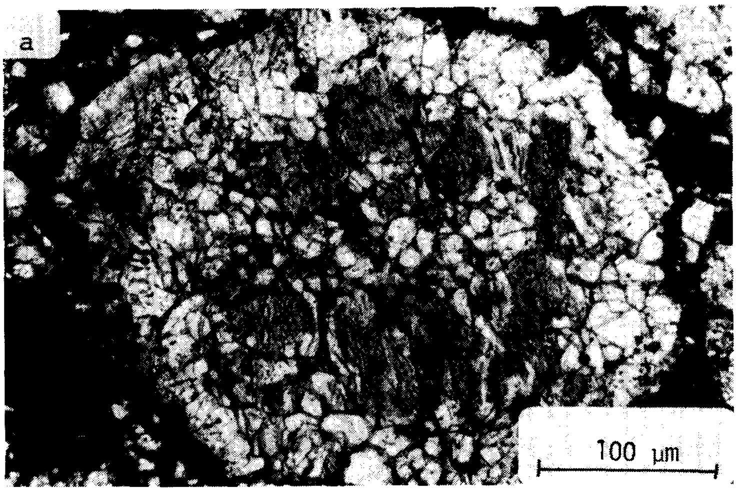


Fig. 4a. Typical relict olivine-bearing chondrule. Relict olivine seen in the center of the chondrule is large and dusty, and has high FeO and low CaO contents. Newly crystallized olivine which is small and clear surrounds the relict olivine. Existence of relict minerals indicates incomplete melting of the precursor minerals. Transmitted, plane polarized light.

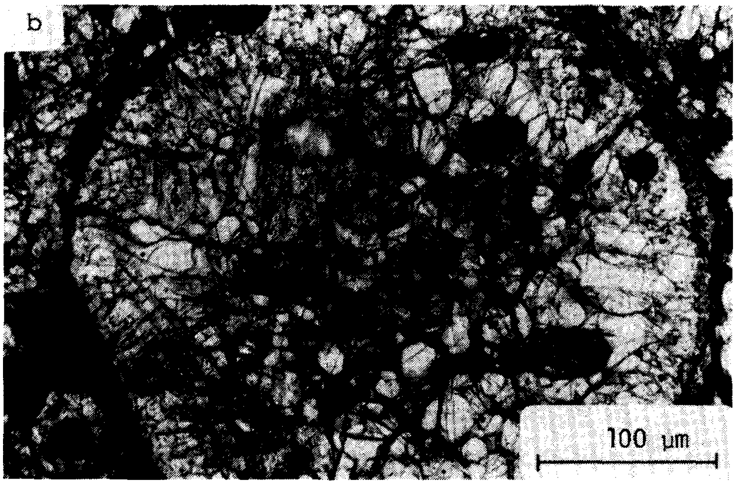


Fig. 4b. Ibid. Large ovoids are holes made by IMA beam.

Fig. 4c. Relict olivine, surrounded by newly crystallized olivine and pyroxene. Microporphyritic olivine and pyroxene would have been formed in the presence of nuclei; that is, they would have overgrown on the pre-existing olivine and/or pyroxene. Transmitted, plane polarized light.

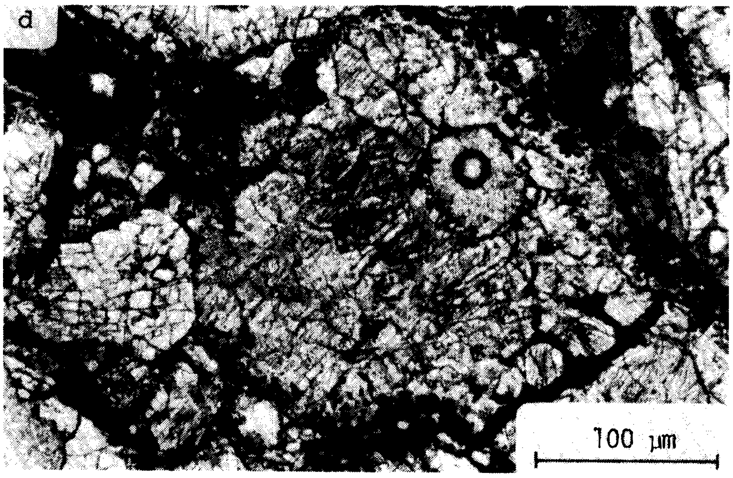


Fig. 4d. Large relict olivine with dusty inclusions. This clast is composed mainly of relict olivine surrounded by minor amounts of newly crystallized olivine crystals. This is interpreted to have been heated to about 1400°C and subsequently cooled relatively rapidly. Transmitted, plane polarized light.

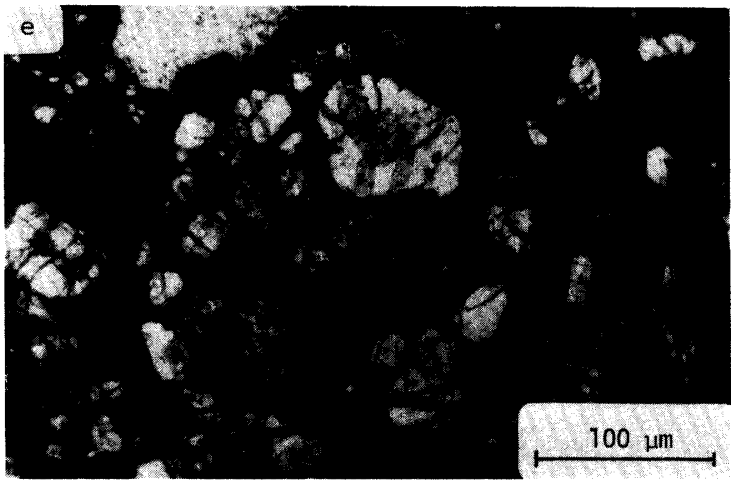


Fig. 4e. POP chondrule with olivine containing dusty inclusions like large relict olivine in Figs. 4a–4d. These olivine chadacrysts may also be relict minerals. Transmitted, crossed nicols.

