

# PETROLOGY OF CHONDRULES, INCLUSIONS AND ISOLATED OLIVINE GRAINS IN ALH-77307 (CO3) CHONDRITE

Hiroko NAGAHARA and Ikuo KUSHIRO

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

**Abstract:** A petrological study has been conducted on ALH-77307 (CO3) chondrite. Chondrules are classified into magnesian type and iron-rich type. The magnesian chondrules contain olivine and clinoenstatite with a small amount of groundmass, whereas the iron-rich chondrules contain only olivine as phenocrysts in the groundmass. Inclusions show gradual changes in crystallinity, grain size of constituents, texture and shape. The difference among the inclusions is considered to be due to the difference of heating temperature of the precursor fine-grained materials. Intensive heating of the inclusions might have formed the magnesian chondrules. Isolated olivine grains are also classified into magnesian and iron-rich types, which are thought to have been derived from the magnesian and iron-rich chondrules, respectively. Genetical relations of chondrules, inclusions and isolated olivine grains are discussed by the process of condensation, successive heating, break up, and accretion.

## 1. Introduction

ALH-77307 is a CO3 chondrite, and has been classified as a least metamorphosed type by SCOTT *et al.* (1981). It consists of abundant chondrules, inclusions and isolated olivine grains set in a dark, fine-grained matrix (Fig. 1a). Chondrules are small ( $>0.52$  mm) similar to those in the other CO chondrites and are not so abundant as in the unequilibrated ordinary chondrites. Inclusions comprise amoeboid and refractory (CAIs) types; the former is far more abundant than the latter. "Inclusion" (except for the CAIs) used here corresponds to "aggregate" by OLSEN and GROSSMAN (1978) and DESNOYERS (1980), "amoeboid aggregate" by GROSSMAN and STEELE (1976)

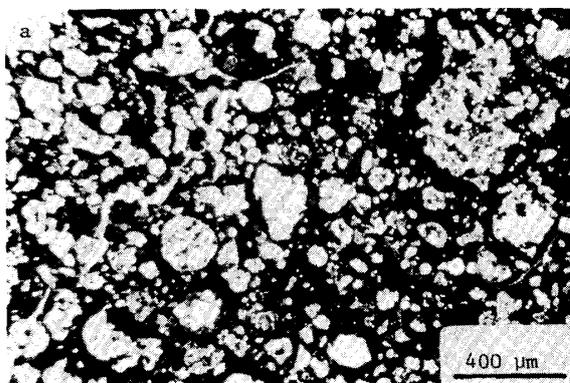


Fig. 1a. Photomicrograph showing the texture of ALH-77307 chondrite.

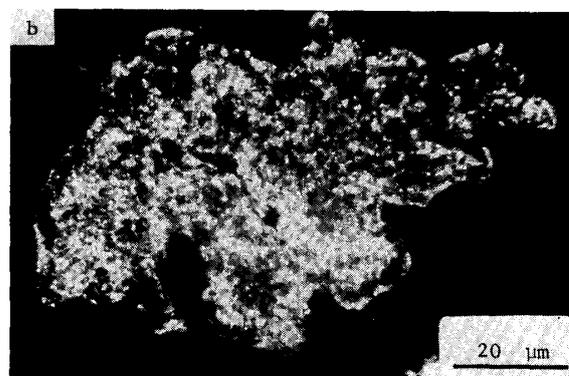


Fig. 1b. Calcium-aluminium-rich inclusion in ALH-77307 chondrite.

and “amoeboid inclusion” by McSWEEN (1977a). CAIs in this chondrite are fine-grained, small and irregularly shaped (Fig. 1b).

In this paper, a petrological study of chondrules, inclusions (except for the CAIs) and isolated olivine grains is presented and their genetical relations are discussed.

## 2. Chondrules

Chondrules in ALH-77307 are classified into two types on the basis of their texture and chemistry. One is magnesian and contains subhedral to anhedral olivine and pyroxene, and the other is rich in iron and contains euhedral olivine phenocrysts in a fine-grained or glassy groundmass, showing a porphyritic texture.

The magnesian chondrules consist of aggregates of olivine in the center often with blebs of magnetite and surrounding pyroxene (Fig. 2a). The bulk chemical composition of this type of chondrules is rich in MgO,  $X_{Mg}$  (Mg/Mg+Fe) ranging from 0.97 to 0.85. Olivine in these chondrules is homogeneous and has composition of

