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SHOCK MELTING ORIGIN OF A TROILITE-RICH CLAST IN THE MOORABIE CHONDRITE (L3)

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Abstract: A troilite-rich clast enclosing chondrules was found in the Moorabie chondrite (L3). This chondrite is characterized by elongate morphology of chondrules produced by shock deformation. Average composition of the metal and troilite grains in the clast is close to the eutectic composition of the Fe-S system, indicating the melting origin of the clast. The eutectic composition provides the heating temperature to be around 1000°C. Size and distribution of troilite and metal grains in the clast suggest the slow cooling after the melting. Pentlandite as an exsolved phase of troilite in the clast, found first in ordinary chondrites, also supports the melting and slow cooling. Thermal history of the clast indicates that the melting of the opaque minerals and the elongate morphology of chondrules were caused inside the parent body by the shock event which occurred at an early hot stage (around 400°C) of the cooling after the accretion of the chondrite.

1. Introduction

Chondrites include metallic irons and troilite grains in them as major constituent minerals. Some large grains of metal, troilite or metal-troilite compounds in ordinary chondrites have been interpreted, not to be fragments, but to have crystallized from melt in the chondrites (Ramsdorf (L6): BEGEMANN and WLOTZKA, 1969; Tysnes Island (H4): WILKENING, 1978; Shaw (L6): TAYLOR *et al.*, 1979; 12 ordinary chondrites: SCOTT, 1982). These grains and clasts occur accompanied by silicate minerals with crystallization texture from their melts (BEGEMANN and WLOTZKA, 1969; TAYLOR *et al.*, 1979). Then, the opaque grains and clasts as well as the melting texture of silicates have been interpreted to be formed by shock melting in the chondrites.

Sizes and textures of these metal and troilite grains vary depending upon heating temperature (or degree of partial melting), heating duration, cooling rate and others. The texture of kamacite-taenite grains allows an estimate of the cooling rate around 600°C. In the case of the Shaw chondrite, the cooling rate has been estimated to be several degrees per thousand years (TAYLOR *et al.*, 1979). This rather slow cooling rate indicates that the shock melting and subsequent cooling occurred inside the parent body of the chondrite.

When the solidification of the eutectic melt of the Fe-S system is fast, a dendritic texture of Fe-Ni metal and troilite is formed. Since the arm-spacings of dendrites depend upon the solidification rate, tney can be used as a cooling ratemeter.

SCOTT (1982) applied this method of cooling rate calculation to metal-troilite clasts in several ordinary chondrites including unequilibrated ones, and suggested that some of the clasts were formed by melting resulting from shock impact on the surface of the parent bodies. Thus, the thermal history of the opaque grains and clasts also allows speculation on the locations of shock melting event in the parent body.

Shock deformation textures of unequilibrated chondrites, other than the large grains and clasts of opaque minerals have also been reported. One of the typical examples is elongate morphology of chondrules with a preferred orientation, which has been observed in some unequilibrated chondrites. This type of the texture has been interpreted to have resulted from the shock impact process (SNEYD *et al.*, 1988 in ordinary chondrites; WASSON, 1985 and NAKAMURA *et al.*, 1990 in Leoville (CV3)), but no description was given of any metal-sulfide clasts in these chondrites except for a xenorithic chondrite (Mezö-Madaras: SCOTT, 1982).

In the course of the study on shock deformation of unequilibrated chondrites including the elongate chondrules, a large troilite-rich clast was found in the Moorabie chondrite (L3). The clast is unique in that it encloses chondrules. In the present paper, the troilite-rich clast is described, and the origin of the clast is discussed in relation to the deformation which produced elongate chondrules in Moorabie.

2. Experimental and Results

A polished thin section of the Moorabie chondrite (L3) was examined with an optical microscope and a scanning electron microscope (HITACHI-S530) using a backscattered electron image technique. The chemical composition of minerals was determined by an electron probe microanalyzer (a KEVEX DELTA EDX system) with a focused beam. Standards were prepared for twelve elements. The accelerating voltage was 20 kV and the beam current was 1.65 nA. X-ray intensities were corrected by the ZAF method.