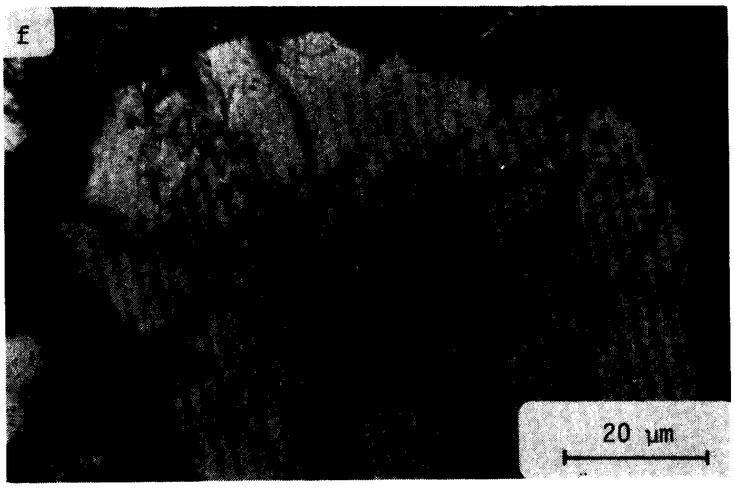


Fig. 4f. Enlarged view of an olivine chadacryst in Fig. 4e. Dusty inclusions are mostly metalic iron, and the opaque rectangular crystal is spinel. This chondrule is considered to have been heated up to subliquidus temperature. Transmitted, plane polarized light.

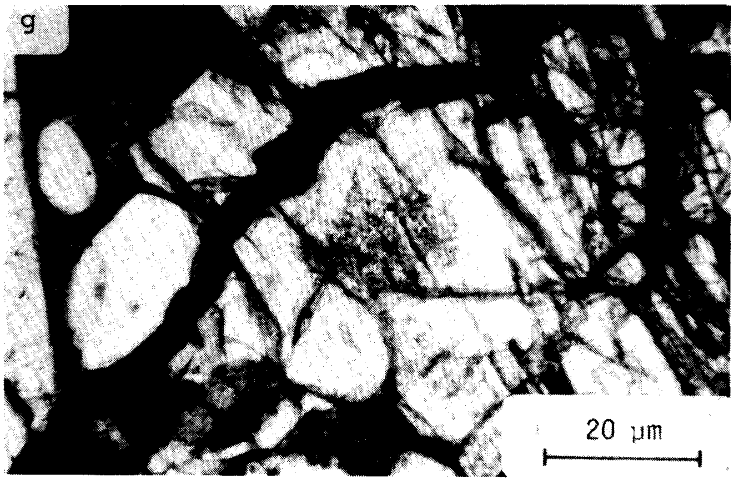


Fig. 4g. Enlarged view of another olivine chadacryst with dusty inclusions. Plane polarized light.

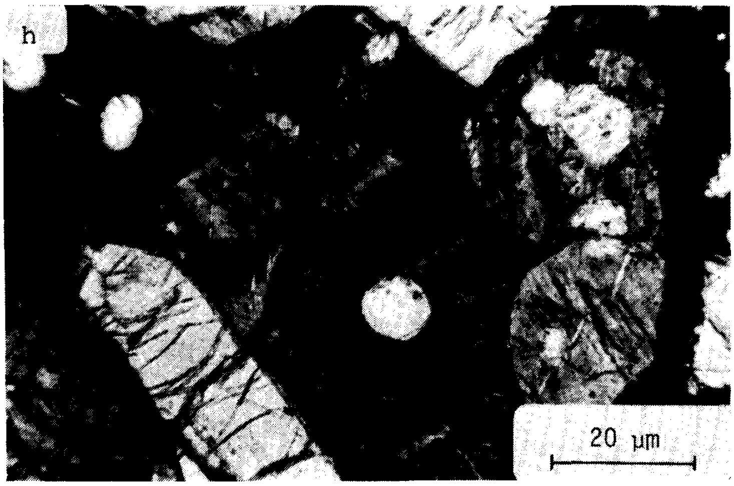


Fig. 4h. Part of POP chondrule with a poikilitic texture, where a large euhedral pyroxene oikocryst includes the small olivine chadacrysts without dusty inclusions. Based on the similarity to Figs. 4f and 4g, these olivine chadacrysts are also considered to be relict. Transmitted, crossed nicols.

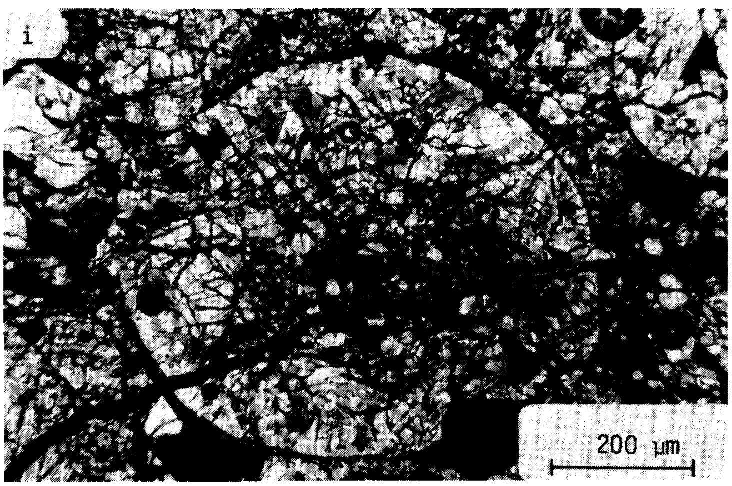


Fig. 4i. Rare Ca-Al-rich chondrule. It consists of abundant fassaite and small amounts of olivine and spinel phenocrysts. Bulk chemical composition is intermediate between those of CAI's in the carbonaceous chondrites and most chondrules in the ordinary chondrites. Based on the experimental results in the system Di-An, cooling rate is estimated to be 10^2 *°/hr, which is consistent with those for other chondrules. Transmitted, plane polarized light.*