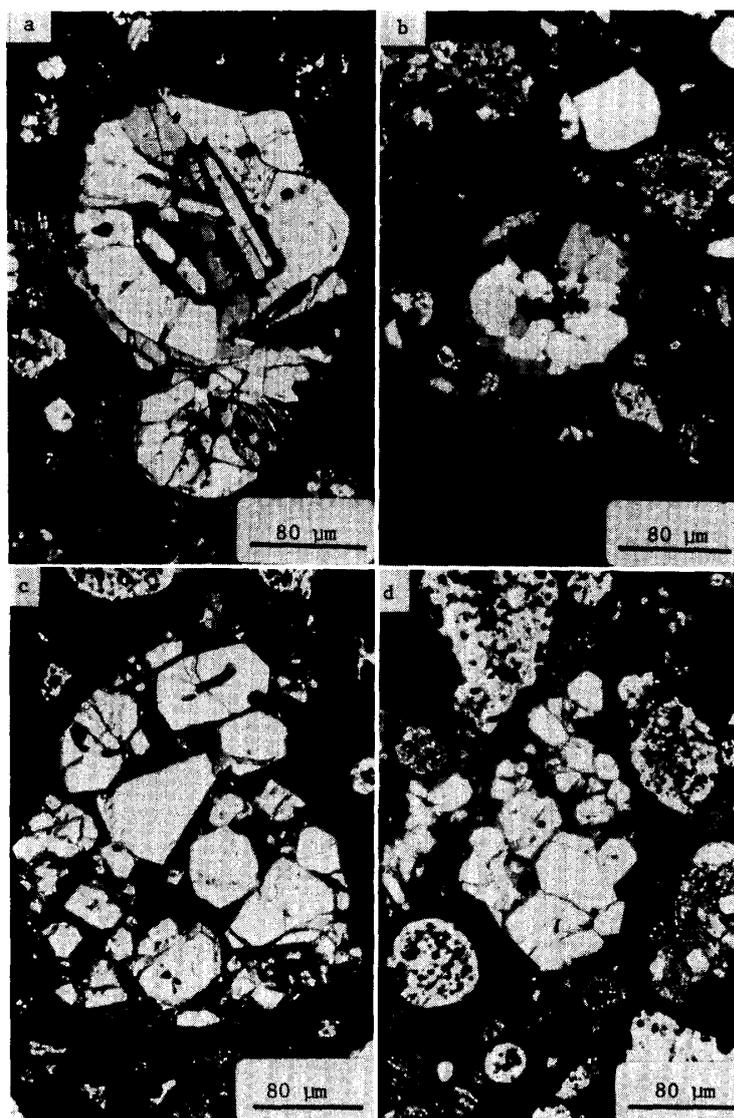


Fig. 2a. A magnesian chondrule in ALH-77307 chondrite. It consists of barred and granular olivines and surrounding clinoenstatite with magnetite blebs.

Fig. 2b. A magnesian chondrule composed of granular olivine and surrounding clinoenstatite.

Figs. 2c and 2d. An iron-rich chondrule in ALH-77307 chondrite. They consist of olivine phenocrysts set in brown groundmass.

nearly pure forsterite (Fo 99.8–98.0). Pyroxene is Mg-rich, Ca-poor clinopyroxene (En 99–96 Wo < 0.5) indicating that these chondrules were rapidly cooled. Pyroxene interstitially surrounds or poikilitically encloses olivine. The modal ratio of olivine and pyroxene varies; some chondrules are composed mostly of olivine with a small amount of interstitial pyroxene and some are composed mostly of pyroxene with a small amount of enclosed olivine. Small blebs of magnetite are often present in the central portion of these chondrules. They sometimes have Ni-Fe metal core and surrounding magnetite, indicating that the Ni-Fe metal was afterward replaced by magnetite. Rarely Ni-Fe metal blebs are included in olivine or clinopyroxene. The chondrules of this type contain a lesser amount of groundmass which is usually brown mesostasis. This type corresponds to Type I granular olivine chondrule of MCSWEEN (1977b), and is characteristic of carbonaceous chondrites and not observed in the unequilibrated ordinary chondrites.

The other type of chondrule, which is iron-rich, consists of olivine phenocrysts set in the fine-grained groundmass showing a typical porphyritic texture (Fig. 2b). The bulk chemical compositions of the chondrules of this type are rich in FeO,  $X_{Mg}$  being from 0.7 to 0.5. Olivine is euhedral and 100–200  $\mu\text{m}$  in size, and often contains glass inclusions. Pyroxene is not present in these chondrules. Olivine shows remarkable compositional zoning with magnesian core and iron-rich rim. The range of the compositional zoning depends on the bulk chemical composition, but usually it ranges from 30 to 40 mol% Fa. Groundmass is brownish and glassy or fine-grained; the amount of groundmass varies from about 20 to 50 vol%. This type of chondrule corresponds to Type II porphyritic olivine chondrule of MCSWEEN (1977b), and resembles the chondrules in the ordinary chondrites.

The bulk chemical compositions of the chondrules of these two types are shown in the MgO-FeO-SiO<sub>2</sub> ternary diagram (Fig. 3). They can easily be defined in the figure. Both types of chondrule contain small amounts of Al<sub>2</sub>O<sub>3</sub>, CaO and Na<sub>2</sub>O, though their total amounts are much less than those of the chondrules in the ordinary chondrites, which indicates a different mechanism of formation of chondrules in the carbonaceous chondrites.