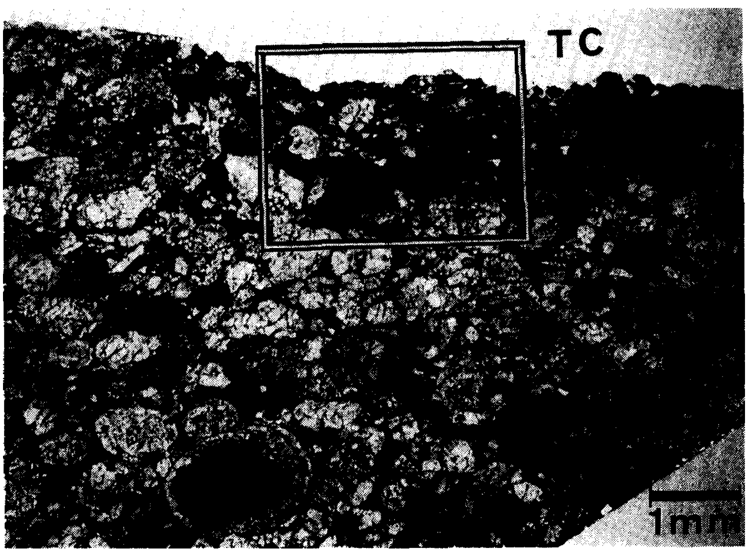

Fig. 1. Optical micrograph of thin section of the Moorabie chondrite. Chondrules have elongate morphology. Alignment of long axes of chondrules are observed along the horizontal axis. Regions in black are mostly opaque minerals. A troilite-rich clast (TC) is observed as the large region in black in the upper-right side of the figure. A part of the clast (within a square frame) is enlarged in Fig. 2.

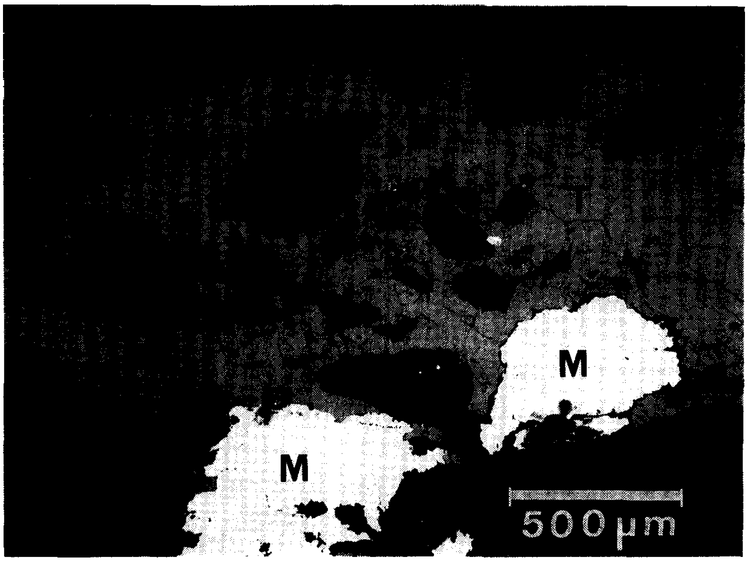

Fig. 2. Backscattered electron image of the part of the troilite-rich clast in Fig. 1. Black parts in the clast are chondrules and their fragments. M: metal, T: troilites.

The Moorabie chondrite contains a large (6×5 mm) troilite-rich clast (Figs. 1 and 2). Texture and chemical compositions of the chondrite and clast are described separately as below. Hereatfer, the part of the chondrite other than the clast will be called the 'host' to prevent confusion.

2.1. *Moorabie host*

The host of Moorabie is composed of several constituents common in L3 chondrites; chondrules, mineral fragments, small metal and sulfide clasts and matrices (Fig. 1). Most chondrules of the host are porphyritic chondrules (porphyritic olivines, porphyritic olivine-pyroxenes, and porphyritic pyroxenes), though some barred olivines and glassy chondrules were also observed. Elongate chondrules in the host have nearly ellipsoidal shapes, the major axes of which in the thin section are roughly aligned in the same orientation (along the horizontal axis of Fig. 1) irrespective of their sizes (a few hundred μm–2 mm in the major axis). Axial ratio of ellipsoidal chondrules (Rf) measured on the thin section is plotted against the direction of long axis (ϕ) in Fig. 3. The axial ratios of three dimensional measurement must be larger than the values observed here. However, the figure clearly shows the elongate chondrules have the preferred orientation.