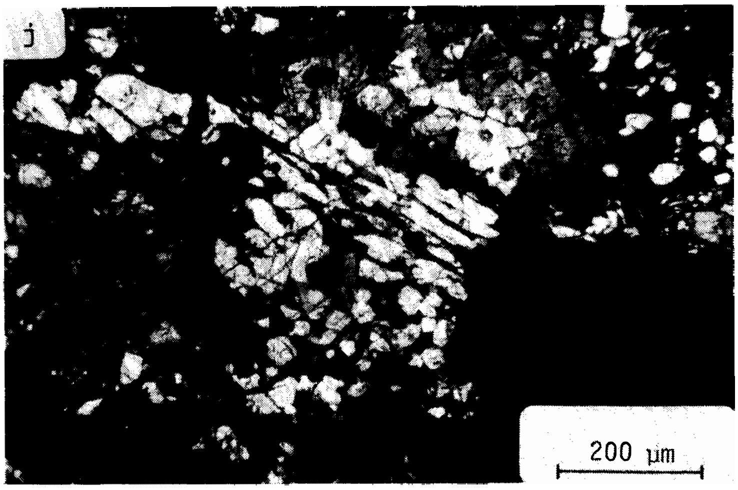


Fig. 4j. Highly crystalline chondrule composed of barred to granular olivine (light), anhedral pyroxene (gray) in the outer portion, and interstitial plagioclase. This would have been cooled much slowly (less than 1°/hr) or held at high temperatures (more than 1000°C) for a long duration. Transmitted, crossed nicols.

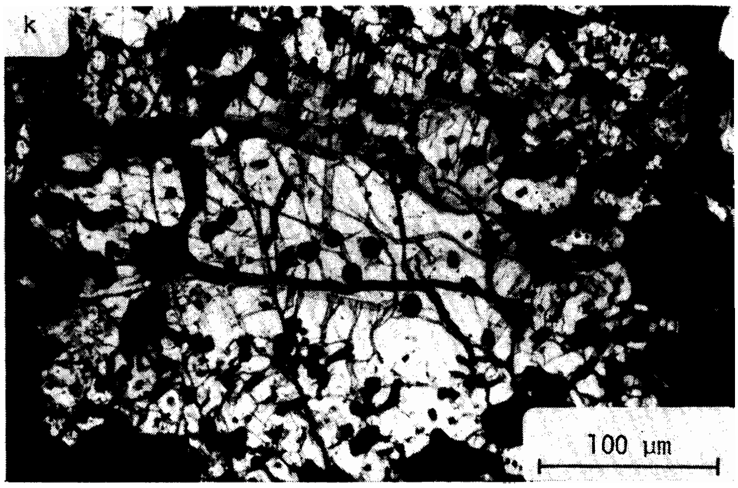


Fig. 4k. Highly crystalline chondrule which is rich in metallic FeNi and troilite. Crystalline phase is olivine. This chondrule is considered to have been cooled extremely slowly or held at high temperatures for a long duration. Transmitted, plane polarized light.

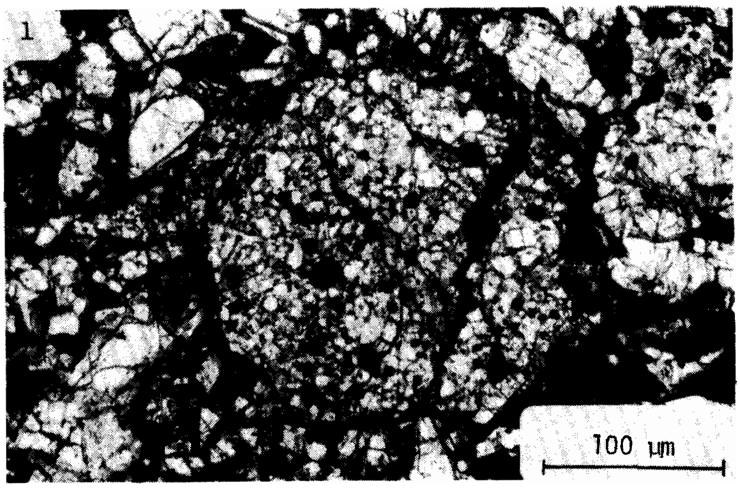


Fig. 4l. Metal-rich porphyritic olivine chondrule. Metal grains are present in the interstices and cracks of olivine phenocrysts, like those formed in experiments under a reducing condition. The metal blebs are considered to have been formed as immiscible droplets at the time of crystallization. Transmitted, plane polarized light.

Most of the chondrules described above are poor in or lack metal and troilite; however, some contain abundant metal and troilite blebs. The metal and troilite in the latter chondrules have spherical shape and seem to have been formed from liquid by liquid immiscibility. As the eutectic temperature of metal-troilite is 988°C, such chondrules would have been heated at least 1000°C. It is not obvious whether the heating mechanism for such chondrules is the same as that for usual chondrules.

3.4. Porphyritic olivine chondrules

Porphyritic olivine (PO) chondrules contain olivine phenocrysts of various morphology. Some are euhedral and granular (Fig. 5a), and some are skeletal or hopper (Fig. 5b and 5c). Groundmass of some chondrules is clear glass (Figs. 5b and 5c), dendritic and crystalline (Fig. 5c), devitrified glass (Fig. 5d), or microcrystalline (Figs. 5e and 5f). Some PO chondrules show spherical shapes, and others show irregular shapes. Especially those with microcrystalline groundmass usually show irregular shapes and heterogeneous size distribution of olivine phenocrysts (Fig. 5f). Those with spherical shapes would have been largely molten, although those with irregular would have been partly molten.

These chondrules would have been heated up to less than 1500°C, mostly less than 1200°C, and cooled relatively rapidly.

4. "Lithic Fragments"

The term "lithic fragment" is used mainly in two different ways. Some use this term for highly crystalline coarse-grained fragments as mentioned in Subsection 3.3, whereas others use it for fine-grained irregular-shaped materials which are considered not to have been heated at above-solidus temperatures.