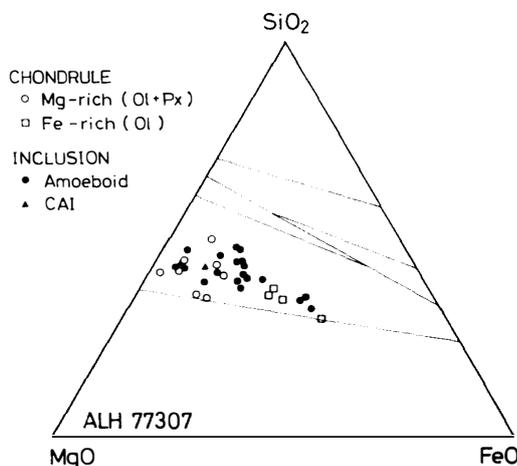


Fig. 3. Chemical compositions of chondrules and inclusions in the system MgO-FeO-SiO<sub>2</sub>.

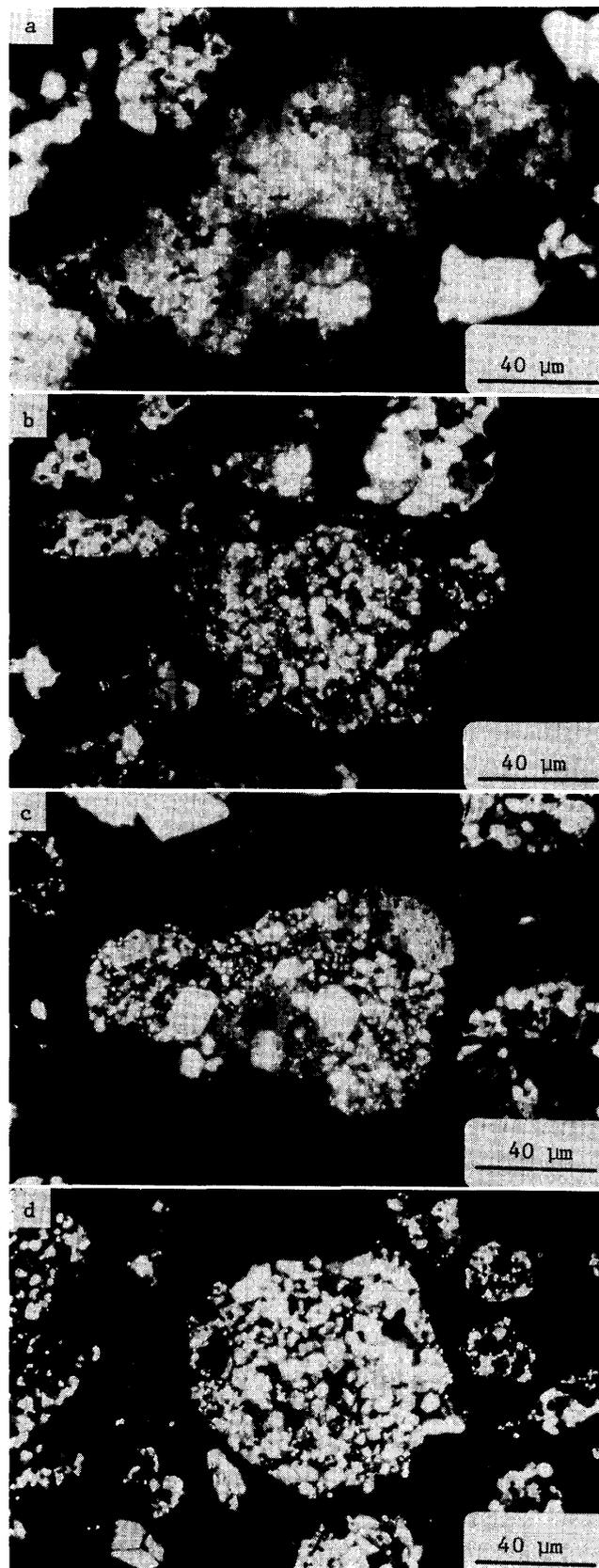
### 3. Inclusions

Inclusions are defined by their irregular shapes compared with the chondrules. They show various size, shape, texture, crystallinity and internal grain size. The latter four factors relate to one another, and the inclusions can be arranged according to the gradual changes of these factors. Figure 4 shows the inclusions arranged in the order of increasing crystallinity, grain size and smoothness of the outline of the shape: (a) irregularly-shaped aggregates of fine-grained minerals resembling fine-grained CAIs, each of which is submicron size and can not be identified under the microscope, (b) fine-grained irregular aggregates with a small amount of euhedral olivine grains of several to several tens  $\mu\text{m}$  size, (c) irregular aggregates of euhedral olivine grains of several tens  $\mu\text{m}$  with dispersed small irregular magnetite grains, (d) aggregates of euhedral to subhedral olivine with dispersed irregular magnetite and surrounding or interstitially embedded clinoenstatite, (e) somewhat smoothly outlined aggregates of relatively large olivine and clinoenstatite with relatively large magnetite grains, (f) more smoothly outlined aggregates of coarse-grained olivine often poikilitically enclosed by clinoenstatite with large magnetite blebs in the center, (g) those similar to the former but with coarser grains and smoother outline resembling chondrules of the magnesian type (Fig. 2a).