Olivine grains in chondrules show undulatory or mosaic extinction. Polysynthetic twin boundaries on (100) of clinopyroxene in chondrules are not straight but are curved intensely due to deformation after the transformation from protoenstatite. The morphology of chondrules and the micro-textures of their constituent minerals suggest deformation of the chondrite, but no remelting of chondrules has occurred during or after the accretion.

The mineral assemblages and compositions of chondrules in Moorabie are essentially the same as those in typical L3 chondrites. Fe-Mg compositions of olivine grains in the host are shown in Fig. 4. Ca-poor pyroxenes in chondrules show striated Fe-Mg heterogeneity as commonly observed in those in L3 chondrites (TSUCHIYAMA *et al.*, 1988; NOGUCHI, 1988).

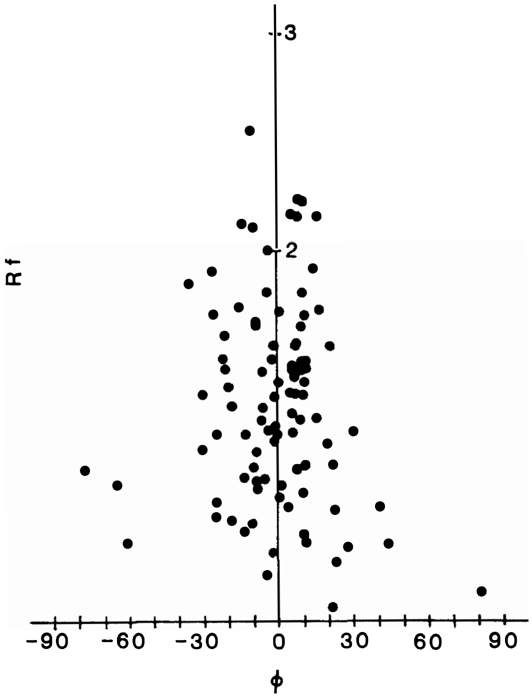

Fig. 3. Rf/ϕ diagram of the elongate chondrule in a thin section of Moorabie (Fig. 1). The average direction of long axis of chondrules is fixed to be ϕ=0.

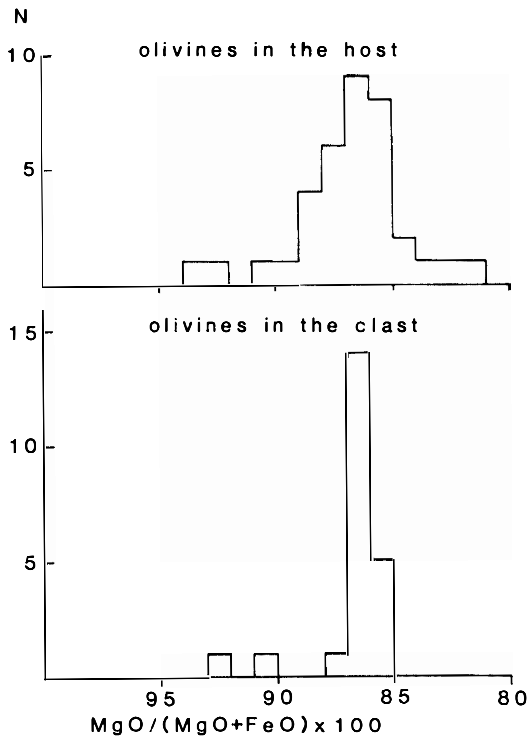

Fig. 4. Mg numbers (MgO/(MgO+FeO)×100) of olivines in the host and those in the troilite-rich clast. Compositional ranges of olivines in the two regions coincide with each other.