These fine-grained, irregular-shaped materials are, however, considered to be products of lower temperature heating of the same precursor materials as chondrules. Absence of liquid was responsible for the non-spherical shape, but it obscured the outline during accretion to chondrites (Fig. 6a). Some of them are coated by thick fine-grained rims, which are called "dark-zoned" chondrules by DODD and VAN SCHUMUS (1971) (Fig. 6b). As DODD and VAN SCHUMUS have pointed out, these contain only olivine as large crystals and the size distribution of phenocrysts varies widely (Fig. 6c).

This group often contains abundant metals and troilite which are irregular in shape (Figs. 6d and 6e). This fact supports their low-temperature heating (below 1000°C). The difference of temperature would have induced the difference between PO chondrule in Fig. 5f and "lithic fragment" in Fig. 6, which can be attributed to the different heating history. Rarely a fragment composed of two parts with different grain sizes is observed (Fig. 6e). This texture resembles experimental results of low-temperature heating of the precursor mineral aggregates (Fig. 6f).

5. Complex Chondrules

Some chondrules show accreted or compound features (Fig. 7). These features indicate that accretion and collision often happened while they were still unsolidified (probably at temperatures higher than 1000°C).

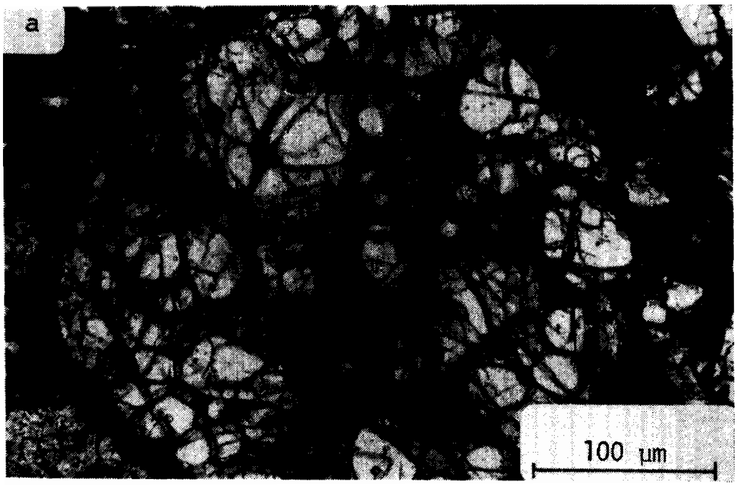


Fig. 5a. Porphyritic olivine (PO) chondrule consisting of granular olivine phenocrysts and brown to purple clear glass. This chondrule would have been nearly or completely molten and cooled relatively rapidly. It resembles the experimentally produced porphyritic olivine texture (Figs. 1d and 1e of TSUCHIYAMA *and* NAGAHARA, *1981), which were heated at subliquidus temperature and cooled at a rate of several thousands°/hr. Transmitted, plane polarized light.*

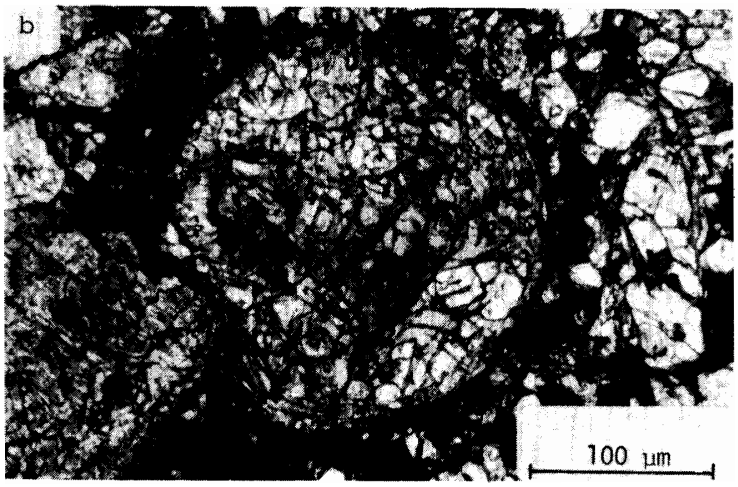


Fig. 5b. PO chondrule with euhedral to skeletal olivine grains and clear glass. This texture resembles the experimentally produced one (Fig. 4 of TSUCHIYAMA *et al., 1980). This texture was formed when heated near the liquidus temperatures and cooled relatively rapidly, probably at a rate greater than one thousand°/hr. Transmitted, plane polarized light.*

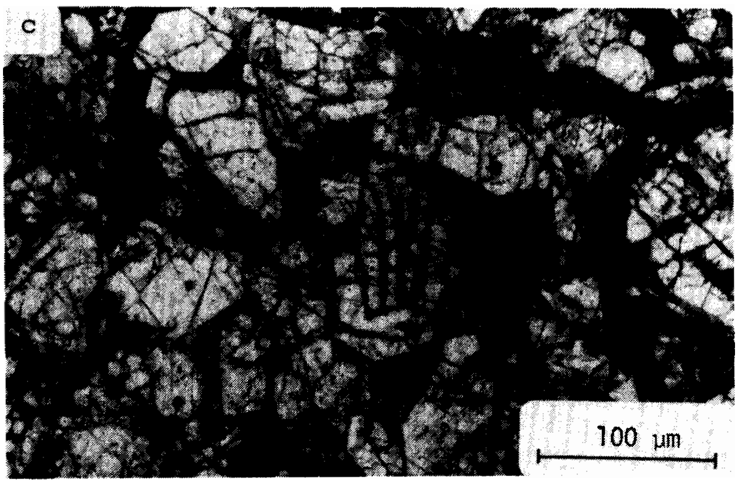


*Fig. 5c. PO chondrule with euhedral hopper olivine phenocrysts and dendritic groundmass. Based on the experimental results on the olivine texture (*DONALDSON, *1976), this chondrule may have been formed from entirely molten liquid at a cooling rate of several thousands°/hr. However, if it were not entirely molten, it must have been cooled at a greater rate. Transmitted, plane polarized light.*