These sequences can be explained as the result of heating at successively higher temperatures of the originally fine-grained aggregates such as Fig. 4a. Heating at higher temperature and/or longer duration would result in the increase of grain size of olivine and pyroxene, and smoothness of the outline of the aggregates. The temperature of heating is considered to be lower than the liquidus temperatures because entirely melted aggregates should become spheres to form the chondrules. Smooth outline of some aggregates, such as Figs. 4f–4g, indicates existence of a considerable amount of liquid; they were heated above the solidus temperatures. On the contrary, some with irregular outline, such as Figs. 4a–4c, should have been heated below the liquidus temperatures. The existence of clinoenstatite indicates that they have cooled rapidly, as have the magnesian chondrules.

The remarkable resemblance of coarse-grained inclusions (Fig. 4g) and magnesian chondrules (Fig. 2a) indicates that the magnesian chondrules may also have formed from the fine-grained materials by intensive heating, probably near the liquidus temperatures. It is not known whether they were once wholly melted or not because there is no direct evidence to show it, but it is evident that they were at least nearly melted because of the round shape. MCSWEEN (1977c) treated the inclusions composed of granular olivine in the interior and clinoenstatite in the outer portion, like Fig. 4a, as a type I chondrule, though OLSEN and GROSSMAN (1978) treated such inclusion as an “aggregate”. This confusion results from the similarity of the coarse-grained inclusions and magnesian chondrules, as well as from the ambiguity of the definition of “chondrules”. The above described model that the magnesian chondrules and the coarse-grained inclusions were formed by the same mechanism (*i.e.* heating of fine-grained inclusions) and that their difference is due to the difference of heating temperature can well explain the above similarities.

Close similarity in texture between the magnesian chondrules and inclusions is



*Fig. 4.*

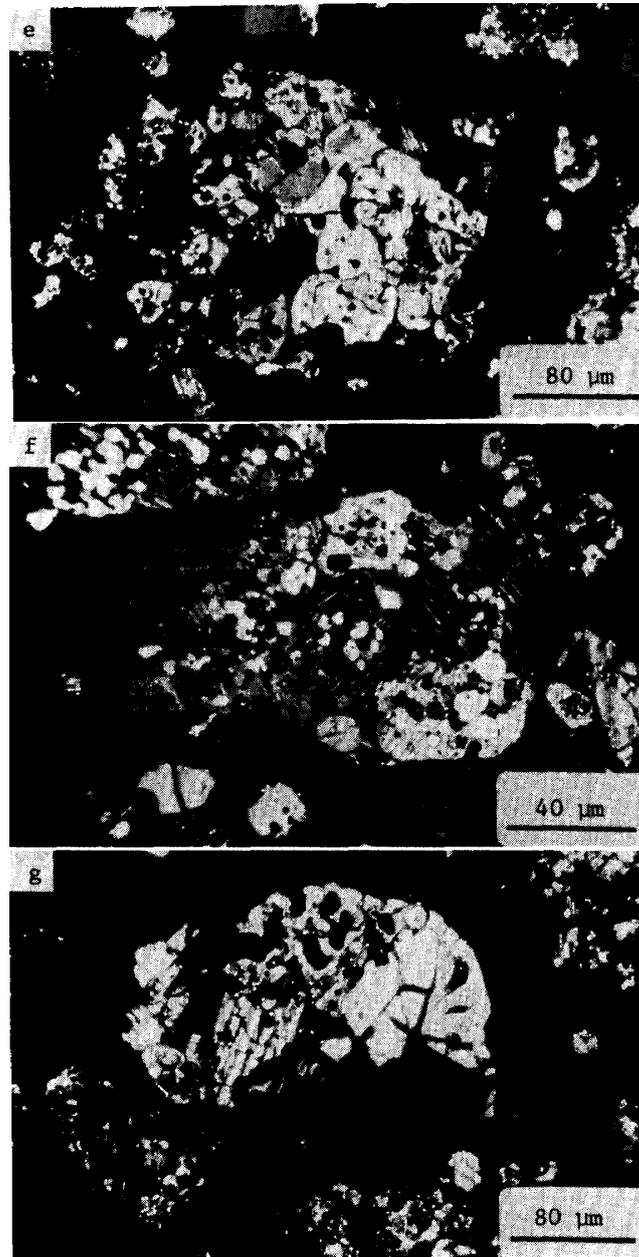


Fig. 4. Texture of inclusions in the order of increasing crystallinity and grain size.

supported by their chemical compositions. Bulk compositions of the inclusions shown in Fig. 3 indicate that they have similar compositional ranges. In the figure, the coarse-grained inclusions are apparently plotted on the magnesian side and the fine-grained ones are on the iron-enriched side. This is thought to be an analytical effect; fine magnetite in the fine-grained inclusions could not be excluded in the analyses by the defocused broad beam of EPMA, whereas coarse magnetite in the coarse-grained inclusions could be excluded. As a result, the coarse-grained inclusions are apparently richer in MgO than the fine-grained ones. The real compositions of the silicate portion of both should be magnesian, and fall in a narrow compositional range.