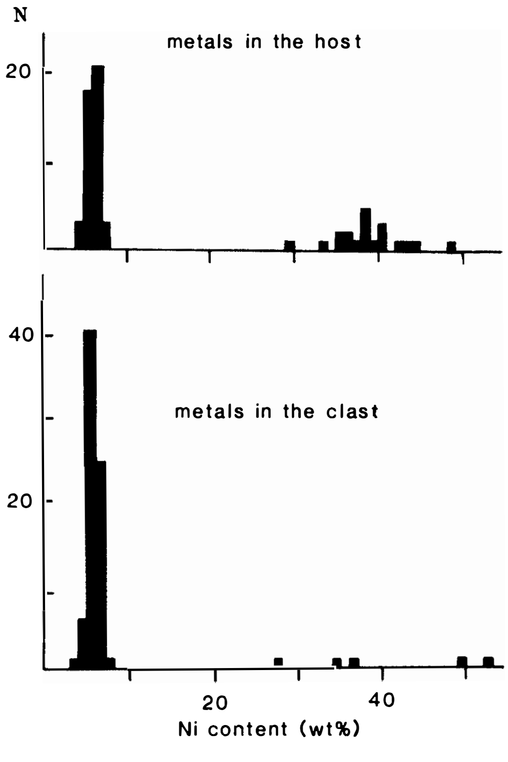

Fig. 5. The Ni content of grains of Fe-Ni metal in the host (upper) and those in the troilite-rich clast (lower).

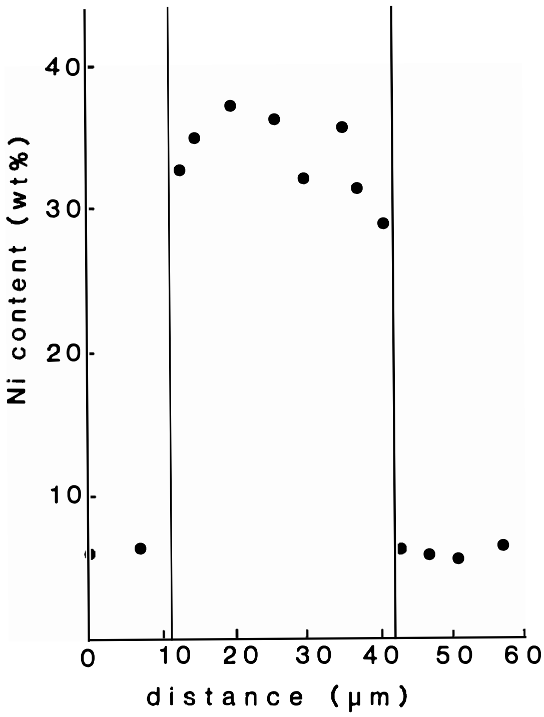

Fig. 6. Profile of Ni wt% (vertical axis) against distance (horizontal axis) in a metal grain in the host. Kamacite-taenite boundaries are shown as two vertical lines.

Grains of Fe-Ni metal and troilite in the host occur as inclusions in chondrules and as fine grains on chondrule rims or in the matrices among chondrules. The metal and troilite grains are mostly smaller than 300 μm in diameter. Most of the metal grains are kamacite ($\sim$6 wt% of Ni), but there are also some grains of taenite. Figure 5 shows the Ni content of the metal in the host. Taenite grains coexisting with kamacite usually show the reverse zoning (the core is richer in Ni than the rims). Figure 6 shows an example of profile of metal composition in a grain of kamacite-taenite. Taenite with high Ni content (which should be tetrataenite: Ni $\sim$50 wt%) occurs as separated grains. Almost all the sulfides are troilites, and some of them enclose small grains (a few μm in size) of pentlandite with an atomic ratio of Fe/Ni $\sim$2.8 (Fig. 7).

Grains of metal are more abundant than troilite everywhere in the host. However, the modal ratio of the metal to troilite increases toward the troilite-rich clast. Two regions with the area of 3×4 mm, departed from the clast by 2 and 7.5 mm

Fig. 7. Backscattered electron image of a troilite grain in the host. Pentlandite grains are enclosed in the troilite grain. P: pentlandite, Tr: troilite.