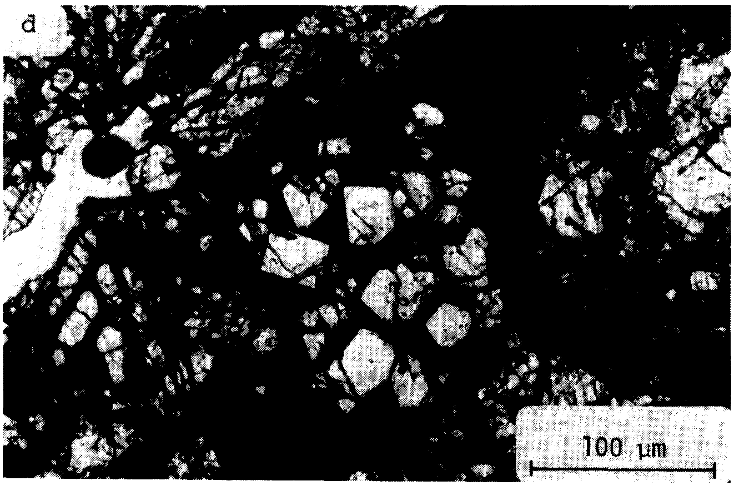


Fig. 5d. PO chondrule with euhedral olivine phenocrysts and devitrified groundmass. It would have been heated to near the liquidus temperature and olivine grew on the nuclei. Transmitted, plane polarized light.

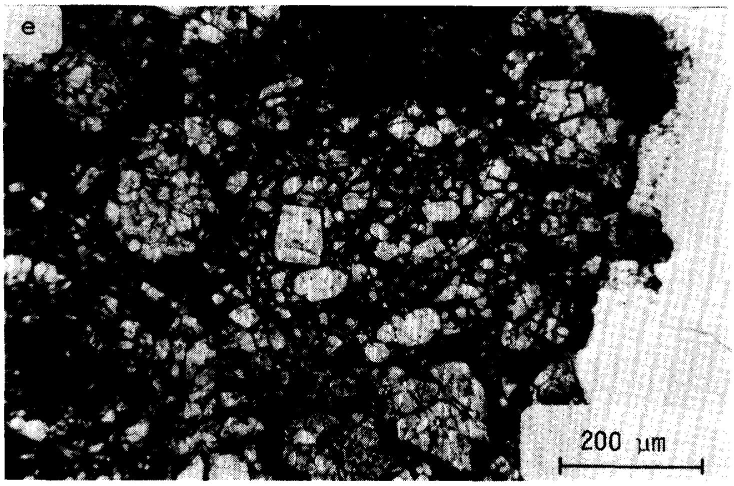


Fig. 5e. PO chondrule. Size distribution of phenocrysts is wide and the groundmass is crystalline. It would have been partly molten. The maximum temperature of heating was about 1300–1500°C. Transmitted, plane polarized light.

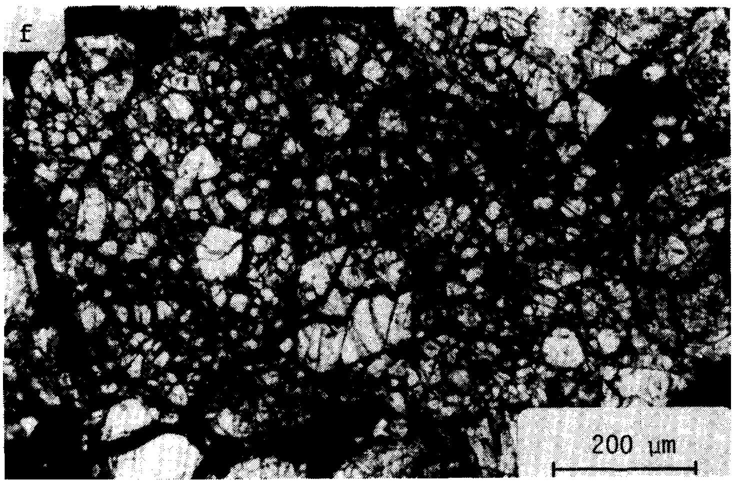


Fig. 5f. PO chondrule. Internal texture resembles that of Fig. 5e. Its irregular outline indicates the presence of a small amount of liquid; this chondrule would have been heated up to a temperature lower than that of Fig. 5e. Transmitted, plane polarized light.

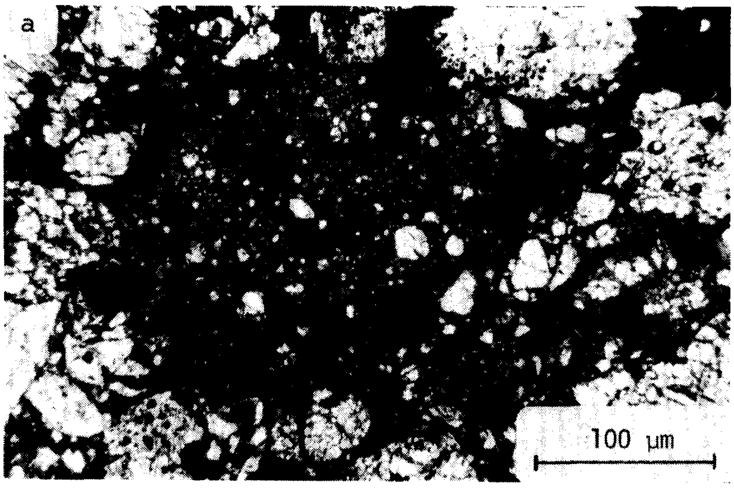


Fig. 6a. "Lithic fragment" consisting of sporadic large olivine grains and microcrystalline groundmass. Absence of liquid (glass) and irregular outline indicate that this would not have been molten. Probably it was not heated to solidus temperature. It resembles the subsolidus experimental results, in which heating was made at temperature lower than the liquidus temperature. Transmitted, plane polarized light.