Compositional similarity of the magnesian chondrules and inclusions is further

supported by the relation between  $\text{Al}_2\text{O}_3$  and CaO (Fig. 5). Both the magnesian chondrules and the inclusions have similar  $\text{Al}_2\text{O}_3$  and CaO contents, and their CaO/ $\text{Al}_2\text{O}_3$  ratios are near the "cosmic abundance" ratio. MCSWEEN (1977d) has already pointed out this relation for several carbonaceous chondrites and discussed the compositional difference of chondrules and inclusions in the carbonaceous chondrites. However they have nearly the same compositions in the range of low  $\text{Al}_2\text{O}_3$  and CaO contents in Fig. 5. The compositional difference between the chondrules and inclusions with high  $\text{Al}_2\text{O}_3$  and CaO contents might have developed after their formation and before accretion to the chondrite, perhaps by reaction with the ambient gas or by the attachment of finer-grained materials rich in these elements.

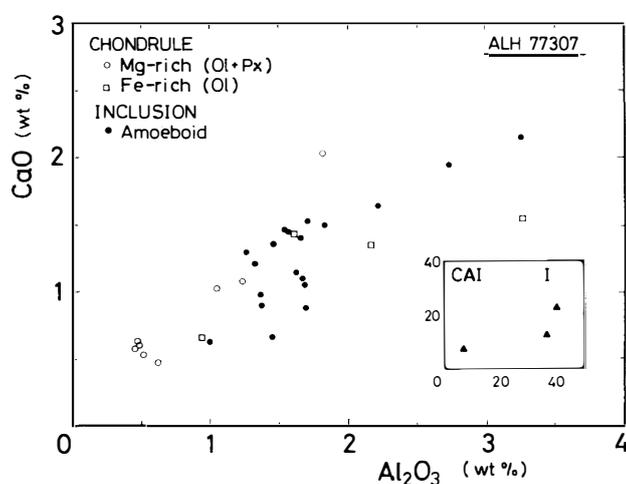


Fig. 5.  $\text{Al}_2\text{O}_3$ -CaO relations of chondrules and inclusions.

Relations between the bulk chemical composition and the olivine composition prove the subliquidus heating of the inclusions and the magnesian chondrules. Figure 6 shows the relations of  $X_{\text{Mg}}$  ( $\text{Mg}/\text{Mg} + \text{Fe}$ ) between the bulk composition and olivine of magnesian and iron-rich chondrules and the inclusions. The curved line is for  $K_D = 0.3$  ( $K_D = X_{\text{Mg}}^{\text{Liq}}/X_{\text{Fe}}^{\text{Liq}} \cdot X_{\text{Fe}}^{\text{Ol}}/X_{\text{Mg}}^{\text{Ol}}$ ), which represents the equilibrium olivine and liquid (ROEDER and EMSLIE, 1970). The magnesian chondrules and inclusions have extremely magnesian olivine, which is more magnesian than those in equilibrium with the bulk chondrule composition. Furthermore, the composition of olivine is nearly constant, though the bulk composition varies significantly. The facts suggest that the composition of crystallizing olivine was buffered by metallic iron under the reducing condition (that is, the liquid was more magnesian than the bulk chondrules). On the contrary, the iron-rich chondrules, excluding one exception, contain olivines with reasonable composition formed by crystallization from the entirely melted precursor materials under more oxidized conditions.

The above described close similarity between the magnesian chondrules and the inclusions and the difference of their heating temperature require the condition that the precursor fine-grained materials were heated at various temperatures up to near the liquidus temperatures for considerably long durations. Further, they should have cooled rapidly to contain clinopyroxene instead of orthopyroxene. The existence