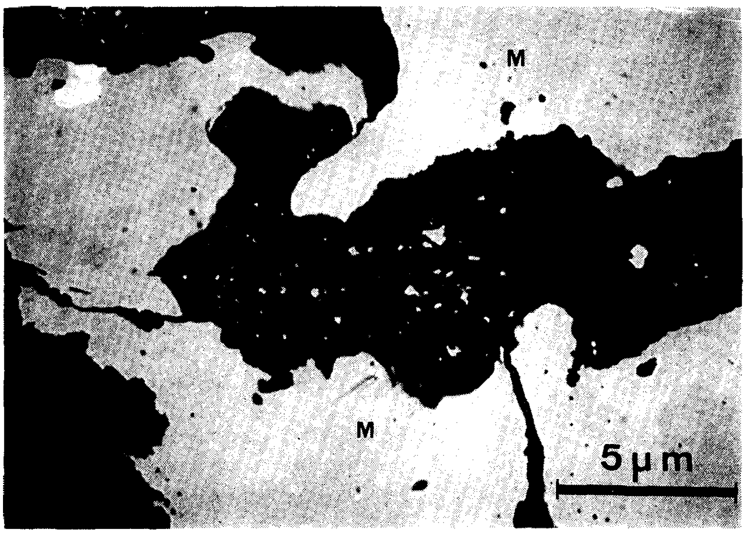

Fig. 8. Backscattered electron image of metal and troilite grains in the host. Sulfide-rich droplets a few to sub-μm in diameter are observed near the larger grains. M: metal, T: troilite.

Table 1. Composition of glassy material.

	M7	M9	M10	GL2
Na_2O	0.00	3.98	4.34	10.29
MgO	30.69	16.44	15.98	0.00
Al_2O_3	0.00	7.02	7.45	19.85
SiO_2	55.80	51.31	50.93	67.60
K_2O	0.04	0.06	0.05	0.57
CaO	0.72	1.64	2.13	0.53
TiO_2	0.10	4.28	2.02	0.06
Cr_2O_3	0.26	0.33	0.35	0.08
MnO	0.50	0.40	0.41	0.05
FeO	10.33	12.57	12.12	0.51
NiO	0.21	0.75	1.02	0.25
Total	98.65	98.79	96.79	99.78

M7, M9, M10: composition of melt texture. GL2: maskelynite. Two types of glassy texture indicate clear difference in composition.

have the metal/sulfide ratio of 5 and 1.6, respectively. This change in the mode of occurrence of metal and sulfide indicates sulfide depletion in the neighboring area of the clast.

Small metal-troilite droplets, a few μm to sub-μm in diameter, are observed near some metal-troilite grain boundaries (Fig. 8), and in the matrix among chondrules and mineral fragments. The droplets are richer in troilite than in metal. The textures and compositions of the droplets suggest that they must be formed by the eutectic melting of metal and troilite.

The interstitial regions or matrices among chondrules and mineral fragments are filled with three types of materials instead of opaque matrix of normal L3 chondrites. The first type is composed of olivine, pyroxene, metal, and troilite grains whose texture is similar to the transparent matrix commonly observed in some type 3 ordinary chondrites. The second type is melt-pockets including unhedral olivine, pyroxene, and metal-troilite droplets. The molten parts are not homogeneous and change their composition in relation to adjacent mineral grains (Table 1: M7, 9, 10). The third type is the clear maskelynite with composition close to albite-rich feldspar (Table 1: GL2).

2.2. *Troilite-rich clast*

The large clast consists mainly of opaque minerals and encloses chondrules and chondrule fragments (Fig. 2). The size of the clast is $6 \times 5 \times$ a few mm^3. The opaque region of the clast is composed of troilite grains, Fe-Ni metal (Fig. 2), and small amounts of pentlandite enclosed within troilite (Fig. 9). Most of the metal grains are kamacite (5–6 wt% of Ni) and small amounts of taenite and high Ni taenite (tetrataenite: Ni$\sim$50 wt%) grains of a few μm in size are also observed. The Ni contents of kamacite and taenite in the clast are shown in Fig. 5. The modal ratio of metal to troilite of the clast in the thin section is about 0.18. The troilite grains in the clast are significantly larger (max. 630 μm in diameter) than those in the host. Small metal-sulfide droplets, similar to those in the host, are also