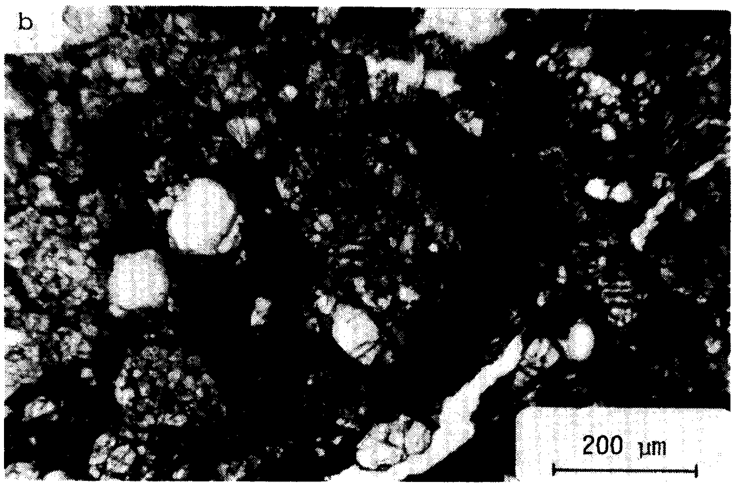


Fig. 6b. "Dark zoned chondrule" (DODD and VAN SCHUMUS, 1971). The interior is composed of olivine phenocrysts with heterogeneous size distribution and microcrystalline groundmass. Similarly to "lithic fragment" in Fig. 6a, it does not contain glass and would not have been molten. The maximum heating temperature would have been about 1000°C. The rim consists of abundant troilite and fine-grained silicate minerals.

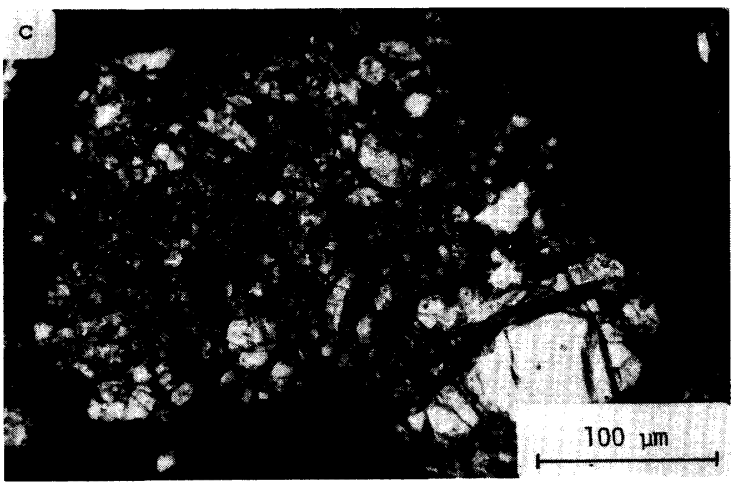


Fig. 6c. Enlarged view of the interior of Fig. 6b. Shape of olivine is ambiguous, and the groundmass is rich in olivine. Transmitted, plane polarized light.

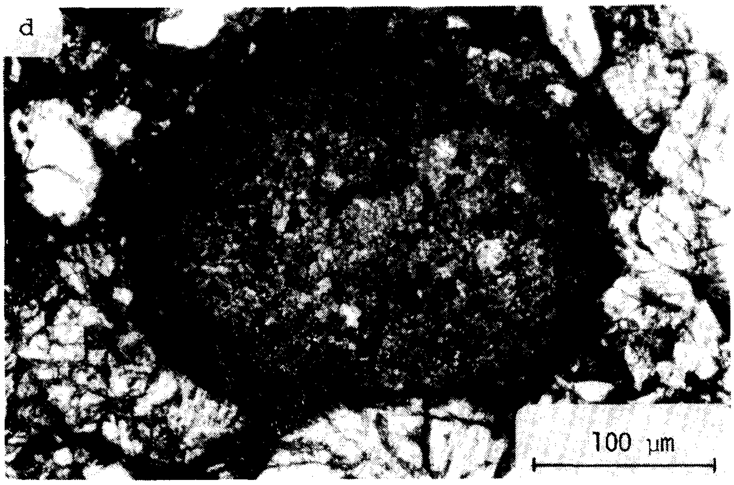


Fig. 6d. Metal-rich chondrule with zonal structure produced by difference in grain size. It does not contain large crystals and glass, indicating that heating temperature was probably below the solidus; however, it shows a smooth outline, which requires a relatively long heating duration. Transmitted, plane polarized light.

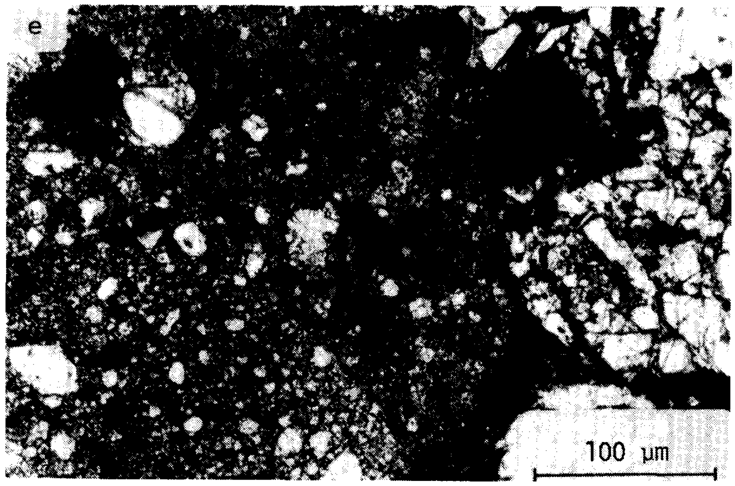


Fig. 6e. "Lithic fragment" composed of two portions with different grain sizes. The lower left portion is coarser than the upper right portion. It would have been accreted while they were still ductile. Transmitted, plane polarized light.