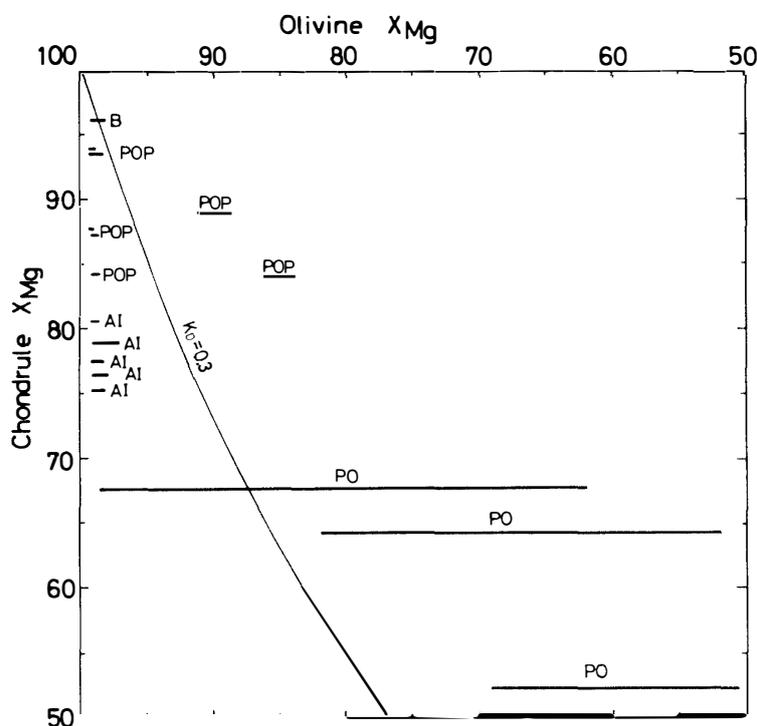


Fig. 6. Relations of  $X_{Mg}$  ( $Mg/Mg + Fe$ ) between bulk chondrule and zonal range of constituent olivine. One bar represents a chondrule or an inclusion with several olivine grains. B: barred olivine chondrule, POP: porphyritic olivine and pyroxene chondrule, PO: porphyritic olivine chondrule, AI: inclusion.

of products heated at various temperatures in this chondrite indicates that the heating did not occur *in situ*. Therefore, the heating should have been occurred before accretion to the chondrite, perhaps within the nebula or gas. The mechanism of heating, as well as the mechanism of chondrule formation, is still not clear.

#### 4. Isolated Olivine Grains

Isolated olivine grains in ALH-77307 can be classified into two types, like other C2 and C3 chondrites (Fig. 7) (KERRIDGE and MACDOUGALL, 1976; MCSWEEN, 1977d; RICHARDSON and MCSWEEN, 1978; OLSEN and GROSSMAN, 1978; DESNOYERS, 1980); one is magnesian and the other is iron-rich. The mode and the compositional range of the isolated olivine grains are shown in Fig. 8, which shows these two distinct types. The magnesian olivines have a narrow compositional range, and most of them are nearly homogeneous, whereas the iron-rich olivines show a wide compositional range. The modal ratio of the two olivines is nearly the same.

These two types of olivines show different chemical features. The zoning patterns of MgO, FeO and CaO of the two olivines are shown in Fig. 9. The magnesian olivine is nearly homogeneous with slight iron enrichment in the rim, and has a high CaO content with depletion of CaO in the rim. On the contrary, the iron-rich olivine shows a remarkable zoning with an iron enriched rim, and has a low CaO content with increase of CaO in the rim. In general, the CaO content in olivine is controlled

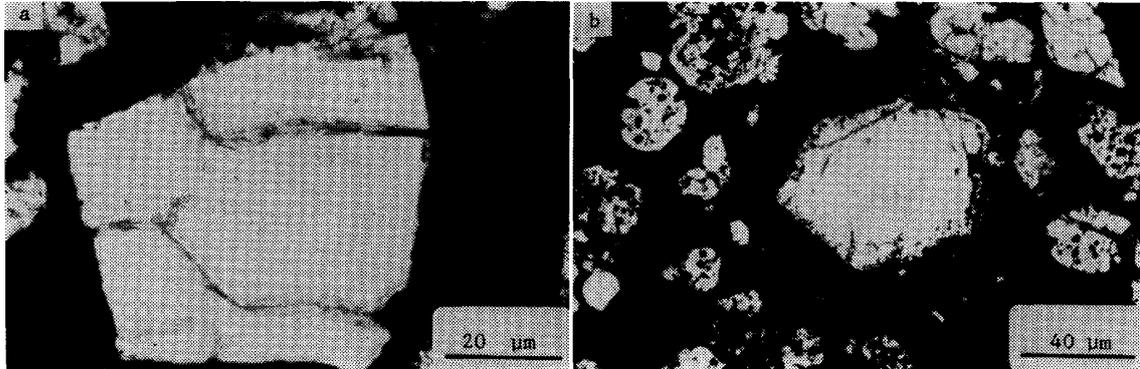


Fig. 7. Photomicrograph of isolated olivines.