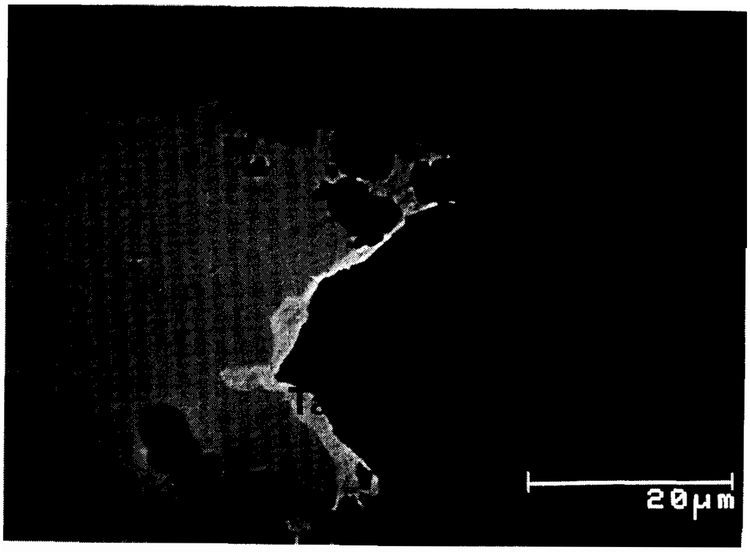

Fig. 9. Backscattered electron image of a part of the troilite-rich clast. Pentlandite grain is observed in a troilite grain. Km: kamacite, Ta: taenite, Tr: troilite, P: pentlandite.

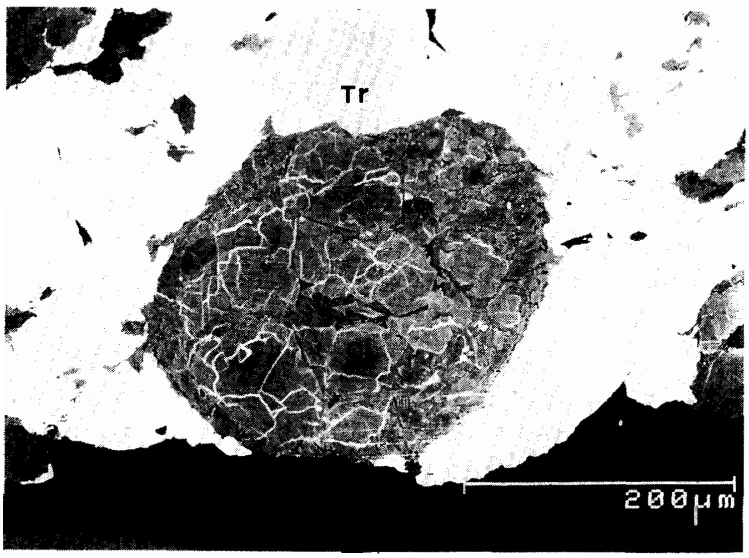

Fig. 10. Backscattered electron image of a chondrule enclosed in the troilite-rich clast. Olivines show compositional zoning. Ol: olivine, Tr: troilite.

observed. However, these do not occur along the boundaries of large grains of metal and troilite, but in the glassy inclusion and in the rim of a chondrule fragment.

Chondrules and their fragments in the clast are porphyritic chondrules mainly composed of olivine, pyroxene, and interstitial glass (Fig. 10). Chondrules in the clast also have the elongate shapes. Undulatory extinction of olivines and curved twin boundaries in clinopyroxene similar to those in chondrules in the host are also observed in the clast. Olivines in the chondrules and fragments have normal Fe-Mg zoning. Compositions of olivine grains (Fo_{85-93}) in the clast shown in Fig. 4 are similar to those in the host. Thus the chemistry, textures, and sizes of chondrules and their fragments are essentially the same as those in the host.

3. Discussion

3.1. Formation stage of the troilite-rich clast

The inclusion of chondrules in the troilite-rich clast found in the present study is unique, since large clusters of opaque minerals found in other chondrites (*e.g.*, SCOTT, 1982) contain no typical chondrules. Chondrules enclosed in the clast have essentially the same textures and compositions as those of chondrules in the host. This indicates that the clast is not an exotic fragment in the chondrite. Furthermore, the fact that the fragments of chondrules as well as chondrules themselves are enclosed in the clast suggests that the clast must have been formed after the solidification and fragmentation of chondrules at the last stage of chondrule formation of the chondrite.