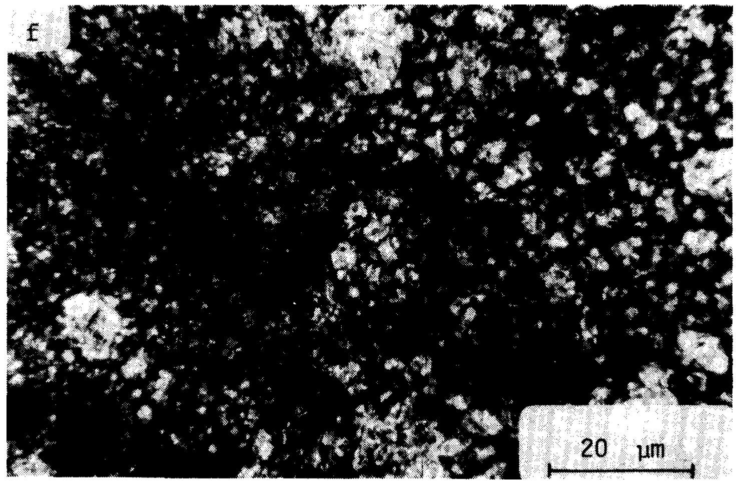


Fig. 6f. Enlarged view of the finer portion of the fragment of Fig. 6e. It consists of aggregates of fine-grained olivine crystals and interstitial dusty materials. It closely resembles experimentally produced microporphyritic textures (Figs. 1g–1j and 2f-2h of TSUCHIYAMA and NAGAHARA, 1981), which were produced by heating to temperatures much lower than the liquidus temperature. Transmitted, plane polarized light.

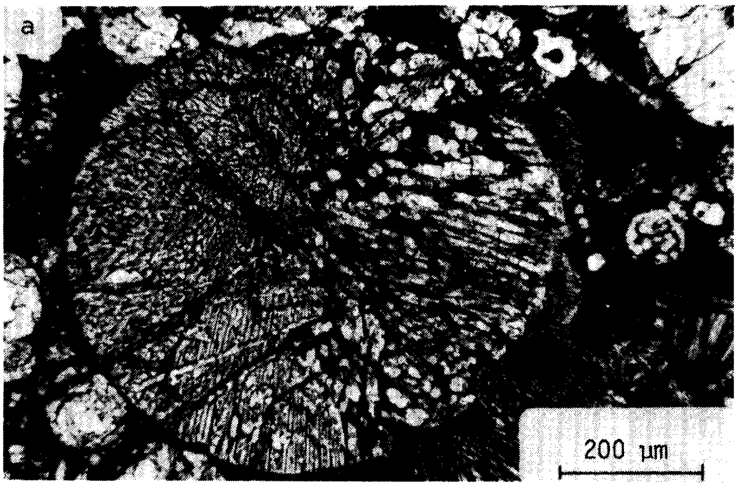


Fig. 7a. Chondrule with a complex texture. Large central body shows radial olivine and pyroxene texture, where olivine (white) is coarse and pyroxene (gray) is fine-grained. Olivine and pyroxene fibers grow in different orientations. Outer zone on the right shows pyroxene radial texture. It is not known whether the smaller chondrules accreted to the larger one while still molten or they were formed from liquid squeezed out from the large body and crystallized separately. Transmitted, plane polarized light.

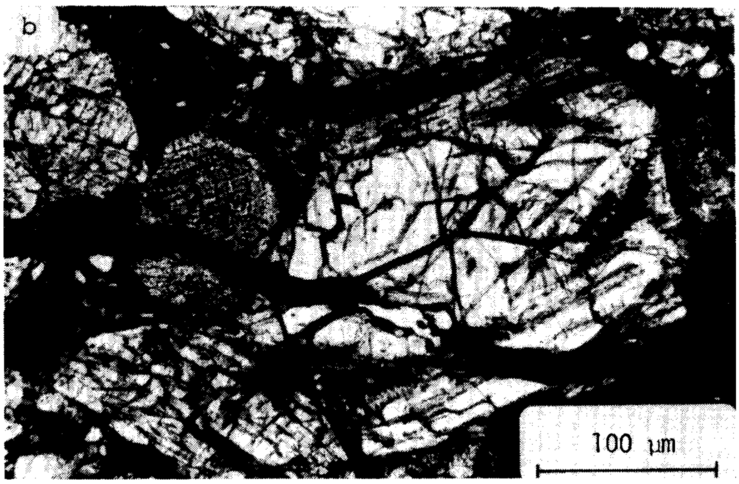
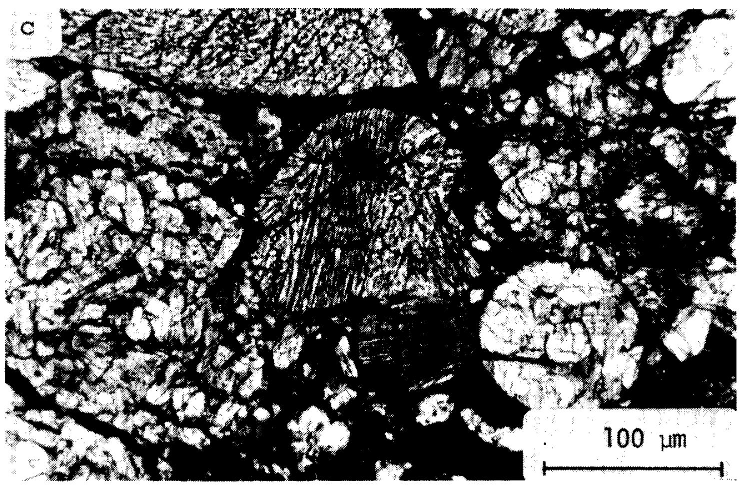


Fig. 7b. Compound chondrule in which a small fine-grained barred olivine chondrule was incorporated into the large irregular chondrule which is composed of large olivine crystal and fibrous groundmass consisting of pyroxene and liquid. KEIL et al. (1978) found a compound chondrule in the Inman chondrite in which a small spherical barred olivine chondrule is included in a large porphyritic chondrule. Transmitted, plane polarized light.