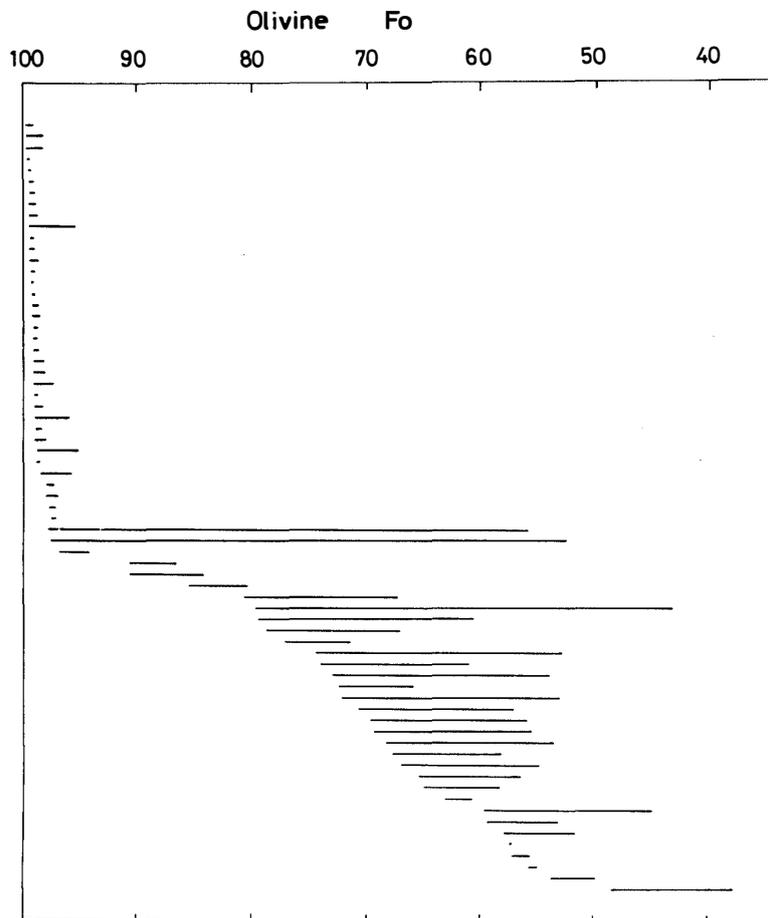


Fig. 8. Compositional range of isolated olivines. One bar represents one grain selected at random.

by the bulk CaO content of the liquid from which olivine crystallizes, temperature of olivine crystallization, presence or absence of coexisting pyroxene, and so on. The high content of the bulk CaO, high crystallization temperature, and the absence of pyroxene would result in the high CaO content of olivine. So the high content and decrease toward the rim of CaO in the magnesian olivine are explained by high temperature of crystallization and successive crystallization of pyroxene. On the other hand,

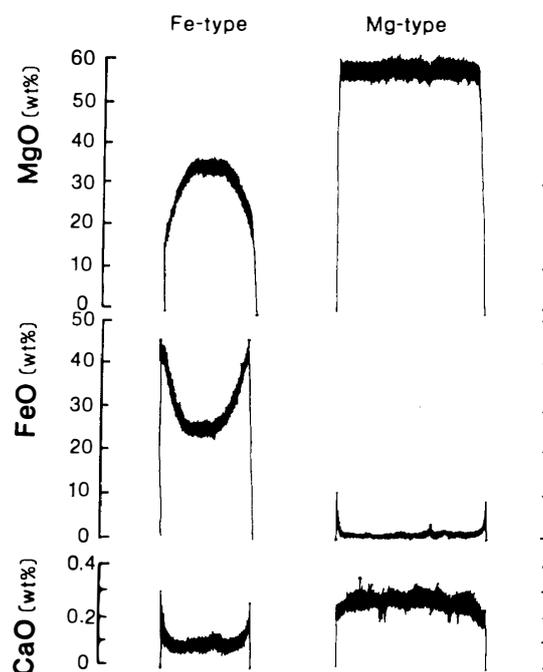


Fig. 9. Zoning pattern of MgO, FeO and CaO of the two types of isolated olivine.

low content and increase toward the rim of CaO in the iron-rich olivine are explained by the crystallization at low temperature and absence of coexisting pyroxene.

These two types of olivines correspond to the two types of chondrules (nearly homogeneous magnesian type and remarkably zoned iron-rich type) suggesting the possibility that the isolated olivine grains have been derived from the chondrules. That is, the magnesian olivines have been derived from the magnesian chondrules and the iron-rich olivines from the iron-rich chondrules, respectively. The zoning pattern of CaO indicates that these olivines were crystallized from a liquid. The range of the compositional zoning also indicates that the isolated olivine grains have been derived from the chondrules. The magnesian olivine has an extremely narrow compositional range, which is similar to the olivines in the magnesian chondrules. The iron-rich olivine has a compositional range of 30–40 mol% Fa, which is similar to the olivine in the iron-rich chondrules. The constant compositional range of the iron-rich olivines and the absence of extensively zoned olivine with more than 50 mol% Fa except for two olivines indicate their similar mechanism of formation.

The above described features of the two olivines have already been found in many carbonaceous chondrites and their origin has been discussed. The main argument is whether the isolated olivine grains are fragments of chondrules or are they direct condensates from the gas. In addition to the above discussions, the existence of glass inclusions within the isolated olivine grains which is often observed in the olivine in the two types of chondrules leads to the conclusion that the isolated olivine grains have been derived from the chondrules.