Before the accretion of the chondrite, adhesion of sulfide liquid onto chondrules to form the clast must not have occurred because sulfide melt would not be stable at low pressure. Furthermore, it is unlikely that the selective clustering of troilite crystals on chondrules occurred before the accretion, because no such a clustering was generally found in both the host and other chondrites. On the other hand, the depletion of troilite in the region adjacent to the clast suggests that the clast must have been formed by the segregation of troilite-rich materials through liquid or solid flow during or after the accretion process.

3.2. Shock melting origin of the clast

The elongate shapes of chondrules with the preferred orientation in Moorabie resemble those observed in some ordinary chondrites (DODD, 1965; MARTIN and MILLS, 1980; SNEYD *et al.*, 1988) and carbonaceous Leoville chondrite (CV3) (WASSON, 1985; CAIN *et al.*, 1986; NAKAMURA *et al.*, 1990). The texture has recently been interpreted to be formed neither by deposition (DODD, 1965) nor by gravity compaction (CAIN *et al.*, 1986; MARTIN and MILLS, 1980), but by shock impact (WASSON, 1985), based on the micro-textures of constituent minerals by SNEYD *et al.* (1988) and NAKAMURA *et al.* (1990). SNEYD *et al.* (1988) studied the elongate shapes of chondrules and magnetic susceptibility anisotropy in fifteen ordinary chondrites, and suggested that they were formed by shock compaction based on the optical micro-texture and high dislocation densities of the deformed chondrules. The Moorabie chondrite also has the micro-textures such as undulatory extinction of olivine in the elongate chondrules, like Leoville and those reported by SNEYD *et al.* (1988) (*e.g.*, Mezö-Madaras (L3)).

Furthermore, the coexistence of the glassy matrix with the metal-troilite droplets and the crystalline matrix indicates an inhomogeneous melting event, and then the local shock melting. In the artificial shock experiments by SEARS *et al.* (1984) and KITAMURA *et al.* (1992), it is reported that olivine grains with deformation texture and mosaic extinction coexist with partial melt of the chondritic material. Therefore, the characteristics of the host of Moorabie; elongate morphology of chondrules, undulatory and mosaic extinction of olivine grains, partially molten matrix material and maskelynite, can be interpreted as the evidence of shock impact process during or after the accretion of chondrites.

Shock deformation of chondrites must allow the flows of solid phases, especially metal and sulfide (KITAMURA *et al.*, 1992). However, the selective flow and concentration of solid troilite grains is unlikely to form the large clast occurring beyond chondrules and mineral fragments. The difference between the grain sizes of troilite in the host and clast also suggests that the clast is not a simple aggregate of the metal-troilite grains by solid flow.

The modal ratio of metal to troilite in the clast (metal/troilite ~0.18), corresponding to the Fe/S ratio of 2.13 in weight, is different from typical Fe/S ratio of L chondrites (Fe/S=3; *e.g.*, DODD, 1981), but close to the eutectic composition (Fe/S~2.22) of the Fe-S system (*e.g.*, KULLERUD, 1963). Therefore, the composition of the clast suggests a possible formation process of the clast where the melt with eutectic composition in the Fe-S system was formed and then cooled.

The occurrence of pentlandite in troilite grains both within the clast and in the host chondrite is different from that of weathering products commonly encountered in weathered meteorites but displays the exsolution textures (*e.g.*, RAMDOHR, 1963). This is a first report of pentlandite in an ordinary chondrite, except for the cases of weathering products. The texture indicates that the sulfides originally contained a significant amount of Ni before the exsolution of pentlandite, and that the high Ni content was caused by rapid solidification from the melt of troilite and Fe-Ni metal. Therefore, the existence of pentlandite grains in the clast and host also suggests the melting origin of the clast and the local melting of the host, respectively.

Reverse zoning of the taenite cannot be interpreted by the simple cooling history. The formation of the texture can be explained by the following process. Firstly, slow cooling around 500°C provided the taenite composition around 40 wt% of Ni. Then, in the reheating process, since the stable compositions of the kamacite and taenite moved towards the Ni-poor value, taenite rim grew with the Ni-poor composition by the dissolution of the kamacite and then reverse zoning profile was formed. Cooling process after the reheating should have modified the compositional zoning in taenite. This model on the formation the reverse zoning in the taenite by reheating process after the condensation, implies that the reheating event was temporal and moderate so that kamacite was not completely changed to taenite phase, and then the shock heating event.