Fog. 7c. Compound chondrules with radial olivine textures. Most accreted chondrules show the same texture and those with different textures are rare. This indicates that the similar chondrules were formed in a narrow space and they easily collided while they were still unsolidified. Transmitted, plane polarized light.

6. Summary

Textures of chondrules in ordinary chondrites are interpreted on the basis of recent experimental results. Major difference of textures would be due to temperature of heating, cooling rate and chemical composition of the precursor materials. Experimental results offered an important information for the interpretation of difference in texture of chondrules. Barred olivine or radial olivine texture is formed from an entirely molten liquid and by rapid cooling (10^4–10^{2}°/hr) from relatively MgO- and often CaO- and Al_2O_3-rich and SiO_2-poor precursors. Radial pyroxene texture is formed by slow cooling (10^2–1°/hr) from relatively SiO_2- and FeO-rich precursors.

On the contrary, porphyritic texture is formed in the presence of nuclei, that is, through incomplete melting of the precursor materials with various compositions. Euhedral pyroxene phenocrysts would have been formed at the smallest cooling rate (less than 10°/hr), and olivine phenocrysts were formed at various cooling rates. PLANNER and KEIL (1982) produced porphyritic texture by cooling from completely molten states with a temperature plateau; however, it is difficult to consider such a cooling condition in the natural nebula.

These results show that the most abundant porphyritic chondrules were possibly formed through incomplete melting of the precursor minerals, which means that most chondrules were heated below their liquidus temperatures, probably 1500°C or less. Further, fine-grained "lithic fragments" are interpreted to be lower temperature products of precursor aggregates.

Acknowledgments

The author thanks Dr. E. R. D. SCOTT of University of New Mexico, another unnamed reviewer, and Prof. I. KUSHIRO of University of Tokyo for reading the manuscript. The samples studied were supplied from the National Institute of the Polar Research.

References

DODD, R. T. (1978): Composition of droplet chondrules in Manych (L-3) chondrite and the origin of chondrules. Earth Planet. Sci. Lett., **40**, 71–82.

DODD, R. T. and VAN SCHUMUS, W. R. (1971): Dark-zoned chondrules. Chem. Erde, **30**, 59–69.

DONALDSON, C. H. (1976): An experimental investigation of olivine morphology. Contrib. Mineral. Petrol., **57**, 187–213.

FODOR, R. V. and KEIL, K. (1975): Implication of poikilitic textures in LL-chondrites. Meteoritics, **10**, 325–339.

GOODING, J. L. and KEIL, K. (1981): Relative abundances of chondrule primary textural types in ordinary chondrites and their bearing on conditions of chondrule formation. Meteoritics, **16**, 17–43.

GOODING, J. L., KEIL, K., FUKUOKA, T. and SCHMITT, R. A. (1980): Elemental abundances in chondrules from unequilibrated chondrites; Evidence for chondrule origin by melting of pre-existing materials. Earth Planet Sci. Lett., **50**, 171–180.

GROSSMAN, J. N. and WASSON, J. T. (1982): Evidence for primitive nebular components in chondrules from the Chainpur chondrite. Geochim. Cosmochim. Acta, **46**, 1081–1099.

GROSSMAN, J. N. and WASSON, J. T. (1983): Refractory precursor components of Semarkona chondrules and the fractionation of refractory elements among chondrites. Geochim. Cosmochim. Acta, **47**, 759–771.

IKEDA, Y. (1980): Petrology of Allan Hills-764 chondrite (LL3). Mem. Natl Inst. Polar Res., Spec. Issue, **17**, 50–82.

KEIL, K., LUX, G., BROOKINS, D. G., KING, A. E., KING, T. V. V. and JAROSEWICH, E. (1978): The Inman, McPherson County, Kansas meteorite. Meteoritics, **13**, 11–22.

MCKINLEY, S. G., SCOTT, E. R. D., TAYLOR., G. J. and KEIL, K. (1981): A unique type 3 ordinary chondrite containing graphite-magnetite aggregates—Allan Hills A77011. Proc. Lunar Planet. Sci Conf. 12B, 1039–1048.

NAGAHARA, H. (1981a): Evidence for secondary origin of chondrules. Nature, **292**, 135–136.

NAGAHARA, H. (1981b): Petrology of chondrules in ALH-77015 (L3) chondrite. Mem. Natl Inst. Polar Res., Spec. Issue, **20**, 145–160.

NAGAHARA, H. (1983): Chondrules formed through incomplete melting of the pre-existing mineral clusters and the origin of chondrules. Chondrules and Their Origins. Houston, Lunar Planet. Inst. (in press).

NAGAHARA, H. and KUSHIRO, I. (1982): Calcium-aluminium-rich chondrules in the unequilibrated ordinary chondrites. Meteoritics, **17**, 55–63.

PLANNER, H. N. and KEIL, K. (1982): Evidence for the three-stage cooling history of olivine-porphyritic fluid droplet chondrules. Geochim. Cosmochim. Acta, **46**, 317–330.

RAMBALDI, E. R. (1981): Relict grains in chondrules. Nature, **293**, 558–561.

RAMBALDI, E. R. and WASSON, J. T. (1982): Fine, nickel-poor Fe-Ni grains in the olivine of unequilibrated ordinary chondrites. Geochim. Cosmochim. Acta, **46**, 929–939.

TSUCHIYAMA, A. and NAGAHARA, H. (1981): Effects of precooling thermal history and cooling rate on the texture of chondrules; A preliminary report. Mem. Natl Inst. Polar Res., Spec. Issue., **20**, 175–192.

TSUCHIYAMA, A., NAGAHARA, H. and KUSHIRO, I. (1980): Experimental reproduction of textures of chondrules. Earth Planet. Sci. Lett., **48**, 155–165.

(*Received June 13, 1983; Revised manuscript received September 2, 1983*)