## 5. Conclusion

Chondrules, inclusions and isolated olivine grains except for the matrix of the ALH-77307, one of the least metamorphosed CO<sub>3</sub> chondrites (SCOTT *et al.*, 1981), are thought to have genetical relations. The scenario for the formation of this chondrite is schematically shown in Fig. 10. The fine-grained precursor materials would be condensation products from the solar nebula with or without reaction with the ambient gas. Condensation products at higher temperatures would have accreted to form the CAIs afterwards, but were rarely incorporated into this chondrite. Those at somewhat lower temperatures, which are the most abundant in this chondrite, were slowly heated up to various subliquidus temperatures to have formed the inclusions with various grain size, texture and outline. Some of them were heated to near the

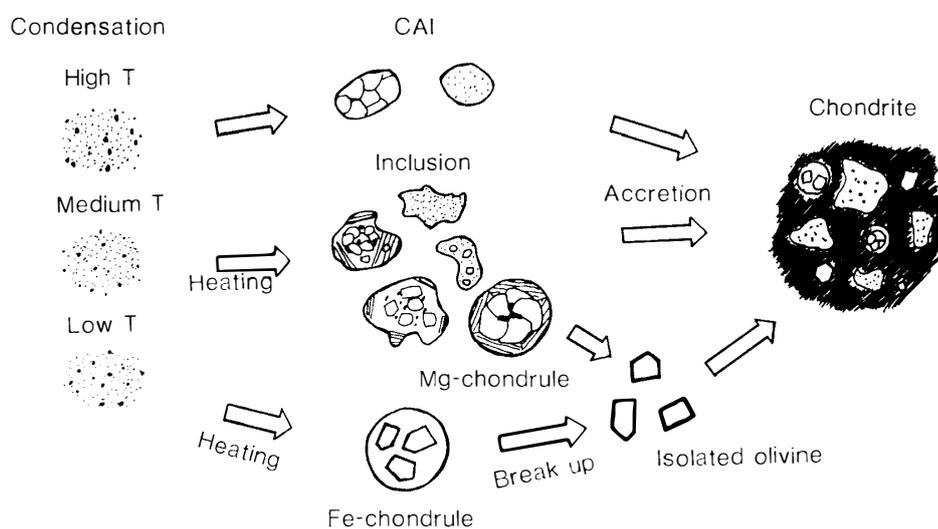


Fig. 10. Schematic genetical relations of CAIs, chondrules, inclusions and isolated olivines of ALH-77307 chondrite.

liquidus temperature and formed the magnesian chondrules. Condensates at lower temperatures were heated, probably rapidly, to form the iron-rich porphyritic olivine chondrules. The inclusions and the two types of chondrules were later broken up and the two types of isolated olivine grains were formed. These coarse constituents were accreted with the matrix, which might be lower temperature condensates, to form the chondrite.

The place where the heating occurred and the inclusions and chondrules were formed is difficult to imagine, but local heating in the dense gas would be the most important condition.

## Acknowledgments

The present study was carried out as part of the consortium work on ALH-77307 chondrite. The authors thank Dr. K. YANAI of the National Institute of Polar Research and Prof. H. NAGASAWA of the Gakushuin University for thin sections used in the present study.

## References

- DESNOYERS, C. (1980): The Niger (I) carbonaceous chondrite and implications for origin of aggregates and isolated olivine grains in C2 chondrites. *Earth Planet. Sci. Lett.*, **47**, 223–234.
- GROSSMAN, L. and STEELE, I. M. (1976): Amoeboid olivine aggregates in the Allende meteorite. *Geochim. Cosmochim. Acta*, **40**, 149–155.
- KERRIDGE, J. F. and MACDOUGALL, J. D. (1976): Mafic silicates in the Orgueil carbonaceous meteorite. *Earth Planet. Sci. Lett.*, **29**, 341–348.
- McSWEEN, H. Y., Jr. (1977a): Carbonaceous chondrites of the Ornans type: A metamorphic sequence. *Geochim. Cosmochim. Acta*, **41**, 477–491.
- McSWEEN, H. Y., Jr. (1977b): On the nature and origin of isolated olivine grains in carbonaceous chondrites. *Geochim. Cosmochim. Acta*, **41**, 411–418.
- McSWEEN, H. Y., Jr. (1977c): Petrographic variations among carbonaceous chondrites of the Vigarano type. *Geochim. Cosmochim. Acta*, **41**, 1777–1790.
- McSWEEN, H. Y., Jr. (1977d): Chemical and petrographic constraints on the origin of chondrules and inclusions in carbonaceous chondrites. *Geochim. Cosmochim. Acta*, **41**, 1843–1860.
- OLSEN, E. and GROSSMAN, L. (1978): On the origin of isolated olivine grains in type 2 carbonaceous chondrites. *Earth Planet. Sci. Lett.*, **41**, 111–127.
- RICHARDSON, S. M. and McSWEEN, H. Y., Jr. (1978): Textural evidence bearing on the origin of isolated olivine crystals in C2 carbonaceous chondrites. *Earth Planet. Sci. Lett.*, **37**, 485–491.
- ROEDER, P. L. and EMSLIE, R. F. (1970): Olivine-liquid equilibrium. *Contrib. Mineral. Petrol.*, **29**, 275–289.
- SCOTT, E. R. D., TAYLOR, G. J., MAGGIORE, P., KEIL, K., MCKINLEY, S. G. and McSWEEN, H. Y., Jr. (1981): Three CO3 chondrites from Antarctica—Comparison of carbonaceous and ordinary type 3 chondrites. *Meteoritics*, **16**, 385.

*(Received May 21, 1982; Revised manuscript received August 12, 1982)*