3.3. *Thermal history of the chondrite*

The nearly eutectic composition of the troilite-rich clast indicates that the original melt must have been formed around the eutectic temperature of the Fe-S system. Because the Ni content slightly lowers the eutectic temperature of the Fe-S system (988°C) (*e.g.*, KULLERUD, 1963), the actual eutectic temperature must have been around 950°C. The facts that (1) chondrules in the clast show no evidence of remelting after a chondrule formation and (2) the deformation of pyroxene in chondrules after the transition from protoenstatite also suggest that melting occurred at a temperature not much higher than the eutectic temperature of the Fe-Ni-S system.

The shock heating temperature of Leoville is estimated by WASSON (1985) to be 1000–1200 K in order to explain the plastic deformation of chondrule silicates.

Therefore, both the elongate chondrules and the clast in Moorabie are considered to have been formed simultaneously by the same shock heating event.

The center composition of the reversely zoned taenite provides a constraint for pre-reheating (pre-shock) temperature. Since the center has the composition of around ~40 wt% of Ni, during the exsolution in kamacite, the metal grains should be cooled to ~400°C before the reheating event. Therefore, the chondrite are concluded to be reheated from ~400 to ~1000°C by the shock event.

Cooling process after the reheating by the shock event will be estimated as follows. Solidification rates of metal and troilite clasts around the solidification temperature have been estimated based on the dendritic or cellular textures found by rapid cooling from the eutectic melt (SCOTT, 1982). However, in the present case, the metal and troilite in the clast lack dendritic or cellular texture. This type of the texture indicates that the solidification rate of the clast should be smaller than the lowest value (~1°C/s) of the SCOTT's rate meter. This slow solidification rate indicates that the shock heating event for formation of the clast must occur inside the parent body.

The estimation of the cooling rate around 500°C based on the kamacite-taenite texture, which was applied to the Shaw chondrites (L6) (TAYLOR *et al.*, 1979), cannot be applied to the clast in Moorabie, because the width of taenite observed at the rim of kamacite grains in the clast is only a few μm. On the other hand, the composition of those grains (up to ~50 wt% of Ni) crystallized from the eutectic melt implies that after the shock event, the cooling rate below 500°C was not much greater than the cooling rate of typical type 3 chondrite determined by NAGAHARA (1982). The result is concordant with that the shock event occurred at the stage where the parent body retained high temperature (not much lower than 400°C).

The above interpretation of the thermal history of the Moorabie chondrite requires high temperature accretion of the parent body. HUTCHISON and BEVAN (1983) reported that some chondrule glass in the Tieschitz chondrite (H3) retained plasticity after their accretion and suggested that ordinary chondrites accreted at 700–900°C. The result of the present study is consistent with their interpretation.

In a summary, the thermal history of the present chondrite can be interpreted as follows: (1) The chondrite accreted to its parent body at high temperature. (2) At the early stage (around 400°C) of the cooling, materials inside the body were reheated by the shock impact process which brought about the plastic deformation of chondrules and partial melting of metal-troilite grains at around 1000°C. (3) After the shock event, the materials cooled monotonously like as ordinary L3 chondrites.

3.4. Implication to the variation of the shock induced texture

As described formerly, there are many metal-troilite clasts interpreted as shock induced textures. However, they are usually accompanied with immiscible silicate melt and require higher melting temperature (*e.g.*, 1200°C for Ramsdorf: BEGEMANN and WLOTZKA, 1969) than that of Moorabie. This difference should be responsible for the absence of chondrule inclusion in the metallic clast reported in the former studies. On the other hand, not all the shocked chondrites enclose metal-troilite large clasts. As shown in the artificial shock experiments by SEARS *et al.* (1984) and KITAMURA *et al.* (1992), a moderate shock pressure on the cold chondritic material with low porosity could show the shock-induced texture such as undulatory extinction in olivine but was not sufficient for melting of metal and troilite. It should be considered that the reheating temperature in the shock event should depend not only on the shock pressure and the porosity of materials, but also on the stages of shocked materials in their thermal history. If the shock event occurred under high temperature condition, melting of chondritic material could occur by the moderate shock event, while it should require more severe shock condition to melt the cold chondritic materials.

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